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Case study of surge avoidance design for centrifugal compressor systems during emergency shut-down (ESD)

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Abstract−Compression systems with centrifugal compressors are widely used in gas involving processes. Surge protection system design is crucial in avoiding any damage in abnormal circumstances such as emergency shutdown (ESD), start-up, coast-down operation, and normal shutdown. We analyzed four cases of existing centrifugal compressor systems, three CO_2 compression systems and one off-gas compression system, to study the surge protection availability during ESD. All compression systems were working well at normal operating condition, but some systems could not avoid surge during ESD. To check the surge cases, the surge criteria flowchart was suggested and surge analysis through dynamic simulation was done using a commercial process simulator. To avoid a surge during ESD, a sensitivity analysis was done while considering the following process parameters: pre-stroke time, anti-surge valve (ASV) type, capacity, and stroke time. We optimized ASV design using response surface method with two selected parameters from the sensitivity study, ASV capacity and stroke time. Finally, the installation of the hot gas recycle system was analyzed to avoid surge occurrence.

Keywords: Compression System, Compressor Surge, Emergency Shutdown (ESD), Surge Protection, Dynamic Simulation

INTRODUCTION

Most gas involving processes, such as a gas injecting oil field, pipeline compression, gas and oil separation process (GOSP), gas liquefaction, refinery and petrochemical process, require a compression system, and a centrifugal compressor is widely used in such processes with its advantages mainly in operability, reliability and high capacity. Furthermore, the centrifugal compressor is a crucial part of plant because of its high cost and importance in operation such that if the compressor is in trouble, the whole plant should be shut down in most of the cases. Thus, compressor protection is highly required in avoiding any damage at an abnormal circumstance such as emergency shutdown (ESD), start-up, coast down operation, and normal shutdown as well as during normal operation. Especially, surge protection is important to protect the compressor from surge over the range of compressor operations [1].

Surge is defined as an unstable operation condition of centrifugal compressors when the operation point of the compressor is on the left of the surge line, which is the stability limit in the compressor performance graph [2]. Surge protection, especially, is a crucial part in design of a centrifugal compression system, and whole system verification is necessary to be done using a dynamic simulation [3]. It is dynamic in nature, so a steady-state model may not be adequate to address issues associated with transient operations, such as startup operation, compressor surge protection, and stability of operation during turn-down.

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Most engineering companies struggle with practical difficulties. The difficulties include (1) the whole system verification is believed to be possible at far later stage with all detailed design information available, (2) engineering company lacks a dynamic simulation specialist and even smaller number of specialists for surge protection system, (3) the responsibility of verification resides somewhere among process engineer, mechanical engineer, control engineer and simulation specialist, (4) the working procedure requires high involvement of project manager, engineering manager and procurement engineer to gather all relevant data, and (5) redesign is potentially required at the final stage after the verification.

For many cases, installing a hot-gas recycle system, which is also called a bypass system, can be the possible solution, but it will cause many changes in most of engineering disciplines such as process, mechanical, piping including plot, even down to structural and civil, which can cause huge cost impact incurring from other procurement and/or schedule delays to the whole EPC project.

In principle, a process system engineer is highly required to have proper guidelines regarding all the impact of design parameters to design the surge protection system, but practically not. The main purpose of this paper is to provide a clear picture of how much impact all of the design parameters have on the surge protection and to optimize the value of surge parameters based on the results of the study. It can be used during the full-course of project development, such as FEED, EPC bidding, and EPC.

CENTRIFUGAL COMPRESSION SYSTEM AND SURGE ANALYSIS

A generalized centrifugal compression system is shown in Fig.

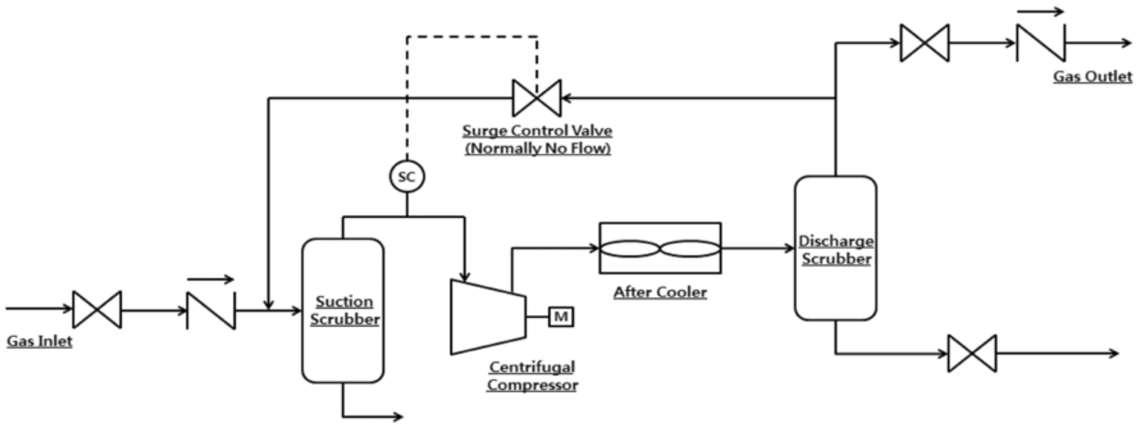

Fig. 1. Generalized scheme of centrifugal compressor and its surrounding system.

1. The entire system is broken down into the compressor, surge control valve, or recycle valve, with controller, and a number of volumes for associated pipes, knockout drums and the gas-cooler [4]. In most of the cases, a recycle line is normally set with no flow during normal operation. The suction scrubber is almost always required to separate any liquid which can cause damage to the impeller. The after-cooler and the discharge scrubber are almost always required as well, but these configurations can be modified depending on the process and its requirement.

The surge controller and its control valve are installed to protect the centrifugal compressor. When fluctuations in flow rate occur, the operating point will move towards the surge line because flow is reduced. If the operating point approaches the surge control line, the surge control valve starts to open to allow recycle flow, and the flow increase beyond the control line accordingly as shown in Fig. 2 [1,5,6]. If the flow to the centrifugal compressor falls below the backup line, more aggressive action is needed to prevent a surge condition. In general, a surge control line is set at approximately 10% higher than surge line, and a backup line is set at 5% higher than surge line. If the compressor is operating on the left side of the surge line, compressor operating variables (e.g., pressure, mass flow, and speed) dramatically change and backflow, which is flow in the reverse direction, occurs [7]. This event only lasts a few seconds; however, it will generate violent and potentially disastrous vibration on the compressor and its components.

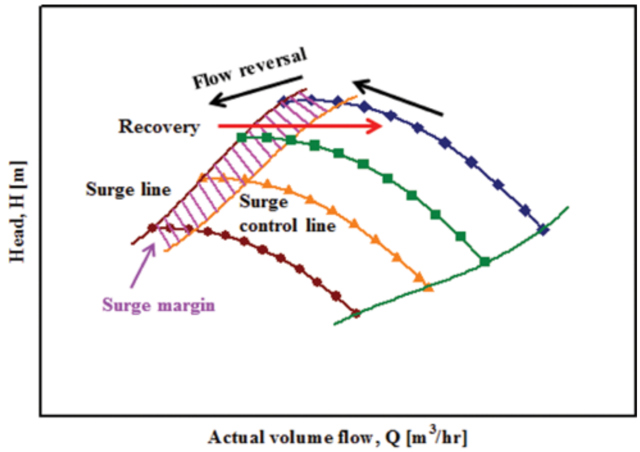

Fig. 2. Typical compressor surge line on performance map.

