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Control Structure Design and Dynamic Simulation of Mixed Fluid Cascade Natural Gas Liquefaction Process

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ABSTRACT

Mixed fluid cascade natural gas liquefaction process control system is designed and analyzed in this study. The specific energy consumption (SEC) of this process is 0.2647 kWh/kg LNG. After steady state simulation and sizing the process components, a control structure is designed to control the whole process. In addition, dynamic simulation is carried out and performance of the controllers is investigated. By dynamic simulation, specific energy consumption is reduced to 0.2574 kWh/kg LNG, which means the designed control structure can stably and accurately control the process. To validate the performance and stability of the control structure, changes in the flow rate and temperature of the feed gas are inflicted as a disturbance to the process.

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1. Introduction

Over the last five decades the global energy demand has been inclined towards fuels with lower carbon content, e.g. natural gas, due to environmental concerns [1]. Today the share of natural gas in primary energy is about 24% and it is predicted that this share will rise to about 27% by 2040 [1]. Generally, there are various methods for natural gas transportation such as pipelines, liquefied natural gas (LNG), compressed natural gas (CNG) and so on. According to the BP Energy Outlook, it is expected that the share of LNG in the worldwide gas trade will grow from 35% in 2017 to above 46% by 2035, and its share of consumption will increase from 10% to 15% [1]. There are several cryogenic processes available for LNG production that the basis of all them is cooling of natural gas to approximately -162 °C at atmospheric pressure. Thus, natural gas becomes an odorless, colorless and noncorrosive liquid and its volume is reduced by about 600 times [2]. In this paper, the Mixed Fluid Cascade (MFC) process is considered for studying.

In the MFC process, three cascade refrigeration cycles are used. In fact, purified natural gas is precooled, liquefied and subcooled by means of three different mixed refrigerants in these cycles [3]. This technology is capable of producing up to 12 million tons per annum LNG in a single train [4]. Despite the complexity of the MFC process (due to the high number of the required equipment) and high investment costs, this process has higher thermodynamic efficiency, lower energy consumption and higher exergy efficiency compared to the other LNG processes [5].

Generally, the liquefaction processes of natural gas consume considerable amounts of energy, making it crucial for the processes to operate efficiently, reliably and safely [6]. In order to achieve these aims and maximize the profit, these processes should be kept well under control [7] hence necessitating the design of a control structure. The main goals of this study include designing an optimized control structure and perform a dynamic simulation of the MFC process. These studies have not been performed up to now because most of the previous studies on the LNG production processes cover their operation in the steady state. For example, in [5, 8], energy, exergy and advanced exergetic analyses of the five conventional LNG processes were carried out. These analyses were performed by simulation of these processes in steady state mode and their results show that the MFC process has better performance compared to the other LNG processes, i.e. it has lower energy consumption (0.2545 kWh/kg LNG), higher coefficient of performance (4.812 for precooling cycle) and higher exergy efficiency (51.82 %). Only in recent years, dynamic simulation and process control of the common C3MR process have been performed by different groups which reported in the literature [7, 9-11]. Husnil *et* al. (2014) [12] developed a control structure for the MSMR process for a floating LNG plant and optimized the cost function by adjusting the controlled variable, i.e. the flow rate ratio of liquid (heavy) and vapor (light) mixed refrigerant. Also, the dynamic modeling and control structure design of the LNG process patented by SINTEF was carried out by Singh *et* al. [13].

In this work, the MFC process is simulated in steady state mode using a conventional commercial chemical simulator (available from Aspen Technologies Inc.). Then, a control structure is designed and analyzed. Followed, dynamic simulation of the MFC process is carried out to test the proposed control structure.

2. Process Description

The number of refrigeration cycles and the required power in the refrigeration systems are effective parameters in the performance of the liquefaction processes. However increasing the number of cycles improves process efficiency and production capacity, but it increases the fixed costs and process complexity [5]. It increases the operating costs as well. The most economical situation can be achieved when the process capacity is increased without adding to the number of cycles [5]. In this regard, Linde AG and Statoil introduced a new LNG process, called Mixed Fluid Cascade or MFC process.

(Figure 1) shows the process flow diagram of MFC process. Treated natural gas (NG) enters the process at 13 °C and 60 bar. Through passing four heat exchangers, E-1-A, E-1-B, E-2 and E-3, the natural gas is completely converted to LNG after being pressure relieved to about atmospheric pressure by J-T valve (V-5). As mentioned, three mixed refrigerant cycles are used to supply the required refrigeration. These cycles are discussed in the next sections.

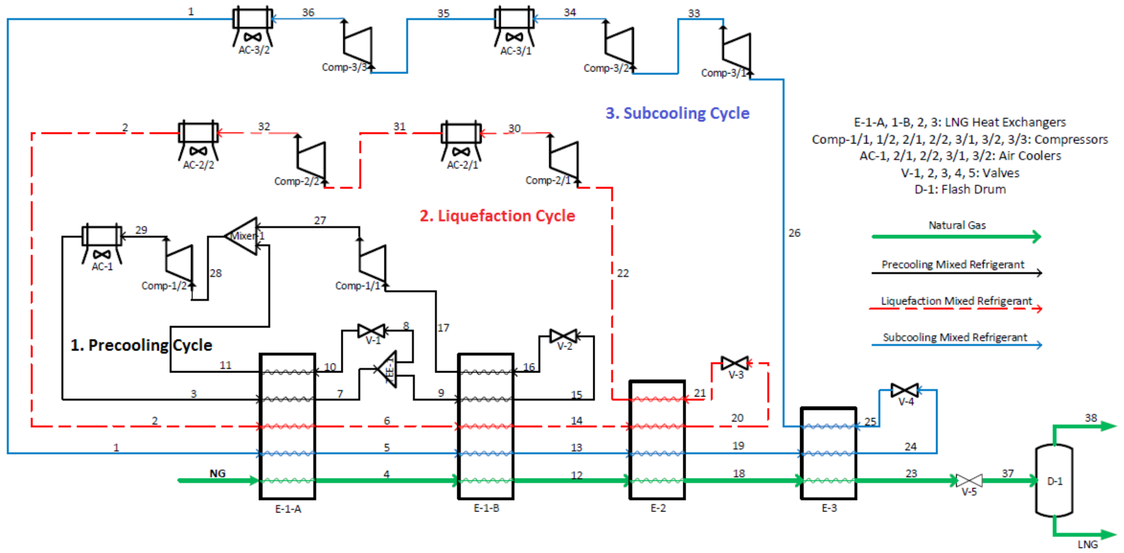


Figure 1: Process flow diagram of MFC process.

2.1. Precooling Cycle

Natural gas enters the precooling cycle (via state points NG⟶4⟶12) and is cooled to approximately the dew point temperature (about -27 °C: stream 12). This cycle consists of two plate fin heat exchangers (PFHEs) (E-1-A and E-1-B) [4]. A mixture of ethylene, ethane, propane and n-butane is used as the mixed refrigerant (MR) in this cycle [8].

The mixed refrigerant (stream 3), after passing through the E-1-A (3⟶7), is divided into two fractions and is used at two pressure levels. Stream 8 enters a J-T valve (V-1) and used as a cooling agent in E-1-A. Another fraction, stream 9, is used in the second heat exchanger, E-1-B, to provide the required cooling. The outlet refrigerant from E-1-B, stream 17, after passing through the Comp-1/1 compressor (17⟶27) is mixed with the outlet refrigerant from E-1-A, stream 11, and follows to another compression section (Comp-1/2: 28⟶29). Next, mixed refrigerant is cooled in an air cooler (AC-1) and re-enters the E-1-A at 36 °C and 16.89 bar (29⟶3).

2.2. Liquefaction Cycle

The liquefaction cycle consists of the E-1-A, E-1-B and E-2 heat exchangers. The E-2 is a spiral wound heat exchanger (SWHE) [4]. The natural gas enters at the dew point temperature and is condensed after leaving E-2 with the temperature of -85.20 °C (12⟶18). In this cycle, the mixed refrigerant (stream 2) is a mixture of methane, ethylene, ethane and propane [8]. The refrigerant is cooled in E-1-A, E-1-B and E-2 before following to V-3 J-T valve and is used again in E-2 but now as a cooling agent (2⟶6⟶14⟶20⟶21⟶22).

