PRODUCTION OF 100K TPA OF METHANOL THROUGH CATALYTIC HYDROGENATION OF CO_2 CAPTURED FROM AIR

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Supervised By

Engr Waqas Ahmed Khan

Group Member

Hashir Farhan Arif	UW-19-CHE-BSC-038
Muhammad Awais	UW-19-CHE-BSC-019
Faisal Malik	UW-19-CHE-BSC-029
Muhammad Daniyal	UW-19-CHE-BSC-024
Mehtab ur Rehman	UW-19-CHE-BSC-013

DEPARTMENT OF CHEMICAL ENGINEERING

WAH ENGINEERING COLLEGE

UNIVERSITY OF WAH, WAH CANTT

Production Of 100 k tons Methanol Through Catalytic Hydrogenation via CO2 Captured from Air

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This report is submitted to the Department of Chemical Engineering, Wah Engineering College, University of Wah for the partial fulfilments of the requirement for the

Bachelor of Science
In
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Internal Examiner

Sign: __________

FYDP Evaluation Committee

Sign: __________ July 17, 2023

Sign: Saleem

Sign: Junaid

Sign: Fareed

Department of Chemical Engineering,
Wah Engineering College,
University of Wah
Wah Cantt.

DEDICATION

TO OUR RESPECTED, ADMIRED, PROUD,

PARENTS AND TEACHERS

&

ALL THOSE WHO GAVE THEIR

YESTERDAY FOR OUR IMMACULATE

PRESENT

ACKNOWLEDGEMENT

We express our gratitude to **ALMIGHTY ALLAH** for granting us the fortitude to complete the last year project. We pay homage to His Holiness, **HOLY PROPHET MUHAMMAD**, whose teachings are a true source of wisdom and guidance for the entire human race.

We extend our sincerest appreciation to the head of the engineering department and our esteemed faculty members for their facility and leadership.

We are immensely grateful to our Parents for their unwavering moral support and commitment to our endeavors. We extend our sincerest gratitude to our Head of Department**, Dr. Shahram Shahzad**, Departmental Coordinator **Engr. Usman Asghar** and our Project Supervisor, **Engr. Waqas Ahmed Khan**, for their invaluable contributions in the form of constructive discussions, encouraging advice, inspiring leadership, astute recommendations, unwavering enthusiasm, constructive criticism, and cordial conversations which enabled us to produce this report. **Engr. Waqas Ahmed Khan** devoted a significant portion of his valuable time to provide guidance and assistance in the preparation of this report. His unwavering guidance, kind patronage, genuine coaching, and ongoing consultation were instrumental in the successful completion of this task.

ABSTRACT

CO_2 emissions are the major threat to our environment. The motive of this project is to remove already present CO_2 in atmosphere. In this project we use CO_2 present in air for the production of Methanol. Hydrogenation of air captured CO_2 is carried out in Multi-Tubular Packed Bed Reactor in the presence of specific combination of ($Cu/Zn/Al_2O_3$) catalyst & for this purpose H_2 is taken from nearby Hydrogen Production Plant. Detail design calculations of 100k tons/year of methanol production by CO_2 capturing along with their relevant aspects such as project feasibility, material of construction, instrumentation and control, environmental aspect and economic analysis has been done. Economic analysis shows that the rate of return would be around 3.4 years which means the project is economically feasible. As per economic analysis, using this emerging technique costs us around $480/t Methanol which is far cheaper than the current market price of $2800/ton Methanol and as a result of this operational plant we can store waste hazardous atmospheric CO_2 in the form of chemical bonds (Fuel/Methanol). Methanol is comparatively a clean-burning fuel that produces fewer smog-causing emissions. Methanol is widely used as (fuel & is also Intermediate for manufacturing of other useful products). Renewable methanol production is an Emerging Technology that bridges the gap in the shift from fossil fuel to renewable energy and as a result of this project we become sufficiently able to store waste hazardous atmospheric CO_2 in the form of high value product (Methanol). The project needs to be incorporated with industries to rely less on fossil fuels and move towards sustainable energy.

Keywords: ***CO_2 Capture, Methanol, Hydrogenation, MEA Solvent, Renewable Fuel, Environmental Pollution***

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1 CHAPTER NO 1: INTRODUCTION

1.1 Introduction:

Today, due to the expansion of the world economy, energy consumption is increasing rapidly. There is an abundance of fossil fuels (oil, coal, and gas) to meet this growing demand. Because burning fossil fuels releases CO2 into the atmosphere, it is often considered one of the worst environmental hazards. Various species, including animals, plants, and microbes, consume and produce CO_2, which is considered one of the greenhouse gases (GHG), and over time on Earth, the river, and air. However, nature must maintain a balance between the process of releasing and absorbing CO_2. Climate change has been an economic activity since the beginning of the industrial revolution in the 1750s. CO_2 sequestration and storage (CSS) systems have attracted much attention as a means of reducing greenhouse gas emissions. However, it will increase the amount of CO_2 that can be supplied as free energy. [1]

Thousands of things are produced every day, including plastics, paints, cosmetics and fuels, including the medical liquid methanol (CH3OH). Syngas, a mixture of hydrogen, carbon dioxide and carbon monoxide, is used to produce liquid methanol. These simple things can be achieved through different tools and by using different technical methods. [2]

1.2 Renewable Methanol:

Methanol is a type of chemical that's made from renewable energy sources like biomass, carbon dioxide, and hydrogen. It's a great way to reduce your carbon footprint. Renewable methanol totally removes Sulphur oxides and particulate matter while reducing nitrogen emissions by 80% and carbon dioxide emissions by up to 95% when compared to conventional fuel. [3]

Methanol is one of the most significant and often used laboratory solvents in scientific settings. This adaptable substance is a crucial component in several daily items and significant chemical processes, not simply in laboratories. Chemically speaking, methanol is an alcohol molecule with a methyl group.

1.3 Raw Materials:

- [Air (CO_2) & H_2] are the primary Raw Materials for this process. [4]
- Concentration of CO_2 in Air is 420.10ppm (by June, 2022). [5]
- We can easily get the required quantity of CO_2 from the Air
- And H_2. Will be consumed by nearby Hydrogen production plant. [6]
- We will use H_2 as per our requirement

1.4 Physical and Chemical Properties:

Air:

Table 1-1: Composition of Air

Important Gases			
Name of the Gas	**Chemical Formula**	**In percentage**	**In ppmv**
Nitrogen	N_2	78.084	780,840
Oxygen	O_2	20.946	209,460
Carbon Dioxide	CO_2	0.039445~0.04	394.45~ 400

Table 1-2: Properties of Air

Parameters	**Value**
Density	1.229 kg/m^3
Pressure	1.013 kN/m^2
Specific Volume	0.814 m^3/kg
Temperature	15°C / 288 K
Specific heat ratio	1.4
Gas Constant	0.286 J/g/K
Viscosity	1.73×10^{-5}N-s/mc
Molecular Weight	28.97 gram per mole
Thermal Conductivity at 0°C	24.35 W/mK
Thermal Conductivity at 20°C	0.026 W/mK
Gravity Acceleration	9.8 ms^{-2}

1.5 Hydrogen:

1.5.1 Physical properties

At standard conditions, H_2 is [7,8]

- Non-Toxic and Non-metallic
- Taste less

- Odorless
- Colorless
- less dense than air
- And highly combustible diatomic gas

1.5.2 Chemical Properties:

- The melting point of hydrogen is -259.14°C.
- The boiling point is - 252.87°C.
- The density of hydrogen is 0.08988 grams per litre (g/L).
- Hydrogen is an oxidizing and reducing agent.
- The combustion enthalpy for hydrogen is - 286 kJ/mol.

1.6 Methanol

1.6.1 Physical Properties

- Colorless
- Volatile
- Flammable
- Faintly sweet pungent odor
- Its vapors are slightly heavier than air

1.6.2 Chemical Properties:

- Molecular mass of 32.04 g/mol
- Molecular density of 792 kg/m³
- Soluble in water
- Boiling point of (64.70°C)
- Melting point (-97.6 °C)

1.7 Chemical Reaction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \Delta H = 41.21$$

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \Delta H = -90.77$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \qquad \Delta H = -49.16$$

1.8 Applications:

Methanol is used in a variety of chemical reactions, common items and innovative technologies like.[9,10]

Formaldehyde:

Methanol is easily turned into formaldehyde, the most frequent industrial product. It includes kitchen countertops, furniture, and automobile interior components. It is also an effective preservative in medicines and personal care items.

Biofuel:

Methanol, rather than petrol, can be utilized as the primary renewable fuel. It is less costly, less flammable, and quicker than petrol. Despite its poor energy density, it is utilized as a fuel in race vehicles all over the world. When coupled with potassium hydroxide, it can potentially substitute diesel.

Windshield Washer Fluid:

Because alcohol has a lower freezing point than water, it is ideal for washing windows. Ice and alcohol mix, lowering the temperature and ultimately melting the ice.

Wastewater Denitrification:

This is a vital procedure because it prevents hazardous and poisonous algal blooms from forming and contaminating our water. Bacteria that thrive in the presence of nitrate generate algal blooms. The addition of methanol to the wastewater system boosts the activity of anaerobic bacteria. These bacteria may degrade nitrate in water and release it into the atmosphere as nitrogen. This procedure is becoming increasingly widespread in wastewater treatment plants around the country.

Fuel Cells:

Methanol functions as a fuel in the fuel because it can store a large quantity of energy while taking up little space. These cells are frequently seen in compact devices like laptop computers and cell phones.

DME:

Methanol may be turned to dimethyl ether, which is a common air conditioner. It also has characteristics that make it an excellent fuel for diesel engines.

Acetyl Resin:

This makes your thermoplastic the most durable, heat resistant, and long-lasting. It is simple to color, has little friction, and is resistant to wear. As a result, it is ideal for heavy-duty machining in areas such as automotive, technology, and healthcare.

Camping Fuel:

Methanol is commonly used to power camping stoves by many hobbyists. In reality, a minimal amount of fuel is required to heat the stove, and it burns rapidly, making it a popular choice for camping trips.

Acetic Acid:

Methanol is a component of acetic acid, which is used in the food sector for pickling, home cleaning, and as an antiseptic in medical operations.

Laboratory Solvent:

It is frequently employed as a solvent in HPLC analysis or UV/VIS spectroscopy. It is also an effective cleanser and solvent for the development of laboratory standards for instrument testing. It can even function as a retainer in gel electrophoresis.

Transportation:

Because of the geographical and demographic character of the methanol industry, obtaining methanol products from manufacturers and consumers is heavily reliant on transportation. Methanol is manufactured all over the world and utilized in a variety of applications. Because of the imbalance between production and demand, up to 80% of the world's yearly methanol output must be moved across continents. The exposed losses from the methanol industry's abrupt and unpredictable discharge include the safety, dependability, and integrity of transoceanic navigation, berth delivery, and port safety.

Ocean-Going Transport:

Methanol is delivered from liquid storage tanks into a closed vessel's cargo hold. Pipeline, barge, rail, or truck delivery to dockside storage are all options. The transient transit of hydrocarbons is comparable to that of crude oil, petrol, diesel and fuels like MTBE. Shippers frequently employ double-decker ships, which will become more widespread as global manufacturing grows.

Rail Transport:

The rail transport precautions include Ethanol, Petrol, Jet Fuel (Kerosene) and Distillate. Vertical discharge shielding is included in the grounding of purpose-built tank cars. The use of pressure relief devices in purpose-built tank cars allows thermal expansion to be handled during transport. The use of a pressure relief device in a purpose-built tank car allows for short transit and short storage pauses (under 30 days). As long as methanol inside the tank car remains stable, the rail shipment is considered safe.

Tanker Truck Transport:

Tank car phrases also refer to tanks installed on truck tractors and vehicles hauled by truck tractors. Methanol transportation via truck is as careful as petrol transportation.

Methanol Storage:

- The safety of methanol is primarily dependent on the same substance that is used to ensure the safety of gasoline. Methanol is always kept in tank farms made up of above-ground and tiny, sophisticated floating tanks. • To avoid the risks associated with vertical discharge, tanks must be levelled. • Fire control can be performed using nitrogen padding, gas, or by identifying risky spots and ignition controls. Because methanol and other solvents are kept in feedstocks, all pipelines and valves capable of carrying methanol should be labelled in the direction of flow at all times.
- Berms and appropriate ventilation are required for any storage, including bins and drums.
- It's important to stabilize the berming by making it smaller, using a fabric that's resistant to methanol, or using concrete.
- Methanol burns inertly, which may be difficult to see in direct sunshine. Responders should have infrared sensors that can detect and measure temperature. If at all practicable, this capacity should be available on emergency response helicopters. [11,12]

Marine Terminals and Docks:

Methanol storage devoted tanks are often used at ports and harbours. To prevent pollution, a floating roof is selected. These installations might include leak detectors and alarms. Appropriate spill mitigation and response skills are critical and will very certainly be needed by insurers.

Tank Farms:

Methanol storage and handling systems may be installed in industrial tank farms such as refineries and chemical facilities. Typically, the tank is elevated above the ground, the pipe is elevated, and the top is elevated above the pipe. In general, fuel safety is adequate for methanol tanks as long as additional procedures for leak detection, chemical risks, and the presence of hot foam associated with wine are adopted. [13]

Portable Containers

Methanol business worked hard to create and produce widely available containers. Because the number of enterprises with high storage and control systems outnumbers the number of users of totes and drums, this handbook emphasizes the necessity of employing methanol storage for storing bins and drums.

Engineering Controls

Wherever feasible, liquid methanol is pumped mechanically from drums or other storage containers to organize containers and reduce the risk of exposure. Methanol should always be stored in a closed system and should never be exposed to the elements. [14]

Ventilation:

The house's ventilation system must offer fresh air for normal functioning and must consider the outcome. Ventilation may be adequate in some circumstances; otherwise, ventilation systems should be supplied. The standards for air emissions should be defined at each site, although the ultimate objective should be to keep air methanol concentrations at or below 200 ppm.

Exposure Monitoring:

Methanol has a somewhat sweet, alcoholic odor but does not become detectable until concentrations of 2000 ppm or more are achieved, which is 10 times the human safety limit of 200 ppm. Because methanol odor is a poor predictor of concentration, determining the amount of exposure is critical. This is required to verify that the employee's health is not jeopardized and to assess compliance with any applicable legislation.

Personal Protective Equipment:

When using or handling methanol, it is possible to become exposed through inhalation, absorption through the skin, contact with the eyes, or ingestion of the substance. The amount of personal protective equipment required will depend on the degree of risk associated with the exposure to methanol. At the very most, safety glasses should be worn with side shields, or safety glasses and work-specific gloves should be worn. Depending on the situation, additional personal protective equipment may be required. [15]

Table 1-3: Respiratory Protection Guide

Concentration of methanol in air	Respiratory Protection
<200 ppm	You don't have to wear any protective gear, but you might still need to cover your skin and eyes.
200 ppm or greater	If you exceed your daily TWA exposure, or if you have other ways of getting exposed (like through your skin, eyes, or food), you'll need protection. If you don't have any protection, you'll need to use the air system provided.
>200 ppm sustained	The air breathing apparatus must be equipped with a supplied (positive-pressure) SCBA system.

1.9 Chemical-Resistant Clothing/Materials:

Chemical-resistant clothing/materials should be used when coming into contact with methanol on a regular or extended basis. Rubber boots, hefty gloves, and other waterproof and heavy apparel are examples. Butyl rubber and nitrile rubber are examples of resistant materials. When there is a possibility of methanol exposure, especially vapour, use chemical goggles. A complete face mask can be worn over the glasses for added protection, but it cannot be used in place of the eyes. [16]

1.10 Safety:

1.10.1 Routine Operations:

It may be ignited by electricity due to the burning of methanol vapor. As a result, grounding and bonding should always be used when static electricity is present and necessary for all equipment. Carbide tips are frequently utilized (to guarantee good paint contact) and tube inserts are frequently used to store electricity. The following is a comprehensive list of additional safety protocols to be adhered to. Specific or high-risk occupations may require additional protective measures, which are addressed in the following section. Smoking must be prohibited.

- Access to vehicles must be restricted.

- Adequate ventilation is required to deal with the amount of dust predicted in the building. In situations where methanol is not available, such as control rooms, switch rooms, and smoke rooms, positive pressure may be necessary.
- The vent from the storage tank to the vent should be sized to allow for the escape of hot steam in an emergency. To fulfil national electrical code criteria, electrical equipment must be non-explosive.
- For usage on methanol fires, alcohol resistant film (AR-AFFF) equipment with a 6% foam dose (with water) is advised. Dry chemical compounds must be resistant to low temperatures.
- Slight spills need to be covered with sand, dirt, or other hot materials before thoroughly wetting the area. Excessive spills will be cleansed with water and disposed off.
- The light must be switched on. A well-grounded fire rod should be installed on boats and high-rise structures. [17]

1.11 Production and Consumption Data:

- The Consumption of the Methanol in Pakistan is quite large than its Production.
- For this reason, we Import more than 100K TPA Methanol worth 15 million $
- Because it is a very important chemical for a range of Industries such as

1.12 Current Methanol Demand by Region:

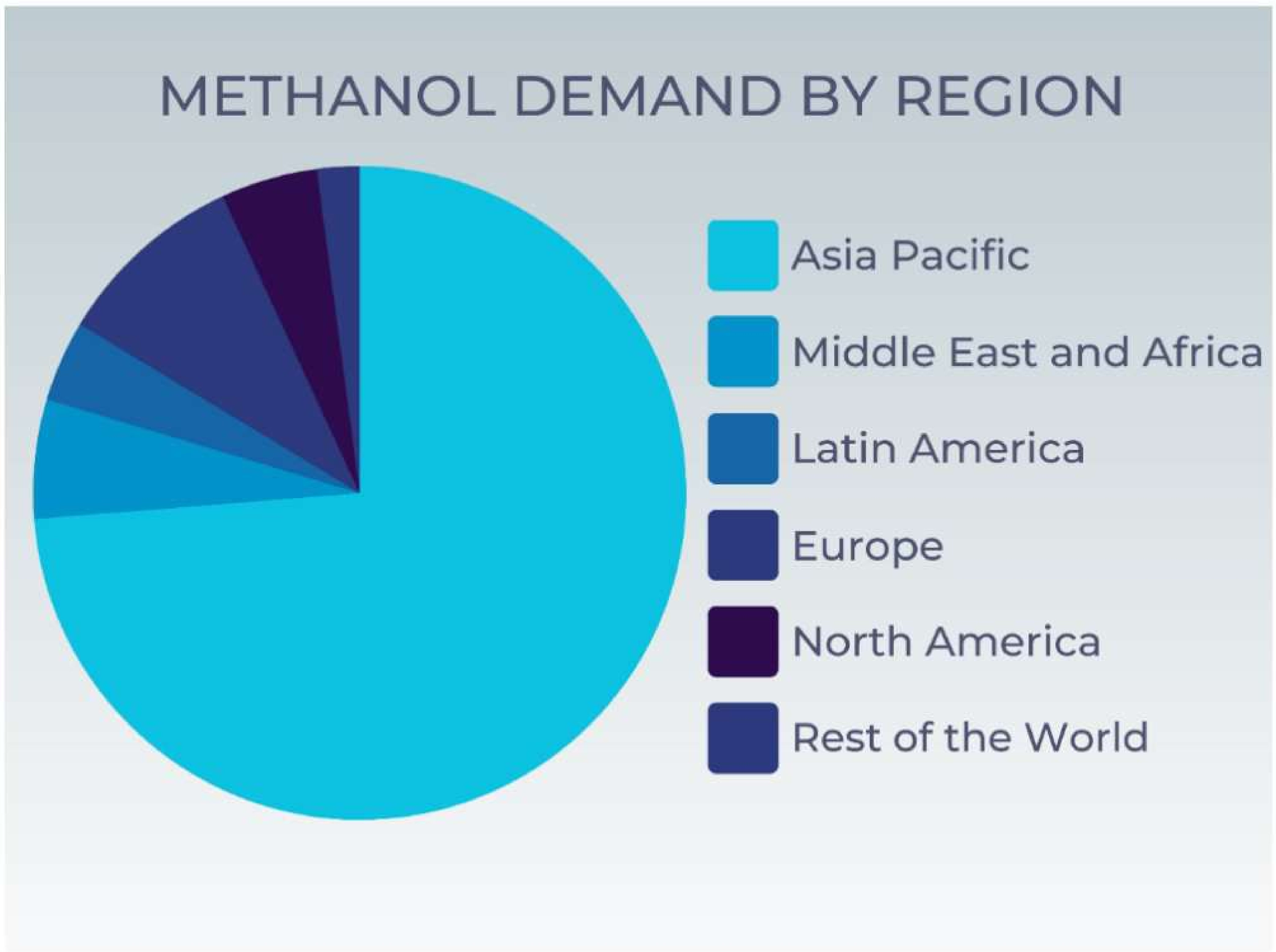


Figure 1-1: Current Methanol demand by Region

1.13 Methanol Demand of Pakistan:

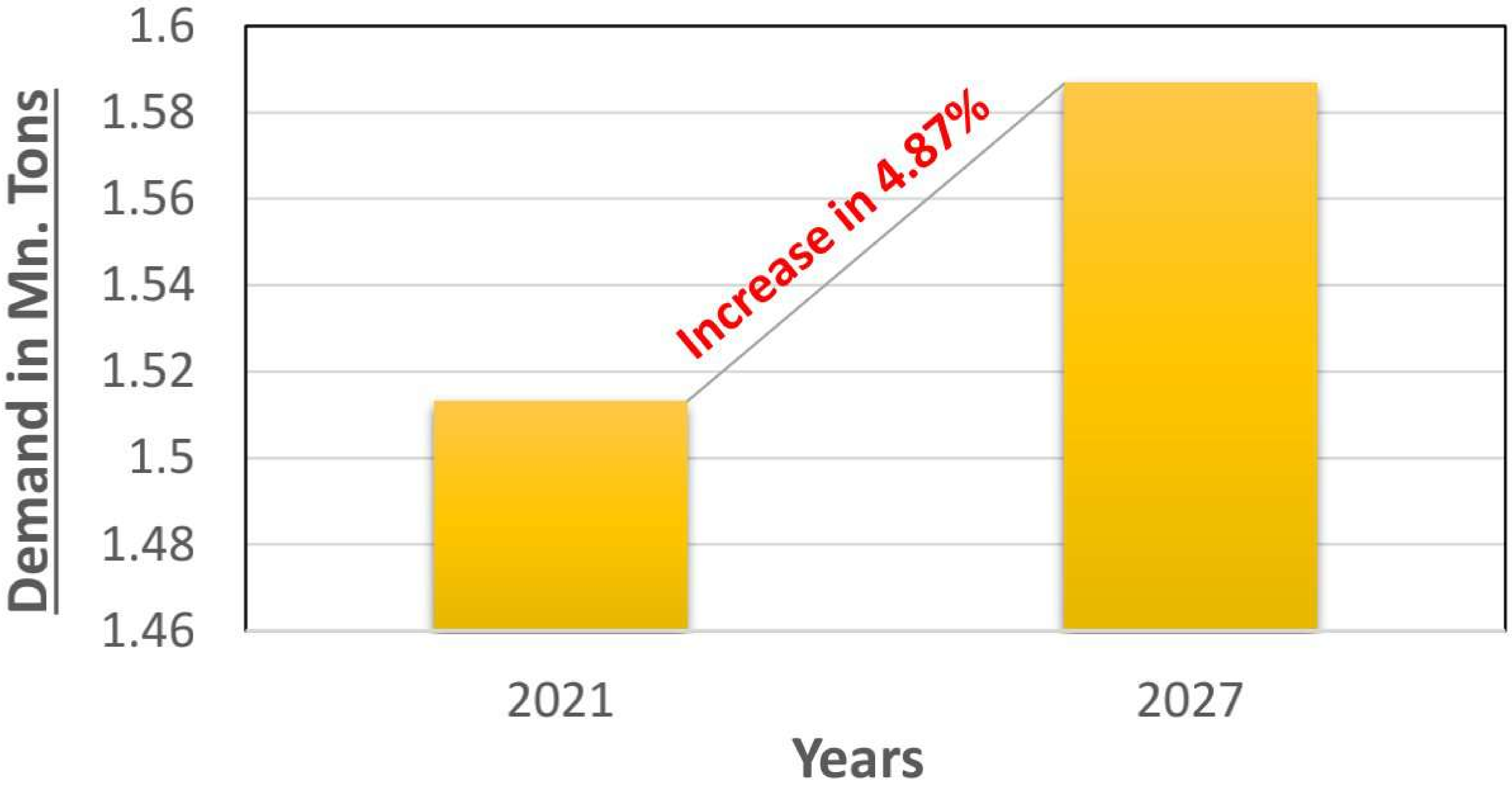


Figure 1-2: Methanol Demand of Pakistan

1.14 Methanol Consumption of Pakistan:

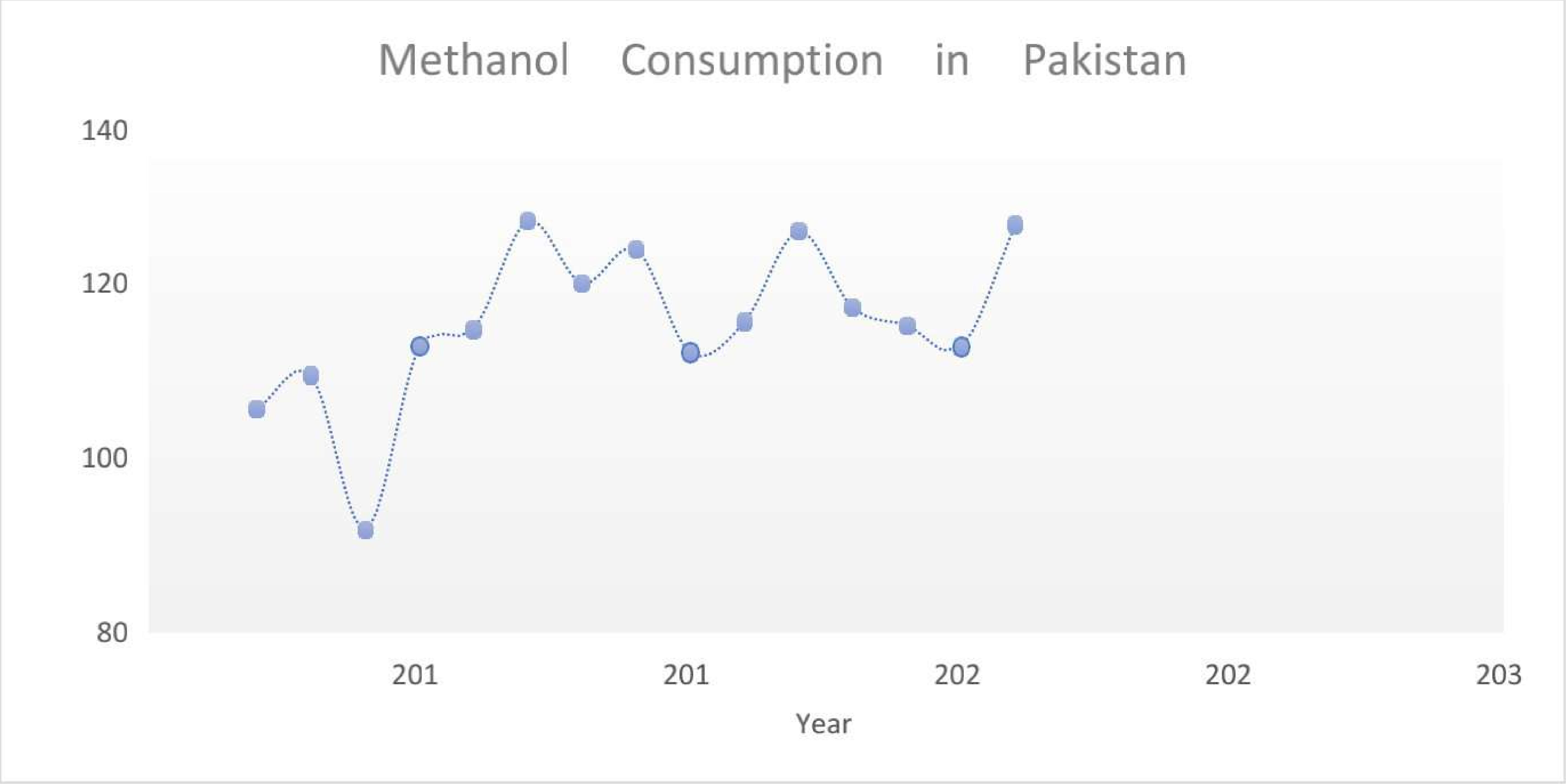


Figure 1-3: Methanol Consumption of Pakistan

1.15 Pakistan Import Data of Methanol:

Table 1-4: Pakistan Import Data of Methanol

Period	Trade flow	Reporter	Partner	Trade value	Net Weight kg	Qty Unit	Qty
2021	Import	Pakistan	World	$ 75,292,312	26,217,034	kg	26,217,034
2021	Import	Pakistan	Belgium	$ 26,574	8,592	kg	8,592
2021	Import	Pakistan	China	$ 313,266	118,676	kg	118,676
2021	Import	Pakistan	France	$ 2,191	637	kg	637
2021	Import	Pakistan	Germany	$ 256,556	62,959	kg	62,959
2021	Import	Pakistan	Iran	$ 39,681	12,000	kg	12,000
2021	Import	Pakistan	Italy	$ 383	120	kg	120
2021	Import	Pakistan	Malaysia	$ 6,849	2,147	kg	2,147
2021	Import	Pakistan	Saudi	$ 74,386,487	25,925,200	kg	25,925,200

1.16 Motivation:

1. Carbon dioxide converts into a form that can be used as a form of fuel, a fuel additive, or a precursor for complex transportation applications, or as an intermediary for a variety of industries.[18]
2. Methanol is stable at room temperature, which makes it much simpler to store and transport.
3. The process of renewable electrical methanol involves the conversion of renewable electrical energy into chemical energy, which is then stored in the molecular bonds of methanol.
4. By capturing CO2 and converting it into methanol, not only does it have the potential to grow exponentially as a raw material or fuel, but it also has the potential to recycle a massive amount of CO2 in the atmosphere.
5. Methanol is traditionally manufactured on an industrial scale from the synthesis gas "syngas". However, processes for the synthesis of methanol using syngas often involve the addition of a variety of light and heavy-weight co-products. These co-products are the result of a complex series of interactions between the three reactants and the catalyst surface.
6. In addition, producing Methanol fulfils the its massive demand in the industries and other applications

It is such a hydrocarbon that is widely used in several industries and also has many other applications. Such as transportation fuel, it also acts as intermediate for the manufacturing of other very useful products. The data shows that it has a huge demand in Asia Pacific Region and Pakistan is one of the countries lie here in this region and has a huge demand of the product. [19]

1.17 Industrial Reference:

The CRI George Olah Facility is the largest carbon dioxide methanol plant in the world, with a capacity of over 5 million litres annually. In 2015, CRI increased this capacity to over 5 million litres, resulting in a total of 5.5 million tonnes of carbon dioxide being recycled annually. The facility is powered solely by Iceland's grid, with the majority of its electricity coming from geothermal and aquatic sources. [20]

2 Chapter NO 2: Process Selection

2.1 Available Manufacturing Processes:

Most commonly produced Methanol on a commercial scale is from:

- Natural gas
- Coal.

And secondly from Renewable Sources i.e:

- Municipal waste
- Biomass

It can also me synthesize through Hydrogenation of $CO_{2.}$ [21]

2.1.1 Conventional Methanol Production Methods:

Methanol was once generated on an industrial scale from "syngas" gas synthesis. Processes for mixing methanol from syngas frequently produce a large number of light and other heavy products in addition to the methanol output. The resulting compound is the result of a complex reaction in which three reactive gases interact with each other and with the catalyst surface. These products are typically the primary source of consumption and associated costs within methanol plants due to the fact that they must be separated from the final product before disposal.

2.1.2 Renewable Methanol Production Method:

Production of Methanol from CO_2 Hydrogenation is a Renewable Methanol Production technique. This technique is the most advance one as it uses the already existing CO_2 in the air and transform this CO_2 to Methanol through Hydrogenation process. Currently World is shifting from Conventional Methanol Production Techniques to Renewable Methanol Production Technique. [22]

Greenhouse gas emissions can be reduced by reducing carbon dioxide emissions and transitioning to renewable energy sources and beneficial chemicals.

As a result, carbon capture and recycling (CCR), the usage of CO_2 and its conversion into fuel and chemicals, is an active alternative that is employed globally to change these products. It is not only employed in beneficial items, but it is also used to minimize CO_2 emissions, which is a factor. better. CSS choices should be compared. In recent years, the conversion of CO_2 into chemicals has contributed value (ie (for example, of fossil fuels)) and energy conservation [8] Methanol is an environmentally friendly fuel that can be used as a transport fuel. It is a renewable resource that can be produced from any carbon-based material (mainly carbon dioxide). In general, to meet market demand for fuel, it must be environmentally friendly, clean, and made from easily accessible resources. Methanol is regarded as one of the most essential raw resources that may be utilised in a global industry that generates 65 million tonnes per year.

2.2 Methods to Convert CO_2 to Methanol:

There are several methods for converting CO_2 as a catalytic process, including conventional, electrocatalytic, photocatalytic, and photo electrocatalytic conversion. [23] Such as

- Heterogeneous Catalysis
- Homogeneous Catalysis
- Electrochemical Process
- Photochemical Process
- Photo-electrochemical Process

2.2.1 Catalytic Hydrogenation:

The simplest technique for producing methanol and DME from CO_2 is catalytic hydrogenation of CO_2 and H_2. The earliest methanol manufacturing was carried out in the United States throughout the 1920s and 1930s, using CO_2 and H_2. A number of researchers have examined both natural and manufactured CO_2 hydrogenation methods. Composite materials, on the other hand, provide several advantages in terms of separation, stability, control, cost, and recycling.

2.2.2 Heterogeneous catalytic conversion:

Although homogeneous catalysis is utilised to produce methanol from CO_2, chemical reaction engineers prefer heterogeneous catalysis due to the benefits of heterogeneous catalysis. This comprises easy water separation from the solid result, effective control, and several types of reactors (ie, liquid, liquid, or bed) and the catalyst, as well as -do something that can be repeated. Many studies, however, have demonstrated that Cu-based catalysts with various additions such as Al_2O_3 an essential role in increasing the stability and performance of various catalysts. [24]

As a result, several metals (such as Cu and Zn) and their oxides have been created for use as catalysts in the CO_2 to methanol conversion process.

2.2.3 Comparison of Available Manufacturing Processes:

Table 2-1: Renewable Methods Comparison

Renewable Methods					
Process	**P (bar)**	**T(^{O}C)**	**Pross**	**Cons**	Effeciency **(%)**
Biomass	50-85	950-1050	Economical Due to abundance of raw material	High silica causes operation problems like clogging and slagging	Upto 40%
Homogeneous CO_2 Hydrogenation	60-75	145	Economicaland Eco Friendly	Silicates and hydrides are main reducing agent. The cost of silicates is high	Upto 45

Table 2-2: Heterogeneous Hydrogenation Process Comparison:

Heterogeneous CO_2 Hydrogenation	40-50	250-270	Convenient Handling in different typesof reactors Economical and Eco-Friendly	Loss of Cu/Zn based catalyst during process	Upto 50%

Table 2-3: Characteristics of Selected Process

Heterogeneous Hydrogenation Process Comparison				
Catalyst	**Temperature (°C) / Pressure (Bar)**	**Cost ($)**	**Conversion %**	**MEOH Selectivity**
Co–O–SiO	320 °C	1100	8.6	70.5%
In2O3/ZrO_2	300 °C	950	17	90.2%
Cu/Zn/Al/Zr	200-260 OC	900	13.1	>70%
Cu-ZnO-Al_2O_3	250-270 OC	875	17.19	99%

2.3 Selected Process Characteristics:

Reaction Temperature	250-270 OC
Pressure	50 bar
Catalyst	Cu-ZnO-Al2O3 (60/30/10) mol%
Conversion per pass	17.19%
Selectivity	99 %

2.4 Process Description:

- Mono-Ethanol-Amine (MEA) absorb CO2 from air. The process has 90% efficiency.
- Then CO2 is desorb from Rich MEA in Stripper and is used in the Hydrogenation Process.
- And we use wet Hydrogen stream here in this process.
- The wet hydrogen enters in stripper and flows in counter-current, resulting in separation of methanol- water mixture & CO/CO2 gases.
- Then the gases CO, CO_2 & H_2 (High Pressure gases) leaving from top of stripper enters a separator where methanol-water mixture is separated from the cooled outlet stream of the reactor thus allowing the complete recycle of CO_2 & CO and avoids its presence in the product.
- This recycle stream then pass through Heat Exchangers and enters the reactor. [25]

2.5 Capacity Selection:

- Total Consumption of Methanol in Pakistan = 113 Tons/year. (83% supply through Import).
- So, our selected Plant Capacity is almost the quantity of Methanol we Import.
- Capacity = 100 Tons/year Methanol
- Physically Running Renewable Methanol Production Plants have average Capacity of 100 Tons/year.

2.6 Already Existing Industries of Similar Capacities:

- ENI Refinery, Livorno. Renewable Methanol Production Plant (Capacity of 115 t/yr).
- Värmlandsmetanol (SE) is a Renewable Methanol Production Plant (Capacity of 100 t/yr).
- GSFC Vadodara, India, Renewable Methanol Plant (Capacity 100 t/yr).
- Low-Land Methanol is a NextChem Technology, Renewable Methanol Production Plant (Capacity of 120 t/year). [26]

2.7 Block flow Diagram:

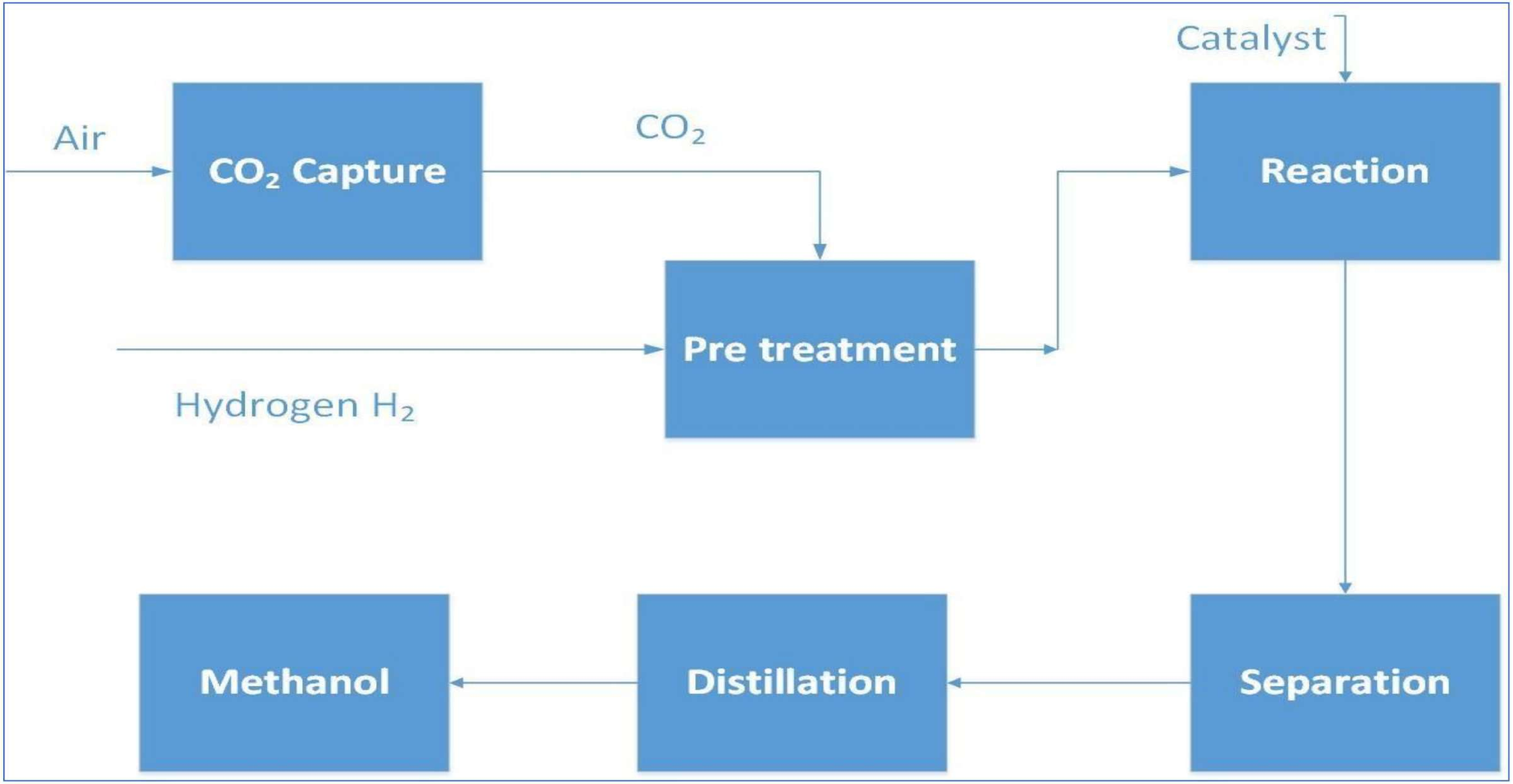


Figure 2-1: Manufacturing of Methanol through Hydrogenation of CO2, captured from Air (BFD)

2.8 Process Flow Diagram:

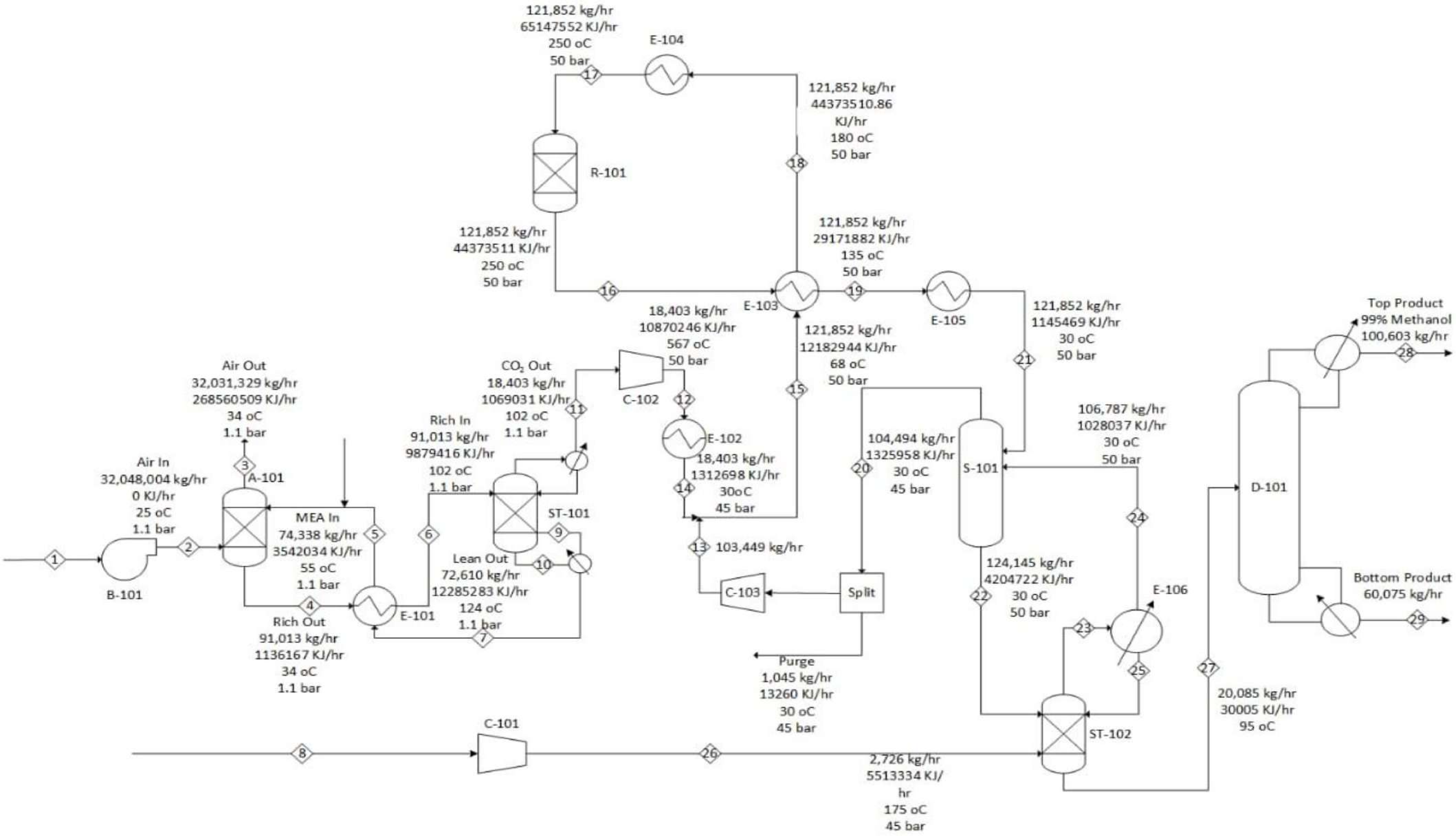


Figure 2-2: Manufacturing of Methanol through Catalytic Hydrogenation of CO_2 Captured from Air (PFD)

3 Chapter NO 3: Material Balance

Material Balance:

Input + Generation– Output – Consumption = Accumulation

At steady state, accumulation becomes zero so

Input – Output + Generation – Consumption = 0

Basis:

1 hr of operation

Assumption:

Plant is running at steady state condition.

Plant Capacity:

Production capacity of plant per year =100K tons/year

Operating Time:

300 DPY

Production Rate:

1000000 Ton	1000 kg	1 year	1 day
Year	1 Ton	300 day	24 hr

For 300-day production rate of methanol is 138888.88 kg/hr and we take the approximate amount of about 138888 kg/hr.

Production rate of Methanol per year = 1000000 TPA

3.1 Material Balance around Absorber (A-101):

In the absorber Air is feed with MEA and product is absorbed CO_2

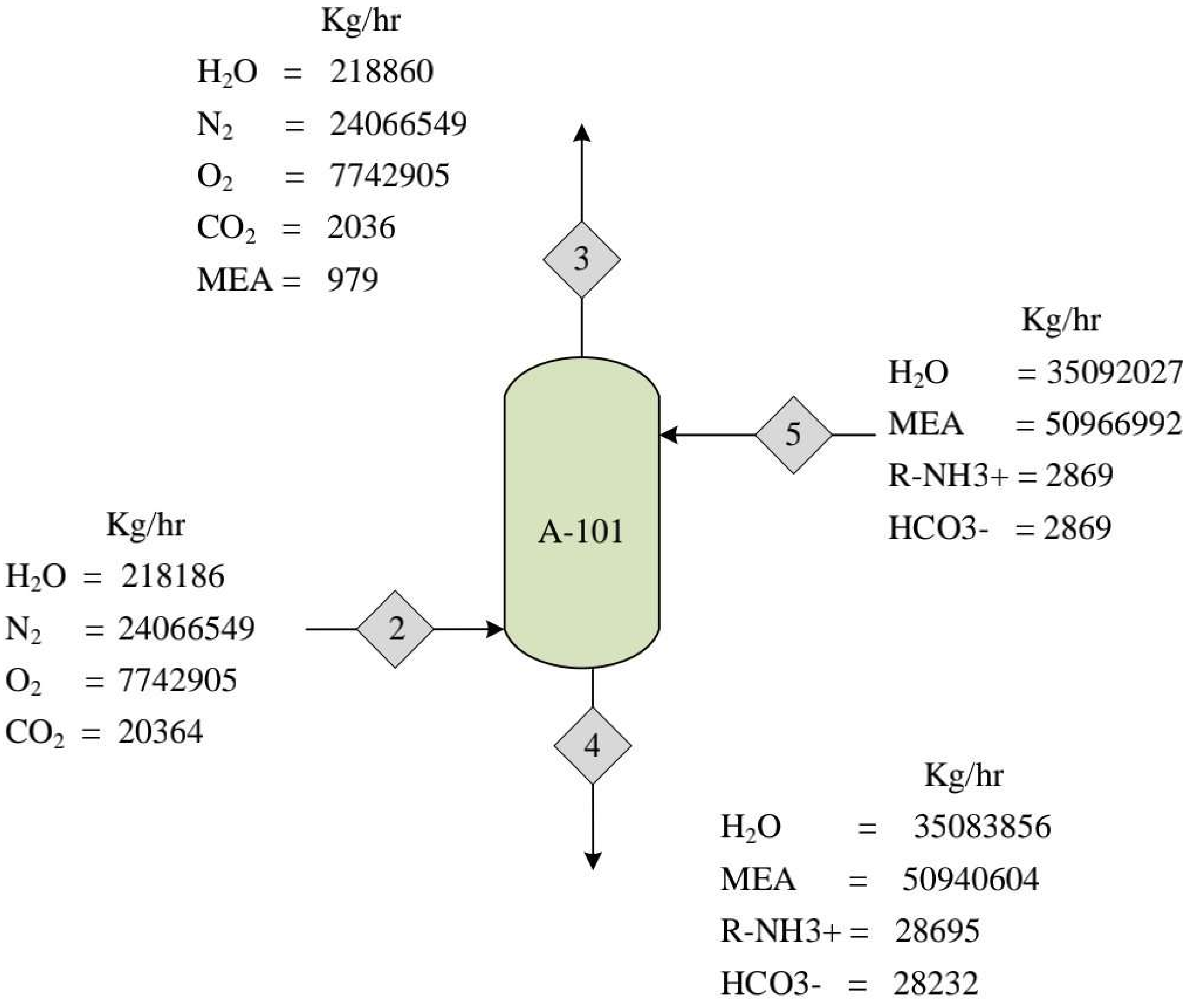


Figure 3-1: Absorber (A-101)

Reaction:

$$R\text{-}NH_2 + CO_2 + H_2O \longrightarrow R\text{-}NH_3 + HCO3^-$$

Table 3-1: Reaction Specifications

Reaction Specifications	
CO_2 Capture Rate	90%
Fraction	0.9
Temperature / Pressure	35 °C / 1 Bar
L/G	2.5

Table 3-2:Air Composition

Components	Components	Mole Fraction	Mol flow rate (Kmol/hr)	Mass flow rate (Kg/hr)
Air	N2	0.780	859,520	24,066,549
	O2	0.220	241,966	7,742,905
	CO2	0.00042	463	20,364
Total Flow Rate		1	1,101,948	31,829,818

Conversion of the CO_2 present in the air feed stream is 90%

Consumption:

Feed K Moles CO_2 × Conversion = CO_2 moles reacted

$462.8182 \times 0.90 = 416.5364205$ Kmol CO_2 Reacted

Moles of water reacted = 416.5364205

Moles of MEA reacted = 416.5364205

Generation:

Stoichiometric coefficients of each reactant & product are 1

416.5364205 moles of $R\text{-}NH_3^+$

416.5364205 moles of HCO_3^-

Table 3-3: Material balance around Absorber

Components	Input (Kg/hr)		Mass Consumed	Mass Generated	Output (Kg/hr)	
	Stream 2	Stream 5			Stream 3	Stream 4
	Air In	Lean In			Air Out	Rich Out
H_20	218,186	35,092,027	7,498	-	218,860	35,083,856
N_2	24,066,549	-	-	-	24,066,549	-
O_2	7,742,905	-	-	-	7,742,905	-
CO_2	20,364	-	18,328	-	2,036	-
MEA	-	50,966,992	25,409	-	979	50,940,604
R-NH3+	-	2,869	-	25,825	-	28,695
HCO3-	-	2,823	-	25,409	-	28,232
Total	32,048,004	86,064,712	51,234	51,234	32,031,329	86,081,387

3.2 Material Balance Around Stripper (ST-101):

In the stripper feed is MEA and Product is CO_2

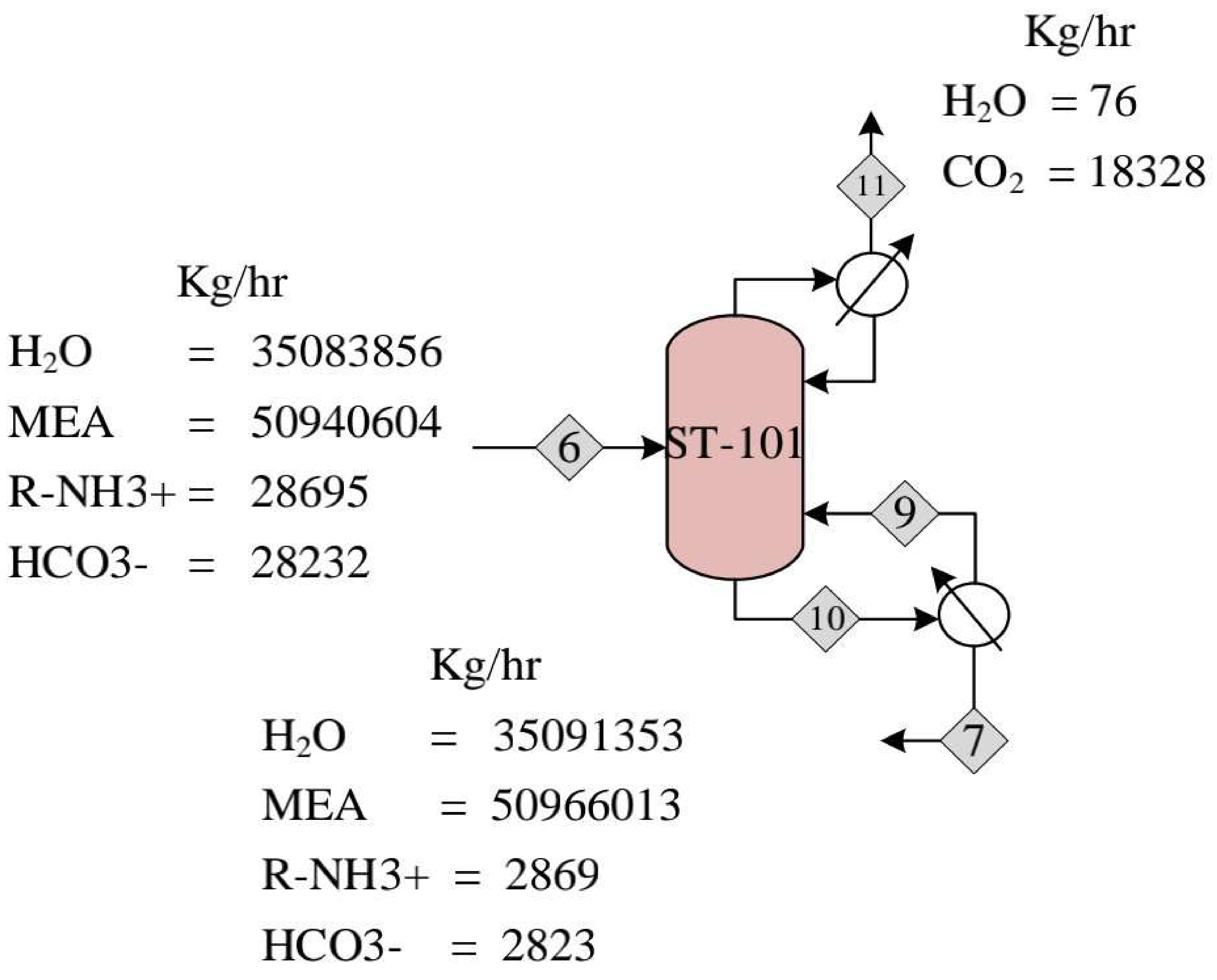


Figure 3-2: Stripper (ST-101)

Reaction:

$$R\text{-}NH_3^+ \; HCO_3^- \xrightarrow{\qquad\qquad} R\text{-}NH_2 + CO_2 + H_2O$$

Conversion = 90%

CO2 Purity = 99%

Temperature = 125°C

Pressure = 2 Bar

Stripper feed contains 462.818 Kmoles R-$NH3^+$ & 462.818 Kmoles $HCO3^-$

Conversion is 90% of this reaction

462.818 Kmoles HCO_3^- × 0.9 (conversion) = 416.536420 Kmoles CO_2 produce

As the CO_2 product is with 99% purity

So, the total CO_2 product stream contains 99% CO_2

Total CO_2 product stream flow rate = 420.744 Kmoles / hr

Unreacted HCO_3^- = (moles of $HCO3^-$ fed) – (moles of $HCO3^-$ reacted)

462.818 Kmoles - 416.536 Kmoles = 46.281 Kmoles HCO3- unreacted (recycle back to the absorption column)

Table 3-4: Material Balance Around Stripper (ST-101)

Component	**Input (Kg/hr)**		**Consumed**	**Generated**	**Output (Kg/hr)**		
	Stream 6	**Stream 9**			**Stream**	**Stream 7**	**Stream 11**
	Rich In	**Steam In**			**Steam Out**	**Lean Out**	**CO_2 Product**
H_2O	35,083,856	4,165	-	7,498	4,090	35,091,353	76
N_2	-	-	-	-	-	-	-
O_2	-	-	-	-	-	-	-
CO_2	-	-	-	18,328	-	-	18,328
MEA	50,940,604	-	-	25,409	-	50,966,013	-
R-NH3+	28,695	-	25,825	-	-	2,869	-
HCO3-	28,232	-	25,409	-	-	2,823	-
Total	86,081,387	4,165	51,234	51,234	4,090	86,063,059	18,403
Total	86,085,552		51,234	51,234	86,085,552		

3.3 Material Balance Around Reactor (R-101):

Kg/hr

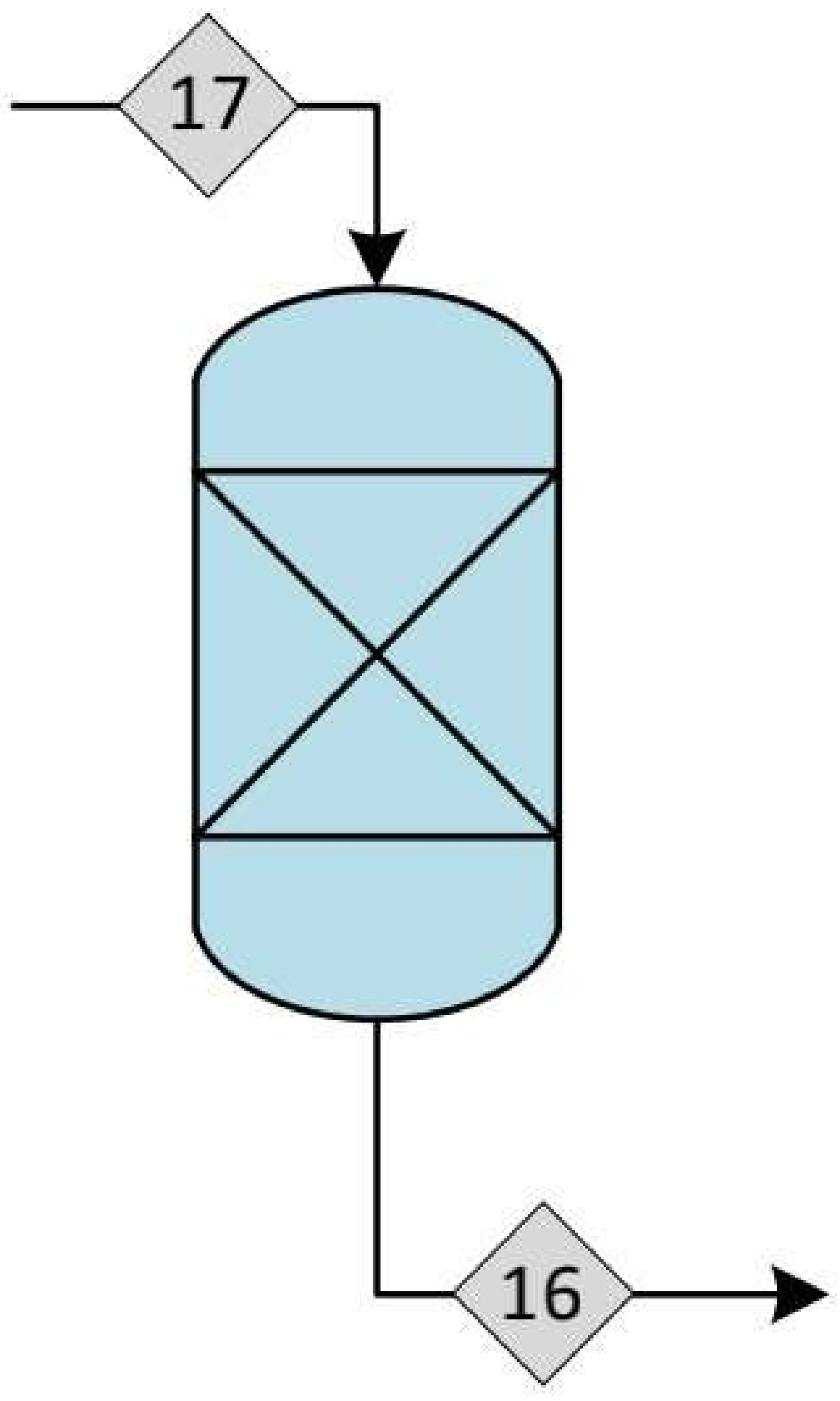
CO_2 = 87283

H_2 = 12475

CH3OH = 126

CO = 21679

H_2O = 290



Kg/hr

CO_2 = 69652

H_2 = 10102

CH3OH = 12698

CO = 21898

H_2O = 7502

Figure 3-3: Reactor (R-101)

Reaction:

$$CO_2 + H_2 \longrightarrow CO + H_2O$$

$$CO + 2H_2 \longrightarrow CH3OH$$

$$CO_2 + 3H_2 \longrightarrow CH3OH + H_2O$$

Temperature = 250°C

Pressure = 50 bar

CO_2 Conversion	20.20%
Fraction	0.202
CO Conversion	22%
Fraction	0.22
Selec. MEOH	0.43
Selec. Co	0.57

$$CO_2 + H_2 \longrightarrow CO + H_2O \qquad 1^{st} \text{ reaction}$$

Overall CO_2 Conversion = 20.20 %

Overall CO_2 Conversion = 20.20 %

Total Moles of CO_2 fed into the reactor = 1983.695 Kmoles

Total Moles of CO_2 reacted in (reaction 1 & reaction 2) = 1983.695 K moles × 0.2020 = 400.706 K mol

Moles of methanol generated in reaction 1 = 400706.5279 × 0.43 = 172. 303 K moles

$$CO + 2H_2 \longrightarrow CH_3OH \qquad 2^{nd}\ \text{Reaction}$$

Moles of CO generated = total moles of CO reacted × 0.57

Moles of CO generated = 400.706 × 0.57 = 228.402 Kmoles

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O \qquad 3^{rd}\ \text{Reaction}$$

CO conversion = 0.22

Moles of Methanol generated in reaction 3 = (774.243 + 228.402) × 0.22 = 220.582 Kmoles methanol

Table 3-5: Material Balance Around reactor

Component	**Input (Kg/hr)**	**Consumed**	**Generation**	**Output (Kg/hr)**
	Stream 17			**Stream 16**
	Feed			**Output**
CO_2	87,283	17,631	0	69,652
H_2	12,475	2,373	0	10,102
CH3OH	126	0	12,572	12,698
CO	21,679	6,176	6,395	21,898
H_2O	290	0	7,213	7,502
Total	121,852	26,180	26,180	121,852

3.4 Material Balance Around Phase Separator (S-101):

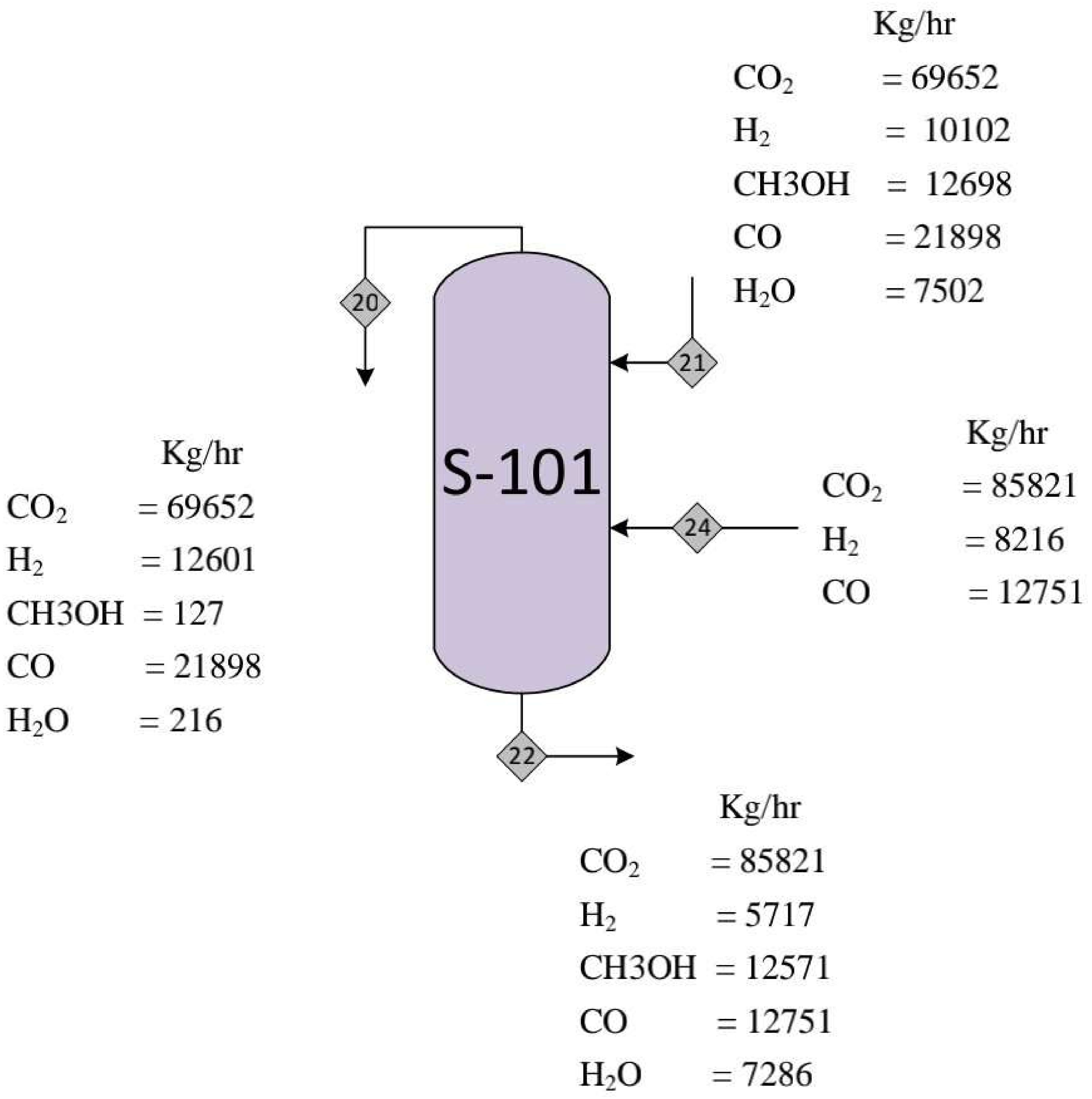


Figure 3-4: Phase Separator (S-101)

Table 3-6: Mole fraction of (S101)

Components	mole fractions of feed in bottom product
CO_2	0.552
H_2	0.310
CH_3OH	0.990
CO	0.320
H_2O	0.970

CO_2:

(1582.989 + 1950.468) × 0.552 = 1950.468 Kmoles/hr

H_2:

(5051.114 + 4107.930) × 0.310 = 2858.446 (Kmoles/hr)

CH3OH:

(396.814 + 0.00) × 0.990 = 392.846 kmoles/hr

CO:

(782.063 + 455.378) × 0.320 = 455.378 Kmoles/hr

H_2O:

(416.797 + 0.00) × 0.970 = 404.793 Kmoles/hr

Table 3-7: Material Balance Around Phase Separator

Component	Input (Kg/hr)		Output (Kg/hr)	
	Stream 21	Stream 24	Stream 22	Stream 20
	RT-Mixture In	Stripper-In	Bottom out	Top out
CO_2	69,652	85,821	85,821	69,652
H_2	10,102	8,216	5,717	12,601
CH3OH	12,698	0	12,571	127
CO	21,898	12,751	12,751	21,898
H_2O	7,502	0	7,286	216
Total	121,852	106,787	124,145	104,494
Total mass	228,639		228,639	

3.5 Material Balance Around Stripper (ST-102):

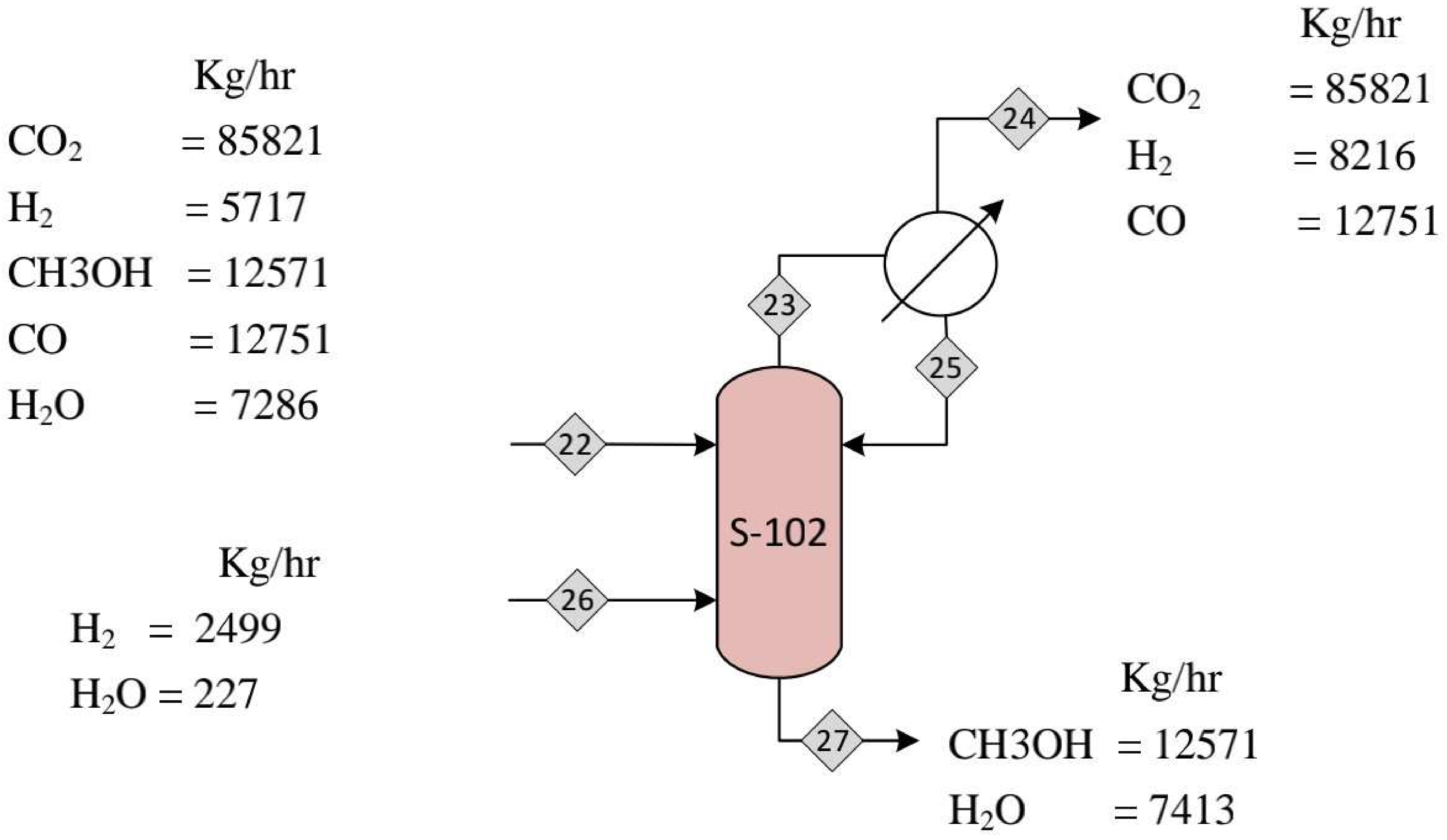


Figure 3-5: Stripper (ST-102)

Top Outlet stream:

CO_2 = (1950.468) × 1 = 1950.468 Kmoles/hr

H_2 = (2858.446 + 1249.609) × 0.999 = 4107.930 Kmoles/hr

CH3OH = (392846.2093) × 0 = 0 moles

CO = (455378.8934) × 1 = 455.378 Kmoles/hr

H_2O = (404.793 + 12.622) × 0 = 0 moles

Bottom Outlet stream:

CO_2 = Total Input feed = Top Product + Bottom Product

1950.468 Kmoles/hr = 1950.468 Kmoles + bottom product

H_2 = Total Input feed = Top Product + Bottom Product

(2858.446 + 1249.609) = 4107.930 moles + Bottom Product

Bottom product = 0.125 Kmoles/hr

CH_3OH = Total Input feed = Top Product + Bottom Product

(392.846) = 0 Kmoles + Bottom Product

Bottom Product = 392.846

CO = Total Input feed = Top Product + Bottom Product

455.378 K moles = 455.378 kmoles + bottom Product

H_2O = (404.793 + 12.622) = 0 moles + bottom product

Bottom product = 417.416 Kmol/hr

Table 3-8: Material Balance Around Stripper (ST-102)

Component	**Input (kg/hr)**		**Output (kg/hr)**	
	Stream 22	**Stream 26**	**Stream 24**	**Stream 27**
CO2	85,821	0	85,821	0
H2	5,717	2,499	8,216	0
CH3OH	12,571	0	0	12,571
CO	12,751	0	12,751	0
H2O	7,286	227	0	7,513
Total	124,145	2,726	106,787	20,085

3.6 Material Balance Around Distillation Column (D-101):

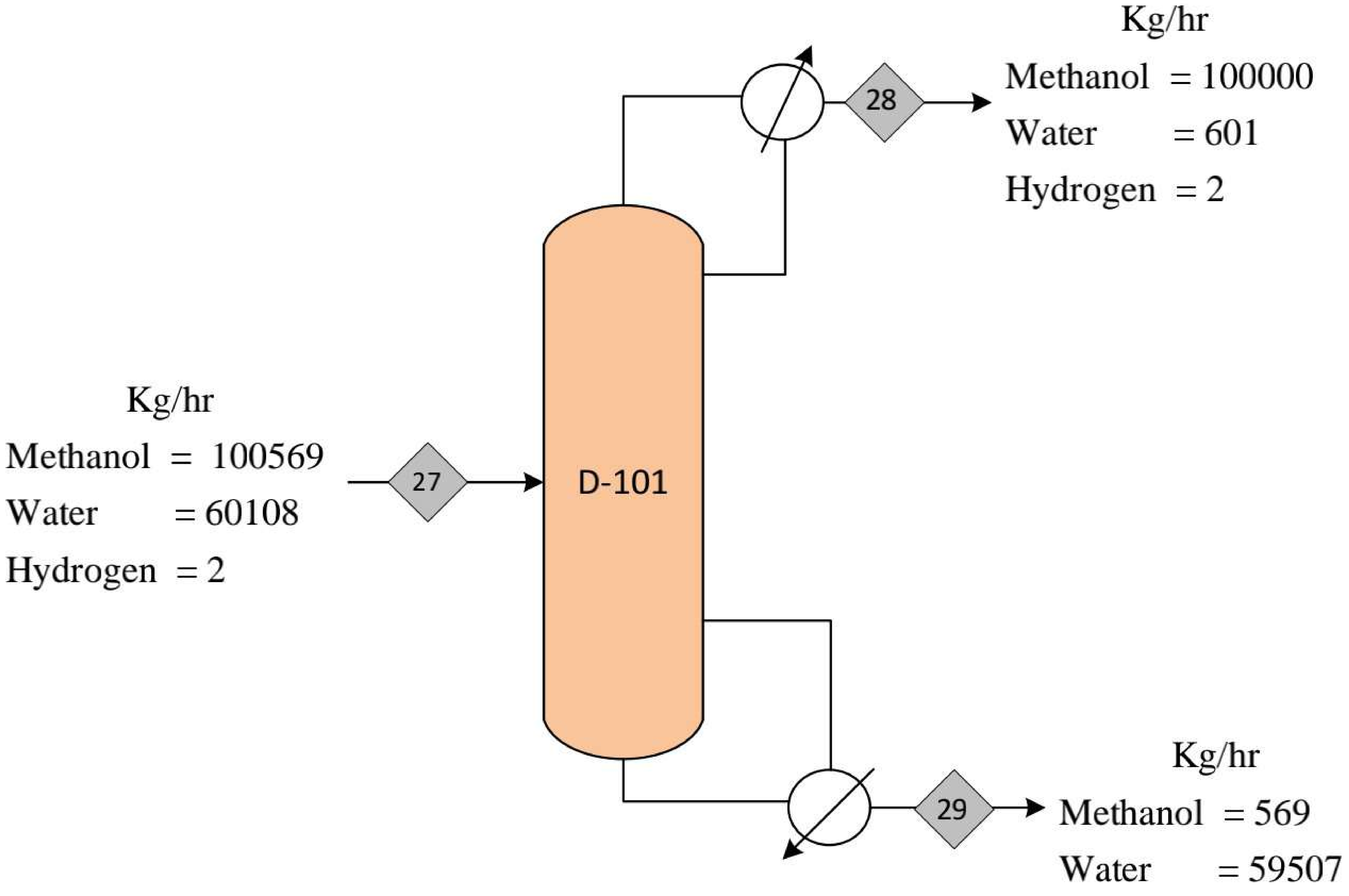


Figure 3-6: Distillation Column (D-101)

Overall Balance:

$$F = D + W$$

$$810387 \text{ moles} = D + W$$

Component Balance:

CH_3OH = Total Input feed = Top Product + Bottom Product

392.846 moles = (0.994 × 392846) + bottom product

Top product = (0.994 × 392.846) = 390.625

Bottom product = feed CH3OH - Top product CH3OH = 2221 Kmol/hr

H_2 = Total Input feed = Top Product + Bottom Product

H_2 is lighter than light key, H_2 moles in Top Product = 125 Kmol/hr

H_2O = Total Input feed = Top Product + Bottom Product

417.41 moles = top product + (0.99 ×417.41)

H_2O in bottom = (0.99 ×417.416) = 413.242 moles

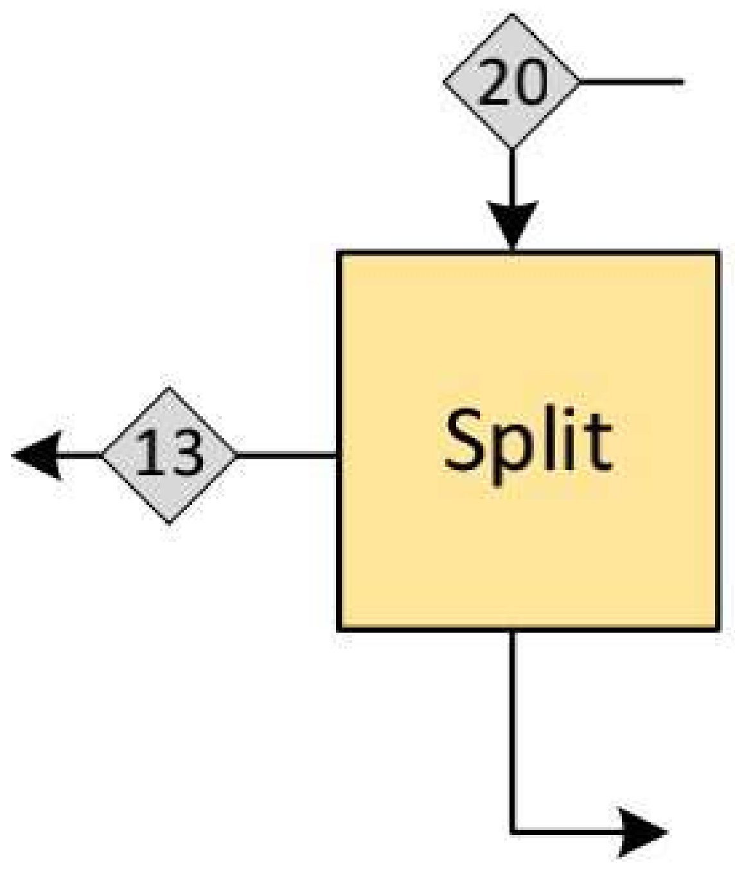
H_2O in Top = Feed H2 - H2 in bottoms = 417.41 – 413.242 = 4.17 moles

Table 3-9: Material Balance Around Distillation Column (D-101)

Component	**Input (Kg/hr)**	**Output (Kg/hr)**	
	Stream 27	**Stream 28**	**Stream 29**
	Feed (F)	**Top Product (D)**	**Bottom product (W)**
Methanol	100,569	100,000	569
Water	60,108	601	59,507
Hydrogen	2	2	0
Total	160,679	100,603	60,075

3.7 Material Balance Around (Splitter):

Kg/hr
CO_2 = 69652
H_2 = 12601
CH3OH = 127
CO = 21898
H_2O = 216



Kg/hr
CO_2 = 68955
H_2 = 12475
CH3OH = 126
CO = 21679
H_2O = 214

Kg/hr
CO_2 = 697
H_2 = 126
CH3OH = 1
CO = 219
H_2O = 2

Figure 3-7: Splitter

Flow rate (mol/hr) Flow rate (mol/hr)

Input = Output

Input = Purge + Recycle

8681.623 = (0.01 × Input) + Recycle

8681.623 = 86.816 + Recycle

8594.807 = Recycle

Purge Flow Rate (Kmol/hr) = 868.162

Table 3-10 : Material Balance around splitter

Component	Input (Kg/hr)	Output (Kg/hr)	
	Stream 20	**Purge**	**Stream 13**
	Input		**Recycle**
CO_2	69,652	697	68,955
H_2	12,601	126	12,475
Methanol	127	1	126
CO	21,898	219	21,679
H_2O	216	2	214
Total	104,494	1,045	103,449