To design the surge protection system, all possible cases of (1) normal operation, (2) emergency shutdown (ESD), (3) normal start-up, (4) normal shutdown, and (5) coast-down operation should be considered. However, the ESD case is the most crucial that requires faster action to protect the centrifugal compressor from the fastest surge approach. The action requires to fully open the surge control valve in at least 2 seconds after the ESD signal is detected [8].

To verify the proper design of surge protection, dynamic simu-

Table 1. Data required for surge analysis of centrifugal compressor

Category	Data	Description
Compressor	Performance curve	Flow vs. Head for different case of speed
	Efficiency curve	Flow vs. Efficiency for different case of speed
	Compressor inertia	Rotational inertia including motor, gear box and coupling
Suction scrubber	Volume	From dimension data
Discharge scrubber	Volume	From dimension data
After cooler	Volume	From detailed dimension data
Piping	Volume	From isometric data
Control valve	Cv	Valve capacity
	Valve type	Linear / Quick-opening / Equal-percentage
	Actuator speed	Valve stroke time

lation is required. Many researchers studied the surge protection caused by pipe rupture that requires fast action [9,10], but this paper focused on the case of ESD because it requires faster action than any other cases. The dynamic simulation also requires full-range data of centrifugal compressors, its surrounding equipment and piping in addition to the data required for steady-state simulation. The required data are summarized in Table 1.

The final design of a surge protection system shall be evaluated in detail through dynamic simulation. There are two general criteria that need to be fulfilled for surge protection [8]:

(1) The surge must not occur above 75% speed of the compressor operation speed.

(2) The surge must not occur for more than 2 seconds on the left-side of surge line.

Surge analysis procedure of the compression system follows the flow chart of Fig. 3. For surge analysis, compressor specification details, such as performance and efficiency curves of compressor stream data, are required. Based on these data, the compressor speed at the point where the surge line and pre-stroke delay line meet can be calculated using the pre-stroke delay line equation [11]. If the compressor speed at that point is smaller than 75% of compressor speed at steady state, (first criterion is fulfilled), it should be reviewed whether the time spent by the operating line in the left-side of the surge line is less than 2 seconds (second criterion is fulfilled). If it exceeds 2 seconds, the compression system should be redesigned to prevent compressor damage.

If the compressor speed surpasses 75% of the compressor's steady state speed, it should be reviewed whether the compressor operating point meets the surge line. If it intersects with the surge line, surge will occur and the system should be redesigned. For the suitable and economical redesign of the system, sensitivity analysis and response surface method are recommended. After these steps, the redesigned system should be reviewed to make sure it meets surge prevention criteria.

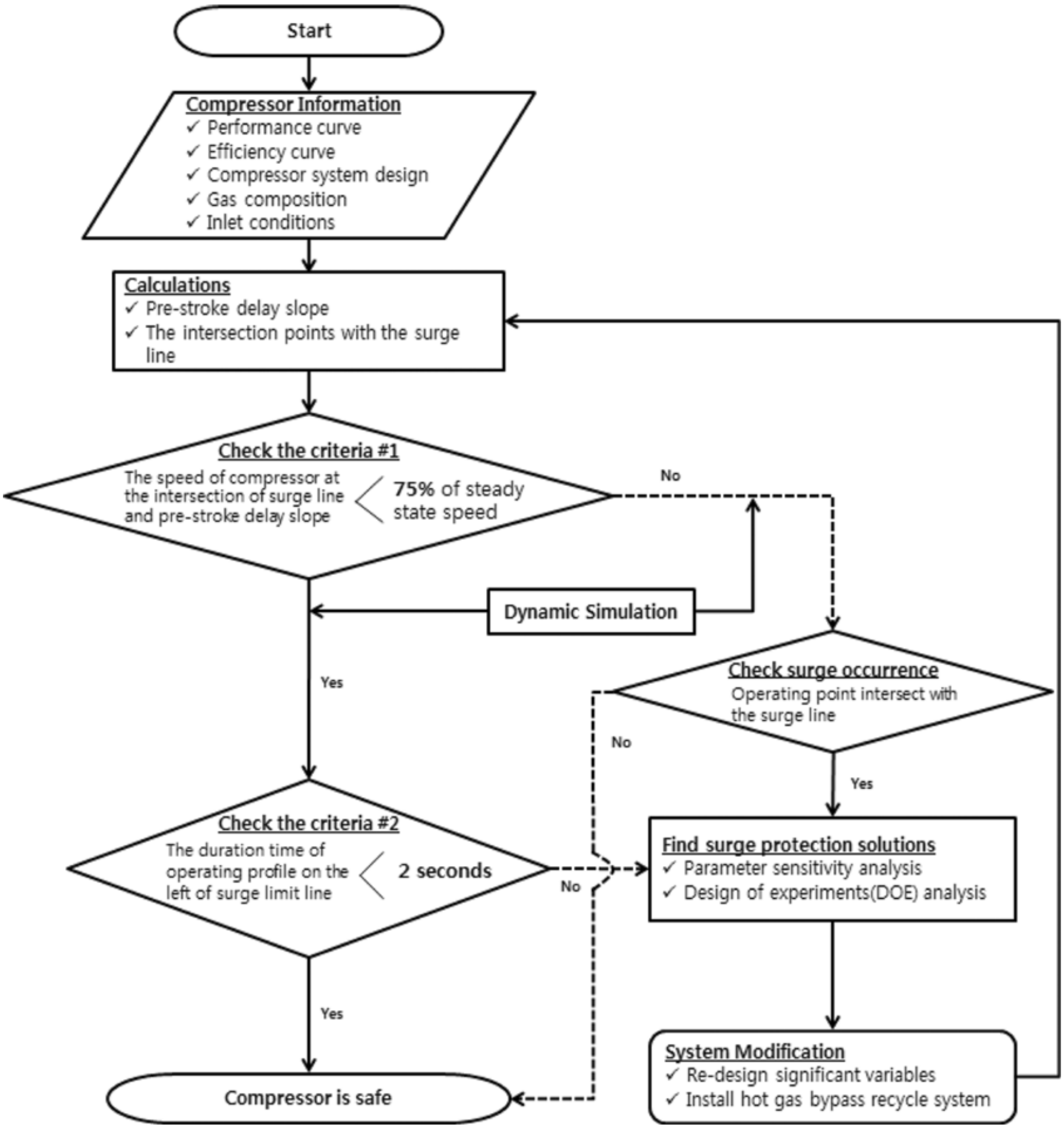

Fig. 3. Flow chart for surge analysis.