The compression of mixed refrigerant is done in two stages (Comp-2/1 & Comp-2/2) with an intermediate air cooler (AC-2/1). The refrigerant is also cooled in another air cooler (AC-2/2) before entering E-1-A. After passing through the compressors and air coolers, the refrigerant operating condition reaches to 36 °C and 27.89 bar (22⟶30⟶31⟶32⟶2).

2.3. Subcooling Cycle

The subcooling cycle consists of E-3 spiral wound heat exchanger in addition to the prenominated heat exchangers [4]. The condensed natural gas is sub-cooled in this heat exchanger and leaves it at -158 °C (18⟶23). The pressure is reduced to atmospheric pressure after passing through V-5 expansion valve. Finally, LNG is produced at -163.4 °C and 1 bar. Here, the mixed refrigerant (stream 1) is a mixture of methane, ethylene and nitrogen [8]. It is cooled in E-1-A, E-1-B, E-2 and E-3 (1⟶5⟶13⟶19⟶24). After following to V-4 expansion valve (24⟶25), the MR (stream 25) is used again in E-3 as a cooling agent. Then it is compressed in the same procedure as the liquefying refrigerant (26⟶33⟶34⟶35⟶36⟶1).

3. Steady State Simulation of MFC Process

3.1. Process Simulation

In this paper, simulation of the entire process is carried out using Aspen HYSYS 7.2 software. Cryogenic processes are somewhat different from the general chemical processes [14]. Some of the characteristics of the cryogenic processes include multi-stream heat exchangers, low temperature, and high operating pressure. For performing thermodynamic calculations and process simulation, an equation of state (EOS) is required. For the cryogenic natural gas processes, PR (Peng-Robinson) and PRSV (Peng-Robinson-Stryjek-Vera) equations of state are suggested [15]. Thermodynamic fluid package of PRSV is used for the simulation in this study. Specifications and operating conditions of feed gas, mixed refrigerants and LNG product that were used as a basis for the simulation model are given in Table 1.

Table 1. (a) Feed gas and mixed refrigerants specifications of MFC process

Stream Name	NG	LNG	1	2	3
	Natural Gas Feed	Liquid Product	Sub cooling Mixed Refrigerant	Liquefaction Mixed Refrigerant	Precooling Mixed Refrigerant
Molar Flow (kmol/h)	25120.00	23653.26	18100.00	25700.00	34390.00
Temperature (°C)	13.00	-163.40	36.00	36.00	36.00
Pressure (bar)	60.00	1.01	33.89	27.89	16.89
Components (mol %)					
CH_4	89.00	89.65	42.45	12.65	0.00
C_2H_6	5.50	5.84	0.00	32.92	0.01
C_2H_4	0.00	0.00	40.24	27.77	11.29
C_3H_8	2.50	2.66	0.00	26.66	73.57
$n\text{-}C_4H_{10}$	1.00	1.06	0.00	0.00	15.13
N_2	2.00	0.79	17.31	0.00	0.00

3.2. Simulation Results

The MFC process is simulated in the steady-state mode and is validated against literature data which can be found in [8]. Tables 2-5 present results of the simulation. These results include performance of the equipment in the process and overall performance of the process.

Table 2. Performance of the heat exchangers of MFC process.

LNG HE Name	Number of Sides	Duty (kW)	Min. Approach Temp. (°C)	LMTD* (°C)
E-1-A	5	100553.99	2.919	4.219
E-1-B	5	73339.21	2.321	3.796
E-2	4	118416.28	2.119	3.342
E-3	3	59060.57	4.254	5.541

* Log Mean Temperature Difference

Table 3. Performance of the air coolers of MFC process.

Air Cooler Name	Number of Fans*	Working Fluid Duty (kW)	Total Mass Air Flow×10^{-7} (kg/h)	Total Fan Power (kW)*	Air Outlet Temp. (°C)
AC -1	51	-164817.11	2.0670	977.991	53.33
AC-2/1	23	-12640.03	0.9689	690.471	29.64
AC-2/1	37	-21112.41	1.5580	1064.946	29.82
AC-3/1	13	-5589.24	0.5486	354.407	28.62
AC-3/2	13	-3919.00	0.5496	355.863	27.53

* These results are obtained from the air coolers simulation with EDR software.

Table 4. Performance of the compressors of MFC process.

Compressor Name	Power Consumed (kW)	Pressure Ratio	Outlet Temp. (°C)
Comp-1/1	9123.90	2.233	36.19
Comp-1/2	27438.88	2.522	78.75
Comp-2/1	32902.32	4.839	64.64
Comp-2/2	14120.01	1.861	78.78
Comp-3/1	16778.12	4.286	5.94
Comp-3/2	10076.55	1.867	62.08
Comp-3/3	3202.66	1.211	53.96

Table 5. Overall performance of MFC process.

Total Power Consumed in Compressors (kW)	113642.44
Total Power Consumed in Air Coolers (kW)	3443.678
Overall Required Power (kW)	117086.118
Mass Flow of LNG Product (kg/h)	429267
Specific Energy Consumption (kWh/kg LNG)	0.2647*

* For calculating of the SEC, energy consumption of the air coolers is neglected because its value is negligible compared to the energy consumption of the compressors.

As can be seen in Table 5, the specific energy consumption or SEC of the process is equal 0.2647 kWh/kg LNG. Here, SEC is defined by the ratio of the total required power (energy) in the process to the mass flow rate of produced LNG:

$$\mathrm{SEC\ (kWh/kg\ LNG)} = \frac{\text{total required power in the process (kW)}}{\text{mass flow rate of produced LNG (kg/h)}} \quad (1)$$

Low SEC value means the energy efficiency of the process is high and vice versa. Different values for this index in different processes can be found in the related references [16, 17]. For example, value of the SEC for multi-stage processes should be less than 0.3 kWh/kg LNG [17]. In this study, the specific energy consumption is less than 0.3 kWh/kg LNG which corroborates that the process model simulated is valid when compared to the real world scenario.

The composite curve of the MFC process is illustrated in (Figure 2). Totally a composite curve shows the overall heating and cooling of a process and the quality of thermal design through the process. So (Figure 2) also validates that the process is thermally efficient and the LNG heat exchangers have appropriate performance due to using mixed refrigerants and three refrigeration cycles.

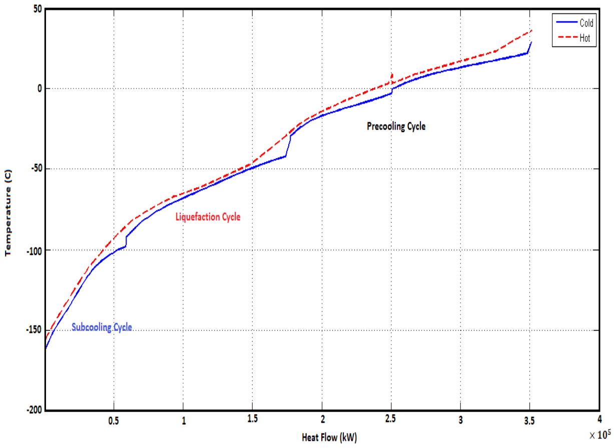


Figure 2: Composite curve of MFC process.

3.3. Equipment Sizing

After static simulation, all components in the process should be sized as it is necessary for entering the dynamic environment of the simulator. The equipment used in the MFC process includes centrifugal compressors, LNG heat exchangers, air coolers, expansion valves and a vertical separator. In following sections, the main equipment (heat exchangers and compressors) and their required sizing parameters are explained. It is worth noting that there is no need to size all of the equipment in detail and only parameters which are required to run the dynamic simulation should be determined.

3.3.1. Heat Exchangers

Multi-stream LNG heat exchangers are the most important equipment of the gas liquefaction processes and are considered as the heart of the process. As mentioned before, PFHEs are used in the precooling cycle and SWHEs are used for liquefaction and subcooling cycles in the MFC process. Since these heat exchangers are proprietary equipment, so sizing information is unavailable in the open literature. Dynamic modeling of such heat exchangers has been discussed for simple processes in a few publications [6, 10, 18].