3.8 Material Balance Around (Mixer):

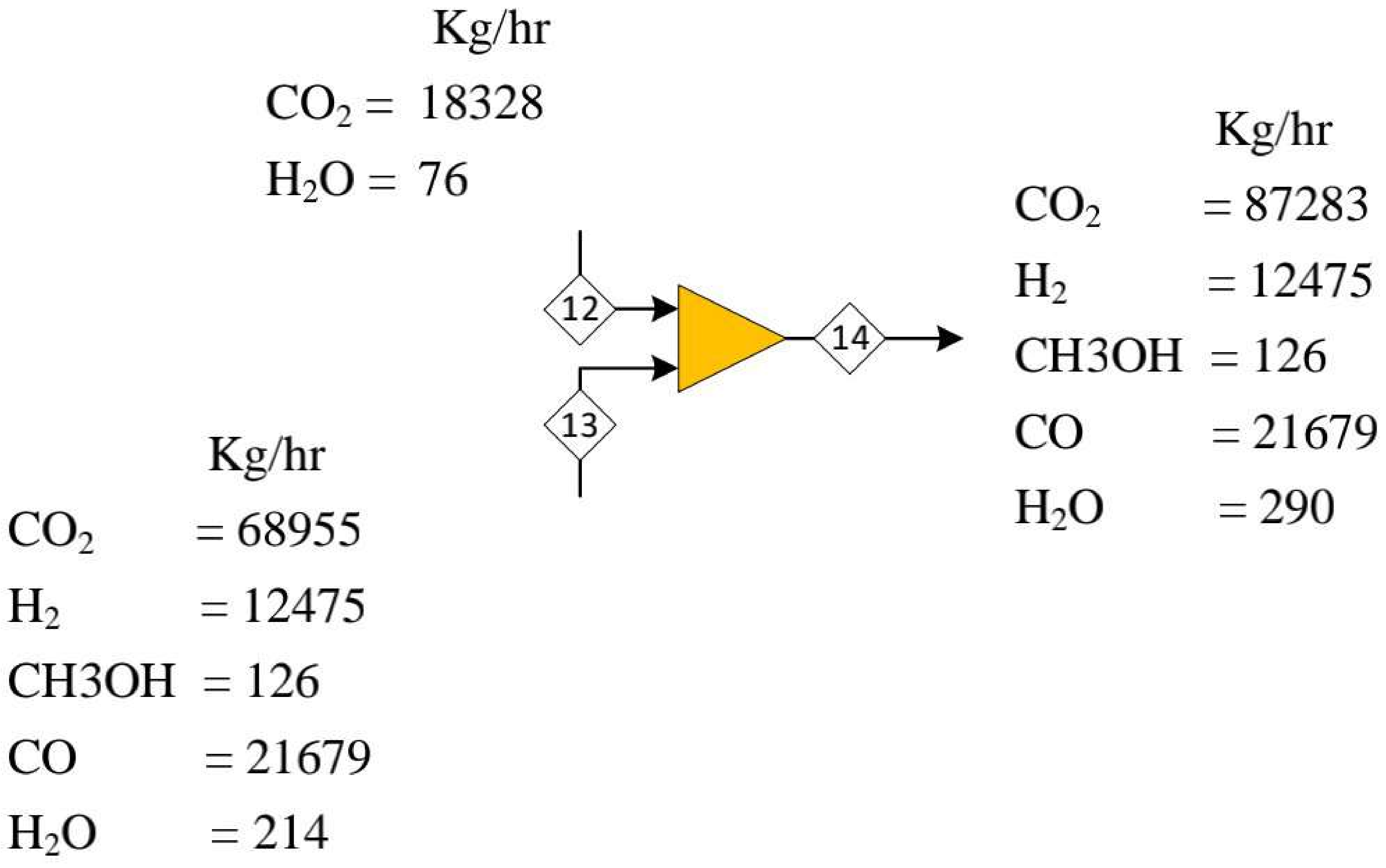


Figure 3-8: Mixer

Input = Output

CO2 Feed + Recycle = Output

420.743 + 8594.807 = 9015.551

9015.551 kmol/hr = 9015.551 kmol/hr

Table 3-11: Material Balance Around (Mixer)

Component	Input Stream		Output Stream
	Stream 12	Stream 13	Stream 15
	CO_2 Feed	Recycle	Out (Rx-In)
CO_2	18,328	68,955	87,283
H_2	0	12,475	12,475
Methanol	0	126	126
CO	0	21,679	21,679
H_2O	76	214	290
Total	18,403	103,449	121,852

4 Chapter NO 4: Energy Balance

General Energy Balance Equation:

Input – Output + Generation – Consumption = Accumulation

At steady state accumulation becomes zero so

Input – Output + Generation – Consumption = 0

4.1 Energy Balance Around Absorber:

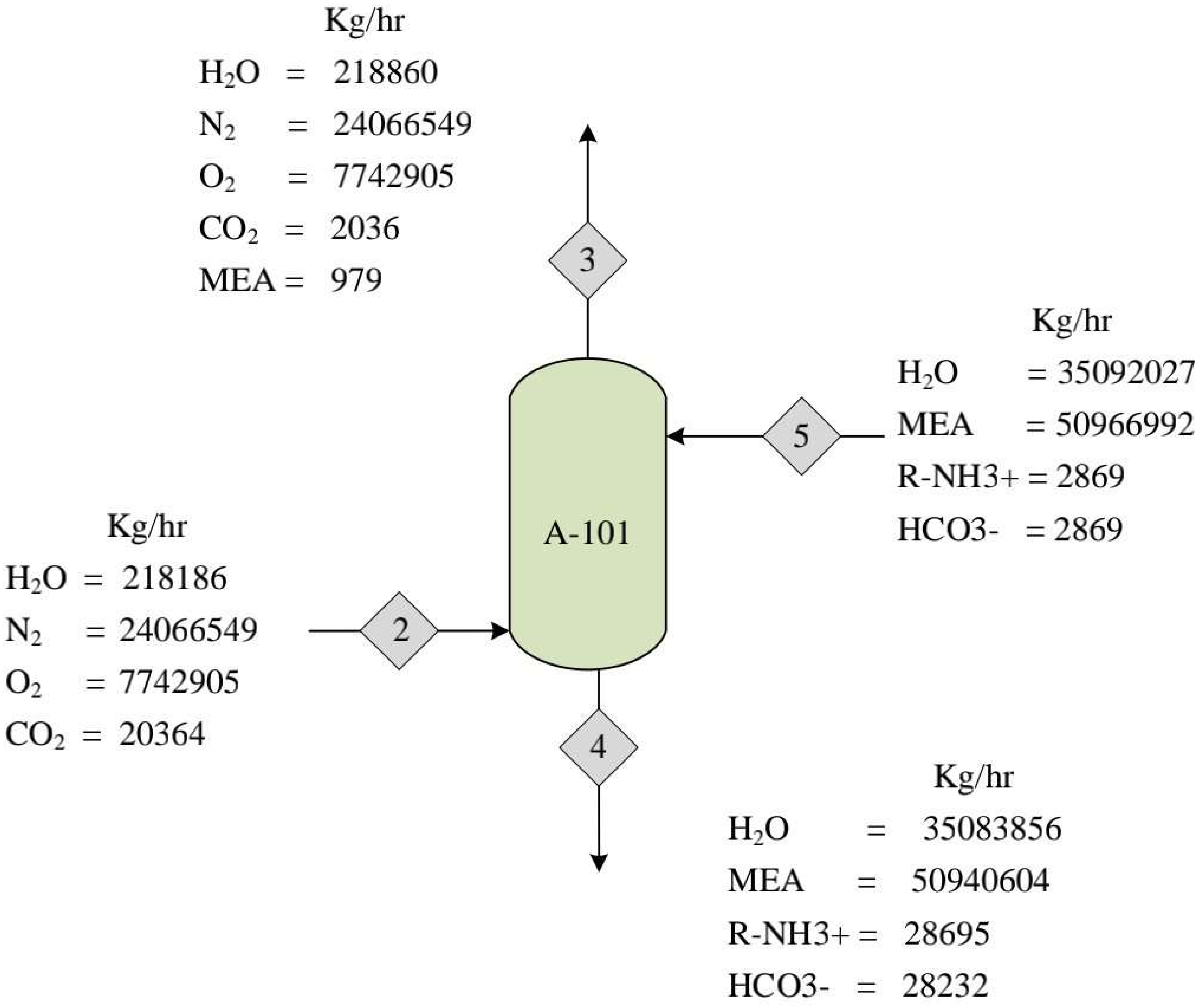


Figure 4-1: Absorber (A-101)

Table 4-1: Energy Balance Around Absorber (Input Stream)

Input Streams						
Components	**Air In (Kmol/hr)**	**H' = ∫Cp ΔT (J/kmol)**	**H (KJ/hr)**	**Lean In (Kmol/hr)**	**H' = ∫Cp ΔT (J/kmol)**	**H (KJ/hr)**
H_2O	12121	0	0	1555	1003	1559231
N_2	859520	0	0	0	867	0

O_2	241966	0	0	0	876	0
CO_2	463	0	0	0	1138	0
MEA	0	0	0	666	2817	1877293
$R\text{-}NH3^+$	0	0	0	46	2530	117076
$HCO3^-$	0	0	0	46	1629	75383
Total	1114070	0	0	2314	10859	3628982
	T_{ref} (K)	T (K)	P (Bar)	T_{ref} (K)	T (K)	P (Bar)
	298.0	298.0	1.1	298.0	327.7	1.1

Table 4-2: Energy Balance Around Absorber (Output Stream)

Output Streams						
Components	**Air Out (Kmol/hr)**	**H' = ∫Cp ΔT (J/kmol)**	**H (KJ/hr)**	**Rich Out (Kmol/hr)**	**H' = ∫Cp ΔT (J/kmol)**	**H (KJ/hr)**
H_2O	12159	277	3372194	1101	313	344234
N_2	859520	240	206587606	0		0
O_2	241966	242	58574019	0		0
CO_2	46	311	14415	0	351	0
MEA	16	765	12275	234	863	201874
$R\text{-}NH_3^+$	0	687	0	463	775	358612
HCO_3^-	0	443	0	463	500	231447
Total	1113707	2966	268560509	2261	2802	1136167
	T_{ref} (K)	T (K)	P (Bar)	T_{ref} (K)	T (K)	P (Bar)
	298.0	306.2	1.1	298.0	307.3	1.1

Reaction:

$$R\text{-}NH_2 + CO_2 + H_2O \longrightarrow R\text{-}NH_3 + HCO3^-$$

Table 4-3: Energy Balance Around Absorber (Reaction)

Reactant				**Product**			
Component	**Kmol/ hr**	**H' = ∫Cp ΔT (KJ/kmol)**	**Enthalpy KJ/hr**		**Kmol/ hr**	**H' = ∫Cp ΔT (J/kmol)**	**H (KJ/hr)**
MEA	416.54	-863	-359538	C2H8NO	416.54	774.845	322751
CO_2	416.54	-351	-146319	HCO3	416.54	500.08	208302
H_2O	416.54	-313	-130221	H2O	0	0	0
Total	1250		-636078	Total	833.07		531053
∑σ ∫Cp DT (KJ/kmol)		-1527		∑σ ∫Cp DT (KJ/kmol)		1274.92	

T_{ref} (K)	**T (K)**	**P (Bar)**
298	307.3	1.1

ΔHr° (KJ/kmol) = -638510

ΔHr (kJ/kmol) = reactant ∑σ ∫Cp DT + ΔHr° + Product ∑σ ∫Cp DT = -638762

ΔH (KJ/hr) = -266067694.3

4.2 Energy Balance Around Heat Exchanger (E-101)

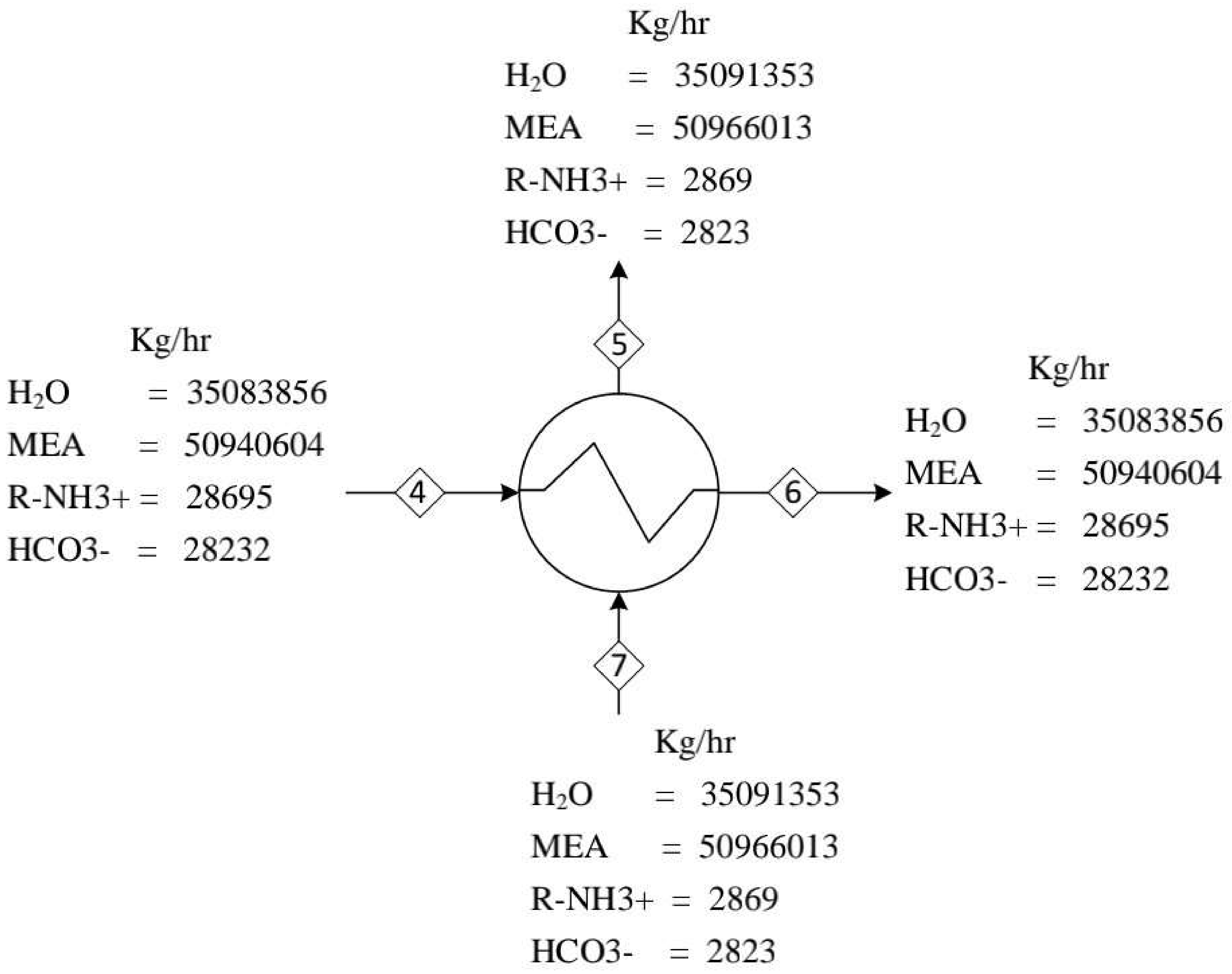


Figure 4-2: Heat Exchanger (E-101)

Table 4-4: Energy Balance Around E-101 (Stream 4)

Stream 4			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy KJ/hr**
MEA	233.9	863.1609709	201874.0929
C2H8NO	462.8	774.8450823	358612.4411
$HCO3^{-}$	462.8	500.0812412	231446.7224
H_2O	1101.1	312.6282306	344233.8508
Total	2260.61068	2631.578679	1136167.107
P (bar)	**T_{ref} (K)**	**T (ºC)**	**T (K)**
1.1	298	34.27906024	307.2790602

Table 4-5: Energy Balance Around E-101(Stream-6)

Stream 6			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy KJ/hr**
MEA	233.9	7637.708651	1786289.647
C2H8NO	462.8	6865.635365	3177541.31
HCO3	462.8	4394.249339	2033738.767
H2O	1101.1	2617.251738	2881846.731
Total	2260.61068		9879416.454
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
1.2	298	102.0875645	375.0875645

E-101 Duty = Q		
Q =	8743249	KJ/hr

Stream 7			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy KJ/hr**
MEA	650	9999	6503339
C2H8NO	46	8992	416171
HCO3	46	5738	265569
H2O	1513	3370	5100203
Total	2256	28099	12285283
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
1.1	298	124	397

Stream 5			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy KJ/hr**
MEA	650	2817	1832099
C2H8NO	46	2530	117076
HCO3	46	1629	75383
H2O	1513	1003	1517475
Total	**2256**	**7978**	**3542033**
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
1.2	298	55	328

E-101 Duty = Q		
Q = $Stream_7$ - $Stream_5$	8743249	KJ/hr

4.3 Energy Balance Around Stripper (ST-101):

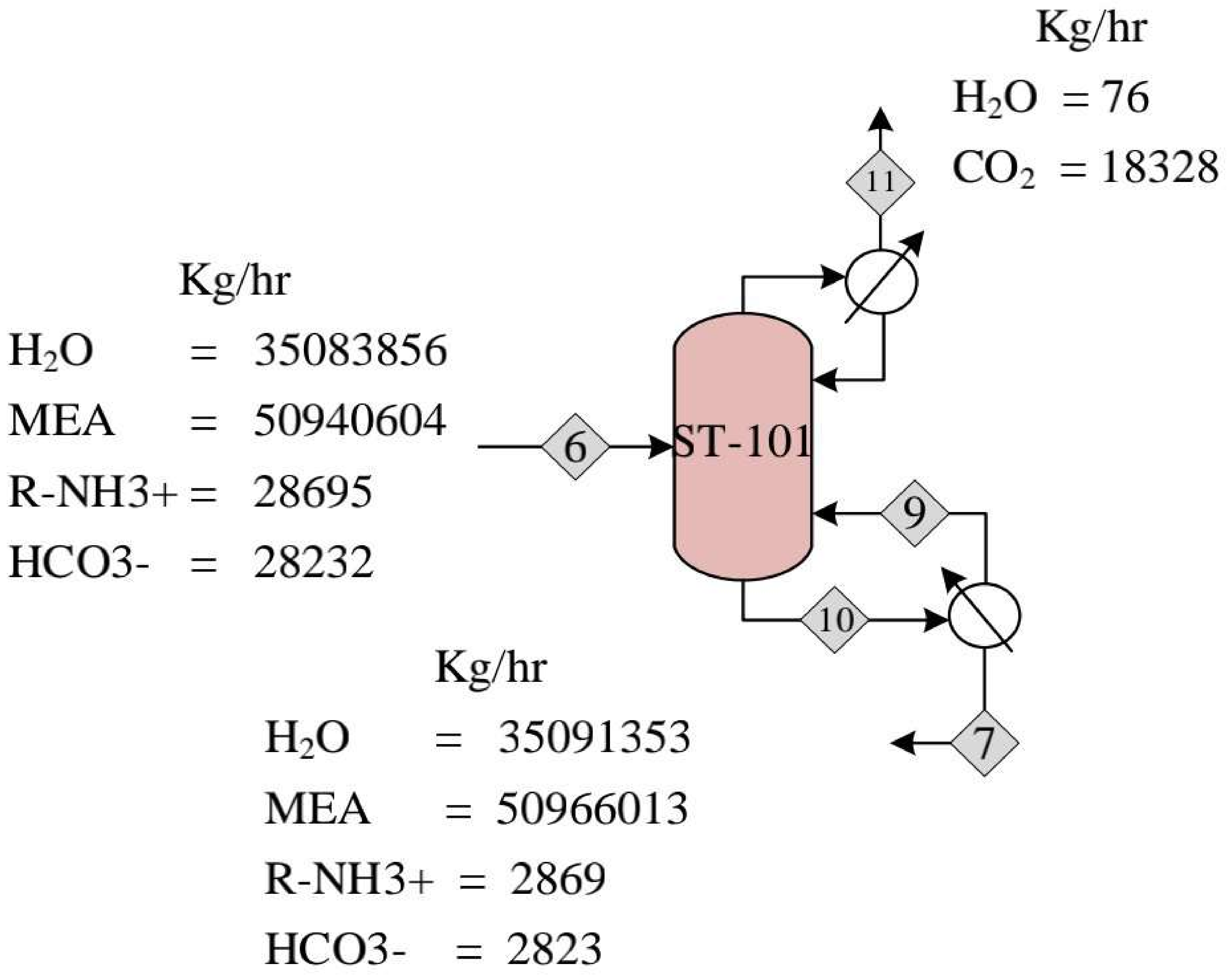


Figure 4-3: Stripper (ST-101)

Table 4-6: Energy Balance Around Stripper-101 (Stream 6)

Stream 6			
Components	**Kmol/hr**	**Specific Enthalpy**	**Ethalply (H) kJ/hr**
MEA	233.9	7637.708651	1786289.647
C2H8NO	462.8	6865.635365	3177541.31
HCO3	462.8	4394.249339	2033738.767
H_2O	1101.1	2617.251738	2881846.731
Total	2260.61068		9879416.454
P (Bar)	**T_{ref} K**	**T (°C)**	**T (K)**
1.2	298	102.0875645	375.0875645

Reaction:

$$\text{R-NH3+ HCO}_3\text{-} \xrightarrow{\hspace{3cm}} \text{R-NH}_2 + CO_2 + H_2O$$

Table 4-7: Energy Balance Around Stripper-101 (Reaction)

Reactant				**Product**			
Component	**Kmol/hr**	**H' = ∫Cp ΔT (KJ/kmol)**	**Ethalply (H) KJ/hr**		**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**H (KJ/hr)**
C2H8NO	417	-6857	-2856311	MEA	417	7628	3177523
HCO3	417	-4389	-1828162	CO_2	417	3035	1263993
				H_2O	417	2614	1088931
Total	833		-4684473	Total	833	10663	5530447
∑σ ∫Cp DT (kJ/kmol)		-11246		∑σ ∫Cp DT (kJ/kmol)		10663	

T_{ref} K	**T (K)**	**P (Bar)**
298	375	1.1

$$\Delta Hr^o \text{ (KJ/kmol)} = 638510$$

$$\Delta Hr \text{ (kJ/kmol)} = \text{reactant } \sum\sigma \int Cp\, DT + \Delta Hr^o + \text{Product } \sum\sigma \int Cp\, DT = 637927$$

$$\Delta H \text{ (KJ/hr)} = 265719712.6$$

Table 4-8: Energy Balance Around Reboiler

Qb = Qc + Hw + HD - Hf		
Hf	9879416	KJ/ hr
Hw =	12957490.22	KJ/ hr
Qc =	204663.27	KJ/ hr
H D	1108593	KJ/ hr

Cp (KJ/Kmol. K)	58.00547401	(KJ/Kmol. K)
Qb =	4391329.75	KJ/ hr

Table 4-9: Energy Balance Around Condenser

R =	0	
L =	0	kmol/hr
V =	420.74	kmol/hr
H D	1108593	KJ/hr
Hv	1313255.99	KJ/hr
HL	0	KJ/hr
Cp (KJ/Kmol. K)	40.5359989	(KJ/Kmol. K)
Qc = Hv - HD - HL		
Qc =	204663.27	KJ/hr

4.3.1 Utilities Requirement for Stripper:

Table 4-10: Utility for Condenser

Condenser Duty = Qc		
Qc (KJ/hr)	204663	
Cooling Water Flow Rate		
T-IN (K)	T-OUT (K)	
298	318	
Qc	204663	kJ/hr

m	?	(Kg/hr)
Cp	4.187	(K J/Kg.K)
DT (K)= Tout - Tin	20	K
m = Q / Cp × ΔT		
m =	2444	Kg/hr

Table 4-11: Utility for Reboiler

Reboiler Duty		
Q_B	4391330 (KJ/hr)	
Steam Flow Rate		
Q_B	4391330	kJ/hr
m	?	(Kg/hr)
λ	1909	(K J/Kg)
Saturated Steam	2 Bar	
Q = m λ		
m = Q/λ		
mass	2300	Kg/ h

4.4 E.B around Heat Exchanger (E-102):

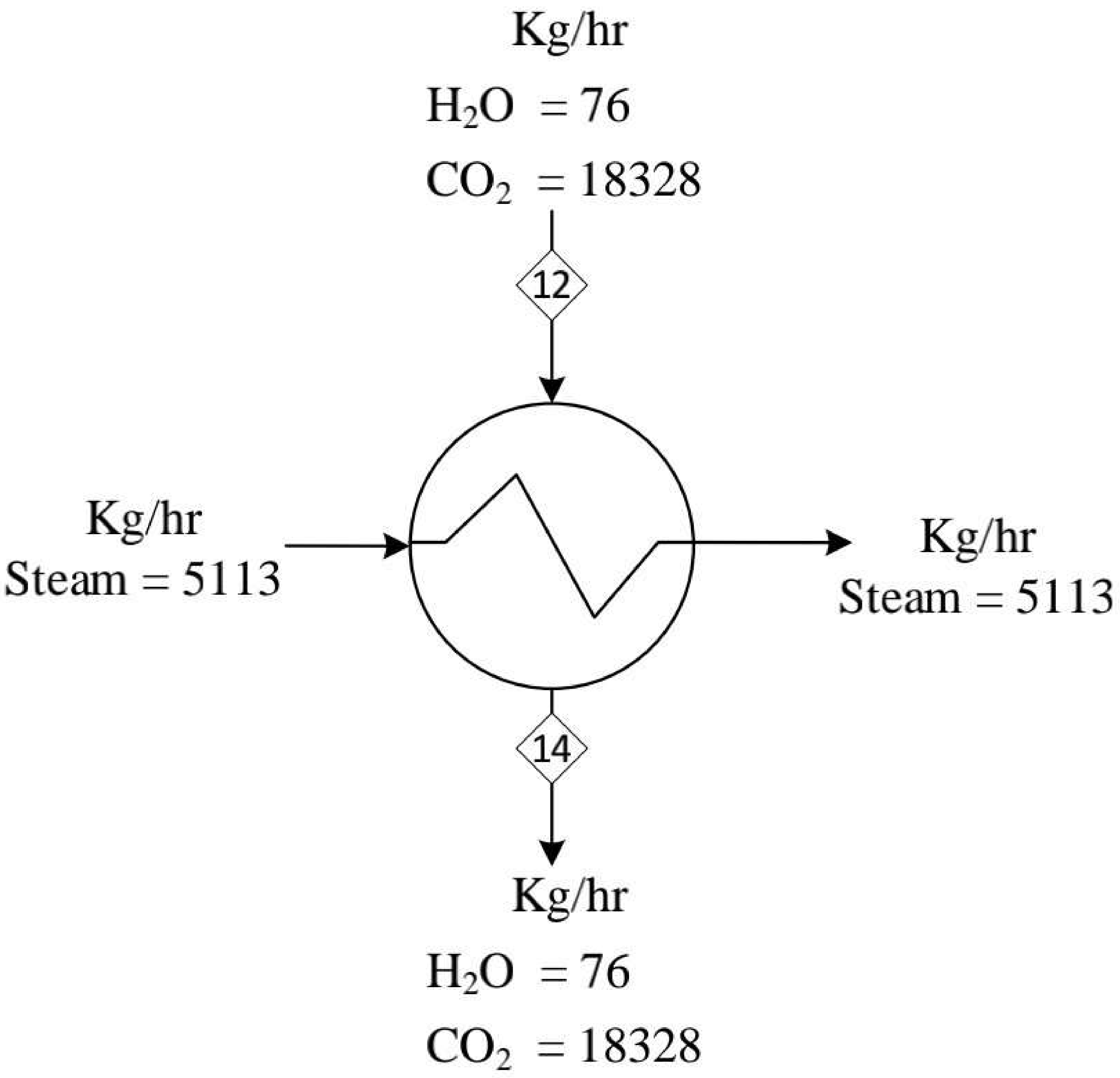


Figure 4-4: Heat Exchanger (E102)

Table 4-12: Energy Balance E-102 (Stream-14)

Stream 14			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (KJ/kmol)**	**Enthalpy KJ/hr**
CO_2	416.5364205	25898.72331	10787761.5
H_2O	4.20743859	19604.40767	82484.34139
Total	420.743859		10870245.84
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	566.595	839.595

Table 4-13: Hot Utility Requirement E-102

E-102 Duty (Q)		
Q (KJ/hr)	9761653	
Steam Flow Rate		
Q_c	9761653	kJ/hr
m	?	(Kg/hr)
λ	1909	(K J/Kg)
Saturated Steam	2 Bar	
$Q = m\,\lambda$		
$m = Q/\lambda$		
m	5113	Kg/ h

4.5 E.B around Reactor (R-101):

Kg/hr

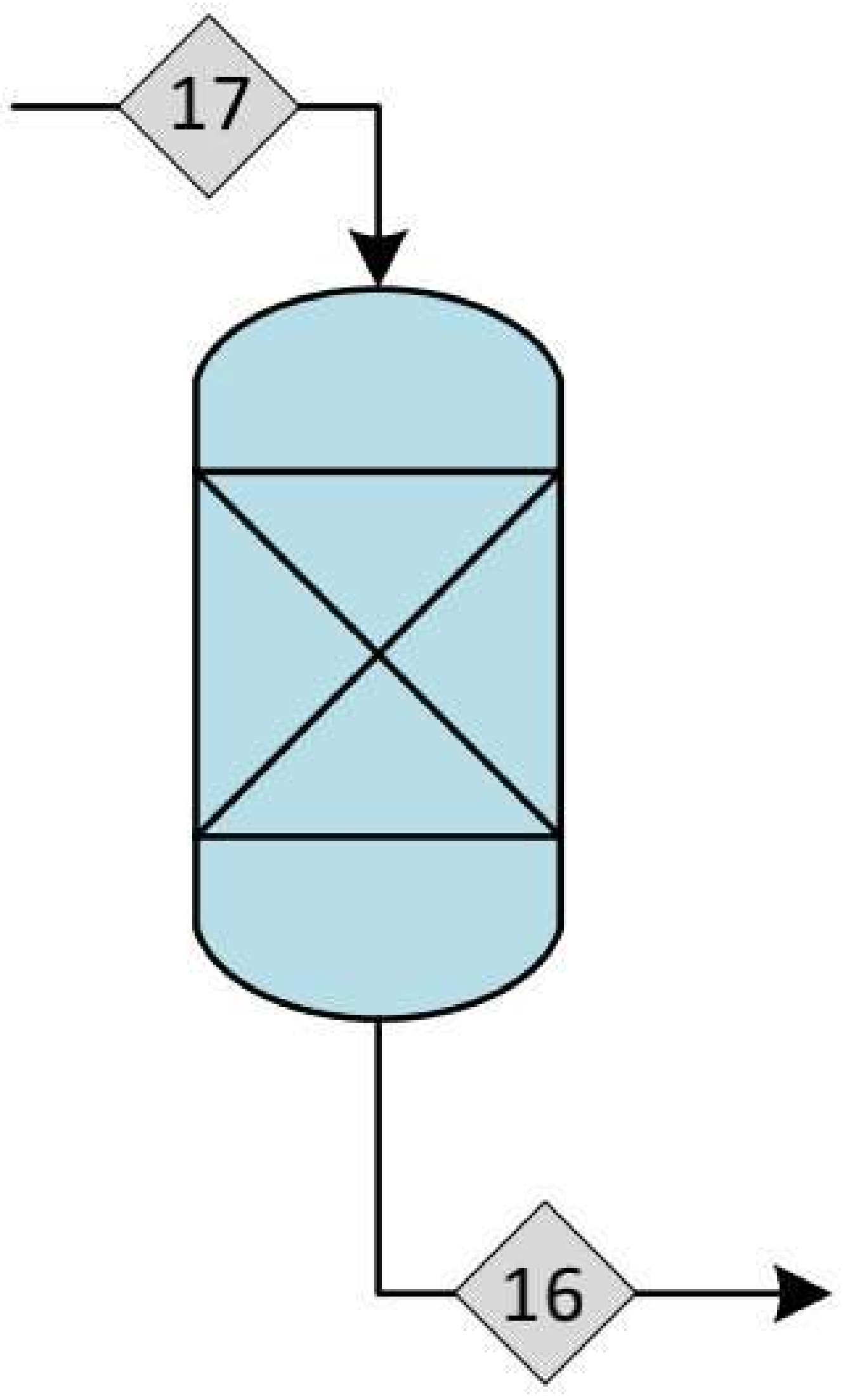
CO_2 = 87283

H_2 = 12475

CH3OH = 126

CO = 21679

H_2O = 290



Kg/hr

CO_2 = 69652

H_2 = 10102

CH3OH = 12698

CO = 21898

H_2O = 7502

Figure 4-5: Reactor (R-101)

Temperature = 250°C

Pressure = 50 bar

$CO_2 + H_2 \longrightarrow CO + H_2O$ 1st reaction

Table 4-14: Energy Balance Around Reactor (Reaction-1)

Reactant				**Product**			
	Kmol/hr	**H' = ∫Cp ΔT (KJ/kmol)**	**Ethalply KJ/hr**		**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**H (J/hr)**
CO_2	172	-9556	-1646497	**CH_3OH**	172	11838	2039745
H_2	517	-6555	-3388322	**H_2O**	172	7782	1340908
∑σ ∫Cp DT (J/kmol)		-29221		∑σ ∫Cp DT (J/kmol)		19620.3027	

T_{ref} (K)	**T (K)**
298	523

ΔHr^o = -49530 (KJ/kmol) at 25°C

ΔHr (KJ/kmol) at 250 °C = reactant ∑σ ∫Cp ΔT + ΔHr^o + Product ∑σ ∫Cp ΔT = -59130

ΔHr = -10188374 (KJ/hr)

$CO + 2H_2 \longrightarrow CH_3OH$ 2nd Reaction

Table 4-15: Energy Balance Around Reactor (Reaction-2)

Reactant				**Product**			
	Kmol/hr	**H' = ∫Cp ΔT (KJ/kmol)**	**Enthalpy (KJ/hr)**		**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (KJ/hr)**
CO_2	228	-9556	-2182566	**CO**	228	6630	1514251
H_2	228	-6555	-1497166	**H_2O**	228	7782	1777483
∑σ ∫Cp DT (J/kmol)		-16111		∑σ ∫Cp DT (KJ/kmol)		14411.973	

T_{ref} (K)	**T (K)**
298	523

$$\Delta Hr^o = 41150 \text{ (KJ/kmol) at } 25\ ^oC$$

$$\Delta Hr \text{ (KJ/kmol) at } 250^oC = \text{reactant } \sum\sigma \int Cp\ \Delta T + \Delta Hr^o \quad + \text{Product } \sum\sigma \int Cp\ \Delta T = 39451$$

$$\Delta Hr = 9010775 \text{ (KJ/hr)}$$

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$ 3rd Reaction

Table 4-16: Energy Balance Around Reactor (Reaction-3)

Reactant				**Product**			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (KJ/hr)**	**Components**	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy KJ/hr**
CO	221	-6630	-1462402	**CH3OH**	221	11838	2611266
H_2	441	-6555	-2891804				
∑σ ∫Cp **Δ**T (J/kmol)		-19740		∑σ ∫Cp **Δ**T (KJ/kmol)		11838.07059	

T_{ref} (K)	T (K)
298	523

ΔHr^o = -90680 ((KJ/kmol) at 25 ºC

ΔHr (KJ/kmol) at 250 ºC = reactant $\sum \sigma \int Cp\ \Delta T + \Delta Hr^o$ + Product $\sum \sigma \int Cp\ \Delta T$ = -98582

ΔHr = -**21745323** (KJ/hr)

Table 4-17: Energy Balance Around Reactor

Reactor Input				**Reactor Output**			
Components	**(kmol/hr)**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy KJ/hr**	**Components**	**(kmol/hr)**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy KJ/hr**
CO_2	1983.70	9555.78	18955754.41	CO_2	1582.99	9555.78	15126692.02
H_2	6237.59	6554.94	40887035.36	H_2	5051.11	6554.94	33109743.75
CH3OH	3.93	11838.07	46505.41	CH3OH	396.81	11838.07	4697516.32
CO	774.24	6629.74	5133031.23	CO	782.06	6629.74	5184880.03
H_2O	16.09	7782.23	125225.41	H_2O	416.80	7782.23	3243616.62
Total			65147551.84				61362448.74

Total $\Delta Hr = \Delta Hr_1 + \Delta Hr_2 + \Delta Hr_3$ = 22922922 KJ/sec

ΔH (KJ/hr) = Product $\sum$H - Reactant $\sum H + \sum \Delta Hr$ = -26708025.13 KJ/hr

4.5.1 Cold Utility requirement of Reactor (R-101):

Table 4-18: Cooling Water for Reactor (R-101)

Cooling Water Flow Rate Calculations		
Q	26708025	
T_{ref} (K)		
298	318	
Reactor Duty (Q)	26708025	KJ/hr
Q	26708025	KJ/hr
m	?	
Cp	4.187	KJ/Kg.K
$T = T - T_{ref}$	20	K
Q = m Cp DT		
m		
m	319	T/hr

4.6 Energy Balance Around Heat Exchanger (E-103):

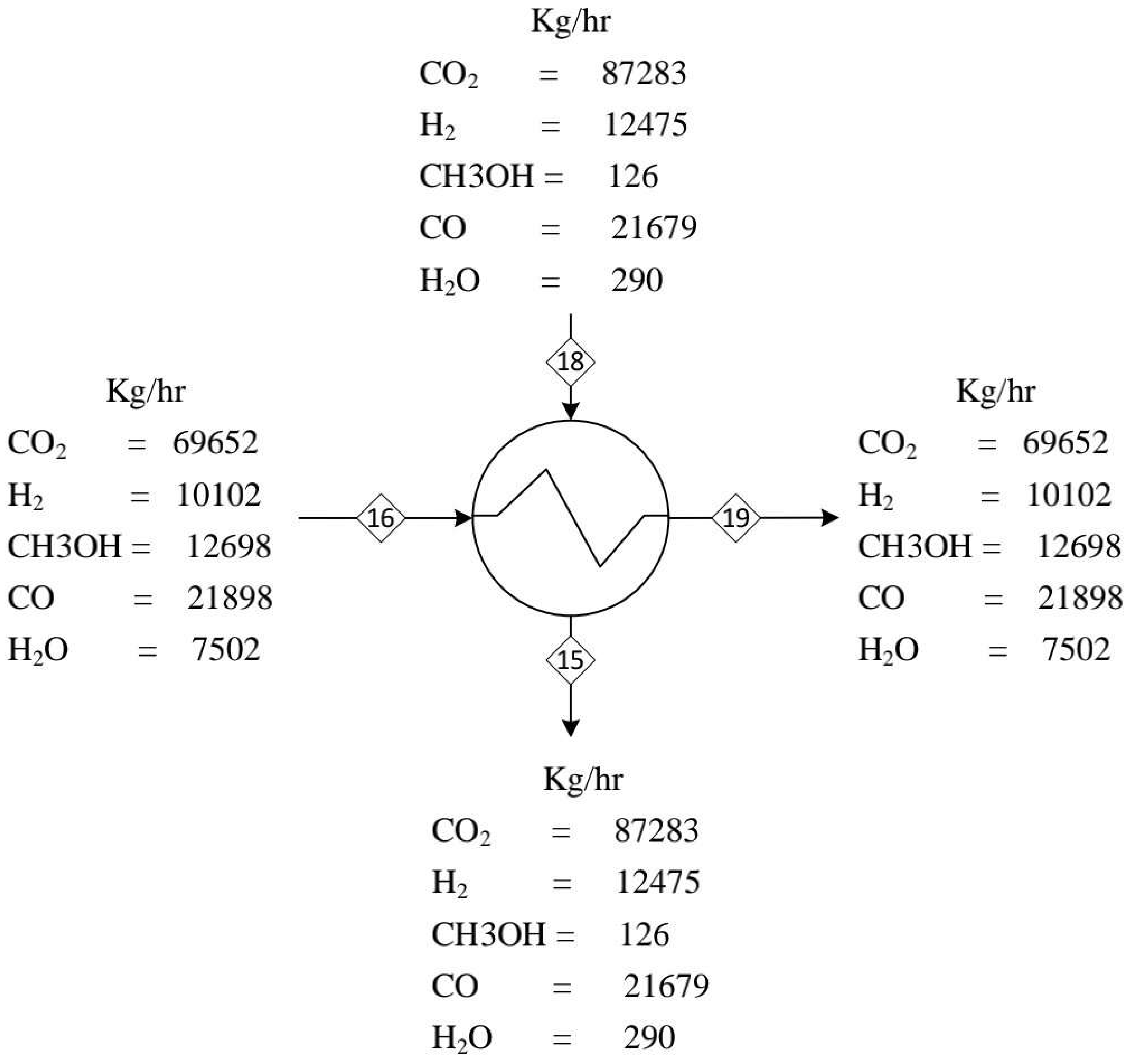


Figure 4-6: Heat Exchanger (E-103)

Table 4-19: Energy Balance E-103 (Stream 15)

Stream 15			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy (H) KJ/hr**
CO2	1983.695682	1678.477194	3329587.963
H2	6237.593109	1256.938281	7840269.558
CH3OH	3.928462096	1977.510717	7768.575895
CO	774.2431142	1267.929774	981685.8968
H2O	16.09119502	1468.626339	23631.95283
Total	9015.551563	7649.482305	12182943.95

P (bar)	T_{ref} (K)	T (°C)	T (K)
50	298	68.42481071	341.4248107

Enthalpy (H) Stream 15 =	Stream 13 + Stream 14
12182944	12182944

Table 4-20: Energy Balance E-103 (Stream 16)

Stream 16			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy (H) KJ/hr**
CO_2	1983.695682	6366.787537	12629768.95
H_2	6237.593109	4506.231435	28108038.14
CH3OH	3.928462096	7735.849051	30389.98978
CO	774.2431142	4546.150637	3519825.827
H_2O	16.09119502	5312.71641	85487.95582
Total			44373510.86
P (Bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	180	453

E-103	
Q	32190566.92

4.7 Energy Balance Around Heat Exchanger (E-104):

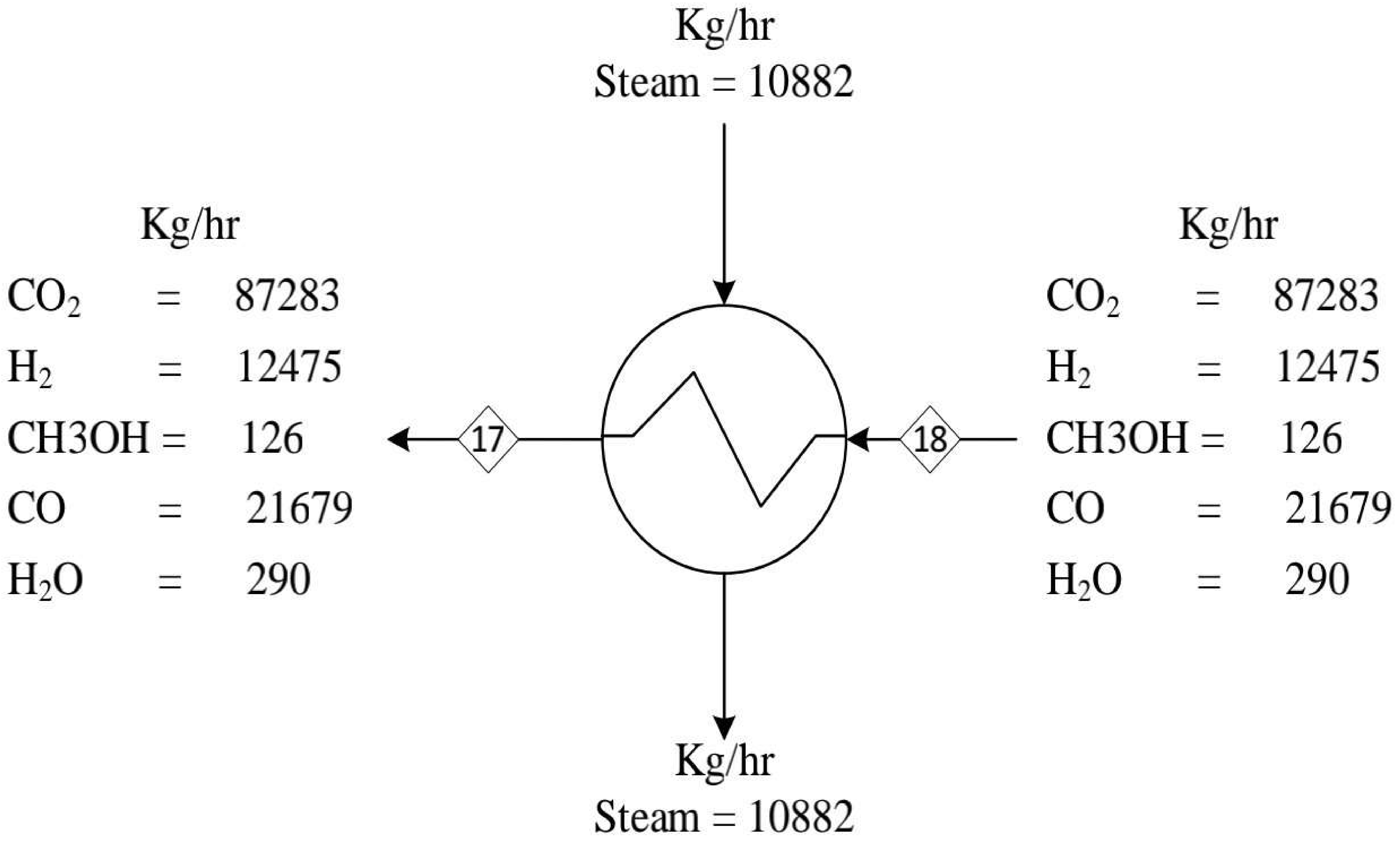


Figure 4-7: Heat Exchanger (E-104)

Table 4-21: Energy Balance E-104 (Stream-17)

Stream 17			
Components	**Kmol/hr**	**Specific Enthalpy**	**Enthalpy KJ/hr**
CO_2	1983.695682	9555.777422	18955754.41
H_2	6237.593109	6554.937882	40887035.36
CH3OH	3.928462096	11838.07059	46505.41159
CO	774.2431142	6629.740889	5133031.232
H_2O	16.09119502	7782.232114	125225.4146
Total			65147551.84
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	250	523

E-104 Duty (Q)	
Q = Stream_{17} - Stream_{16}	20774040.97 KJ/hr

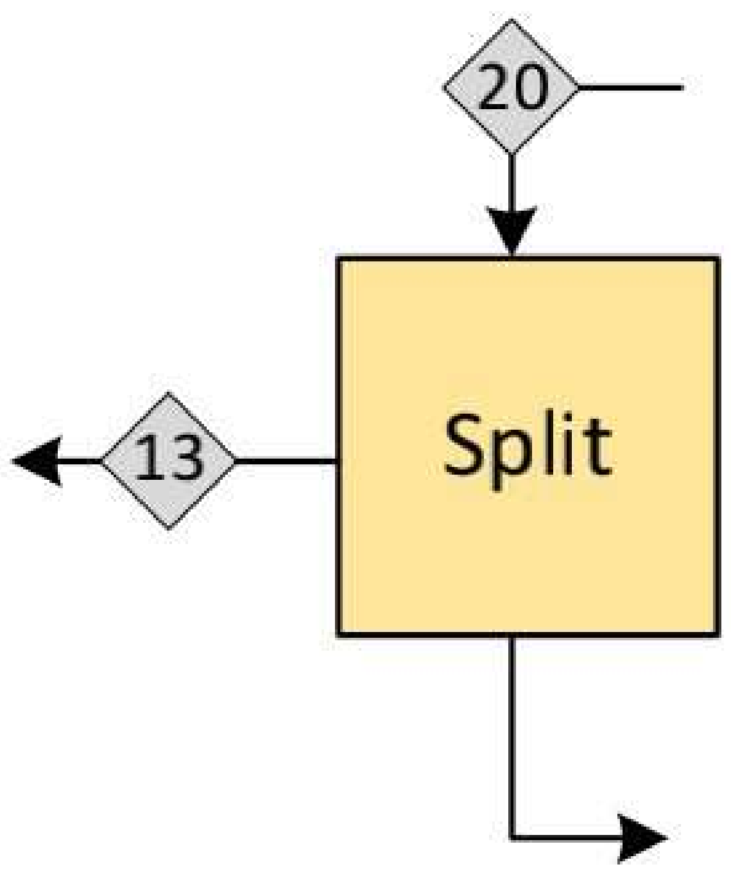
Table 4-22: Hot Utility Requirement of E-104

E-104 Duty (Q)		
Q	20774041 (KJ/hr)	
Steam Flow Rate		
Qc	20774041	kJ/hr
m	?	(Kg/hr)
λ	1909	(KJ/Kg)
Saturated Steam	2 Bar	
Q = m λ		
m=Q/λ		
m =	10882	Kg /h

4.8 Energy Balance Around Splitter

Kg/hr
CO_2 = 69652
H_2 = 12601
CH3OH = 127
CO = 21898
H_2O = 216

Kg/hr
CO_2 = 68955
H_2 = 12475
CH3OH = 126
CO = 21679
H_2O = 214



Kg/hr
CO_2 = 697
H_2 = 126
CH3OH = 1
CO = 219
H_2O = 2

Figure 4-8: Splitter

Table 4-23: Energy Balance Around Splitter (Stream 20)

Stream 20			
Components	**Kmol/hr**	**H specific**	**Enthalpy (H) KJ/hr**
CO_2	1582.989154	188.7754681	298829.5185
H_2	6300.5991	144.4508242	910126.7327
CH3OH	3.968143528	220.1308696	873.5108856
CO	782.0637517	145.9046156	114106.7111
H_2O	12.00377442	168.3806446	2021.203274
Total	8681.623924		1325957.676
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
45	298	30	303
(Recycle + Purge)		1325958 KJ / hr	

Table 4-24: Energy Balance Around Splitter (Purge)

Stream Purge			
Components	**Kmol/hr**	**H specific**	**Enthalpy (H) KJ/hr**
CO_2	15.82989154	188.7754681	2988.295185
H_2	63.005991	144.4508242	9101.267326
CH3OH	0.039681435	220.1308696	8.735108863
CO	7.820637517	145.9046156	1141.067111
H_2O	0.120037944	168.3806446	20.21206633
Total	86.81623943	867.642422	13259.5768
P (Bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
45	298	30	303

Table 4-25: Energy Balance Aroun Splitter (Recycle)

Stream (Recycle)			
Components	**Kmol/hr**	**H specific**	**Enthalpy (H) KJ/hr**
CO_2	1567.159262	188.7754681	295841.2233
H_2	6237.593109	144.4508242	901025.4653
CH3OH	3.928462096	220.1308696	864.7757774
CO	774.2431142	145.9046156	112965.644
H_2O	11.88375643	168.3806446	2000.994567
Total	8594.807703	867.642422	1312698.103

P (Bar)	T_{ref} (K)	T (°C)	T (K)
45	298	30	303

4.9 Energy Balance Around Condenser:

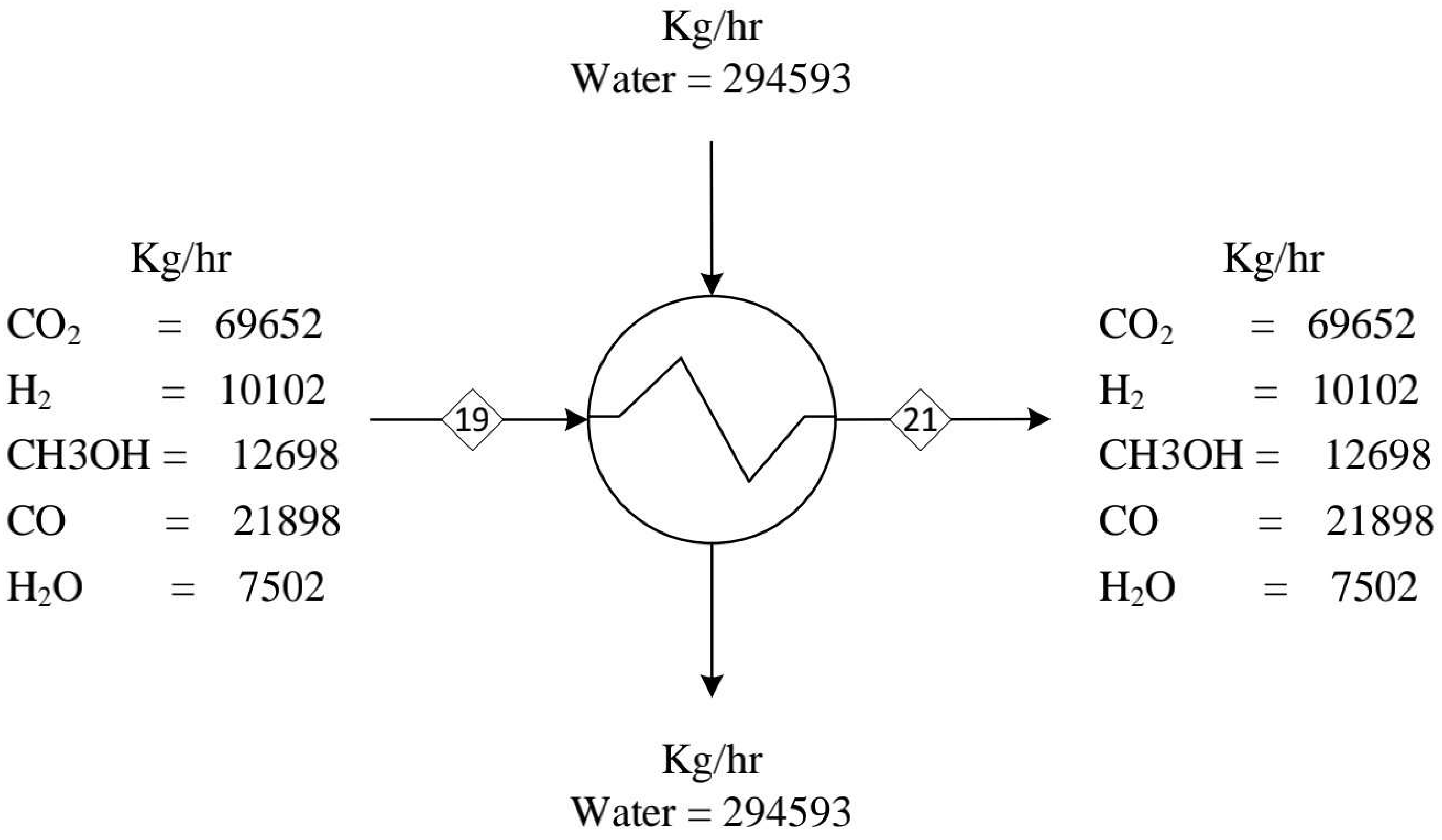


Figure 4-9: Condenser (E-105)

Table 4-26: Energy Balance Around Condenser (Stream-19)

Stream 19			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (KJ/kmol)**	**Enthalpy (H) KJ/hr**
CO_2	1582.989155	4394.721171	6956795.951
H_2	5051.114799	3179.472942	16059882.83
CH3OH	396.8143528	5272.616914	2092250.068
CO	782.0637514	3205.424399	2506846.23

H_2O	416.7977229	3733.481875	1556106.744
Total			29171881.83
P (Bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	134.5394923	407.5394923

Table 4-27: Energy Balance Around Condenser (Stream-21)

Enthalpy of Stream 21			
Vapour Enthalpy	Enthalpy of Condensed Vapours		
	Temp (134 → 50)	Phase Change (Hv)	Temp (50 → 30)
1145469	2800950.942	70806.45562	627030.4516
Total	4502644		

Table 4-28: Cooling Water for Condenser

Cooling Water for Condenser		
E-106 Duty (Q)		
Q	24669238 (KJ/hr)	
Q	ΔH (stream 19) - ΔH (stream 21)	
T-IN (K)	T-OUT (K)	
298	318	
E-106 Duty	24669238	J/hr
m	?	(Kg/hr)
Cp	4.187	(J/Kg.K)

ΔT (K)= T_{out} - T_{in}	20	K
m = Q / Cp × Δ T		
m =	294593	Kg/hr

4.10 Energy Balance Around Gas Liquid Separator (S-101):

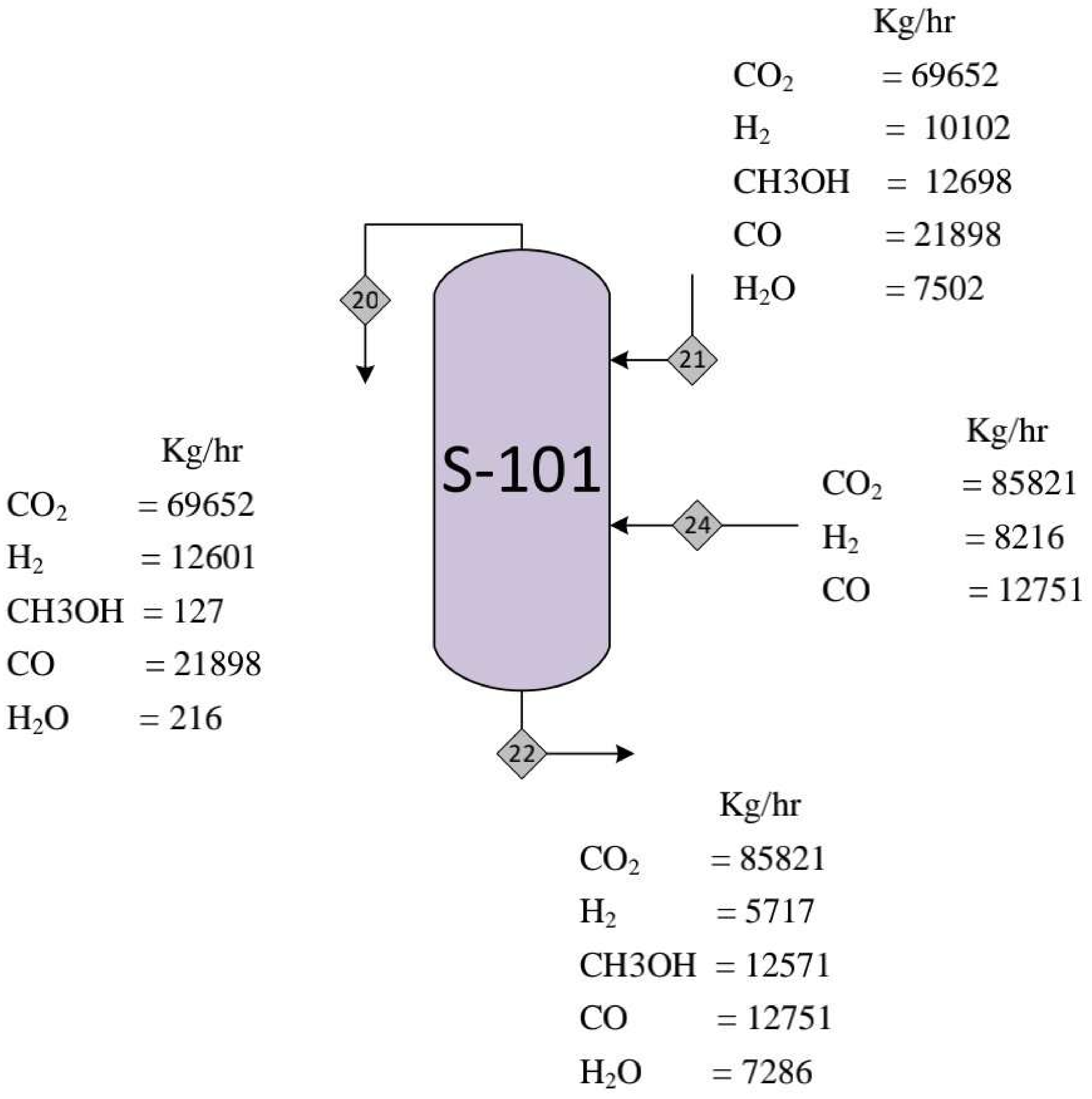


Figure 4-10: Gas-Liquid Separator (S-101)

Table 4-29: Energy Balance Around Gas-Liquid Separator (Stream-20)

Stream 20			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (H) (J/hr)**
CO_2	1582.989154	188.7754681	298829.5185
H_2	6300.5991	144.4508242	910126.7327
CH3OH	3.968143528	220.1308696	873.5108856
CO	782.0637517	145.9046156	114106.7111
H_2O	12.00377442	168.3806446	2021.203274
Total			1325957.676
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	30	303

Table 4-30: Energy Balance Around Gas-Liquid Separator (Stream-24)

Stream 24			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy KJ/hr**
CO_2	1950.468778	188.7754681	368200.6566
H_2	4107.930861	144.4508242	593393.9984
CH3OH	5.01085E-08	220.1308696	1.10304E-05
CO	455.3788937	145.9046156	66441.88245
H_2O	0	168.3806446	0
Total			1028036.537
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	30	303

Table 4-31: Energy Balance Around Gas-Liquid Separator (Stream-21)

Enthalpy of Stream 21			
Vapour Enthalpy	Enthalpy of Condensed Vapours		
	Temp (134 → 50)	Phase Change (Hv)	Temp (50 → 30)
1145469	2800950.942	70806.45562	627030.4516
Total	4502644		

Table 4-32: Energy Balance Around Gas-Liquid Separator (Stream-22)

Stream 22			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (H) (J/hr)**
CO2	1950.468779	188.7754681	368200.6567
H2	2858.44656	144.4508242	412904.9614
CH3OH	392.8462093	220.1308696	1970991.161
CO	455.3788934	145.9046156	66441.8824
H2O	404.7939485	168.3806446	1386183.777
Total			4204722.439
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	30	303

4.11 Energy Balance Around Stripper (ST-102):

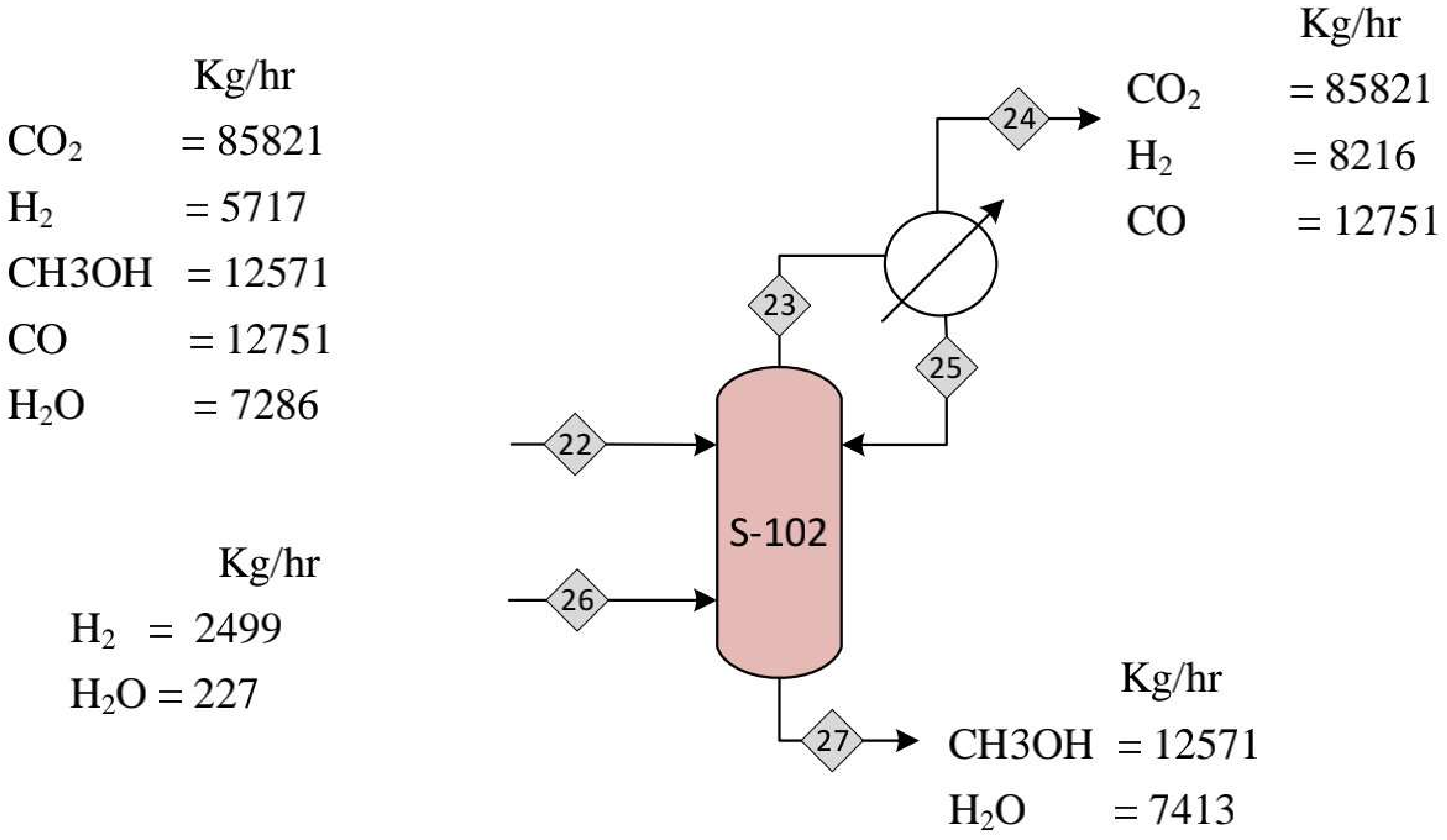


Figure 4-11: Stripper (S-102)

Table 4-33: Energy Balance Around Stripper S-102 (Stream-26)

Stream H2-Feed			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (H) (J/hr)**
CO_2	0	6145.93704	0
H_2	1249.609261	4360.146074	5448478.915
CH3OH	0	7457.118912	0
CO	0	4398.263628	0
H_2O	12.62231577	5138.105319	64854.78781
Total			5513333.703
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
45	298	175	448

Table 4-34:Energy Balance Around Stripper S-102 (Stream-23)

Stream 23			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (H) (J/hr)**
CO_2	1950.468779	1401.67854	2733930.23
H_2	4107.930861	1053.703527	4328541.235
CH3OH	0	1648.270068	0
CO	455.3788934	1063.111566	484118.5684
H_2O	0	1230.595689	0
Total			7546590.033
P (bar)	**T_{ref} (K)**	**T (°C)**	**T (K)**
50	298	61.41546209	334.4154621

Table 4-35: Energy Balance Around Stripper S-102 (Stream-27)

Stream 27			
Vapour Enthalpy	Enthalpy of Condensed Vapours		
	Temp (30----->50)	Phase Change (Hv)	Temp (50----->94.48)
0	627030.4517	70806.45562	1443624.486
Total	2171466		

Total Enthalpy Input - Total Enthalpy Out = 0		KJ/hr
H Stream H2-Feed + H Stream 22 - H Stream 23 = H Stream 27	2171466	KJ/hr
H Stream	2171466	KJ/hr

Table 4-36: Cooling water for Condenser

Condenser Duty			
Q c	ΔH (stream 23) - ΔH Stream 24 (KJ/hr		
Q	6518553 (J/hr)		
Cooling Water Flow Rate			
	T-IN (K)	T-OUT (K)	
	298	318	
m	?		(Kg/hr)
Cp	4.187		(J/Kg.K)
ΔT (K)= T_{out} - T_{in}	20		K
m = Q / Cp × Δ T			
m	77843		Kg/hr

4.12 E.B around Distillation Column (D-101):

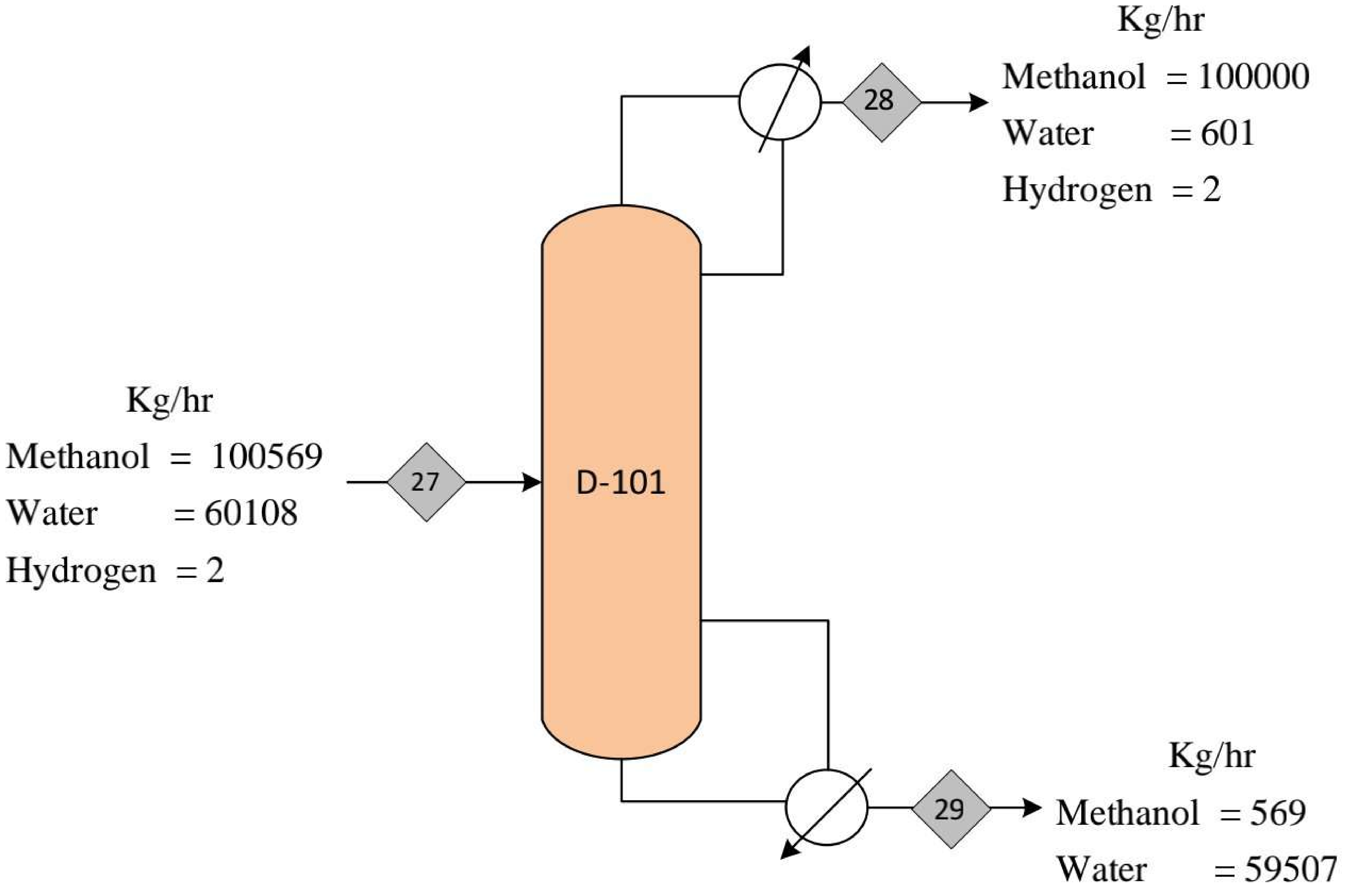


Figure 4-12: Distillation Column (D-101)

Table 4-37: Energy Balance Around Distillation Column D-101 (Stream 28)

Stream 28				
Components	**Feed (Kmol/hr)**	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (H) (J/hr)**
H_2	0.124960926	0.12	404.6508362	50.56554326
CH3OH	392.8462093	390.63		0
H_2O	417.4162642	4.17		0
Total		394.92		51

Table 4-38: Energy Balance Around Distillation Column D-101 (Stream 29)

Stream 29			
Components	**Kmol/hr**	**H' = ∫Cp ΔT (J/kmol)**	**Enthalpy (H) (J/hr)**
CH3OH	2.22	3508.500079	7793.113052
H_2O	413.24	2545.751705	1052011.785
Total	415		1059805

Table 4-39: Cold Utility Requirement for Condenser

Qc = Hv - HD - HL		
R = 1.2	0	
L	0	kmol/hr
V	394.92	kmol/hr
H_D	230359	KJ/hr
Hv	1229682.49	KJ/hr
HL	0	KJ/hr
Cp (KJ/Kmol. K)	44.80861102	(KJ/Kmol. K)
Qc	999323.68	KJ/hr

Cooling Water Flow Rate		
Condenser Duty		
Qc	999324 (KJ/hr)	
T-IN (K)	T-OUT (K)	
298	318	
Qc	999324	kJ/hr
m	?	(Kg/hr)
Cp	4.187	(K J/Kg.K)
ΔT (K)= T_{out} - T_{in}	20	K
m = Q / Cp × Δ T		
m =	11934	Kg/hr

Table 4-40: Hot Utility Requirement for Reboiler

$Q_B = Qc + Hw + HD - Hf$		
H_F	2171466	KJ/ hr
H_W	1069544.877	KJ/ hr
Qc	999323.68	KJ/ hr
H_D	230359	KJ/ hr
Cp (KJ/Kmol. K)	34.32456727	(KJ/Kmol. K)
Q_B	127761.26	KJ/ hr

Reboiler Duty (Q_B)		
Q	127761 (KJ/hr)	
	127761	KJ/hr
Steam Flow Rate		
Q_B	127761	kJ/hr
m	?	(Kg/hr)
λ	2569	(K J/Kg)
$Q = m\lambda$		
$m = Q/\lambda$		
m	50	Kg/hr

5 Chapter NO 5: Process Equipment Design

5.1 Design of Multi-Tube Packed Bed Reactor:

Production of Methanol from CO_2 Hydrogenation is a Renewable Methanol Production technique. This technique is the most advance one as it uses the already existing CO_2 in the air and transform this CO_2 to Methanol through Hydrogenation process. Currently World is shifting from Conventional Methanol Production Techniques to Renewable Methanol Production Technique. CO_2 reduction and conversion to renewable fuels and useful chemicals are two viable strategies for lowering greenhouse gas emissions.

Table 5-1: Comparison between Different Types of Reactors

Classification	Use	Typical Applications
Single adiabatic bed	Non-equilibrium that is somewhat exothermic or endothermic, with limited	Mild hydrogenation
In series adiabatic beds with interim cooling or heating	High conversion, equilibrium, and a restricted number of reactions	Catalytic reforming, SQ2 oxidation, and hydrocracking styrene from ethylbenzene
Multi-tabular (Shell & Tube configuration)	Highly endothermic or exothermic processes that need precise temperature control in order to achieve high selectivity	Many hydrogenations, ethylene oxidation to ethylene oxide, methanol oxidation of formaldehyde, isomerization
Direct-fired non-adiabatic	High-temperature endothermic reactions	Steam reforming

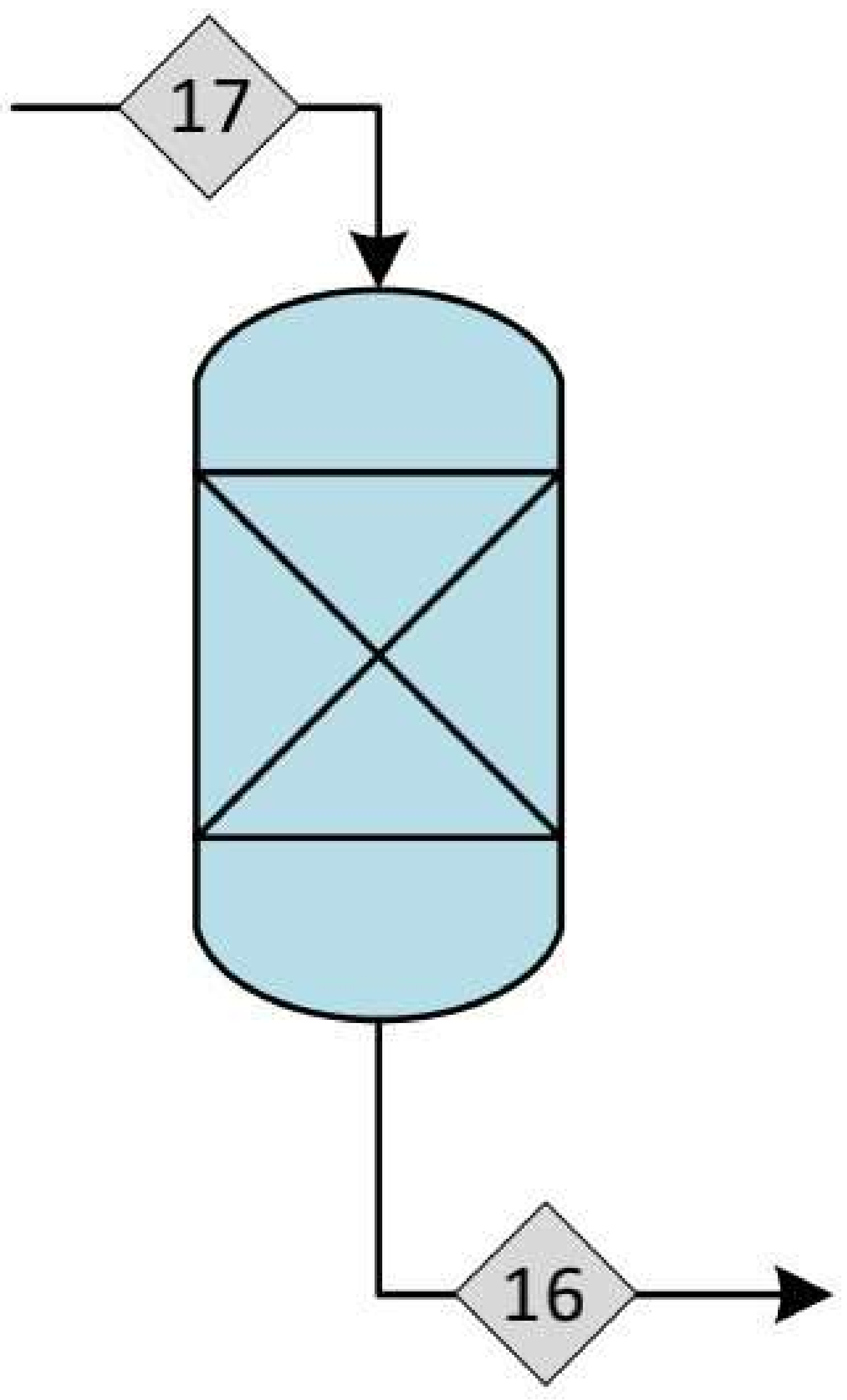
Selection of Multi-Tube Packed bed reactor:

The multi-tubular packed-bed reformer is frequently shown as a complete bundle of bath tubes and an external heating source in the same coat and temperature. In practice, however, the temperature of the hot water in the inter-tubular space changes over the length of the converter, affecting its performance significantly. As a result, the temperature profiles along the reactor's tube and shell sides should be considered. Due to the high heat transmission resistance of the tube wall between the catalyst bed and the reactor, the convection and conductive heat transfer within the catalyst bed is relatively efficient. To simplify the model, the gas layer heat transfer resistance was used and the radial temperature gradient within the catalyst bed was disregarded due to the large L/W ratio of the reactor.

Advantages:

- Technology concept that has been tested in other petrochemical applications;
- Scaling up is as simple as multiplying tubes.
- A uniform distribution of catalysts;
- Absolute separation of products and catalysts, removing the need for expensive catalyst separation and filtering facilities.
- Product contamination and catalyst losses are kept to a minimum.