Table 2. Design and results comparison of four different compression cases

Case	Base case	Case A	Case B		Case C	
Process	GOSP compressor	Cracked gas compressor	Off-gas compressor		NGL recovery compressor	
No. of stage	Single-stage	Single-stage	Two-stage		Two-stage	
Main composition	CO_2 81%	CO_2 87%	Methane 38% C1-C3 76%		CO_2 84%	
ASV type	Quick	Linear	Linear	Linear	Equal	Linear
Pipe total length [m] (main/recycle)	200/200	645.8/17.7	200/200	200/200	281.2/47.3	279.3/222.8
Recycle line inner diameter [inch] (low P/high P)	36/24	15.25/11.75	21.56/12.5	12.5/7.625	16/10	10/8
Volume of cooler [m^3]	0.1	0.1	1.4	2.3	2.25	1.29
Inertia [$kg.m^2$]	25	19.39	25	25	14.05	11.73
Pressure ratio [-]	3.8	3	6.2	2.8	3.9	2.7
Compressor speed [rpm]	6,780	8,386	8,431	8,431	11,210	11,210
Polytropic efficiency [%]	83.6	77.0	81.5	75.4	84.4	70.6
Inlet power [kW]	2,466	3,334	5,245		3,822	
Cv [USGPM]	3000	1500	600	200	228	103
Stroke time [sec]	2	1	1	1	1	1
Pre-stroke time [sec]	0.2	0.3	0.1	0.1	0.3	0.3
Time to surge [sec]	0.27	0.44	0.09	-	0.52	0.06
Speed at surge [%]	95.2	93.6	98.3	-	94.7	99.3
Surge on ESD	Surge	Surge	Surge	No Surge	Surge	Surge
Surge avoidance availability	Possible surge avoidance with Cv↑, stroke time↓ or hot gas recycle system	Possible surge avoidance with Cv↑, stroke time↓ or hot gas recycle system	1st Stage: Unavoidable surge because pre-stroke time is greater than time to surge 2nd Stage: No surge		1st Stage: Possible surge avoidance with Cv↑, stroke time↓ or hot gas recycle system 2nd Stage: Unavoidable surge because pre-stroke time is greater than time to surge	

DYNAMIC SIMULATION OF A BASE CASE OF COMPRESSION SYSTEM

A one-stage compression system with cold gas recycle being used in a gas-oil separation plant (GOSP) was selected for a base case analysis. All operating conditions and mass balance are the same as the original design except simplified piping isometric for sensitivity study. For the surge analysis during ESD, dynamic simulation involved using a commercial process simulator.

1. Base Case of Compression System with Cold Gas Recycle

The base case system is a CO_2 compression system using a single stage centrifugal compressor. The piping isometrics are simplified for sensitivity study purpose. The compressor suction piping and ASV discharge piping are set to be 36-inch in diameter and straight 100 m in length, and the compressor discharge piping and ASV suction piping are set to be 24-inch in diameter and straight 100 m in length as well. All pipes have no elevation change. Also the compressor suction scrubber and discharge scrubber are removed for simplicity on the basis that no liquid is formed at any case. Volume of the compressor after-Cooler is not considered only for sensitivity purpose as well. A quick-opening butterfly-type anti-surge valve (ASV) was chosen and its capacity is 3,000 USgpm. The details of design specification are summarized in the second column of Table 2.

A simplified configuration of surge analysis in dynamic simulation is shown in Fig. 4. The commercial process simulator program, Aspen HYSYS, is used for dynamic simulation.

2. Dynamic Simulation of the Base Case System

For dynamic simulation, two time-related parameters are selected. One is pre-stroke time, which is the time required for a signal to be delivered from ESD detection to start of valve opening, and is set to be 0.2 second. The other is valve stroke time, which is the time required to fully open the surge control valve, which is set to be 2 seconds.

To generate a surge during ESD, a step-wise scenario of ESD needs to be incorporated using an event scheduler in the program. Time sequences of ESD scenario are set: normal operation from 0 second, ESD occurred at 5 seconds, ASV started to open at 5.2 seconds due to 0.2 second pre-stroke time, and lastly, dynamic simulation ended in 30 seconds.

Onset of ESD, or power off, the speed of compressor starts to decelerate, which is governed by its combined rotational inertia, and as a result, the volumetric flow rate of compressor starts to decrease as well. After the pre-stroke time, 0.2 seconds after ESD,

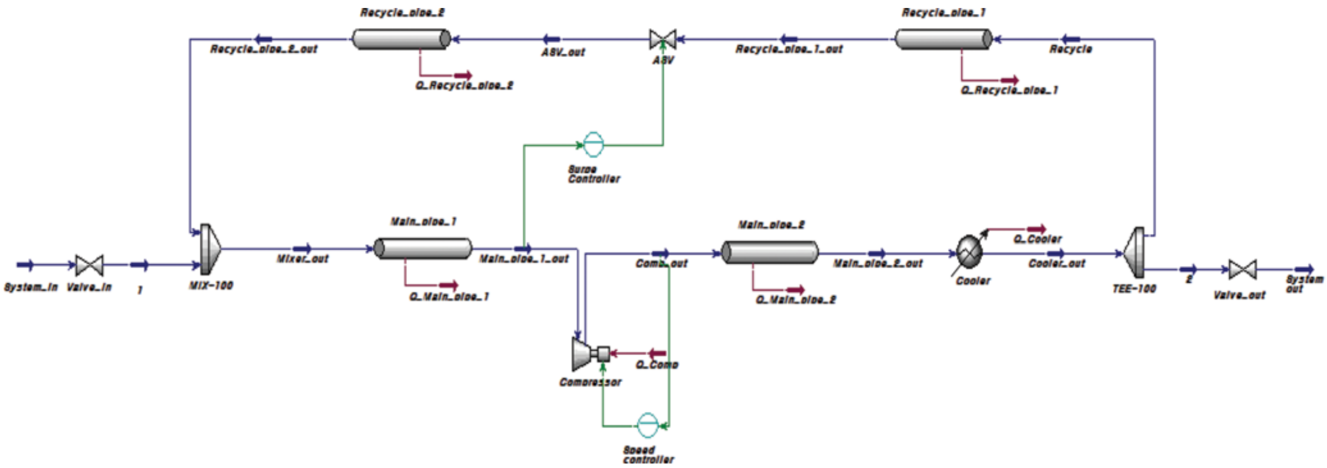

Fig. 4. Process flow diagram of the base case in dynamic simulation.

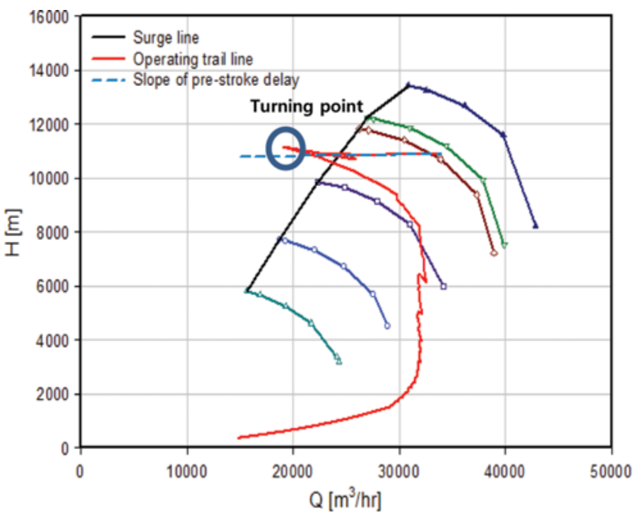

Fig. 5. Head-flow through the compressor during ESD for the base case compression.

the ASV starts to open, which allows the gas to recycle back to the suction of the compressor leading the compressor to recover back from the surge region.