In this paper, PFHEs and SWHEs are modeled as shell and tube heat exchangers for the purpose of simplification so that the total heat load generated by shell and tube heat exchangers is equal to the heat load of a LNG heat exchanger and the main specifications of the streams are not changed. As a result, there is no change in the overall performance of the MFC process and SEC. Shell and tube heat exchangers have several calculation models that can be used. Generally, the simulator models shell & tube Heat Exchangers based on the following equations (Eqs. 2 & 3) [19]:

1) $$\text{Balance Error} =(\dot{m}_{cold}[h_{out}-h_{in}]_{cold}-Q_{leak})-(\dot{m}_{hot}[h_{in}-h_{out}]_{hot}-Q_{loss}) \quad (2)$$

where: $\dot{m}$ = fluid mass flow rate, h = specific enthalpy, Q leak = heat leak (the loss of cold side duty to leakage), Q loss = heat loss (the loss of hot side duty to leakage), Balance Error= a heat exchanger specification that equals zero for most applications.

2) $$Q_{\text{transferred}} = \text{U.A.CMTD} \quad (3)$$

where Q transferred is the total heat transferred between the tube and shell sides (heat exchanger duty), U is the overall heat transfer coefficient, A is the surface area available for heat transfer, and CMTD is the corrected log mean temperature difference. Here, the EDR-Shell & Tube model is selected for simulation of these heat exchangers and the heat leak and heat loss are neglected. By using this model, the heat transfer coefficients and areas are calculated from the geometric data (EDR results) and feed streams.

3.3.2. Compressors

Compressors can be modelled with a determined constant efficiency or by supplying compressor performance curves (head versus volumetric flow curves) where in fact the efficiency is calculated as a function of volumetric flow for various compressor speeds. Fan Laws are used to model speed dependent variations in performance, so that a single performance curve is enough to describe the compressor behavior at any speed and simulates it more precisely. These laws reveal the fundamental operating principles of compressors that volume capacity (actual volume flow) is proportional to the compressor speed and head is proportional to the square of compressor speed and power to cube (Eqs. 4,5 and 6) [20]:

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \quad (4)$$

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2 \quad (5)$$

$$\frac{W_2}{W_1} = \left(\frac{N_2}{N_1}\right)^3 \quad (6)$$

In these equations, V is the volume flow, H is the head, W is the power (work) and N is the compressor speed. The fan laws generate approximate results which are reasonable in the 80 to 105% speed range [20]. And the adiabatic efficiency of the compressor is calculated as Eq. 7 [19]:

$$\text{Head} = \frac{\text{Work Required}_{\text{(actual)}}}{\text{Mass Flow Rate}} \times \text{Adiabatic Efficiency} \times \frac{1}{g} \quad (7)$$

where g is the acceleration of gravity. In the MFC process, performance curves combined with the simulator are used for simulation of compressors. For example, the performance curve of comp-1/1 is illustrated in (Figure3). These curves are obtained based on the fan laws.

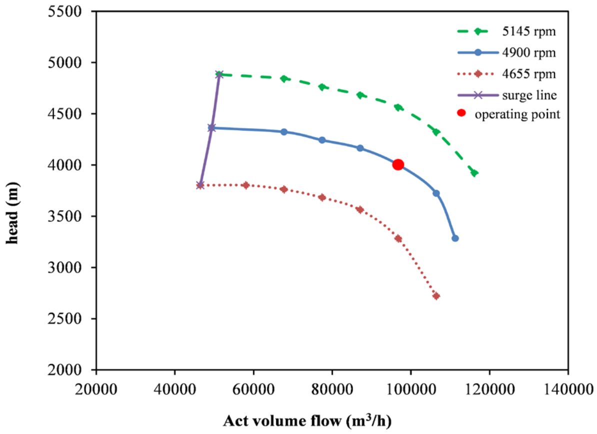


Figure 3. Performance curve of Comp-1/1 at different compressor speeds.

4. Control Structure Design of MFC Process

4.1. Process Control

In general, process control refers to the techniques which are used to control process variables when manufacturing a product. A control system is based on the following demands [21]: to eliminate the effect of external disturbances and reduce variability, to ensure the stability and safety, to optimize the performance of chemical processes and increase their efficiency. According to Skogestad [22], control structure design for complete chemical plants is known as plant-wide control which deals with the control philosophy of the overall plant and it is defined as the structural decisions involved in control system design, such as:

- Selection of controlled variables (CVs) and set points (SPs)
- Selection of manipulated variables (MVs)
- Selection of measurements
- Selection of control configuration
- Selection of controller type (control law specification, e.g. PID, etc.).

In the remainder of section 4, the tasks listed above will be discussed to achieve purpose of this paper.

4.2. Selection of Controlled Variables

The issue of selecting controlled variables or process variables (PVs) is the first and main decision in the control structure design problems. While selecting process variables, these four requirements should be observed [22]:

- The optimal value of the PV should be insensitive to disturbances
- The PV should be easy to measure and control
- The PV should be sensitive to changes in the manipulated variables
- In case of multiple PVs, the selected PVs should be independent.

Also, there are different criteria that contribute to this decision, such as product quality requirements, energy consumption, equipment capacity, and limitations due to safety. It should be said that the focus of this study is on the specific energy consumption (SEC) of the whole process, i.e. this parameter is the objective function and the selected process variables must be controlled in a way that the SEC remains lower than 0.3 kWh/kg LNG.

In the discussed process (MFC), flow rate of refrigerants, outlet temperature of heat exchangers, outlet temperature of air coolers, outlet pressure of compressors, and liquid level of vertical separator must be controlled. These are selected controlled variables. Each of these PVs except liquid level of separator can affect the SEC.

4.3. Selection of Manipulated Variables and Degrees of Freedom (DOF) Analysis

After selection of process (controlled) variables, it should be decided which manipulated variable has to be linked with which process variable. Variables (MV & PV) should be paired in such a way that the MV has a considerable effect on the PV and any time lag from a change in the MV should be short in PV response [9]. Selection of the manipulated variables is usually not an individual decision of control structure design problem, since these variables are the direct consequence of the "selection of controlled variables" step [23].

According to [22], the number of dynamic or control degrees of freedom is equal to the number of manipulated variables. In most cases, the MVs are obtained by the design, and a DOF analysis should be used to check that there is enough DOF to meet the operational objectives [22]. If the DOF analysis and/or the subsequent design indicates that there are not enough degrees of freedom, then DOF should be added with the addition of equipment like control valves [22]. The variables that can be manipulated in the MFC process are 18 in total including:

- Molar flow of mixed refrigerants (steams: 10, 16, 21 and 25), using the V-1, V-2, V-3 and V-4 control valves
- Speed of air coolers' driving motor, using the "Control OP Port" option for these variables
- Compressor powers, using the "Control Valve" option for these energy streams
- LNG molar flow rate, using the V-6 control valve
- NG molar flow rate (can also be considered as a disturbance)

So DOF equals 18.

4.4. Selection of Control Configuration and Equipment Control Structure

The control configuration is the structure of a controller that interconnects the process variables, manipulated variables and measured variables [23]. Here, feedback and cascade control configurations are selected for controlling the PVs. These two types are the most conventional in plant-wide control. In the following, the selected control structures and methods for controlling the selected PVs will be discussed:

- *Control of flow rate of mixed refrigerants*:

Since the flow rate of refrigerants has a great impact on the SEC, flow controllers for all MR streams must be added. For control of these variables, cascade control structure can be used. In cascade control structure, natural gas temperature controllers (primary or master controllers) send their output as set point to flow controllers (secondary or slave controllers) that manipulates the control valves.

- *Control of outlet temperature of heat exchangers and air coolers*:

Feedback control systems are used to control temperatures. In the MFC process, outlet temperatures on the tube side of all heat exchangers are controlled by manipulating the flow rates of the cooling fluids (mixed refrigerants). And outlet temperatures of all air coolers are controlled by manipulating the speed of the air coolers' driving motor.

- *Control of discharge pressure of compressors*:

Compressors are critical equipment in ensuring the stable and safe operation of the LNG plants. Improper operation of compressors increases the value of the SEC, so it is essential to design control systems for these equipment. The control structure of compressors is selected based on their type and size. Because of using centrifugal compressors in the MFC process, discharge pressures are controlled by varying the energy input to the compressors (in fact, work of the turbines).