Kg/hr
CO_2 = 87283
H_2 = 12475
CH3OH = 126
CO = 21679
H_2O = 290



Kg/hr
CO_2 = 69652
H_2 = 10102
CH3OH = 12698
CO = 21898
H_2O = 7502

Figure 5-1: Multi-Tube Packed bed reactor

Design Steps:

Calculate:

1. Weight of catalyst

2. volume of Catalyst bed
3. Volume of Reactor
4. Space time
5. Tube diameter
6. Number of tubes
7. Shell Diameter
8. Pressure Drop
9. Cooling water requirement

Design Calculations:

Reactions:

$CO + 2H_2 \leftrightarrow CH_3OH$ $x_{CO} = 0.22$

$CO_2 + H_2 \leftrightarrow CO + H_2O$ $x_{CO_2} = 0.202$

$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$ $x_{CO_2} = 0.202$

The rate equations for these reactions are:

$$r_A = \frac{K_A K_{CO}[C_{CO}\left(\frac{1 - X_{CO}}{1 + \varepsilon_1 X_{CO}}\right)(C_{H2})^{3/2}(RT)^{2.5}(C_{H2}) - \left(\left(\frac{K_{CO}}{K_A}\right) * Cmeoh * CH_2{}^{-1/2}\,(RT)^{1/2}\right)}{\Big[1 + K_{CO}\left(C_{CO}\frac{1 - X_{CO}}{1 + \varepsilon_1 X_{CO}}\right) + K_{CO}\left(C_{CO}\frac{1 - X_{CO}}{1 + \varepsilon_1 X_{CO}}\right)RT\Big]\,[(C_{H2}RT)^{1/2} + \frac{K_{H2O}}{\sqrt{K_H}}\,(C_{H2O}RT]}$$

$$r_B = \frac{K_B K_{CO2}[C_{CO2}\left(\frac{1 - X_{CO2}}{1 + \varepsilon_2 X_{CO2}}\right)(C_{H2})^1(RT)^2 - \left(\left(\frac{K_{CO2}}{K_B}\right) * Cco * CH_{2O} * (RT)^2\right)}{\Big[1 + (K_{CO} * C_{CO} * RT) + (K_{CO2} * C_{CO2}\left(\frac{1 - X_{CO2}}{1 + \varepsilon_2 X_{CO2}}\right)RT)\Big]\,[(C_{H2}RT)^{1/2} + \frac{K_{H2O}}{\sqrt{K_H}}\,(C_{H2O}RT]}$$

$$r_C = \frac{K_{C.}\,K_{CO2}[C_{CO2}\left(\frac{1 - X_{CO2}}{1 + \varepsilon_3 X_{CO2}}\right)(C_{H2})^1(RT)^{3/2} - \left(\left(\frac{K_{CO2}}{K_c}\right) * (Cmeoh * (RT)^{1/2} * CH_{2O} * CH^{-3/2}\right)}{\Big[1 + (K_{CO} * C_{CO} * RT) + (K_{CO2} * C_{CO2}\left(\frac{1 - X_{CO2}}{1 + \varepsilon_3 X_{CO2}}\right)RT)\Big]\,[(C_{H2}RT)^{1/2} + \frac{K_{H2O}}{\sqrt{K_H}}\,(C_{H2O}RT]}$$

Where

Temperature = 523 K,

Pressure = 50 bar,

$R = 8.314 \frac{\mathrm{J}}{\mathrm{mol.K}}$

$$K_{CO} = (8.396 \times 10^{-11}) \exp\left(\frac{118270}{RT}\right)$$

$$K_{CO2} = (1.7214 \times 10^{-10}) \exp\left(\frac{81287}{RT}\right)$$

$K_A = 0.040638$ mol/s.Pa

$K_B = 9.0421$ mol/s.Pa

$K_C = 151.88$ mol/s.Pa

$\varepsilon_1 = \frac{3-1}{3} = -0.67$

$\varepsilon_2 = \frac{2-2}{2} = 0$

$\varepsilon_2 = \frac{4-2}{4} = -0.5$

$$C_{CO} = \frac{F_{ACo}}{V_{Co}} = \frac{870600 mol/hr}{21382.46\, m^3/hr} = 40.71\, mol/m^3$$

$$C_{CO_2} = \frac{F_{ACO_2}}{V_{CO_2}} = \frac{288900 mol/hr}{6797.9\, m^3/hr} = 42.5\, mol/m^3$$

Weight of Catalyst:

Reaction 1:

$$\frac{V}{F_{AO}} = \int_0^{XCo} \frac{d_X}{-r_A}$$

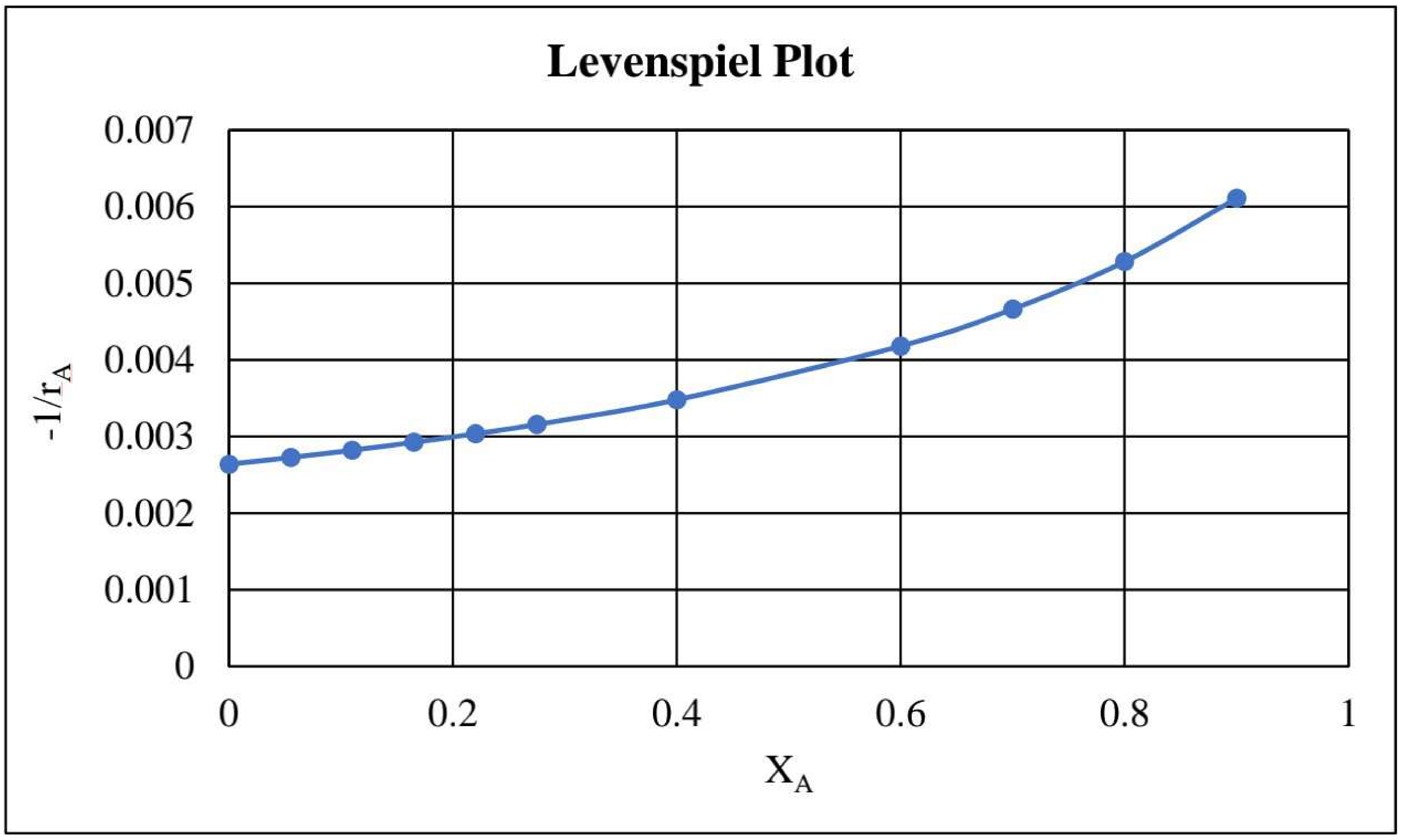


Figure 5-2: Levenspiel Plot for reaction 1

(Through Area Under the curve)

$$\frac{V}{F_{AO}} = 0.000622$$

$$F_{AO} = 401.05 \, {}^{mol}/_{s}$$

$$W_{A.\ Catalyst} = 324 \text{ Kg}$$

Weight of Catalyst:

Reaction 2:

$$\frac{V}{F_{BO}} = \int_{0}^{XCo2} \frac{d_X}{-r_B}$$

(Through Area Under the curve)

$$\frac{V}{F_{AO}} = 0.000979$$

$$F_{BO} = 1533 \, {}^{mol}/_{s}$$

$$W_{B.\ Catalyst} \ 1952 \text{ Kg}$$

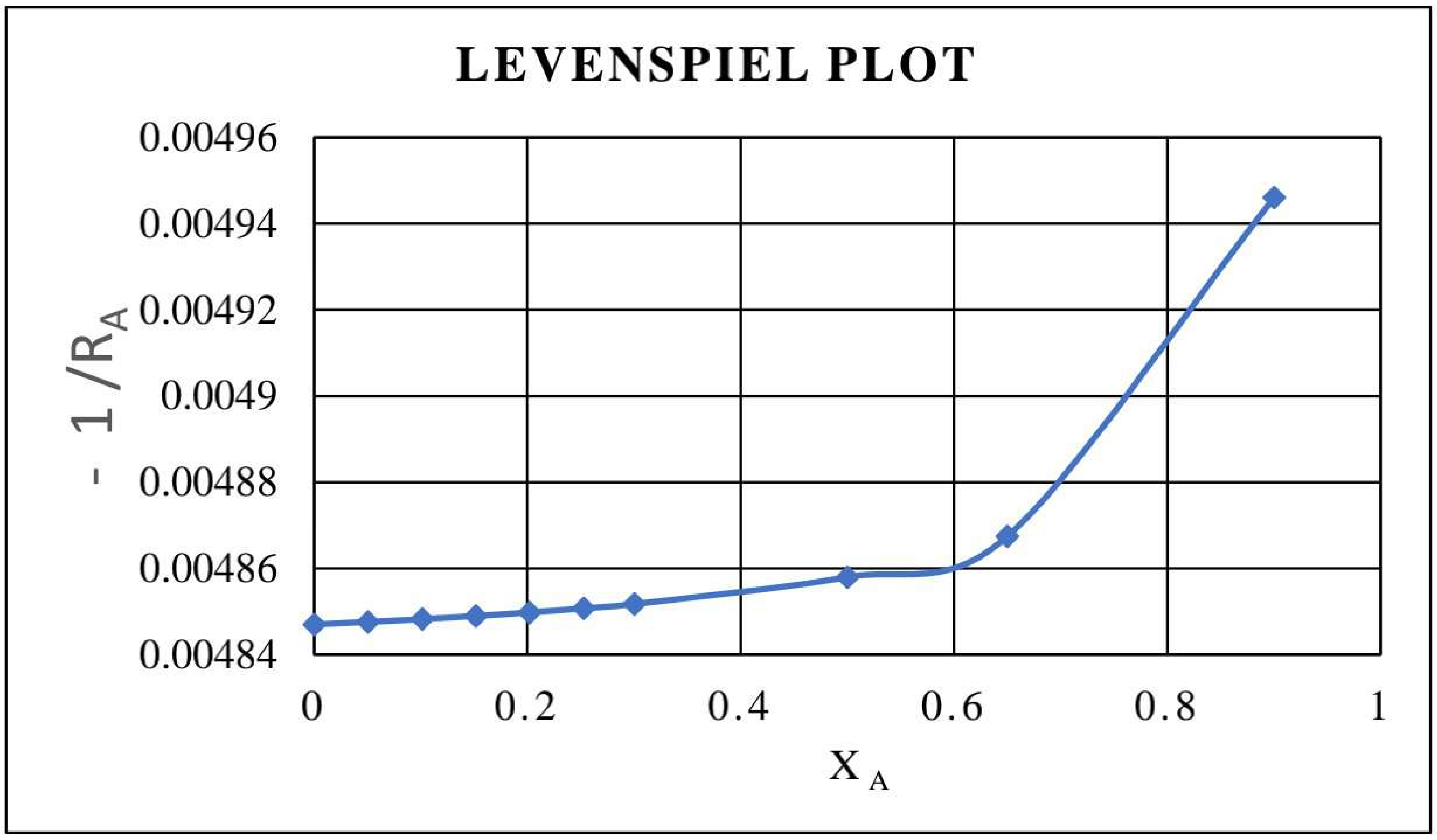


Figure 5-3: Levenspiel Plot for reaction 2

For Weight of bed:

Reaction 3:

$$\frac{V}{F_{AO}} = \int_{0}^{XA} \frac{d_X}{-r_A}$$

(Through Area Under the curve)

$$\frac{V}{F_{AO}} = 0.000588$$

$$F_{CO} = 2061 \ {}^{mol}/_{s}$$

$$W_{B.\ Catalyst} = 1574 \text{ Kg}$$

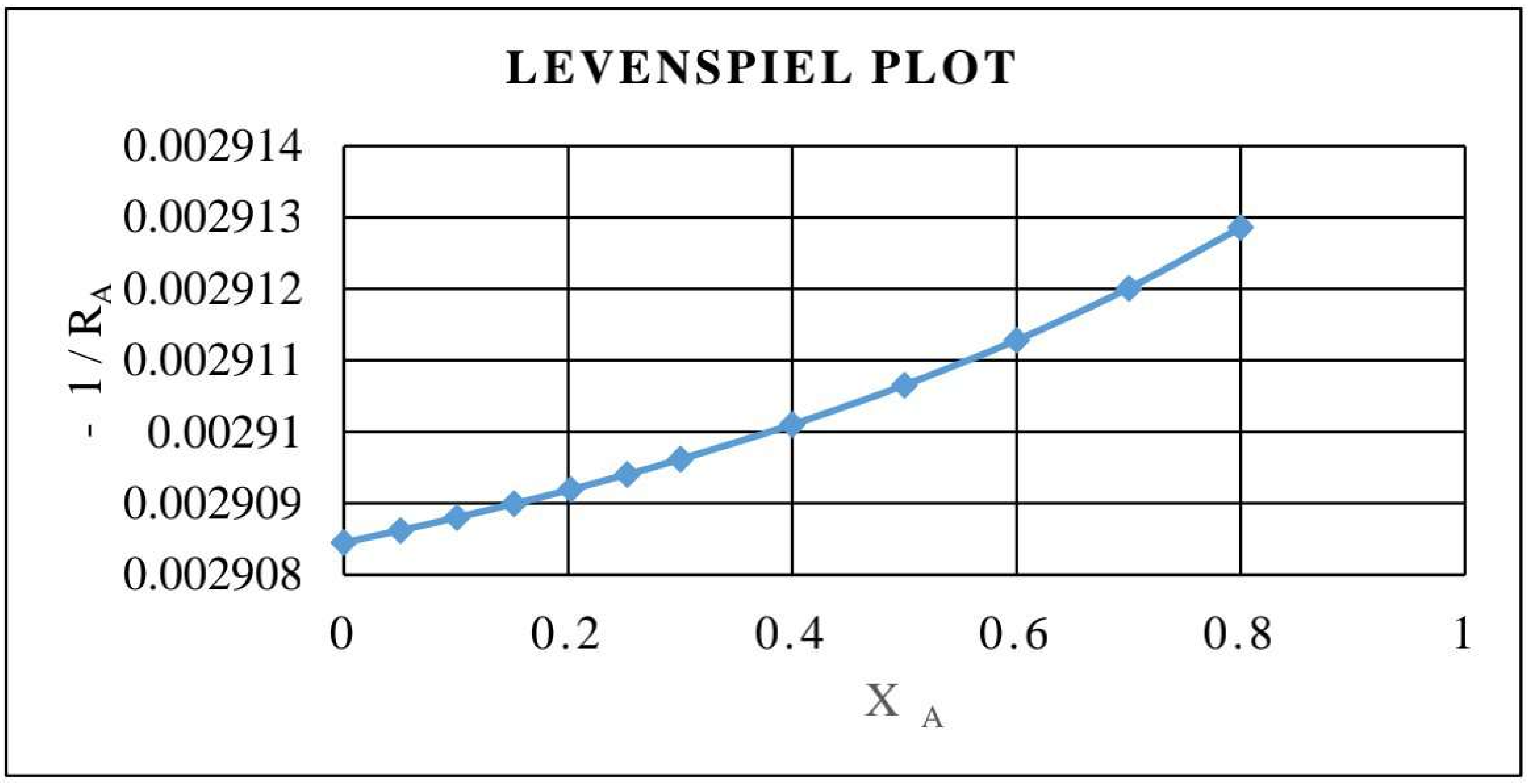


Figure 5-4: Levenspiel plot for reaction 3

Total Weight of bed:

WT = 324 kg+ 1952 kg + 1574 kg = 3850 kg

Volume of Catalyst:

$$\text{Bulk density of catalyst} = 1300\ {}^{\text{kg}}/_{\text{m}^3}$$

$$\text{Voidage} = \varepsilon = 0.25$$

$$\text{Catalyst diameter} = 3\text{mm} = 0.003\ \text{m}$$

$$\text{Vcatalyst} = {}^{\text{m}}/_{\rho} = \frac{\text{weight of bed}}{\text{density}} = \frac{3850}{1300} = 0.50\ \text{m}^3$$

Volume of Reactor:

$$\text{Volume of reactor} = \frac{V_{\text{Catalyst}}}{1-\varepsilon} = \frac{2.96}{1-0.25} = 3.9\ \text{m}^3$$

Space Time:

$$\tau = \frac{V}{V_O} = \frac{3.9}{54.5} = 0.072\ \text{sec}$$

Tube Diameter:

$$L\text{ength of tubes} = 20\text{ft} = 6.096\ \text{m}$$

to prevent deviationsfrom plug flow assumption

$$D_T/D_P > 15$$

D_T = diameter of tube = (8 − 15)cm = 10cm = 0.10 m

D_P = diameter of Particle = 3mm = 0.003m

$D_T/D_P = 0.10/0.003 = 33.3$ (satisfactory)

Volume of one tubes $= \frac{\pi}{4} \times Dt^2 \times L_t = 0.0306\ m^3$

Number of Tubes:

Number of tube required $= \frac{\text{Volume}}{\text{Volume of one tube}} = 129$

Length of Reactor:

After 20 % safety allowance = 7.3152 m

Diameter of Shell:

Length of Shell = 7.3152 m

Taking L/D = 5

So,

D s= L/5

Ds = 7.3152 /5

Ds = 1.4 m

Pressure Drop:

$\frac{\Delta P}{L} = \frac{150\mu G(1-\varepsilon)^2}{\rho D^2 \varepsilon^3} + \frac{1.75G^2(1-\varepsilon)}{\rho D \varepsilon^3} = \Delta P = 0.3$ bar

G = Mass Velocity $= \frac{\text{Mass flowrate}}{\text{Diamter of reactor}} = 29\ {}^{kg}/_{m^2 s}$

$$A = \text{Area of Reactor} = \frac{\text{Volume of Reactor}}{\text{Diamter of reactor}} = 1.17\ \text{m}^2$$

Viscosity of

$CO2\ = 2.71 \times 10^{-5}$

$CO = 2.90 \times 10^{-5}$

$H2 = 1.37 \times 10^{-5}$

$W = (0.307)(2.71 \times 10^{-5}) + (0.307)(2.71 \times\ 10^{-5}) + (0.307)(2.71 \times 10^{-5})$

$\text{Weighted Viscosity} = 2.5 \times 10^{-5}$

Cooling water Requirement:

$Q = \text{Heat Load} = -\mathbf{26708025}\frac{KJ}{hr} C_p\ \ = 4.18\frac{kJ}{kg\ K}$

$\Delta T =\ T_2\ \text{-} T_1\ \ = 45 - 25 = 20°C$

$Q = mC_p\Delta T$

$$m = \frac{Q}{C_p\Delta T} = 319\frac{T}{hr}$$

Specification Sheet	
Identification	
Item	Reactor
Item No	R-101
No of Require	1
Operation	Continuous
Type	Packed Bed Reactor

<table>
<tr><th colspan="2">Function</th></tr>
<tr><td colspan="2">CO2 Hydrogenation to Methanol</td></tr>
<tr><th colspan="2">Chemical Reactions</th></tr>
<tr><td colspan="2">$CO + 2H_2 \leftrightarrow CH3OH$</td></tr>
<tr><td colspan="2">$CO_2 + H_2 \leftrightarrow CO + H_2O$</td></tr>
<tr><td colspan="2">$CO_2 + 3H_2 \leftrightarrow CH3OH + H_2O$</td></tr>
<tr><td>Weight of Bed</td><td>3850 Kg</td></tr>
<tr><td>Volume of Catalyst</td><td>3 m^3</td></tr>
<tr><td>Volume of Reactor</td><td>3.9 m^3</td></tr>
<tr><td>Space time</td><td>0.07 s</td></tr>
<tr><td>Diameter of tube</td><td>0.080 m</td></tr>
<tr><td>No of tubes</td><td>129</td></tr>
<tr><td>Diameter</td><td>1.2 m</td></tr>
<tr><td>Length of Reactor</td><td>7.3 m</td></tr>
<tr><td>Pressure Drop</td><td>0.3 bar</td></tr>
</table>

5.2 Design of Absorber:

Absorption, also known as mass transport, is the process of transferring a solute gas to a liquid solvent in order to separate it from a non-solute gas mixture. It is the second most important function in chemical engineering. Absorption occurs when the gas stream is contacted with a liquid that is sufficiently solubile or selective to absorb the solute gas.

Comparison between Packed and Plate Column:

Packed Column	Plate Column
To decrease liquid holdup And to make the unit as compact as possible for safety, A packed column is chosen over a plate column for handling poisonous and combustible liquids	As the flow rates increase, plate towers have significant pressure drops and liquid holdup.
Foaming and corrosive services are better served by packed towers.	Plate columns are often used to foul fouling liquids or solids.

Packing Material:

Based on the foregoing principles, a packed column is chosen as the absorber. Because a liquid's solubility is unlimited, it will absorb as many gases as it comes into touch with, resulting in greater interaction in a densely packed tower. It's quite easy to use. The following are the most important requirements for tower packing:

- It must be chemically inert to the tower's fluids.
- It should be strong yet not too hefty. It must have enough passages to allow both streams to flow freely without producing liquid back up or pressure drops.
- It must be cost-effective and allow for good liquid-to-gas contact

As a result, the majority of packaging is made of low-cost, inert, and lightweight materials like clay, porcelain, or graphite. Some limes are steel or aluminum rings with a thin wall.

Selection of packing:

A ceramic Intalox saddle has been chosen. Intalox saddle and pall rings are the most popular choices. We picked ceramic Intalox saddles because they are the most efficient. We picked ceramic packing material since our system contains oxygen and water, both of which can cause corrosion, and ceramic material prevents corrosion.

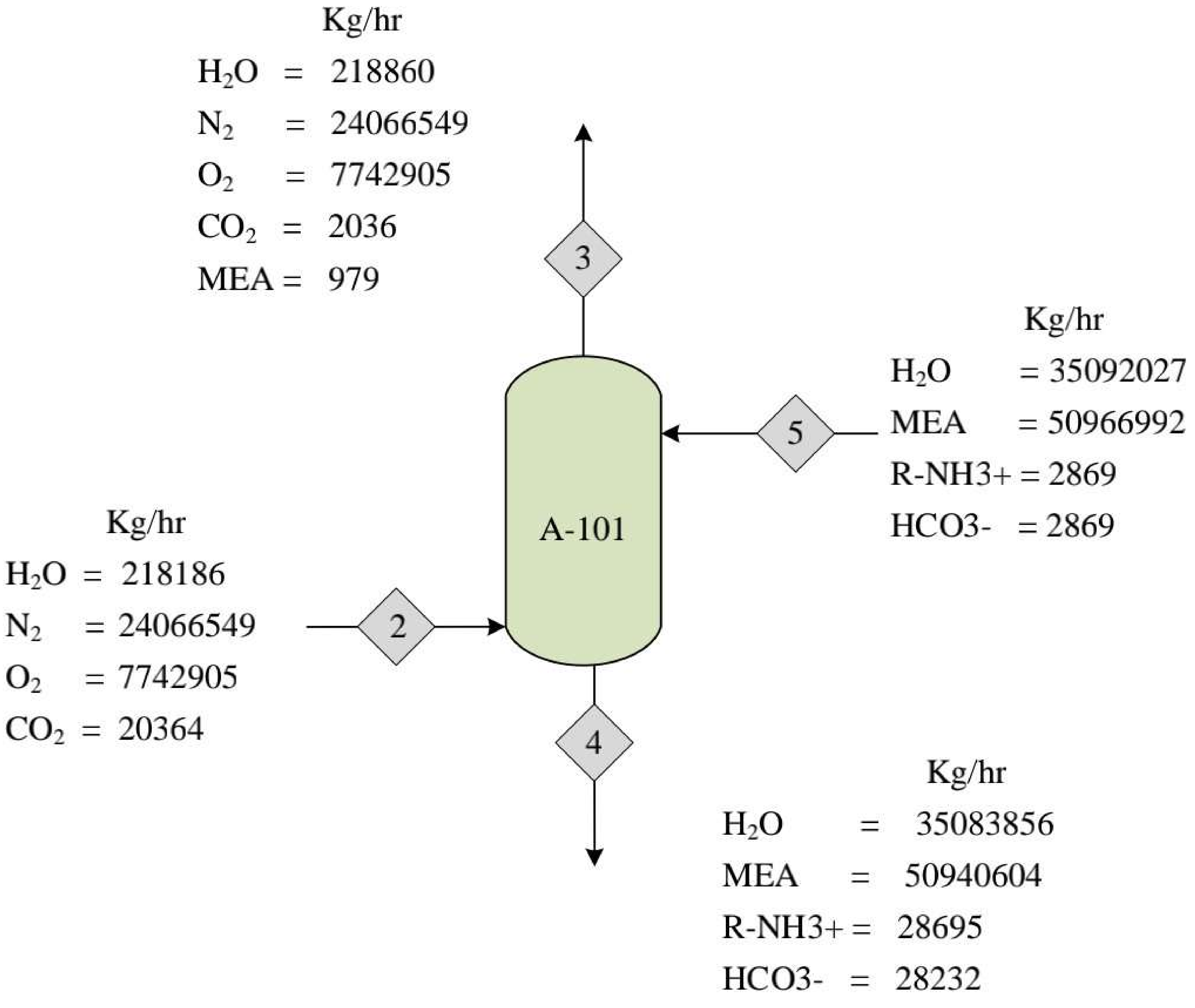


Figure 5-5: Absorber (A-101)

Design Steps:

- Calculation of Flow Factor
- Column Diameter Calculation •
- Transfer Unit Height Calculation
- Calculation of the Liquid Film Mass Transfer Coefficient
- Calculation of the Gas Film Mass Transfer Coefficient
- Calculation of the Gas Film Transfer Unit Height
- Calculation of height of tower
- Calculation of wetting rate
- Calculation of Pressure drop
- Calculation of liquid transfer unit height
- Calculation of height of transfer unit height
- Calculation for Operating velocity

Design Calculations:

Flow Factor (FLV):

$$F_{LV} = \frac{L}{G}\sqrt{\frac{\rho_g}{\rho_l}}$$

$$F_{LV} = 0.13$$

The relation for flow factor is

Flow rate of entering gas = G = 5.66 kg⁄s

Flow rate of entering solvent = L = 20.65 kg⁄s

For 42 mm of $\frac{H_2O}{m}$ of packing

K_4 = 1.3 (from graph)

Operating Velocity:

Viscosity of gas mixture = $\mu g = 1.79\times10^5$ Pa.s

Viscosity of liquid(solvent) = μl = 2.50 Pa.s

Density of liquid(solvent) = $\rho l = 1010$ kg/m^3

Density of gas mixture = $\rho_{g =}$ 1.29 kg/m^3

Packing parameter for 2- inch intalox sddles = $F_P = 170$ m^{-1} (Source R.K Sinnott)

$$G = \left[\frac{K_4\rho_v(\rho_L-\rho_v)}{13.1F_p\left(\frac{\mu_L}{\rho_L}\right)^{0.1}}\right]^{1/2}$$

G = 0.37 kg/m^{2}s

For Area

$$A = \frac{Gas\ flowrate}{V_w}$$

A = 15.20 m^2

For Diameter:

$$D = \sqrt{\frac{4\times A}{\pi}}$$

D = 4.4 m

Calculation of Height Transfer units:

$$\frac{a_w}{a} = 1 - \exp\left[-1.45\left(\frac{\sigma_c}{\sigma_L}\right)^{0.75}\left(\frac{L_w}{a\mu_L}\right)^{0.1}\left(\frac{Lw^2}{\rho l^2 g}\right)^{0.05}\left(\frac{L_w}{\rho_L \sigma_L a}\right)^{0.2}\right]$$

a_w = Effective interfacial are of packing per unit volume, m^2/m^3

L_w = liquid mass flow rate per unit cross-sectional area = 1.36 kg/m^2s

σ_c = critical surface tension for the particular packing material = 0.061 N/m (R.K Sinott)

a = 194 m^2/m^3 (R.K Sinott Book)

σ_L = liquid surface tension = 0.63 N/m

g = 9.8 m/s^2

Putting above values will give us

a_w = 6990.83 m^2/m^3

Calculation of Liquid film Mass transfer co-efficient:

a_w = Effective interfacial are of packing per unit volume, m^2/m^3

L_w = 1.36 kg/m^2s

g = 9.8 m/s^2

D_L = diffusivity of liquid (solvent) = 0.538×10^{-9} m^2/s

d_p = 38 mm

K_L = liquid Film coefficient

$$K_L\left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0.0051\left(\frac{L_w}{a_w\mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-1.2}(adp)^{0.4}$$

Putting the values will give us

$K_L = 3.37\times10^{-5}$ m/s

Calculation of gas film Mass transfer Coefficient:

For gas film Mass transfer Coefficient

V_w= 0.37 kg/m^{2}s

L_w = 1.36 kg/m^{2}s

dp = 38 mm

K_5 = 5.23 for packing above 15mm

D_g = Diffusivity of gases = 1×10^{-5} m^2/s

R = 0.08314 bar m^3/kmol K

T_g = 308 K

$$\frac{K_G}{a}\frac{RT_g}{D_g} = K_5\left(\frac{V_w}{a\mu_g}\right)^{0.7}\left(\frac{\mu_g}{\rho_g D_g}\right)^{1/3}(adp)^{-2}$$

$K_G = 2.66\times10^{-12}$ kmol/sm^2.bar

Gas Film Transfer Unit Height:

For gas film transfer unit height

$$H_G = \frac{G_m}{K_G a_w P}$$

G_m = Gas mass velocity = 8.46×10^{-3} kmol/m^{2}s

K_G = Gas film coefficient = 2.66×10^{-12} kmol/sm^2.bar

H_G = Gas film transfer unit height, m

$H_G = 4.48$ m

Calculation of Liquid transfer unit height:

For liquid transfer unit height

$$H_L = \frac{L_m}{K_L a_w C_t}$$

L_m = Liquid mass velocity = 0.0454 kmol/m^{2}s

C_t = Total Concentration = ρL / molecular weight of solvent = 16 kmol/m3

K_L = Liquid film coefficient = 3.37×10^{-5} m/s

$H_L = 0.0108$ m

Calculation of height of transfer unit:

For height of transfer unit

$$H_{OG} = H_G + m\frac{G_m}{L_m}H_L$$

H_G = Gas film transfer unit height = 4.48 m

$m\frac{G_m}{L_m} = 0.70$ (Range 0.7 – 0.8)

$H_L = 0.0108$ m

Putting values

$H_{OG} = 4.49$ m

Equation for equilibrium curve:

Form equilibrium curve

P_1 = Partial pressure of solute at outlet solvent concentration =0.012 MPa

P_2 = Partial pressure of solute at inlet solvent concentration = 0.002 MPa

$$\frac{y_1}{y_2} = \frac{p_1}{p_2} = 6$$

N_{OG} = 3.05 (from figure)

Calculation of height of Tower:

For height of Tower

$Z = N_{OG} \times H_{OG}$

Putting values will give us

Z = 13.71 m

Allowance for liquid distribution & redistribution = 0.7m + 0.7m

Z = 15.11 m

Calculation of wetting rate:

For wetting rate, we have

$$\text{Wetting rate} = \frac{\text{Volumetric flowrate}}{a}$$

Volumetric liquid flowrate = 0.0204 m^3/s

a = 194 m2/m3 (R.K Sinott Book)

Wetting rate = 1.05×10^{-2} m^2/s

Flooding Velocity:

For flooding velocity, we have

$$V_w = \left[\frac{K_4 \rho_v (\rho_L - \rho_v)}{13.1 F_p \left(\frac{\mu_L}{\rho_L}\right)^{0.1}}\right]^{1/2}$$

At Flooding K_4 = 4 (from figure)

V_w = 0.65 kg/m^2s

Pressure Drop:

We required

$$\frac{G_L}{G_g}\sqrt{\frac{\rho_g}{\rho_L - \rho_g}} = 0.13$$

$$\frac{G_g{}^2 F_p \mu_L{}^{0.1}}{g_c(\rho_L - \rho_v)\rho_L} = 0.03$$

$$G_L = \frac{\text{Liquid mass flowrate}}{\text{Area}}$$

$$G_g = \frac{\text{Gas mass flowrate}}{\text{Area}}$$

ΔP = 1.80 inch of H_2O/ foot of packed height

ΔP = 81.60 inch of H_2O

Height = 45 ft

Total pressure drop = 2072.53 mm of H_2O

Total pressure drop= 0.20 bar

Specification Sheet	
Identification	
Item	Absorber
Item No	A - 101
No of Required	1
Operation	Continuous
Type & Packing	Packed Bed / Intalox Saddles Packing
Function	
CO_2 Absorption	
Operating Pressure	1 bar
Operating Temperature	34 ^{o}C
Diameter	4.40 m
Interfacial Area of Packing	194.00 m^2
Height of Transfer Unit	4.49 m
Number of Transfer Units	3.05
Column Height	13.71 m
Pressure Drop	0.20 bar
Wetting Rate	1.05×10^{-4} m^2/s
Flooding	57 %

5.3 Design of Stripper (ST-101):

"Stripping is a group operation in which one or more components of a liquid stream are removed by bringing them into contact with an insoluble material in a gas stream." Evaporation is a physical separation process that removes vapours from one another or from other sources of water. Continuous or transient current may be present in liquid and steam flows in industrial equipment. Most separations are performed in packed columns or plates.

Comparison between Packed and Plate Column:

Table 5-2: Comparison between Packed and Plate Column

Packed Column	Plate Column
Due to decrease liquid holdup and the need to make the unit as compact as possible for safety, a packed column is chosen over a plate column for handling poisonous and combustible liquids.	At greater gas flow rates, plate towers have significant pressure dips and liquid holdup.
Columns with a small diameter (less than 0.6m). More material options for packing's, particularly in corrosive applications (e.g., plastic, ceramic, metal alloys).	They are easy to clean and can withstand significant temperature changes while in use.

Selection of Packing:

Based on the foregoing principles, a packed column is chosen as the absorber. Because a liquid's solubility is unlimited, it will absorb as many gases as it comes into touch with, resulting in greater interaction in a densely packed tower. It's quite easy to use. The following are the most important requirements for tower packing:

- It must be chemically inert to the tower's fluids.
- It should be strong yet not too hefty. And have enough passages to allow both streams to flow freely without producing liquid back up or pressure drops.
- It must be cost-effective and allow for good liquid-to-gas contact

As a result, the majority of packaging is made of low-cost, inert, and lightweight materials like clay, porcelain, or graphite. Some limes are steel or aluminium rings with a thin wall.

Selection of Packing:

Ceramic Intalox Saddles have been selected. The most popular options are the Intalox Saddle and the Pall Ring. We chose the Ceramic Intalox because it is the most efficient option. We also chose the Ceramic packing material because our system contains both oxygen and water which can lead to corrosion. Ceramic material prevents corrosion.

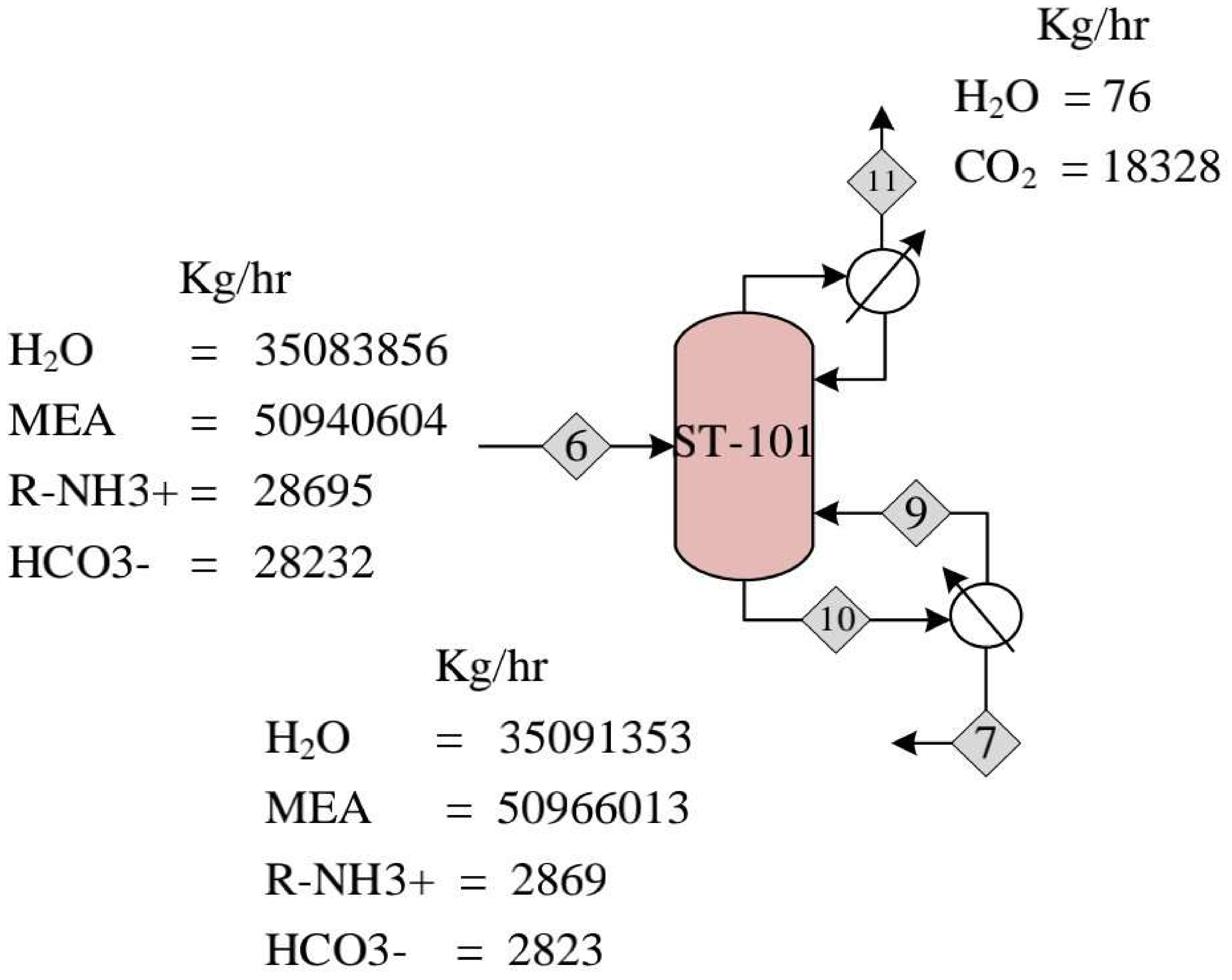


Figure 5-6: Stripper (S-101)

Design Calculations:

Flow Factor (F_{LV}):

Flow rate of entering gas = G = 4165 kg/hr

Flow rate of entering solvent = L = 91013 kg/hr

For 42 mm of $\frac{H_2O}{m}$ of packing

Viscosity of gas mixture = µg = 0.012 cp

Viscosity of liquid(solvent) = $\mu l = 0.681$ cp

Density of liquid(solvent) = $\rho l = 937\ kg/m^3$

Density of gas mixture = $\rho_g = 1.156\ kg/m^3$

Packing parameter for 2- inch intalox sddles = $F_P = 130\ m^{-1}$

$$F_{LV} = \frac{L_w}{V_w}\sqrt{\frac{\rho_g}{\rho_l}}$$

$F_{LV} = 0.77$

$K_4 = 0.6$ (from graph)

Operating Velocity:

$$V_w = \left[\frac{K_4 \rho_V(\rho_L - \rho_V)}{13.1 F_p \left(\frac{\mu_L}{\rho_L}\right)^{0.1}}\right]^{1/2}$$

$V_w = 0.886\ kg/m^2s$

For Area

$$A = \frac{\text{Gas flowrate}}{V_w}$$

$A = 1.31\ m^2$

For Diameter:

$$D = \sqrt{\frac{4 \times A}{\pi}}$$

$D = 1.3$ m

Calculation of Height Transfer units:

$$\frac{a_w}{a} = 1 - \exp\left[-1.45\left(\frac{\sigma_c}{\sigma_L}\right)^{0.75}\left(\frac{L_w}{a\mu_L}\right)^{0.1}\left(\frac{Lw^2}{\rho l^2 g}\right)^{0.05}\left(\frac{L_w}{\rho_L \sigma_L a}\right)^{0.2}\right]$$

a_w = Packing's effective interfacial area per unit volume , m^2/m^3

L_w = flow rate of liquid mass per unit cross-sectional area , kg/m^{2}s

σ_c the required surface tension for the specific packing material N/m (R.K Sinott Book)

$a = 108\ m^2/m^3$ (R.K Sinott Book)

σ_L = liquid surface tension, N/m

g = 9.8 m/s

Putting above values will give us

$\frac{a_w}{a} = 0.804$

$a_w = 87\ m^2/m^3$

Liquid film transfer co-efficient calculation:

$L_w = 19\ kg/m^2s$

g = 9.8 m/s

$D_L = 5.3\times10^{-9}\ m_2/s$

$a = 108\ m^2/m^3$ (R.K Sinott Book)

$$K_L\left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0.0051\left(\frac{L_w}{a_w\mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-1.2}(a dp)^{0.4}$$

Putting the values will give us

$K_L = 3\times10^{-3}$ m/s

Gas film mass transfer calculation Coefficient:

For gas film Mass transfer Coefficient

$V_w = 0.886\ kg/m^2s$

$L_w = 19\ kg/m^2s$

dp = 51 mm

K_5 = 5.23 for packing above 15mm

R = 0.08314 bar m^3/kmol K

T_g = 375 K

$$\frac{K_G}{a}\frac{RT_g}{D_g} = K_5\left(\frac{V_w}{a\mu_g}\right)^{0.7}\left(\frac{\mu_g}{\rho_g D_g}\right)^{1/3}(adp)^{-2}$$

K_G = 4.4 ×10^{-3} kmol/sm^2.bar

Gas Film Transfer Unit Height:

For gas film transfer unit height

$$H_G = \frac{G_m}{K_G a_w P}$$

P = 1.1 bar

G_m = Gas mass velocity = 0.39 kmol/m^2s

a_w = Effective interfacial area of packing per unit volume = 87 m^2/m^3

K_G = Gas film coefficient = 3×10^{-3} kmol/sm^2.bar

H_G = Gas film transfer unit height, m

H_G = 1.4 m

Liquid transfer unit height calculation:

For liquid transfer unit height

$$H_L = \frac{L_m}{K_L a_w C_t}$$

L_m = Liquid mass velocity = 0.5 kmol/m^2s

C_t = Total Concentration = ρ_L / Molecular weight of solvent = 30.5 kmol/m3

K_L = Liquid film coefficient = 3×10^{-3} m/s

H_L = 0.1 m

Height of transfer unit calculation:

For height of transfer unit

$$H_{OG} = H_G + m\frac{G_m}{L_m}H_L$$

H_G = Gas film transfer unit height = 0.368 m

$m\frac{G_m}{L_m}$ = 0.75 (Range 0.7 – 0.8)

Putting values

H_{OG} = 2.25 m

Equation for equilibrium curve:

Form equilibrium curve

$\frac{y_1}{y_2}$ = 1.32

y_1 = The mole proportion of gas entering the stream

y_2 = The mole proportion of gas leaving the stream

N_{OG} = 0.75

Calculation of height of Tower:

For height of Tower

$Z = N_{OG} \times H_{OG}$

Putting values will give us

Z = 1.7 m

Allowance for liquid distribution & redistribution = 0.5m + 0.5m

Z = 2.7 m

Wetting rate Calculation:

For wetting rate, we have

$$\text{Wetting rate} = \frac{\text{Volumetric flowrate}}{\text{a}}$$

volumetric liquid flowrate = 0.03 m^3/s

a = 108 m2/m3 (R.K Sinott Book)

Wetting rate = 2.7×10^{-3} m^2/s

Pressure Drop:

We required

$$\frac{G_L}{G_g}\sqrt{\frac{\rho_g}{\rho_L - \rho_g}}$$

$$\frac{{G_g}^2 F_p {\mu_L}^{0.1}}{g_c(\rho_L - \rho_v)\rho_L}$$

$$G_L = \frac{\text{Liquid mass flowrate}}{\text{Area}}$$

$$G_g = \frac{\text{Gas mass flowrate}}{\text{Area}}$$

$g_c = 32$

Area = 11.6 m^2

$G_L = 0.480$ kg/m^2s

$G_g = 2.55$ kg/m^2s

$$\frac{G_L}{G_g}\sqrt{\frac{\rho_g}{\rho_L - \rho_g}} = 0.77$$

$$\frac{{G_g}^2 F_p {\mu_L}^{0.1}}{g_c(\rho_L - \rho_v)\rho_L} = 2\times10^{-3}$$

From figure

ΔP = 0.057 inch of water/ foot of packed height

$\Delta P = 1.524$ mm of H_2O /m

Total pressure drop= $\Delta P \times$ Height of tower

Total pressure drop = 11.35 mm of H_2O

SPECIFICATION SHEET	
Identification	
Item	Stripper
Item no.	ST-101
No. of required	1
Operation	Continuous
Type	Packed Column
Packing	Ceramics Intalox Saddles
Function	
To regenerate the absorbent by removing absorb CO_2, H_2S, CH_4	
Operating Pressure	45 bar
Operating Temperature	30℃
Diameter	2.2 m
Height of transfer unit	1.21m
Number of transfer unit	0.75
Column Height	3.34 m
Pressure Drop (ΔP)	11.6 mm of H_2O

SPECIFICATION SHEET	
Identification	
Item	Stripper
Item no.	ST-102
Operation	Continuous
Type	Packed Column
Packing	Ceramics Intalox Saddles
Function	
To remove Gases from methanol and recycle the gases CO, CO_2 & H_2	
Operating Pressure	45 bar
Operating Temperature	30°C
Diameter	1.53 m
Area	1.85 m^2
Effective Interfacial Area	98 m^2/m^3
Height of Gas Transfer Unit	0.644 m
Height of Liquid transfer Unit	0.11 m
Height of transfer unit	0.73 m
Column Height	3.7 m
Pressure Drop (ΔP)	0.00048 bar

5.4 Design of Condenser:

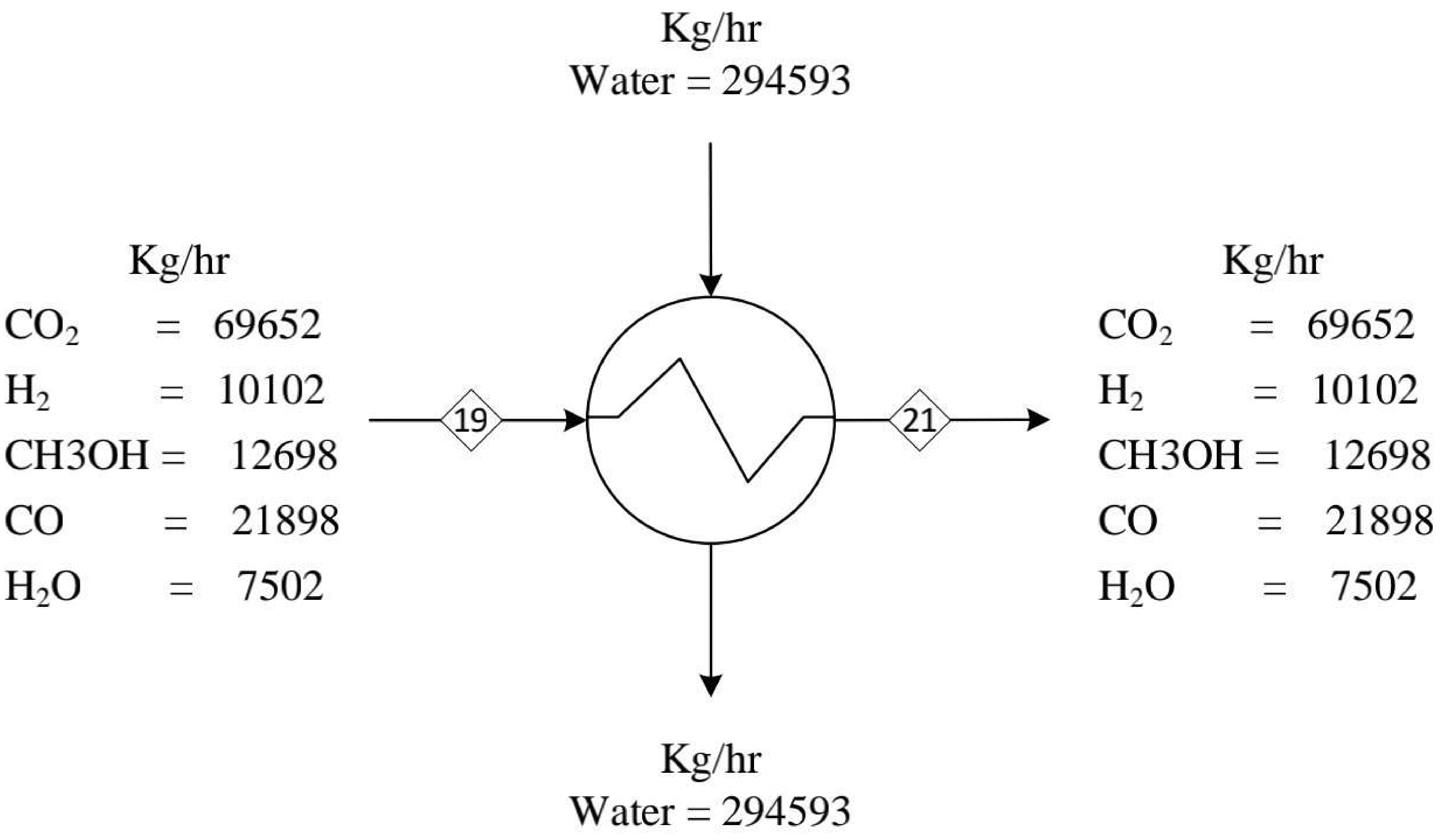


Figure 5-7: Condenser (E-105)

Design calculation:

Operating Conditions:

Q = 23381926 (btu/hr)

Water =649466 (lb/hr)

$T_1 = 274\ ^oF$

$T_2 = 86\ ^oF$

$t_1 = 77\ ^oF$

$t_2 = 104\ ^oF$

$\Delta t1 = 170\ ^oF$

$\Delta t2 = 9\ ^oF$

$$\text{LMTD} = \frac{\Delta t_2 - \Delta t_1}{\ln\left(\frac{\Delta t_2}{\Delta t_1}\right)}$$

LMTD = 54.7 °F

Area

$Q = U_d \times A \times \text{LMTD}$

Assume $U_d = 450$

Area= 949 ft^2

No of Tubes:

Calculated:

N_t = area/ length×surface per linear ft.

$N_t = 949/16 \times 0.3925$

$N_t = 151$

Actual (from table)

$N_t = 154$

Tubes Specifications:

Tube OD =1.5 in =0.125 ft

BWG = 16

Tube ID = 1.37 in=0.114

Flow Area/Tube = 1.47 in^2 = 0.114 ft^2

Triangular Pitch = 1.875 in = 0.156 ft

Shell	**Tubes**
Hot Fluid (gases)	**Cold Fluid (water)**
Flow Area: as = CB×ID/144p C = 0.375in B = shell ID/5 B = 5.8 $a_s = 0.25ft^2$	**Flow Area:** at = No. of tubes × flow area per tube/144×N at =154×1.47/144×2 at = 0.0339 ft^2
Mass Velocity: Gs = $\frac{w}{as}$ Gs = $\frac{504062}{0.23}$ Gs = 2191573 lb/hr.ft^2	**Mass Velocity:** Gt =$\frac{w}{at}$ m = 26310 lb/hr Gs = $\frac{26310}{0.0339}$ Gs = 832648 lb/hr.ft^2
Loading: G` = $\frac{W}{L\times {N_T}^{2/3}}$ G` = $\frac{504062}{16*154^{2/3}}$ G` =1096 lb/hr.lin ft	**Velocity:** Velocity =$\frac{Gt}{3600\times g}$ g = 62.5lb/ft^3 Velocity = 3.70fps
Convective heat transfer coefficient: From fig h_o=190 BTU/hr.ft^2.F	**Convective heat transfer coefficient:** Viscosity = 1.74 (at t_{Avg}) D=1.37/12 Re = D_G/viscosity Re = 54477 hi (from Fig.25) = 850 h_{io} = hi×(ID/OD) h_{io} = 776 BTU/hr.ft^2.F

Clean overall coefficient:

$U_c = \frac{h_{io}\, h_o}{h_{io}+h_o}$ = 152 BTU/hr.ft^2.F

Dirt Factor:

$\mathbf{R_D} = \frac{U_C - U_D}{U_C\, U_D}$ = 0.0004

Pressure Drop:

Shell	Tube
f from using Re Re= De × Gt/viscosity Re = 458,701 f= 0.0015 (from figure) baffle spacing = shell ID/5 baffle spacing = 5.8 no of crosses (N+1) = 12×L/B (N+1) = 33.4 ΔPs = (1/2) × (fG2×Ds× (N+1)/(5.22×1010)De×s ΔPs = 5.3 psi	Re = 24735.09 f = 0.0002 (from fig.26) ΔP_t = 0.708 $V^2/2g$ = 0.05 ΔPr = ($V^2/2g$) × (4n/5) ΔPr = 0.708 $\Delta P_T = \Delta P_t + \Delta Pr$ ΔP_T =1.108 psi

5.5 Design of Shell and Tube Heat Exchanger:

Shell & Tube Heat Exchanger:

Because shell and tube heat exchangers deliver more heat than other types of heat exchangers, they are frequently employed in chemical processing industries, particularly refineries. There is a wealth of information on their design and construction accessible. These remarks are simply meant to serve as a starting point.

Heat exchangers operate on the same premise: hot water flows over/around the cooler, transferring heat (and hence energy) to the cold water. (For a refresher on thermodynamic laws, visit our page on heat exchangers). Consider how it feels to put your hand on the stairs in the winter: the temperature difference between your hand and the boat is noticeable at first, but you may notice how cold it is; however, if you continue to hold the wheel, some of the heat in your hands will be transferred to the cold feet, and the wheel will "warm up."

Advantages:

- The condensation process allowed in either the tubes or the shell, with either horizontal or vertical orientation.
- Pressures and pressure dips may be adjusted to a broad range.
- Thermal strains may be accommodated affordably.
- There is considerable flexibility in building materials to handle problems.
- Heat transmission can be improved by using wider heat transfer surfaces (fins).
- Cleaning and maintenance are simple because the equipment may be disassembled for this reason.

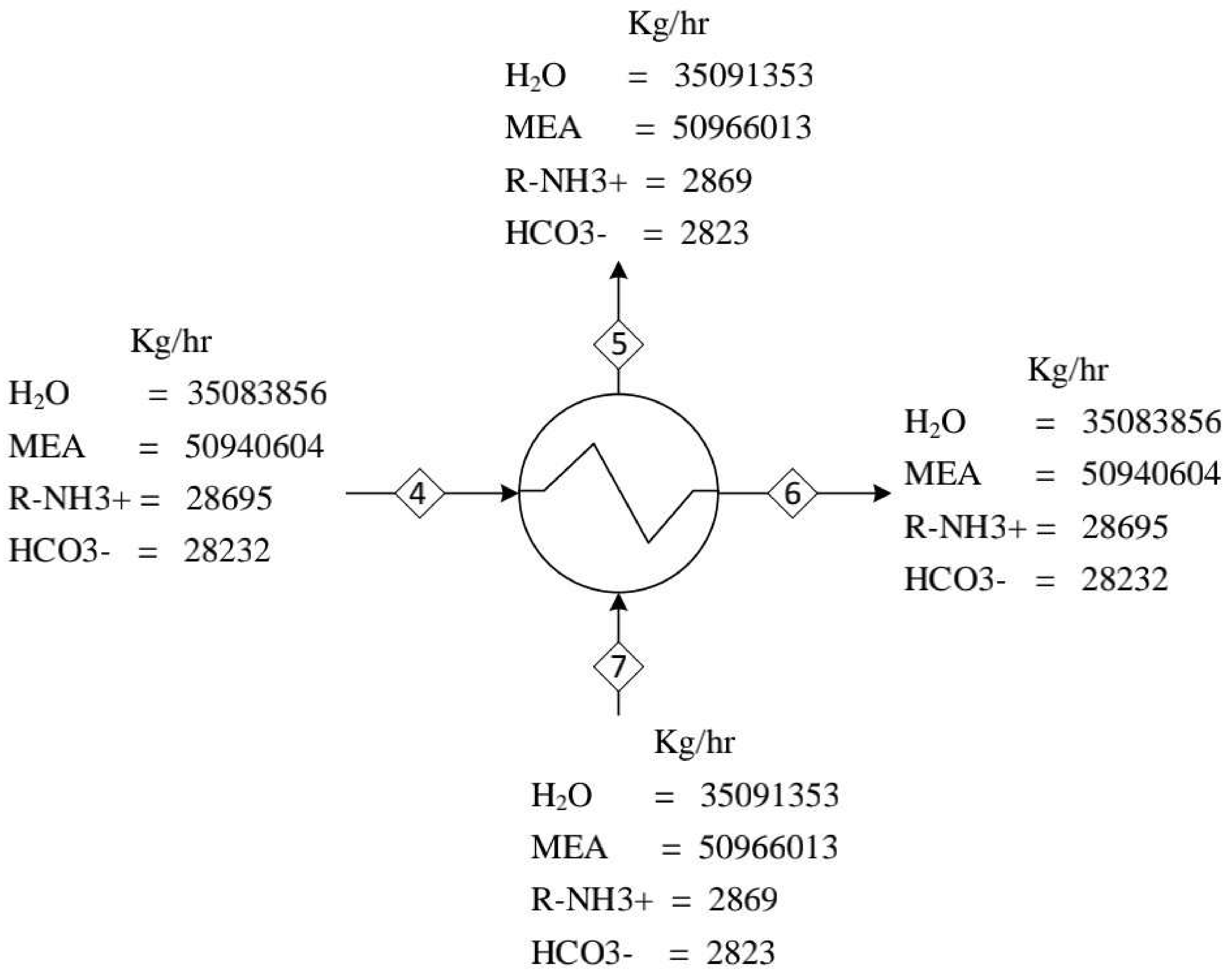


Figure 5-8: Shell and Tube Heat Exchanger (E-101)

Design Calculation:

Hot Fluid Components:

- R-NH3
- MEA
- H_2O
- HCO_3

Cold Fluid component:

- Steam

LMTD:

Hot Fluid $131^{O}F \longrightarrow 255^{O}F$

Cold Fluid $93^{O}F \longleftarrow 215^{O}F$

$$\Delta t_1 = T_2 - t_1 = 131 - 93 = 38°F$$

$$\Delta t_2 = T_1 - t_2 = 255 - 215 = 40°F$$

$$\text{LMTD} = \frac{\Delta t_2 - \Delta t_1}{\ln\left(\frac{\Delta t_2}{\Delta t_1}\right)}$$

$$\text{LMTD} = \frac{40 - 38}{\ln\left(\frac{40}{38}\right)}$$

$$\text{LMTD} = 34.7°F$$

From kern

Assume $U_D = 60\,\frac{Btu}{hr.ft^2°F}$ (From Kern)

$$\dot{Q} = U_D A F_T \text{LMTD}$$

$$A = \frac{\dot{Q}}{U_D F_T \text{LMTD}}$$

$$A = \frac{8743249}{60 \times 34.7}$$

$$A = 345.2 ft^2$$

Selection of Tubes:

$$\mathrm{OD} = \frac{3}{4}\,\mathrm{in}$$

$$\mathrm{BWG} = 13$$

$$\text{Tube Pitch} = \mathrm{P_T} = 1\frac{1}{4}\ \text{in Square}$$

$$\text{Tube Length} = \mathrm{L} = 16\ \mathrm{ft}$$

$$\mathrm{N_T} = \frac{345.2}{\mathrm{L} \times \text{Surface per line ft, ft}^2}$$

$$\mathrm{N_T} = \frac{345.2}{16 \times 0.1963}$$

$$\mathrm{N_T} = 110$$

From Table 9

$$\text{Corrected number of tubes} = 137$$

$$\text{Shell ID} = 21\frac{1}{4}\,\mathrm{in}$$

$$\text{Tube Passes} = 4$$

$$\text{Baffle Spacing} = 5\mathrm{in}$$

$$\text{Actual Area} = \mathrm{N_T} \times \mathrm{L} \times \text{Surface per lin.}$$

$$\mathrm{A} = 137 \times 16 \times 0.1963$$

$$\mathrm{A} = 430\mathrm{ft}^2$$

$$\dot{\mathrm{Q}} = \mathrm{U_D A F_T LMTD}$$

$$U_D = \frac{\dot{Q}}{AF_T LMTD}$$

$$U_D = \frac{8743249}{430 \times 40}$$

$$U_D = 508 \frac{\text{Btu}}{\text{lbft}^2 \text{°F}}$$

Heat Balance:

$$\dot{Q} = 8743249 \frac{\text{Btu}}{\text{hr}}$$

LMTD:

$$\text{LMTD} = 37.4\text{°F}$$

Corrected LMTD:

$$F_T \text{LMTD} = 40\text{°F}$$

Shell-Side (Hot-Fluid)	**Tube-Side (Cold-Fluid)**
Flow area: $a_S = D_S \times \frac{CB}{144P_T}$ $C = P_T - Tube\ OD$ $C = 1 - 0.75$ $C = 0.25in$ $a_S = \frac{21.25 \times 0.25 \times 5}{144 \times 1.25}$ $a_S = 0.149ft^2$	$a_t = \frac{N_T a_t'}{144n}$ $a_t' = 0.302\ in^2$ $a_t = \frac{158 \times 0.51652}{144 \times 2}$ $a_t = 0.141ft^2$
Mass Velocity: $G_S = \frac{W}{a_S}$ $G_S = 491937 \frac{lb}{hr\ ft^2}$ $D_e = 0.95in$ $D_e = 0.079ft$	$G_t = \frac{W}{a_t}$ $G_t = 645482 \frac{lb}{hr\ ft^2}$ $D = 0.620\ in$ $D = 0.01567ft$
Reynold Number: $Re_S = \frac{D_e G_S}{\mu}$ $Re_S = 193260$	$Re_t = \frac{DG_t}{\mu}$ $Re_t = 73847$
Prandtl Number:	$j_H = 160$ from fig. $h_i = j_H \frac{k}{D_e} (Pr)^{1/3}$

$$k = 0.9\frac{Btu}{hr\ ft^2\ {}^\circ\mathrm{F}/ft}$$

$$(Pr)^{1/3} = \left(\frac{c\mu}{k}\right)^{1/3}$$

$$(Pr)^{1/3} = \left(\frac{o.646 \times 3.13}{0.37}\right)^{1/3}$$

$$(Pr)^{1/3} = 0.64$$

$j_H = 104$ from fig.

$$h_o = j_H\frac{k}{D_e}(Pr)^{1/3}$$

$$h_o = 100 \times \frac{0.37}{0.079} \times 1.76$$

$$h_o = 726\frac{Btu}{lb\ ft^2{}^\circ\mathrm{F}}$$

$$h_i = 160 \times \frac{1.27}{0.0075} \times 0.3$$

$$h_i = 1075\frac{Btu}{lb\ ft^2{}^\circ\mathrm{F}}$$

From Fig. 25

$$h_{io} = 1075 \times \frac{0.0516}{0.75}$$

$$h_{io} = 870\frac{Btu}{lb\ ft^2{}^\circ\mathrm{F}}$$

Clean overall coefficient:

$$U_C = \frac{h_{io} \times h_o}{h_{io} + h_o}$$

$$U_C = 395.7\frac{Btu}{lb\ ft^2{}^\circ F}$$

Actual Area:

$$A = N_T \times L \times \text{Surface per lin.}$$

$$A = 137 \times 16 \times 0.1963$$

$$A = 430 ft^2$$

Design overall coefficient:

$$\dot{Q} = U_D A F_T LMTD$$

$$U_D = \frac{\dot{Q}}{AF_T LMTD}$$

$$U_D = \frac{8743249}{430 \times 40}$$

$$U_D = 335\frac{Btu}{lbft^2{}^\circ F}$$

Dirt factor:

$$R_d = \frac{U_C - U_D}{U_C U_D}$$

$$R_d = \frac{395 - 335}{395 \times 335}$$

$$R_d = 0.00028$$

Pressure Drop:

Shell-Side (Hot-Fluid)	**Tube-Side (Cold-Fluid)**
From Fig. 29 $f = 0.0016$ $\text{Number of cross} = N + 1 = 12\frac{L}{B}$ $\text{Number of cross} = N + 1 = 12\frac{16}{5}$ $\text{Number of cross} = N + 1 = 38.4$ $\text{Specific gravity} = s = 1.55$ $D_S = 1.271 ft$ $\Delta P = \frac{f G_S^2 D_S (N+1)}{5.22 \times 10^{10} D_e s}$ $\Delta P = \frac{0.0012 \times (1322099.698)^2 \times 1.271 \times 38.4}{5.22 \times 10^{10} \times 0.95 \times 1.55}$ $\Delta P = 7.85 psi$	From Fig. 26 $f = 0.000167$ $Specific\ gravity = s = 1$ $\Delta P_t = \frac{f G_t^2 L n}{5.22 \times 10^{10} D_L}$ $\Delta P_t = \frac{0.000187 \times 645482 \times 16 \times 2}{5.22 \times 10^{10} \times 0.0516}$ $\Delta P_t = 1.4 psi$ $\Delta P_r = \frac{4 n v^2}{2 g s}$ $\Delta P_r = \frac{4 \times 2}{2 \times 1}(0.041)$ $\Delta P_r = 0.650 psi$ $\Delta P_T = \Delta P_t + \Delta P_r$ $\Delta P_T = 1.4 + 0.650$ $\Delta P_T = 2.0 psi$

<table>
<tr><th colspan="3">Specification-Sheet</th></tr>
<tr><th colspan="3">Identification</th></tr>
<tr><td>Item</td><td colspan="2">Heat-Exchanger (E-101)</td></tr>
<tr><td>Type</td><td colspan="2">(Shell and Tube) Heat-Exchanger</td></tr>
<tr><th colspan="3">Function</th></tr>
<tr><td>Heat duty</td><td colspan="2">$8743249 \frac{Btu}{hr}$</td></tr>
<tr><td>Area</td><td colspan="2">$430 ft^2$</td></tr>
<tr><td>Uc Calculated</td><td colspan="2">$395.7 \frac{Btu}{lb\ ft^2 °F}$</td></tr>
<tr><td>Ud Calculated</td><td colspan="2">$335 \frac{Btu}{lbft^2 °F}$</td></tr>
<tr><td>Fouling factor</td><td colspan="2">0.00028</td></tr>
<tr><th>Fluid Placement</th><th>Shell-Side</th><th>Tube-Side</th></tr>
<tr><td>Fluid Name</td><td>MEA</td><td>Rich Out</td></tr>
<tr><td>Pressure Drop</td><td>$7.85 psi$</td><td>$2.0 psi$</td></tr>
<tr><td colspan="3">Tube No: 110 OD: $\frac{3}{4} in$ BWG: 13 Pitch: $1\frac{1}{4}\ in\ Square$</td></tr>
<tr><td colspan="3">Shell ID: $21\frac{1}{4} in$</td></tr>
</table>

Specification-Sheet		
Identification		
Item	Heat Exchanger (E-102)	
Type	Shell and Tube Heat Exchanger	
Function		
Heat duty	$9761653\frac{KJ}{hr}$	
Area	$578ft^2$	
Uc Calculated	$415.3\,\frac{Btu}{lb\ ft^2{}^\circ\mathrm{F}}$	
Ud Calculated	$384\,\frac{Btu}{lbft^2{}^\circ\mathrm{F}}$	
Fouling factor	0.00022	
Fluid Placement	**Shell-Side**	**Tube-Side**
Fluid	Gases	Steam
Pressure Drop	$6.8psi$	$2.0psi$
Tube No: 154 OD: $\frac{3}{4}in$	BWG: 16	Pitch: $1\frac{1}{4}\ in\ triangluar$
Shell ID: $21\frac{1}{4}in$		

Specification Sheet		
Identification		
Item	Heat Exchanger (E-103)	
Type	Shell and Tube Heat Exchanger	
Function		
Heat duty	$32190566.92\frac{KJ}{hr}$	
Area	$896ft^2$	
Uc Calculated	$553\frac{Btu}{lb\ ft^2{}^\circ F}$	
Ud Calculated	$446\frac{Btu}{lbft^2{}^\circ F}$	
Fouling factor	0.0004	
Fluid Allocation	**Shell Side**	**Tube Side**
Fluid Name	Gases (hot)	Gases (cold)
Pressure Drop	$5.4psi$	$1.3psi$
Tube No: 282 OD: 1 in BWG: 16 Pitch: $1\frac{1}{4}\ in\ triangluar$		
Shell ID: $25in$		

SPECIFICATION-SHEET		
Identification		
Item		Heat-Exchanger (E-104)
Type		Shell and Tube
Function		
Heat Duty		19689990.77 Btu/h
Actual Surface Area		997 ft^2
Uc calculated		264 BTU/ hr ft^2 ^oF
U_D calculated		50BTU/hr ft^2 ^oF
Fouling Factor		0.007 hr.ft^2 ^oF/ BTU
Fluid Allocation	**Shell-side**	**Tube-side**
Fluid Name	Feed	Steam
Fluid Quantity	268638 lb/hr	23991 lb/hr
Temperature	356 – 482 ^oF	752^oF
Pressure	2 bar	50 bar
Viscosity	0.04 lb/ft.hr	0.498 lb/ft.hr
Thermal Conductivity	0.0349 Btu/hr.ft ^oF	0.121 Btu/hr.ft ^oF
Pressure Drop	5.47 psi	6.63 psi
Tubes No: 238 OD: 1 in BWG: 16 Pitch: 1 ¼ Square Shell ID: 25 in		

5.6 Design of Gas-Liquid Separator:

Introduction

To separate the input into pure vapours and pure liquids, a vapor-liquid separator is utilised. It aids in the recovery of valuable products and increases product purity. A hot distributor is one that uses a second distributor to force hot water through the valve.

Separator Types:

- Vertical
- Horizontal
- Knock-out Drum

Vertical separator:

- When vapor flow is greater than liquid flow.
- High separation efficiency.
- As a general rule, it is preferred in oil refineries.
- During operation, 50 percent L.L must be kept.

Horizontal separator:

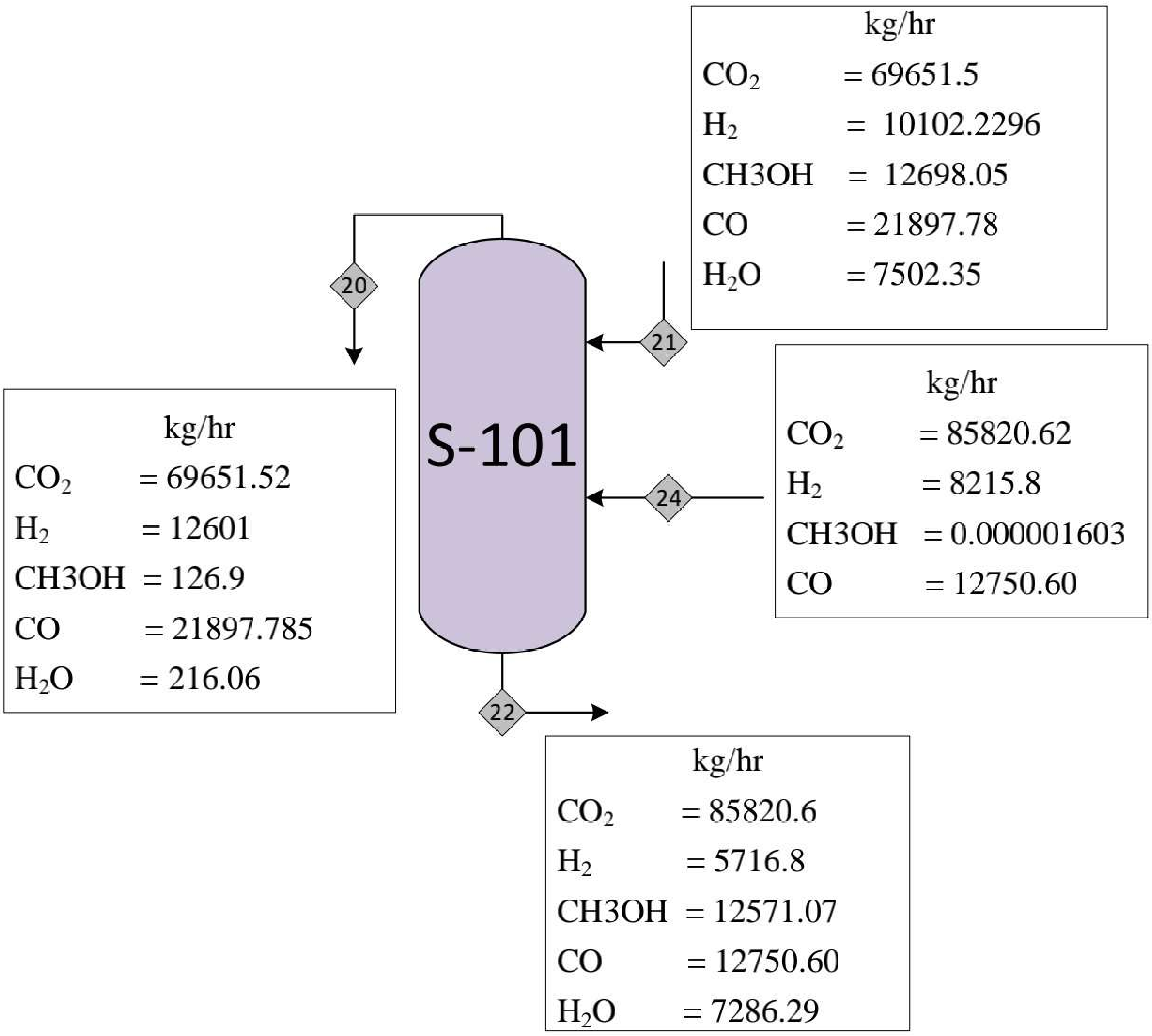
- When feed contains high liquid amount.

L/D ratio specification:

- In the event of a knockout drum, the (L/D) ratio is 2.
- If the (L/D) value is between 3 and 5 then use Vertical.
- If the (L/D) value is more than 5, the separator will be horizontal.

Working Principal:

Gravity and influence on separation separate vapour and liquid mixes. The mixture falls through the separator and onto the spray plate, where it loses heat. The majority of the liquid evaporates, with the dry liquid rising to the surface. The bulk of water descends to the bottom as the steam rises. With the application of a weed remover, the separation efficiency may be raised to 99.9%.



kg/hr
CO_2 = 69651.5
H_2 = 10102.2296
CH3OH = 12698.05
CO = 21897.78
H_2O = 7502.35

kg/hr
CO_2 = 69651.52
H_2 = 12601
CH3OH = 126.9
CO = 21897.785
H_2O = 216.06

kg/hr
CO_2 = 85820.62
H_2 = 8215.8
CH3OH = 0.000001603
CO = 12750.60

kg/hr
CO_2 = 85820.6
H_2 = 5716.8
CH3OH = 12571.07
CO = 12750.60
H_2O = 7286.29

Figure 5-9: Gas-Liquid Separator

Splash plate:

It is employed to initiate the partial separation of the liquid and the gas. It enables a rapid change in the velocity (speed) and direction of the incoming flow. If not present, vapours will evaporate rapidly without contact with the liquid to attain equilibrium.

Vortex breaker:

When the liquid outlet valve is open, a vortex breaker is normally placed to prevent the creation of a vortex. If a vortex forms near the liquid outflow, the gas may be extracted and entrained with the departing liquid. This can lead to vapor loss, damage to the pump, and irregular liquid level measurements.

Mist eliminator:

The mechanical separation of fluids from gases is referred to as mist elimination, also referred to as demisting. Mesh is typically composed of 0.011-inch diameter wires that form a 4- to 6-inch-thick pad with a drop in pressure of less than 1 inch of water.

Design steps:

Calculate:

1. Vapor velocity.
2. Cross-sectional area.
3. Diameter.
4. Vapor height.
5. Volume.
6. Liquid height.
7. Total length.
8. L/D value.

Operating Conditions:

Pressure = 50 bar

Temperature = 30°C

Mass flow of liquid = 124145 kg/hr

Mass flow of vapor = 104493 kg/hr

$V_L = 573\ m^3/hr$

$V_L = 0.1592\ m^3/s$

$V_v = 1282\ m^3/hr$

$V_v = 0.356\ m^3/s$

$\rho_L = 216.62\ kg/m^3$

$\rho_v = 81.51\ kg/m^3$

Calculation of vapor velocity:

put K_v in the equation given below:

$K_v = 0.185$ m/s

Maximum vapor velocity (Shouder Brown Equation):

$$V_v = \left(\frac{K_v(\rho_L - \rho_V)}{\rho_V}\right)^{0.5}$$

$V_v = 0.238$ m/s

Calculation of cross-sectional area:

$$A = \frac{Q_v}{V_v}$$

$$A = \frac{0.35612}{0.238} = 1.496\ m^2$$

Calculate Diameter:

$$D = \sqrt{\frac{4 \times A}{\pi}}$$

$$D = \sqrt{\frac{4 \times 1.496}{3.14}}$$

D = 1.380 m

Surge time selection:

(Times, t lies from 2 to 5 min) Let us use t = 4 min.

Separator Height:

Vapor height h_v:

$h_v = 1.5\ D + 1.5$

$h_v = 1.5\ (1.380) + 1.5 = 3.57$ m

Liquid height h_L:

$h_L = \frac{Q_L \times t}{A}$

$h_L = (0.1592 * 4)/1.496 = 0.425$ m

Total Height:

$h = h_L + h_v$

$h = 3.57 + 0.425$

$h = 3.9965$ m ≈ 4 m

Check L/D ratio:

$L/D = 4/1.380 = 3 < 5$

So, we can use Vertical separator.

Specification-Sheet	
Identification	Gas-Liquid Separator S-101
Types	Phase Separator
Function	
To separate CO, CO_2 & H_2 from methanol	
Operating Pressure	45 bar
Operating Temperature	30° C
Area	1.496 m^2
Diameter	1.38 m
Length	4 m
Material of Construction	Stainless Steel

5.7 Distillation Column Design:

Distillation:

The separation of a mixture according to its boiling point and volatility. The process of distillation is applied to a wide range of applications, such as alcohol purification, crude oil refining, and the generation of liquid gases from air.

Distillation Column Types:

- There are several varieties of distillation columns available, each intended to perform different sorts of separations and have varying levels of complexity.
- Batch columns
- Continuous columns

Batch Column:

The feed is given to the column one at a time in batch mode. The next batch of feed is supplied after the desired degree of cleanliness has been attained.

Continuous Columns:

Continuous columns, on the other hand, process a continuous stream of feed. Unless there is a failure in the column or nearby process units, there are no interruptions. Continuous columns are the more popular of the two and can handle high throughputs.

Choice between Plate and Packed Column:

Table 5-3: Difference between plate and packed column

Plate Column	**Packed Column**
• This column is utilized to accommodate a wide variety of flow rates. • Less Flooding • Cleaning of plate column is easy.	• This sort of column is utilized to manage a narrower range of flow rates. • More flooding

Distillation Column Main Components:

- Column internals such as trays/plates and/or packing that improve component separation.

- The distillation process requires the employment of a reboiler to achieve the vaporization required for the operation. Bottom's product or simply "bottoms" is the liquid that is extracted from this reboiler.
- A condenser for chilling and condensing the vapour at the top of the column. The distillate, or top product, is the condensed liquid collected from the system.
- A reflux drum catches condensed vapor at the top of a column and pumps it back down as a liquid into the column. The condensed liquid is kept in a container known as a reflux drum. When part of the condensed liquid is pushed back up into the column, this is referred to as reflux.

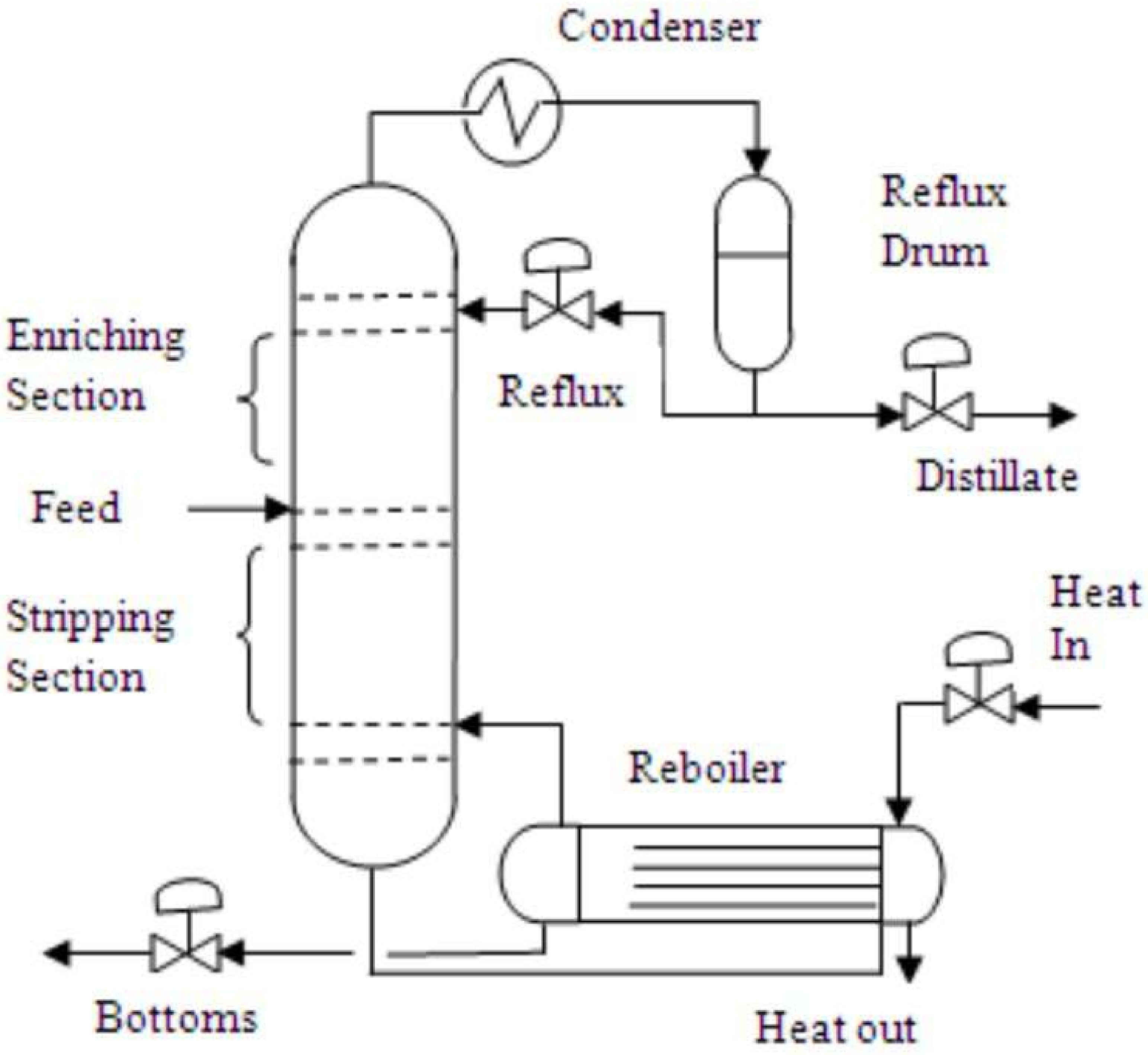


Figure 5-10: Schematic Distillation Column Design

Factor affecting the distillation column operation

1. Vapor Flow Conditions
2. Reflux Conditions
3. Feed Conditions
4. State of Trays and Packing

Design Calculations

Designing steps of distillation column includes to calculate:

- Bubble point and dew point.
- Minimum Reflux Ratio Rm.
- Actual Reflux Ratio R.

- Theoretical number of stages.
- Actual number of stages.
- Physical properties of top and bottom product.
- Column Diameter
- Weeping point, entrainment etc.
- Pressure-Drop in column
- Column Height

Equilibrium Data for Methanol and Water Mixture

X	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Y	0	0.38	0.53	0.61	0.68	0.74	0.80	0.85	0.90	0.95	1

Here we can use the Mc-Cabe-Thiele method,

Assumptions

- Continuous molar overflow
- There are no chemical reactions.
- There are no mass generation, accumulation, or generation.

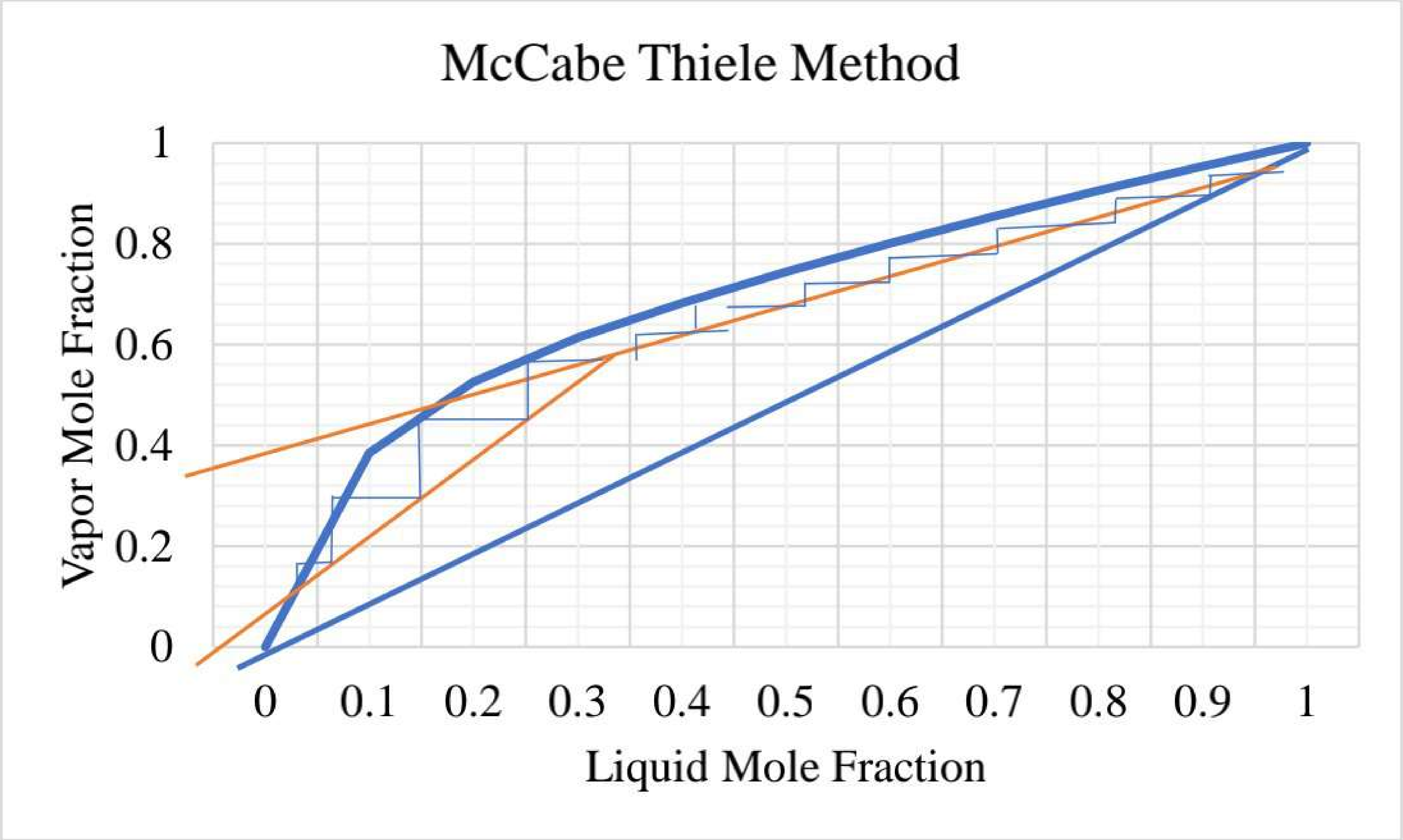


Figure 5-11: Vapor-Liquid Equilibrium Diagram

Components	**Feed Mole Fraction**	**Distillate Mole Fraction**	**Bottom Mole Fraction**	**K value**
Methanol	0.49	0.99	0.01	1.495
Water	0.51	0.01	0.99	0.5244
Hydrogen	0.00015	-	-	-

The amount of hydrogen is very small so it can be neglected

F = 810 kmol/hr

W = 415 kmol/hr

D = 395 kmol/hr

$$\alpha = \frac{K_A}{K_B} = \frac{1.495}{0.5244} = 2.851$$

$$R_m = \frac{1}{(\alpha - 1)}\left[\frac{x_{dA}}{x_{fA}} - \alpha\frac{x_{dB}}{x_{fB}}\right]$$

$$R_m = \frac{1}{2.85 - 1}\left[\frac{0.99}{0.63} - (2.851)\frac{0.01}{0.37}\right]$$

$$R_m = 1.061$$

$$R = 1.5R_m$$

$$R = 1.5 \times 1.061 = 1.5915 \approx 1.6$$

$$R = \frac{L_n}{D}$$

$$L_n = 1.6 \times 395 = 632\frac{\text{kmol}}{\text{hr}}$$

$$V_n = L_n + D$$

$$V_n = 632 + 395 = 1027\frac{\text{kmol}}{\text{hr}}$$

$$y_{n=}\frac{L_n}{V_n}x_{n+1} + \frac{D}{V_n}x_d$$

$$y_{n=}\frac{632}{1027}x_{n+1}+\frac{395}{1027}(0.99)$$

$$y_{n=}0.61x_{n+1}+0.38$$

$$\theta=\tan^{-1}(0.61)$$

$$\theta=31^{o}$$

$$L_m=L_n+F$$

$$L_m=632+810$$

$$L_m=1442\frac{\text{kmol}}{\text{hr}}$$

$$V_m=L_m-W$$

$$V_m=1027\frac{\text{kg}}{\text{hr}}$$

$$y_{m=}\frac{L_m}{V_m}x_{m+1}-\frac{W}{V_m}x_w$$

$$y_{m=}\frac{1442}{1027}x_{m+1}-\frac{415}{1027}(0.01)$$

$$y_{m=}1.4x_{m+1}-0.004$$

$$\theta=\tan^{-1}1.4$$

$$\theta=55^{o}$$

By using McCabe Thiele Method, the theoretical stages are

$$\text{Theoretical stages}=11$$

$$E_o=0.17-0.616\log\mu$$

$$\mu=0.2616\text{cp}$$

$$E_o=0.17-0.616\log(0.2616)$$

$$E_o=0.53$$

$$E_{o=}\frac{\text{Theoretical Stages}}{\text{Actual Stages}}$$

$$0.53=\frac{11}{N_{\text{Actual}}}$$

$$N_{\text{Actual}}=21\text{ stages}$$

Feed Location:

$$\log\left(\frac{N_e}{N_s}\right)=0.2061\log\left[\left(\frac{W}{D}\right)\left(\frac{x_{f,HK}}{x_{f,LK}}\right)\left(\frac{x_{w,LK}}{x_{d,HK}}\right)^2\right]$$

$$\frac{N_e}{N_s}=0.805$$

$$N_e=0.805N_s$$

$$N=N_E+N_s$$

$$N_s=12$$

$$N_e=9$$

This means that the feed is at 9th stage.