The quick-opening ASV opens for 2 seconds and allows nearly maximum flow at the beginning of recycle. In this ESD case, the time to surge, which is the time delay from onset of ESD to surge, is 0.27 second and compressor speed decelerates to 95.2% of steady state speed at the surge line. The response of compressor operating point during ESD for the base case is shown in Fig. 5. The slope of pre-stroke delay line was calculated using the equations of Botros and Richards [11]. This slope was very well fit to the dynamic simulation results.

In this base case system, the compressor reaches the surge line at a speed higher than 75% of normal operating speed, and total time spent at the left of surge line, surge region, is less than 2 seconds. By the surge criteria, this system is violating one of the surge criteria and it is recommended to redesign using the flowchart of surge analysis in Fig. 4. Many design modifications could be considered in terms of a surrounding system such as valve capacity, stroke time, and installation of a hot gas recycle system.

DESIGN PARAMETER OPTIMIZATION FOR SURGE PROTECTION

For surge protection, process design parameter sensitivity analysis and ASV optimal design using response surface method (RSM) were studied with the parameters which will affect the compressor surge. The purpose of parameter sensitivity study is to evaluate how much impact the design parameters have on the compressor surge. The range of parameters for no surge condition is selected by the response surface method.

Many researchers have studied some parameters considered to be crucial in determining the conditions for dynamic instabilities to occur: fluid inertias and compressor/driver inertias, gas volume capacitance in the recycle path, anti-surge valve pre-stoke and stroke time, recycle valve characteristics and capacity, check valve dynamic characteristics, compressor performance characteristics, and all dynamic parameters of gas flow, equipment, and control, etc. [12,13].

High compressor inertia is believed to alleviate the ESD surge because the compressor will decelerate at a lower rate, which has been proven to be true. However, it is not practically feasible to change the compressor inertia, and the high inertia value will lead to high capital expenditure (or total installed cost, CAPEX) and operational expenditure (or operational cost, OPEX) as well.

During ESD, the parameters that affect the potential for the compressor are the recycle valve characteristics such as maximum valve capacity (Cv), flow versus opening characteristics (type), opening delay (pre-stroke time), and valve travel time (stroke time) [14, 15]. Thus, four process parameters were selected for the sensitivity study: pre-stroke time, anti-surge valve (ASV) type, ASV capacity, and ASV stroke time.

1. Design Parameter Sensitivity Analysis

For the purpose of sensitivity study, the point where the performance trail turns from decreasing to increasing flow rate was compared and defined as turning point while its time as turning point time. In the base case, the turning point is marked as a black cir-

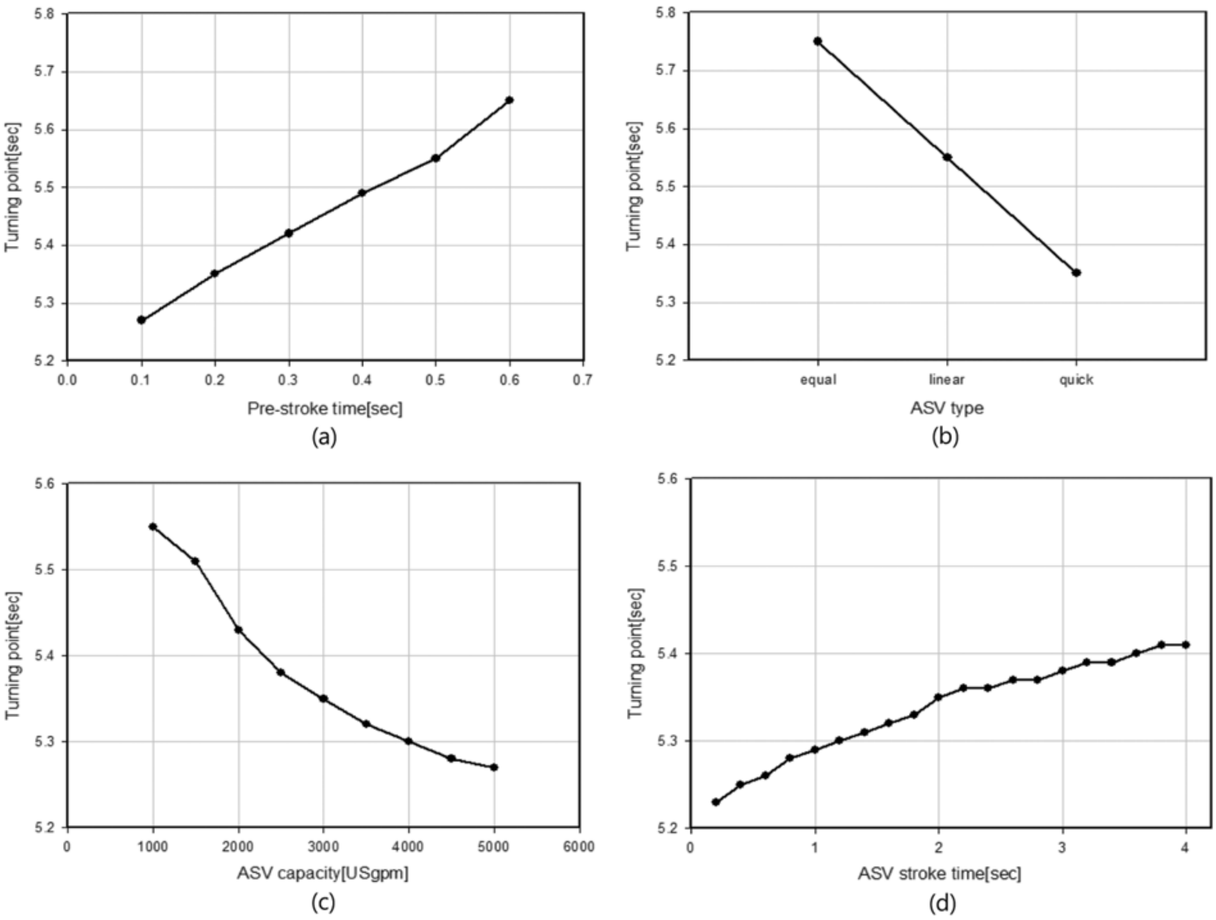

Fig. 6. Turning point vs. design parameter. (a) Pre-stroke time, (b) ASV type, (c) ASV capacity, (d) ASV stroke time.

cle and the turning point time is 5.33 second as shown in Fig. 5.

1-1. Pre-stroke Time

Pre-stroke time is a time delay between the ESD signal and the opening of anti-surge valve. In this study, ASV pre-stroke time was changed from 0.1 to 0.6 seconds with 0.1 second interval. As a result, the turning point time is linearly dependent on pre-stroke time, and fast pre-stroke time can significantly lessen the turning point time as shown in Fig. 6(a). The sooner the ASV opening, the shorter the surge time.

The result confirms some general conclusions that the pre-stroke time is more important than other process parameters, and shorter pre-stroke time is recommended. In this work, the pre-stroke time range is based on the references: below 0.3 second [1], 0.02 second [4], and 0.1 second [16]. However, there has been no reference or guideline to reduce the pre-stroke time, and it must be depend on plant site condition.