- *Control of liquid level in the vertical separator*:

Basically, change of liquid level in a separator depends on the volume and shape and the flow rate of the input and output streams of the separator. Here, the liquid level is controlled by using a feedback configuration which is very common. In this system, the level controller controls the PV by manipulating a control valve which is located on the outlet stream of the separator vessel. According to the above explanations, the control structure is designed for the MFC process which is shown in (Figure 4).

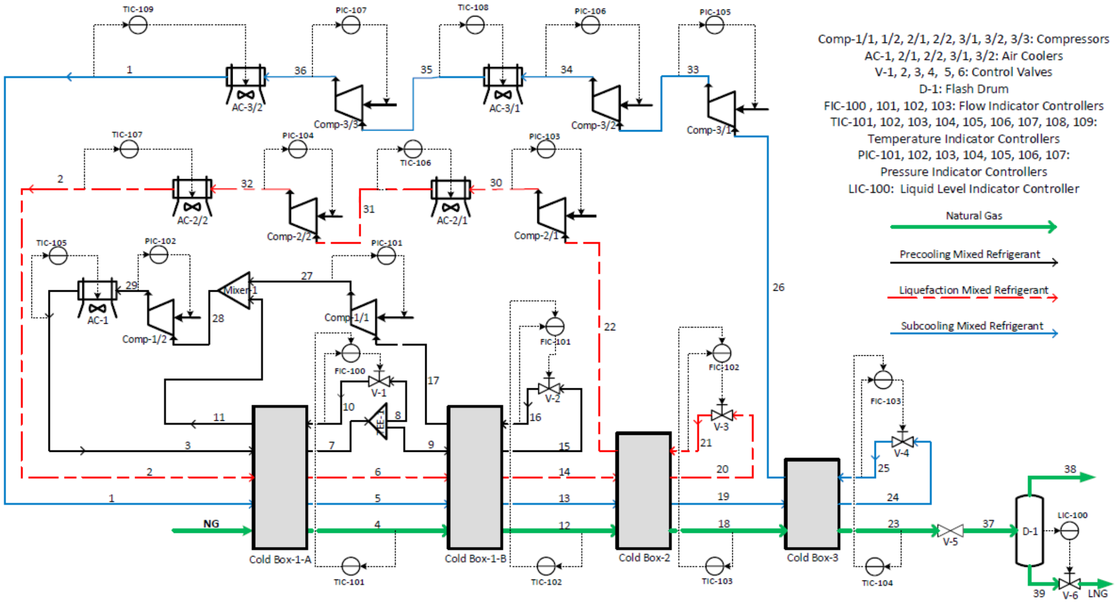


Figure 4. Designed control structure for MFC process.

4.5. Selection of Controller Type

One of the important issues in simulation and process control is the selection of the appropriate controller and tuning of its parameters. The most widely used control technology in the plants is the PID controller. The PID controller algorithm utilizes proportional (P), integral (I) and derivative (D) action to maintain the process variable at a set point. One or more of these actions can be selectively employed, according to what process variables that are being controlled. The output of the PID controller is defined as [24]:

$$\mathrm{OP}(t) = K_c\,\varepsilon(t) + \frac{K_c}{T_i}\int \varepsilon(t) + K_c T_d \frac{d\varepsilon(t)}{dt} \qquad (8)$$

where ε is the error or deviation from set point, Kc is the controller gain, T_i and T_d are two constants called the integral time and derivative time, respectively. The value of these parameters depends on the type of controller and to a lesser extent the process features, and there are various methodologies for deciding these values and the PID controller tuning. Here, for controller tuning, approximate values of controller parameters suggested in reference [24] are used. Appropriate controller according to the process variables and the range of values used for each controller parameter are given in Table 6. In general, K_c is the most principal parameter of controller equation, and T_i and T_d are auxiliary parameters that are used to trim the proportional response. Therefore, the controller gain has to be tuned first and the response of the controller should be close to the desired response before any changes in integral and derivative parameters. If the controller does not work well and instability occurs, the controller gain should be adjusted first and T_i and T_d should be adjusted afterwards.

Table 6. Appropriate controller according to process variables and its parameters [24].

Process Variable	Controller	K_c	T_i (min)	T_d (min)
Flow	PI	0.40-0.65	0.05-0.25	---
Temperature	PID	2-10	2-10	0-5
Gas Pressure	PI	2-10	2-10	---
Liquid Level	P	2	---	---

5. Dynamic Simulation of MFC Process

5.1. Dynamic Simulation

Design and optimization of chemical processes requires the study of both steady state and dynamic behavior. Dynamic simulation shows the behavior of the process over time to reach a new steady state and ensures that the plant produces the desired product in a way that is safe and easy to operate.

The dynamic mode of the simulator calculates the pressure and flow profile of a simulation by utilization of pressure flow solver (P-F solver). In this mode, all equations of equipment are solved simultaneously at any time, and calculations at any interval of time are transferred from an earlier time to a later time and this procedure continues until the final time that the user determines. For dynamic simulation, specifications or dynamic characteristics of equipment and boundary streams should be determined. The pressure-flow specifications must be chosen so that the degrees of freedom of the process equal zero in order for the software to run the simulation successfully. These specifications (Spec) are discussed in the following:

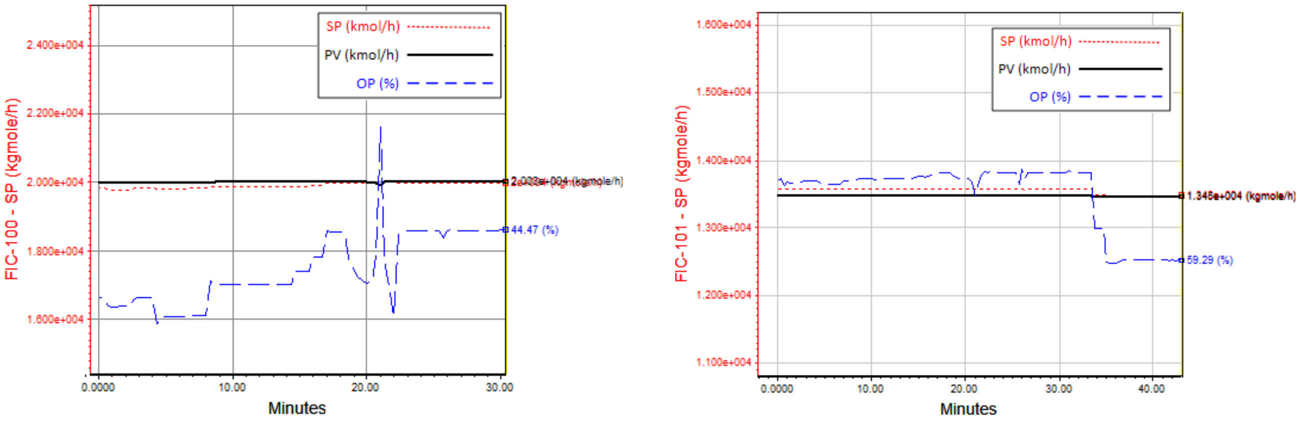
- A dynamic specification- pressure or flow- should be selected for each boundary stream (feed and product). In the MFC process, pressure is specified for the NG and 38 streams, and flow is specified for the LNG stream.
- In resistance equipment, such as compressors, heat exchangers, air coolers and control valves, the required parameters must be imported to the simulator in order to determine the relationship between pressure drop and flow rate. This relationship is known as the resistance equation (Eq. 9). The resistance equation calculates flow rates from the pressure differences of the equipment.

$$\mathrm{Flow} = k\ \sqrt{\rho.\Delta \mathrm{P}} \qquad (9)$$

According to the equation 9, in these equipment the flow rate is directly related to the square of the pressure drop and if the flow rate through the equipment increases, the pressure drop will also increase. k is the density and k is a constant that depends on mechanical properties of the equipment and represents the reciprocal of resistance to flow. So the k value should be selected as a Spec in heat exchangers and air coolers. In valves, the pressure-flow relation option should be selected as a dynamic Spec so that the pressure drop across the valve at any moment is calculated based on the basic valve operation equation. And in compressors, performance curves at different speeds, such as that in (Figure 3), should be used and the compressor speed should be considered as a dynamic Spec.