Top Product:

$\rho_L = 684\ kg/m^3$

$\rho_v = 5.34\ kg/m^3$

$\sigma = 0.01613\ N/m$

Bottom Product:

$\rho_L = 897\ kg/m^3$

$\rho_v = 2.671\ kg/m^3$

$\sigma = 0.048\ N/m$

Column Diameter:

$$\text{Top } F_{lv} = \frac{L_n}{V_n}\sqrt{\frac{\rho_v}{\rho_l}}$$

$$\text{Top } F_{lv} = \frac{632}{1027} \times \sqrt{\frac{5.34}{684}} = 0.05$$

$\text{Plate Spacing} = 0.45\text{m}$

From graph 11.27

$\text{Top } K_1 = 0.079$

$$\text{Bottom } F_{lv} = \frac{L_m}{V_m}\sqrt{\frac{\rho_v}{\rho_l}}$$

$$\text{Bottom } F_{lv} = \frac{1442}{1027} \times \sqrt{\frac{2.671}{897}} = 0.08$$

From Graph 11.27

$\text{Bottom } K_1 = 0.08$

Correction of K_1

$$\text{Top } K_1 = K_1\left(\frac{\sigma}{0.02}\right)^{0.2}$$

$$\text{Top } K_1 = 0.08 \times \left(\frac{0.01613}{0.02}\right)^{0.2} = 0.077$$

$$\text{Bottom } K_1 = K_1\left(\frac{\sigma}{0.02}\right)^{0.2}$$

$$\text{Bottom } K_1 = 0.06 \times \left(\frac{0.048}{0.02}\right)^{0.2} = 0.094$$

$$\text{Top } u_f = K_1\sqrt{\frac{\rho_l - \rho_v}{\rho_v}}$$

$$\text{Top } u_f = 0.077 \times \sqrt{\frac{684 - 5.34}{5.34}} = 0.86 \text{ m/s}$$

Bottom $u_f = K_1 \sqrt{\frac{\rho_l - \rho_v}{\rho_v}}$

Bottom $u_f = 0.094 \times \sqrt{\frac{897 - 2.671}{2.671}} = 1.72\ m/s$

Design for 80% flooding at maximum flowrate

Top $\widehat{u_v} = u_f \times \%flooding$

Top $\widehat{u_v} = 0.86 \times 0.80 = 0.69 m/s$

Bottom $\widehat{u_v} = u_f \times \%flooding$

Bottom $\widehat{u_v} = 1.72 \times 0.80 = 1.4\ m/s$

Maximum Volumetric flowrate

Molecular Weight Top (M.W) = 18 kg/kmol

Molecular Weight Bottom (M.W) = 32 kg/kmol

$V'_m = L'_m - W$

$\frac{L'_m}{V'_m} = \text{slope of bottom operating line}$

$\frac{L'_m}{V'_m} = 1.4$

$L'_m = 1038 \frac{kmol}{hr}$

$V'_m = 1038 - 415 = 632 \frac{kmol}{hr}$

$V = D(1 + R)$

$V = 395 \times (1 + 1.6)$

$V = 1027 \frac{kmol}{hr}$

$$\text{Top} = \frac{\text{V} \times \text{M.W}}{\rho_v}$$

$$\text{Top} = \frac{1027 \times 18}{5.34 \times 3600} = 0.96\text{m}^3/\text{s}$$

$$\text{Bottom} = \frac{\text{V}'_m \times \text{M.W}}{\rho_v}$$

$$\text{Bottom} = \frac{632 \times 32}{2.671 \times 3600} = 2.1\text{m}^3/\text{s}$$

Net area required:

$$\text{Top} = \frac{0.96}{0.69} = 1.4\text{m}^2$$

$$\text{Bottom} = \frac{2.1}{1.4} = 1.5\text{m}^2$$

Column Cross-Sectional Area:

$$\text{Top} = \frac{1.4}{0.88} = 1.6\text{m}^2$$

$$\text{Bottom} = \frac{1.5}{0.88} = 1.7\text{m}^2$$

Column Diameter:

$$\text{Top} = \sqrt{\frac{4\text{A}}{\pi}}$$

$$\text{Top} = \sqrt{\frac{4 \times 1.6}{\pi}} = 1.43\text{m}$$

$$\text{Bottom} = \sqrt{\frac{4 \times 1.7}{\pi}} = 1.47\text{m}$$

Liquid Flow Pattern:

$$\text{Maximum volumetric liquid rate} = \frac{1038 \times 18}{897 \times 3600} = 6 \times 10^{-3}\,\frac{\mathrm{m}^3}{\mathrm{s}}$$

The plate diameter is in the range of Figure 11.28, but it is clear that a single pass plate can be used.

Provisional Plate Design:

$\text{Column Diameter } \mathrm{D_c} = 1.5\mathrm{m}$

$$\text{Column Area } \mathrm{A_c} = \frac{4\mathrm{D}^2}{\pi} = \frac{4(1.5)^2}{\pi} = 1.86\mathrm{m}^2$$

$\text{DownCommer Area } \mathrm{A_d} = 0.12\mathrm{A_c} = 0.12 \times 1.86 = 0.22\mathrm{m}^2$

$\text{Net Area } \mathrm{A_n} = \mathrm{A_c} - \mathrm{A_d} = 1.86 - 0.22 = 1.64\mathrm{m}^2$

$\text{Active Area } \mathrm{A_a} = \mathrm{A_c} - 2\mathrm{A_d} = 1.86 - 2 \times 0.22 = 1.42\mathrm{m}^2$

$\text{Hole Area} \mathrm{A_h} = 0.10\mathrm{A_a} = 0.10 \times 1.42 = 0.142\mathrm{m}^2$

$\text{Weir length } \mathrm{l_w} = 0.77\mathrm{D_c} = 0.77 \times 1.5 = 1.15\mathrm{m}$

$\text{Hole Diameter } \mathrm{d_h} = 5\mathrm{mm}$

$\text{Plate Thickness} = 5\mathrm{mm}$

$\text{Weir height } \mathrm{h_w} = 70\mathrm{mm}$

$\text{Area of one Hole} = 1.30 \times 10^{-4}\mathrm{m}^2$

$$Number\ of\ Holes = \frac{hole\ area}{area\ of\ one\ hole}$$

$$= \frac{0.142}{1.30 \times 10^{-4}} = 1092 holes$$

Height of Column:

No. of trays = 21

Tray spacing = 0.45m

Distance b/w trays = 0.45×21=9.45m

Top Clearance = 0.5m

Bottom Clearance = 0.5m

Tray thickness = 5mm = 0.005m

Total tray thickness = 0.005×21=0.105m

Total height of Column = 0.45+9.45+0.5+0.5+0.105 =11m

Pressure Drop:

$$h_r = \frac{12.5 \times 10^3}{\rho_l}$$

$$h_r = \frac{12.5 \times 10^3}{897} = 14\text{mm}$$

$$\text{Liquid rate } L_w = \frac{L'_m \times \text{M.W}}{3600}$$

$$\text{Liquid rate } L_w = \frac{1038 \times 18}{3600} = 5.2\ \text{kg/s}$$

$$h_{ow} = \left(\frac{L_w}{\rho_l l_w}\right)^{\frac{2}{3}}$$

$$h_{ow} = 750 \times \left(\frac{5.2}{897 \times 1.15}\right)^{\frac{2}{3}} = 22\text{mm}$$

$$\frac{A_h}{A_p} \cong \frac{A_h}{A_a} = 0.1$$

$$\frac{\text{Plate Thickness}}{\text{Hole diameter}} = 1$$

Form Figure 11.34 volume 6

$$C_o = 0.84$$

$$h_w = 70\text{mm}$$

$$h_d = 51 \times \left(\frac{u_h}{C_o}\right)^2 \frac{\rho_v}{\rho_L}$$

$$\mathrm{u_h} = \frac{\mathrm{Q_v}}{\mathrm{A_h}} = \frac{2.1}{0.142} = 15\ \mathrm{m/s}$$

$$\mathrm{h_d} = 51 \times \left(\frac{15}{0.84}\right)^2 \times \frac{2.671}{897} = 48\mathrm{mm}$$

$$\mathrm{h_t} = \mathrm{h_d} + \mathrm{h_w} + \mathrm{h_{ow}} + \mathrm{h_r}$$

$$\mathrm{h_t} = 48 + 70 + 22 + 14 = 154\mathrm{mm}$$

$$\Delta \mathrm{P_t} = 9.81 \times 10^{-3} \times \mathrm{h_t} \times \rho_\mathrm{l}$$

$$\Delta \mathrm{P_t} = 9.81 \times 10^{-3} \times 154 \times 790$$

$$\Delta \mathrm{P_t} = 1194\mathrm{Pa}\ \ (0.01194\mathrm{bar})$$

Check Entrainment:

$$u_v = \frac{2.1}{1.64} = 1.28\ m/s$$

$$\%\ flooding = \frac{1.28}{1.72} \times 100 = 74\%$$

$F_{Lv} = 0.08$, from Figure 11.29

$$\Psi = 0.04$$

<table>
<tr><th colspan="4">Specification Sheet</th></tr>
<tr><th colspan="4">Identification</th></tr>
<tr><td colspan="2">Item</td><td colspan="2">Distillation Column D-101</td></tr>
<tr><td colspan="2">Type</td><td colspan="2">Binary Component Distillation Column</td></tr>
<tr><th colspan="4">Function</th></tr>
<tr><td colspan="4">To separate methanol from water</td></tr>
<tr><td>Operating Pressure</td><td>500kPa</td><td>No. of Holes</td><td>1092</td></tr>
<tr><td>No. of Stages</td><td>21</td><td>Feed Location</td><td>9th</td></tr>
<tr><td>Plate type</td><td>Sieve Plate</td><td>Hole Diameter</td><td>0.005m</td></tr>
<tr><td>Plate Spacing</td><td>0.45m</td><td>Total Pressure Drop in Distillation Column</td><td>1.194 kPa</td></tr>
<tr><td>Plate Thickness</td><td>0.005m</td><td>Reflux Ratio</td><td>1.6</td></tr>
<tr><td>Diameter of Column</td><td>1.5m</td><td>Percent Flooding</td><td>74%</td></tr>
<tr><td>Height of Column</td><td>11m</td><td>Frictional Entrainment</td><td>0.04</td></tr>
</table>

6 Chapter NO 6: Compressor

6.1 Compressor:

A compressor is a mechanical device that increases the pressure of a compressible fluid or gas, with air being the most common. It is widely used in many industries to supply air for instrumentation, air-powered equipment, sprayers and blast abrasives, phase-shift refrigerants for refrigeration and air conditioning, as well as to push gas through pipeline-lines. The size of a compressor can vary, ranging from a small, glovebox-size unit used for tire inflation to a large, massive, or turbo compressor unit used for pipeline servicing.

6.2 Types of Compressors:

Depending upon the task. Compressors are available in a variety of forms and sizes, these are as follows:

6.2.1 Positive displacement compressors:

Basically, a positive displacement air compressor works by pulling air in through an intake and gradually reducing the air volume until it reaches a certain pressure. Then, the compressed air is pushed out through a valve at the pressure it's supposed to be at. A positive displacement compressor usually has one or more intake chambers and one or more compression chambers.

6.2.2 Rotary compressor:

Rotary positive displacement compressors are the most common type of compressor on the market today. They suck in air, seal the opening, and compress it using two rotating rotors that move through the cavity continuously. The air pressure is increased with each rotation until the desired pressure is reached.

6.2.3 Reciprocating piston compressor:

In reciprocating piston compressors, a piston in constant motion is used to draw in air and then compress it. Generally, one movement of a piston draws in air while the other movement compresses it. This type of reciprocating piston compressor is available in single-chamber and double-chamber design, meaning that air is compressed simultaneously on either side of the piston. This type of compressor is cooled by air or water, and can generate up to 1000 horsepower.

6.2.4 Dynamic Compressors:

A dynamic compressor is the ideal solution when you need a lot of horsepower. They come in both axial and radial forms. They are often known as turbo compressors. Radial centrifugal compressors are ones with a radial design. In contrast to a displacement compressor, which operates at a constant flow, a dynamic compressor runs at a constant pressure. External factors impact dynamic compressor performance; for example, a change in input temperature causes a change in capacity.

6.2.5 Centrifugal Compressor:

The centrifugal compressor is one of the most well-known dynamic compressor types. This compressor compresses the gas by delivering an inertial force (turning, deceleration, and acceleration) to it via a revolving impeller. In the case of this compressor, air is drawn into the impeller centre and then centrifugally accelerated toward the circumference. The diffuser will scroll there as it compresses to this air.

6.2.6 Axial flow Compressor:

Another important form of dynamic compressor is the axial flow compressor. As a result, it can manage high air flow rates in a tiny housing with adequate power needs. These compressors have a modest to moderate pressure range. To drive air into smaller and smaller spaces, the axial compressor employs a series of blades that resemble jet engines. These sorts of dynamic displacement compressors are scarce in the business. In general, an axial compressor is lighter, smaller, and quicker than a comparable centrifugal compressor.

6.3 Design steps of Compressor:

Design of Compressor includes to select and calculate:

1. Reduce temperature and pressure
2. Compressibility at the inlet of compressor
3. Specific volume
4. Volumetric flow rate
5. Hydraulic efficiency
6. Work of compressor
7. Discharge temperature

8. Reduce temperature and pressure at outlet conditions
9. Overall compressibility factor
10. Shaft work
11. Power

6.4 Compressor Calculation:

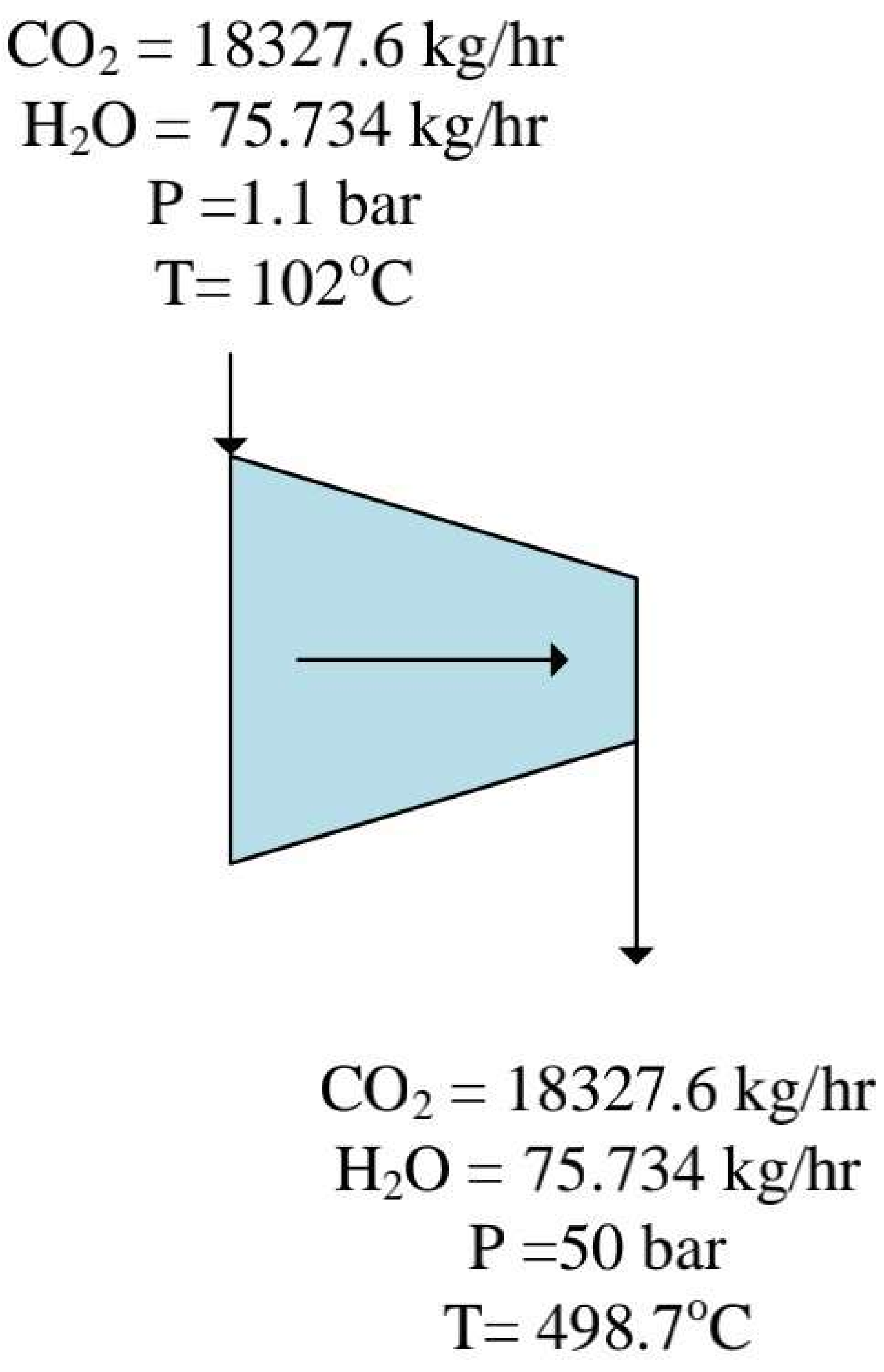


Figure 6-1: Compressor (C-101)

Flowrate = 18403 kg/hr = 9201.5 m^3/hr

P_1 = 1.1 bar

P_2 = 50 bar

T_1 = 102°C

6.5 Compressor Selection:

Compressor is selected from A-2 (Appendix A)

As a result, a centrifugal compressor was chosen. The following are the benefits of a centrifugal compressor:

- Larger amounts of gas can be handled in one or two tiny casings, resulting in a smaller overall package.
- Vibration-free for the most part. Only a pad adequate for sustaining the package's static weight is required.
- Centrifugal compressors have a lengthy mean time between failures.
- Independent analysis has proven that the product has an industry-leading availability of 99.7%. Gear that is conservative and of good quality.
- For constant gas delivery, include intake guide vane control and bypass.
- For most operational situations, automatic operation and precise control are required.
- Control systems for PLCs (Programmable Logic Controller) are available

Calculating T_c and P_c of gaseous mixture:

Component	Mol frac (X)	K	T_c (°C)	P_c (bar)	X×K	X×T_c (°C)	X×P_c (bar)	ρ (kg/m3)	ρ (kg/m3)
CO_2	0.99	1.26	31.03	73.8	1.2474	30.7197	73.062	1.42	1.4058
H_2O	0.01	1.12	373.85	220.64	0.0112	3.7385	2.2064	59.6	0.596
Total					1.2586	34.4582	75.2684	61.02	2.0018

Calculation of reduce temperature and reduce pressure:

Reduce temperature:

$$T_r = \frac{T_1}{T_c}$$

$$T_r = 2.96$$

Reduce pressure:

$$P_r = \frac{P_1}{P_c}$$

$$P_r = 0.0146$$

Calculate compressibility at the inlet of compressor:

Compressibility Factor:

$z = 1$

Calculation of specific volume:

$$v = \frac{1}{\rho}$$

$v = 0.5\ m^3/kg$

Calculation of volumetric flow rate:

$$V = \frac{m}{\rho}$$

$V = 9201.5\ m^3/hr$

Hydraulic Efficiency:

From graph the Polytrophic efficiency = $\eta_p = 0.72$

$$\frac{n-1}{n} = \frac{\frac{k-1}{k}}{\eta_p}$$

$$\frac{n-1}{n} = 0.284$$

Calculate the work of compressor:

Assume no stages = N = 1

$$W = \frac{ZRT_1}{\frac{n-1}{n}} \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$W_{P1} = 21533.21$ J/mol

Discharge Temperature:

$$W_{CN} = \frac{R}{\frac{k-1}{k}} \times (T_D - T_1)$$

$T_D = 907.3$ K ($T_D > T_{max}$)

So, Temperature of gases rise because of compression due to which increase no of stages to achieve the desire pressure

Assume no of Stages = N = 2

For two stage compression:

$$\frac{P_2}{P_1} = \frac{P_4}{P_2 - 0.1P_2^{0.7}}$$

$P_4 = P_D$

$P_2 = 7.62$ bar

Calculate the work of compressor:

$$W_{P2} = \frac{ZRT_1}{\frac{n-1}{n}} \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1 \times \left(\frac{P_4}{P_2 - 0.1P_2^{0.7}}\right)^{\frac{n-1}{n}} - 2\right]$$

$W_{P2} = 10614.3$ J/mol

Discharge Temperature:

$$W_{CN} = \frac{R}{\frac{k-1}{k}} \times (T_D - T_1)$$

$T_D = 637.45$ K ($T_D > T_{max}$)

So, Temperature of gases rise because of compression due to which increase no of stages to achieve the desire pressure

Assume no of Stages = N = 3

For three stage compression:

$P_6 = P_D$

$$\frac{P_4}{P_3} = \frac{P_6}{P_4 - 0.1P_4^{0.7}}$$

$$P_3 = P_2 - 0.1P_2^{0.7}$$

$P_3 = 7.21$ bar

$P_4 = 19.39$ bar

$P_5 = P_4 - 0.1P_4^{0.7}$

$P_5 = 18.59$ bar

Calculate the work of compressor:

$$W_{P3} = \frac{ZRT_1}{\frac{n-1}{n}} \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1 + \left(\frac{P_4}{P_2 - 0.1P_2^{0.7}}\right)^{\frac{n-1}{n}} - 2 + \left(\frac{P_6}{P_4 - 0.1P_4^{0.7}}\right)^{\frac{n-1}{n}} - 3\right]$$

$W_{P3} = 4801$ J/mol

Calculate the discharge temperature:

$$W_{CN} = \frac{R}{\frac{k-1}{k}} \times (T_D - T_1)$$

$T_D = 493.79$ K ($T_D < T_{max}$)

Calculating the T_r and P_r at outlet conditions:

Reduce temperature:

$$T_r = \frac{T_D}{T_c}$$

$T_r = 6.40$

Reduce pressure:

$$P_r = \frac{P_D}{P_c}$$

$P_r = 0.66$

Calculate the Average compressibility factor

$$z = \frac{z_1 + z_D}{2}$$

$z = 1$

Calculate the actual work:

Ep = 0.71 (from graph)

$$W_A = \frac{W_{P3}}{E_P}$$

$W_A = 6761.97$ J/mol

Power calculation:

Power = $W_{P3} \times m$ (m = 420700 mol/hr)

Power = 561 KW

Specification-Sheet	
Item	Compressor (C-102)
Type	Centrifugal Compressor
Function	
To increase pressure 1.1 bar to 50 bar	
Stages	3
Mass Flowrate	18403 kg/hr
P_{in}	1.1 bar
P_{out}	50 bar
Power	561 KW

Specification Sheet	
Item	Compressor (C-101)
Type	Reciprocating Compressor
Function	
To increase pressure 1.1 bar to 45 bar	
Stages	4
Mass Flowrate	2726 kg/hr
P_{in}	1.1 bar
P_{out}	45 bar
Power	2610 KW

Specification-Sheet	
Item	Compressor (C-103)
Type	Reciprocating Compressor
Function	
To increase pressure 45 bar to 50 bar	
Stages	1
Mass Flowrate	103449 kg/hr
P_{in}	45 bar
P_{out}	50 bar
Power	96.13 KW

7 Chapter NO 7: Cost Estimation

7.1 Cost Estimation:

The capital expenditure required for any industrial process is a critical factor in a plant design project.

7.2 Capital Investment:

A considerable quantity of money must be paid before a manufacturing facility can be put into operation in order to purchase and install the essential machinery and equipment. The plant must be built with the requisite pipes, controls, and service, and the site and service facilities must be bought. Furthermore, funds must be available to cover plant running expenditures. The total capital investment refers to the total amount of money required to develop and run a facility.

Total Capital Investment = Fixed Capital + Working Capital

Fixed Capital investment is divided into two distinct subheadings, Direct and indirect costs

1. Direct Cost:

The construction costs of the plant, in addition to the cost of equipment, shall be carried out directly.

- Cost of purchased equipment
- Cost of purchased equipment installation
- Cost of purchased insulation
- Cost of purchased instruments and control
- Cost of purchased piping
- Cost of purchased electrical installation
- Cost of building including services
- Cost of backyard improvement
- Cost of service facilities
- Cost of land

2. Indirect Cost:

We can figure out how much indirect costs are by looking at the following:

- Engineering and supervision

- Construction costs
- Construction fees
- Construction contingencies
- Construction startup expenses

7.2.1 Working Capital:

The amount of capital necessary to maintain the operations of the plant is referred to as working capital. It includes the following elements to be taken into account:

- Stocks of raw materials and supplies
- Stocks of finished goods in stock
- Stocks of semi-finished goods in production
- Accounts receivable
- Cash available for monthly payments of operating costs (salaries, wages, raw materials, etc.)
- Accounts payable
- Taxes payable

7.3 Capital Cost Estimates:

A capital investment estimate for a process might range from a pre-design estimate that uses little information other than the size of the planned project to a thorough estimate produced from full drawings and specifications. Within these two extremes of capital investment estimates, there can be several more estimates whose accuracy varies depending on the project's level of development. These estimations are known by a number of names, but the five categories listed below reflect the accuracy level and classification often used for design reasons.

- Order of magnitude estimates
- Study estimate (factorial estimate)
- Preliminary estimates (budget authorization estimate)
- Definitive estimate (project control estimate)
- Detailed estimate (Contractor's estimate)

7.4 Cost Indexes:

A cost is almost any index number for a particular moment in time that shows the cost at that point in time in relation to a specified base time. As a result, the current cost is approximated using the cost index as follows:

$$\frac{\text{Present Cost}}{\text{Index at Present Time}} = \frac{\text{Original Cost}}{\text{Index value at the time of original cost}}$$

A wide range of cost indices are provided on a regular basis. Some may be used to estimate equipment costs, while others are more relevant to labor, building, materials, or other specialized industries. The most often used of these indexes are

- Marshal-and-Swift all industry and process industry equipment index
- Engineering news record contraction cost index

7.5 Total Cost of Equipment in 2021:

7.5.1 Cost of Multi tube fixed bed Reactor:

Temperature = 250°C

Pressure = 50 bar

Material of construction = Stainless Steel

Length = 7.32m

Diameter = 1.46 m

Material Factor = 2

Pressure Factor = 2.2

Volume of Reactor = 3.9 m^3

Bare Cost = $ 11000

Purchase equipment cost inn 2004 = $ 48400

$$\text{Present Cost} = \text{Original Cost} \times \frac{\text{Index at Present Time}}{\text{Index value at the time of original cost}}$$

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 88115

7.5.2 Catalytic packing cost:

Catalyst weight = 3850.2 kg

Price = 1.5 $/kg

Total Cost of Packing = $ 5775.38

Total Equipment Cost = Reactor cost + Packing Cost

Total Equipment Cost = $ 93,891.28

7.5.3 Cost of Absorber:

Temperature = 34.3°C

Pressure = 1.1 bar

Material of construction = Carbon Steel

Height = 15.1 m

Diameter = 4.4 m

Material Factor = 2

Pressure Factor = 1

Bare Cost = $ 90000

Purchase equipment cost in 2004 = $ 180000

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 327703.73

7.5.4 Packing Cost:

Height of Packing = 13.71 m

Radius of column = 2.20 m

Volume of Packing = 208.32 m^3

Packing Cost = 430 $/kg

Total Cost of Packing = $ 93742.19

Total Equipment Cost = $ 421445

7.5.5 Cost of Stripper (101):

Temperature = 102°C

Pressure = 1 bar

Material of construction = Stainless Steel

Height = 5.05 m

Diameter = 1.3 m

Material Factor = 2

Pressure Factor = 1

Bare Cost = $10100

Purchase equipment cost in 2004 = $ 20200

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 36775.64

7.5.6 Packing Cost:

Height of Packing = 4.05 m

Radius of column = 0.65 m

Volume of Packing = 5.4 m^3

Packing Cost = 450 $/kg

Total Cost of Packing = $ 2417.8

Total Equipment Cost = $ 39193.46

7.5.7 Cost of Stripper (102):

Temperature = 30°C

Pressure = 45 bar

Material of construction = Stainless Steel

Height = 3.70 m

Diameter = 1.53 m

Material Factor = 2

Pressure Factor = 1.80

Bare Cost = $10020

Purchase equipment cost in 2004 = $ 36072

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 65671.8

7.5.8 Packing Cost:

Height of Packing = 2.70 m

Radius of column = 0.77 m

Volume of Packing = 4.96 m^3

Packing Cost = 450 $/kg

Total Cost of Packing = $ 2232.7

Total Equipment Cost = $ 67904.5

7.5.9 Cost of Liquid-Gas Separator:

Temperature = 30°C

Pressure = 45 bar

Material of construction = Stainless Steel

Height = 4 m

Diameter = 1.38 m

Material Factor = 2

Pressure Factor = 1.8

Bare Cost = $10030

Purchase equipment cost in 2004 = $ 36108

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 65737.3

7.5.10 Cost of Distillation Column:

Temperature = 94.5°C

Pressure = 1 bar

Material of construction = Carbon Steel

Height = 11 m

Diameter = 1.5 m

Material Factor = 1

Pressure Factor = 1

Bare Cost = $30000

Purchase equipment cost in 2004 = $ 30000

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 54617.2

Cost of 1 plate = $ 190

Total no of plates = 21

Total Cost of Plates = $ 3990

Cost of Plates in 2022 = $ 7,264.10

Total Cost of Column = $ 61,881

7.5.11 Cost of Heat Exchanger (HX-101):

Material of Construction = Stainless Steel

Operating Pressure = 1 bar

Heat Transfer Surface Area = 39.9 m^2

Pressure factor = 1

Type factor = 0.8

Bare Vessel Cost = $ 60050

Actual Vessel Cost in 2004 = $ 48040

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 87460.4

7.5.12 Cost of Heat Exchanger (HX-102):

Material of Construction = Carbon Steel

Operating Pressure = 50 bar

Heat Transfer Surface Area = 53.69 m^2

Pressure factor = 1.5

Type factor = 0.8

Bare Vessel Cost = $ 11300

Actual Vessel Cost in 2004 = $ 13560

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 24687

7.5.13 Cost of Heat Exchanger (HX-103):

Material of Construction = Stainless Steel

Operating Pressure = 50 bar

Heat Transfer Surface Area = 51.37 m^2

Pressure factor = 1.5

Type factor = 0.8

Bare Vessel Cost = $ 71000

Actual Vessel Cost in 2004 = $ 85200

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 155113.10

7.5.14 Cost of Heat Exchanger (HX-104):

Material of Construction = Carbon Steel

Operating Pressure = 50 bar

Heat Transfer Surface Area = 92.62 m^2

Pressure factor = 1.5

Type factor = 0.8

Bare Vessel Cost = $ 12010

Actual Vessel Cost in 2004 = $ 14412

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 26238.14

7.5.15 Cost of Condenser (C-101):

Material of Construction = Carbon Steel

Operating Pressure = 1 bar

Heat Transfer Surface Area = 31 m^2

Pressure factor = 1

Type factor = 0.8

Bare Vessel Cost = $ 10700

Actual Vessel Cost in 2004 = $ 8560

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 15584.13

7.5.16 Cost of Condenser (C-102):

Material of Construction = Carbon Steel

Operating Pressure = 50 bar

Heat Transfer Surface Area = 88.1 m^2

Pressure factor = 1.5

Type factor = 0.8

Bare Vessel Cost = $ 12200

Actual Vessel Cost in 2004 = $ 14640

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 26653.23

7.5.17 Cost of Condenser (C-103):

Material of Construction = Carbon Steel

Operating Pressure = 45 bar

Heat Transfer Surface Area = 29.8 m^2

Pressure factor = 1.3

Type factor = 0.8

Bare Vessel Cost = $ 10800

Actual Vessel Cost in 2004 = $ 11232

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 20448.71

7.5.18 Cost of Condenser (C-104):

Material of Construction = Carbon Steel

Operating Pressure = 1 bar

Heat Transfer Surface Area = 53.09 m^2

Pressure factor = 1

Type factor = 0.8

Bare Vessel Cost = $ 10200

Actual Vessel Cost in 2004 = $ 8160

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 14855.90

7.5.19 Cost of boiler:

Steam =2 bar

Capacity = 2.35×10^3 kg/hr

S = size parameter = 5000 kg/hr

C (Cost Constant) = $ 90

n = 0.8

Ce = Purchase equipment cost = $ 81925.38

Purchase equipment Cost in 2004 = $ 81925.38

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 149151.42

7.5.20 Cost of Compressor (C-101):

Pressure = 50 bar

Capacity = 96.13 kW

Compressor Type = Centrifugal Rotary

Purchase cost on 2002 =$ 62000

Material adjustment factor = 1

Actual Vessel Cost in 2002 = $ 62000

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 126742.66

7.5.21 Cost of Compressor (C-102):

Pressure = 50 bar

Capacity = 516 kW

S = size parameter = 500 kW

C (Cost Constant) = $ 1920

n = 0.8

Ce = Purchase equipment cost = $ 276998.38

Purchase equipment Cost in 2004 = $ 276998.38

Cost Index in 2022 = 808.7

Cost Index in 2004 = 444.2

Purchased equipment cost in (2022) = $ 504296.6

7.6 Fixed Capital Investment:

7.6.1 Direct Cost:

Table 7-1: Direct Cost

Direct Cost			
Items	**Range**	**%**	**Cost, $**
Purchased equipment		100	$ 1,901,285.5
Installation	25 - 55% of Purchased Equipment Cost	47	$ 893,604.2
Instrumentation & Control	6 - 30% of Purchased Equipment Cost	18	$ 342,231.4
Piping	40 - 80% of Purchased Equipment Cost	65	$ 1,235,835.6
Electricity	10 - 15% of Purchased Equipment Cost	12.5	$ 237,660.7
Building	15% of Purchased Equipment Cost	15	$ 285,192.8
Land	4 - 8% of Purchased Equipment Cost	6	$ 114,077.1
Service Facility	30 - 80% of Purchased Equipment Cost	55	$ 1,045,707.0
Yard Improvement	10 - 20% of Purchased Equipment Cost	15	$ 285,192.8
Insulation cost	8 - 9% of Purchased Equipment Cost	8	$ 152,102.8
Total Direct Cost			$ 4,591,604.4

7.6.2 Indirect Cost:

Table 7-2: Indirect Cost

Indirect Cost			
Items	Range	%	Cost, $
Engr. & supervision	33 % of (Total direct cost)-TDC	33	1515229.5
Contractor fee	22 % of TDC	22	1010153.0
Construction expenses	41 % of TDC	41	1882557.8
Contingences	44 % TDC	44	2020305.9
Total Indirect Cost			6428246.2

Fix Capital Investment:

FCI =Direct Cost + Indirect Cost

FCI =5455+1881041.2

FCI =$ 11,019,850.59

7.7 Working Capital Investment:

WCI =15%FCI

WCI = 0.15×FCI

WCI = $1,652,977.59

7.8 Total Capital Investment:

Total Capital Investment (TCI) =WCI + FCI

TCI = $ 12,672,828.18

TCI =12.67 M

7.9 Direct Operational Cost:

7.9.1 Variable Cost:

Table 7-3: Variable Cost

Raw Material Cost	
Hydrogen Cost	
H_2 cost	1.5 $/Kg
H_2 Require	2499.2 kg /hr
For 8000hrs Operating time	19993748.2
H_2 require	19993748.2 kg /year
H_2 Cost	29990622.3 $/yr
Air Cost	
Flow Rate of Air	32048004 kg /hr
Flow Rate of Air	2.56×10^{11} kg /yr
Cost of Air =2% of FCI	$220,397.01
MEA Cost	
MEA cost	2.0 $/kg
MEA Require	40654.0 /hr
MEA Cost	$ 81307.9

7.9.2 Utility Cost:

Table 7-4: Utility Cost

Utilities Cost	
Cooling Water Cost	
Flow Rate of Water	528565 kg /hr
Flow Rate of Water	4228517993 kg /hr
cost of water	0.008 $/1000kg
Cost of Water	33828.14394 $/yr
Steam Cost	

Flow Rate of Steam	13232 kg /hr
Flow Rate of steam	105857764 kg /hr
cost of steam	4.4 $/1000kg
Cost of Steam	465774.1615 $/yr
Total Variable Cost =	Raw Materials + Utilities
Total Variable Cost	$30.79 M

7.9.3 Fixed Cost:

Table 7-5: Fixed Cost

Fixed Cost		
Function	% FCI	Cost ($)
Maintenance	9	991786.55
Operating Labor	10	1101985.06
Laboratory Cost	10	1101985.06
Supervision	15	1652977.59
Clerical Labor	15	1652977.59
Capital Charges	10	1101985.06
Insurance	1	110198.51
Local Taxes	2	220397.01
Royalties	2	220397.01
Total		8154689.43

Direct Cost = Variable Cost + Fixed Cost

Direct Cost = $ 38,946,618

7.10 Overhead Cost:

Overhead Cost = 30% of DPC

Overhead Cost = $ 11,683, 985

7.11 Manufacturing Cost:

Cost of Manufacturing = Overhead Cost + Direct Production Cost

Manufacturing Cost = 50,630,604

7.12 General Expenses

Table 7-6: General Expenses

General Expenses		
Function	Percentage of Manufacturing Cost	Cost ($)
Administration	3%	$ 15,189.18
Distribution and Marketing	3%	$ 15,189.18
Research and Development	5%	$ 25,315.30
Total		$ 55,693.67

7.13 Total Production Cost

Total Production Cost = Manufacturing Cost +General Expenses

Total Production Cost = 50,686,298

7.14 Total Production Rate:

Production Rate = 100000 t/year

Total Production Cost = $50,686,298/year

Production Cost = $506.86/t

Production Cost = $0.51/kg

7.15 Profitability Analysis:

7.15.1 Selling Price:

Price of methanol in market= $820/ ton

Total income = $ 82,000,000

Production Cost = \$507/ton

7.16 Profit:

Profit = Selling price - production cost = 313 \$/ton

Profit per year = \$31,313,702/year

7.17 Depreciation:

FCI = V = 11,019,850

Salvage value = Vs = 5% of FCI

Salvage value = 550,992

Number of years = 20

Depreciation = 523,442.9 \$/yr

7.18 Gross Profit:

Gross Profit = Profit - Depreciation

Gross Profit = \$ 30,790,258.82/year

7.19 Net Profit:

Net Profit = Gross Profit –Income Taxes

Income Taxes = 35 % of Gross Profit

Income Taxes = \$10,776,591/year

Net Profit = \$20,013,668/year

7.20 Rate of Return:

$$\text{Rate of Return} = \frac{\text{Net Profit}}{\text{Total Initial Investment}}$$

Rate of return = 0.32

7.21 Payback Period:

$$\text{Payback Period} = \frac{1}{\text{Rate of Return}}$$

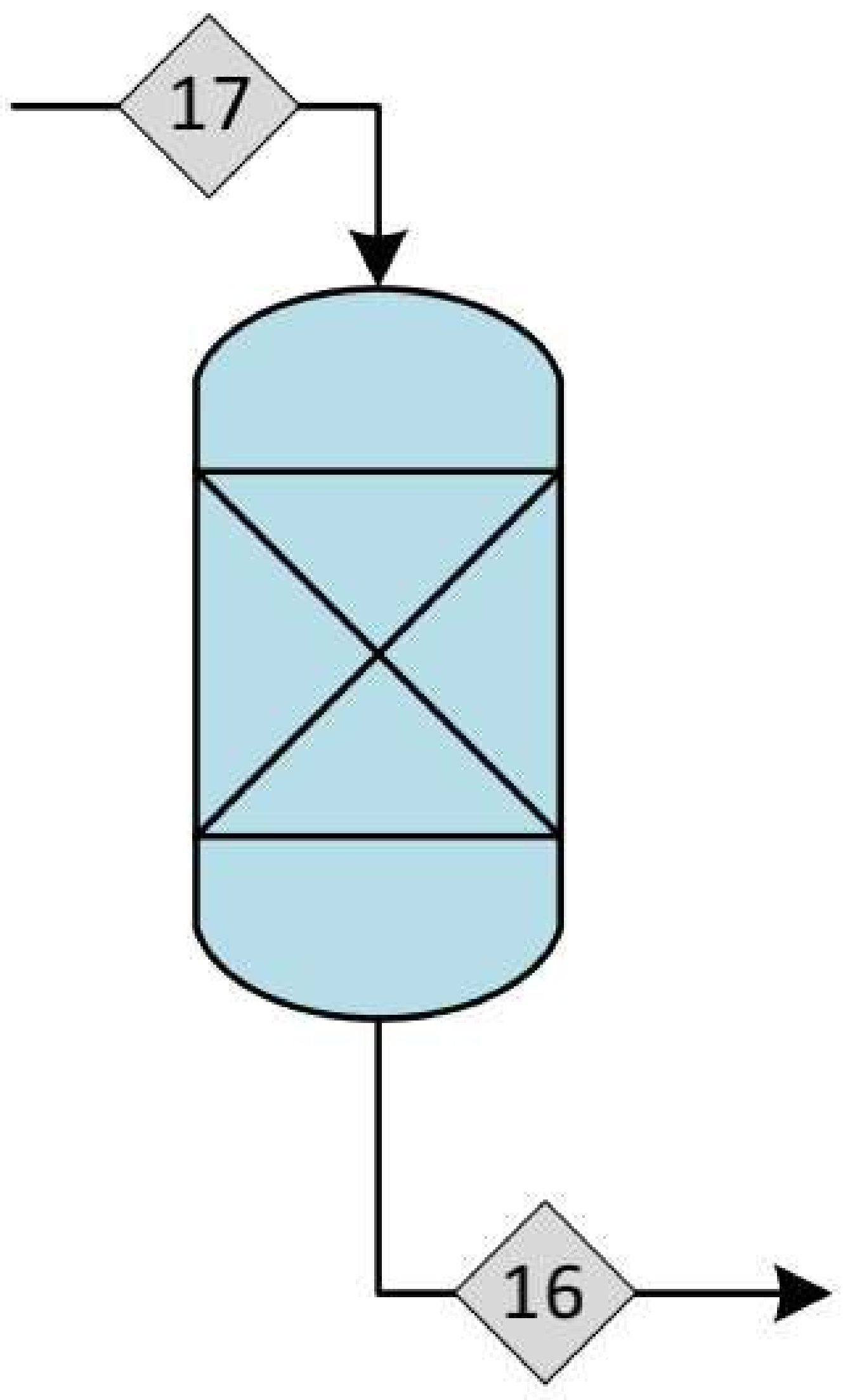
$$\text{Payback Period} = \frac{1}{0.32}$$

Payback Period = 3.2

8 Chapter NO 8: Mechanical Design

8.1 Mechanical Design of Reactor:

Kg/hr
CO_2 = 87283
H_2 = 12475
CH3OH = 126
CO = 21679
H_2O = 290



Kg/hr
CO_2 = 69652
H_2 = 10102
CH3OH = 12698
CO = 21898
H_2O = 7502

Figure 8-1: Reactor (R-101)

8.1.1 Material Selection:

For Reactor:

Stainless Steel Grade-A

- High-strength and high-temperature scaling resistance.
- This alloy has a higher resistance to corrosion at high temperatures

8.1.2 Minimum Practical wall thickness:

We'll need to know the minimum wall thickness to ensure that it can support your weight and any related stresses. In general, the wall thickness of any specific vessel should be at least the figures indicated below, plus a corrosion allowance of 2mm.

Vessel Diameter (m)

1 to 2 (meter)

Minimum Thickness:

7mm (Coulson Richardson vol.06)

8.1.3 Wall Thickness:

Diameter of shell = 1.4 m = 1400 mm;

Maximum Thickness = 7 mm

Material = stainless steel

Corrosion Allowance = Ce = 2 mm

At 250°C

Maximum Allowance stress = f = 95 N/mm2 Table 13.7

Joint Efficiency = 1 Table 13.3

Maximum Allowable Pressure = Pi = 0.22 N/mm2

Wall Thickness = $t = \frac{D_i P_i}{2Jf - P_i}$

$$t = \frac{1400 \times 0.22}{2(1)(95) - 0.22}$$

t = 1.62 mm

Adding corrosion allowance = (1.62 + 2) mm

Wall Thickness = 3.62 mm

Outer Diameter of the shell;

D_o = Di + 2e

D_o = 1.4 + 2(3.62×10-3)

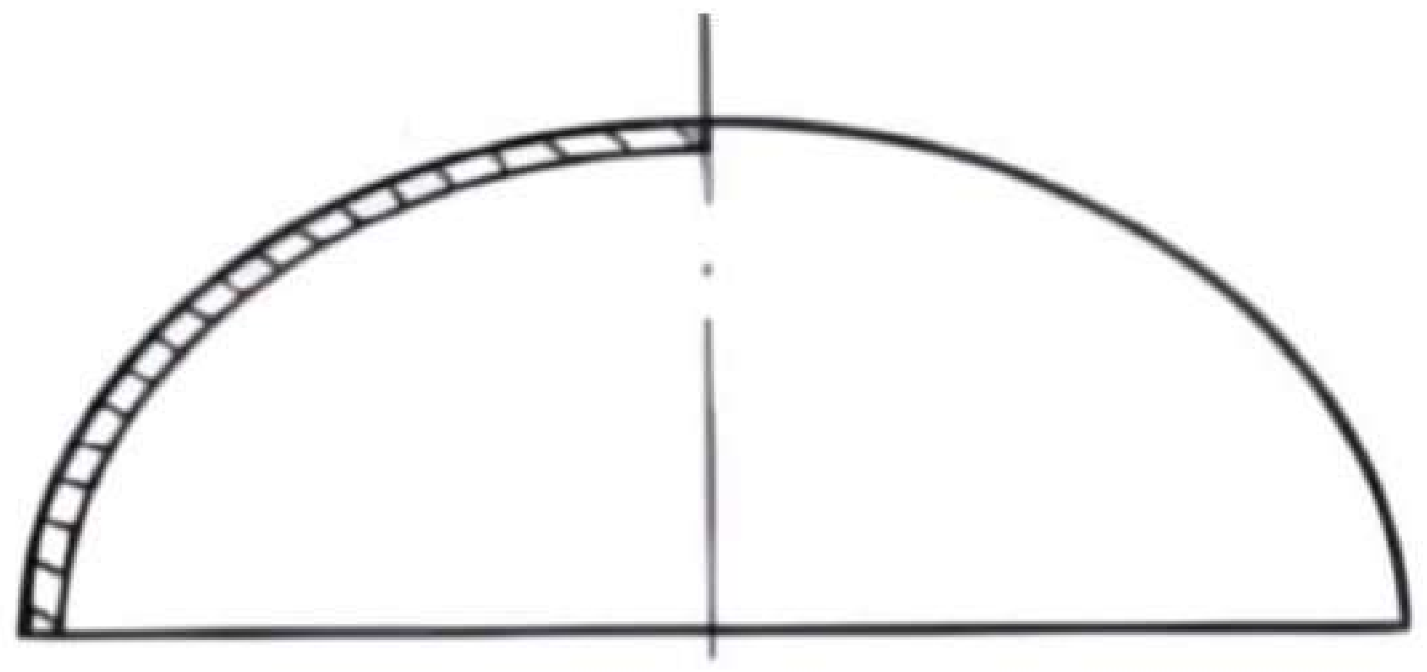
D_o = 1.407 m

8.1.4 Heads and closures:

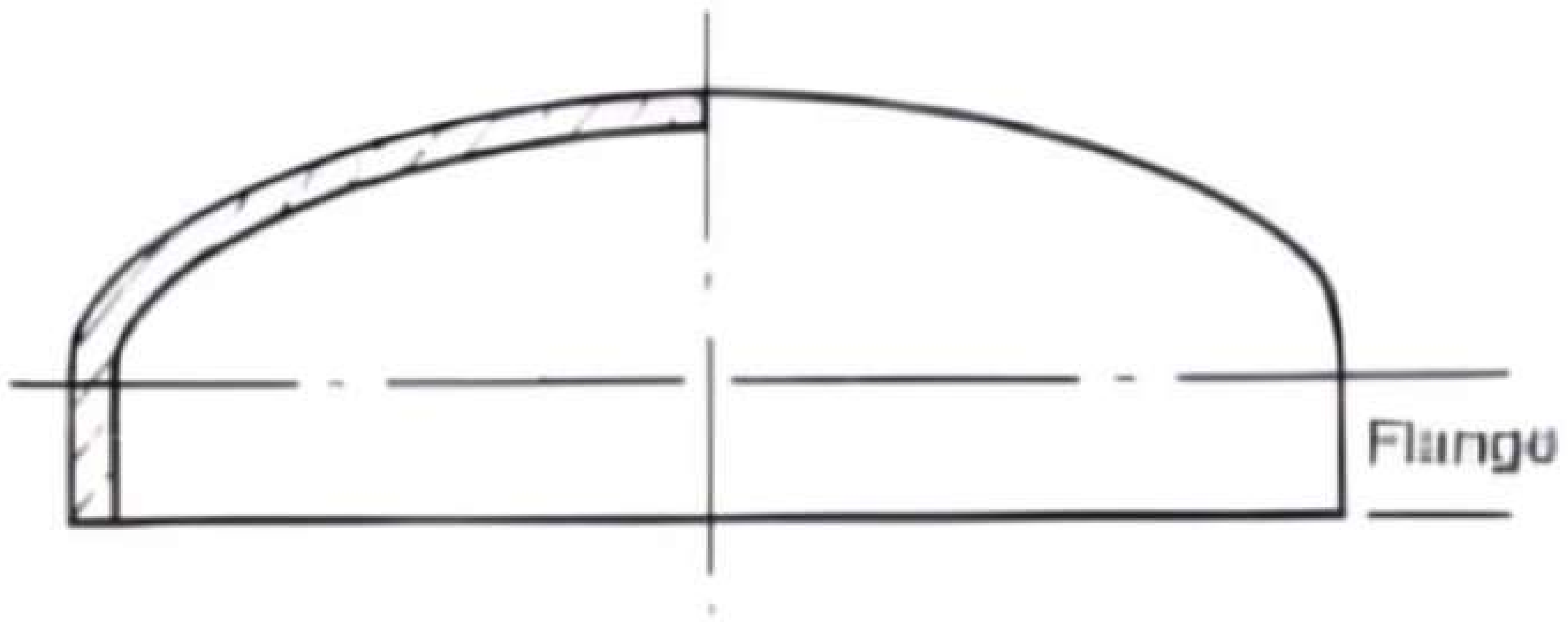
A cylindrical vessel's ends are closed by heads of various shapes. The most common types are:

- Flat plates and formed flat heads
- Hemispherical heads

- Ellipsoidal heads

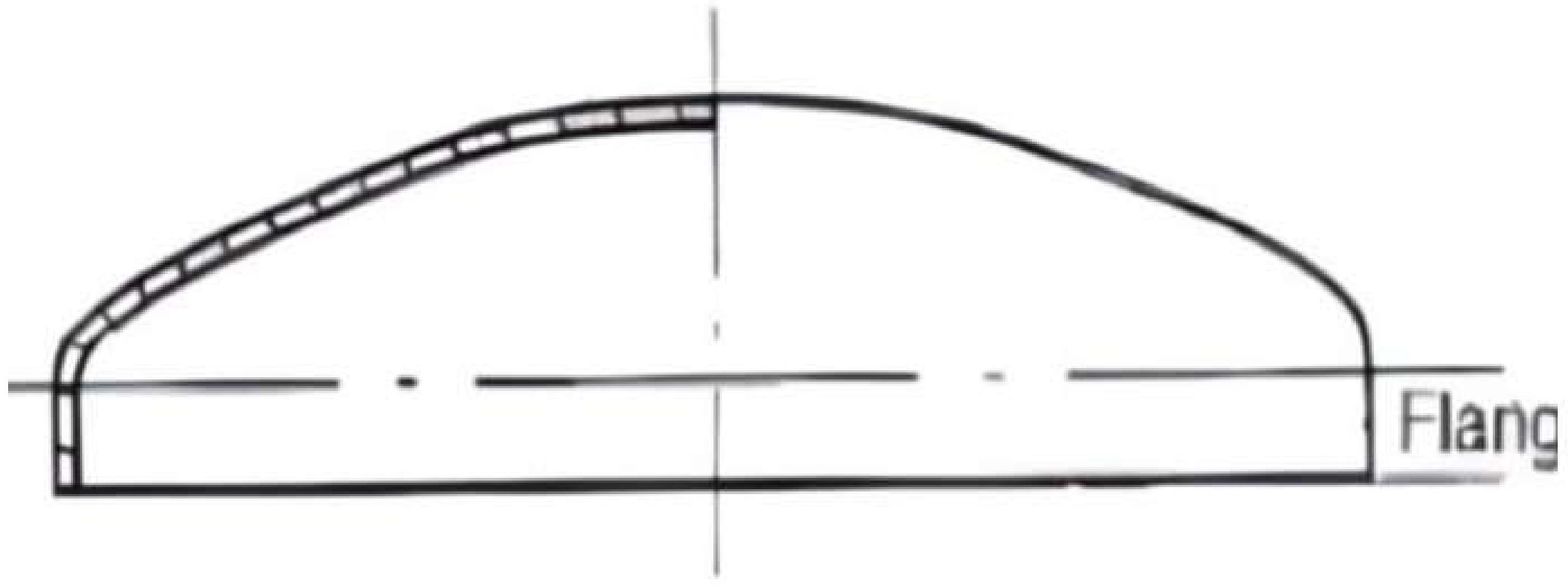


(a)
Hemispherical heads.



(b)

Hemispherical heads.



(c)
Torispherical heads.

Figure 8-2: Type of Heads

Domed heads are a group of heads that are made up of hemispheres, with ellipsoids and tori heads being the most common. Large heads are made up of sections that are pressed or spun, and dished ends are used to describe tori heads.

8.1.5 Thickness of Head:

Ellipsoidal heads:

Ellipsoidal heads are also called elliptical heads or elliptical dish ends. This shape is more cost-effective because the head is only a fraction of the size of the dish. The radius of the elliptical dish end varies between the main and minor axis, usually with a ratio of 2:1. Ellipsoidal tank heads are the most cost-effective option for medium pressure tanks because they don't require as much metal thickness.

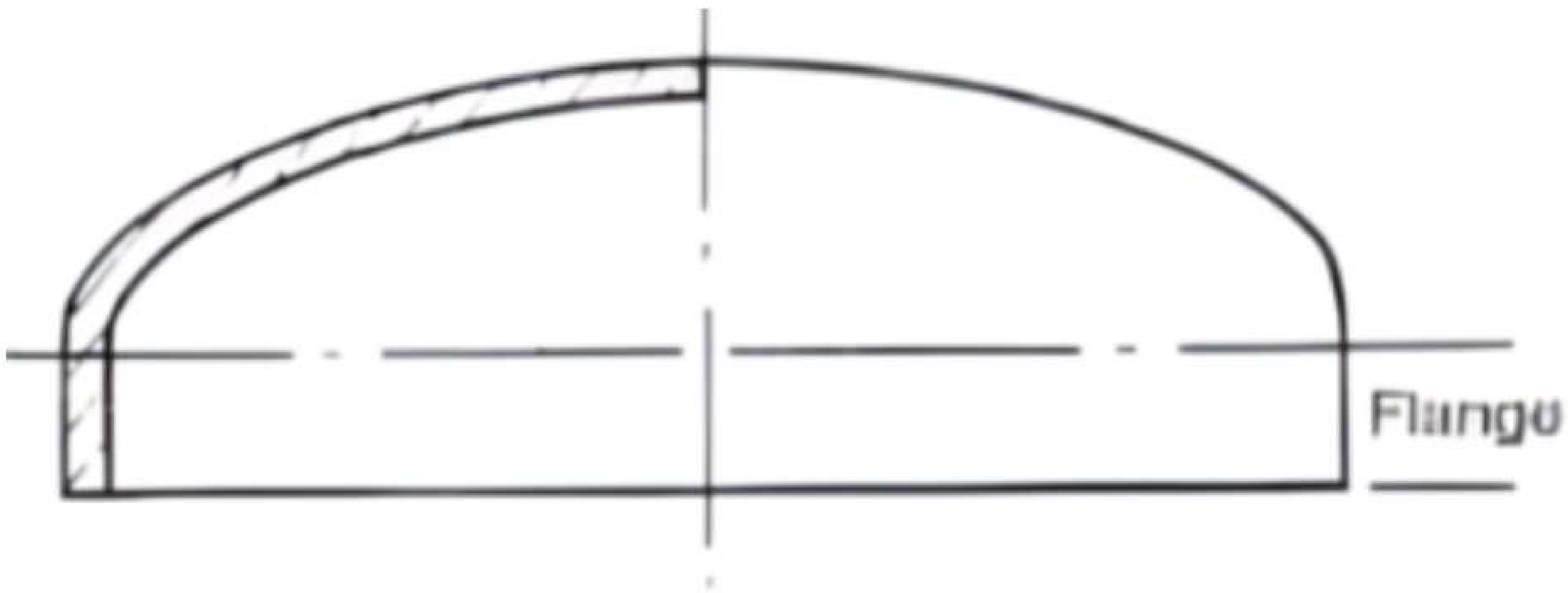


Figure 8-3: Ellipsoidal Head

$$t = \frac{D_i P_i}{2fJ - 0.2P_i}$$

$$t = \frac{1400 \times 0.22}{2(95)(1) - 0.2(0.22)}$$

t = 1.62 mm

Vessel Support:

The sort of support you employ for a vessel is determined by several factors, including the vessel's size, shape, and weight, the temperature and pressure it is meant to resist, and how it is positioned and placed. Here are some examples of the various forms of assistance available.

- Saddle (for horizontal vessels)
- Brackets (for vertical vessels).
- Skirt (for vertical vessels, especially if the length is long and the wind influence is significant)

We have chosen Bracket support by considering our conditions

Dead Weight of Shell:

$W_v = 240$ C.V.Dm (H V + $0.8D_m$) × t

W_v = weight of shell excluding internal fittings

C_v = factor to account for the weight of nozzles

C_v = 1.08 ***(for vessels; Page 833, Vol.6)***

t = thickness of shell = 1.62 mm

D_m = mean diameter

$D_m = [D_i + (t\times10^{-3})]$

$D_m = [1.4 + (1.62\times10^{-3})]$

$D_m = 1.40$ m

H_v = height of vessel = 7.3 m

$W_v = 240CVD_m\,(H_V + 0.8D_m) \times t$

$W_v = 240\times1.08\times1.40\times (7.3 + 0.8(1.4) \times (1.62\times10^{-3})$

$W_v = 4.95$ N

8.1.6 Wind Load

Wind Pressure = 1280 N/m2

D_m including Corrosion allowance

$D_m = 1.4 + 0.002 = 1.402$ m

$F = 1280 \times1.402 = 1794.5$ N/m

Wind load (F) = 1794.5 N/m

8.1.7 Stress Calculations

Longitudinal Stress:

$$\sigma_n = \frac{P_iD_i}{2t}$$

$$\sigma_n = \frac{0.22 \times 1400}{2 \times 1.62}$$

$$\sigma_n = 95\ \mathrm{N/mm^2}$$

Circumferential Stress:

$$\sigma_L = \frac{P_iD_i}{4t}$$

$$\sigma_L = \frac{0.22 \times 1400}{4 \times 1.62}$$

$$\sigma_L = 47.5\ \mathrm{N/mm^2}$$

Dead Weight Stress:

$$\sigma_w = \frac{W}{\pi(D_i + t)t}$$

$$\sigma_w = \frac{4.95}{\pi(1400 + 1.62)1.62}$$

$$\sigma_w = 6.9 \times 10^{-4}\ \mathrm{N/mm^2}$$

Radial Stress:

$$\sigma_r = \frac{P_i}{2}$$

$$\sigma_r = \frac{0.22}{2}$$

$$\sigma_r = 0.11\ \mathrm{N/mm^2}$$

Bending Stress:

$$\sigma_b = \frac{M}{I_v}\left(\frac{D_i}{2} + t\right)$$

I_v = moment of inertia (measure to its bending)

$$I_v = \frac{\pi}{64}(D_o^4 - D_i^4)$$

$$I_v = \frac{\pi}{64}(1.4034^4 - 1.4^4)$$

$$I_v = 1.62 \times 10^{-3}\mathrm{m^4}$$

M = Bending moment

$$M = \frac{W_v x^2}{2}$$

x = distance from the fixed end to the point where bending moment is being calculated (height between tangent lines)

x = height of the column – Dm (including corrosion allowance)

x = 7.3 – 1.402

x = 5.89 m

$$\mathrm{M} = \frac{(4.95)(5.89)^2}{2} = 86.09\ \mathrm{Nm}$$

$$\sigma_\mathrm{b} = \frac{\mathrm{M}}{\mathrm{I_v}}\left(\frac{\mathrm{D_i}}{2} + \mathrm{t}\right)$$

$$\sigma_\mathrm{b} = 37\,\frac{\mathrm{kN}}{\mathrm{m}^2}$$

9 Chapter NO 9: Process Simulation

9.1 Aspen Introduction:

ASPEN is a well-known industrial process simulation software suite. ASPEN predicts the performance of a process using mathematical models based on the process design and a sufficient number of thermodynamics models. ASPEN did not create the procedure. It takes a user-supplied design and duplicates the process specified in that design's performance. As a result, a solid understanding of the underlying chemical engineering principles is required to supply appropriate input parameter values and judge the acceptability of the results obtained. For example, before using ASPEN, a user needs have a basic grasp of column behavior. This information might be obtained by an approximation approach such as the McCabe-Thiele methodology, generic modeling of T-x-y behavior, or residue curve mapping. [27]

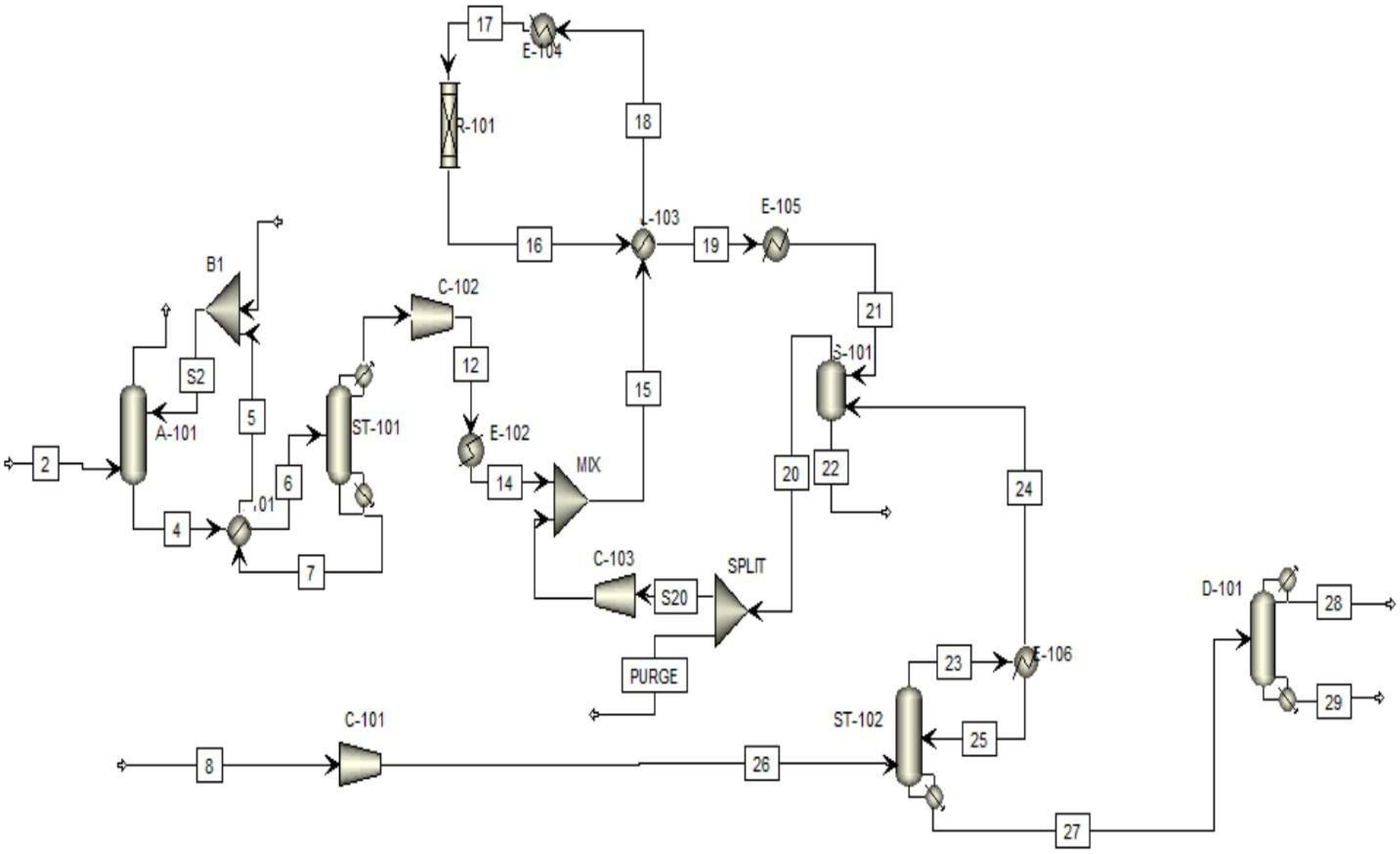
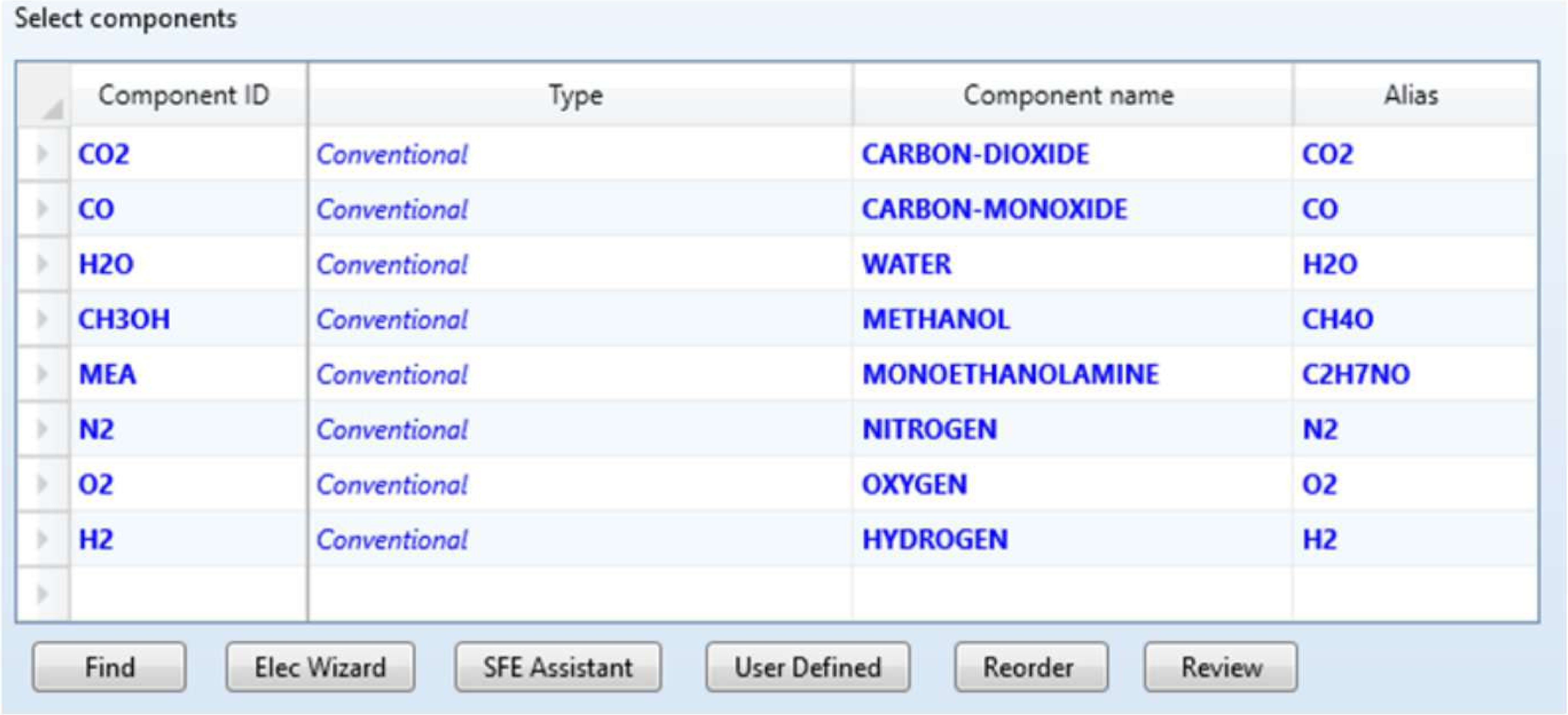


Figure 9-1: Flowsheet of Plant on Aspen Plus

9.2 Simulation:

To initiate the simulation of the Aspen plus V10, select New | Blank, and New | Blank Simulation, and click Create.

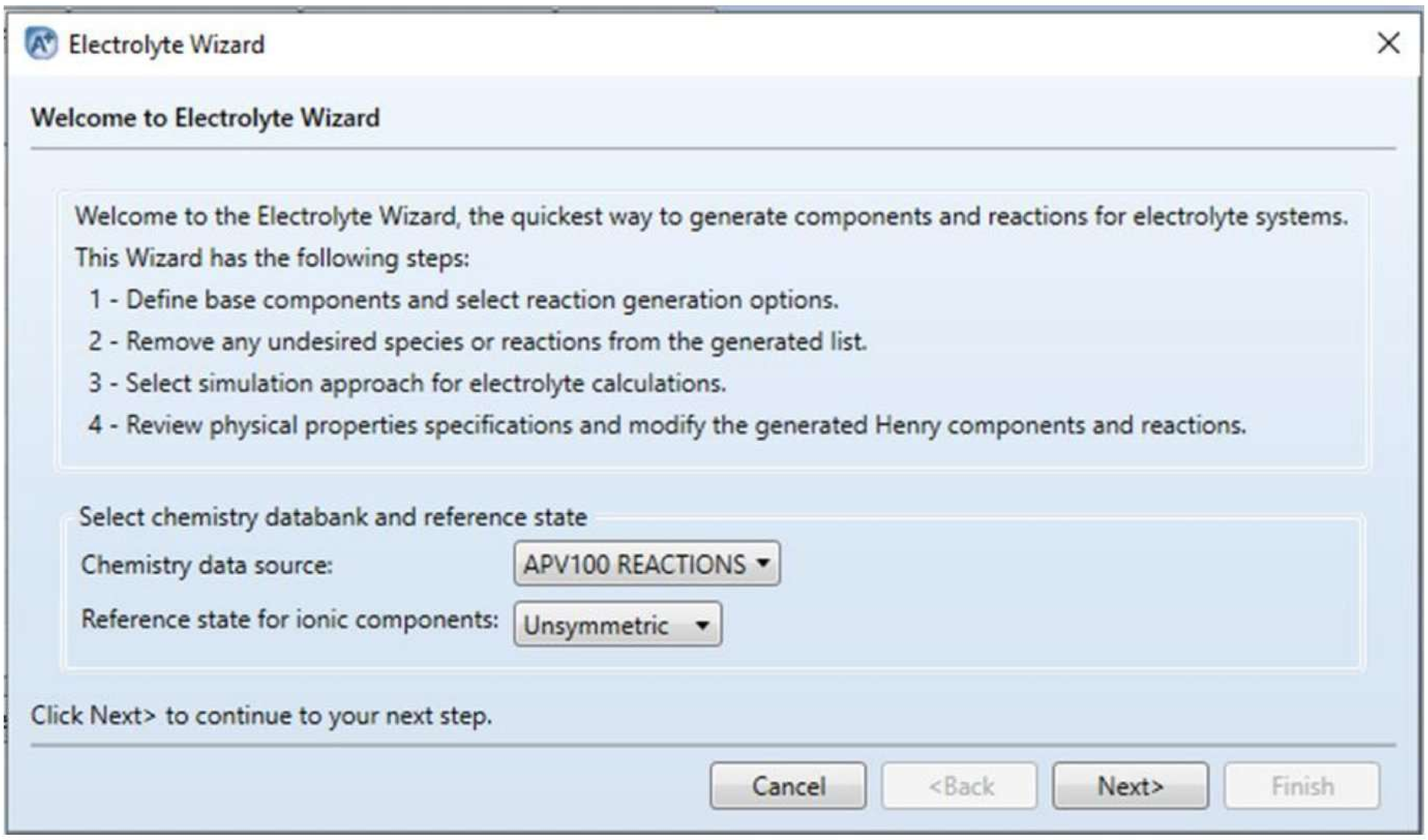
To define components, enter the Component ID's shown in Figure 01. Aspen Plus recognizes these components and fills in the rest of the component information.


Select components

Component ID	Type	Component name	Alias
CO2	Conventional	CARBON-DIOXIDE	CO2
CO	Conventional	CARBON-MONOXIDE	CO
H2O	Conventional	WATER	H2O
CH3OH	Conventional	METHANOL	CH4O
MEA	Conventional	MONOETHANOLAMINE	C2H7NO
N2	Conventional	NITROGEN	N2
O2	Conventional	OXYGEN	O2
H2	Conventional	HYDROGEN	H2

Figure 9-2: Components

To figure out what electrolytes are in your system, use the Elec Wizard. Look for the Elec Wizard on the Components | Spec | Selection sheet. In the window that appears, pick unsymmetrical for the reference state for your ionic components. Then click Next.


Electrolyte Wizard

Welcome to Electrolyte Wizard

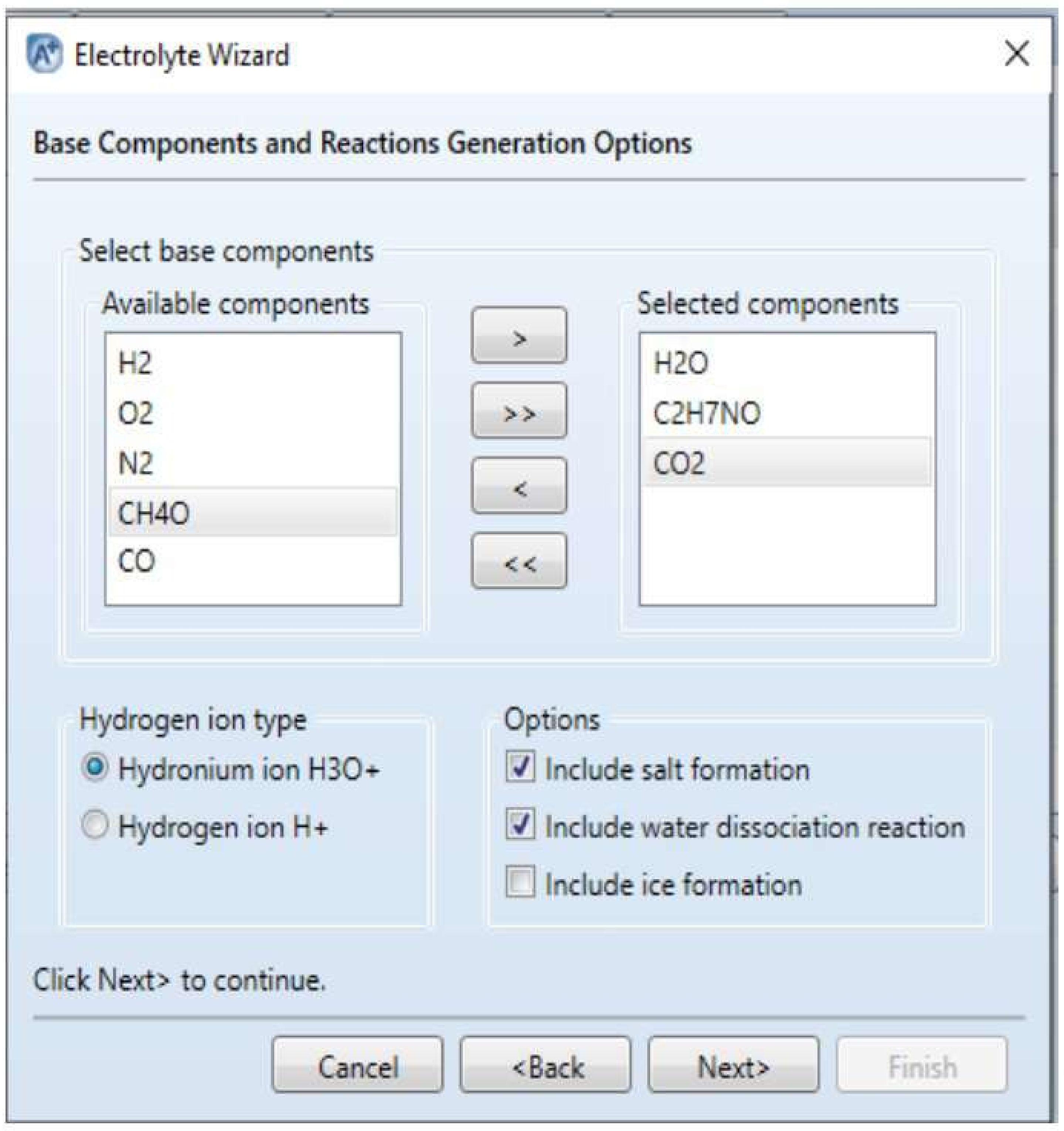
Welcome to the Electrolyte Wizard, the quickest way to generate components and reactions for electrolyte systems.
This Wizard has the following steps:
1 - Define base components and select reaction generation options.
2 - Remove any undesired species or reactions from the generated list.
3 - Select simulation approach for electrolyte calculations.
4 - Review physical properties specifications and modify the generated Henry components and reactions.

Select chemistry databank and reference state
Chemistry data source: APV100 REACTIONS
Reference state for ionic components: Unsymmetric

Click Next> to continue to your next step.

Figure 9-2: Electrolyte Wizard

In the next window, choose all the parts you want to use and tick the box that says "Water Dissociation Reactions". Click Next.



Base Components and Reactions Generation Options

Select base components

Available components: H2, O2, N2, CH4O, CO

Selected components: H2O, C2H7NO, CO2

Hydrogen ion type

● Hydronium ion H3O+

○ Hydrogen ion H+

Options

☑ Include salt formation

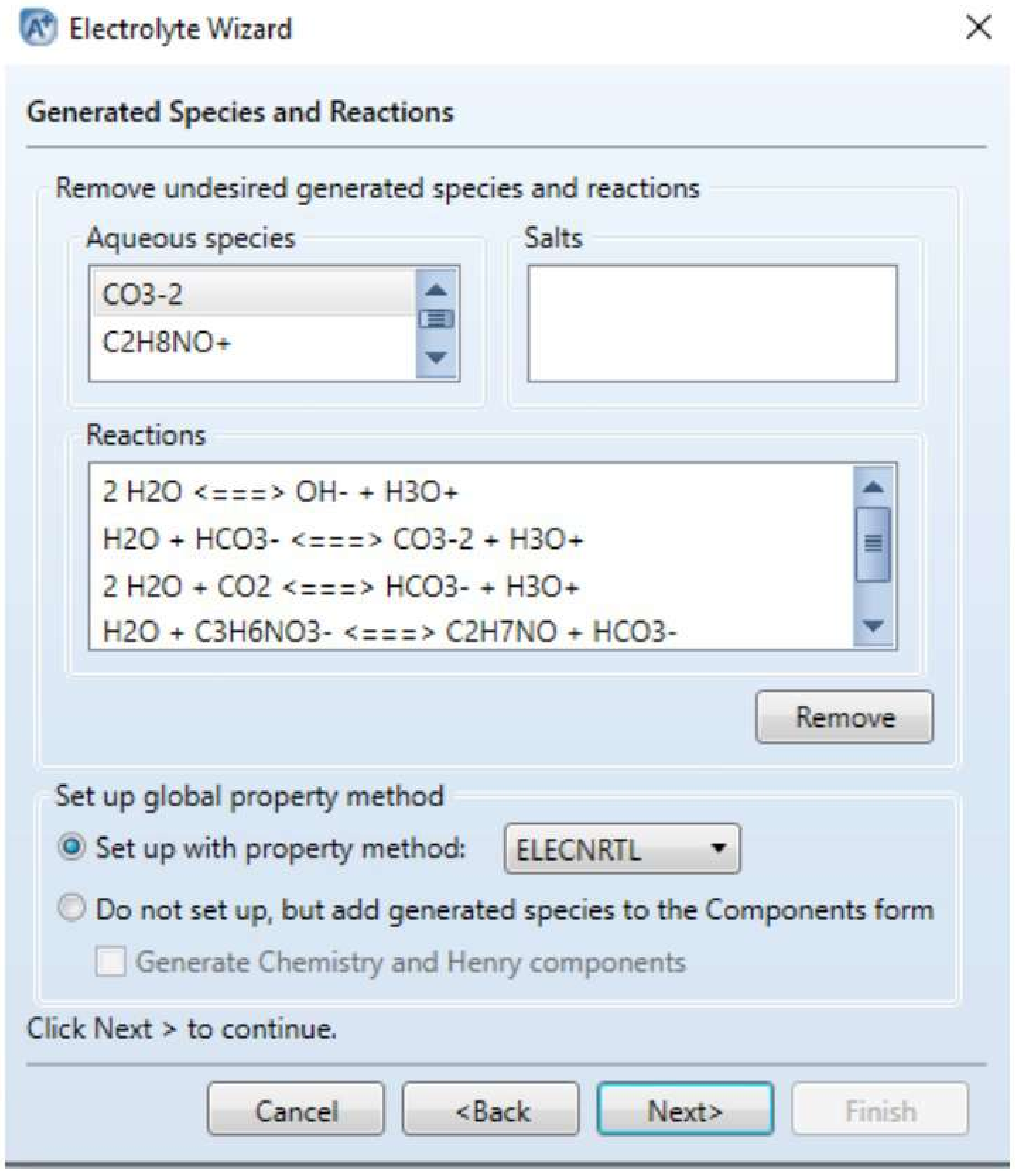
☑ Include water dissociation reaction

☐ Include ice formation

Click Next> to continue.