1-2. ASV Type

ASV type is selected as linear, quick-opening and equal-percentage, respectively. The valve type makes a significant difference in terms of surge as much as 0.4 seconds between quick-opening and equal-percentage as shown in Fig. 6(b). The quick-opening type valve such as butterfly-type valve can be a good candidate in terms of surge protection. However, engineers cannot always choose quick-opening type, and need to consider many engineering factors to choose the most suitable valve type such as the case of normal operation and start-up operation.

1-3. ASV Capacity

ASV capacity is changed from 1,000 to 5,000 USgpm with 500 USgpm interval. As a result, larger ASV capacity surely be able to alleviate the compressor surge by 0.28 second as shown in Fig. 6(c).

The use of larger (higher capacity) ASV generally will lower the dynamic instability during ESD. Engineers need to find the required ASV capacity with dynamic simulation, and it is normally recommended to select 1.8-2.2 times capacity than the actual requirement. However, considering ESD surge, around twice the capacity is too much as it does not allow any margin with increased ASV capacity. It might lead to control problem during turn-down operation and during slow approach to surge line. Also, it would lead to higher costs than required.

1-4. ASV Stroke Time

On ESD, the anti-surge valves are opened based on their stroke times. The stroke time is defined as the time taken for the valve to travel from closed to open position. In this study, ASV stroke time was changed from 0.2 to 4.0 seconds with 0.2 second intervals. The turning point time is almost linearly dependent on ASV stroke time as shown in Fig. 6(d). Faster ASV opening is proven to alleviate the compressor surge. The fast stroke time can alleviate compressor surge by 0.18 second in this range. However, with the stroke

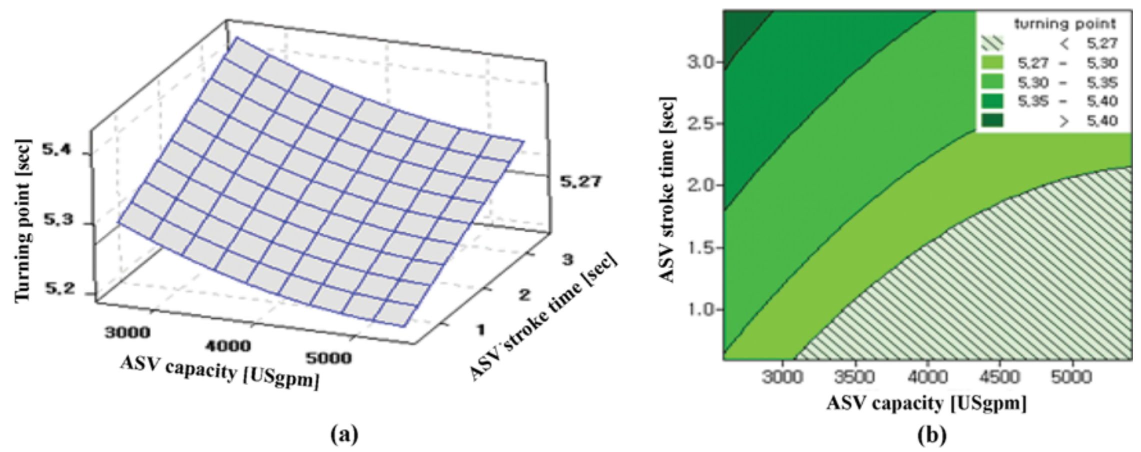

Fig. 7. Response surface plots. (a) Surface plot. (b) Contour plot.

time lower than 1 second it is practically impossible to manufacture such fast actuators.

2. ASV Optimal Design Using Response Surface Method

Based on the results of the sensitivity study, we found that ASV capacity and stroke time are the only adjustable significant parameters to redesign ASV for compressor surge avoidance. Thus the values of ASV capacity and stroke time were optimized using response surface method (RSM). RSM is a mathematical and statistical technique for modeling and analysis in applications where a response of interest is influenced by several variables [17-19]. With this method, we tried to find the levels of ASV capacity and ASV stroke time that minimize the surge turning point time, and suggest which levels of the parameters are suitable for the surge protection.

A central composite design (CCD) was used with two parameters and the responses were analyzed by Minitab program. The corresponding three-dimensional surface plot is shown in Fig. 7(a). Higher ASV capacity and shorter ASV stroke time make shorter turning point time. The region with turning point time shorter than 5.27 seconds, which is the time that the compressor operating point passes the surge limit line, is depicted as the shaded area in Fig. 7(b). Therefore, it is recommended to redesign an ASV with the parameter values in this region.

As shown in Fig. 5, the surge occurred during ESD for the base case. To avoid the surge, the ASV capacity value was increased from 3,000 USgpm to 4,500 USgpm, and the stroke time decreased from 2 seconds to 1.5 seconds based on the results of the RSM study. The compressor performance trails of the base and the redesigned case are compared in Fig. 8, and no surge was found in the redesigned case.

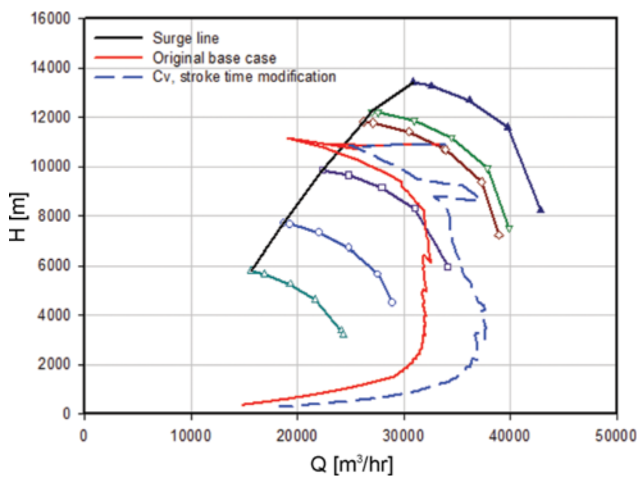

Fig. 8. Comparison of responses of operating points during ESD.

INSTALLATION OF HOT GAS RECYCLE SYSTEM

Another known surge protection method is the installation of hot-gas recycle loop known as hot gas recycle system. With hot gas recycle system, the surge control system can respond faster to operational changes [1]. However, it cannot be used independently for long period without cold gas recycle due to temperature increase such as in the case of start-up. Therefore, the cold gas recycle system is 1st priority and hot gas recycle system is 2nd priority considering start-up.

To avoid a compressor surge, a hot gas recycle system was installed to the base case system. The process flow diagram of hot gas recycle system is shown in Fig. 9. Cold gas recycle loop and other units are same as the base case, and the capacity of hot gas recycle valve, 1,500 USgpm, was set to half of the capacity of cold gas recycle valve, 3,000 USGpm. Pipe diameters of two recycle loops are same, while the pipe length of hot gas recycle system is 50 m.

The simulation results of the base case and the hot gas recycle case are compared in Fig. 10. The turning point time of the base case is at 5.33 seconds, while the turning point time of hot gas recycle system is at 5.26 seconds. The surge problem could be alleviated by the installation of hot gas recycle system to the original base case. Fully opening both the hot and cold gas recycle valves simultaneously on ESD is very effective to avoid surge occurrence.