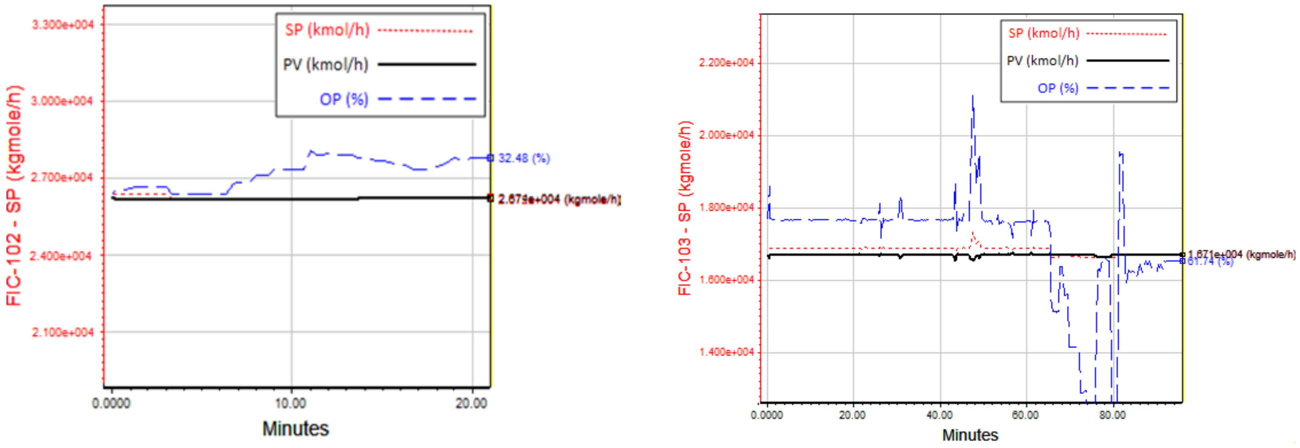
5.2. Simulation Results and Discussion

Dynamic simulation of the MFC process is run to check the performance of the designed control structure. Results from the simulations are shown in (Figures 5-9) as plots of set points (SP), process variables (PV) and operating variables (OP). In fact, OP is the manipulated variable which the controller controls the PV by changing it. Here, the output of the controller is a control valve, i.e. OP is the percent opening (OP %) of the control valve. In addition, the OP can be specified as a physical valve in the plant, a material stream, or an energy stream [24]. In all figures, the red dotted line represents the set point, the black solid line represents the process variable and the blue dashed line denotes the valve opening. As can be seen in the figures, all the controllers do well and the PVs will reach the desired SPs with the least amount of offset. It should be noted that controller parameters are tuned so that the controllers have stability, the amount of their offset is as small as possible, have shorter response times and can also eliminate any disturbances.



a. FIC-100 controller
(with Remote SP= 2.000×10⁴ kmol/h)

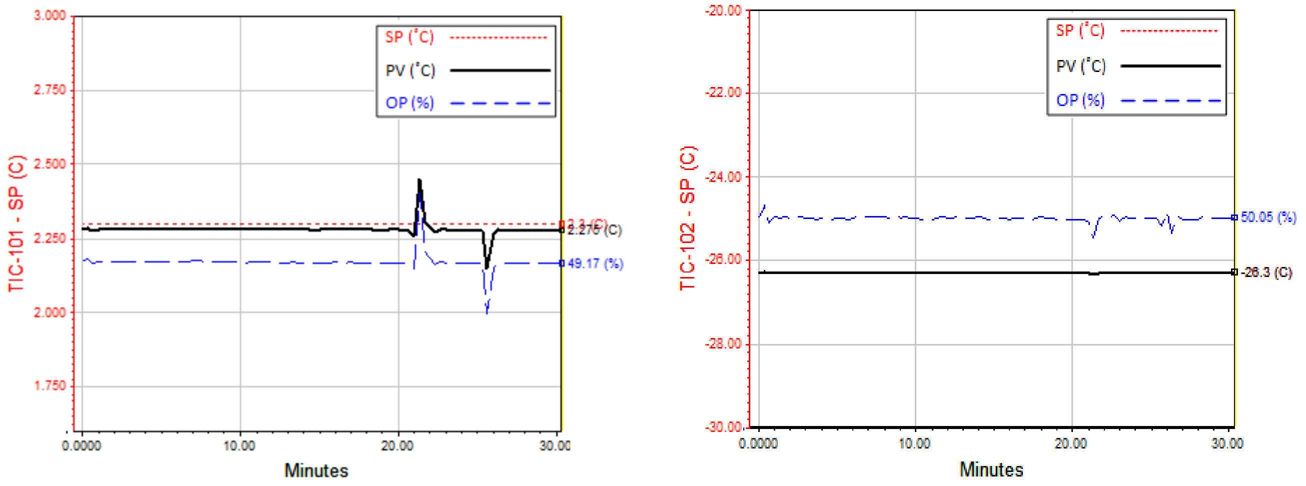
b. FIC-101 controller
(with Remote SP= 1.348×10⁴ kmol/h)



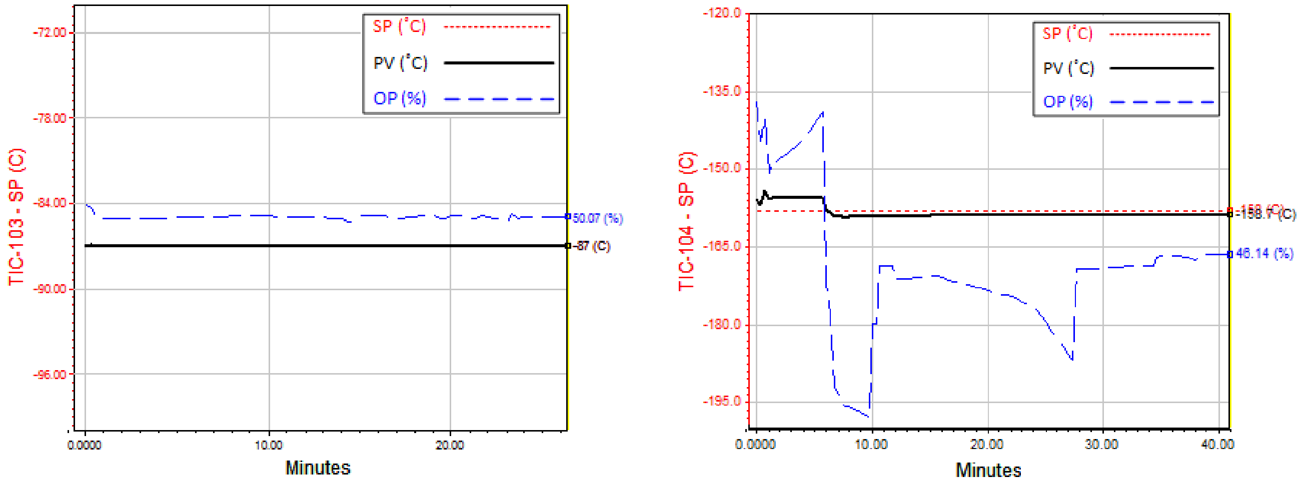
c. FIC-102 controller
(with Remote SP= 2.672×10⁴ kmol/h)

d. FIC-103 controller
(with Remote SP= 1.671×10⁴ kmol/h)

Figure 5. (a-d). Response of flow controllers.