Figure 9-3: Base Components and Reaction Generation option

In the following window, you will be able to edit any unwanted reactions or species, as well as select the property method. We will not be making any modifications in this case. Click the Next button.



Generated Species and Reactions

Remove undesired generated species and reactions

Aqueous species: CO3-2, C2H8NO+

Salts

Reactions

2 H2O <===> OH- + H3O+

H2O + HCO3- <===> CO3-2 + H3O+

2 H2O + CO2 <===> HCO3- + H3O+

H2O + C3H6NO3- <===> C2H7NO + HCO3-

Set up global property method

● Set up with property method: ELECNRTL

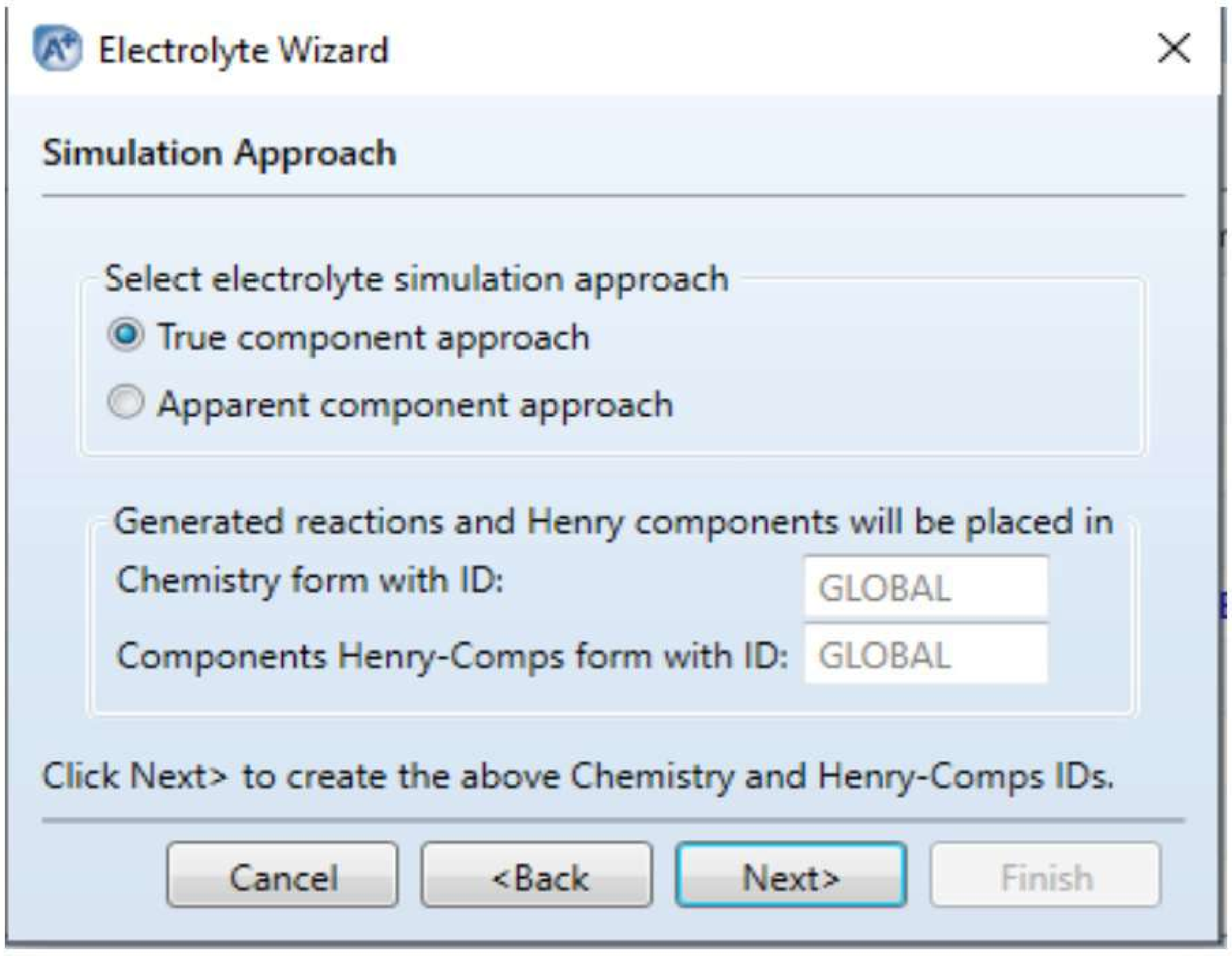
○ Do not set up, but add generated species to the Components form

☐ Generate Chemistry and Henry components

Click Next > to continue.

Figure 9-4: Generated Species and reactions

A new window will pop up asking you to choose the electrolyte simulation method. The default method is the true component approach. Please confirm that you have chosen this method and click Next.



Simulation Approach

Select electrolyte simulation approach

● True component approach

○ Apparent component approach

Generated reactions and Henry components will be placed in

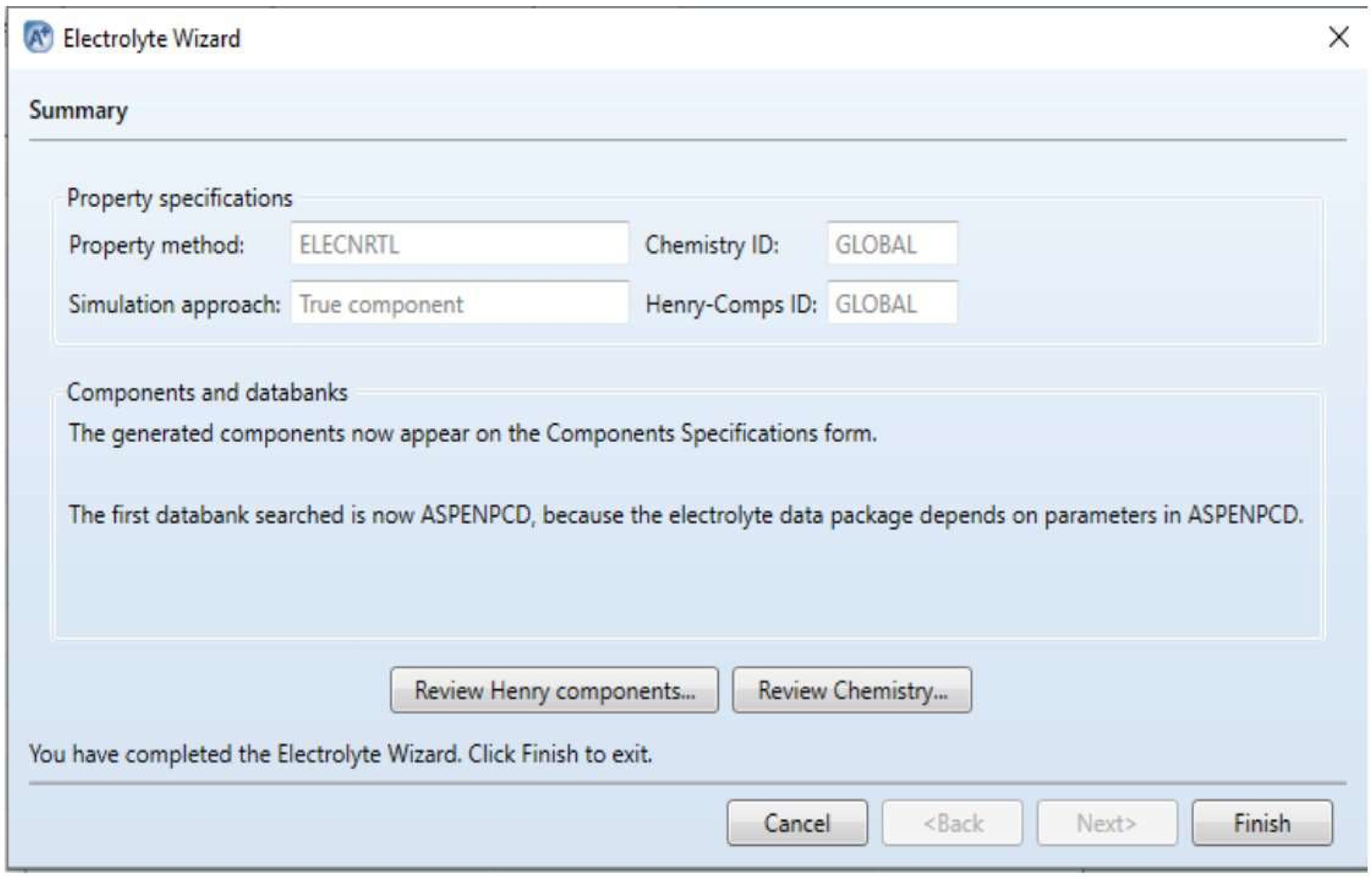
Chemistry form with ID: GLOBAL

Components Henry-Comps form with ID: GLOBAL

Click Next> to create the above Chemistry and Henry-Comps IDs.

Figure 9-5: Simulation Approach

Finally, you'll see a summary window pop up. Tap the Finish button on your Electrolyte Wizard.



Summary

Property specifications

Property method: ELECNRTL

Chemistry ID: GLOBAL

Simulation approach: True component

Henry-Comps ID: GLOBAL

Components and databanks

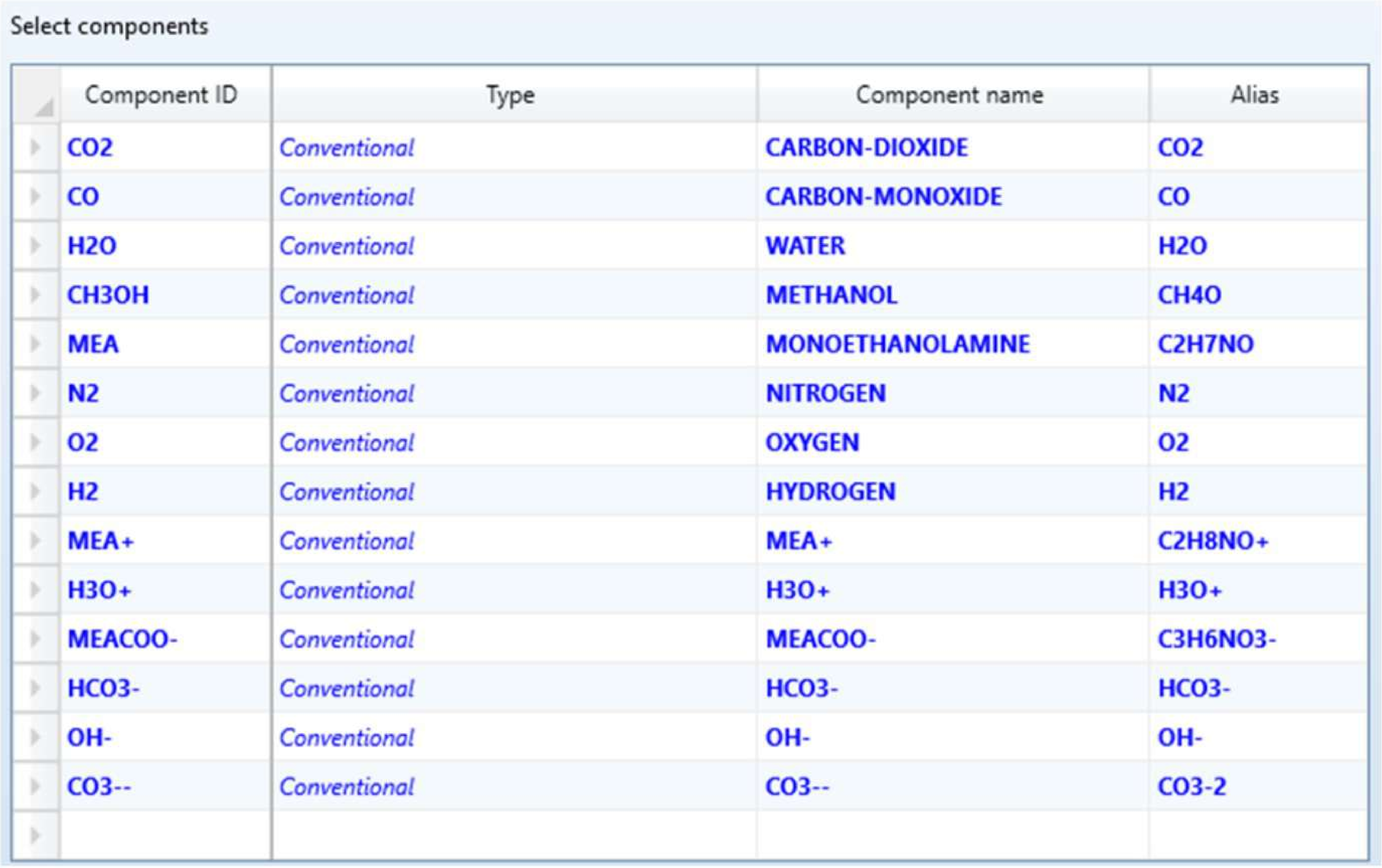
The generated components now appear on the Components Specifications form.

The first databank searched is now ASPENPCD, because the electrolyte data package depends on parameters in ASPENPCD.

You have completed the Electrolyte Wizard. Click Finish to exit.

Figure 9-6: Summary

You’ll see that all the parts are now defined.



Select components

Component ID	Type	Component name	Alias
CO2	Conventional	CARBON-DIOXIDE	CO2
CO	Conventional	CARBON-MONOXIDE	CO
H2O	Conventional	WATER	H2O
CH3OH	Conventional	METHANOL	CH4O
MEA	Conventional	MONOETHANOLAMINE	C2H7NO
N2	Conventional	NITROGEN	N2
O2	Conventional	OXYGEN	O2
H2	Conventional	HYDROGEN	H2
MEA+	Conventional	MEA+	C2H8NO+
H3O+	Conventional	H3O+	H3O+
MEACOO-	Conventional	MEACOO-	C3H6NO3-
HCO3-	Conventional	HCO3-	HCO3-
OH-	Conventional	OH-	OH-
CO3--	Conventional	CO3--	CO3-2

Figure 9-7: Final Components

Next button (F4 key) is used to confirm methods and parameters. On the Methods | Specimens | Global sheet, click Next to confirm Base method.

Press the F4 key three times (one at a time) to confirm Binary Interaction parameters.

To see Electrolyte pairs, press F4 twice (one after the other).

To create a flowsheet, click on the Simulation bar in the lower left corner of your screen. To access the simulation environment, click on the Place the equipment's given in above flowsheet

- Absorber
- Stripper
- Heat Exchanger
- Reactor
- Distillation column
- Pumps & Compressors

Join all the equipment's as shown in flowsheet.

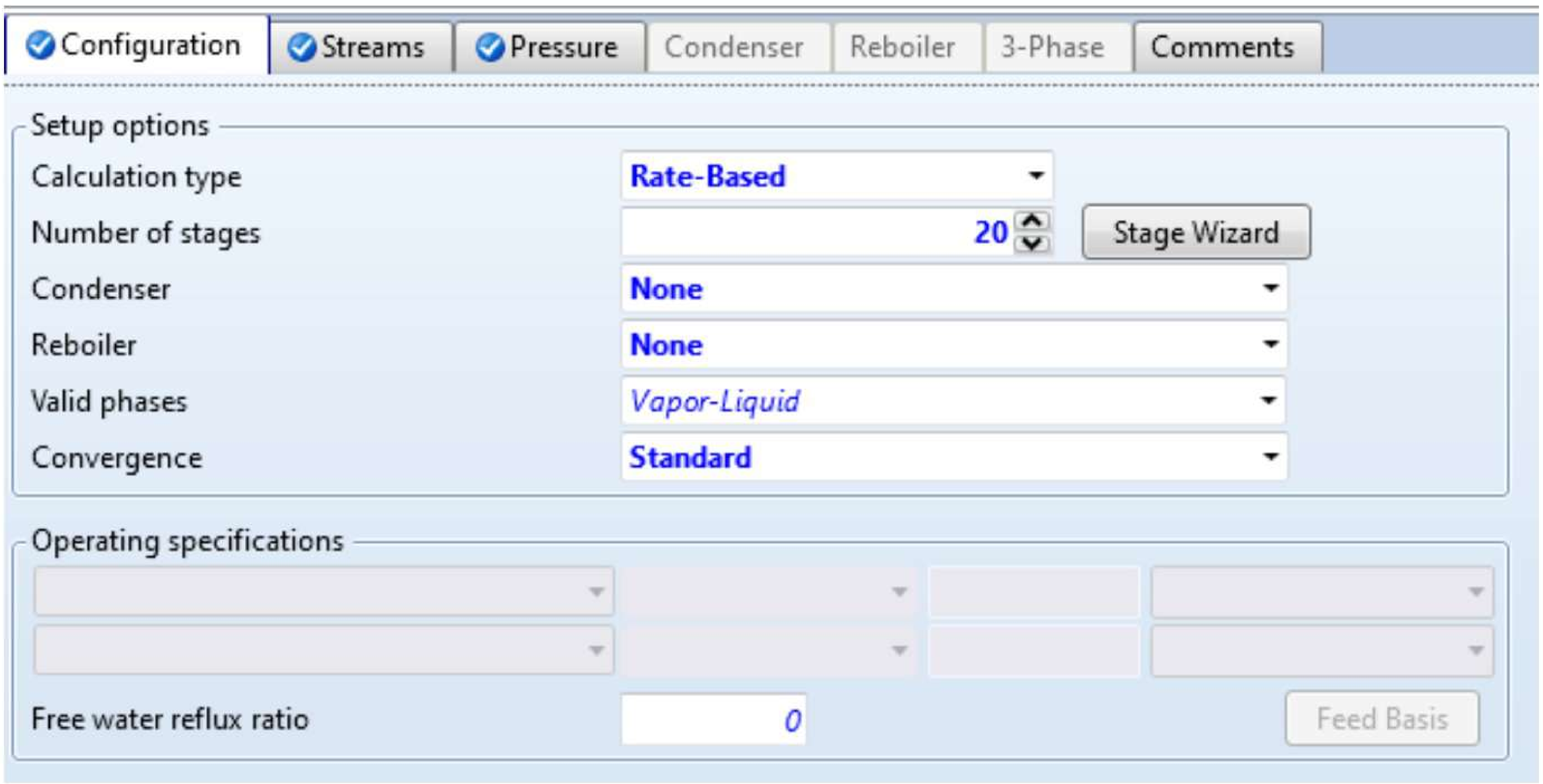
9.3 Absorber (A-101):

For rate-based absorption we have to give following conditions:

- Operating conditions
- Column intervals

9.3.1 Operating Conditions:

Give all the operating conditions given below of configuration, stream and pressure of the column.



Setup options

Calculation type: Rate-Based

Number of stages: 20

Condenser: None

Reboiler: None

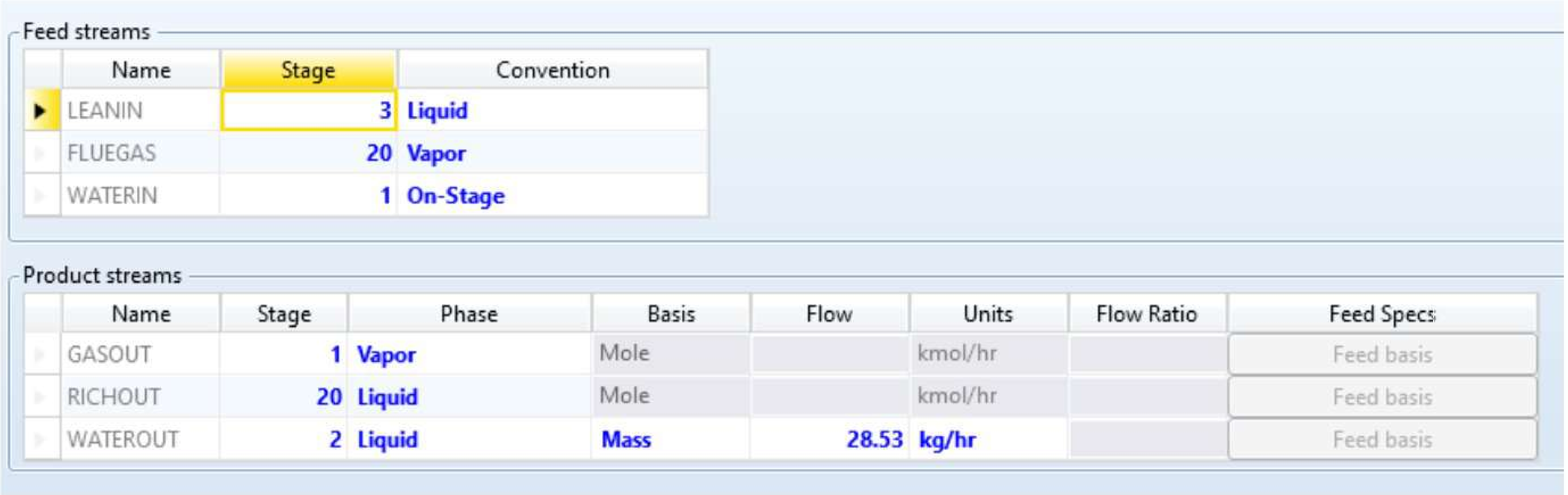
Valid phases: Vapor-Liquid

Convergence: Standard

Operating specifications

Free water reflux ratio: 0

Figure 9-8: Configuration for A-101



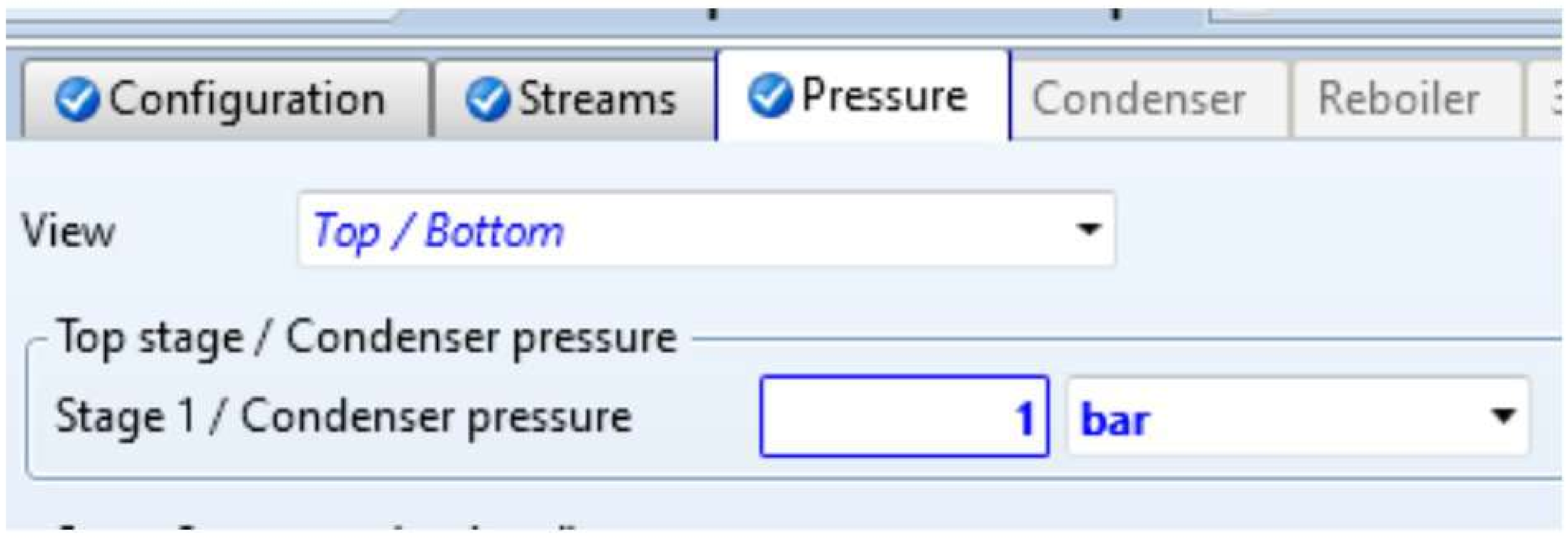
Feed streams

Name	Stage	Convention
LEANIN	3	Liquid
FLUEGAS	20	Vapor
WATERIN	1	On-Stage

Product streams

Name	Stage	Phase	Basis	Flow	Units	Flow Ratio	Feed Specs
GASOUT	1	Vapor	Mole		kmol/hr		Feed basis
RICHOUT	20	Liquid	Mole		kmol/hr		Feed basis
WATEROUT	2	Liquid	Mass	28.53	kg/hr		Feed basis

Figure 9-9: Feed streams for A-101



View: Top / Bottom

Top stage / Condenser pressure

Stage 1 / Condenser pressure: 1 bar

Figure 9-10: Operating Pressure of A-101

9.3.2 Column Intervals:

For reactive absorption we must have to specify column intervals. Specify all the required specification for column interval.

Name	Start Stage	End Stage	Mode	Internal Type	Tray/Packing Type	Tray Details	Packing Details			Tray Spacing/Section Packed Height	
						Number of Passes	Vendor	Material	Dimension		
CS-1	1	20	Rating	Packed	INTX		MTL	CERAMIC	1-IN OR 25-M	4.5	meter

Figure 9-11: Column Internals for A-101

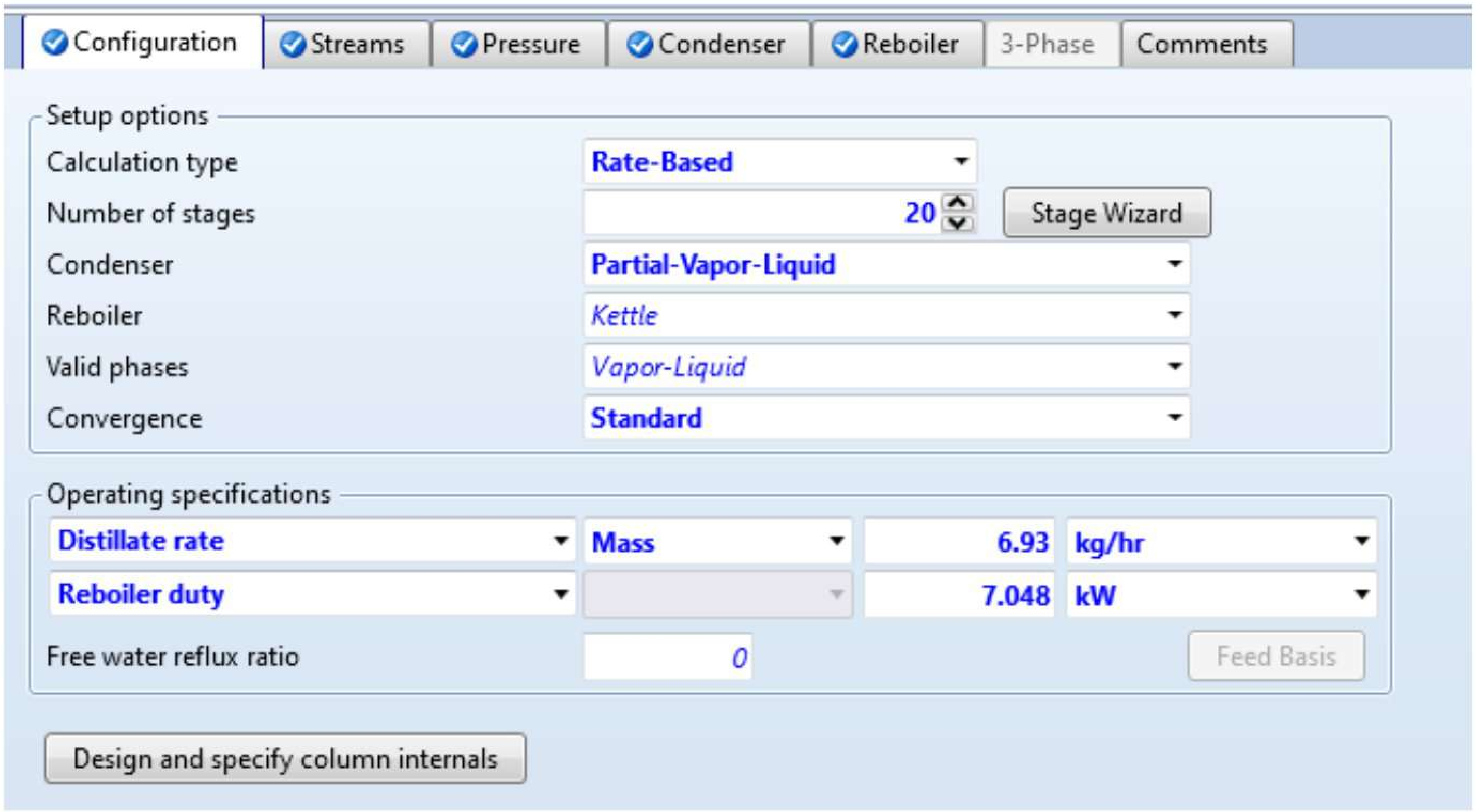
9.4 Stripper (ST-101):

In stripper the reverse reactions take place in stripper. For stripper conditions are following:

- Operating Conditions
- Column Intervals
- Rate-Based Modelling/Setup

9.4.1 Operating Conditions:

Specify all the operating conditions in configuration section of ST-101.



Setup options

Calculation type: Rate-Based
Number of stages: 20
Condenser: Partial-Vapor-Liquid
Reboiler: Kettle
Valid phases: Vapor-Liquid
Convergence: Standard

Operating specifications

Distillate rate: Mass 6.93 kg/hr
Reboiler duty: 7.048 kW
Free water reflux ratio: 0

Figure 9-12: Configuration of ST-101

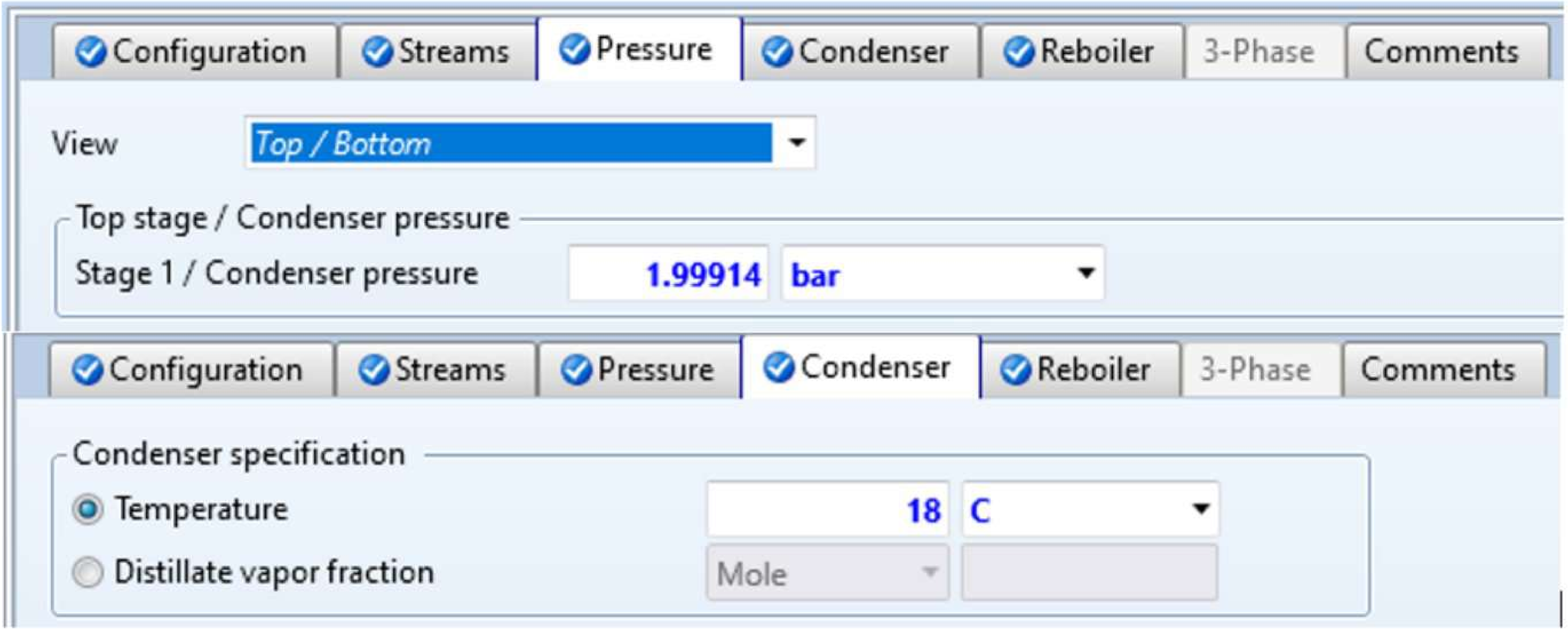
Feed streams

Name	Stage	Convention
RICHIN	3	On-Stage

Product streams

Name	Stage	Phase	Basis	Flow	Units	Flow Ratio	Feed Specs
CO2OUT	1	Vapor	Mole		kmol/hr		Feed basis
COND	1	Liquid	Mole		kmol/hr		Feed basis
LEANOUT	20	Liquid	Mole		kmol/hr		Feed basis

Figure 9-13: Streams



View: Top / Bottom

Top stage / Condenser pressure

Stage 1 / Condenser pressure: 1.99914 bar

Condenser specification

● Temperature: 18 C
○ Distillate vapor fraction: Mole

Figure 9-14: *Operating Temperature of Condenser and Pressure of Column*

9.4.2 Column Internals:

Add column intervals of ST-101

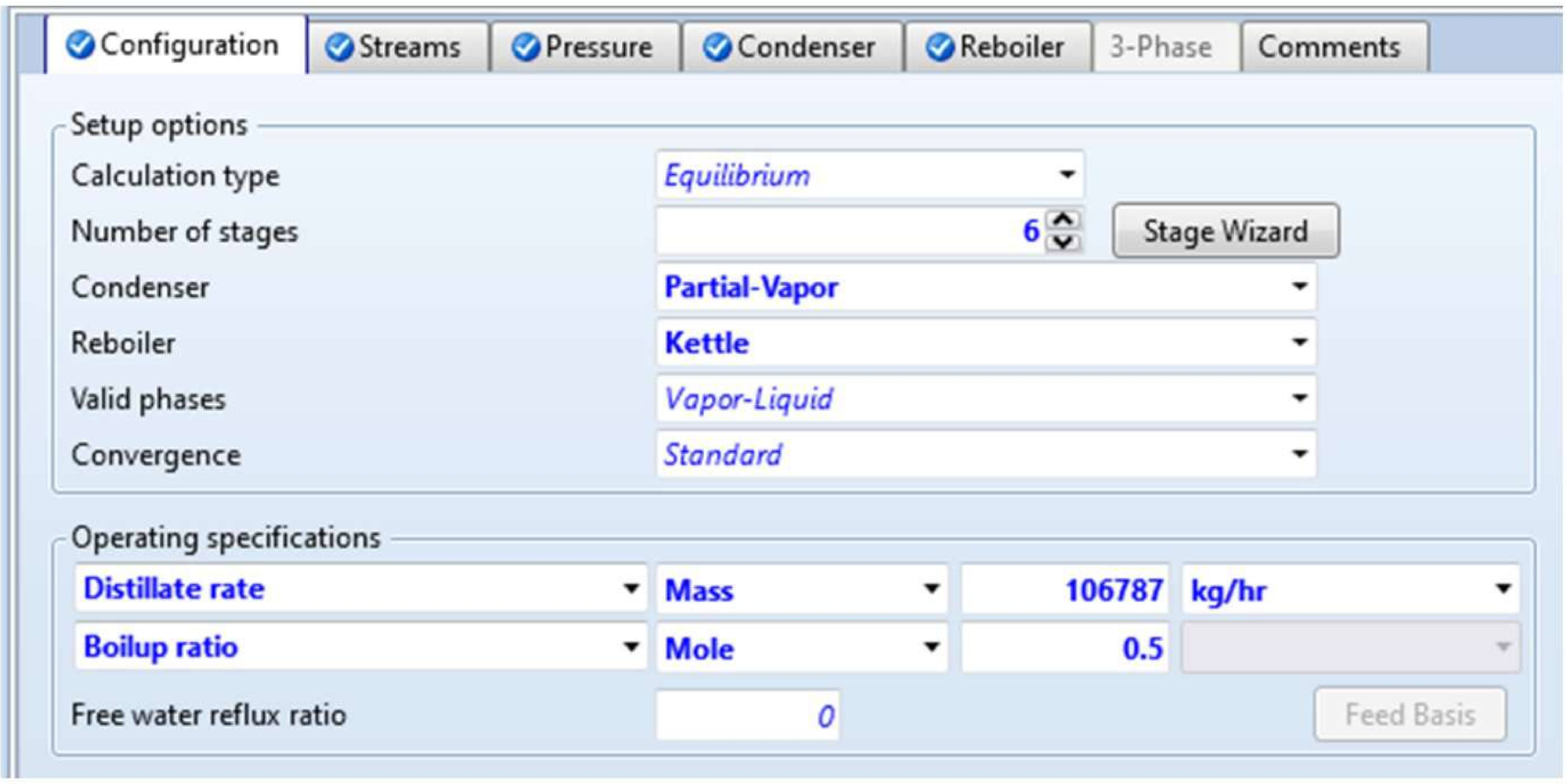
Column description

Name	Start Stage	End Stage	Mode	Internal Type	Tray/Packing Type	Tray Details	Packing Details			Tray Spacing/Section Packed Height	
						Number of Passes	Vendor	Material	Dimension		
CS-1	1	20	Rating	Packed	INTX		MTL	CERAMIC	1-IN OR 25-M	4.5	meter

Figure 9-15: Column Internals

9.5 ST-102:

Add the Configuration, Streams and Pressure for ST-102.



Setup options

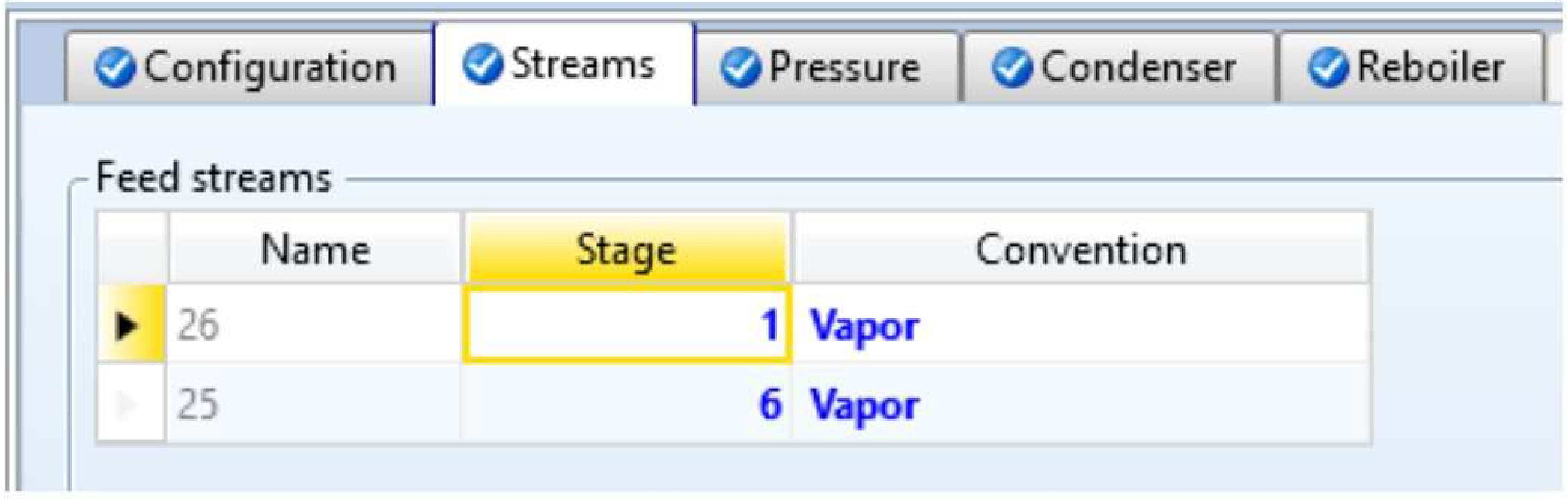
Calculation type: Equilibrium
Number of stages: 6
Condenser: Partial-Vapor
Reboiler: Kettle
Valid phases: Vapor-Liquid
Convergence: Standard

Operating specifications

Distillate rate	Mass	106787	kg/hr
Boilup ratio	Mole	0.5	

Free water reflux ratio: 0

Figure 9-16: Operating Conditions of ST-102



Feed streams

Name	Stage	Convention
26	1	Vapor
25	6	Vapor

Figure 9-17: Streams of ST-102

View: Top / Bottom

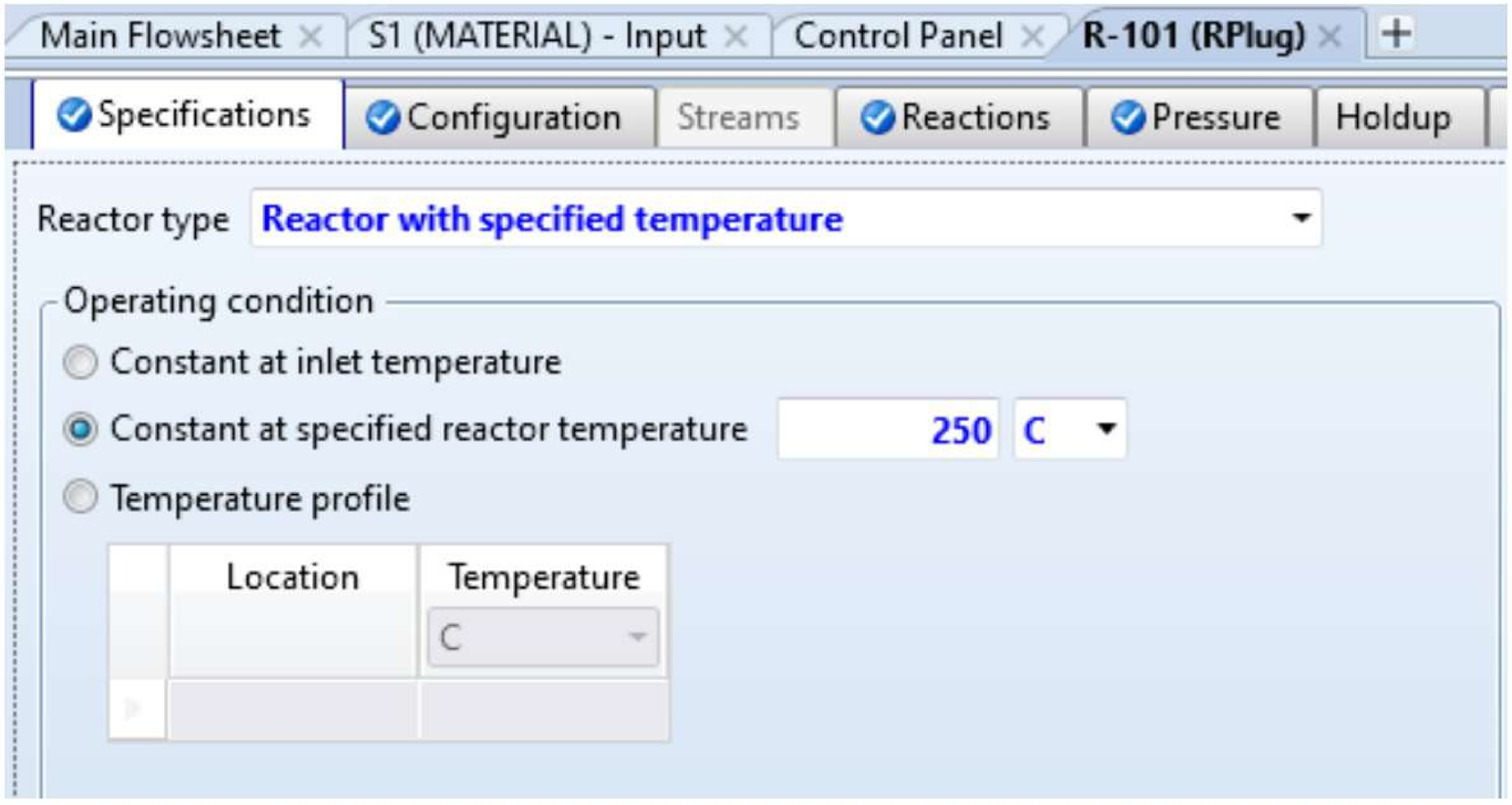
Top stage / Condenser pressure

Stage 1 / Condenser pressure 45 bar

Figure 9-18: Pressure of ST-102

9.6 Reactor (R-101):

- Type of reactor is isothermal packed bed reactor.
- Temperature 250^{O}C
- Pressure 50 bar
- Specify the length and diameter and reaction set



Reactor type: Reactor with specified temperature

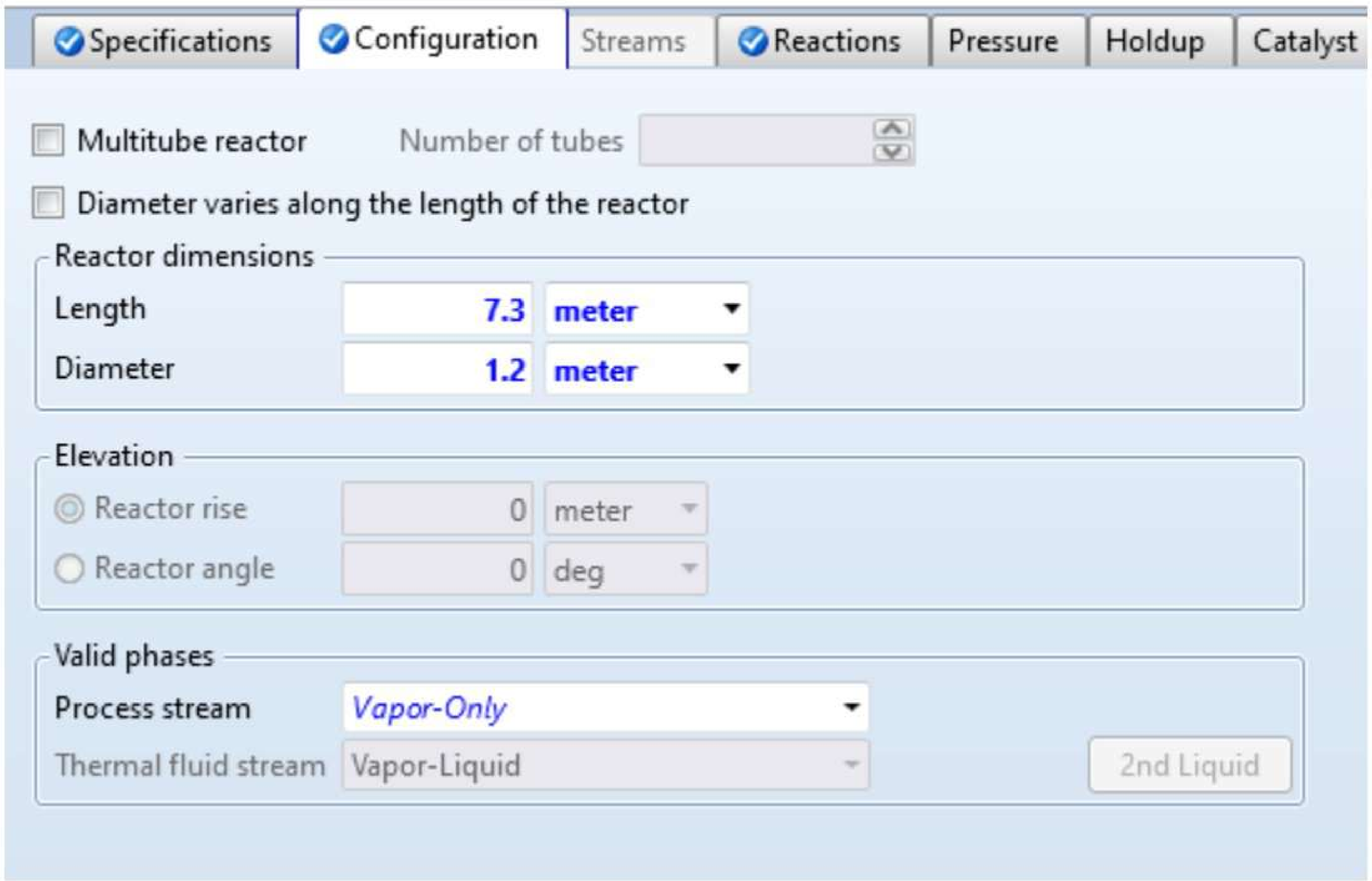
Operating condition

○ Constant at inlet temperature

● Constant at specified reactor temperature 250 C

○ Temperature profile

Figure 9-19: Specifications of R-101



☐ Multitube reactor Number of tubes

☐ Diameter varies along the length of the reactor

Length 7.3 meter

Diameter 1.2 meter

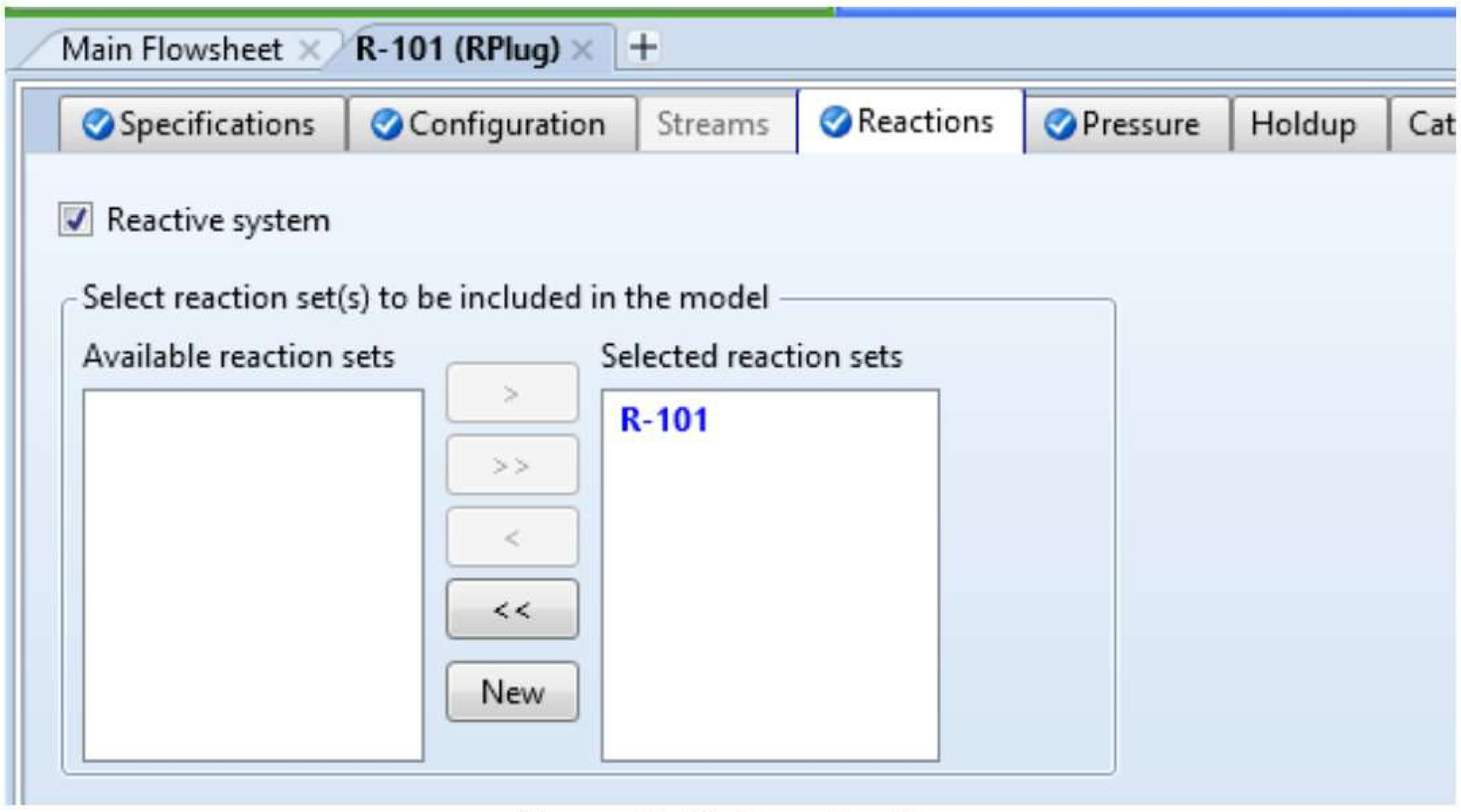
○ Reactor rise 0 meter

○ Reactor angle 0 deg

Process stream Vapor-Only

Thermal fluid stream Vapor-Liquid

Figure 9-20: Configuration of R-101



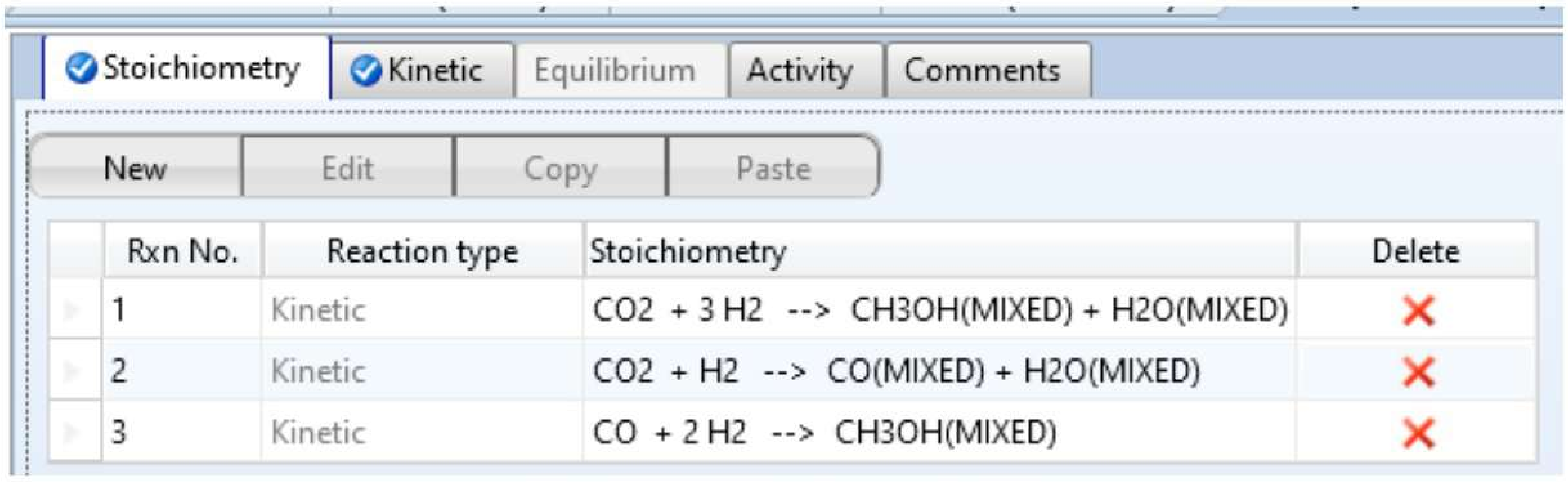
☑ Reactive system

Selected reaction sets: R-101

Figure 9-21: Reaction Set

9.6.1 Reactions of R-101:

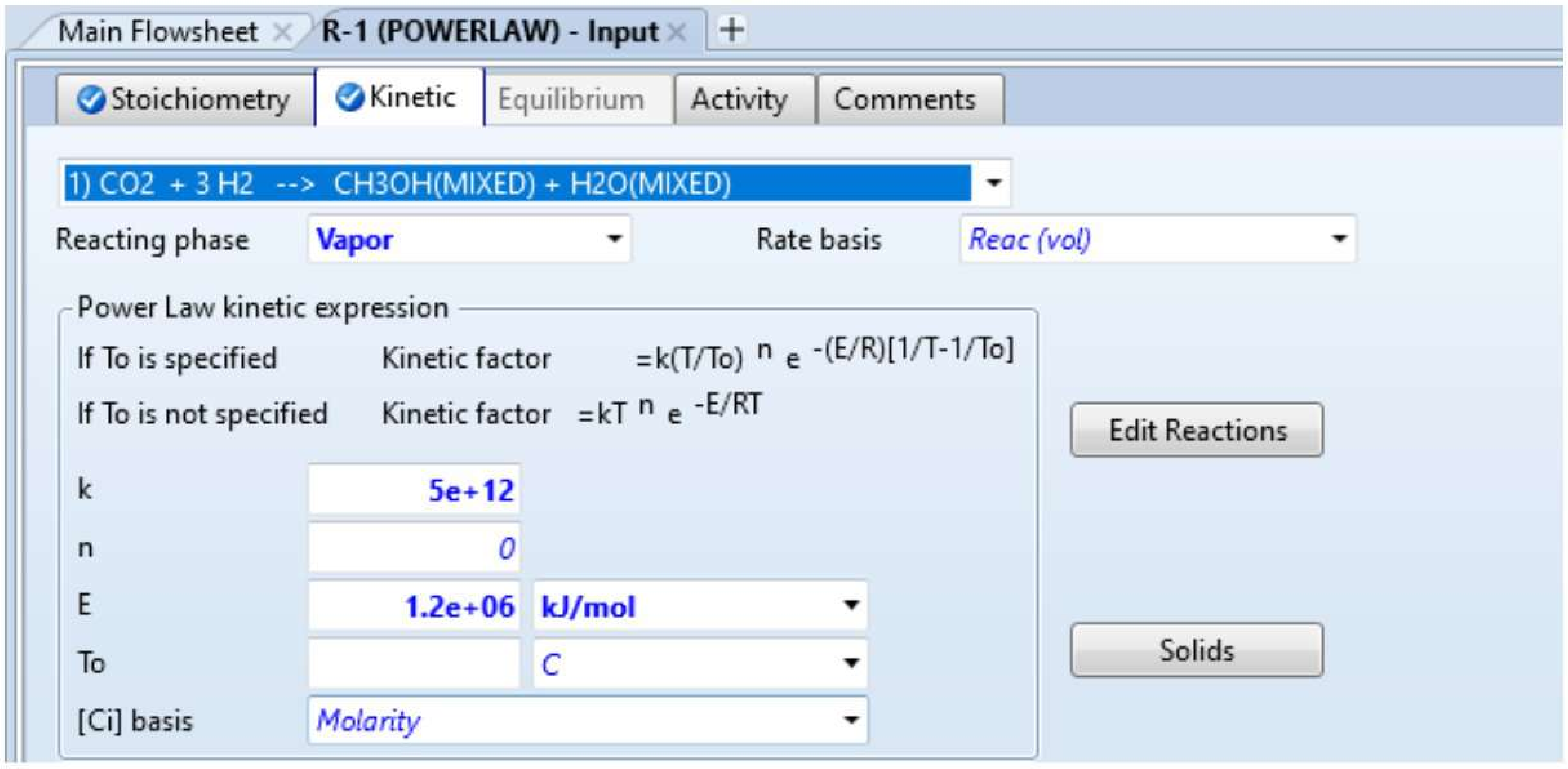
Specify the following reactions for reactor R-101



Rxn No.	Reaction type	Stoichiometry	Delete
1	Kinetic	CO2 + 3 H2 --> CH3OH(MIXED) + H2O(MIXED)	✗
2	Kinetic	CO2 + H2 --> CO(MIXED) + H2O(MIXED)	✗
3	Kinetic	CO + 2 H2 --> CH3OH(MIXED)	✗

Figure 9-22: Reactions in R-101

Specify the rate law constant k, order of reaction n and Activation Energy E for Reaction no 01, 02&03



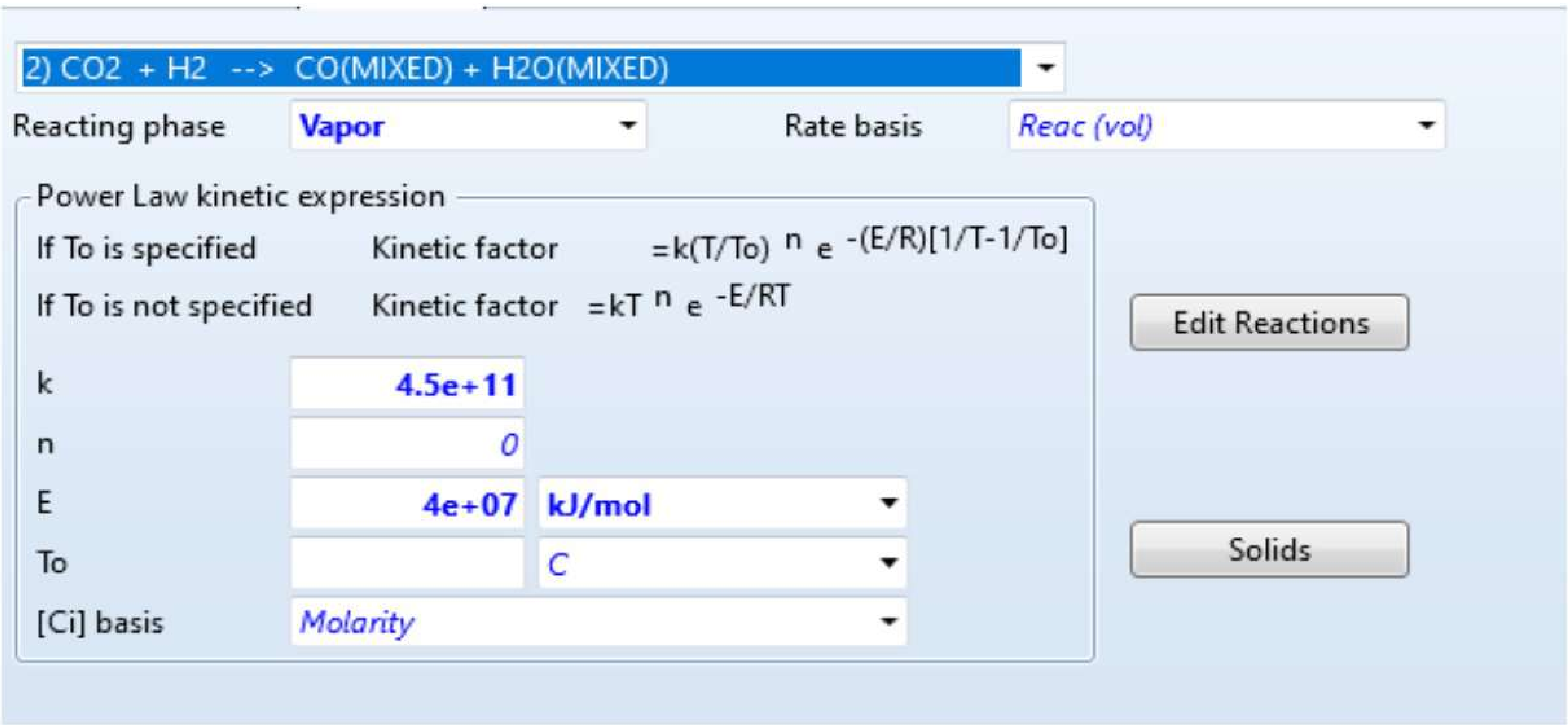
1) CO2 + 3 H2 --> CH3OH(MIXED) + H2O(MIXED)

Reacting phase: Vapor
Rate basis: Reac (vol)

Power Law kinetic expression
If To is specified: Kinetic factor $=k(T/To)^n e^{-(E/R)[1/T-1/To]}$
If To is not specified: Kinetic factor $=kT^n e^{-E/RT}$

k: 5e+12
n: 0
E: 1.2e+06 kJ/mol
To: C
[Ci] basis: Molarity

Figure 9-23: n, k and E for Rxn 01



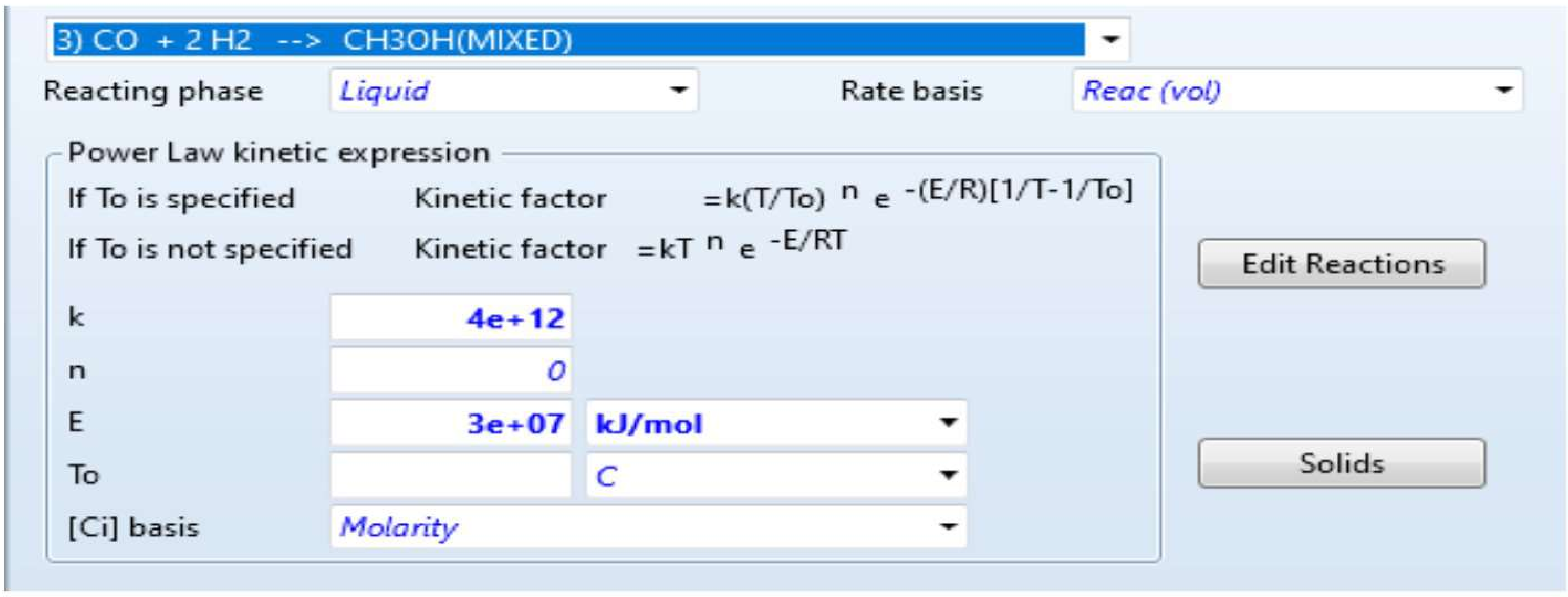
2) CO2 + H2 --> CO(MIXED) + H2O(MIXED)

Reacting phase: Vapor
Rate basis: Reac (vol)

Power Law kinetic expression
If To is specified: Kinetic factor $=k(T/To)^n e^{-(E/R)[1/T-1/To]}$
If To is not specified: Kinetic factor $=kT^n e^{-E/RT}$

k: 4.5e+11
n: 0
E: 4e+07 kJ/mol
To: C
[Ci] basis: Molarity

Figure 9-24: n, k and E for Rxn 02



3) CO + 2 H2 --> CH3OH(MIXED)

Reacting phase: Liquid
Rate basis: Reac (vol)

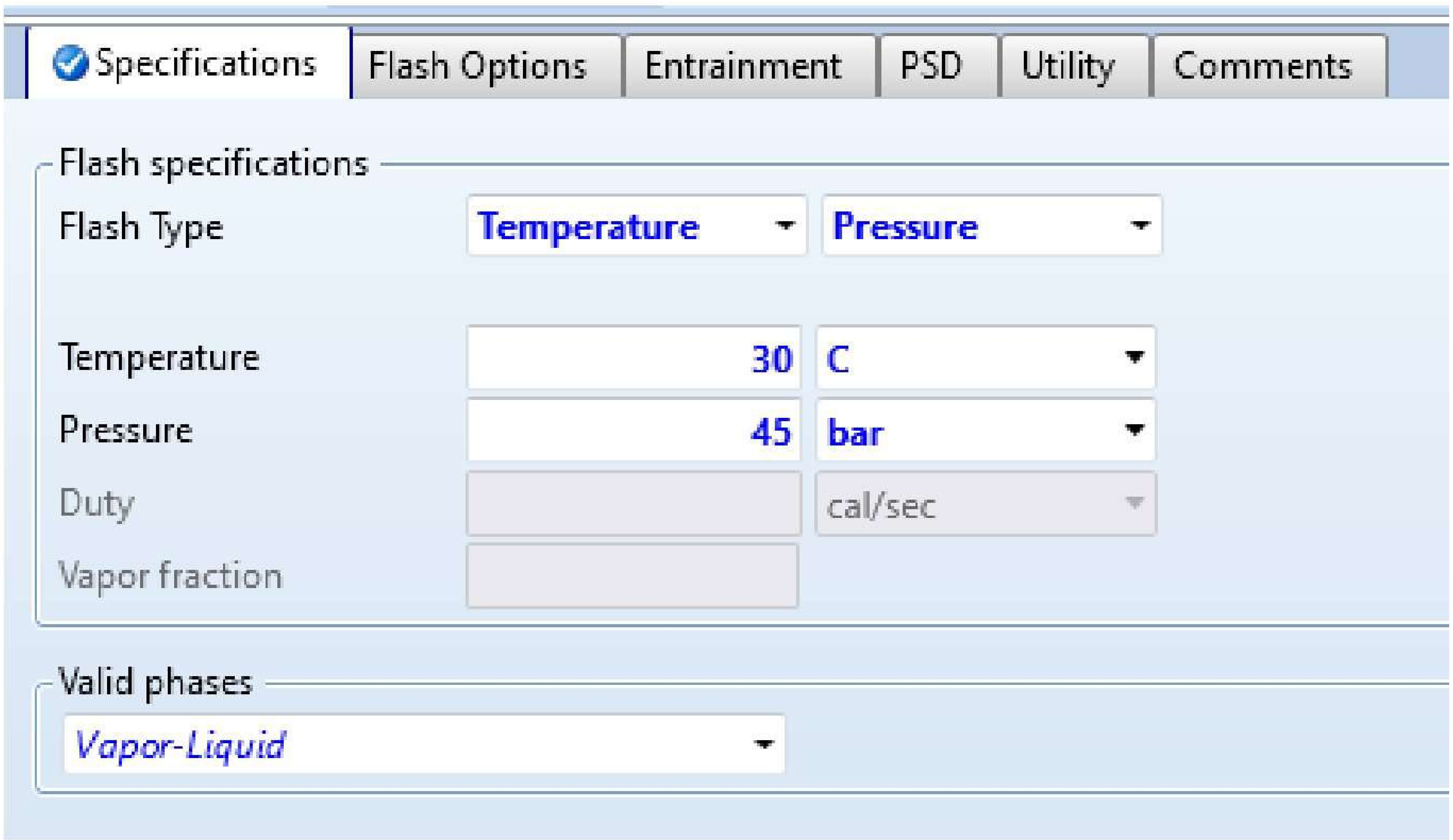
Power Law kinetic expression
If To is specified: Kinetic factor $=k(T/To)^n e^{-(E/R)[1/T-1/To]}$
If To is not specified: Kinetic factor $=kT^n e^{-E/RT}$

k: 4e+12
n: 0
E: 3e+07 kJ/mol
To: C
[Ci] basis: Molarity

Figure 9-25: n, k and E for Rxn# 03

9.7 Separator (S-101):

Add temperature, pressure and valid phase for separator 101.



Flash specifications

Flash Type: Temperature, Pressure

Temperature: 30 C

Pressure: 45 bar

Duty: cal/sec

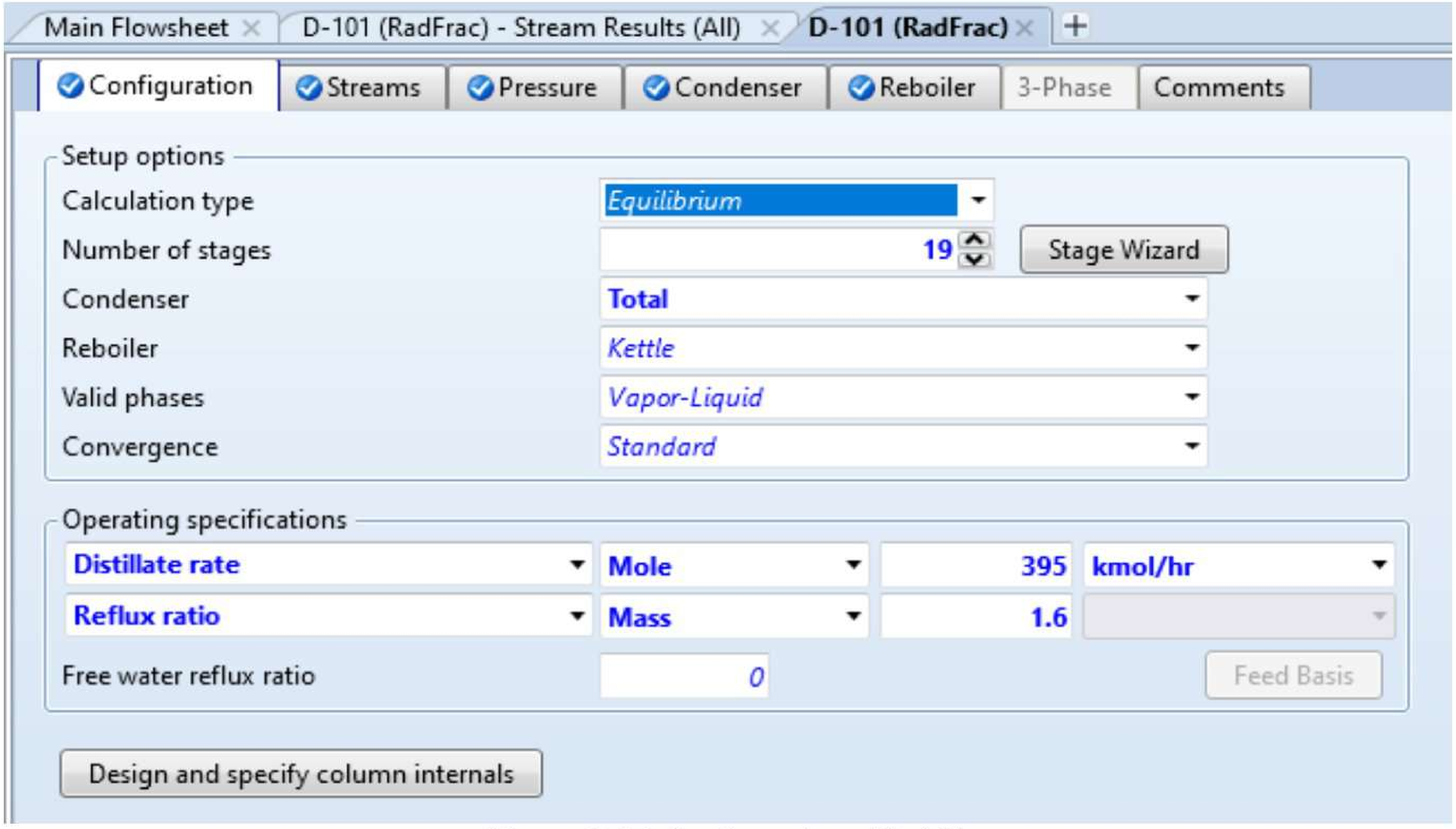
Vapor fraction

Valid phases: *Vapor-Liquid*

Figure 9-26: Specification for S-101

9.8 Distillation Column (D-101):

Specify the Configuration, Stream and Pressure of Distillation Column D-101.



Setup options

Calculation type: *Equilibrium*

Number of stages: 19

Condenser: Total

Reboiler: *Kettle*

Valid phases: *Vapor-Liquid*

Convergence: *Standard*

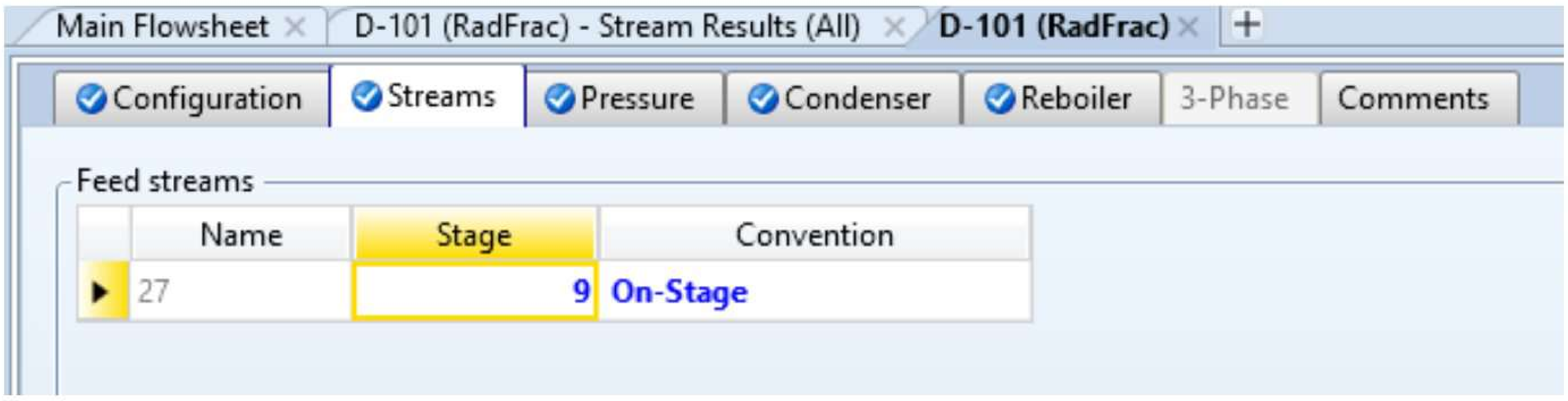
Operating specifications

Distillate rate: Mole 395 kmol/hr

Reflux ratio: Mass 1.6

Free water reflux ratio: *0*

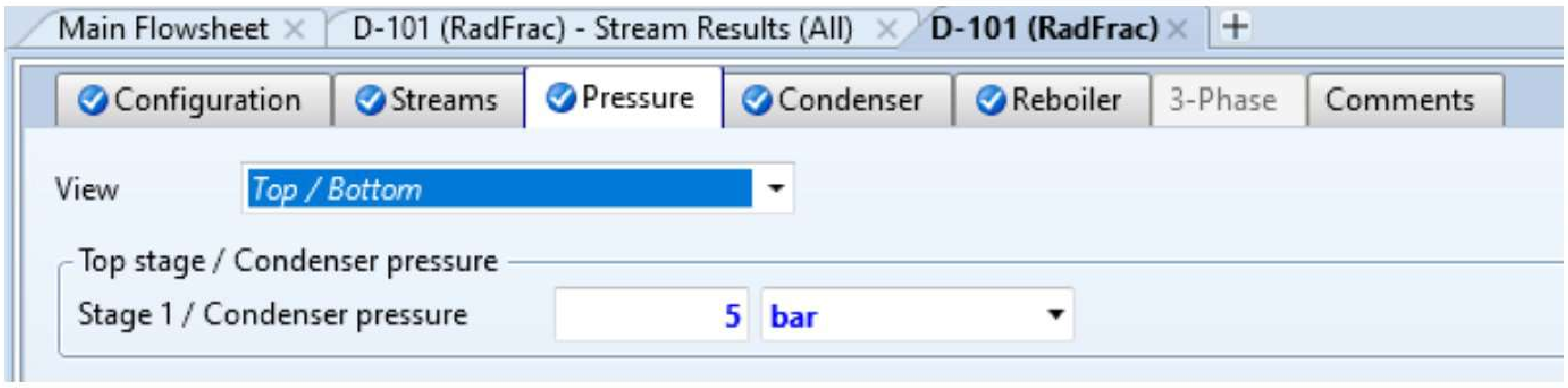
Figure 9-27: Configuration of D-101



Feed streams

Name	Stage	Convention
27	9	On-Stage

Figure 9-28: Feed Streams



View: Top / Bottom

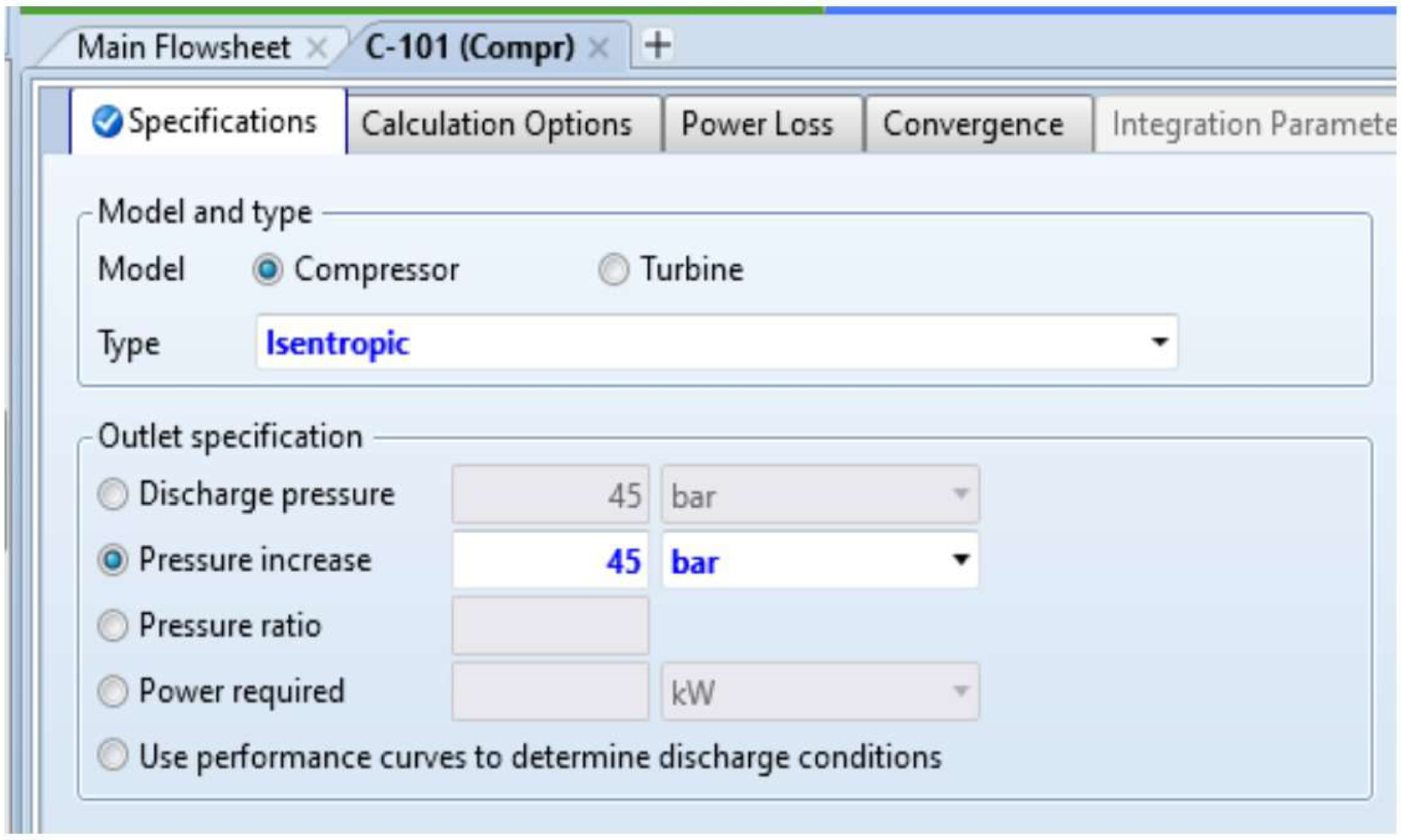
Top stage / Condenser pressure

Stage 1 / Condenser pressure: 5 bar

Figure 9-29: Operating Pressure for D-101

9.9 Compressors (C-101):

Specify the type of compressor and pressure increase of 45 bar.