From the results, even though we can conclude that the hot gas recycle system definitely helps avoid surge problems, the later redesign of the hot gas recycle system is a challenging problem to modify the original design due to limited plot space, time required

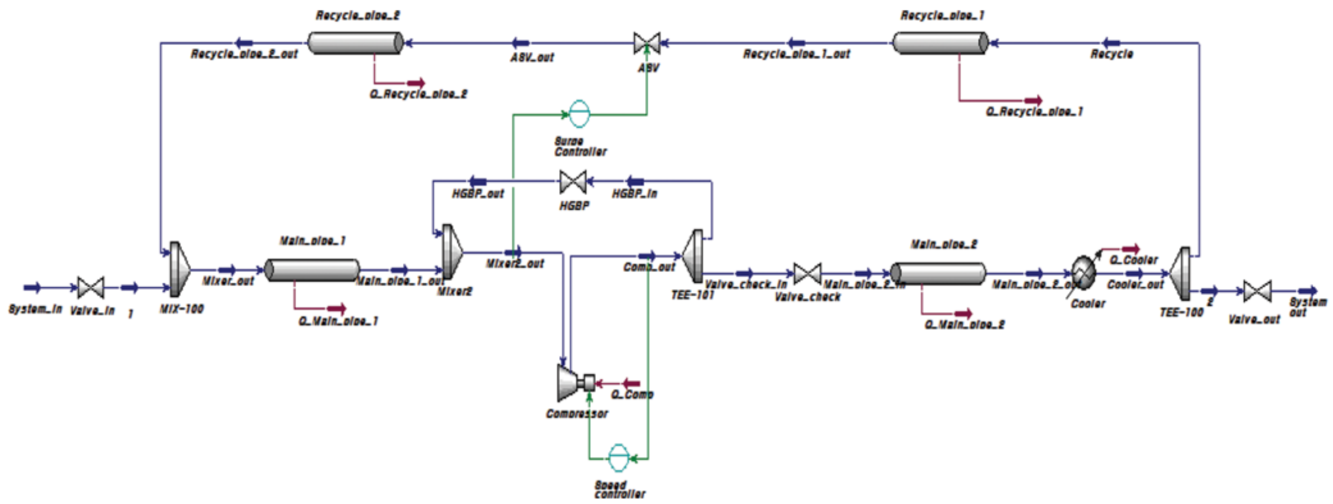

Fig. 9. Process flow diagram involving hot and cold recycle system in dynamic simulation.

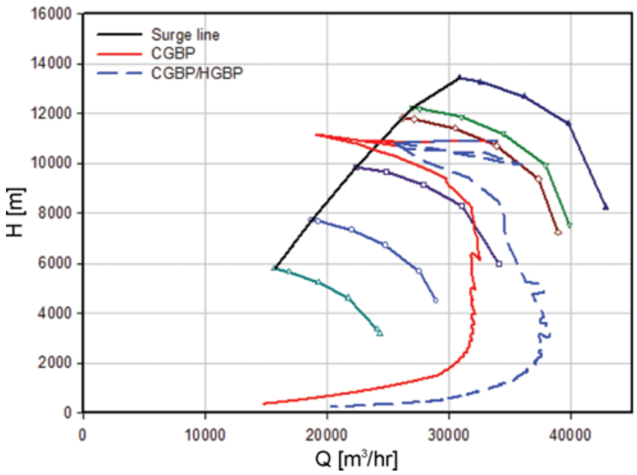

Fig. 10. Performance trails on ESD for the base case and hot gas recycle case.

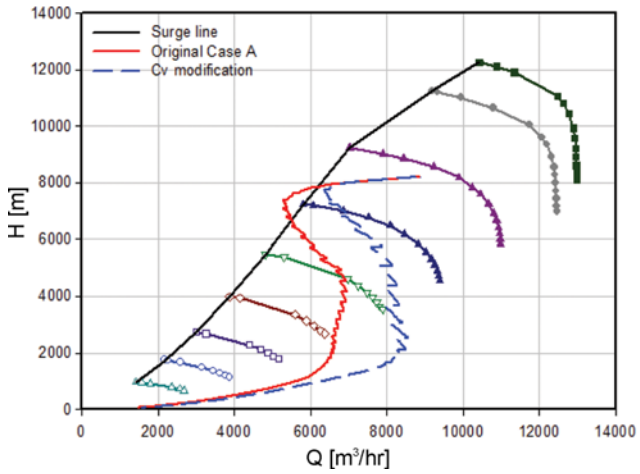

Fig. 11. Response of compressor operating point during ESD for case A.

for new order and manufacture, and delayed project schedule. Thus, a surge analysis of hot gas recycle system in the event of an ESD should be considered in the very early stages of the compression system design.

MORE CASE STUDIES

Surge avoidance system during ESD was analyzed with three more existing compression system cases by dynamic simulation. An emergency shutdown in every case and the performance trails were analyzed. Based on the previous work in sections 4 and 5, some systems were re-redesigned to avoid surge occurrence. The detail design parameters and results of ESD are compared in Table 2.

1. Case A: Cracked Gas Single-stage Compression System

Case A is a cracked gas compression system using a single stage centrifugal compressor. Stroke time and pre-stroke time are set to be 1 second and 0.3 second. The PFD for dynamic simulation of Case A is shown in Fig. A.1, attached in the Appendix.

The time from the operating point to surge line is 0.44 second and compressor speed decelerates to 93.6% of the speed at steady state, thus a surge occurs. To avoid the surge, the redesign of ASV capacity value from 1,500 USgpm to 4,000 USgpm was tried and the compressor performance trails of the base and the redesigned case are compared in Fig. 11.

2. Case B: Off-gas Two-stage Compression System

Case B is an off-gas compression system using two trains of VFD motor driven two-stage centrifugal compressors installed at an oil and gas terminal. The main composition of the gas is methane. Stroke time and pre-stroke time are set to be 1 second and 0.1 second, respectively. The simplified PFD for dynamic simulation of Case B is shown in Fig. A.2, attached in the Appendix.

In this case, a surge occurs at the 1st stage compressor, but no surge at the 2nd stage during ESD. Time to surge is 0.09 second and compressor speed decelerates to 98.3% of the speed at steady state. The performance trails during ESD are shown in Fig. 12.

The normal operating point at the 1st stage compressor is too close to the surge line, located at 7.27% to the right of surge line.