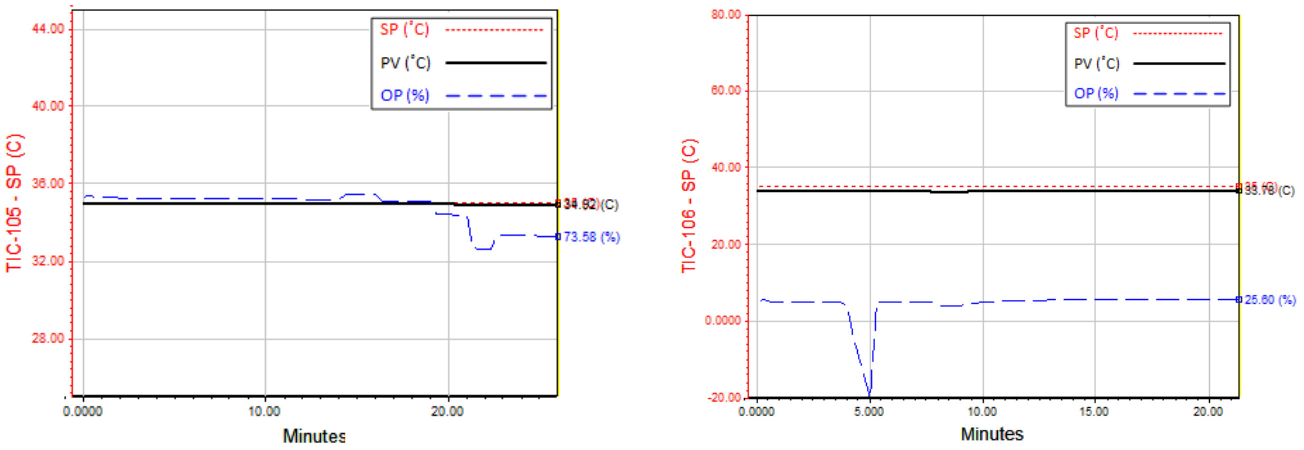
a. TIC-101 controller (with SP= 2.3 °C) **b.** TIC-102 controller (with SP= -26.3 °C)



c. TIC-103 controller (with SP= -87 °C) **d.** TIC-104 controller (with SP= -158 °C)

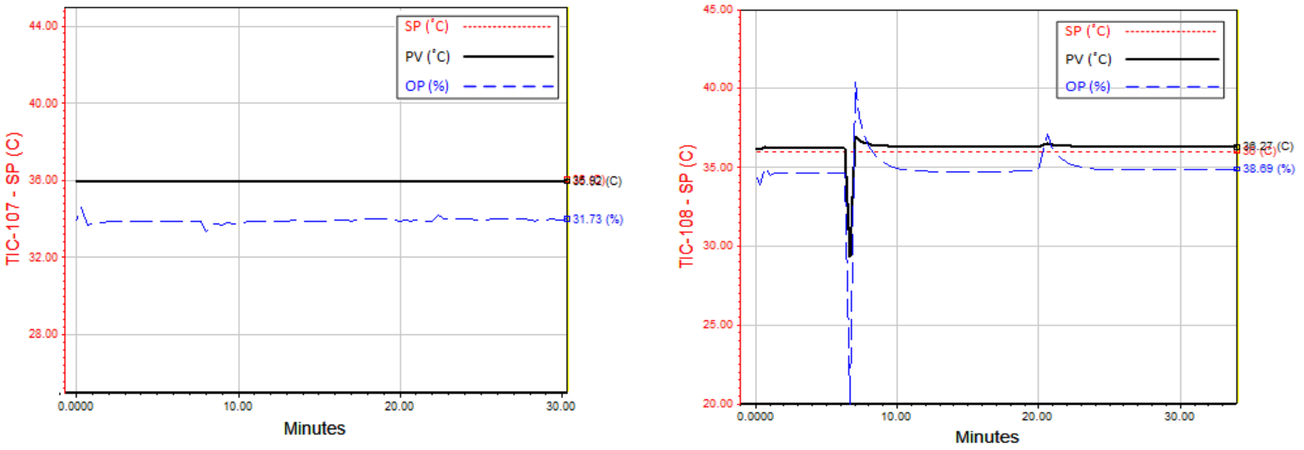
Figure 6. (a-d). Response of temperature controllers for heat exchangers.

(Figure 5) illustrates the responses of the flow controllers. These controllers are slave controllers and get their SPs from related temperature controllers (master controllers), i.e. their SPs are remote. The action of FICs: 100-104 is reverse which means that when the PV rises above the SP, the OP decreases, and when the PV falls below the SP, the OP increases. The responses of the temperature controllers (TICs: 101-104) are shown in (Figure 6). These controllers are set to control the temperatures at the tube outlet of heat exchangers and they have direct action. In direct action, if the PV rises above the SP, the OP increases and vice versa. From the figures, it can be found that if there is little MR in the heat exchangers, this will mean there is less heat transfer than necessary and it causes a rise in the temperature at the tube outlet. Of course, this will lead to an increase in the flow rate of MR to the heat exchangers, and the temperatures or PVs will reach the desired SPs. (Figure 7) shows the responses of the temperature controllers (TICs: 105-109) for air coolers. The action of such controllers is direct, i.e. if the outlet temperature of air coolers is higher than the desired SPs, the rotational speed of the driving motors increases in order for the PVs to reach the SPs. As can be seen, these controllers do not show much oscillation and the PV was kept close to the SP throughout most of the simulation. (Figure 8). (a-g) shows how the discharge pressure varies with time in the compressors. These pressure controllers have reverse action, meaning that more power (energy) will be required if the PV is less than the SP. One can see that these compressors never need to go to full power (OP=100 %) in order to maintain the desired pressure and have approximately stable behavior. Finally, (Figure 9) indicates the level controller (LIC-100) response. The level controller acts directly and keeps the liquid level in the separator close to the SP.



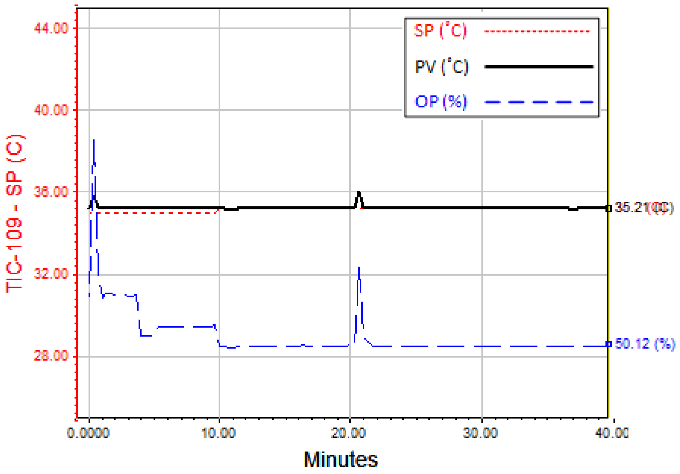
a. TIC-105 controller (with SP= 35 °C)

b. TIC-106 controller (with SP= 35 °C)



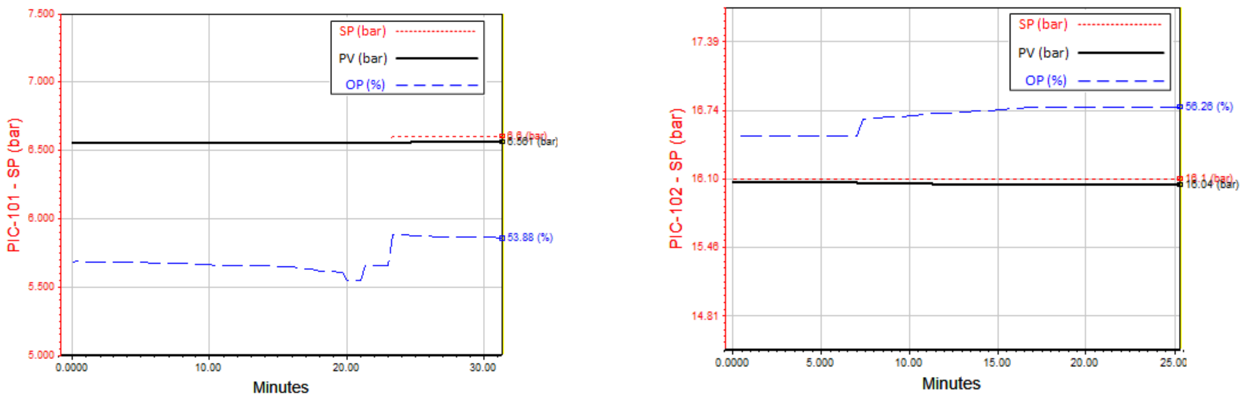
c. TIC-107 controller (with SP= 36 °C)

d. TIC-108 controller (with SP= 36 °C)