Model and type

Model: ● Compressor ○ Turbine

Type: Isentropic

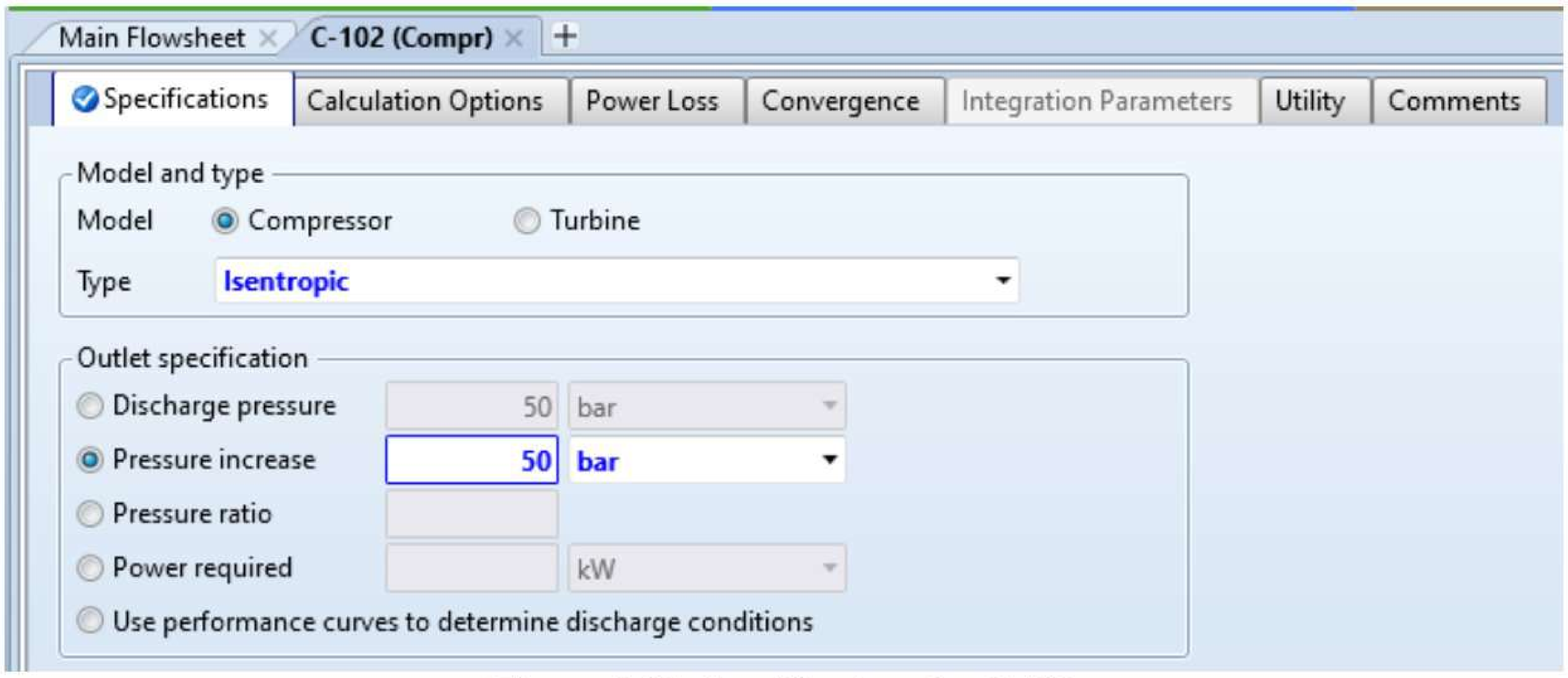
Outlet specification

○ Discharge pressure 45 bar
● Pressure increase 45 bar
○ Pressure ratio
○ Power required kW
○ Use performance curves to determine discharge conditions

Figure 9-30: Specifications for C-101

9.10 C-102

Specify the type of compressor and pressure increase of 50 bar.



Model and type

Model ● Compressor ○ Turbine

Type Isentropic

Outlet specification

○ Discharge pressure 50 bar

● Pressure increase 50 bar

○ Pressure ratio

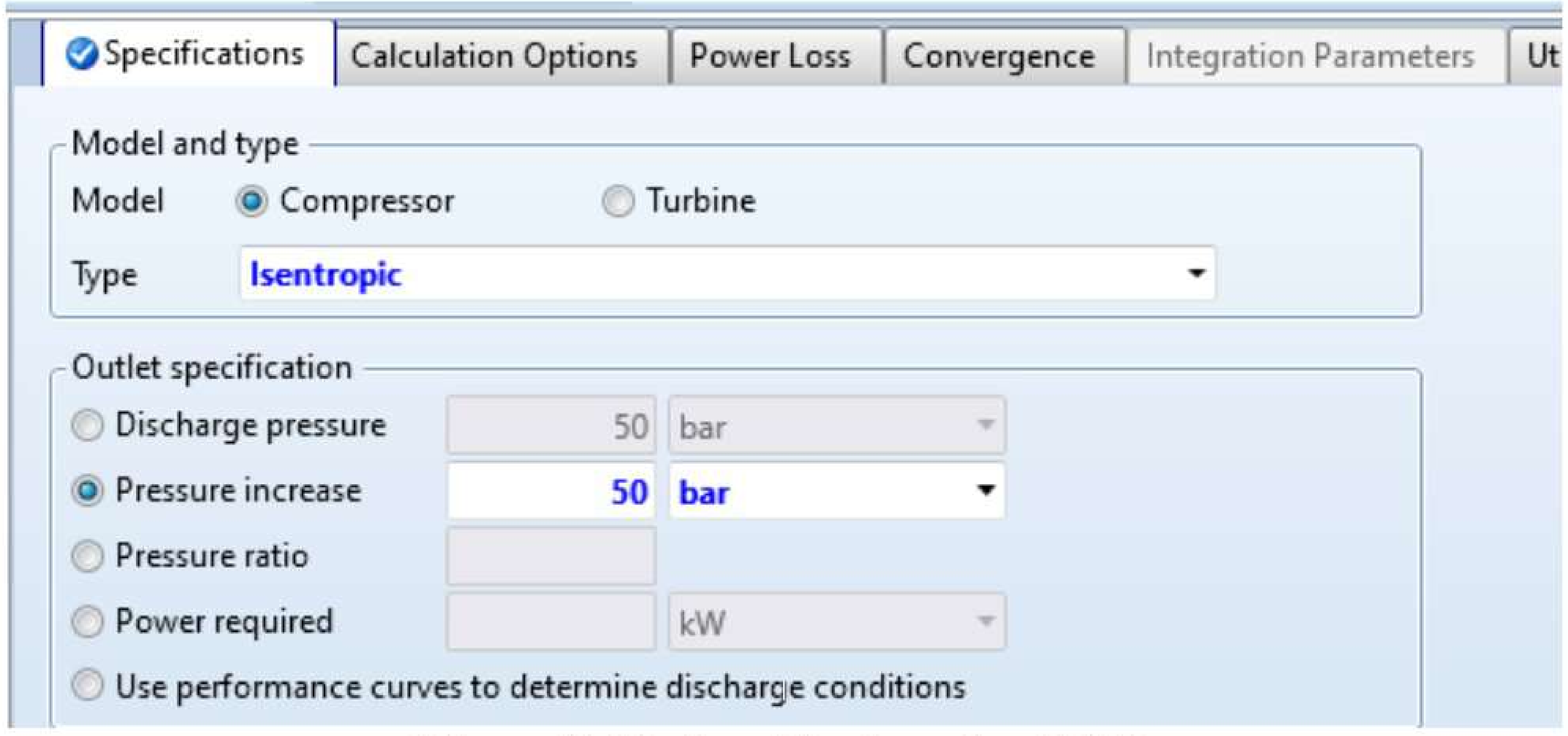
○ Power required kW

○ Use performance curves to determine discharge conditions

Figure 9-31: Specifications for C-102

9.11 C-103

Specify the type of compressor and pressure increase of 50 bar.



Model and type

Model ● Compressor ○ Turbine

Type Isentropic

Outlet specification

○ Discharge pressure 50 bar

● Pressure increase 50 bar

○ Pressure ratio

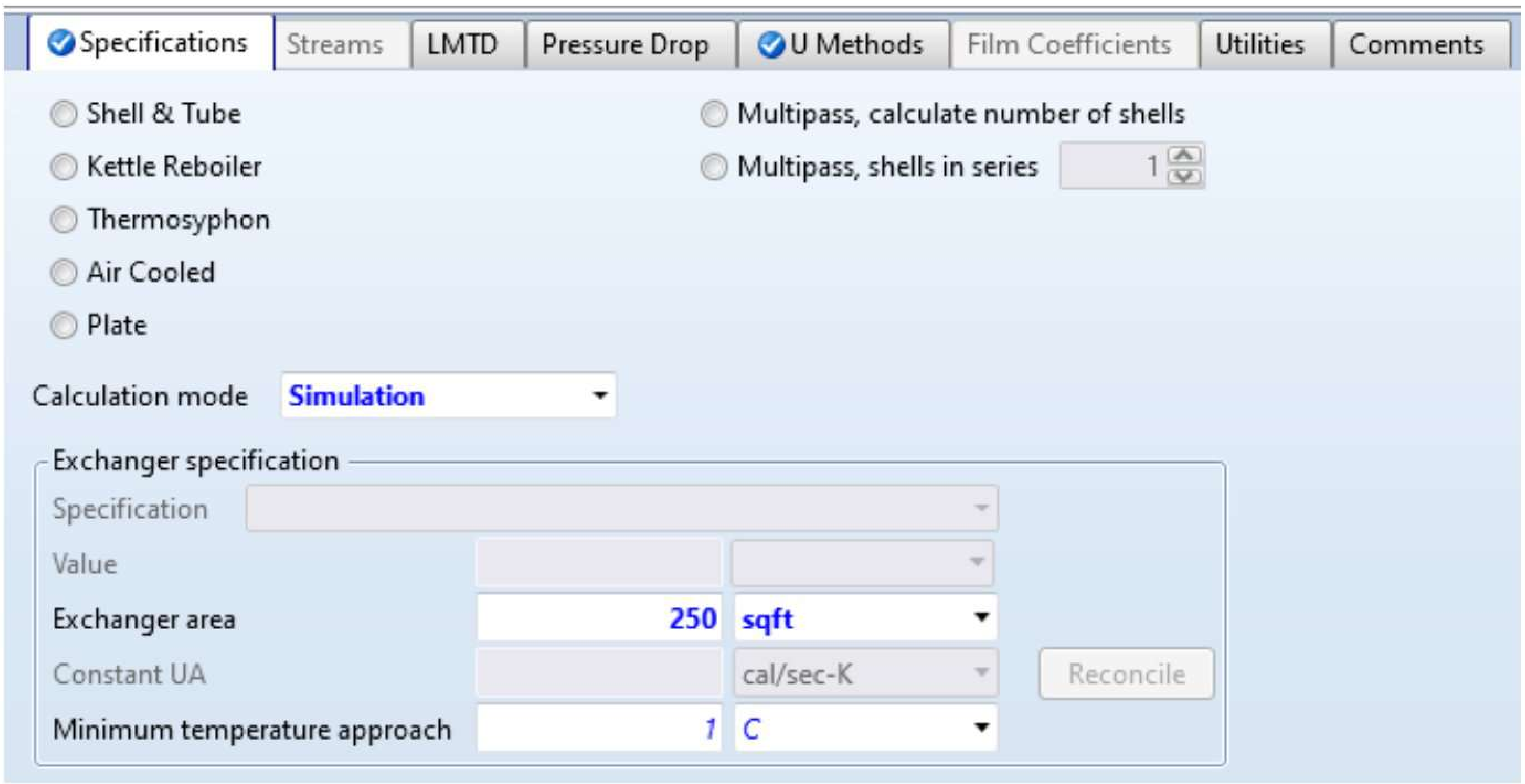
○ Power required kW

○ Use performance curves to determine discharge conditions

Figure 9-32: Specifications for C-103

9.12 Heat Exchanger (E-101):

Specify the conditions for heat exchangers E-101 to E-106 as shown in figure below. Set calculation mode to Simulation and area 250 ft^2.



○ Shell & Tube
○ Kettle Reboiler
○ Thermosyphon
○ Air Cooled
○ Plate

○ Multipass, calculate number of shells
○ Multipass, shells in series 1

Calculation mode: Simulation

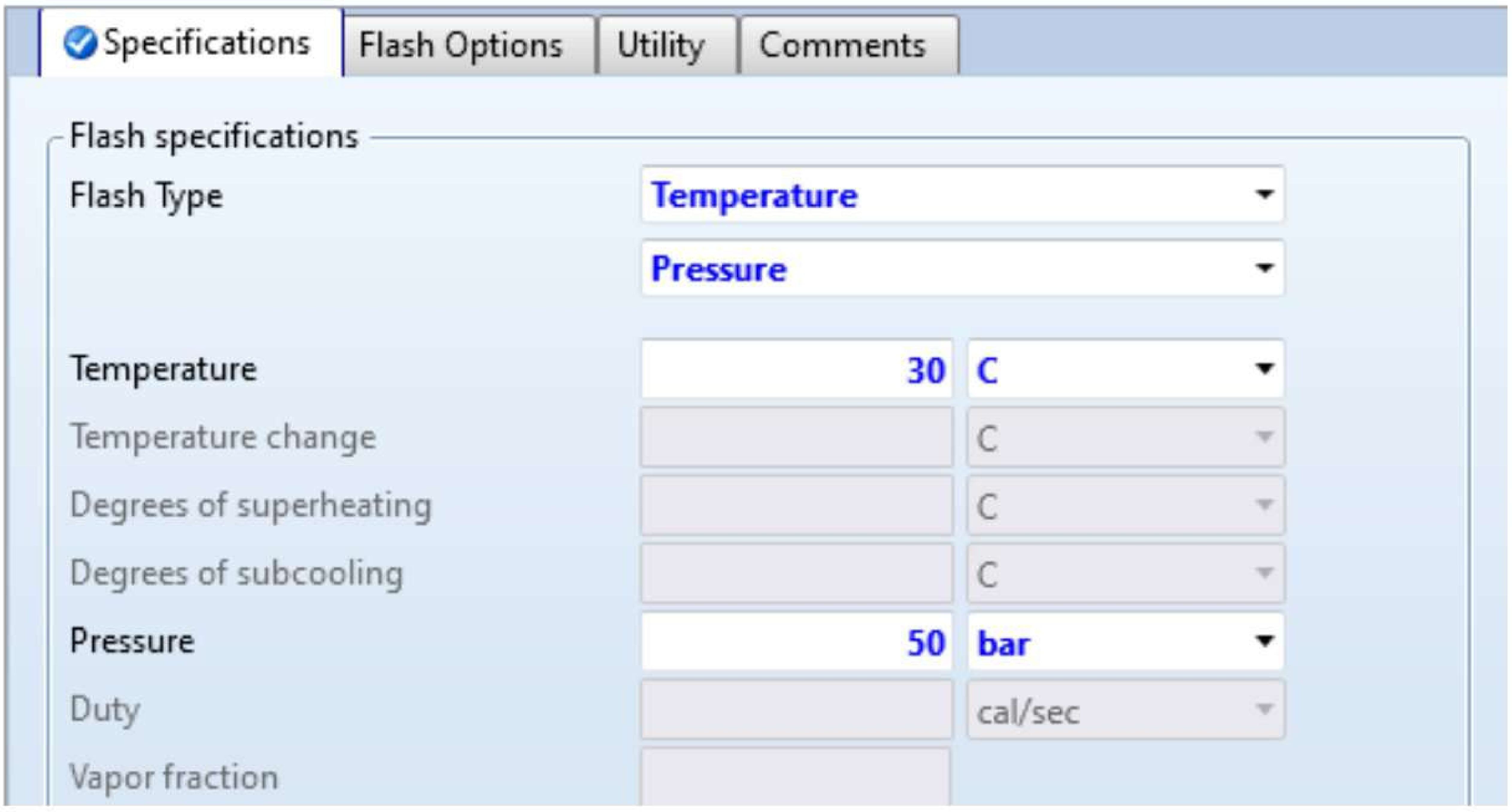
Exchanger specification

Specification		
Value		
Exchanger area	250	sqft
Constant UA		cal/sec-K
Minimum temperature approach	1	C

Figure 9-33: Specifications for E-101

9.13 Heat Exchanger (E-102):

Specify the temperature and Pressure of heat exchanger E-102 30^{O}C and 50 bar.



Flash specifications

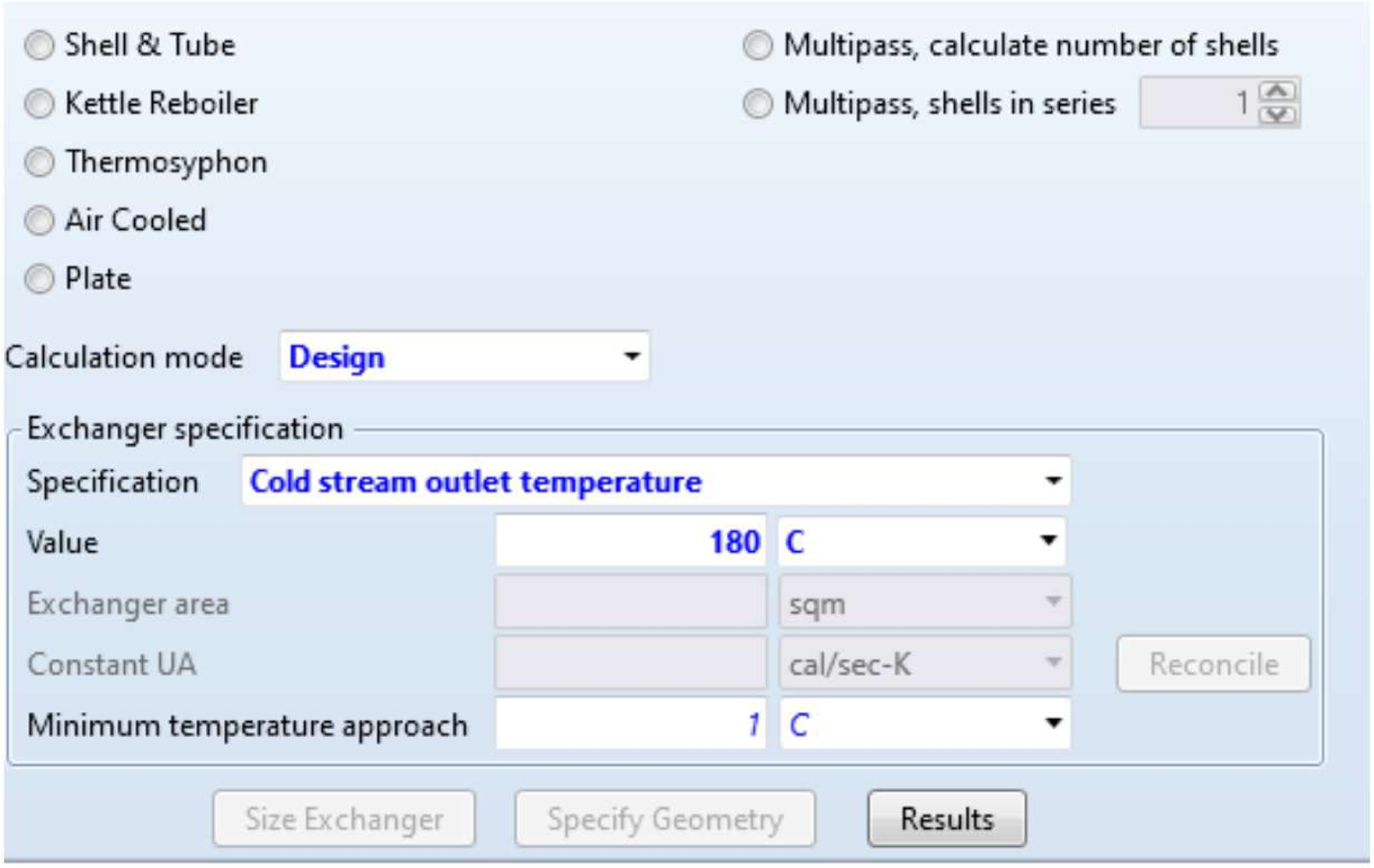
Flash Type: Temperature, Pressure

Temperature	30	C
Temperature change		C
Degrees of superheating		C
Degrees of subcooling		C
Pressure	50	bar
Duty		cal/sec
Vapor fraction		

Figure 9-34: Specification of E-102

9.14 Heat Exchanger (E-103):

Set calculation mode to simulation and Exchanger area 250ft^2.



○ Shell & Tube
○ Kettle Reboiler
○ Thermosyphon
○ Air Cooled
○ Plate
○ Multipass, calculate number of shells
○ Multipass, shells in series 1

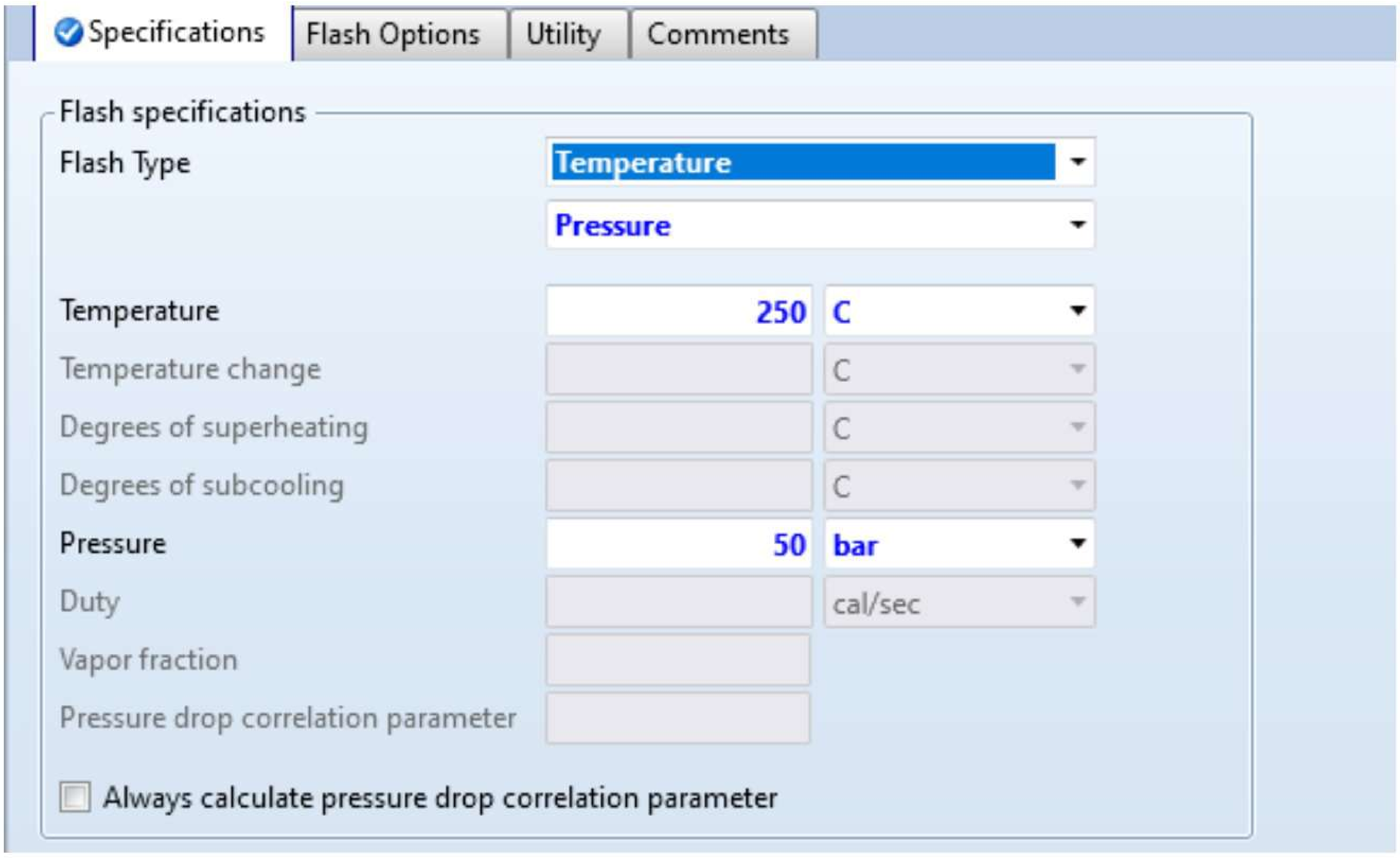
Calculation mode: Design

Exchanger specification

Specification	Cold stream outlet temperature	
Value	180	C
Exchanger area		sqm
Constant UA		cal/sec-K
Minimum temperature approach	1	C

9.15 Heat Exchanger (E-104):

Enter Specification of E-104 temperature 250^{O}C and Pressure of 50 bar.



Flash specifications

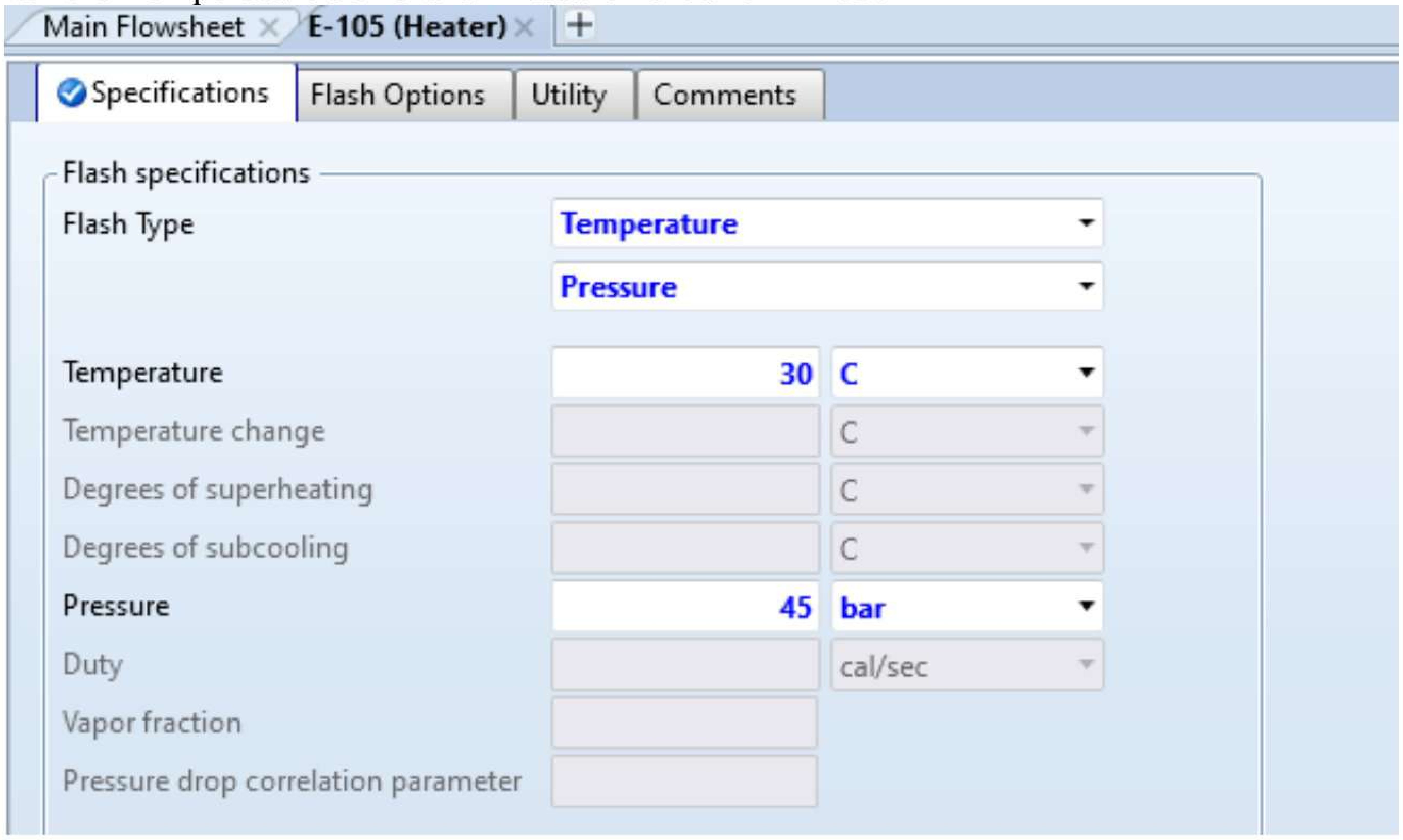
Flash Type	Temperature	
	Pressure	
Temperature	250	C
Temperature change		C
Degrees of superheating		C
Degrees of subcooling		C
Pressure	50	bar
Duty		cal/sec
Vapor fraction		
Pressure drop correlation parameter		

☐ Always calculate pressure drop correlation parameter

Figure 9-35: Specifications of E-104

9.16 Heat Exchanger (E-105):

Enter the Temperature 30^{O}C and Pressure 45 bar of E-105.



Flash Type: Temperature, Pressure

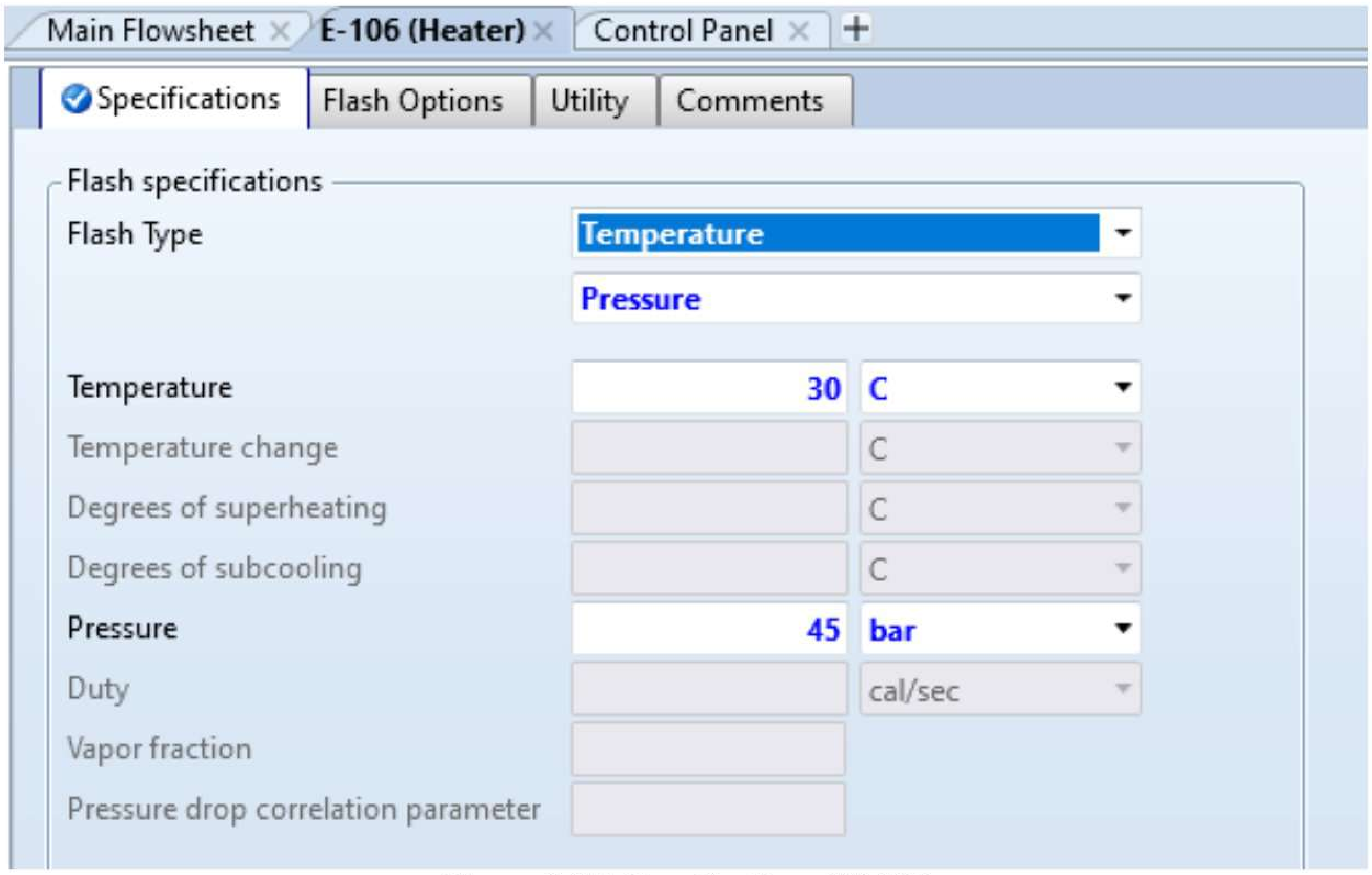
Temperature: 30 C

Pressure: 45 bar

Figure 9-36: Specifications of E-105

9.17 Heat Exchanger (E-106):

Enter the Temperature 30^{O}C and Pressure 45 bar.



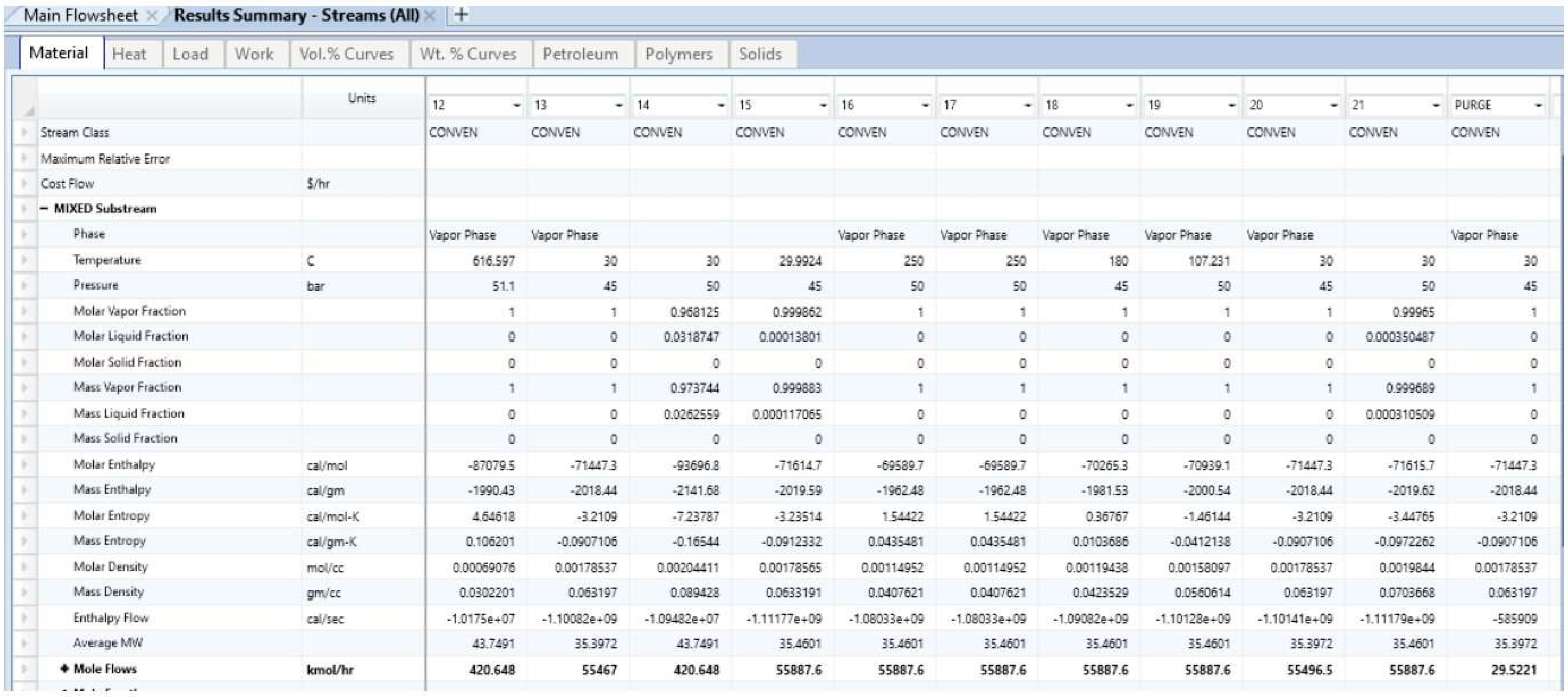
Flash Type: Temperature, Pressure

Temperature: 30 C

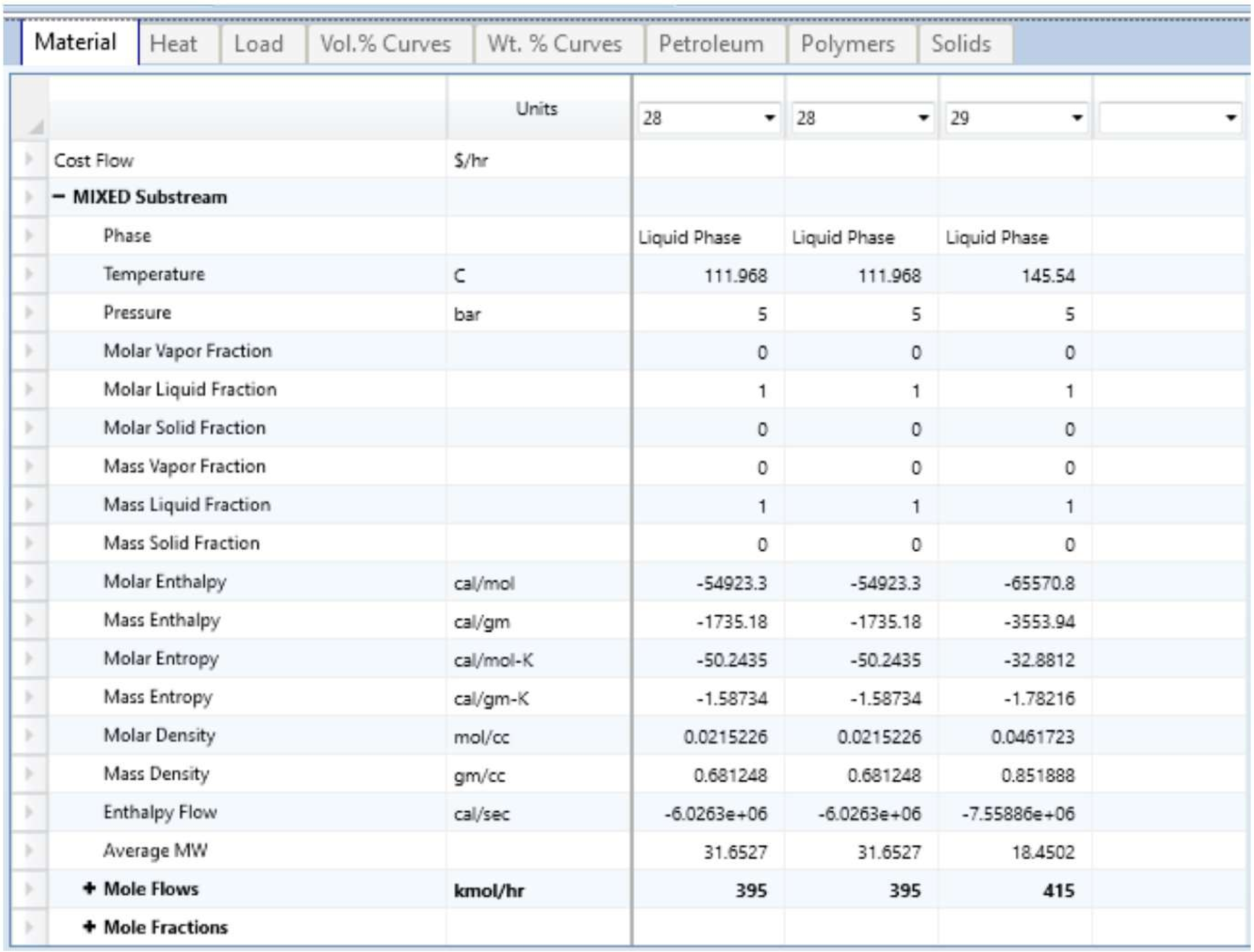
Pressure: 45 bar

Figure 9-37: Specification of E-106

9.18 Results:



	Units	12	13	14	15	16	17	18	19	20	21	PURGE
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error												
Cost Flow	$/hr											
− MIXED Substream												
Phase		Vapor Phase	Vapor Phase			Vapor Phase	Vapor Phase	Vapor Phase	Vapor Phase	Vapor Phase		Vapor Phase
Temperature	C	616.597	30	30	29.9924	250	250	180	107.231	30	30	30
Pressure	bar	51.1	45	50	45	50	50	45	50	45	50	45
Molar Vapor Fraction		1	1	0.968125	0.999862	1	1	1	1	1	0.99965	1
Molar Liquid Fraction		0	0	0.0318747	0.00013801	0	0	0	0	0	0.000350487	0
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	0.973744	0.999883	1	1	1	1	1	0.999689	1
Mass Liquid Fraction		0	0	0.0262559	0.000117065	0	0	0	0	0	0.000310509	0
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	cal/mol	-87079.5	-71447.3	-93696.8	-71614.7	-69589.7	-69589.7	-70265.3	-70939.1	-71447.3	-71615.7	-71447.3
Mass Enthalpy	cal/gm	-1990.43	-2018.44	-2141.68	-2019.59	-1962.48	-1962.48	-1981.53	-2000.54	-2018.44	-2019.62	-2018.44
Molar Entropy	cal/mol-K	4.64618	-3.2109	-7.23787	-3.23514	1.54422	1.54422	0.36767	-1.46144	-3.2109	-3.44765	-3.2109
Mass Entropy	cal/gm-K	0.106201	-0.0907106	-0.16544	-0.0912332	0.0435481	0.0435481	0.0103686	-0.0412138	-0.0907106	-0.0972262	-0.0907106
Molar Density	mol/cc	0.00069076	0.00178537	0.00204411	0.00178565	0.00114952	0.00114952	0.00119438	0.00158097	0.00178537	0.0019844	0.00178537
Mass Density	gm/cc	0.0302201	0.063197	0.089428	0.0633191	0.0407621	0.0407621	0.0423529	0.0560614	0.063197	0.0703668	0.063197
Enthalpy Flow	cal/sec	-1.0175e+07	-1.10082e+09	-1.09482e+07	-1.11177e+09	-1.08033e+09	-1.08033e+09	-1.09082e+09	-1.10128e+09	-1.10141e+09	-1.11179e+09	-585909
Average MW		43.7491	35.3972	43.7491	35.4601	35.4601	35.4601	35.4601	35.4601	35.3972	35.4601	35.3972
+ Mole Flows	**kmol/hr**	**420.648**	**55467**	**420.648**	**55887.6**	**55887.6**	**55887.6**	**55887.6**	**55887.6**	**55496.5**	**55887.6**	**29.5221**



	Units	28	28	29	
Cost Flow	$/hr				
− MIXED Substream					
Phase		Liquid Phase	Liquid Phase	Liquid Phase	
Temperature	C	111.968	111.968	145.54	
Pressure	bar	5	5	5	
Molar Vapor Fraction		0	0	0	
Molar Liquid Fraction		1	1	1	
Molar Solid Fraction		0	0	0	
Mass Vapor Fraction		0	0	0	
Mass Liquid Fraction		1	1	1	
Mass Solid Fraction		0	0	0	
Molar Enthalpy	cal/mol	-54923.3	-54923.3	-65570.8	
Mass Enthalpy	cal/gm	-1735.18	-1735.18	-3553.94	
Molar Entropy	cal/mol-K	-50.2435	-50.2435	-32.8812	
Mass Entropy	cal/gm-K	-1.58734	-1.58734	-1.78216	
Molar Density	mol/cc	0.0215226	0.0215226	0.0461723	
Mass Density	gm/cc	0.681248	0.681248	0.851888	
Enthalpy Flow	cal/sec	-6.0263e+06	-6.0263e+06	-7.55886e+06	
Average MW		31.6527	31.6527	18.4502	
+ Mole Flows	**kmol/hr**	**395**	**395**	**415**	
+ Mole Fractions					

10 Chapter NO 10: Instrumentation and Control

10.1 Introduction:

Automated measurement and control (AMC) is the science of instrumentation. There are many applications of AMC in research, industry and everyday life. From vehicle engine control systems (ECCs) to home thermostats (HVACs), to aircraft autopilots (Aeroplanes), to pharmaceutical medication production (Pharmaceuticals), automation is everywhere. Therefore, selecting the most efficient measuring method is an essential first step in the development and formulation process control system. In manual control, the process variable is read on a regular basis by an operator and the input is adjusted up or down so that the desired temperature is reached. In non-critical applications, where any process condition occurs slowly and in small increments, and where the operator's attention needs to be kept low, manual control is used. In automated control, all measurements and adjustments are made automatically. The reasons why automation is so popular in industry today are as follows.

- Product quality enhancement
- Increase in the manufacturing rate's process yield
- Boost employee and equipment safety.
- Economic savings in materials and time
- Enhancement of working conditions
- Manual control does not allow for the completion of the procedure.

10.2 Objectives of Instrumentation and Control System:

The following are the goals of the Instrumentation and Control System:

- Suppressing and eliminating external disruptions
- Maintain the process's stability.
- Optimize the functioning of the process

10.3 Components of Control System:

Following are the components of Control System

- Process
- Measuring Element
- Process Variable
- Controller

10.4 Process:

A process is any activity or combination of operations that results in the intended end result.

10.5 Measuring Element:

Like other parts of your control system, your measuring element is probably the most important. If you don’t take the right measurements, everything else in your control system won’t work as it should. You also want the measured variable to match the intended conditions in the process.

10.6 Process Variable:

Control of process variables is essential for the efficient operation of a process. Process variables are described as changes in the conditions of process materials or process equipment. The main process variables are temperature (in degrees Celsius), pressure (in degrees Kelvin), flow (in degrees Fahrenheit), and liquid level (in degrees Celsius). There is another dozen or so less common process variables, such as chemical composition (in degrees centigrade), viscosity (in degrees centimeter), density (in degrees centimetres), humidity (in degrees centimeters), moisture content, etc.

Measurement is a fundamental requirement for process control whether it is automated, semi-automated, or manual. An automated control measures, corrects, and changes the four main categories of process variations.

- Temperature measurements
- Pressure measurements
- Flow rate measurements
- Level measurements

There are several types of measuring devices for temperature, pressure, flow, and level.

Table 10-1: Temperature, pressure, flow, and level devices for measuring.

Measured Process Variable	Measuring Devices	Comments
Temperature	• Thermocouples, • Thermometer, • Thermistor, • Bimetallic • Thermometers,	Most frequently used for radiation pyrometers with low temperatures High-temperature applications

	• Radiation Pyrometers	
Pressure	• Manometers • Bourdon tube • Elements Bellow • Elements Strain • Gauges • Capsule gauges • Thermal conductivity • Gauge • McLeod gauge	Based on the elastic deformation of materials, floats or displacers are used. Pressure is converted to an electrical signal using this device. For the purpose of measuring vacuum
Flowrate	• Orifice plate • Venture flow nozzle • Pitot tube • Turbine flow meter • Hot wire anemometry • Positive displacement • Mass flowmeter	Pressure decrease over a flow restriction is measured. Positive displacement and mass flowmeters for Quantity Flowmeters with High Precision
Liquid Level	• Float actuated devices • Displacer devices Liquid head pressure devices Dielectric measurement	This two-phase system works effectively when combined with different kinds of indicators and signal converters. The Method of Indirect Hydrostatic Pressure

- **Temperature Measurement and Control:**

Readings of temperature are utilized to manage the output and intake temperatures. Flows in heat exchangers, reactors, and other similar devices. Thermocouples are used in the majority of temperature measurements in the industry to simplify delivering the measurement to a centralized place. For local measurements of equipment, Bimetallic or Filled System Thermometers are used to a lesser extent. Resistance Thermometers with high measurement precision are employed. All of the meters are protected by Thermo-Walls when used locally to protect against atmospheric elements and other physical conditions.

• Pressure Measurement and Control:

Pressure, like temperature, is a variable that indicates the condition and composition of a substance. In fact, when taken together, these two metrics are the fundamental evaluation devices for industrial materials. Pressure measurements are extremely important in the reactor. Pressure measurement devices (PMDs) are connected to process equipment that is associated with pressure variations in the process material, resulting in pressure measurements that are used as an indicator of energy gain or loss. In industry, the majority of pressure measurements are conducted with elastic element devices, which are either connected to one another for local application or sent to a centralised location. The most widely used industrial PMD type is the Bourdon tube (Bordord tube) or Diaphragm Bellows.

• Flow Measurement and Control:

Flow measurement typically uses the same method of pressure measurement, which is the sensing device connected to the DP cell. However, other flow meters can be used for specific applications, for example, when no external disturbance is present in the fluid flow, as in the case of a magnetic flow meter. Flow indicator controllers control the volume of the liquid. All manually configured streams also require some type of flow indication or some simple mechanism for regular sampling.
In industrial applications, flow measurement is typically performed using variable head devices. The variables are used to a lesser degree, and the various accessible types are used when specific measurement scenarios arise.

• Controller:

The controller is a mechanism responsible for reacting to any method of fault detection. The output of the controller is a pre-defined function of the fault. The final control element receives the output of the controller and modulates the energy input of the process according to a specific relationship.

10.7 Type of Controls:

In industry, several sorts of controls are utilized depending on the requirements and individual demands. They span from very simple controls to highly complicated systems, and may be divided into two primary categories:

- ➢ Feed forward control
- ➢ Feed Backward control

Feed forward control:

A feedback control, as the name indicates, operates on the same principle. When any input to a system is modified, it causes changes in the system that are referred to as "disturbances." These disruptions are recorded, and corrective action is conducted on the input to reverse the effect of the alteration.

Advantages:

- It is not necessary to identify and measure the disruption.
- Insensitive to modelling flaws.
- Changes in parameters have no effect

Disadvantages:

- After irregularities have been detected, control action is done.
- Unsatisfactory due of a lengthy and considerable dead time procedure.
- It has the potential to cause instability in the closed-loop response.

Feed Backward Control:

Adjusts the value of manipulated variables based on direct measurement of disturbances.

Advantages:

- It takes action before the disruption has even reached the system.
- It's great for systems that are slow or have a lot of idle time.
- It doesn't make the control system unstable.

Disadvantages:

- It necessitates the identification of all potential disruptions as well as their immediate measurement.
- unmeasured disturbances Cannot be handled
- Sensitive to changes in process parameters.
- It is not possible to eliminate steady-state offset.
- It necessitates a thorough understanding of the process model.

10.8 Cascade Control Loop:

Where there are two control loops that modify each other’s S.P., and one control element’s output influences the output of another control element. Control loop is used in situations where feedback control or feed front control is insufficient for efficient and rapid control. Feedback control loop is often called the initial loop.

10.9 Component of Control System:

The primary components of a control system are as follows:

- ### Measuring devices:

The measuring element, as with other elements of the control system, is likely to be the most important. Failure to measure accurately will impede the functioning of the other components of the system; furthermore, the measured parameter is selected to correspond to the intended conditions of the process.

- ### Transducer:

A device that interprets and/or processes standardized instrumentation signals to create a new signal.

- ### Transmission Lines:

Transmission lines are used to transfer measurement information from a measuring instrument to a controller. Transmission lines were originally pneumatic (carrying pressurized air or liquid), but with the advent of electronic analogue controllers, and in particular, the growing use of digital computers, transmission lines now transmit electrical signals.

- ### Amplifier:

Sometimes the signal from a measuring device is really weak and can't be sent over long distances. That's when the transmission cables are equipped with amplifiers that make the signal stronger.

- ### Controller:

The controller is the system that reacts to any kind of fault detection. The output of the controller is the result of the error.

- ### Final Control Element:

The end-to-end control element receives the controller signal and modulates the energy output to the process according to a defined relationship

.Control Schemes of Distillation Column:

The altered variables might be any one or a combination of the following.

- Steam flow rate to Reboiler
- Reflux Rate
- Overhead product withdrawn rate
- Bottom product withdrawn rate
- Water flow rate to condenser

10.10 Loads or Disturbances:

The following are examples of typical disruptions.

- Flow rate of feed
- Composition of feed
- Temperature of feed
- Pressure drops of steam across Reboiler
- Inlet temperature of water for condenser

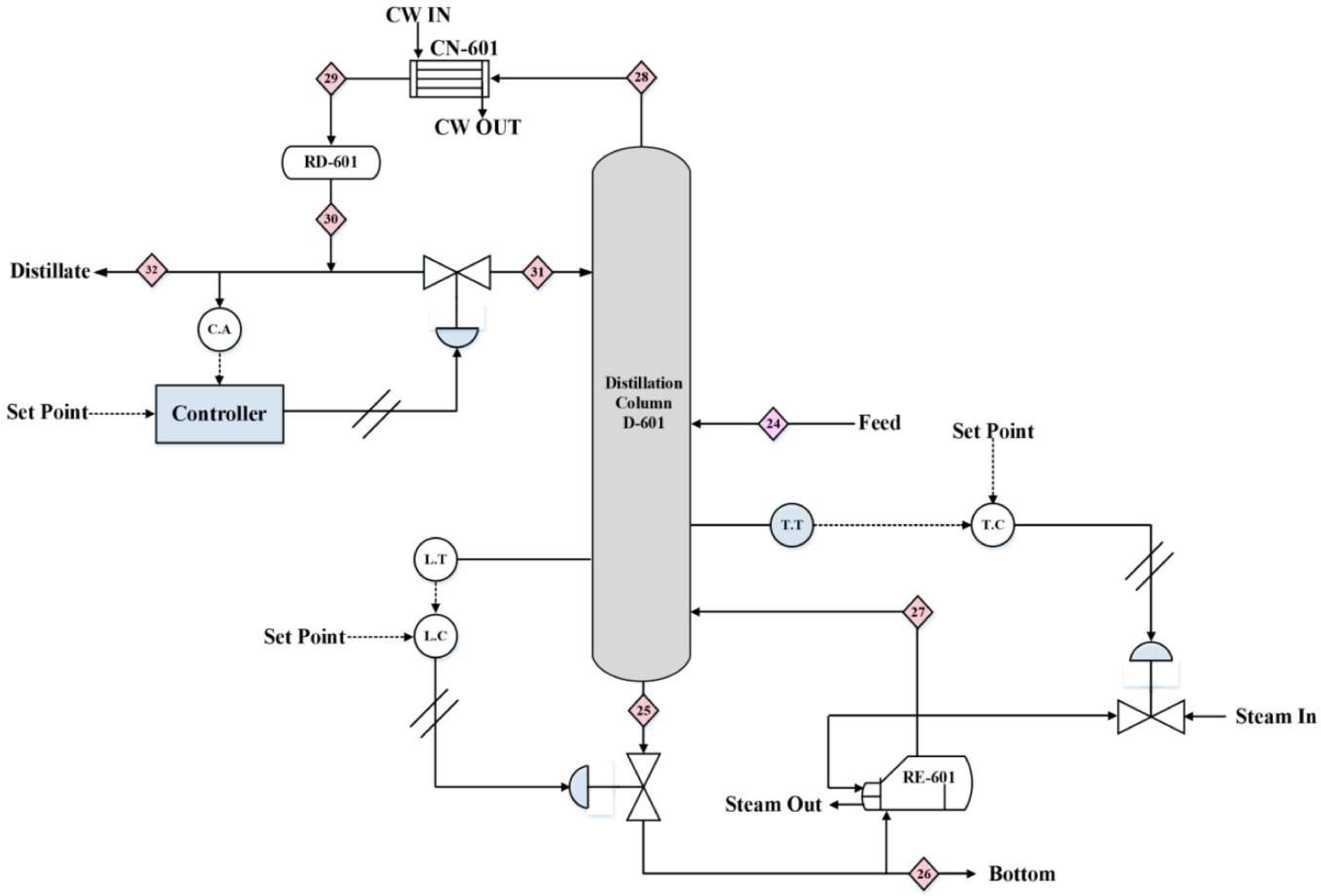


Figure10-1: Distillation Column Control Configuration

10.11 Control on Distillation Column:

Temperature Control:

The temperature is measured by the thermocouple at the base of a distillation column. The transducer converts the signal type detected into an electric signal. The electrical signal is then sent to a PID controller. The PID controller checks the process value against the set temperature. The controller will follow the instructions given by the final control element, a valve, if the process temperature is different from the set temperature.

Table 10-2: Temperature Control Process

Process	**Distillation**
Controller	PID Controller
Controller Variable	Temperature (At bottom of Distillation Column)
Manipulating Variable	Steam flow rate
Measuring Element	Thermocouple
Final Control Element	Valve
Set Point	95 ºC

- ### Composition Control:

The composition analyser will sense or measure the distillate's composition, and the transducer will transform the kind of signal and deliver it to the controller. It will compare the measured composition to the predefined point and respond based on the divergence. The final control device, in this case a reflux valve, will enforce this action.

Table 10-3: Composition Control Process

Process	**Distillation**
Controller	PID Controller
Controller Variable	Distillate Composition
Manipulating Variable	Reflux Ratio
Measuring Element	Composition Analyzer
Final Control Element	Reflux Valve
Set Point	99.6 mol% $CH3OH$

- ### Level Control:

The magnetic level sensor detects the level at the base of the column. The transducer converts the type of signal to an electrical signal and transmits it to the controller. The controller compares the signal to the specified value and arranges the final control element according to the deviation.

Table 10-4: Level Control Process

Process	Distillation
Controller	PID Controller

Controller Variable	Liquid Level at the bottom
Manipulating Variable	Bottom product flowrate
Measuring Element	Magnetic Level Sensor
Final Control Element	Valve (Bottom Product)
Set Point	Changes in input flow rate or feed temperature, changes in gas-to-liquid ratio, and valve characteristics

11 Chapter NO 11: HAZOP STUDY

11.1 HAZOP:

The most frequent and well accepted systematic qualitative hazard assessment approach is HAZOP. HAZOP can be used to a whole facility, a production unit, or a piece of equipment. It may be used to both new and existing infrastructures. As a database, HAZOP relies on the judgment of engineers and safety specialists in the areas they are most familiar with. It is based on standard plant and process data. The final HAZOP result is thus trustworthy in terms of engineering and operational expectations, but it is not quantitative and may not account for the effects of complicated human mistake sequences.[28]

11.2 Objectives of HAZOP study:

- A HAZOP study's aims can be described as follows:
- To locate (areas in the design that might provide a substantial threat).
- To discover and investigate design aspects that impact the likelihood of a failure.
- There is a dangerous situation taking place.
- To acquaint the research team with the available design information.
- To guarantee that the regions of substantial hazard are studied in a methodical manner
- To find important design information that the team doesn't have access to right now.[29]

11.3 HAZOP Study Guide Words and Meanings:

Table 11-1: Guide Words for HAZOP Study

Guide Words	Meanings
No	Negation of design intent
Less	Quantitative Decrease
More	Quantitative Increase
Part off	Qualitative Increase
As well as	Qualitative Decrease
Reverse	Logical opposite of the intent
Other than	Complete substitution

11.4 Hazard and Operability Studies:

Hazard and Operability Studies (HAZOPs) are an essential part of any accident prevention plan. A HAZOP is a critical, systematic review of a process by a group of engineers and operators to evaluate the risk of malfunctions or malfunctions of individual equipment and the consequences on the entire facility. It is common practice to conduct safety audits. These can take a variety of shapes. Experts can be consulted individually, without regard for one another. Instead, they could be gathered in long meetings to discuss a specific topic. In order to enhance efficiency, the structure of the HAZOP meeting should be different, and the structure imposes a particular organization. HAZOPs are a generic research method that can be used in any process, such as microchip production, pharma synthesis, sewage treatment plant operation, etc. However, they should not be used as a cure-all or as the end-all. It does not replace existing codes of practice, but rather adds to them. It cannot, however, completely replace experience. However, both Codes of Practice and experience are the result of real-world situations. Innovative developments necessitate a thorough examination of the unknown. HAZOP is a method of determining problems that is both systematic and illogical. [30]

11.5 Types of HAZOP:

- Process HAZOP:

The HAZOP approach was created to evaluate plants and process systems in the first place.

- Human HAZOP:

A group of specialized HAZOPs referred to as a "family." Human mistakes are being emphasized more than technical failures.

- Procedure HAZOP:

SAFOP - SAF operation Study – is a term used to describe a review of procedures or operational sequences.

- Software HAZOP:

Errors in software development are identified and corrected.

11.6 Success or Failure of HAZOP:

The HAZOP’s success or failure is dependent on a number of factors:

- The accuracy and completeness of the drawings and other information used as the basis for the study.
- The technical skills insights of the team.
- The team's capacity to apply the Asian aid approach to their imaginations in terms of conceptualizing variations, drivers, and outcomes.
- The team's capacity to focus on the more significant risks that are identified.
- It's all done in a neat and organized way, and it's useful to know what the terms mean. [31,32]

11.7 Steps to conduct HAZOP study:

The steps of a HAZOP investigation are as follows:

1. Description of the purpose, objective, and scope of the study. The purpose of the study may be to evaluate an existing plant or to evaluate the risk associated with an existing unit. Depending on the purpose and circumstances of the study, the above-mentioned goals can be further refined. The physical unit's limits, as well as the range of events and variables studied, define the study's scope. For example, HAZOPs used to be solely focused on fire and explosion endpoints, but now they often contain toxic release, disagreeable odor, and environmental endpoints as well.
2. Select a HAZOP research group. The team leader needs to be familiar with HAZOP and human-centered methods to facilitate good team collaboration. The team should have as many diverse experts as possible to address all aspects of design, operations, process chemistry and safety. The team leader should review the HAZOP methodology with the team and emphasize that the ultimate objective of the HAZOP survey “is to identify hazards”; finding solutions to problems is a separate activity. [33,34]
3. The following items are frequently required

- Gather Information
- Description of the procedure
- Flowcharts for processes
- Every raw material, intermediate and final product has chemical, physical and toxicological properties.
- Diagrams of piping and instruments (P&IDs)
- Specifications for equipment, pipelines, and instruments
- Logic diagrams for process control
- Drawings for the layout

- Operating procedures are a set of rules that govern how things are done.
- Procedures for routine maintenance
- Procedures for dealing with emergencies

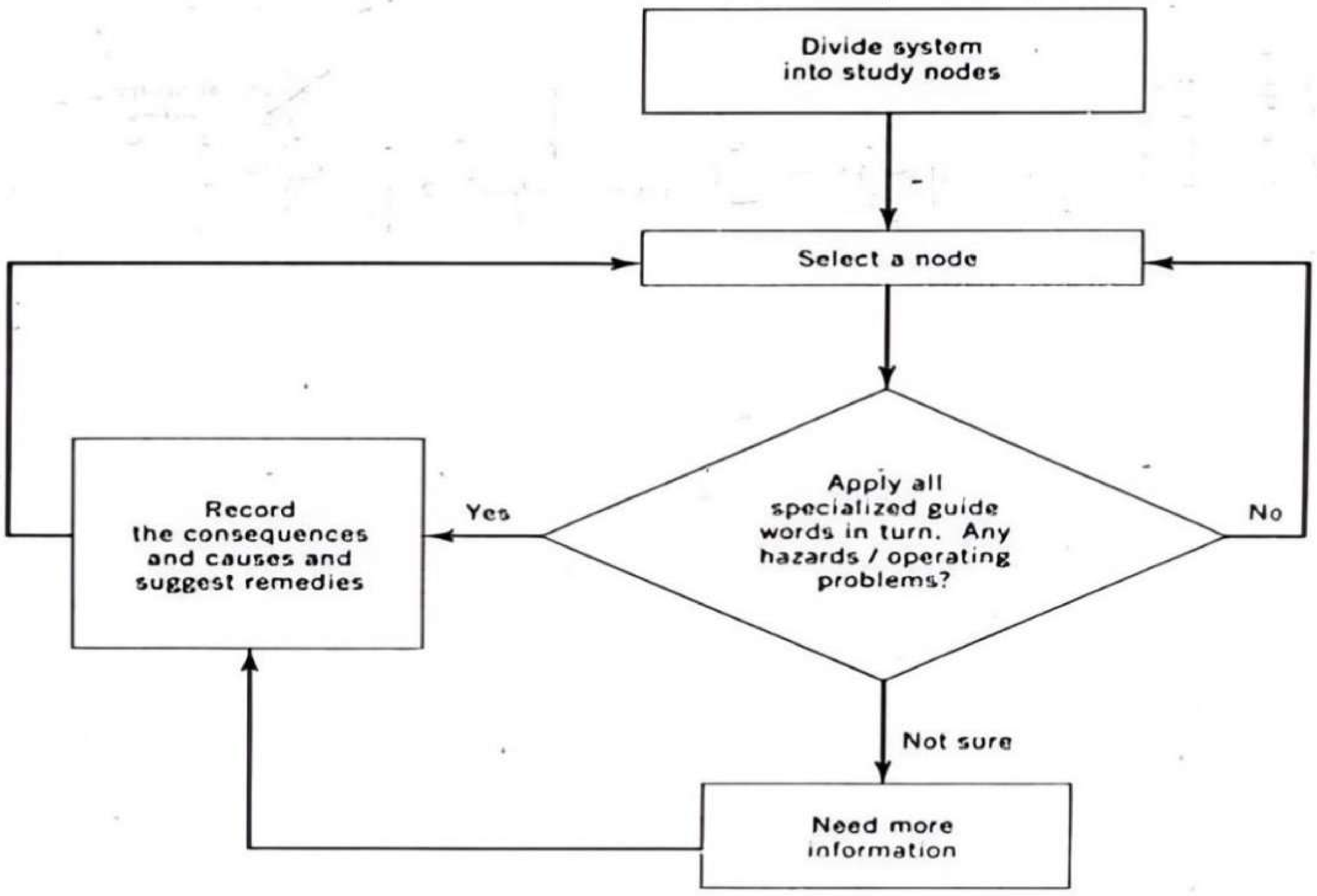


Figure 11-1: Hazop Method Flow Diagram [35]

4. Carry out the research. The unit is split into study "nodes" using the data obtained, and the procedure shown in Figure 1 is followed for each node. Process nodes are places in the process where known and desired values for process parameters (pressure, temperature, composition, and so on) exist. The functioning of various pieces of equipment, such as distillation columns, heat exchanges, and pumps, causes these values to fluctuate between nodes. To assist arrange the node process parameters and control logic information, several forms and work sheets have been designed.
5. At its core, HAZOP research involves a cycle of iteration through this process, where each parameter is evaluated for how and why it could deviate from the planned parameters and the associated impacts.
6. Prepare a report. The study should reveal as much information as possible concerning events and their consequences. Clearly, if the HAZOP detects a not-too-improbable sequence of circumstances that might lead to a disaster, suitable follow-up action is required. Although risk reduction activity is not part of the HAZOP, it may be required as a result of the HAZOP.
7. HAZOP studies take a long time and are costly. Bringing an older plant's P&IDs up to date might be a big technical undertaking. Even yet, when weighed against the possible loss of life,

property, business, and even the survival of the company that a catastrophic spill may cause, they are cost effective. [36]

11.8 HAZOP study on Distillation Column:

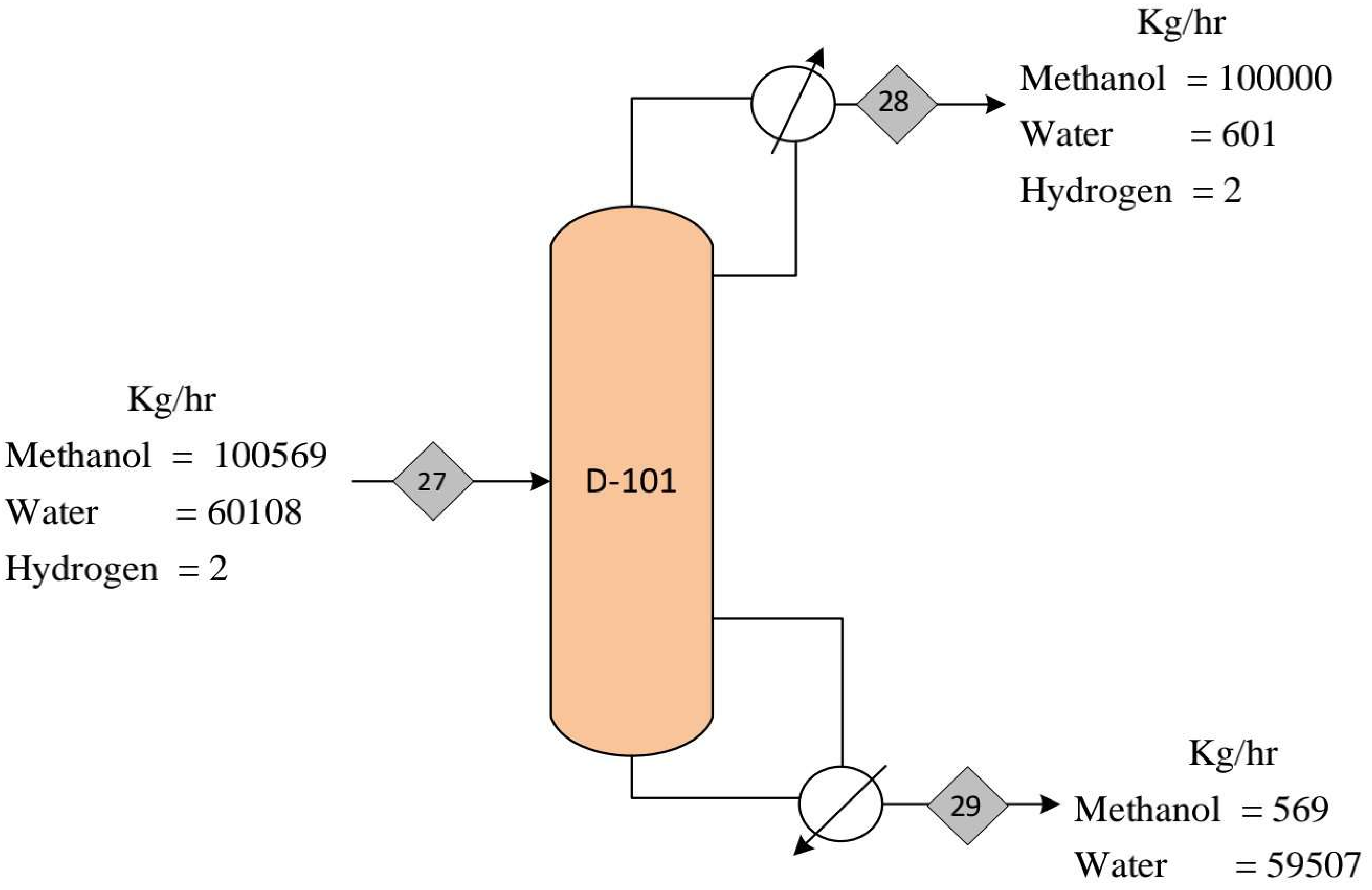


Figure 11-2: Distillation Column (D-101)

Table 11-2: Hazop on Distillation Column

Process parameter	Deviation (guide word)	Possible causes	Possible consequences	Action required
Flow	No	Pipe damage or clogging	The loss of input into the column (D-601) results in the required output.	Schedule inspection.
Flow	High	Source of high pressure.	(D-601) Flooding in the distillation column	-
Flow	Low	Pipe is partially plugged or leaking.	Level decrease in thevessel.	Scheduling inspection. Install valve.

Temperature	Low	High condenser incoming flow (E-007)	Low level within the Reboiler (RE-601).	Scheduling inspection.
Temperature	Low	High incoming flow from Condenser (E-007)	Low level within the Reboiler (RE-601) Non-standard product.	Inspection schedule. Install temperature sensors.
Pressure	More	Valve close	Line over pressure	Compressor failure
Flow	More	Reboiler (RE-601) high level Leakage in Condenser (CN-601) (CN-601)	Level high in condenser (CN-601)	Level controller (LLC)

11.9 HAZOP study of Heat Exchanger (HX-101):

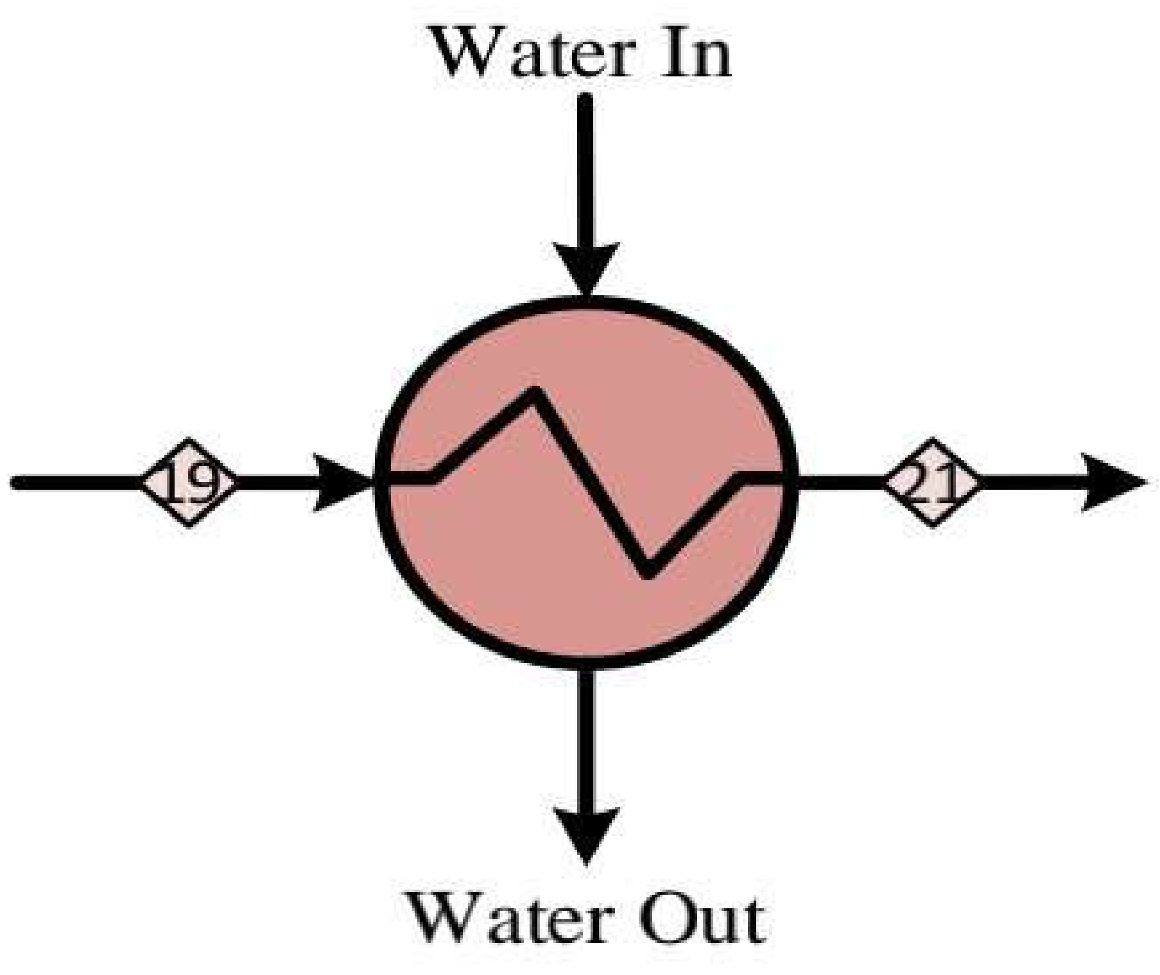


Figure 11-3: Heat Exchanger (HX-103)

Table 11-3: Hazop on Heat Exchanger

Process Parameter	Guide Word	Deviation	Possible Causes	Possible Consequences	Required Action
Temperature	Less	Less flow of cooling water in heat exchanger (HX-301)	Pipe clogging	The process fluid's temperature remains constant.	High-temperature warning

Temperature	More	More cooling water flow in the heat exchanger (HX-301)	Cooling water valve failure	The temperature of the process fluid falls.	Low temperature waring
Pressure	More of	Increased pressure on the tube side	Process fluid valve failure	Heat exchanger tube bursting (HX-301)	Install high pressure alarm
Temperature	None	No cooling water flow in heat exchanger (HX-301)	Failure to open the intake cooling water valve	The temperature of the process fluid is not reduced appropriately.	Fit a temperature gauge before and after the process fluid line.
Flow	Reverse	Reverse process fluid flow	Failure of process fluid inlet valve	Product off set	Install check valve

12 Chapter NO 12: Assessment Environmental Impact

12.1 Environmental Impact Assessment:

Environmental Impact Assessment (EIA) is a process that evaluates the potential effects of human activities on the recipient environment, including development projects. It also examines how the environment's potentials and limitations affect the planned human activities. The EIA process is a systematic and thorough way of collecting comprehensive data on the social, economic and environmental impacts of a development proposal. The data collected during the EIA process are then used by the relevant environmental authority to determine whether or not to proceed with a development proposal. [37]

An Environmental Impact Assessment (EIA) evaluates the possible effects (both positive and negative) of public and private development initiatives. The focus is often on the environmental effect (biophysical), but in excellent practice, social and economic concerns are also taken into account. Dams, industrial facilities, transportation infrastructure (e.g., airport runways, roads), agricultural activities, and natural resource extraction are examples of EIA projects. (e.g. sand extraction). [38]

12.2 Methanol:

Methanol, also known as CH_3OH, is an organic compound made up of 4 parts hydrogen, 1 part oxygen, and 1 part carbon. It's the simplest compound in the alcohol family. Methanol is water soluble and can be biodegraded. It is a clean-burning, environmentally friendly fuel that's becoming increasingly attractive as an alternative fuel for cars, ships, cooking, and heating homes.

The purpose of an environmental impact report (EIA) is to look at the pros and cons of any planned public or private development projects. Usually, the focus is on the environmental impact (biophysical), but good practice also looks at social and economic impacts. Examples of EIA projects are dams, industrial sites, transportation infrastructure (like airports and highways), agriculture, and natural resources (like sand mining). [39]

12.3 Exposure to Methanol:

Because methanol is poisonous, even a single exposure can result in severe and perhaps deadly acute toxic consequences. As a result, the main worry is acute exposure from any primary source. Signs and symptoms may not be obvious at first. The time lag between exposure and the start of symptoms may result in misdiagnosis, particularly for people who are unaware of their exposure or do not comprehend the toxicity or variations between methanol toxicity, ethanol toxicity, and isopropyl alcohol toxicity. [40]

12.4 Reactivity Profile:

Methanol reacts Methanol has a strong reaction with acetyl bromide. It can also cause an explosion when it is mixed with concentrated sulphuric acid or hydrogen peroxide. Methyl Hypochlorite (MCH) When MCH reacts with a hypochloric acid in water, or a mixture of water/carbon Tetrachlorides, MCH is formed. MCH decays in the cold, and may explode if exposed to sunlight or heat. Chlorine (Chlorine) . Under basic circumstances, it can react explosively with isocyanates. This reaction is slowed down by the presence of an inert solvent. In a mixing cylinder, methyl alcohol and bromine had a strong exothermic reaction. When a flask of anhydrous lead perchlorate dissolved in methanol was disturbed, it exploded. Methanol reacts aggressively with P_4O_6. When ethanol or methanol comes into touch with a platinum-black catalyst, it can ignite. [41]

12.5 Skin, and Eye Irritations:

Methanol has a mild irritant effect on the skin. Methanol may be absorbed via the skin, and this route of entry has been linked to negative consequences. The effects are similar to those discussed in the "inhalation" section. Methanol is a mild to severe irritant to the eyes. Irritation, tearing, and burning are caused by high vapor concentrations or liquid contact with the eyes.[42]

12.6 First Aid:

First aid is a form of temporary medical treatment administered to an exposed individual prior to referral to a medical professional. It is imperative to act promptly if medical assistance is needed.

12.7 Eyes:

If contact is made with the eyes, they should be flushed with a sufficient amount of lukewarm water for a minimum of 20 minutes. The eyelids should be separated during the flushing process to guarantee that all available eye tissues and the eyelids are exposed to the water.

12.8 Skin:

In the case of skin contact, the affected area should be flushed with a sufficient amount of lukewarm water for a minimum of 15 minutes, followed by an emergency eye washing or safety shower. Clothing and footwear that has been contaminated should be cleaned in the shower. With soap and water, thoroughly clean the area. If symptoms of irritation or discomfort persist or symptoms of poisoning appear, seek medical attention. Before using infected clothing and footwear, it is recommended to wash them first.

12.9 Inhalation:

In the event of inhaling methanol fumes, it is essential to move the patient to a clean environment as soon as possible, if feasible, and to maintain the patient's warmth and comfort. Monitor the patient for any symptoms of respiratory distress. If breathing becomes labored or ceases, administer artificial respiration or CPR immediately and seek medical assistance. If necessary, deliver supplemental oxygen with assisted breathing, if trained to do so.

12.10 Ingestion:

Methanol ingestion has the potential to be fatal. Symptoms may not appear for up to 36 hours after intake. Do not force yourself to vomit. Seek medical help right away. For many days, the person should be under strict medical supervision and monitoring.18

12.11 Spillage Disposal:

Evacuate the hazardous zone! Seek advice from a professional! Remove all sources of ignition. Personal protection includes full protective gear, as well as self-contained breathing apparatus. Do not flush down the toilet. This chemical must not be released into the environment. Fill a sealable container with the liquid that's leaking out. Then, use an inert absorbent to cover the spilled stuff. Depending on your state's laws, store and get rid of it.

12.12 Disposal Methods:

SRP - Contain and evaluate wastewater from Contaminant Suppression, Washing of Protective Clothing/Equipment, or Polluted Places for concentrations of Subject Chemicals or Decomposition Products. Concentrations need to be lower than what's allowed by the environmental discharge / disposal rules. Pretreatment &/or Discharge to an Approved Wastewater Treatment Facility is only allowed if the controlling body approves it and they're sure there won't be any 'pass through' infractions. Employee exposure (inhaling, cutting, and eating) and fate during Treatment, Transport, and Disposal should be taken into account. If this isn't possible, the chemical needs to be evaluated according to EPA 40 CFR part 261, specifically Title B, to figure out the right EPA, state, or federal disposal requirements.

This material is highly flammable, so it should be incinerated in a chemical combustion chamber with a burn source and scrubber. However, due to the combustibility of this material, caution should be exercised when lighting it. Non-recyclables and excess items should be offered to a certified disposal business. For the disposal of this product, it is recommended to contact a professional garbage disposal service. Unused packing should be disposed of as unused merchandise.

12.13 Handling and Storage:

- **Incompatible Materials**

Examples of hazardous materials include lead, aluminum, zinc; oxidizing agents; strong acids; strong bases; polyethylene; polyvinyl chloride; and nitrile.

- **Handling Procedures**

In the storage, usage, and handling areas, no smoking or open flames are permitted. Use electrical equipment that is explosion-proof. Make sure you're following correct electrical grounding techniques. Avoid making contact with your skin and eyes. Inhaling vapor or mist is not recommended.

- **Storage**

Store in equipment that is completely enclosed to prevent ignition and human touch. Grounding, venting, and vapors emission controls are required for all tanks. Diking is required for tanks. At room temperature, most metals are unaffected by anhydrous methanol. For the substance being housed, storage tanks should be designed and constructed according to good engineering practice. Plastics are acceptable for short-term storage but are not suggested for long-term storage.