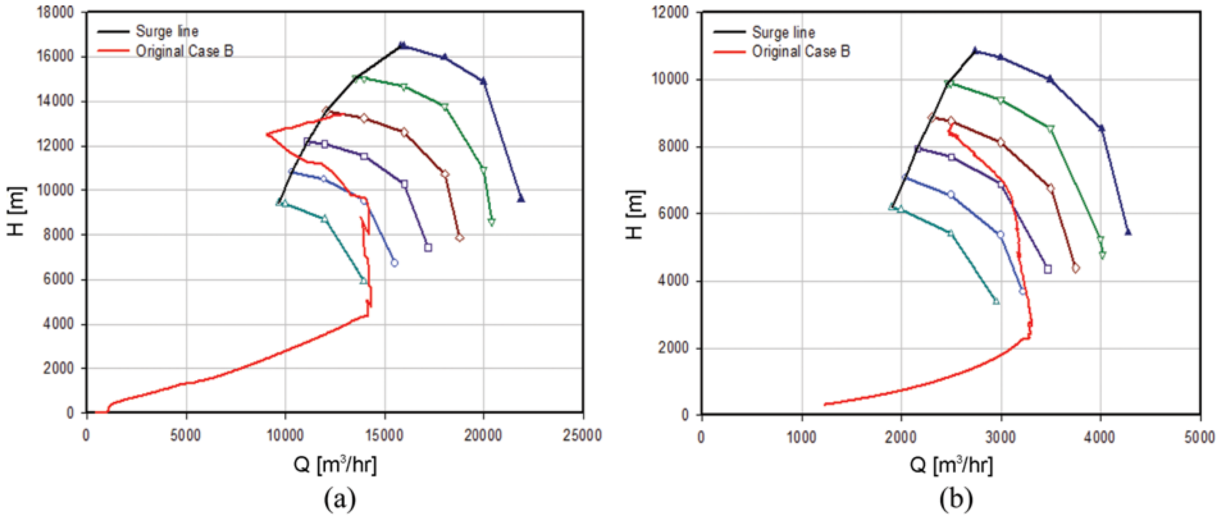

Fig. 12. Response of compressor operating point during ESD for Case B. (a) 1st Stage. (b) 2nd Stage.

As a consequence, the surge margin or operating window is significantly reduced. The pre-stroke time of this case is 0.1 second, but the time to the surge line is only 0.09 second. Thus, we cannot avoid a surge problem during ESD even though the compressor surge does not occur during normal operation. In this case, many redesign cases can be studied, but basically a different compressor should have been selected at an early stage in terms of a surge protection system.

3. Case C: NGL Recovery Two-stage Compression System

Case C is the part of an NGL recovery facility which includes acid gas compression using two-stage compressors. Stroke time and pre-stroke time are set to be 1 second and 0.3 second. The simplified PFD for dynamic simulation of Case C is shown in Fig. A.3, attached in the Appendix.

In this case a surge occurs at both stages. Time to surge is 0.52 and 0.06 second, compressor speed decelerates to 94.7% and 99.3% of the speed at steady state at the surge line. The performance trails during ESD are shown in Fig. 13.

For the 1st stage of Case C, the installation of a hot gas recycle system helps in avoiding a surge, and the ASV capacity in cold gas recycle system is 250 USgpm, and that in the hot gas recycle system is 250 USgpm. Like the 1st stage of Case B, the 2nd stage of Case C could not avoid surge because the pre-stroke time of this case is 0.3 second, but the time to the surge line is only 0.06 second.

CONCLUSIONS

A surge protection system for a centrifugal compressor is crucial to avoid any damage during emergency shut-down. Four cases of existing centrifugal compressor systems were analyzed to study the surge protection availability during ESD. The surge criteria flowchart was suggested and surge analysis through dynamic simulation was done using a commercial process simulator.

As a result of sensitivity study, it is found that ASV capacity and stroke time are the only adjustable significant parameters for surge protection system during ESD. With those findings, response surface method was applied to find an optimized design of a surge protection system. A hot-gas recycle system can be another candi-

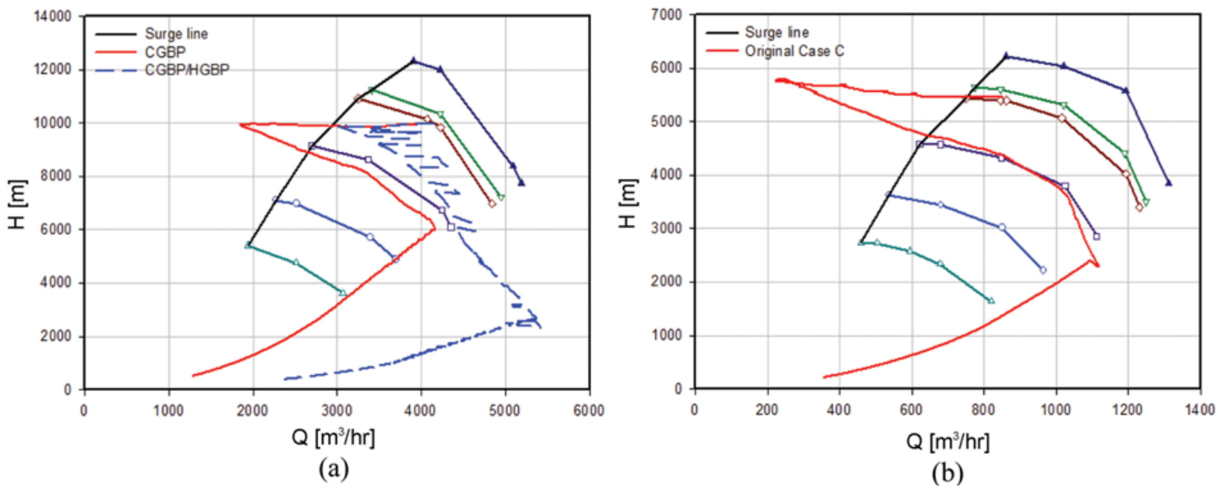

Fig. 13. Response of compressor operating point during ESD for Case C. (a) 1st Stage. (b) 2nd Stage.

date, but any of selection should be based on cost, schedule and status of the project. Based on the results, we devised a step-by-step methodology for the redesign of a surge protection system during ESD.

The surge protection system must function differently in the event of an ESD where the system must respond rapidly compared to normal and startup cases. The surge analysis during ESD through dynamic simulation was essential to redesign the system in the very early stages of the compressor system design, (1) during front-end engineering and design (FEED), to select and novate compressor, (2) during FEED verfication, if the compressor is novated, (3) during EPC proposal phase and EPC execution phase, whenever the decision to purchase the centrifugal compressor is made, as soon as the compressor performance curve is ready from manufaucturer.

ACKNOWLEDGEMENT

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APPENDIX

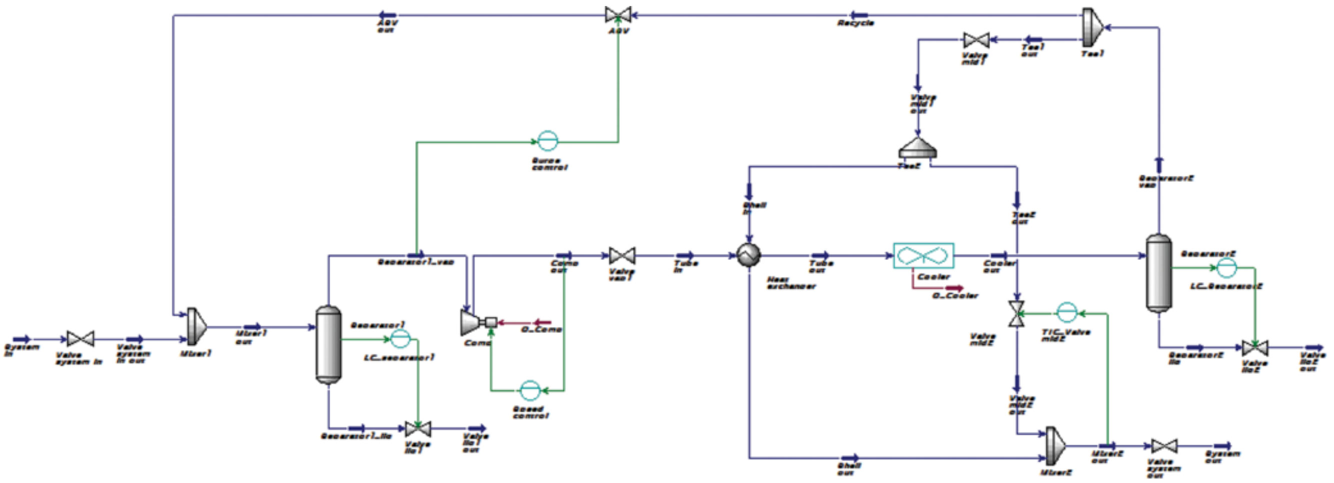

Fig. A.1. Simplified process flow diagram of case A without piping segments.