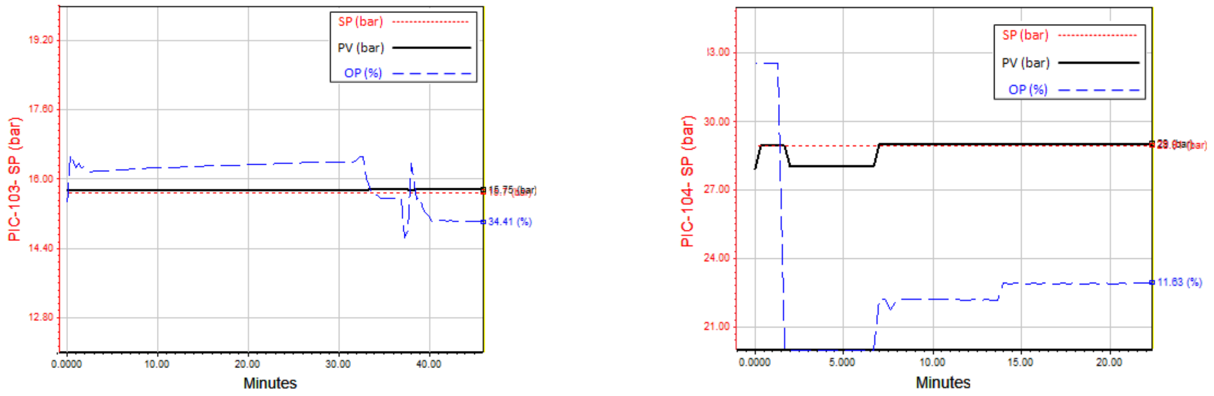


e. TIC-109 controller (with SP= 35.2 °C)

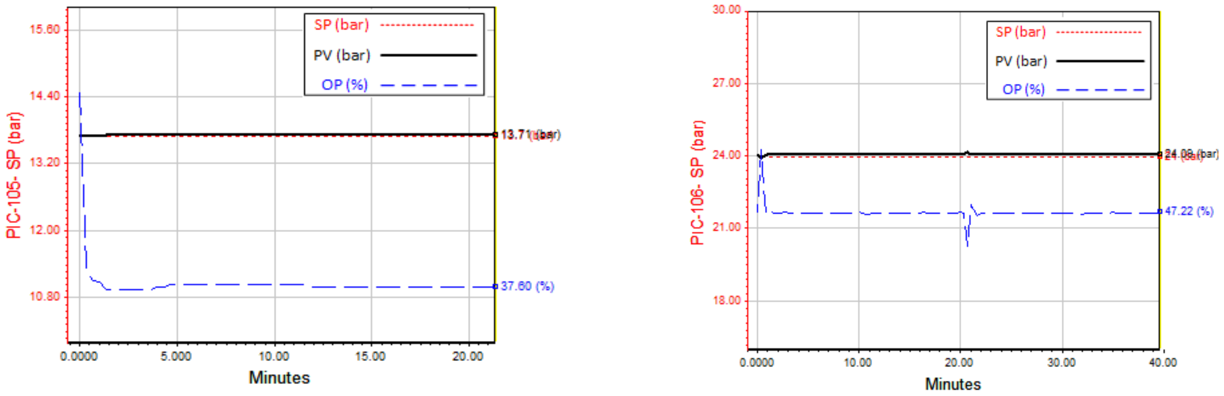
Figure 7. (a-e). Response of temperature controllers for air coolers.



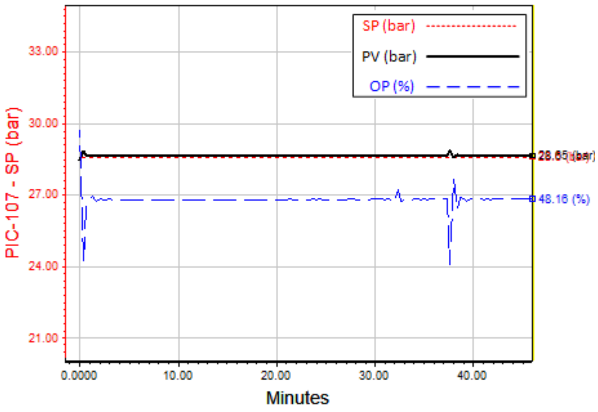
a. PIC-101 controller (with SP= 6.6 bar) **b.** PIC-102 controller (with SP= 16.1 bar)



c. PIC-103 controller (with SP= 15.7 bar) **d.** PIC-104 controller (with SP= 29 bar)



e. PIC-105 controller (with SP= 13.7 bar) **f.** PIC-106 controller (with SP= 24 bar)



g. PIC-107 controller (with SP= 28.6 bar)

Figure 8. (a-g). Response of pressure controllers.

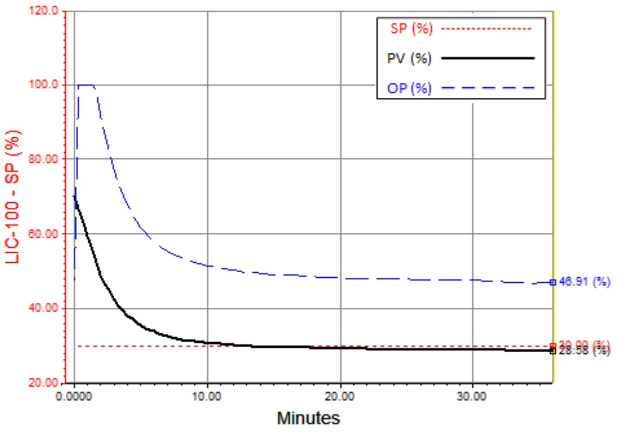


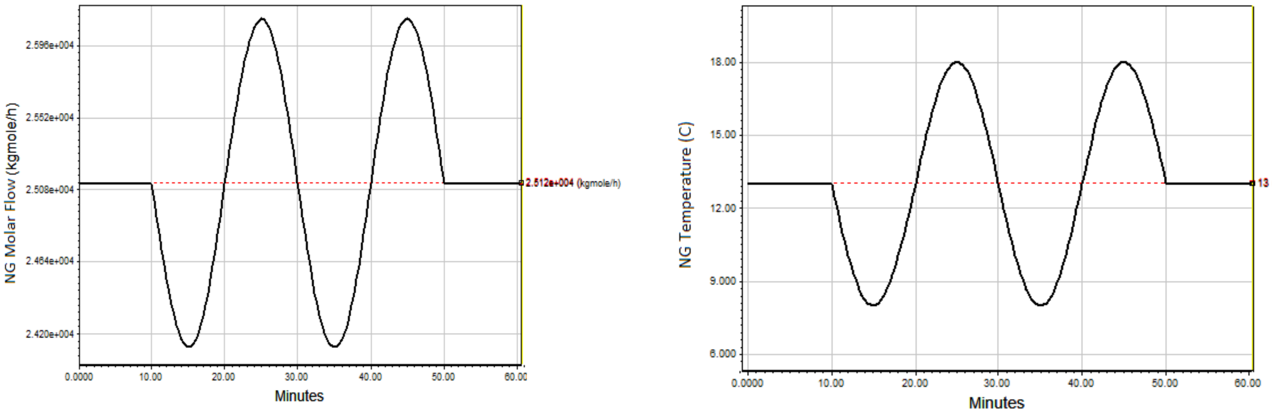
Figure 9. Response of level controller (LIC-100 with SP= 30%).

In the end, it should be mentioned that for all the simulations, there is some deviation from steady state before any disturbances are introduced, i.e. the desired value (SP) of process variables is different from the ones which they have in the steady state mode. The reason is that the controllers have different operation points from which was initially defined and also there is unphysical initial values for liquid hold ups in the heat exchangers, hence the controllers cannot bring the PVs up to the desired values. As mentioned before, the main control objective is, of course, to maintain the value of SEC less than 0.3 kWh/kg LNG. In this regard, after dynamic simulation the amount of SEC in the designed control structure equals 0.2574 kWh/kg LNG and it indicates that this structure controls the process variables desirably.

5.3. Validation of Designed Control Structure

After designing a control structure, it is necessary to validate the designed structure. In fact, a control structure has an appropriate and stable performance when be able to overcome the imposed disturbances in the process. Disturbances upset the process and cause the PVs to deviate from their desired SPs. These disturbances may be caused by the external factors (such as flow rate, temperature or pressure fluctuations in the inlet streams of the process) or internal ones (like defects in the instrumentation).

In the under consideration process, two potential sources of disturbance are identified which include variation of the NG feed stream molar flow rate and temperature. These disturbances can be imposed on the MFC process by means of Transfer Function block provided in the simulator, and thus the performance and responses of the controllers can be studied. For investigating the effect of both increase and decrease of the inlet NG flow rate and temperature on the process, the disturbances are introduced to the process as sinusoidal. (Figure 10.a) shows the disturbance in feed molar flow rate and the disturbance in feed temperature is shown in (Figure 10.b). Here, it is assumed that the disturbances in the process will take 40 minutes (with period= 20 min, i.e. the disturbances are started at 10 minutes and terminated at 50 minutes).