12.14 Exposure Control and Personal Protection:

- **Ventilation**

If you want to meet the TLV/PEL criteria, make sure you have enough ventilation or exhaust to get the job done. If you're exposed to more than the PEL value, use the supplied air or a separate breathing device. Organic vapor cartridge respirators aren't recommended if you're exposed to methanol.

- **Footwear**

Chemical resistant as a minimum.

- **Work / Hygiene Practices**

Use a safety shower in the use area. Use eye wash after skin contact. Use soap and water immediately after contact. Monitor the workplace air to keep the methanol vapor content below the limit value (TLV).

- **Eye Protection**

Have chemical splash goggles or safety glasses on hand and wear them as needed (side shields preferred).

- **Skin Protection**

To avoid skin contact, rubber gloves and protective aprons or garments should be worn. Use impenetrable body covering and footwear for operators who may be exposed to spills or splashes.

- **Respiratory Protection**

To fulfil the TLV / PEL criteria, provide appropriate ventilation or exhaust. For exposures exceeding the PEL, supplied air or self-contained breathing apparatus is suggested. For methanol vapors exposure, organic vapors cartridge respirators are not advised.

- **Footwear**

Chemical resistant as a minimum.

- **Work / Hygiene Practices**

In the area of use, a safety shower and eye wash are recommended. After skin contact, immediately wash with soap and water. It is advised that the air in the workplace be monitored in order to keep methanol vapors below the permissible TLV.20. [43]

12.15 Personal Protective Equipment:

- **Eye/face protection:**

Eye protection and a face shield are essential. Use eye protection that has been tested and approved in accordance with regulatory requirements.

- **Body Protection:**

Chemical protection is the protection of the whole outfit. Flame retardant and anti-static clothing. The type of protective equipment to wear depends on the concentration and quantity of the chemical at the worksite.

- **Respiratory protection:**

As an alternative to engineering controls, it is recommended to utilize a full-face respiratory system equipped with multifunctional respiratory cartridge when risk assessment suggests that air-purifying respiratory systems are appropriate. If the respirator is the sole source of protection, it is advisable to utilize a fully-face supplied respiratory system. It is important to ensure that respirators and components are tested and approved in accordance with regulatory regulations.

12.16 Fire Prevention:

There will be no open fires, sparks, or smoke. Ventilation, explosion-proof electrical equipment, and lighting are all included in the closed system. Prevent electrostatic charges from accumulating (e.g., by grounding). Filling, discharging, or handling with compressed air is not recommended.

12.17 Regulatory Information:

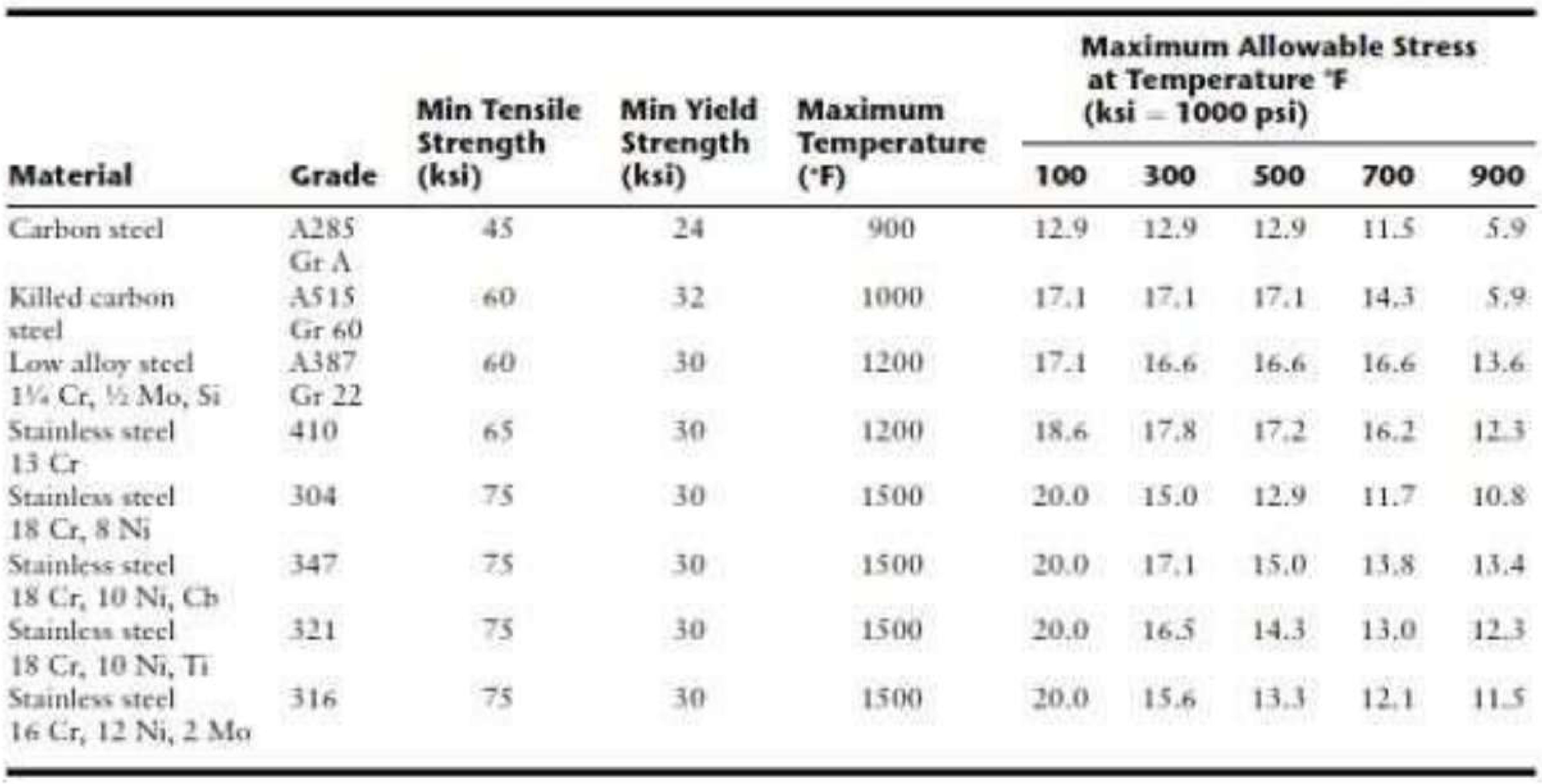
Methanol smells like alcohol, but you can't smell it until it's at or above 2,000 parts per million (ppm), which is 10 times higher than the human safe level of 200 ppm. Since the smell of methanol is a poor indicator of concentration, it's important to measure how much you're exposed. This is to make sure that workers' health isn't at risk, and to make sure you're following all the rules. This action sets out performance criteria for the synthetic organic chemical manufacturing industry's equipment leaks of VOC. The goal is to require all newly built, modified, and rebuilt SOCMI processes to use the most proven system for continuous emission reduction of VOC leaks in the equipment, taking into account costs, non-air quality health and environmental effects, and energy requirements. [44]

Appendices

Appendix-A

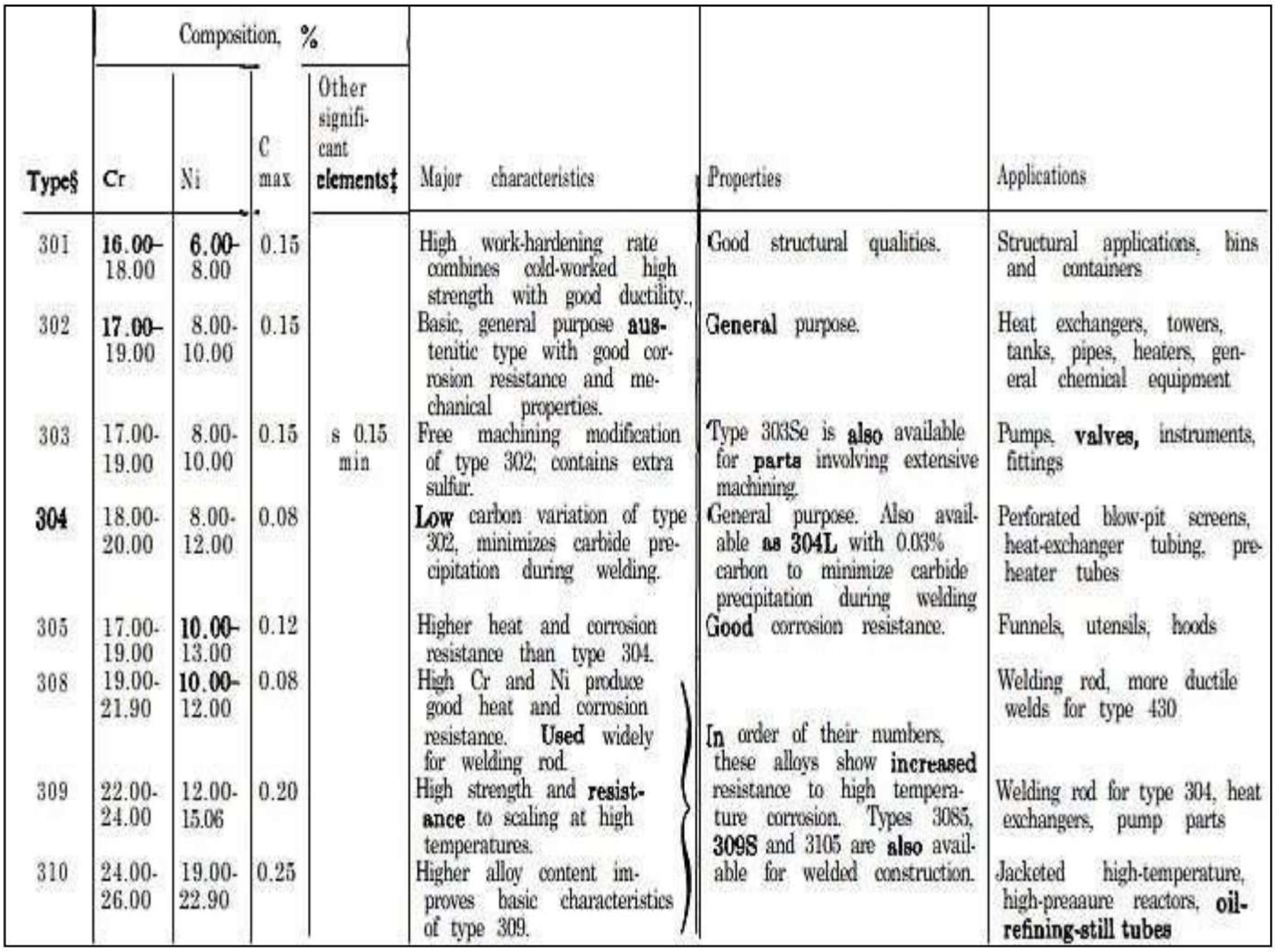
List of Tables

Table A-1: Maximum Allowable Stress



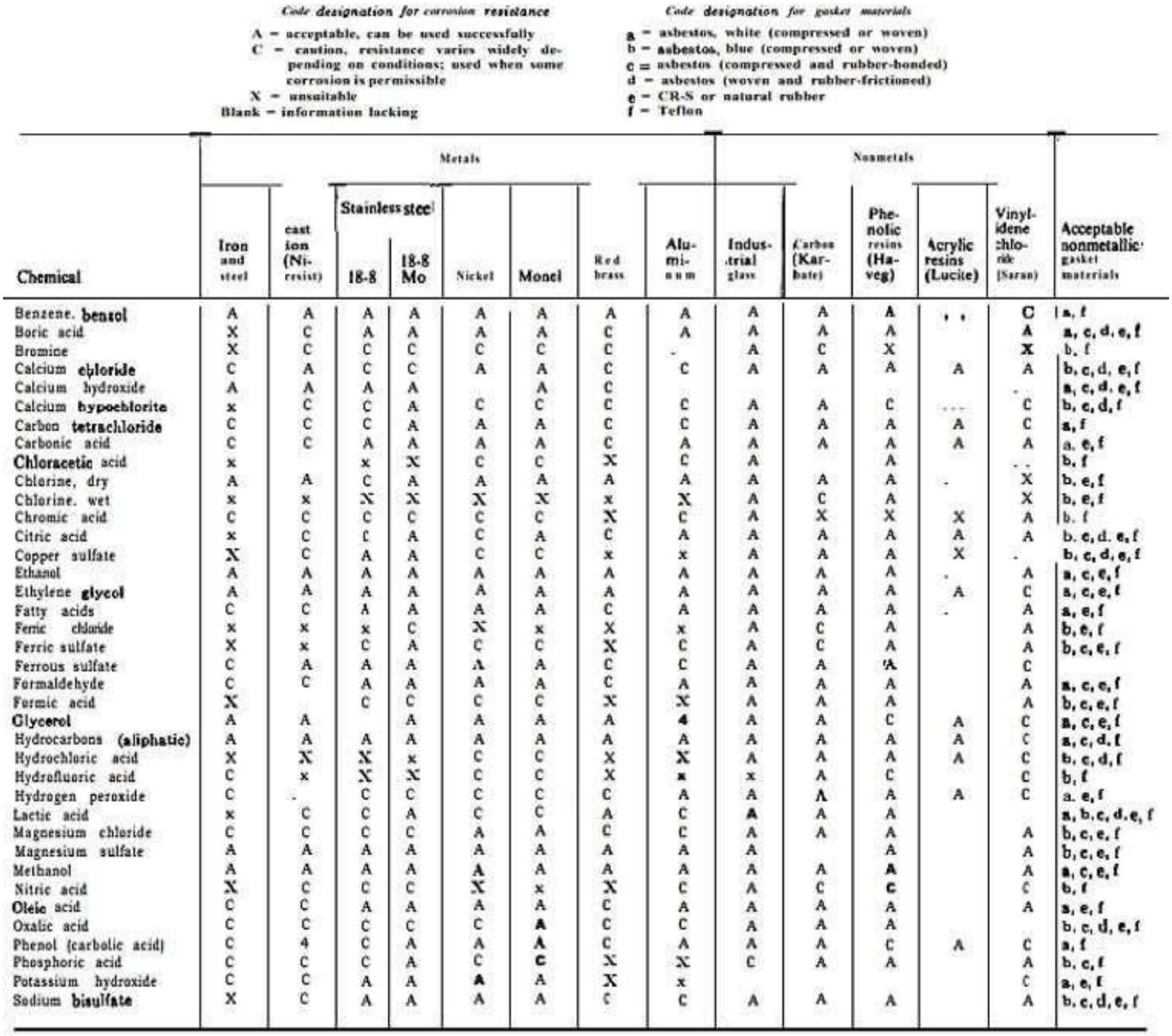
Material	Grade	Min Tensile Strength (ksi)	Min Yield Strength (ksi)	Maximum Temperature (°F)	Maximum Allowable Stress at Temperature °F (ksi = 1000 psi)				
					100	300	500	700	900
Carbon steel	A285 Gr A	45	24	900	12.9	12.9	12.9	11.5	5.9
Killed carbon steel	A515 Gr 60	60	32	1000	17.1	17.1	17.1	14.3	5.9
Low alloy steel 1¼ Cr, ½ Mo, Si	A387 Gr 22	60	30	1200	17.1	16.6	16.6	16.6	13.6
Stainless steel 13 Cr	410	65	30	1200	18.6	17.8	17.2	16.2	12.3
Stainless steel 18 Cr, 8 Ni	304	75	30	1500	20.0	15.0	12.9	11.7	10.8
Stainless steel 18 Cr, 10 Ni, Cb	347	75	30	1500	20.0	17.1	15.0	13.8	13.4
Stainless steel 18 Cr, 10 Ni, Ti	321	75	30	1500	20.0	16.5	14.3	13.0	12.3
Stainless steel 16 Cr, 12 Ni, 2 Mo	316	75	30	1500	20.0	15.6	13.3	12.1	11.5

Table A-4: Stainless Steels most commonly used in the Chemical Process Industries



	Composition, %						
Type§	Cr	Ni	C max	Other significant elements‡	Major characteristics	Properties	Applications
301	**16.00–18.00**	**6.00-8.00**	0.15		High work-hardening rate combines cold-worked high strength with good ductility.,	Good structural qualities.	Structural applications, bins and containers
302	**17.00–19.00**	8.00-10.00	0.15		Basic, general purpose **aus**tenitic type with good corrosion resistance and mechanical properties.	**General** purpose.	Heat exchangers, towers, tanks, pipes, heaters, general chemical equipment
303	17.00-19.00	8.00-10.00	0.15	s 0.15 min	Free machining modification of type 302; contains extra sulfur.	Type 303Se is **also** available for **parts** involving extensive machining.	Pumps, **valves,** instruments, fittings
304	18.00-20.00	8.00-12.00	0.08		**Low** carbon variation of type 302, minimizes carbide precipitation during welding.	General purpose. Also available **as 304L** with 0.03% carbon to minimize carbide precipitation during welding	Perforated blow-pit screens, heat-exchanger tubing, preheater tubes
305	17.00-19.00	**10.00-13.00**	0.12		Higher heat and corrosion resistance than type 304.	**Good** corrosion resistance.	Funnels, utensils, hoods
308	19.00-21.90	**10.00-12.00**	0.08		High Cr and Ni produce good heat and corrosion resistance. **Used** widely for welding rod.	In order of their numbers, these alloys show **increased** resistance to high temperature corrosion. Types 3085, **309S** and 3105 are **also** available for welded construction.	Welding rod, more ductile welds for type 430
309	22.00-24.00	12.00-15.06	0.20		High strength and **resistance** to scaling at high temperatures.		Welding rod for type 304, heat exchangers, pump parts
310	24.00-26.00	19.00-22.90	0.25		Higher alloy content improves basic characteristics of type 309.		Jacketed high-temperature, high-preaaure reactors, **oil-refining-still tubes**

Table A-7: Corrosion Resistance of Constructional Materials



Code designation for corrosion resistance

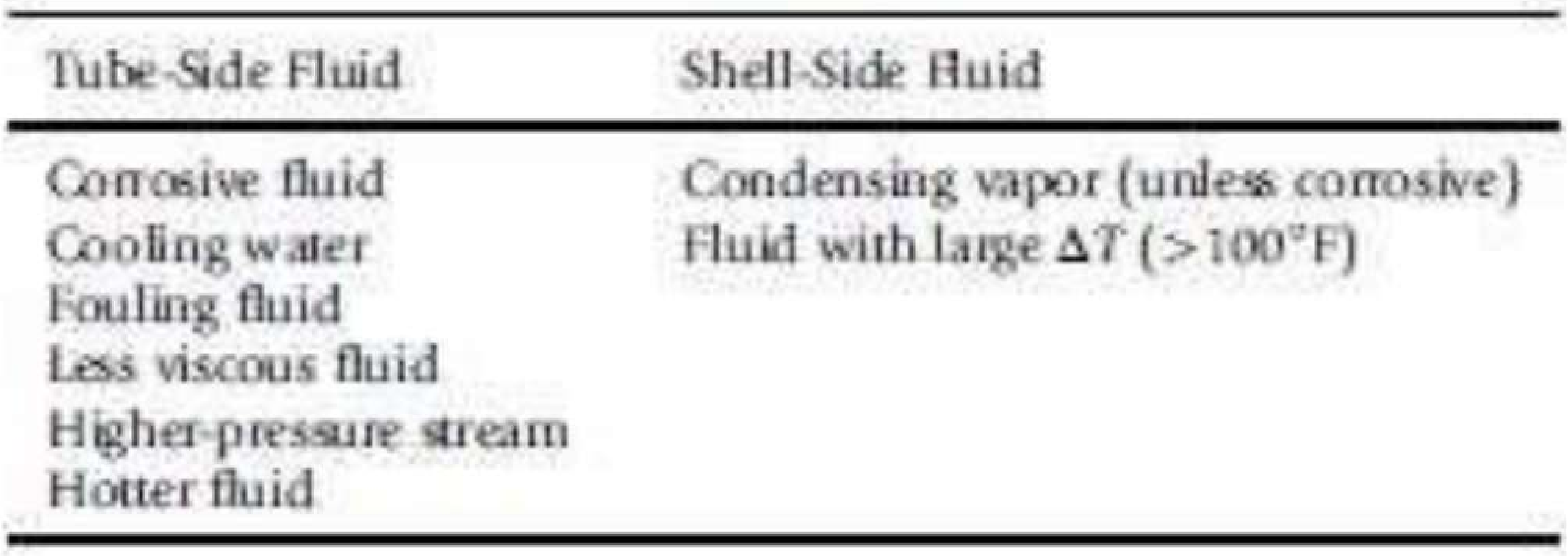
A = acceptable, can be used successfully
C = caution, resistance varies widely depending on conditions; used when some corrosion is permissible
X = unsuitable
Blank = information lacking

Code designation for gasket materials

a = asbestos, white (compressed or woven)
b = asbestos, blue (compressed or woven)
c = asbestos (compressed and rubber-bonded)
d = asbestos (woven and rubber-frictioned)
e = CR-S or natural rubber
f = Teflon

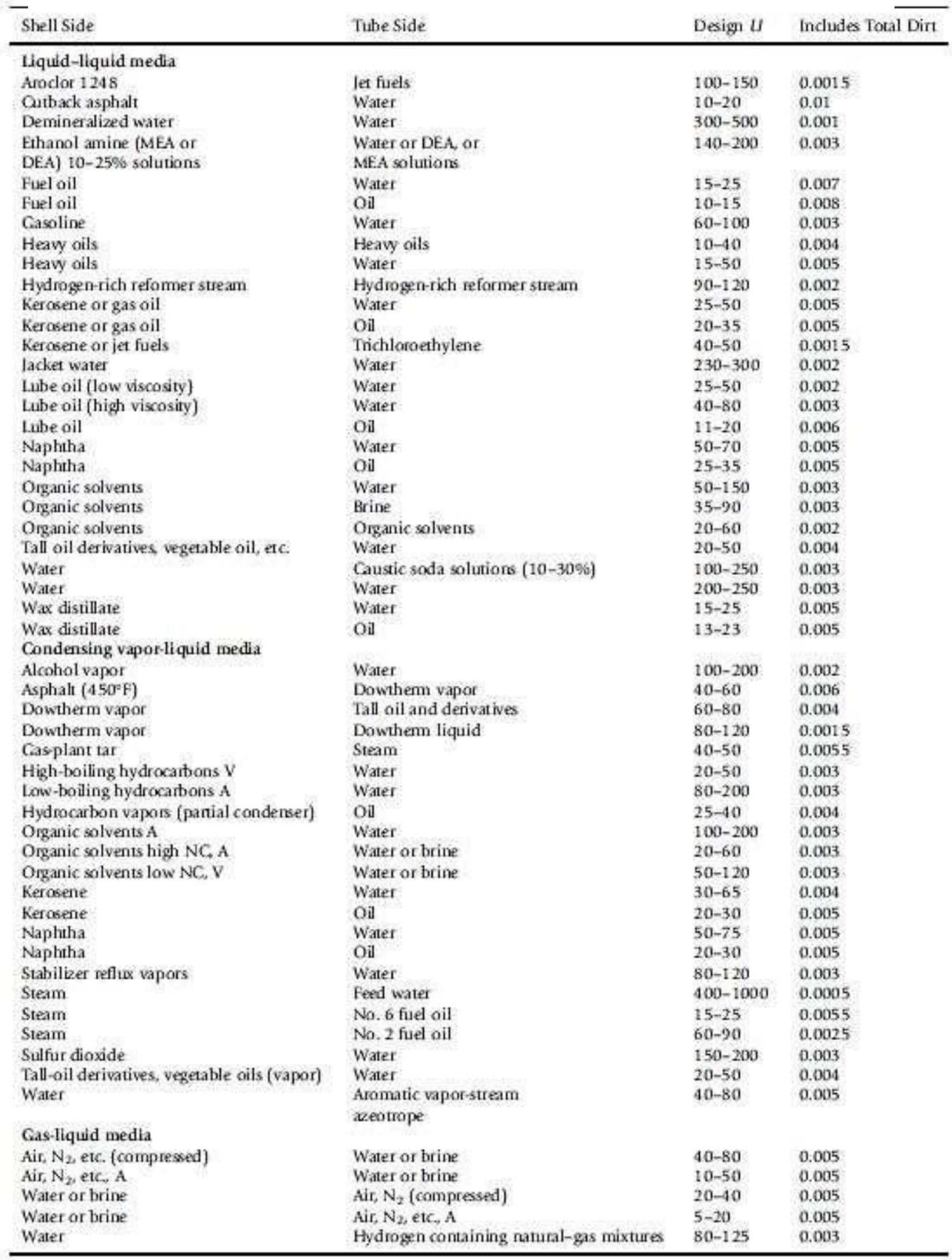
Chemical	Metals								Nonmetals					Acceptable nonmetallic gasket materials
			Stainless steel											
	Iron and steel	cast ion (Ni-resist)	18-8	18-8 Mo	Nickel	Monel	Red brass	Aluminum	Industrial glass	Carbon (Karbate)	Phenolic resins (Haveg)	Acrylic resins (Lucite)	Vinylidene chloride (Saran)	
Benzene, benzol	A	A	A	A	A	A	A	A	A	A	A	. .	C	a, f
Boric acid	X	C	A	A	A	A	C	A	A	A	A		A	a, c, d, e, f
Bromine	X	C	C	C	C	C	C	-	A	C	X		X	b, f
Calcium chloride	C	A	C	C	A	A	C	C	A	A	A	A	A	b, c, d, e, f
Calcium hydroxide	A	A	A	A		A	C						. .	a, c, d, e, f
Calcium hypochlorite	x	C	C	A	C	C	C	C	A	A	C	. . .	C	b, c, d, f
Carbon tetrachloride	C	C	C	A	A	A	C	C	A	A	A	A	C	a, f
Carbonic acid	C	C	A	A	A	A	C	A	A	A	A	A	A	a, e, f
Chloracetic acid	x		x	X	C	C	X	C	A		A		. .	b, f
Chlorine, dry	A	A	C	A	A	A	A	A	A	A	A	.	X	b, e, f
Chlorine, wet	x	x	X	X	X	X	x	X	A	C	A		X	b, e, f
Chromic acid	C	C	C	C	C	C	X	C	A	X	X	X	A	b, f
Citric acid	x	C	C	A	C	A	C	A	A	A	A	A	A	b, c, d, e, f
Copper sulfate	X	C	A	A	C	C	x	x	A	A	A	X	.	b, c, d, e, f
Ethanol	A	A	A	A	A	A	A	A	A	A	A	.	A	a, c, e, f
Ethylene glycol	A	A	A	A	A	A	A	A	A	A	A	A	C	a, c, e, f
Fatty acids	C	C	A	A	A	A	C	A	A	A	A	.	A	a, e, f
Ferric chloride	x	x	x	C	X	x	X	x	A	C	A		A	b, e, f
Ferric sulfate	X	x	C	A	C	C	X	C	A	C	A		A	b, c, e, f
Ferrous sulfate	C	A	A	A	A	A	C	C	A	A	'A		C	
Formaldehyde	C	C	A	A	A	A	C	A	A	A	A		A	a, c, e, f
Formic acid	X		C	C	C	C	X	X	A	A	A		A	b, c, e, f
Glycerol	A	A		A	A	A	A	4	A	A	C	A	C	a, c, e, f
Hydrocarbons (aliphatic)	A	A	A	A	A	A	A	A	A	A	A	A	C	a, c, d, f
Hydrochloric acid	X	X	X	x	C	C	X	X	A	A	A	A	C	b, c, d, f
Hydrofluoric acid	C	x	X	X	C	C	X	x	x	A	C		C	b, f
Hydrogen peroxide	C	.	C	C	C	C	C	A	A	A	A	A	C	a, e, f
Lactic acid	x	C	C	A	C	C	A	C	A	A	A			a, b, c, d, e, f
Magnesium chloride	C	C	C	C	A	A	C	C	A	A	A		A	b, c, e, f
Magnesium sulfate	A	A	A	A	A	A	A	A	A		A		A	b, c, e, f
Methanol	A	A	A	A	A	A	A	A	A	A	A		A	a, c, e, f
Nitric acid	X	C	C	C	X	x	X	C	A	C	C		C	b, f
Oleic acid	C	C	A	A	A	A	C	A	A	A	A		A	a, e, f
Oxalic acid	C	C	C	C	C	A	C	C	A	A	A			b, c, d, e, f
Phenol (carbolic acid)	C	4	C	A	A	A	C	A	A	A	C	A	C	a, f
Phosphoric acid	C	C	C	A	C	C	X	X	C	A	A		A	b, c, f
Potassium hydroxide	C	C	A	A	A	A	X	x					C	a, e, f
Sodium bisulfate	X	C	A	A	A	A	C	C	A	A	A		A	b, c, d, e, f

Table A-10: Criteria for Fluid Placement, in order of Priority



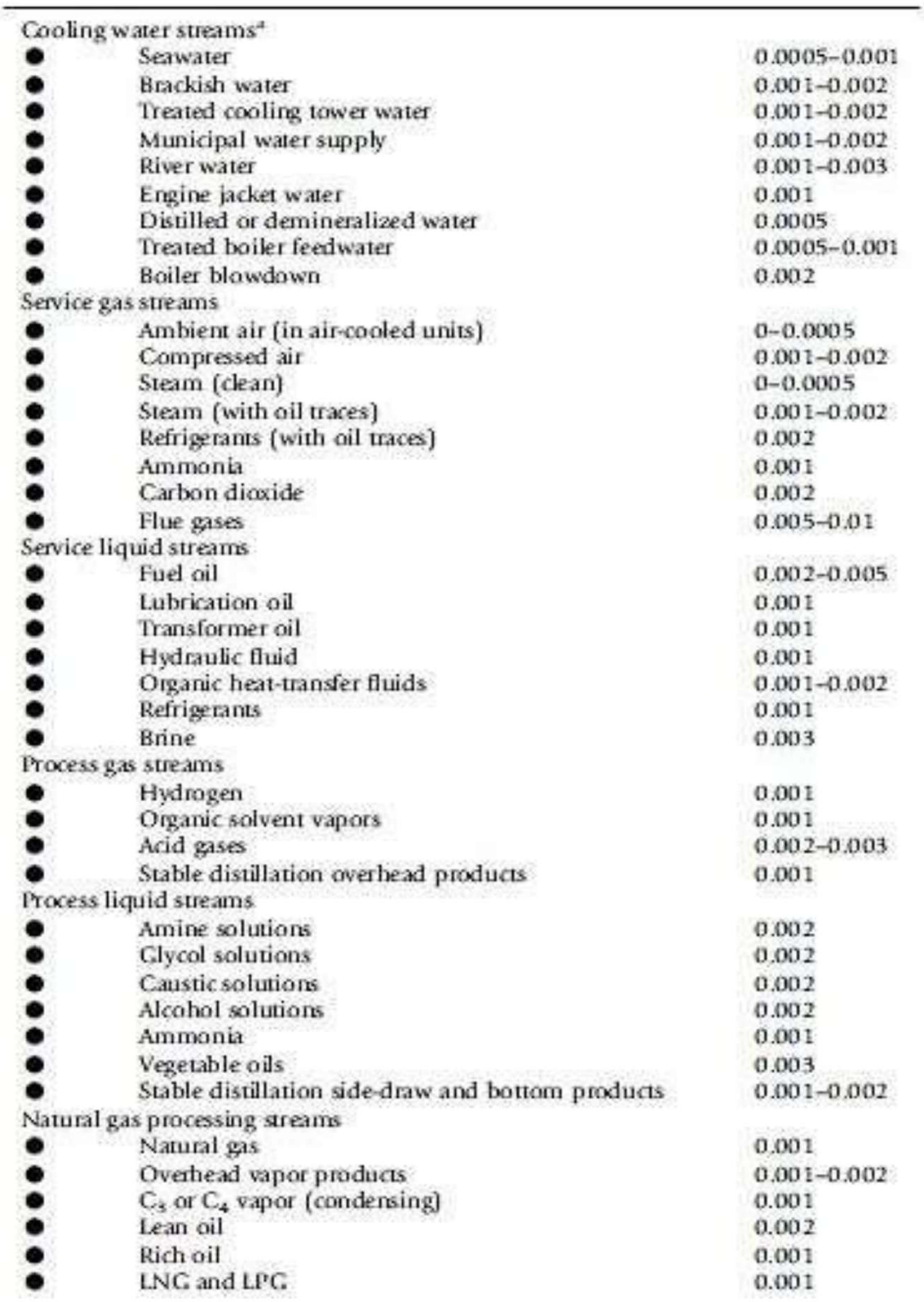
Tube-Side Fluid	Shell-Side Fluid
Corrosive fluid	Condensing vapor (unless corrosive)
Cooling water	Fluid with large ΔT (>100°F)
Fouling fluid	
Less viscous fluid	
Higher-pressure stream	
Hotter fluid	

Table A-13: Typical Values of Overall Heat-Transfer Coefficients in Tubular Heat Exchangers



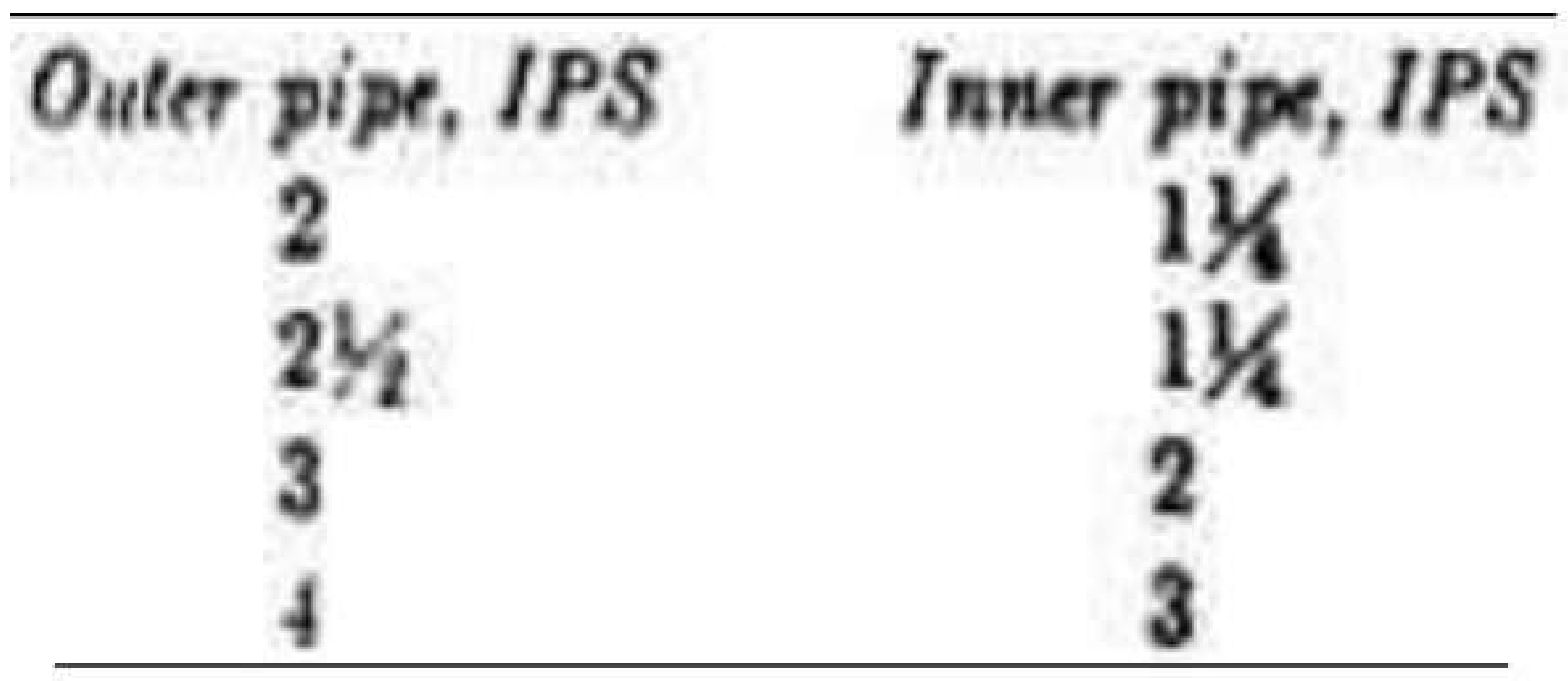
Shell Side	Tube Side	Design *U*	Includes Total Dirt
Liquid–liquid media			
Aroclor 1248	Jet fuels	100–150	0.0015
Cutback asphalt	Water	10–20	0.01
Demineralized water	Water	300–500	0.001
Ethanol amine (MEA or DEA) 10–25% solutions	Water or DEA, or MEA solutions	140–200	0.003
Fuel oil	Water	15–25	0.007
Fuel oil	Oil	10–15	0.008
Gasoline	Water	60–100	0.003
Heavy oils	Heavy oils	10–40	0.004
Heavy oils	Water	15–50	0.005
Hydrogen-rich reformer stream	Hydrogen-rich reformer stream	90–120	0.002
Kerosene or gas oil	Water	25–50	0.005
Kerosene or gas oil	Oil	20–35	0.005
Kerosene or jet fuels	Trichloroethylene	40–50	0.0015
Jacket water	Water	230–300	0.002
Lube oil (low viscosity)	Water	25–50	0.002
Lube oil (high viscosity)	Water	40–80	0.003
Lube oil	Oil	11–20	0.006
Naphtha	Water	50–70	0.005
Naphtha	Oil	25–35	0.005
Organic solvents	Water	50–150	0.003
Organic solvents	Brine	35–90	0.003
Organic solvents	Organic solvents	20–60	0.002
Tall oil derivatives, vegetable oil, etc.	Water	20–50	0.004
Water	Caustic soda solutions (10–30%)	100–250	0.003
Water	Water	200–250	0.003
Wax distillate	Water	15–25	0.005
Wax distillate	Oil	13–23	0.005
Condensing vapor-liquid media			
Alcohol vapor	Water	100–200	0.002
Asphalt (450°F)	Dowtherm vapor	40–60	0.006
Dowtherm vapor	Tall oil and derivatives	60–80	0.004
Dowtherm vapor	Dowtherm liquid	80–120	0.0015
Gas-plant tar	Steam	40–50	0.0055
High-boiling hydrocarbons V	Water	20–50	0.003
Low-boiling hydrocarbons A	Water	80–200	0.003
Hydrocarbon vapors (partial condenser)	Oil	25–40	0.004
Organic solvents A	Water	100–200	0.003
Organic solvents high NC, A	Water or brine	20–60	0.003
Organic solvents low NC, V	Water or brine	50–120	0.003
Kerosene	Water	30–65	0.004
Kerosene	Oil	20–30	0.005
Naphtha	Water	50–75	0.005
Naphtha	Oil	20–30	0.005
Stabilizer reflux vapors	Water	80–120	0.003
Steam	Feed water	400–1000	0.0005
Steam	No. 6 fuel oil	15–25	0.0055
Steam	No. 2 fuel oil	60–90	0.0025
Sulfur dioxide	Water	150–200	0.003
Tall-oil derivatives, vegetable oils (vapor)	Water	20–50	0.004
Water	Aromatic vapor-stream azeotrope	40–80	0.005
Gas-liquid media			
Air, N_2, etc. (compressed)	Water or brine	40–80	0.005
Air, N_2, etc., A	Water or brine	10–50	0.005
Water or brine	Air, N_2 (compressed)	20–40	0.005
Water or brine	Air, N_2, etc., A	5–20	0.005
Water	Hydrogen containing natural–gas mixtures	80–125	0.003

Table A-16: Typical Values of Fouling Factors (H. Ft2.˚f/Btu



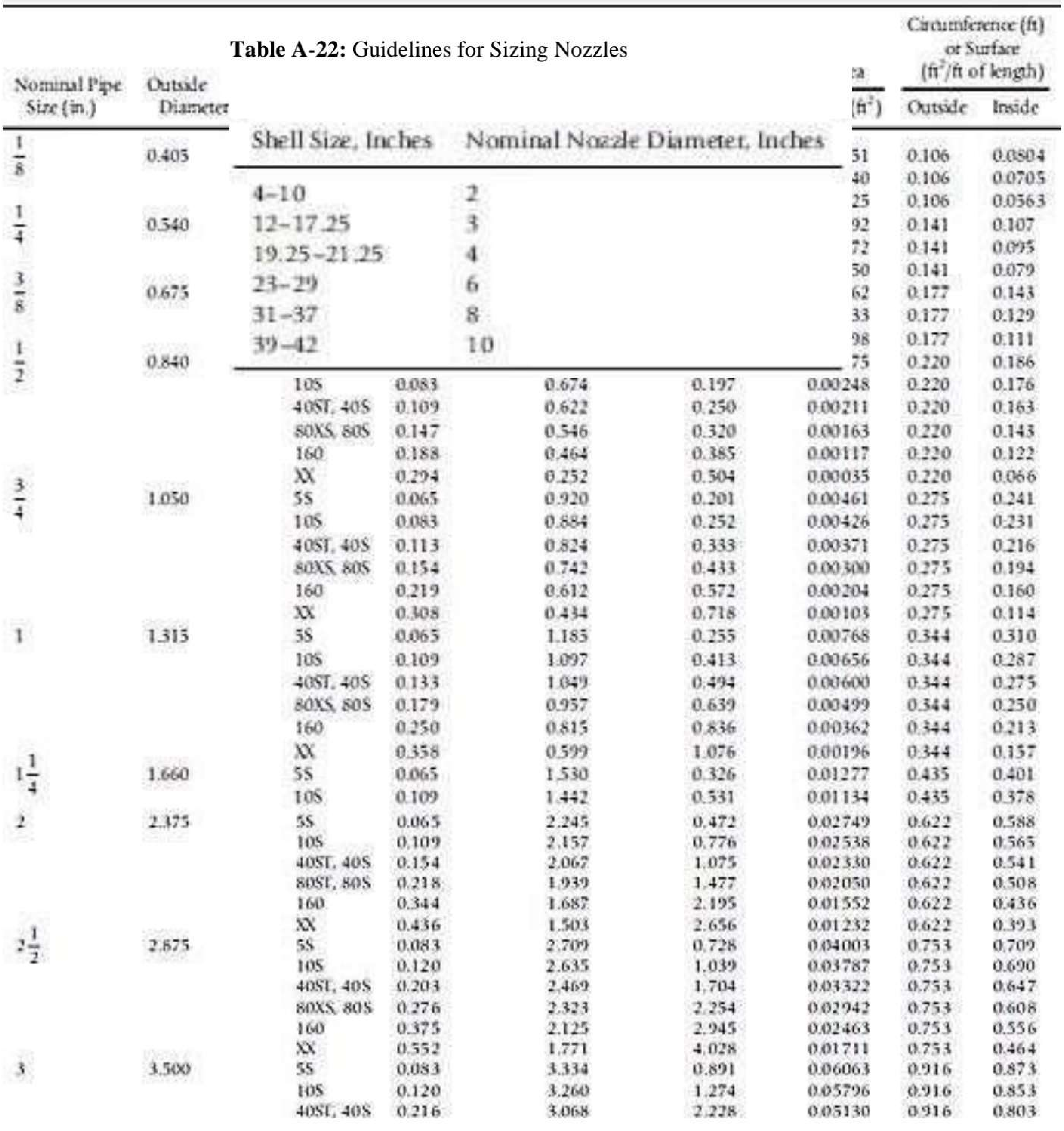
Cooling water streams[a]	
● Seawater	0.0005–0.001
● Brackish water	0.001–0.002
● Treated cooling tower water	0.001–0.002
● Municipal water supply	0.001–0.002
● River water	0.001–0.003
● Engine jacket water	0.001
● Distilled or demineralized water	0.0005
● Treated boiler feedwater	0.0005–0.001
● Boiler blowdown	0.002
Service gas streams	
● Ambient air (in air-cooled units)	0–0.0005
● Compressed air	0.001–0.002
● Steam (clean)	0–0.0005
● Steam (with oil traces)	0.001–0.002
● Refrigerants (with oil traces)	0.002
● Ammonia	0.001
● Carbon dioxide	0.002
● Flue gases	0.005–0.01
Service liquid streams	
● Fuel oil	0.002–0.005
● Lubrication oil	0.001
● Transformer oil	0.001
● Hydraulic fluid	0.001
● Organic heat-transfer fluids	0.001–0.002
● Refrigerants	0.001
● Brine	0.003
Process gas streams	
● Hydrogen	0.001
● Organic solvent vapors	0.001
● Acid gases	0.002–0.003
● Stable distillation overhead products	0.001
Process liquid streams	
● Amine solutions	0.002
● Glycol solutions	0.002
● Caustic solutions	0.002
● Alcohol solutions	0.002
● Ammonia	0.001
● Vegetable oils	0.003
● Stable distillation side-draw and bottom products	0.001–0.002
Natural gas processing streams	
● Natural gas	0.001
● Overhead vapor products	0.001–0.002
● C_3 or C_4 vapor (condensing)	0.001
● Lean oil	0.002
● Rich oil	0.001
● LNG and LPG	0.001

Table A-19: Double Pipe Exchanger Fittings



Outer pipe, IPS	*Inner pipe, IPS*
2	1¼
2½	1¼
3	2
4	3

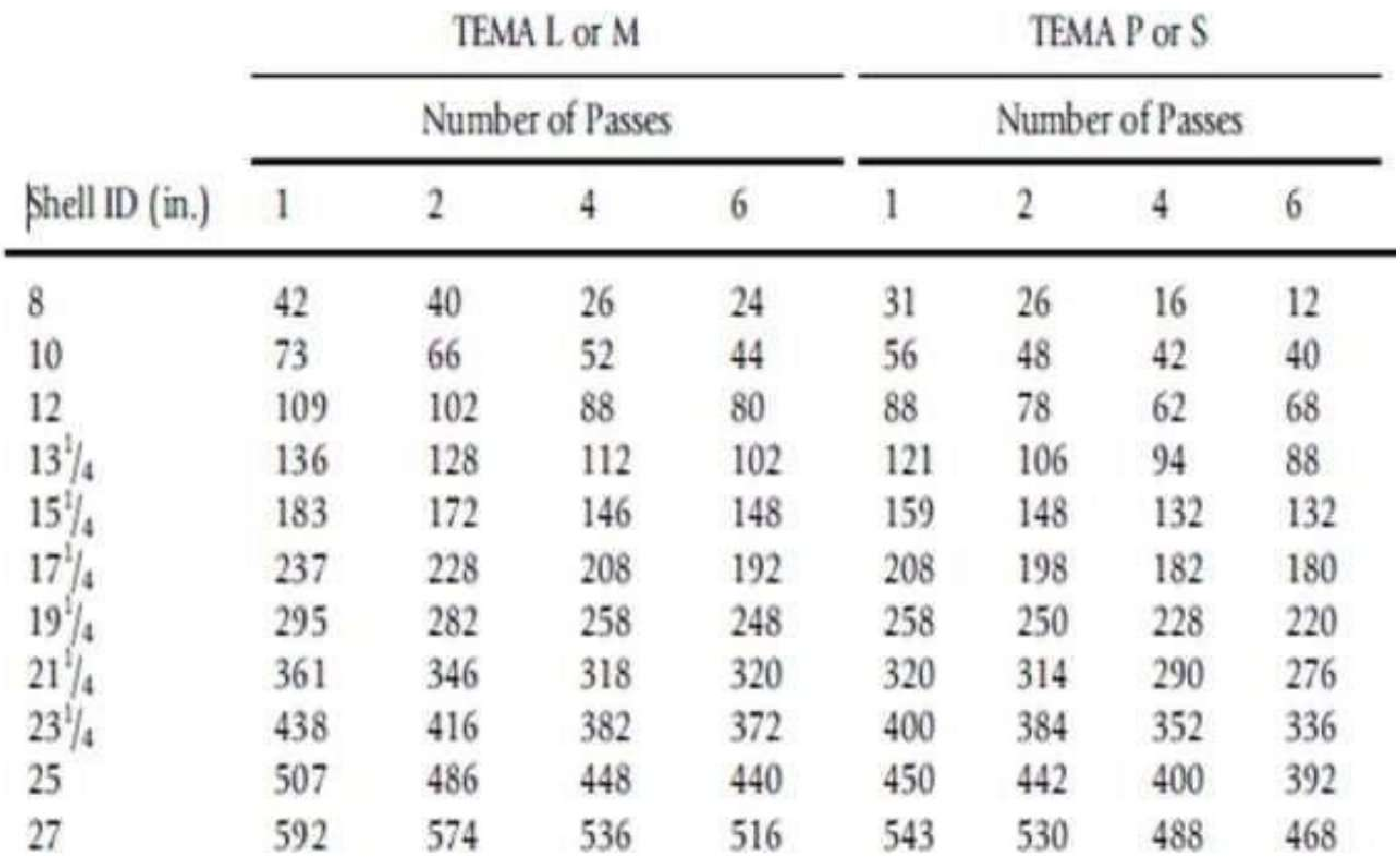
Table A-22: Guidelines for Sizing Nozzles



Shell Size, Inches	Nominal Nozzle Diameter, Inches
4–10	2
12–17.25	3
19.25–21.25	4
23–29	6
31–37	8
39–42	10

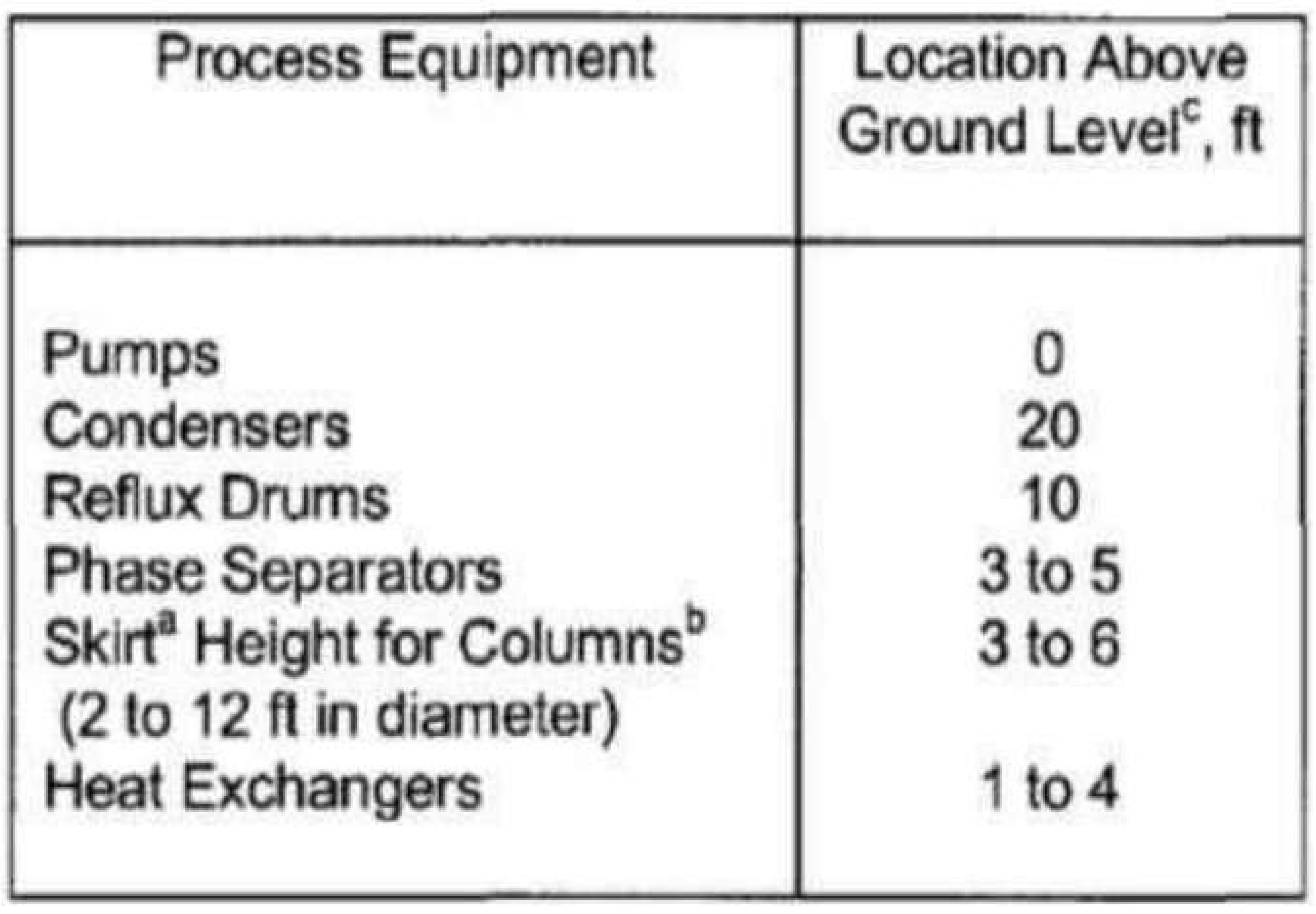
Nominal Pipe Size (in.)	Outside Diameter					a (ft²)	Circumference (ft) or Surface (ft²/ft of length)	
							Outside	Inside
$\frac{1}{8}$	0.405					51	0.106	0.0804
						40	0.106	0.0705
						25	0.106	0.0563
$\frac{1}{4}$	0.540					92	0.141	0.107
						72	0.141	0.095
						50	0.141	0.079
$\frac{3}{8}$	0.675					62	0.177	0.143
						33	0.177	0.129
						98	0.177	0.111
$\frac{1}{2}$	0.840					75	0.220	0.186
		10S	0.083	0.674	0.197	0.00248	0.220	0.176
		40ST, 40S	0.109	0.622	0.250	0.00211	0.220	0.163
		80XS, 80S	0.147	0.546	0.320	0.00163	0.220	0.143
		160	0.188	0.464	0.385	0.00117	0.220	0.122
		XX	0.294	0.252	0.504	0.00035	0.220	0.066
$\frac{3}{4}$	1.050	5S	0.065	0.920	0.201	0.00461	0.275	0.241
		10S	0.083	0.884	0.252	0.00426	0.275	0.231
		40ST, 40S	0.113	0.824	0.333	0.00371	0.275	0.216
		80XS, 80S	0.154	0.742	0.433	0.00300	0.275	0.194
		160	0.219	0.612	0.572	0.00204	0.275	0.160
		XX	0.308	0.434	0.718	0.00103	0.275	0.114
1	1.315	5S	0.065	1.185	0.255	0.00768	0.344	0.310
		10S	0.109	1.097	0.413	0.00656	0.344	0.287
		40ST, 40S	0.133	1.049	0.494	0.00600	0.344	0.275
		80XS, 80S	0.179	0.957	0.639	0.00499	0.344	0.250
		160	0.250	0.815	0.836	0.00362	0.344	0.213
		XX	0.358	0.599	1.076	0.00196	0.344	0.157
$1\frac{1}{4}$	1.660	5S	0.065	1.530	0.326	0.01277	0.435	0.401
		10S	0.109	1.442	0.531	0.01134	0.435	0.378
2	2.375	5S	0.065	2.245	0.472	0.02749	0.622	0.588
		10S	0.109	2.157	0.776	0.02538	0.622	0.565
		40ST, 40S	0.154	2.067	1.075	0.02330	0.622	0.541
		80ST, 80S	0.218	1.939	1.477	0.02050	0.622	0.508
		160	0.344	1.687	2.195	0.01552	0.622	0.436
		XX	0.436	1.503	2.656	0.01232	0.622	0.393
$2\frac{1}{2}$	2.875	5S	0.083	2.709	0.728	0.04003	0.753	0.709
		10S	0.120	2.635	1.039	0.03787	0.753	0.690
		40ST, 40S	0.203	2.469	1.704	0.03322	0.753	0.647
		80XS, 80S	0.276	2.323	2.254	0.02942	0.753	0.608
		160	0.375	2.125	2.945	0.02463	0.753	0.556
		XX	0.552	1.771	4.028	0.01711	0.753	0.464
3	3.500	5S	0.083	3.334	0.891	0.06063	0.916	0.873
		10S	0.120	3.260	1.274	0.05796	0.916	0.853
		40ST, 40S	0.216	3.068	2.228	0.05130	0.916	0.803

Table A-25: Tube Counts for 3/4-In. Od Tubes On 1-In. Triangular Pitch



	TEMA L or M				TEMA P or S			
	Number of Passes				Number of Passes			
Shell ID (in.)	1	2	4	6	1	2	4	6
8	42	40	26	24	31	26	16	12
10	73	66	52	44	56	48	42	40
12	109	102	88	80	88	78	62	68
13¼	136	128	112	102	121	106	94	88
15¼	183	172	146	148	159	148	132	132
17¼	237	228	208	192	208	198	182	180
19¼	295	282	258	248	258	250	228	220
21¼	361	346	318	320	320	314	290	276
23¼	438	416	382	372	400	384	352	336
25	507	486	448	440	450	442	400	392
27	592	574	536	516	543	530	488	468

Table A-27: Selection of Pump Head

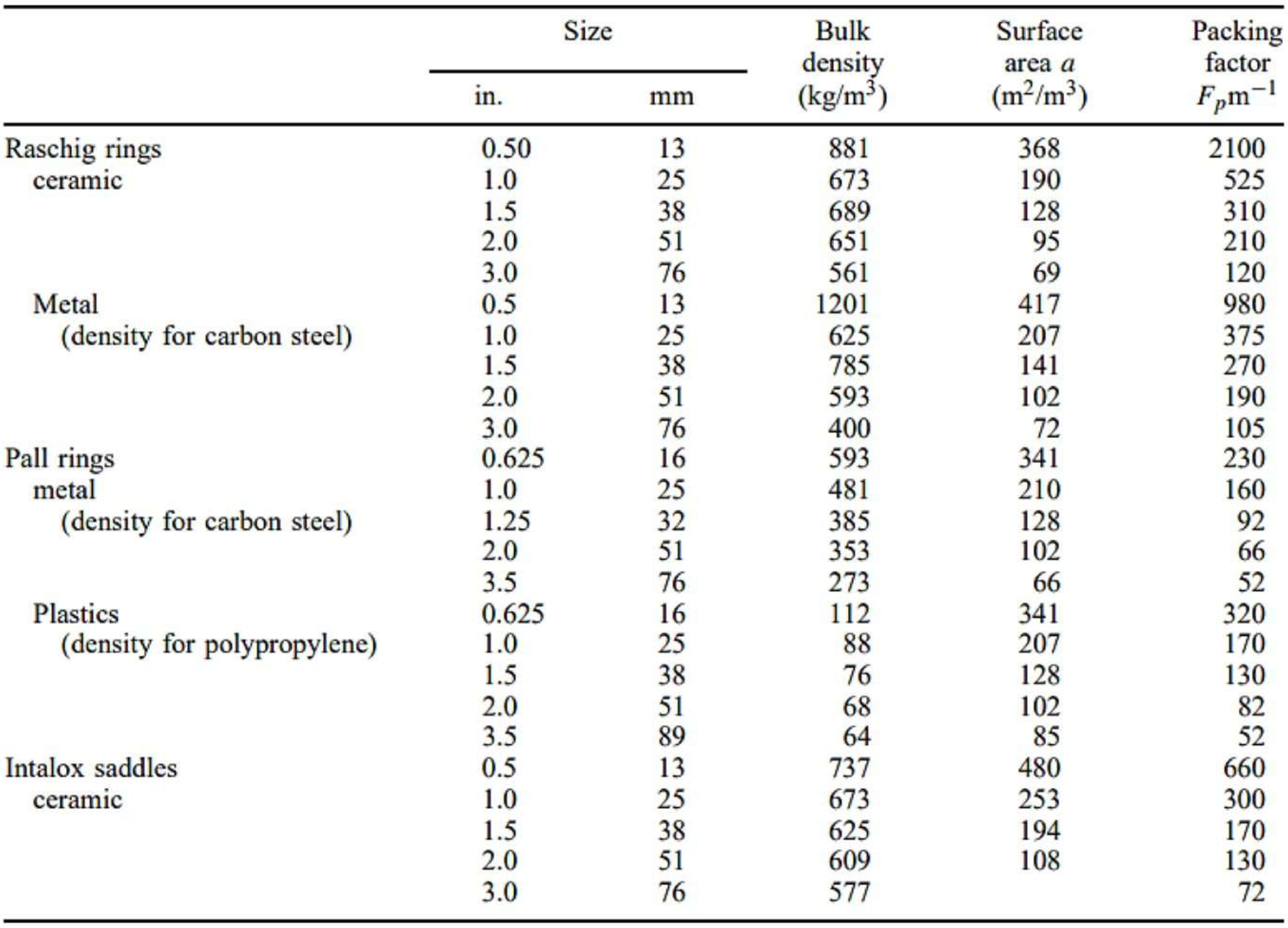


Process Equipment	Location Above Ground Level^c, ft
Pumps	0
Condensers	20
Reflux Drums	10
Phase Separators	3 to 5
Skirt^a Height for Columns^b (2 to 12 ft in diameter)	3 to 6
Heat Exchangers	1 to 4

Table A-30: Dimensions of Heat Exchanger, Tubing Dimensions.

Tube OD (in.)	BWG	Tube ID[a] (in.)	Internal area[b] (in.^{2})	External surface per foot length[c] (ft^2/ft)	$\frac{OD}{ID}$
1/2	16	0.370	0.1075	0.1309	1.351
	18	0.402	0.1269	0.1309	1.244
	20	0.430	0.1452	0.1309	1.163
	22	0.444	0.1548	0.1309	1.126
5/8	12	0.407	0.1301	0.1636	1.536
	13	0.435	0.1486	0.1636	1.437
	14	0.459	0.1655	0.1636	1.362
	15	0.481	0.1817	0.1636	1.299
	16	0.495	0.1924	0.1636	1.263
	17	0.509	0.2035	0.1636	1.228
	18	0.527	0.2181	0.1636	1.186
	19	0.541	0.2299	0.1636	1.155
	20	0.555	0.2419	0.1636	1.126
3/4	10	0.482	0.1825	0.1963	1.556
	11	0.510	0.2043	0.1963	1.471
	12	0.532	0.2223	0.1963	1.410
	13	0.560	0.2463	0.1963	1.339
	14	0.584	0.2679	0.1963	1.284
	15	0.606	0.2884	0.1963	1.238
	16	0.620	0.3019	0.1963	1.210
	17	0.634	0.3157	0.1963	1.183
	18	0.652	0.3339	0.1963	1.150
	20	0.680	0.3632	0.1963	1.103
7/8	10	0.607	0.2894	0.2291	1.442
	11	0.635	0.3167	0.2291	1.378
	12	0.657	0.3390	0.2291	1.332
	13	0.685	0.3685	0.2291	1.277
	14	0.709	0.3948	0.2291	1.234
	15	0.731	0.4197	0.2291	1.197
	16	0.745	0.4359	0.2291	1.174
	17	0.759	0.4525	0.2291	1.153
	18	0.777	0.4742	0.2291	1.126
	20	0.805	0.5090	0.2291	1.087
1.0	8	0.670	0.3526	0.2618	1.493
	10	0.732	0.4208	0.2618	1.366
	11	0.760	0.4536	0.2618	1.316
	12	0.782	0.4803	0.2618	1.279
	13	0.810	0.5153	0.2618	1.235
	14	0.834	0.5463	0.2618	1.199
	15	0.856	0.5755	0.2618	1.168
	16	0.870	0.5945	0.2618	1.149
	18	0.902	0.6390	0.2618	1.109
	20	0.930	0.6793	0.2618	1.075

Table A-31: Design data for various packing



	Size		Bulk density (kg/m^3)	Surface area a (m^2/m^3)	Packing factor F_pm^{-1}
	in.	mm			
Raschig rings	0.50	13	881	368	2100
ceramic	1.0	25	673	190	525
	1.5	38	689	128	310
	2.0	51	651	95	210
	3.0	76	561	69	120
Metal	0.5	13	1201	417	980
(density for carbon steel)	1.0	25	625	207	375
	1.5	38	785	141	270
	2.0	51	593	102	190
	3.0	76	400	72	105
Pall rings	0.625	16	593	341	230
metal	1.0	25	481	210	160
(density for carbon steel)	1.25	32	385	128	92
	2.0	51	353	102	66
	3.5	76	273	66	52
Plastics	0.625	16	112	341	320
(density for polypropylene)	1.0	25	88	207	170
	1.5	38	76	128	130
	2.0	51	68	102	82
	3.5	89	64	85	52
Intalox saddles	0.5	13	737	480	660
ceramic	1.0	25	673	253	300
	1.5	38	625	194	170
	2.0	51	609	108	130
	3.0	76	577		72

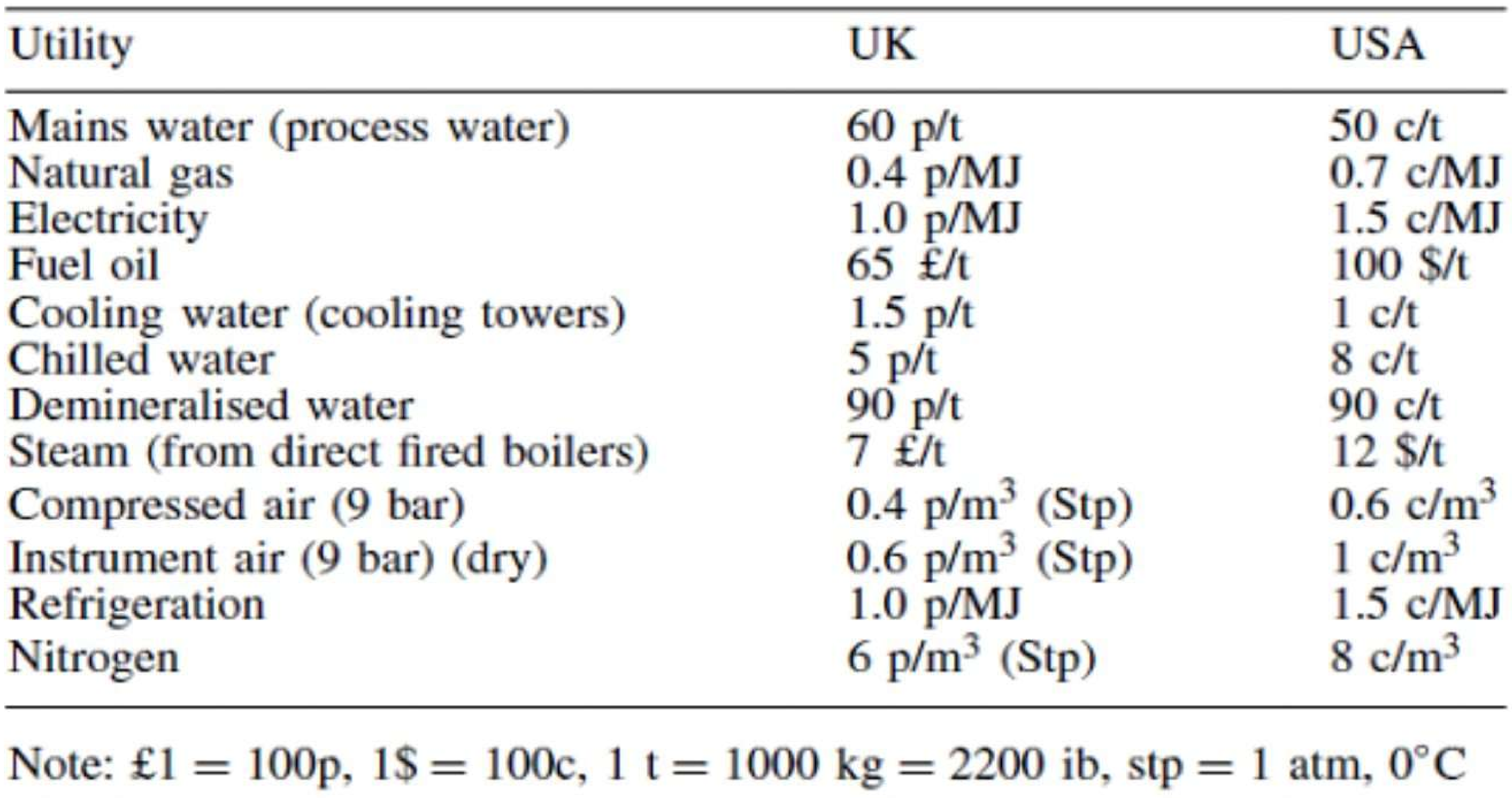
Table A-32: Cost of Equipment, Basis mid 2004

Equipment	Size unit, S	Size range	Constant C,£	Constant C,$	Index n	Comment
Agitators						
Propeller	driver power, kW	5–75	1200	1900	0.5	
Turbine			1800	3000	0.5	
Boilers						
Packaged						oil or gas fired
up to 10 bar	kg/h steam	$(5–50) \times 10^3$	70	120	0.8	
10 to 60 bar			60	100	0.8	
Centrifuges						
Horizontal basket	dia., m	0.5–1.0	35,000	58,000	1.3	carbon steel
Vertical basket			35,000	58,000	1.0	×1.7 for ss
Compressors						
Centrifugal	driver power, kW	20–500	1160	1920	0.8	electric, max. press. 50 bar
Reciprocating			1600	2700	0.8	
Conveyors						
Belt	length, m	2–40				
0.5 m wide			1200	1900	0.75	
1.0 m wide			1800	2900	0.75	
Crushers						
Cone	t/h	20–200	2300	3800	0.85	
Pulverisers	kg/h		2000	3400	0.35	
Dryers						
Rotary	area, m^2	5–30	21,000	35,000	0.45	direct
Pan		2–10	4700	7700	0.35	gas fired
Evaporators						
Vertical tube	area, m^2	10–100	12,000	20,000	0.53	carbon steel
Falling film			6500	10,000	0.52	
Filters						
Plate and frame	area, m^2	5–50	5400	8800	0.6	cast iron
Vacuum drum		1–10	21,000	34,000	0.6	carbon steel
Furnaces						
Process						
Cylindrical	heat abs, kW	$10^3–10^4$	330	540	0.77	carbon steel
Box		$10^3–10^5$	340	560	0.77	×2.0 ss
Reactors						
Jacketed,	capacity, m^3	3–30	9300	15,000	0.40	carbon steel
agitated			18,500	31,000	0.45	glass lined
Tanks						
Process	capacity, m^3					
vertical		1–50	1450	2400	0.6	atmos. press.
horizontal		10–100	1750	2900	0.6	carbon steel
Storage						
floating roof		50–8000	2500	4350	0.55	×2 for
cone roof		50–8000	1400	2300	0.55	stainless

Table A-33: Cost of Column Packing.

	Cost	£/m^3 (\$/m^3)	
Size, mm	25	38	50
Saddles, stoneware	840 (1400)	620 (1020)	580 (960)
Pall rings, polypropylene	650 (1080)	400 (650)	250 (400)
Pall rings, stainless steel	1500 (2500)	1500 (2500)	830 (1360)

Table A-34: Cost of Utilities



Utility	UK	USA
Mains water (process water)	60 p/t	50 c/t
Natural gas	0.4 p/MJ	0.7 c/MJ
Electricity	1.0 p/MJ	1.5 c/MJ
Fuel oil	65 £/t	100 \$/t
Cooling water (cooling towers)	1.5 p/t	1 c/t
Chilled water	5 p/t	8 c/t
Demineralised water	90 p/t	90 c/t
Steam (from direct fired boilers)	7 £/t	12 \$/t
Compressed air (9 bar)	0.4 p/m^3 (Stp)	0.6 c/m^3
Instrument air (9 bar) (dry)	0.6 p/m^3 (Stp)	1 c/m^3
Refrigeration	1.0 p/MJ	1.5 c/MJ
Nitrogen	6 p/m^3 (Stp)	8 c/m^3

Note: £1 = 100p, 1\$ = 100c, 1 t = 1000 kg = 2200 ib, stp = 1 atm, 0°C

Appendix B

List of Figures:

FIGURES

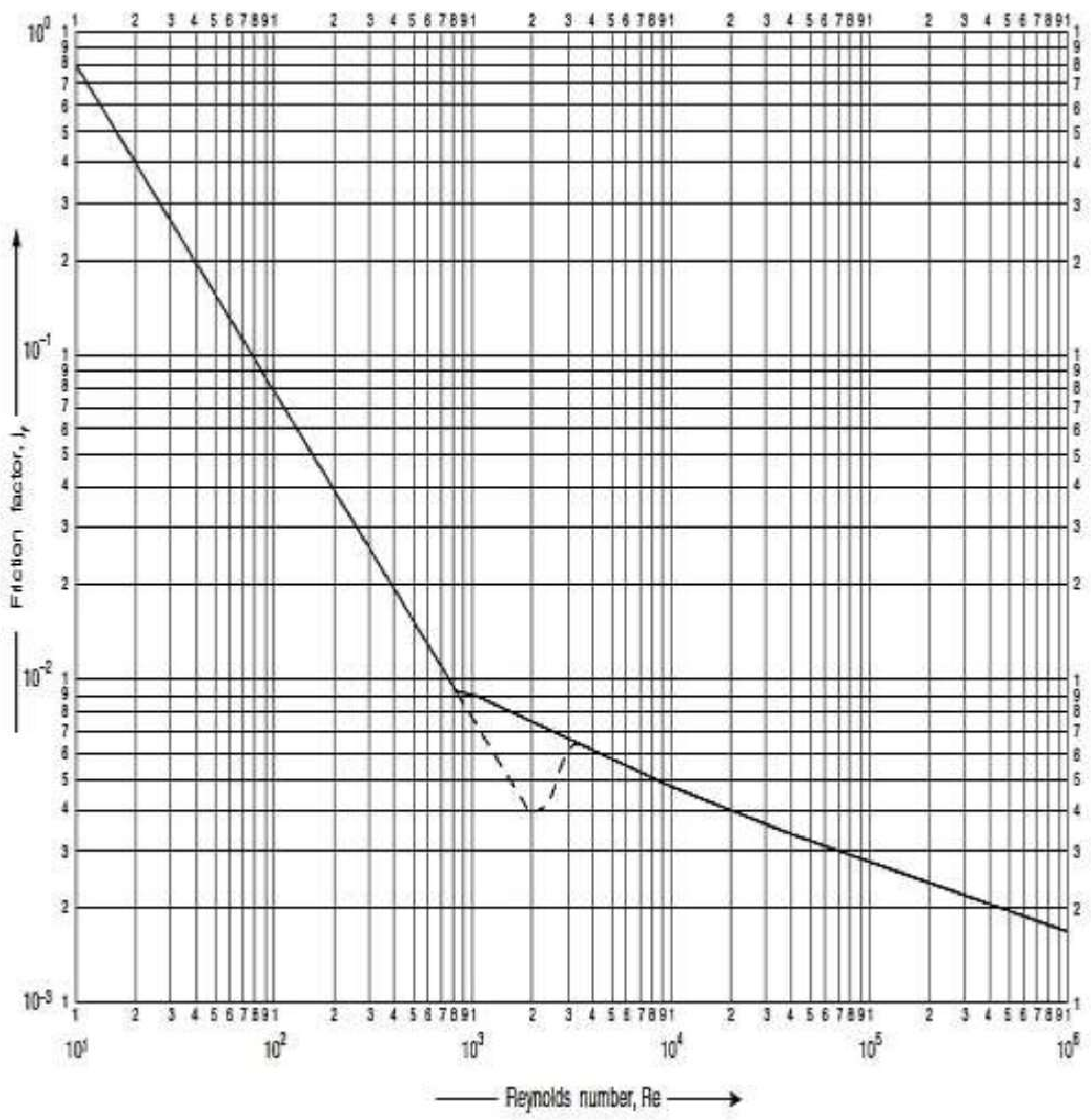


Figure B-1: Tube-Side Friction Factors

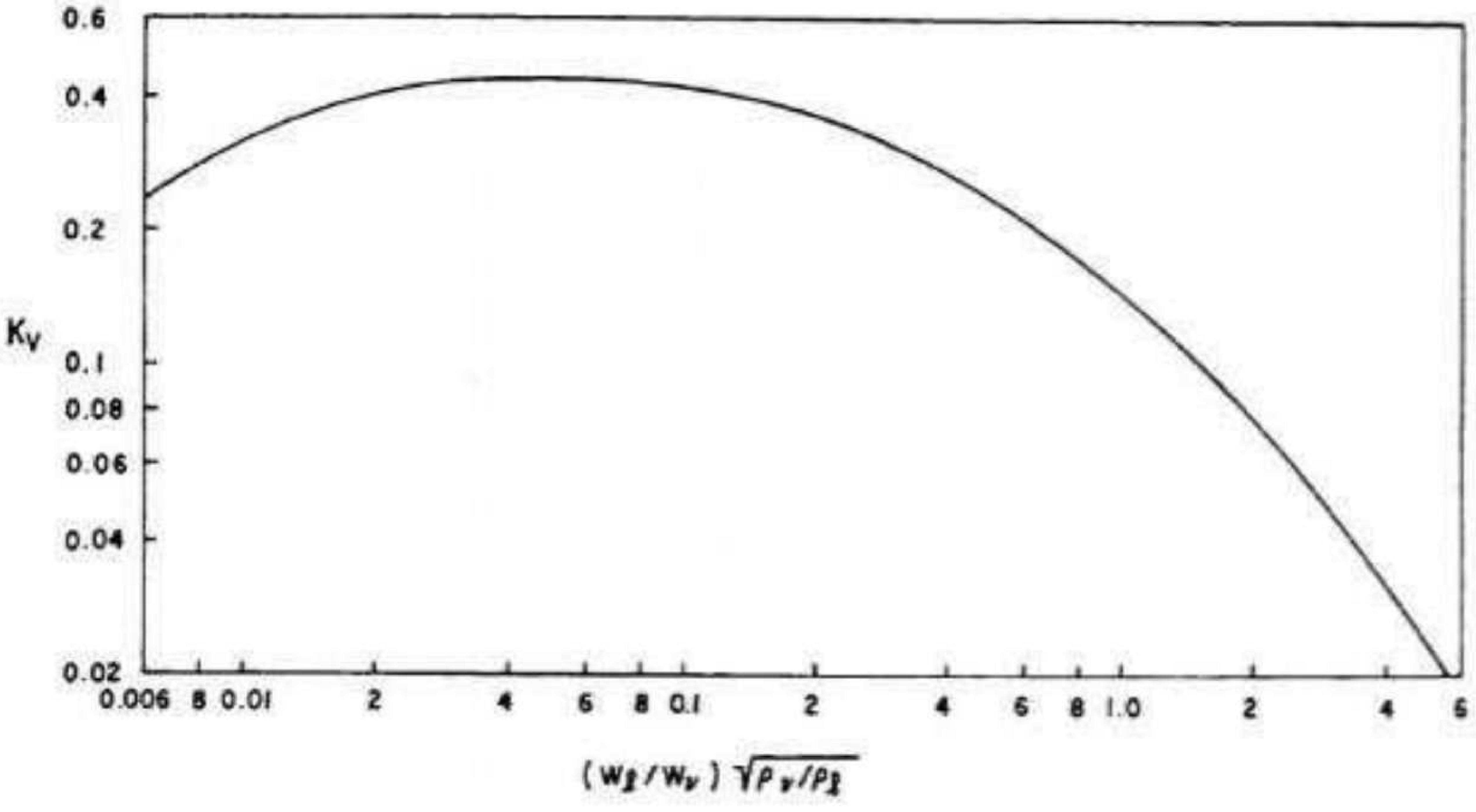


Figure B-2: Design Vapor Velocity Factor for Vertical-Liquid Separators At 85% Of Flooding

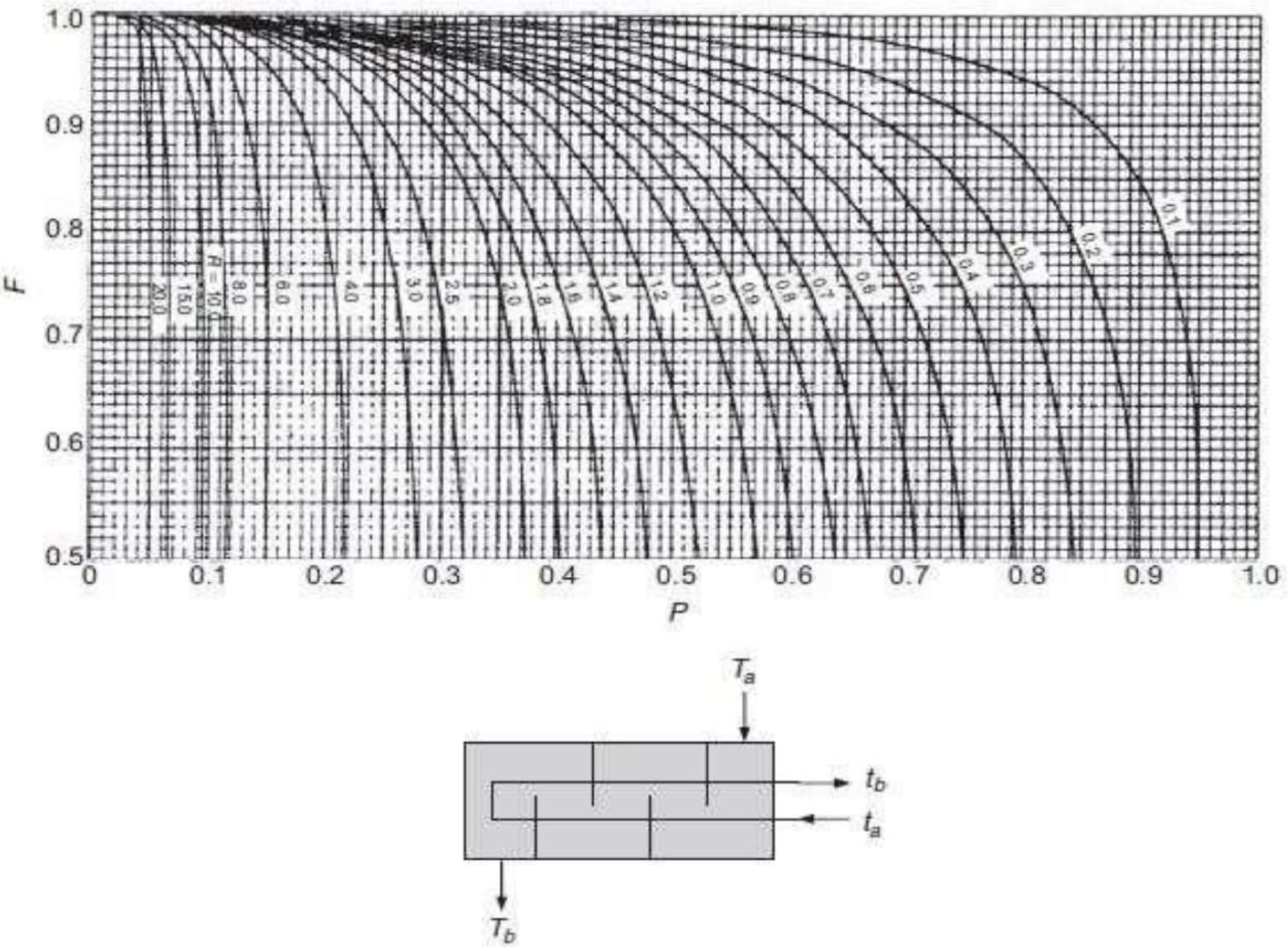
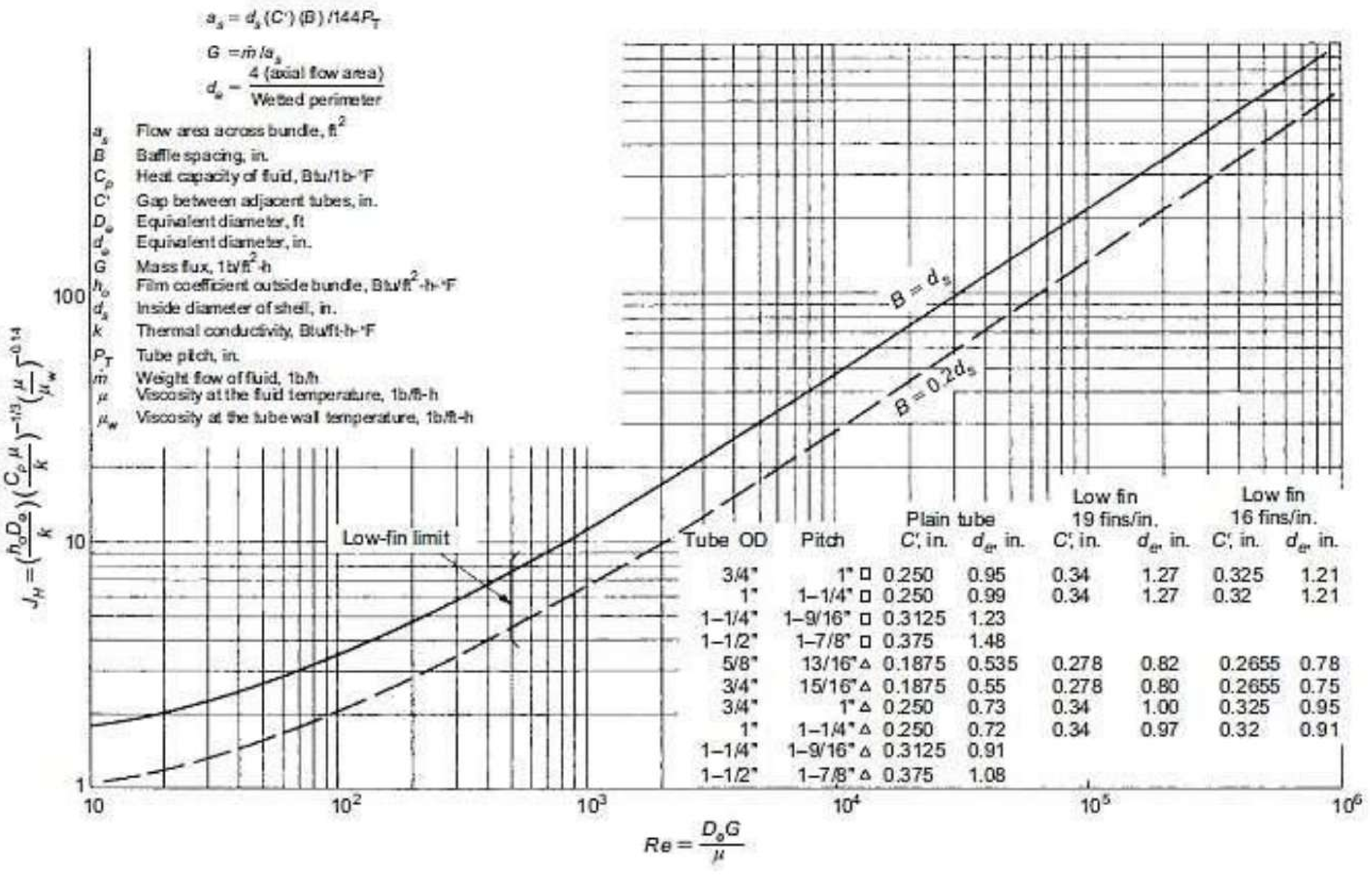