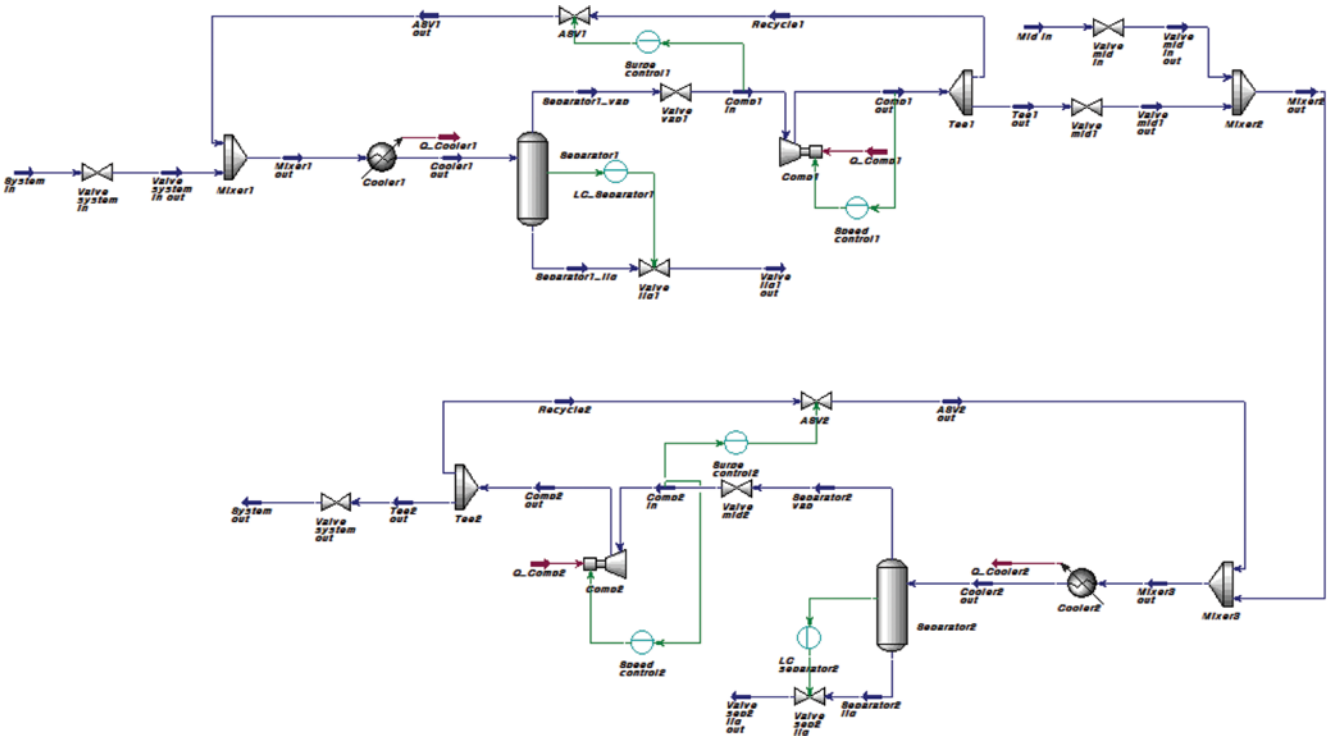

Fig. A.2. Simplified process flow diagram of case B without piping segments.

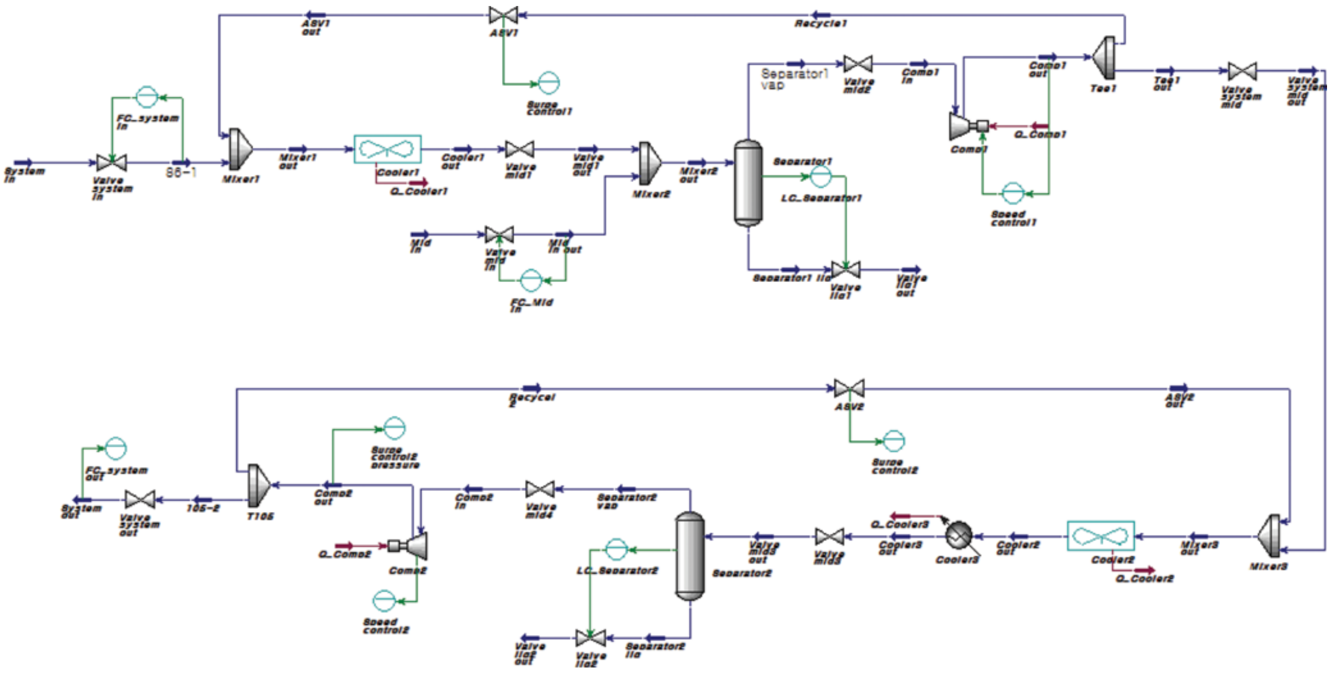

Fig. A.3. Simplified process flow diagram of case C without piping segments.