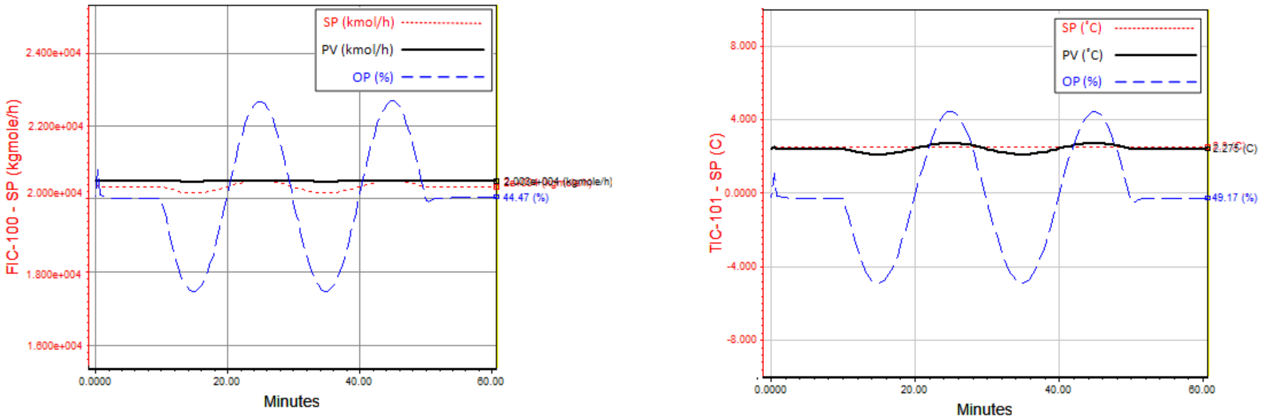


a. NG molar flow rate oscillation

b. NG temperature oscillation

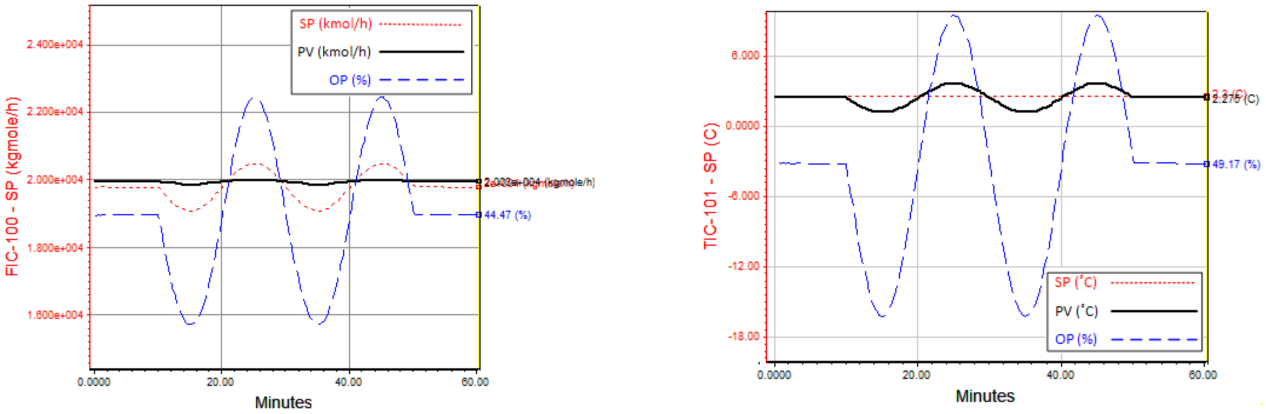
Figure 10. Disturbances of MFC process: a. NG molar flow rate oscillation & b. NG temperature oscillation.

Due to the high number of controllers in the process, only the results of the responses of FIC-100 and TIC-101 controllers are shown in (Figure 11). These figures illustrate how the controllers responded to disturbances. Because these controllers are at the beginning of the process, they eliminate most of the imposed disturbances and prevent them from upsetting the remainder of the process. After introducing the disturbances, all of the controllers try to eliminate these disturbances by sending signals to the control valves to open or close. This indicates that the designed control structure has good stable performance.



a. FIC-100 controller after flow disturbance

b. TIC- 101 controller after flow disturbance



c. FIC-100 controller after temperature disturbance

d. TIC-101 controller after temperature disturbance

Figure 11. (a-d). Response of controllers after introducing disturbances.

6. Conclusions

In this paper, static and dynamic simulation of the MFC process is done. Results of steady state simulation shows that the specific energy consumption (SEC) of the process is 0.2647 kWh/kg LNG. By dynamic simulation, different control strategies are examined in order to select the best controllers and control structure. The process can produce LNG product safely and stably by using the proposed control structure. These control systems are able to sufficiently eliminate the imposed disturbances in the process. Also the amount of SEC of the process is 0.2574 kWh/kg LNG in the designed control structure. These results show that this structure perform accurately.

Nomenclature

$\dot{m}$	fluid mass flow rate (kg/s)
h	specific enthalpy (J/kg)
Q_{leak}	heat leak (W)
Q_{loss}	heat loss (W)
$Q_{transferred}$	heat exchanger duty (W)
U	overall heat transfer coefficient (W/m^2.°C)
A	surface area (m^2)
CMTD	corrected log mean temperature difference (°C)
V	volume flow (m^3/s)
H	head (m)
W	power (work) (W)
N	compressor speed (rpm)
g	acceleration of gravity (m/s^2)
K_c	controller gain (dimensionless)
T_i	integral time (min)
T_d	derivative time (min)
k	specification constant ((kg/s)/(pa.kg/m^3)$^{0.5}$)
ρ	density (kg/m^3)
ΔP	pressure drop (Pa)

Abbreviations

C3MR	Propane Pre-Cooled Mixed Refrigerant
CV	Controlled Variable
DOF	Degrees of Freedom
EDR	Exchanger Design & Rating
EOS	Equation of State
J-T Valve	Joule-Thomson Valve
LNG	Liquefied Natural Gas
MFC	Mixed Fluid Cascade
MR	Mixed Refrigerant
MSMR	Modified Single Mixed Refrigerant
NG	Natural Gas
OP	Operating Variable
PFHE	Plate Fin Heat Exchanger
PR	Peng-Robinson
PRSV	Peng-Robinson-Stryjek-Vera
PV	Process Variable
SEC	Specific Energy Consumption
SP	Set Point
Spec	Specification
SWHE	Spiral Wound Heat Exchanger

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طراحی ساختار کنترلی و شبیه‌سازی دینامیک فرآیند مبرد آمیخته چند مرحله‌ای مایع‌سازی گاز طبیعی

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چکیده

در این مقاله سامانه کنترلی فرآیند مبرد آمیخته چند مرحله‌ای مایع‌سازی گاز طبیعی طراحی شده و بررسی گردیده است. مصرف ویژه انرژی (SEC) این فرآیند برابر با ۰/۲۶۴۷ kWh/kg LNG می‌باشد. پس از شبیه‌سازی استاتیک (پایا) فرآیند مذکور و تعیین اندازه تجهیزات موجود در آن، به‌منظور کنترل کل فرآیند یک ساختار کنترلی طراحی گردید. علاوه بر این، شبیه‌سازی دینامیک (پویا) فرآیند انجام شد و عملکرد کنترلرها مورد بررسی قرار گرفت. با شبیه‌سازی دینامیک، مقدار مصرف ویژه انرژی فرآیند به ۰/۲۵۷۴ kWh/kg LNG کاهش یافت؛ که این موضوع نشان دهنده آن است که ساختار کنترلی طراحی شده می‌تواند فرآیند را به‌صورت پایدار و صحیح کنترل نماید. به‌منظور اعتبارسنجی عملکرد و پایداری ساختار کنترلی، تغییرات در دبی جریان و دمای خوراک گازی به‌عنوان اغتشاش به فرآیند وارد گردید.

واژگان کلیدی: گاز طبیعی مایع (LNG)، فرآیند MFC، کنترل فرآیند، شبیه‌سازی دینامیک

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