Figure B-3: LMTD Correction Factor for 1–2 Exchangers



$a_s = d_s(C')(B)/144P_T$

$G = \dot{m}/a_s$

$d_e = \dfrac{4\text{ (axial flow area)}}{\text{Wetted perimeter}}$

a_s Flow area across bundle, ft^2
B Baffle spacing, in.
C_p Heat capacity of fluid, Btu/1b·°F
C' Gap between adjacent tubes, in.
D_e Equivalent diameter, ft
d_e Equivalent diameter, in.
G Mass flux, 1b/ft^2·h
h_o Film coefficient outside bundle, Btu/ft^2·h·°F
d_s Inside diameter of shell, in.
k Thermal conductivity, Btu/ft·h·°F
P_T Tube pitch, in.
$\dot{m}$ Weight flow of fluid, 1b/h
μ Viscosity at the fluid temperature, 1b/ft·h
μ_w Viscosity at the tube wall temperature, 1b/ft·h

		Plain tube		Low fin 19 fins/in.		Low fin 16 fins/in.	
Tube OD	Pitch	C', in.	d_e, in.	C', in.	d_e, in.	C', in.	d_e, in.
3/4"	1" □	0.250	0.95	0.34	1.27	0.325	1.21
1"	1–1/4" □	0.250	0.99	0.34	1.27	0.32	1.21
1–1/4"	1–9/16" □	0.3125	1.23				
1–1/2"	1–7/8" □	0.375	1.48				
5/8"	13/16" △	0.1875	0.535	0.278	0.82	0.2655	0.78
3/4"	15/16" △	0.1875	0.55	0.278	0.80	0.2655	0.75
3/4"	1" △	0.250	0.73	0.34	1.00	0.325	0.95
1"	1–1/4" △	0.250	0.72	0.34	0.97	0.32	0.91
1–1/4"	1–9/16" △	0.3125	0.91				
1–1/2"	1–7/8" △	0.375	1.08				

Figure B-4: Correlation for Shell-Side Heat-Transfer Coefficient

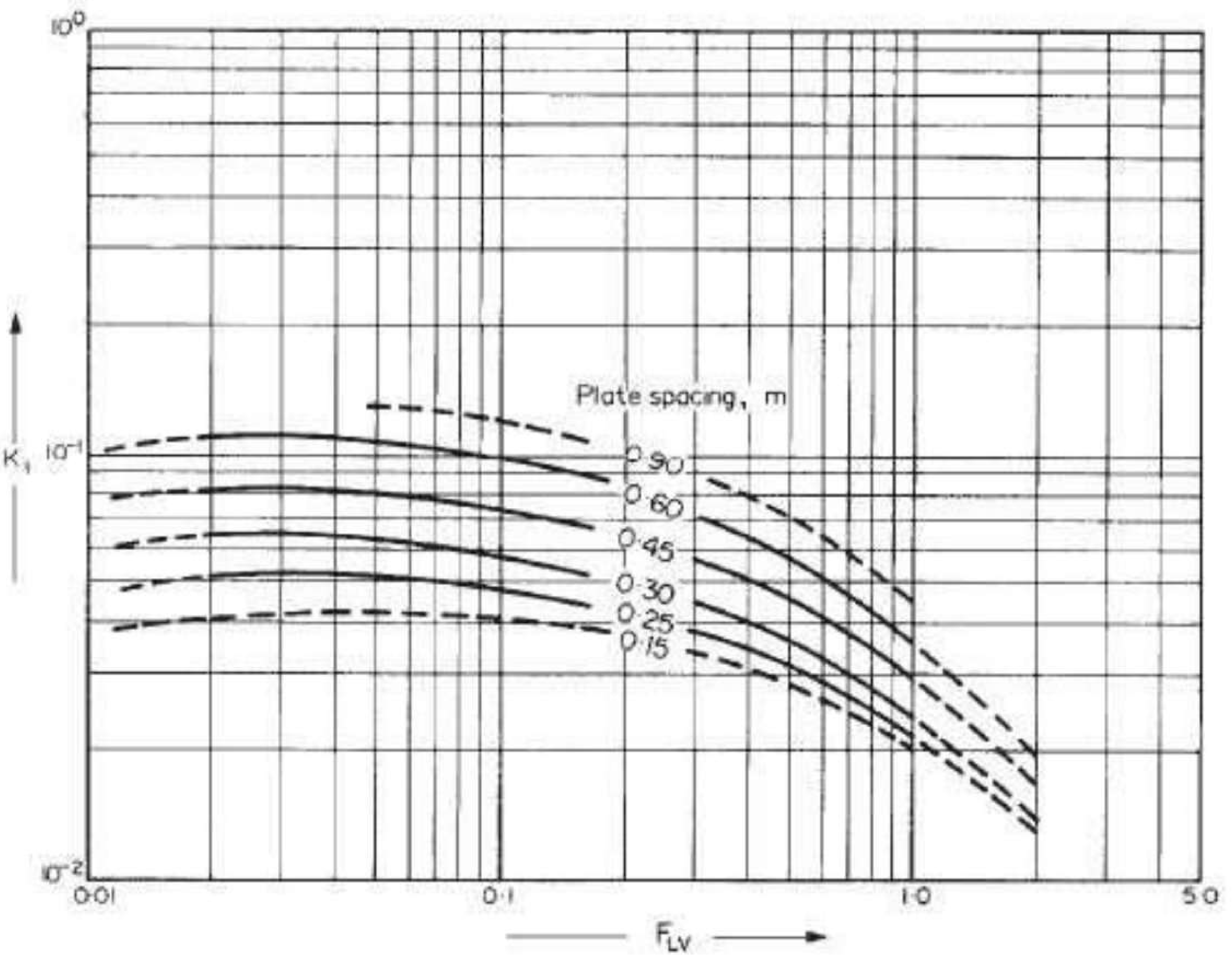


Figure B-5: Flooding Velocity, Sieve Plates

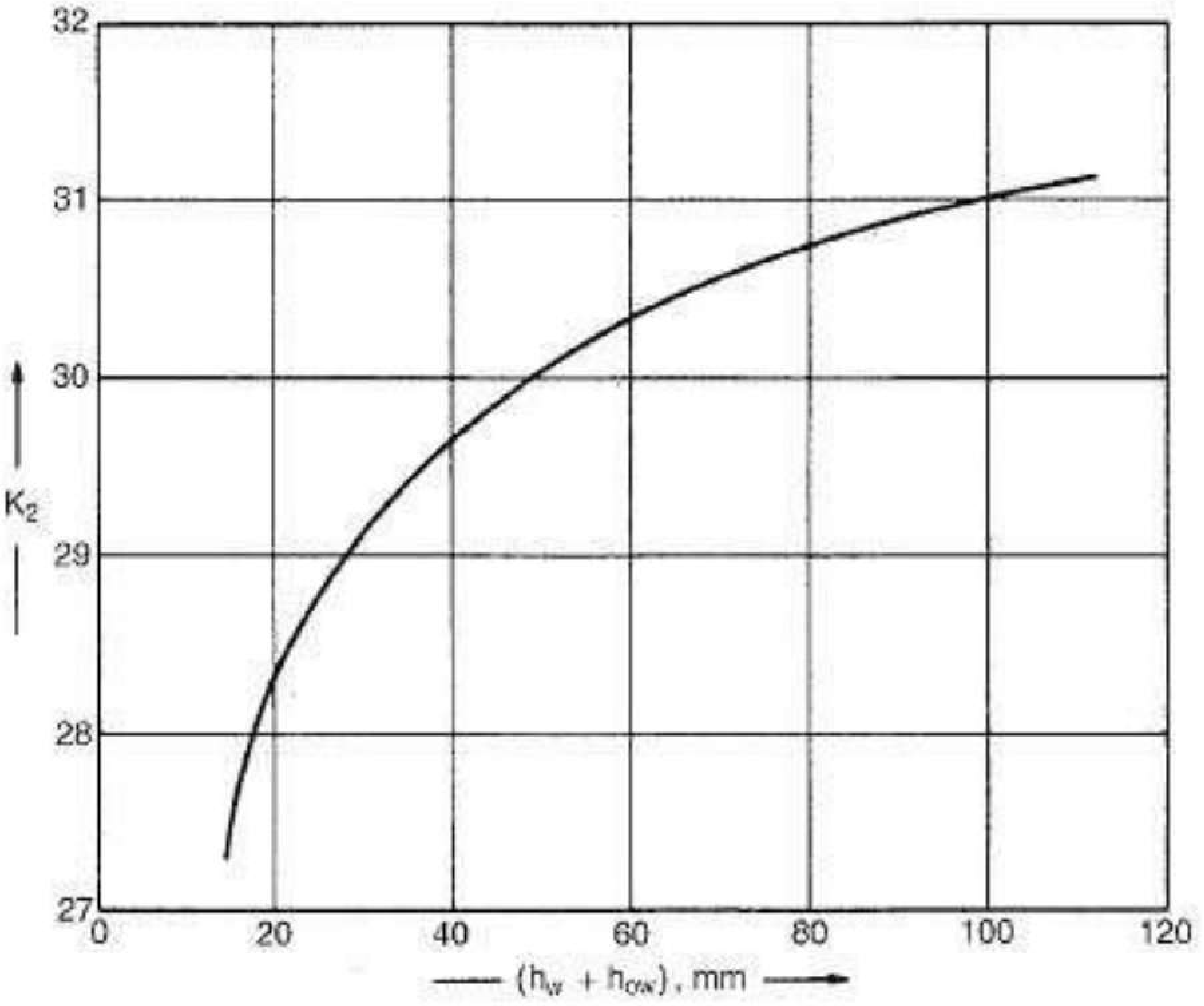


Figure B-6: Weep-Point Correlation

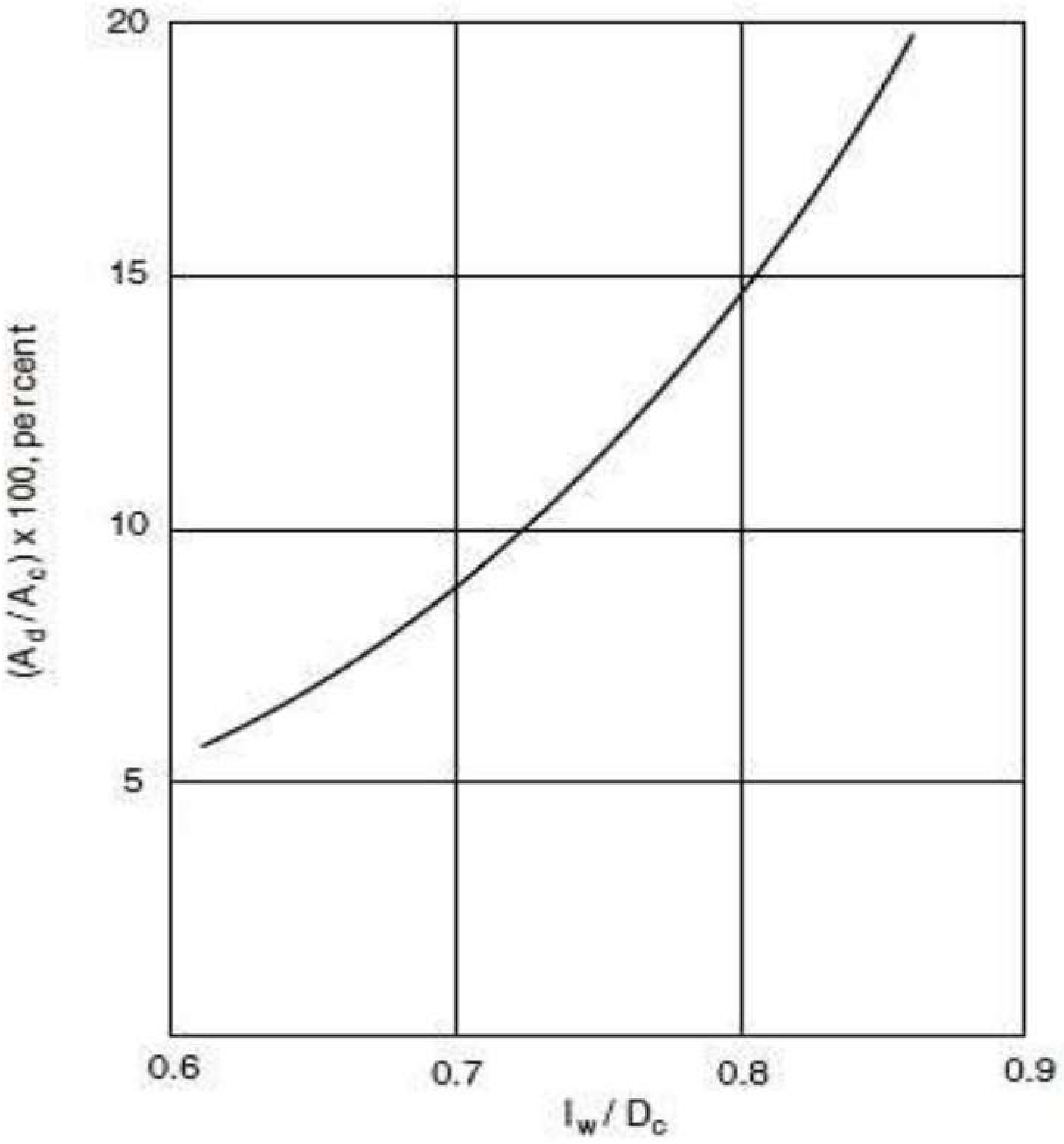


Figure B-7: Relation between down comer area and Weir Length

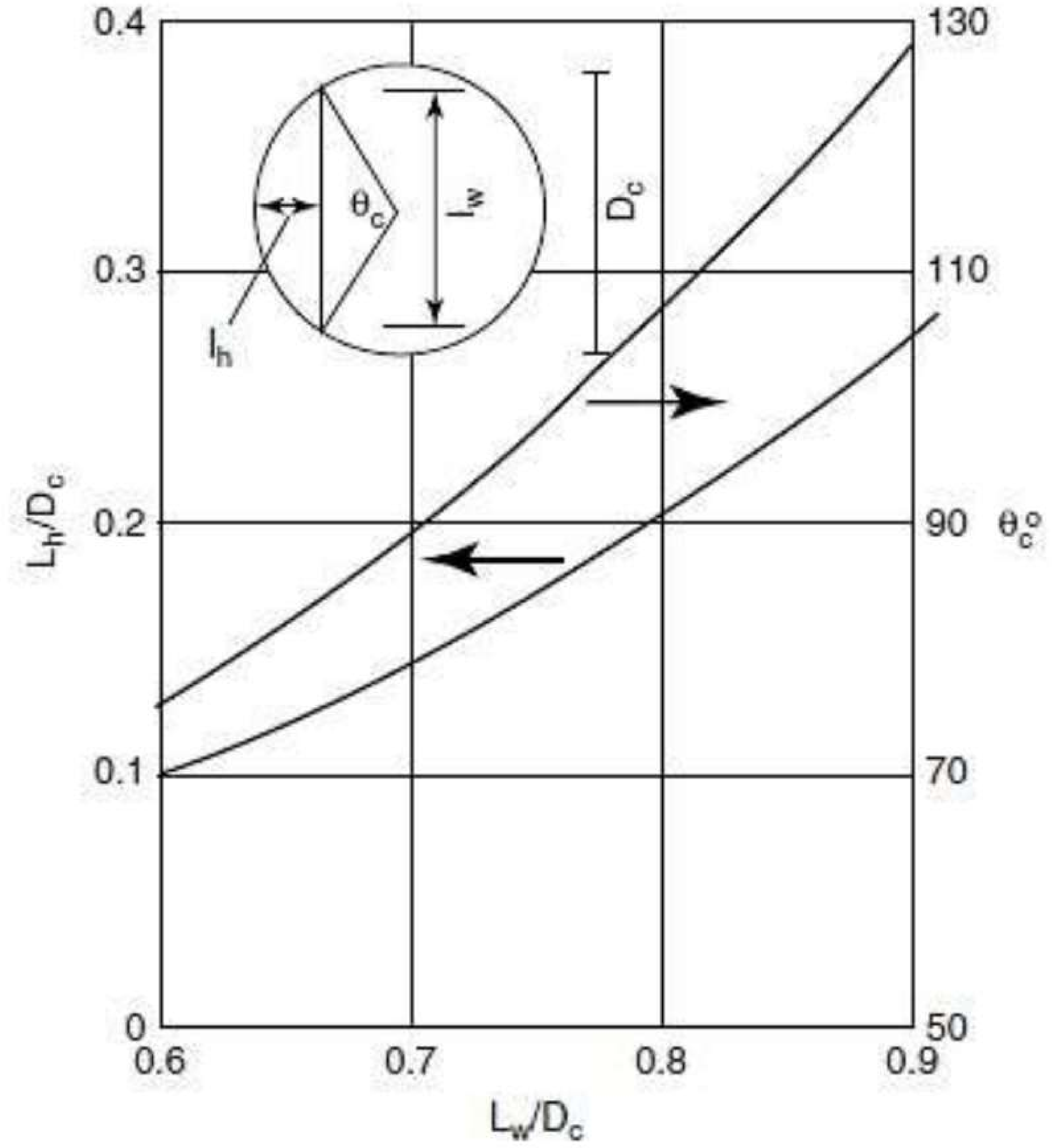


Figure B-8: Relation between angle Subtended By Chord, Chord Height and Chord Length

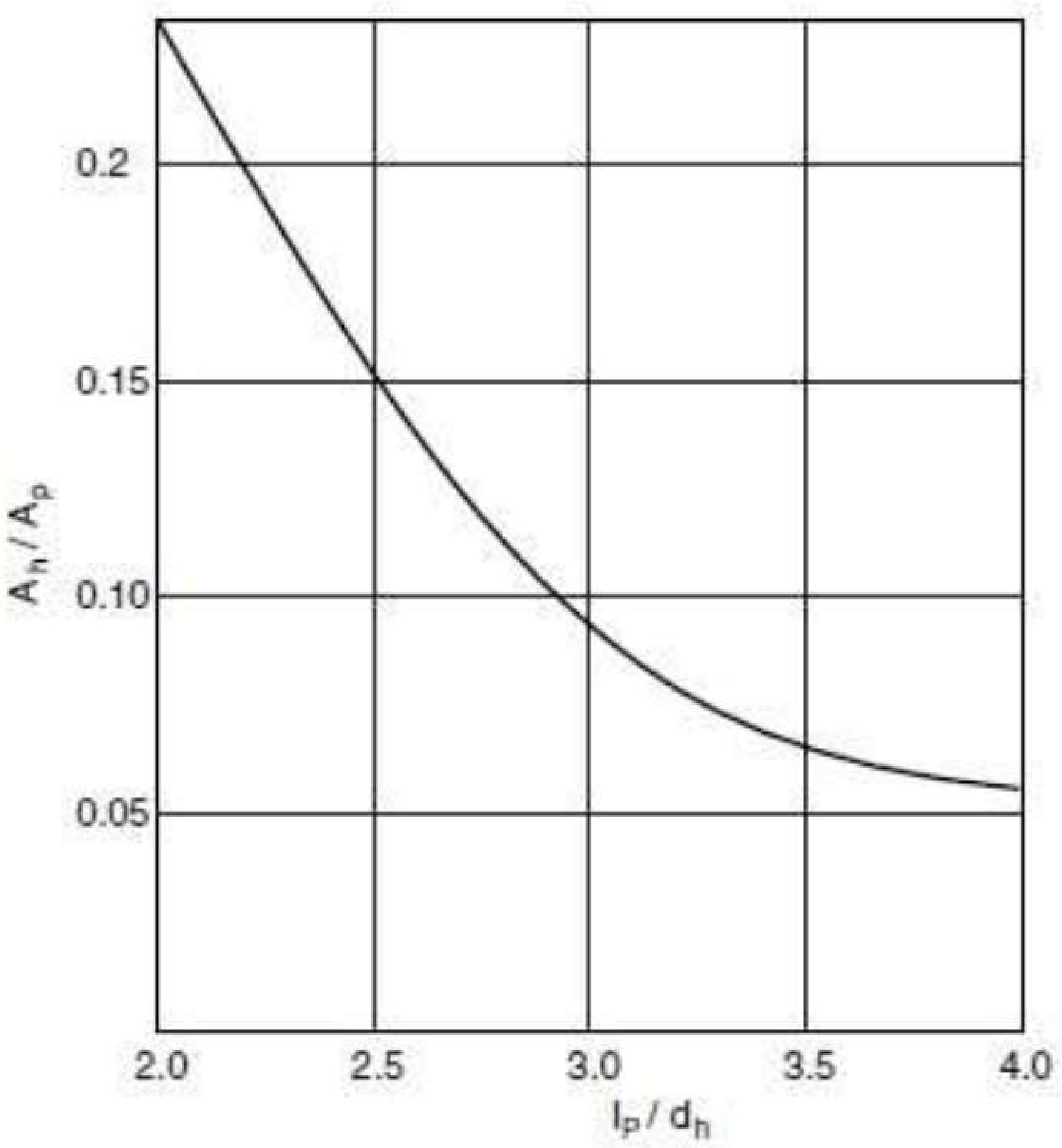


***Figure B-9**: Relation between Hole Area and Pitch*

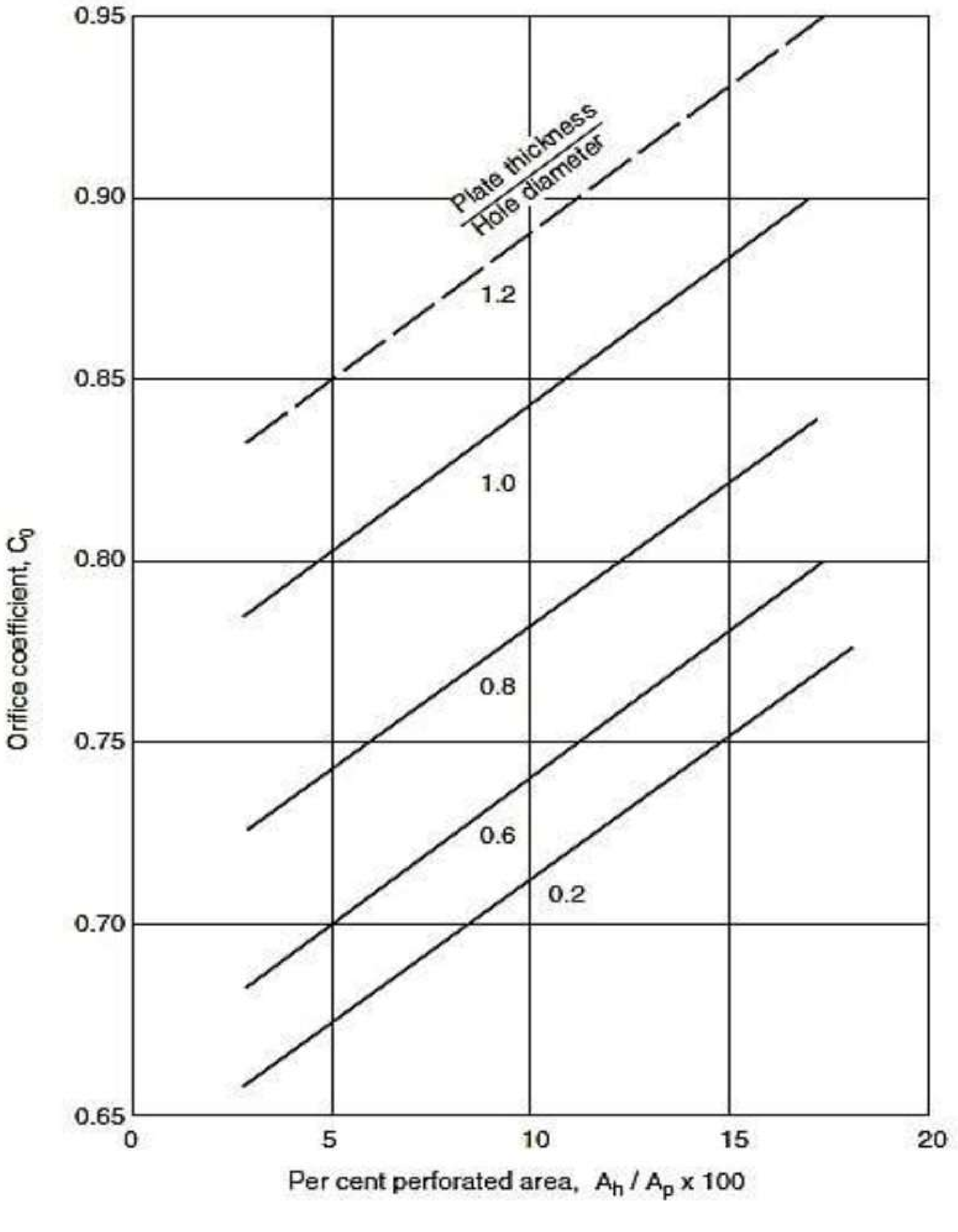


Figure B-10: Discharge Coefficient, Sieve Plates

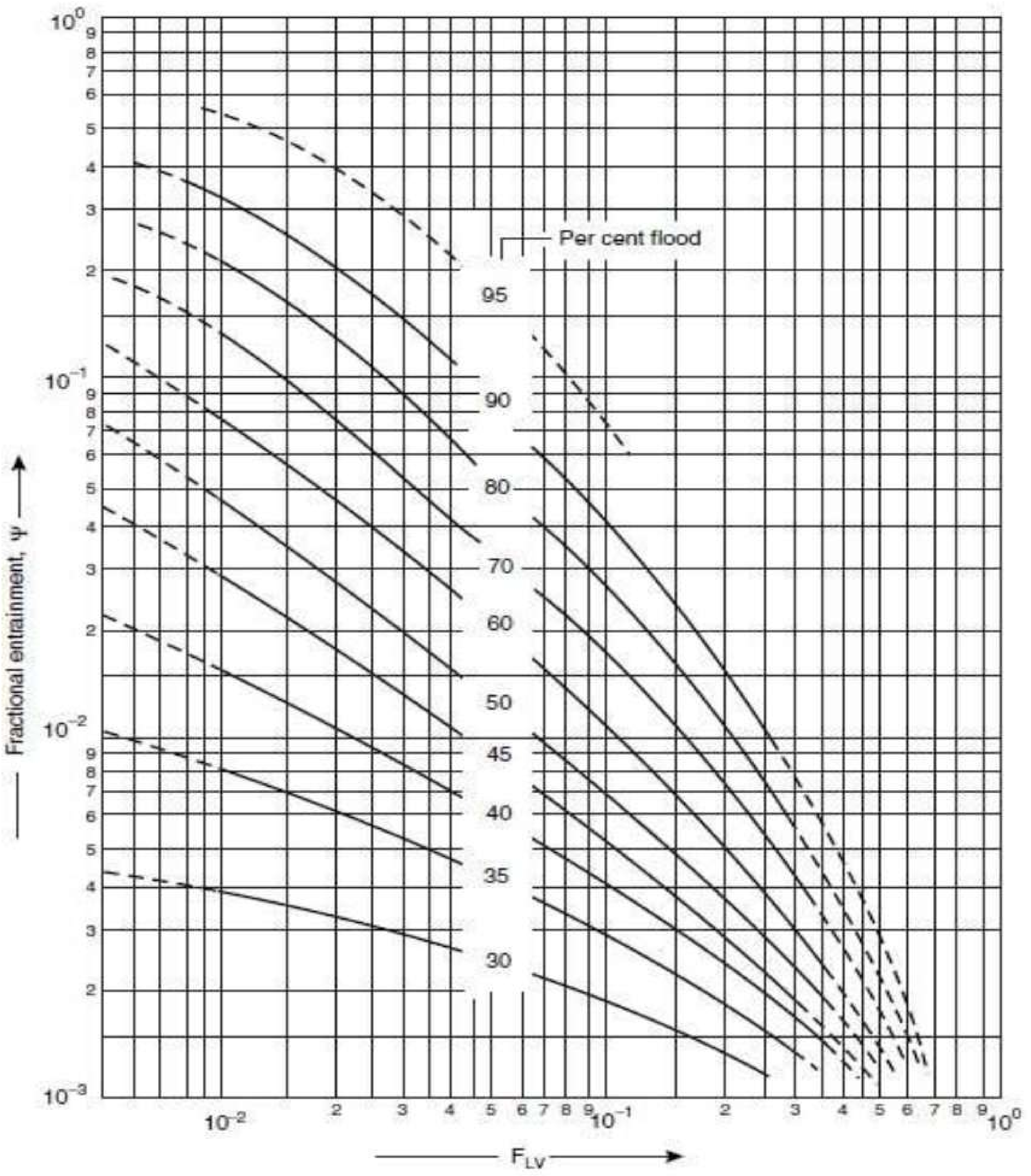


Figure B-11: Entrainment Correlation for Sieve Plates

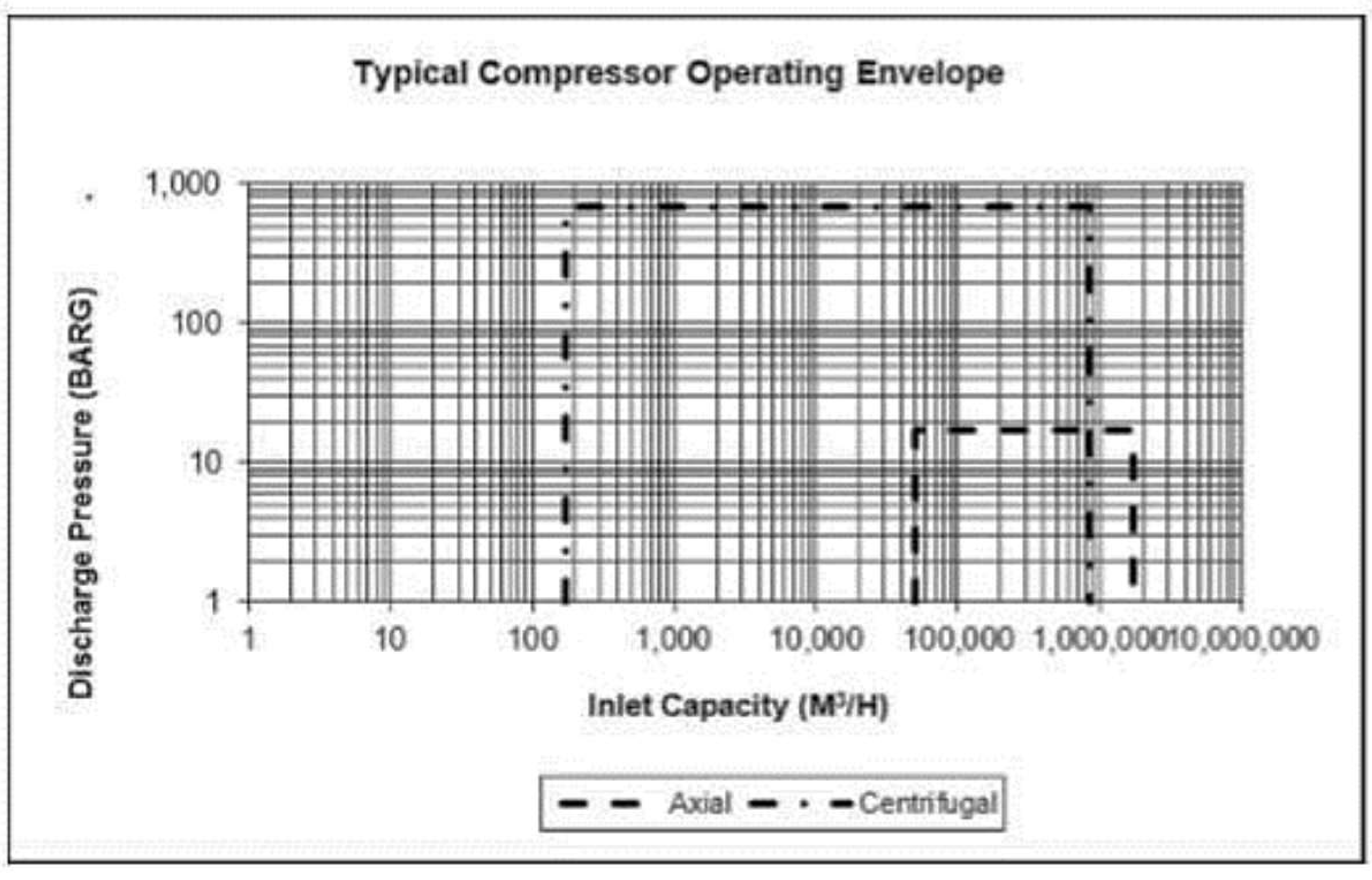


Figure B-12: Compressor Selection Chart

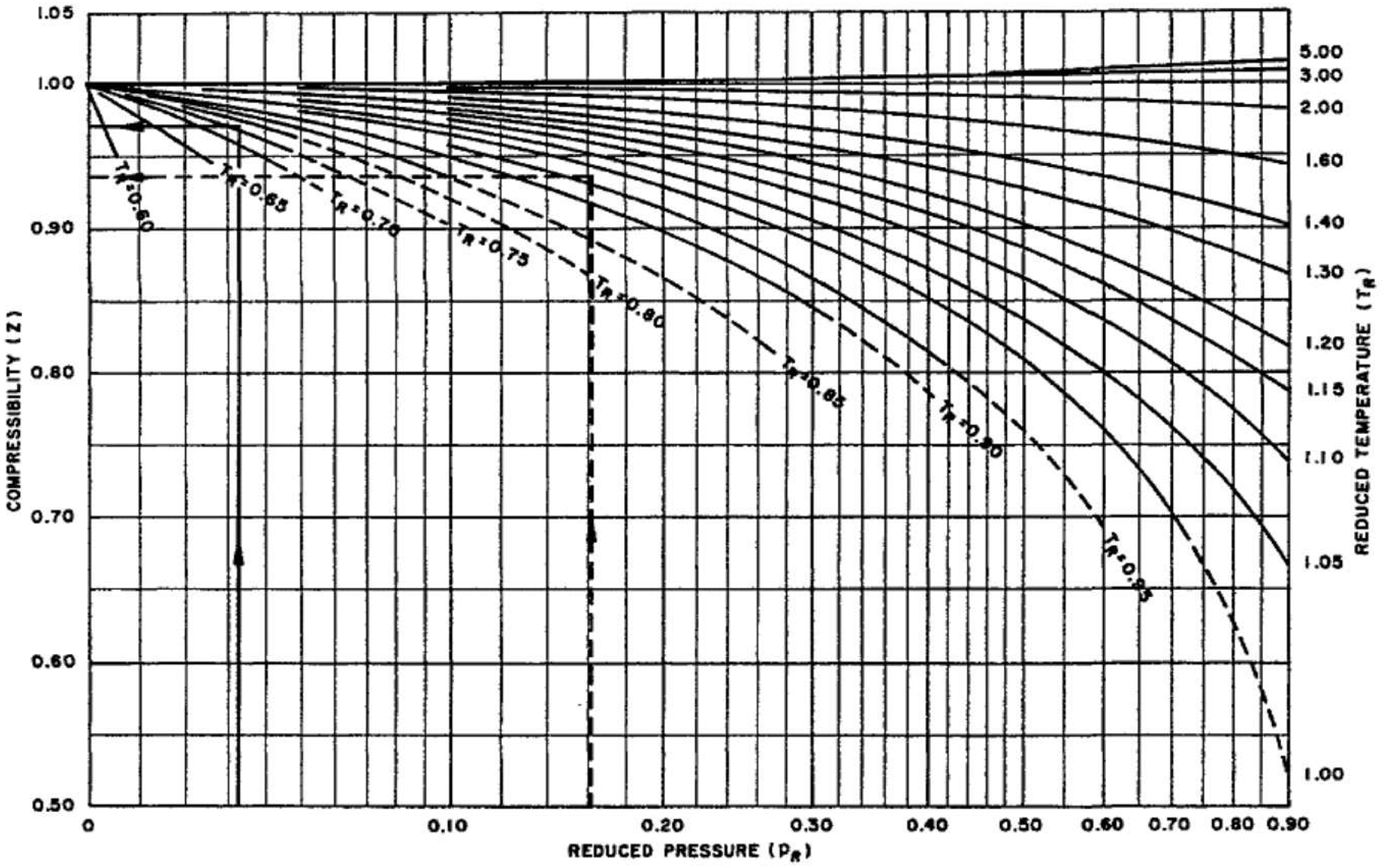


Figure B-13: Compressibility factor chart

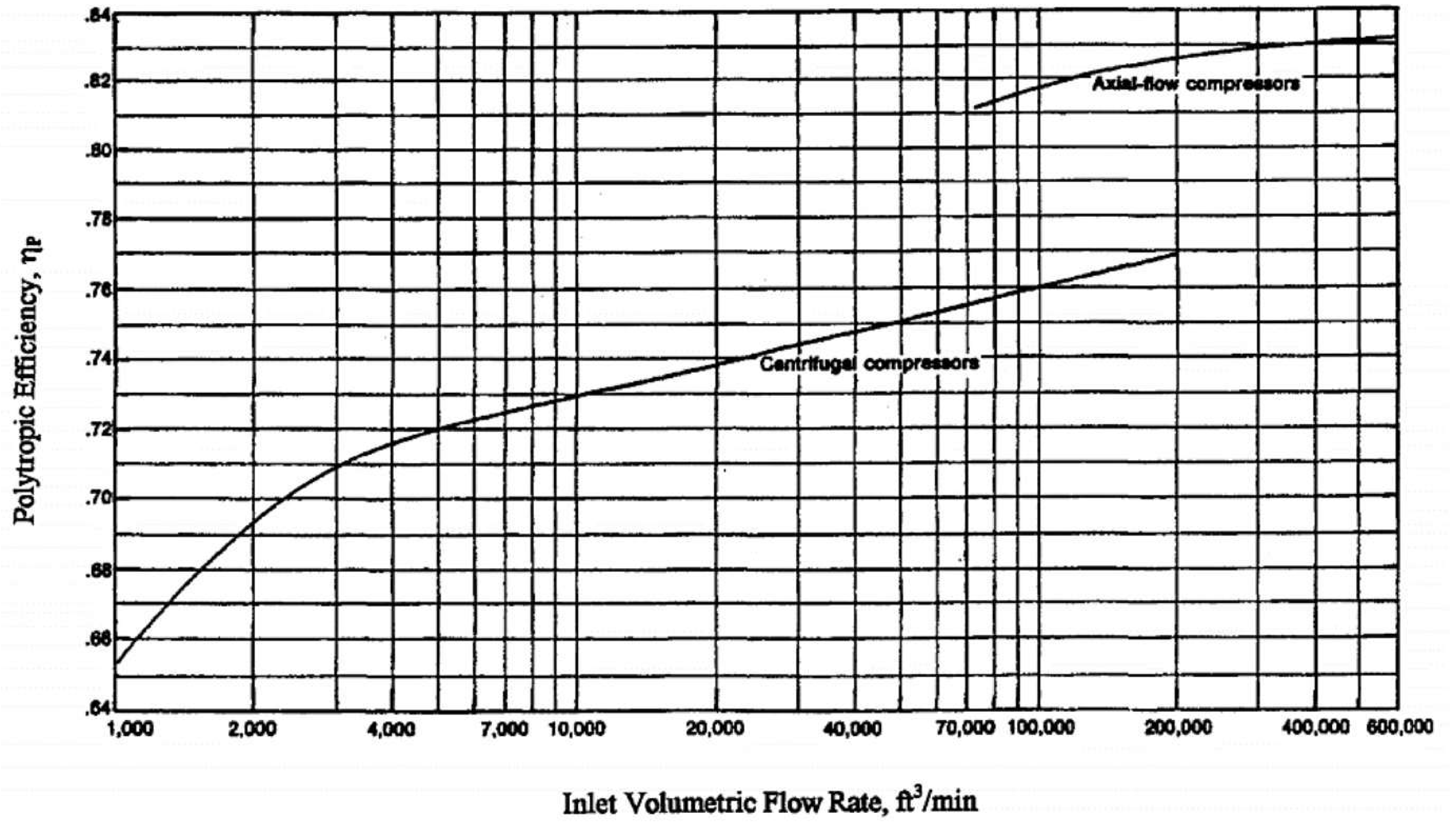
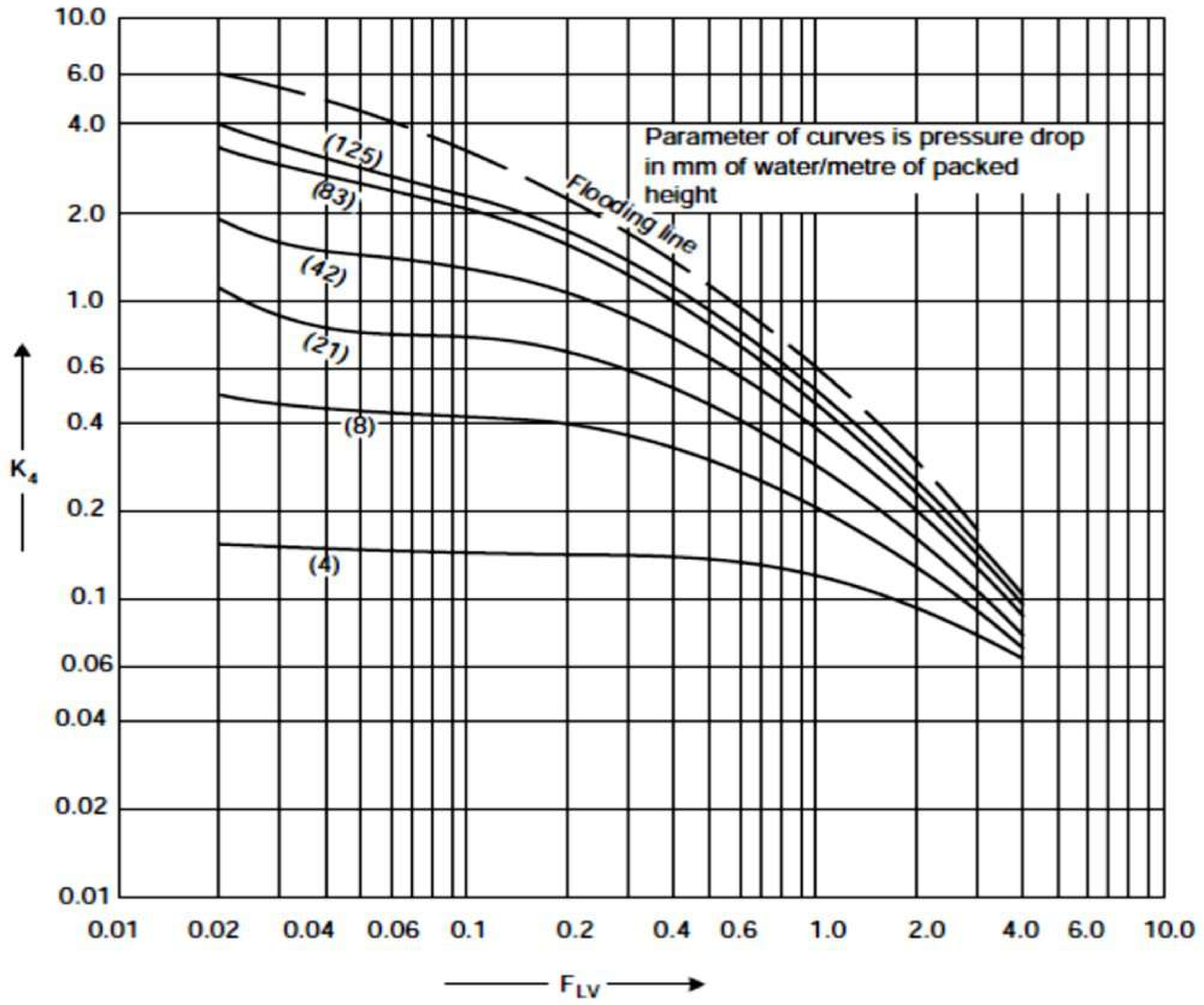


Figure B-14: Polytropic efficiency for Axial and Centrifugal Compressors.



$$F_{LV} = \frac{L_W^*}{V_W^*}\sqrt{\frac{\rho_V}{\rho_L}}$$

Figure B-15: *Generalized pressure drop correlation.*

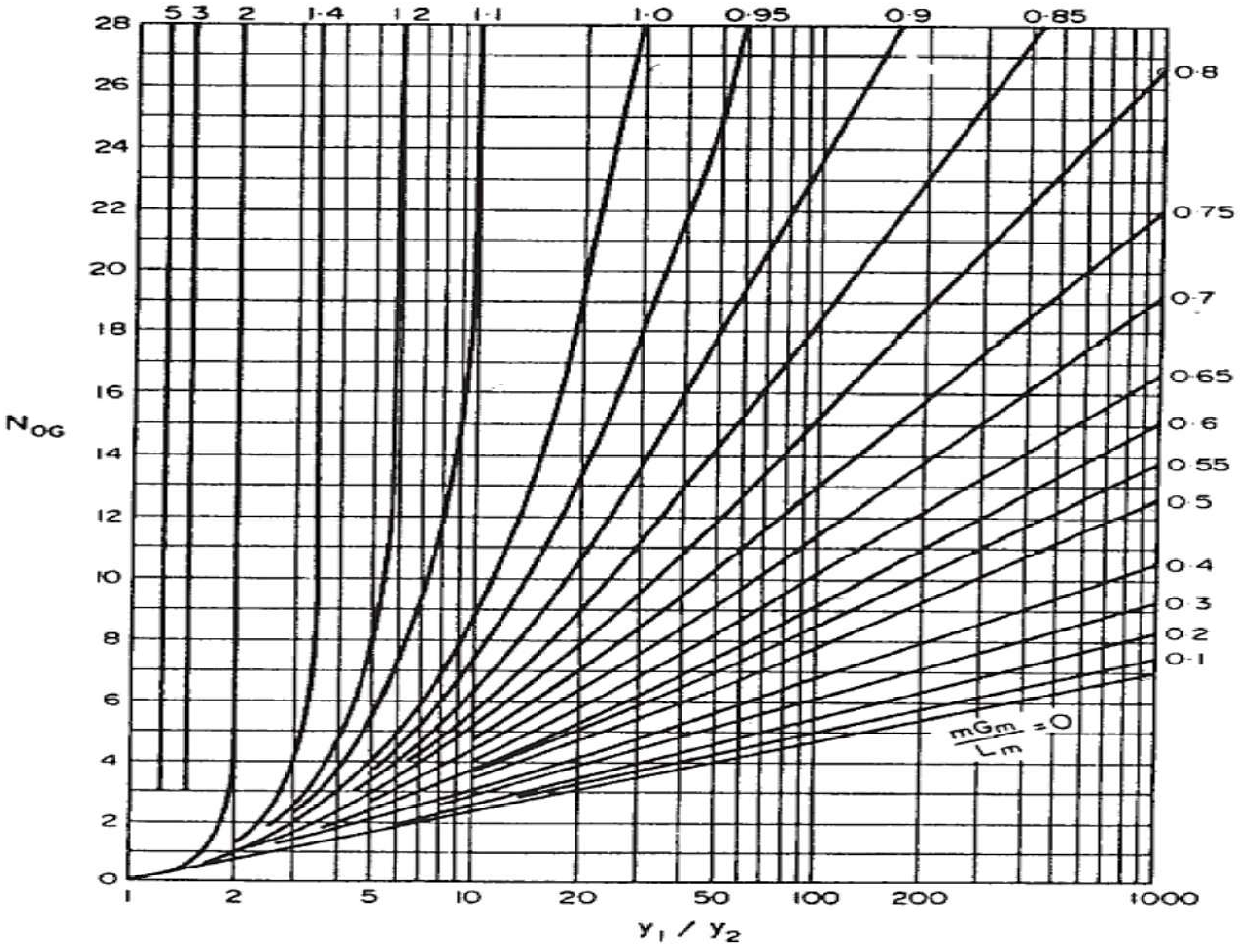


Figure B-16: Number of transfer units NOG as a function of y1/y2 with mGm/Lm as parameter

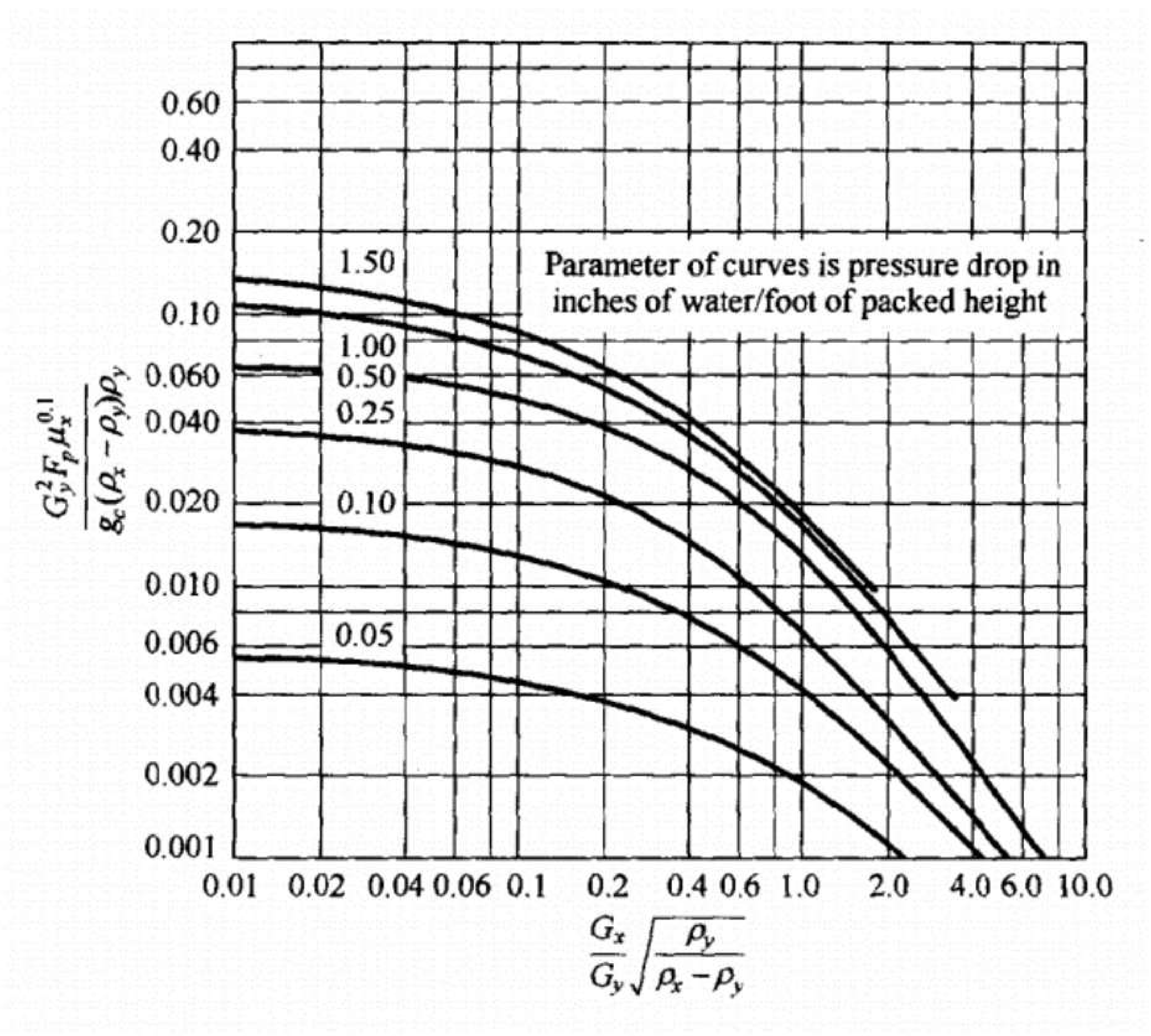
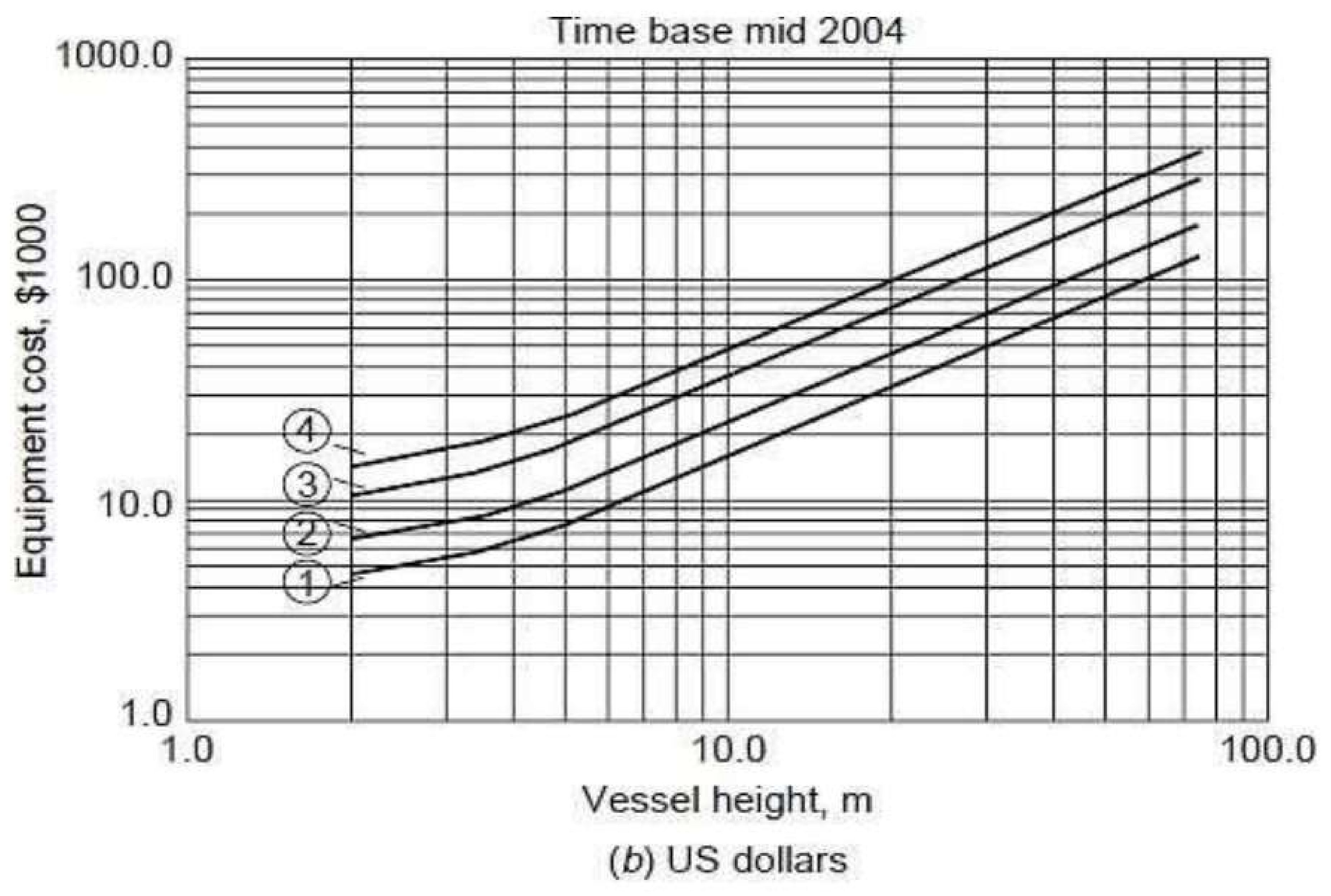


Figure B-17: Generalized correlation for pressure drop in packed columns. (1 in H2O/ft = 817 Pa/m)



(*b*) US dollars

Diameter, m	
①—0.5	③—2.0
②—1.0	④—3.0

Material factors	
C.S.	× 1.0
S.S.	× 2.0
Monel	× 3.4
S.S. clad	× 1.5
Monel clad	× 2.1

Pressure factors	
1–5 bar	× 1.0
5–10	× 1.1
10–20	× 1.2
20–30	× 1.4
30–40	× 1.6
40–50	× 1.8
50–60	× 2.2

Figure B-18: Cost of Reactor

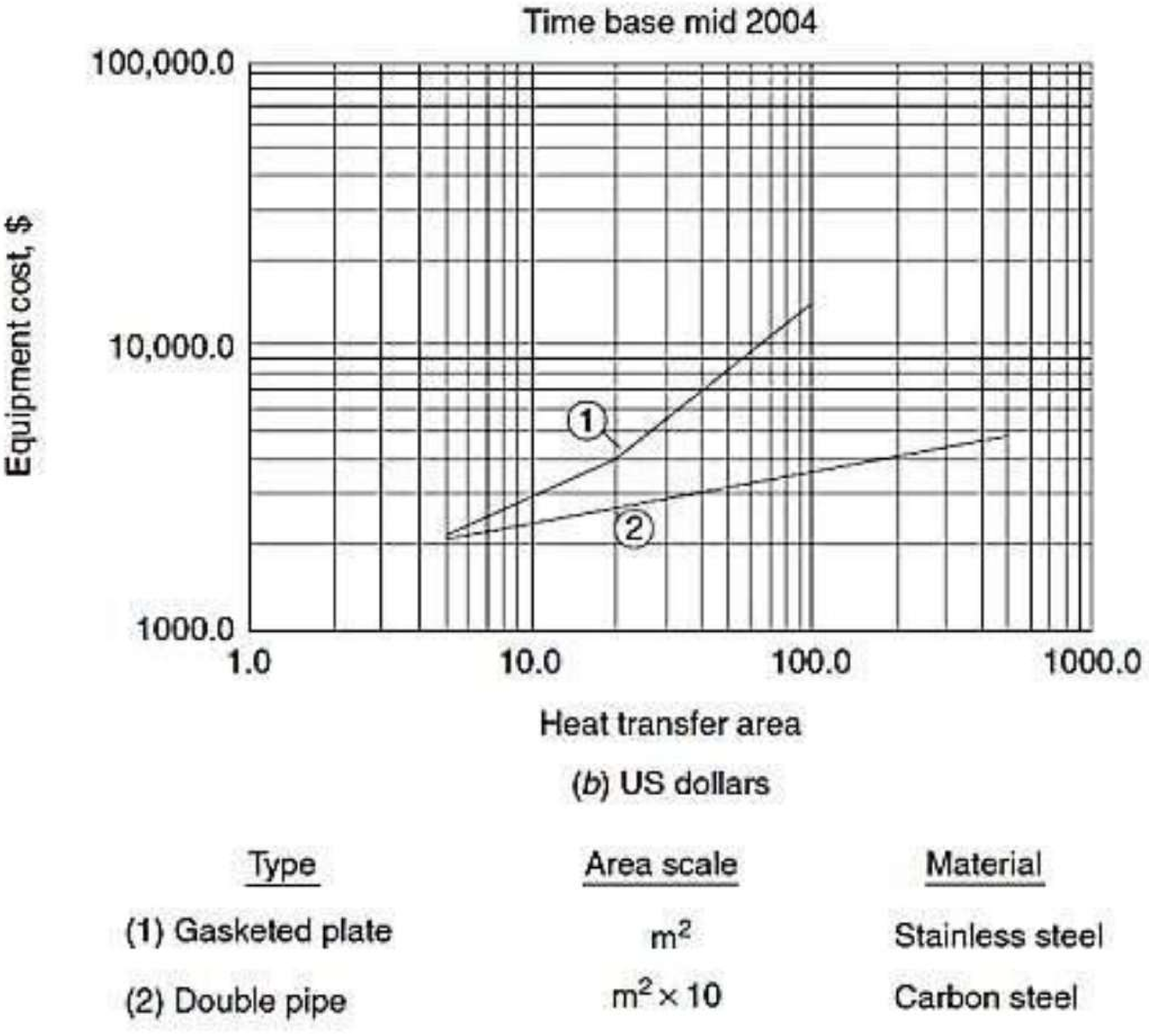


Figure B-19: Cost of Double Pipe Heat Exchanger

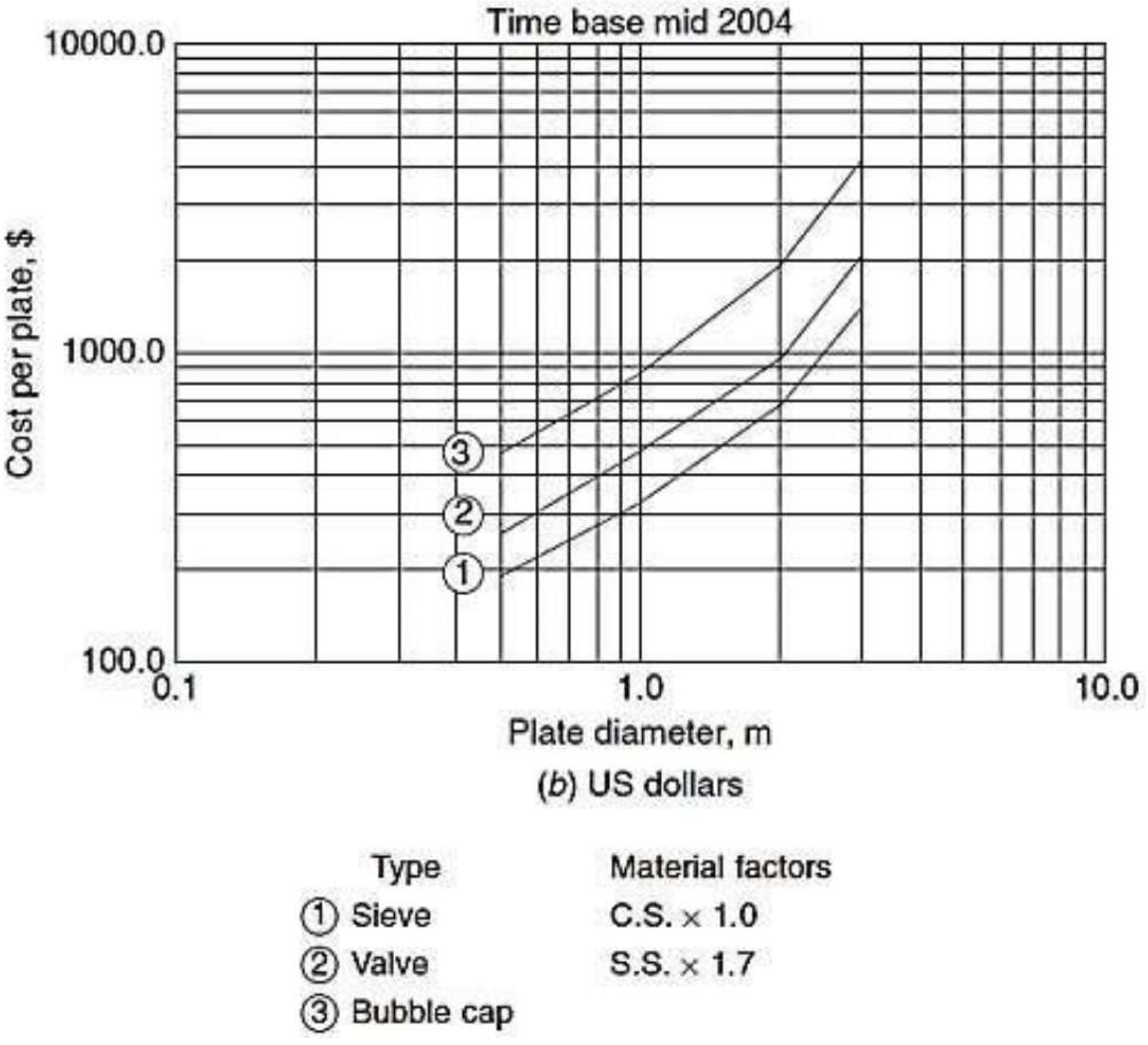
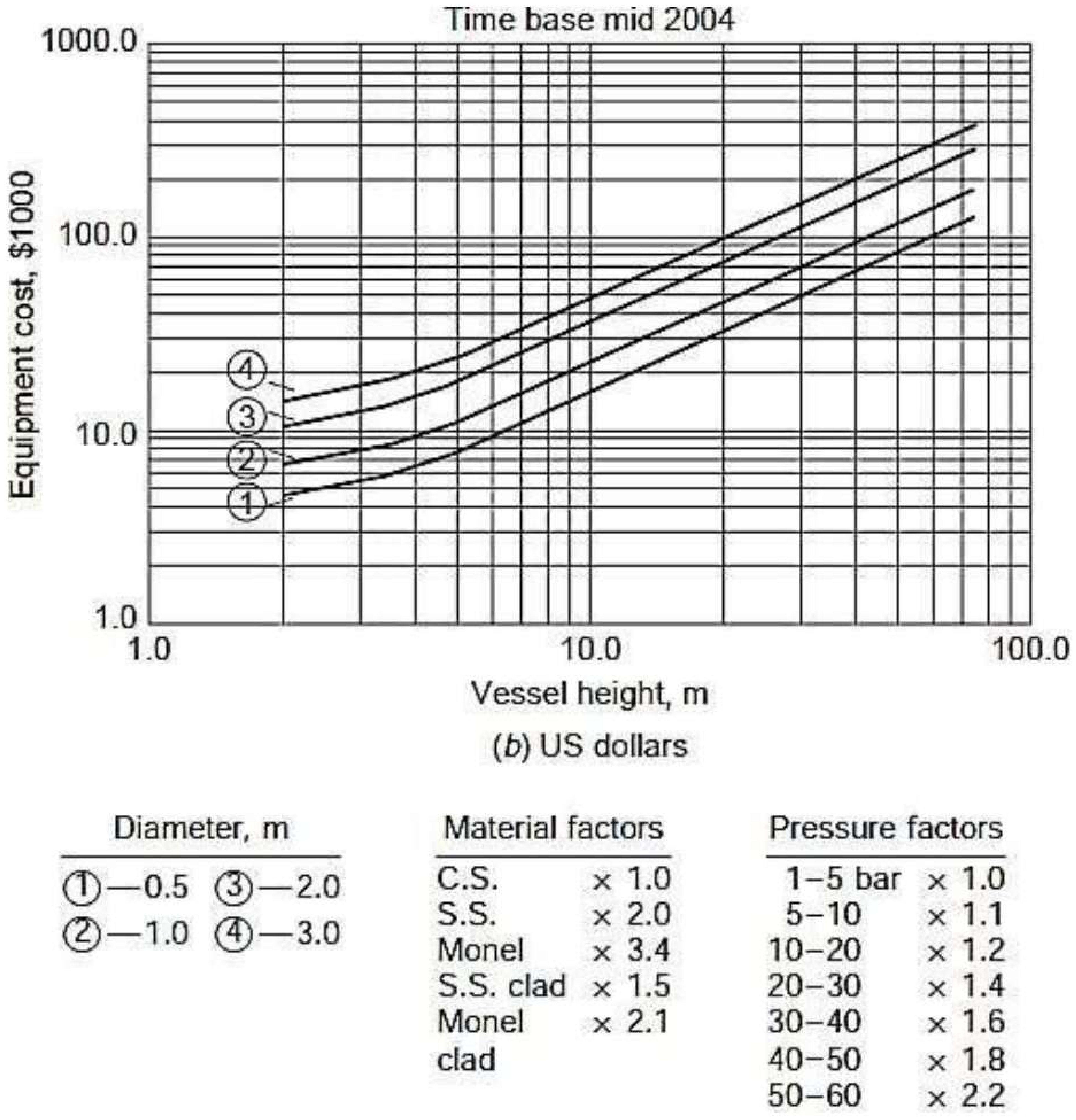


Figure B-20: Cost per Plate

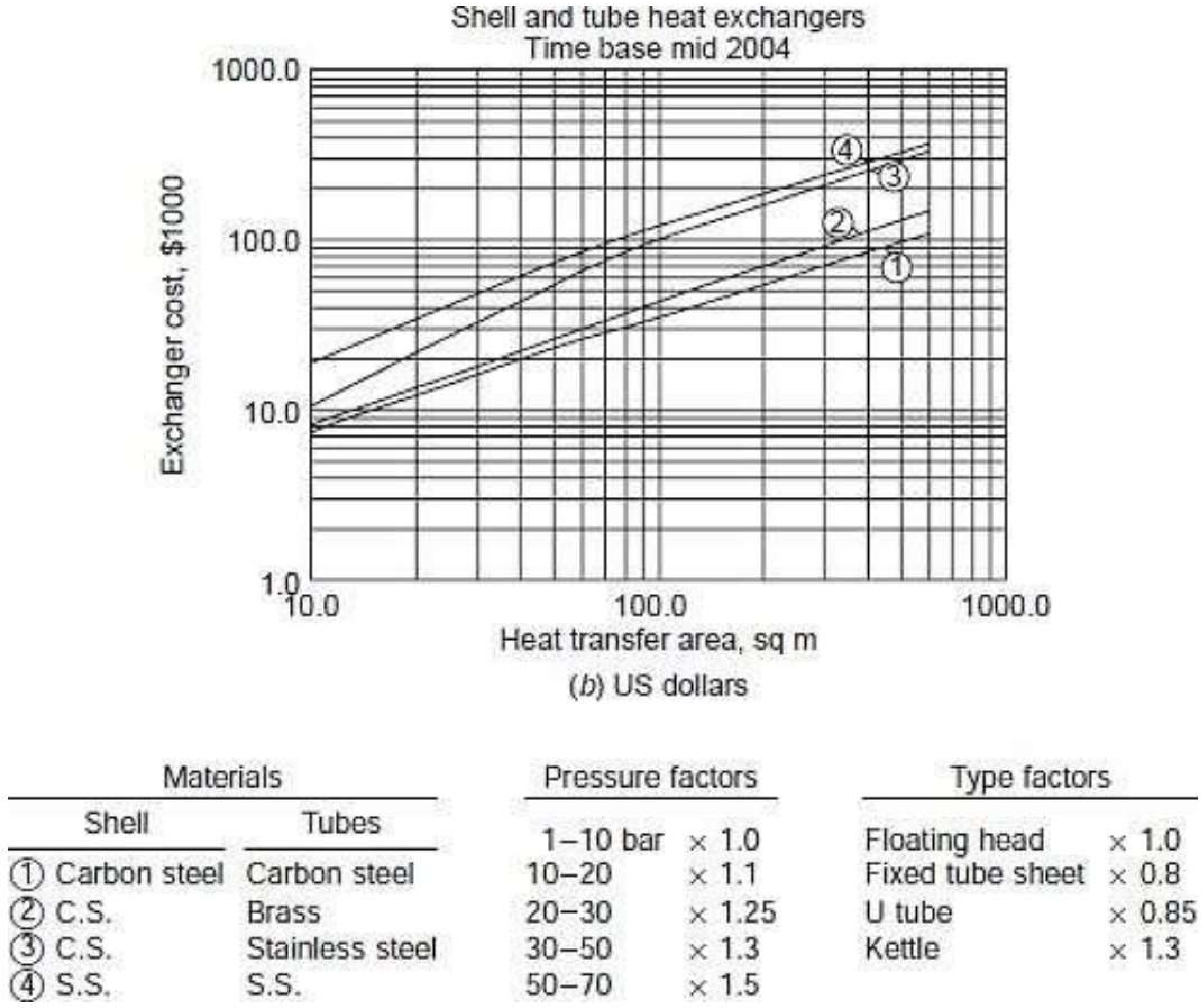


Diameter, m	
①—0.5	③—2.0
②—1.0	④—3.0

Material factors	
C.S.	× 1.0
S.S.	× 2.0
Monel	× 3.4
S.S. clad	× 1.5
Monel clad	× 2.1

Pressure factors	
1–5 bar	× 1.0
5–10	× 1.1
10–20	× 1.2
20–30	× 1.4
30–40	× 1.6
40–50	× 1.8
50–60	× 2.2

Figure B-21: Cost of Tower



Materials	
Shell	Tubes
① Carbon steel	Carbon steel
② C.S.	Brass
③ C.S.	Stainless steel
④ S.S.	S.S.

Pressure factors	
1–10 bar	× 1.0
10–20	× 1.1
20–30	× 1.25
30–50	× 1.3
50–70	× 1.5

Type factors	
Floating head	× 1.0
Fixed tube sheet	× 0.8
U tube	× 0.85
Kettle	× 1.3

Figure B-22: Cost of Shell and Tube Heat Exchanger

References:

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[1] González-Garay, A., Frei, M. S., Al-Qahtani, A., Mondelli, C., Guillén-Gosálbez, G., Pérez-Ramírez, J., et al. (2019). Plant-to-planet analysis of CO2-based methanol processes. Energy Environ. Sci. 12, 3425–3436. doi:10.1039/c9ee01673b

[2] Behrens, M.; Studt, F.; Kasatkin, I.; Kühl, S.; Hävecker, M.; Abild-Pedersen, F.; Zander, S.; Girgsdies, F.; Kurr, P.; Kniep, B.-L.; et al. The Active Site of Methanol Synthesis over Cu/ZnO/Al2O3 Industrial Catalysts. Science 2012, 336, 893–897.

[3] Chinchen, G.; Denny, P.; Parker, D.; Spencer, M.; Whan, D. Mechanism of methanol synthesis from CO2/CO/H2 mixtures over copper/zinc oxide/alumina catalysts: Use of14C-labelled reactants. Appl. Catal. 1987, 30, 333–338.

[4] Jiang, K., Li, K., Puxty, G., Yu, H., and Feron, P. H. (2018). Information derivation from vapour-liquid equilibria data: a simple shortcut to evaluate the energy performance in an amine-based post-combustion CO2 capture. Environ. Sci. Technol. 52, 10893–10901. doi: 10.1021/acs.est.8b 03512

[5] Holmes, G., and Keith, D. W. (2012). An air-liquid contactor for large-scale capture of CO2 from air. Philos. Trans. A Math. Phys. Eng. Sci. 370, 4380–4403. doi: 10.1098/rsta.2012.0137

[6] Heidel, K., Keith, D., Singh, A., and Holmes, G. (2011). Process design and costing of an air-contactor for air-capture. Energy Proc. 4, 2861–2868. doi: 10.1016/j.egypro.2011.02.192

[7] Hero, C. Properties of Hydrogen. [cited 2022 26 September]; Available from: https://www.coursehero.com/study-guides/introchem/properties-of-hydrogen/

[8] Inc., L.P. Chemicals and Solvents. [cited 2022 26 September]; Available from: https://labproinc.com/blogs/chemicals-and-solvents/top-10-uses-for-methanol#comments

[9] Wu, W.; Xie, K.; Sun, D.; Li, X.; Fang, F. CuO/ZnO/Al2O3 Catalyst Prepared by Mechanical-Force-Driven Solid-State Ion Exchange and Its Excellent Catalytic Activity under Internal Cooling Condition. Ind. Eng.Chem. Res. 2017, 56, 8216–8223.

[10] Bellotti, D.; Rivarolo, M.; Magistri, L.; Massardo, A.F. Feasibility study of methanol production plant from hydrogen and captured carbon dioxide. J. CO2 Util. 2017, 21, 132–138.

[11] Bayat, M.; Dehghani, Z.; Hamidi, M.; Rahimpour, M. Methanol synthesis via sorption-enhanced reaction process: Modeling, multi-objective optimization. J. Taiwan Inst. Chem. Eng. 2014, 45, 481–494

[12] Kumari, N.; Haider, M.A.; Agarwal, M.; Sinha, N.; Basu, S. Role of Reduced CeO2(110) Surface for CO2 Reduction to CO and Methanol. J. Phys. Chem. C 2016, 120, 16626–16635.

[13] Yu, K.M.K.; Curcic, I.; Gabriel, J.; Tsang, S.C.E. Recent Advances in CO2 Capture and Utilization. ChemSusChem 2008, 1, 893–899.

---

[14] M. M.-J., Zeng, Z.-Y., Liao, F.-L., Hong, X.-L., and Tsang, S. C. E. (2016). Enhanced CO2 hydrogenation to methanol over CuZn nanoalloy in Ga modified Cu/ZnO catalysts. J. Catal. 343, 157–167. doi:10.1016/j.jcat.2016.03.020

[15] Kaneko, T.; Derbyshire, F.; Makino, E.; Gray, D.; Tamura, M.; Li, K. Coal Liquefaction. In Ullmann's Encyclopedia of Industrial Chemistry; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2012; p. 32.

[16] The Engineering ToolBox, Fuels—Higher and Lower Calorific Values, 2003. Available onlinen https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

[17] Trippe, F.; Fröhling, M.; Schultmann, F.; Stahl, R.; Henrich, E.; Dalai, A. Comprehensive techno-economic assessment of dimethyl ether (DME) synthesis. Fuel Process. Technol. 2013, 106, 577–586.

[18] Yedantu. Air Composition Properties. [cited 2022 26 September]; Available from: https://www.vedantu.com/physics/air-composition-properties.

[19] Aresta M, Dibenedetto A. Utilisation of CO2 as a chemical feedstock: Opportunities and

challenges. Dalton Transactions. 2007;(28):2975-2992

[20] IREN. Renewable Power Generation Costs in 2017; International Renewable Energy Agency: Abu Dhabi, UAE, 2018.

[21] Chen, Y.; Choi, S.; Thompson, L.T. Low-Temperature CO2 Hydrogenation to Liquid Products via a Heterogeneous Cascade Catalytic System. ACS Catal. 2015, 5, 1717–1725.

[22] Wu, W.; Xie, K.; Sun, D.; Li, X.; Fang, F. CuO/ZnO/Al2O3 Catalyst Prepared by Mechanical-Force-Driven

Solid-State Ion Exchange and Its Excellent Catalytic Activity under Internal Cooling Condition. Ind. Eng.

Chem. Res. 2017, 56, 8216–8223.

[23] Bellotti, D.; Rivarolo, M.; Magistri, L.; Massardo, A.F. Feasibility study of methanol production plant from hydrogen and captured carbon dioxide. J. CO2 Util. 2017, 21, 132–138.

[24] Aresta M. Carbon Dioxide as Chemical Feedstock. John Wiley & Sons; 2010

[25] K.A. Ali, A.Z. Abdullah, A.R. Mohamed, Recent development in catalytic technologies for methanol synthesis from renewable sources: a critical review, Renew. Sustain. Energy Rev. 44 (2015) 505–518.

[26] https://www.maximizemarketresearch.com/market-report/methanol-market/126817/

[27] Alie, L. Backham, E. Croiset, P.L. Douglas. Simulation of CO2 capture using MEA scrubbing: a flowsheet decomposition method C. Department of Chemical Engineering, University of Waterloo, Waterloo, Ont., Canada N2L 3G1 Received 28 December 2003; accepted 20 March 2004 Available online 3 August 2004

---

[28] Pakistan Council of Scientific and Industrial Research. (2019). Environmental challenges and their remedies in Pakistan. http://www.pcsir.gov.pk/home/NewsDetails/100

[29] Chemical Process Safety: Fundamentals with Applications" by Daniel A. Crowl and Joseph F. Louvar

[30] Guidelines for Hazard Evaluation Procedures" by the Center for Chemical Process Safety (CCPS)

[31] Relevant articles from reputable journals such as Chemical Engineering Research and Design, Industrial & Engineering Chemistry Research, and Journal of Loss Prevention in the Process Industries.

[32] Process Risk and Reliability Management: Operational Integrity Management" by Ian Sutton

[33] Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design" by Gavin Towler and Ray Sinnott.

[34] Risk Analysis and Control for Industrial Processes - Gas, Oil, and Chemicals" by Hans Pasman and Piet Demeere.

[35] Process Safety Management: Leveraging Networks and Communities of Practice for Continuous Improvement" by Andrew Hopkins and David B. Walters.

[36] Safety and Health for Engineers" by Roger L. Brauer.

[37] Hussain, A., Khan, A., & Alam, M. (2020). Environmental challenges and sustainable solutions in Pakistan. Journal of Cleaner Production, 271, 122492. https://doi.org/10.1016/j.jclepro.2020.122492

[38] Rajaeifar, M. A., & Ismail, A. F. (2020). Mixed matrix membranes: A review of membrane performance enhancement by fillers and the integration of carbon nanotubes. Chemical Engineering Research and Design, 162, 373-402. https://doi.org/10.1016/j.cherd.2020.06.005

[39] Robinson AB, Robinson NE, Soon W. Environmental Effects of increased atmospheric carbon dioxide. Journal of American Physicians and Surgeons. 2007;12:79-90

[40] Ritter SK. What can we do with CO? Chemical & Engineering News Archive. 2007;85(18): 11-17

[41] MI. Methanol Institute. 2013. Available from: The Methanol Industry, http://www.methanol.

org/Methanol-Basics.aspx

[42] Safety Analysis: Principles and Practice in Occupational Safety" by John Channing.

[43] Borgwardt, R H. Shi, Z. S.; Tan, Q. Q.; Wu, D. F. A novel Core-Shell structured CuIn SiO2 catalyst for CO_2 hydrogenation to methanol. AIChE J. 2019, 65 (3), 1047−1058.

[44] Advances in the conversion of methanol to gasoline Jyoti Prasad Chakraborty, Sunil K. Maity, in Hydrocarbon Biorefinery, 2022