Centrifugal compressor anti-surge control system modelling

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ABSTRACT

From the middle of XX century, natural gas is an important mineral, widely used in the energy sector. Transportation of natural gas is carried out via gas pipeline networks and compression stations. One of the key features which need to be implemented for any centrifugal gas compressor is a surge protection. This article describes the method and develops software application intended for simulation and study of surge protection system of a centrifugal compressor used in modern gas compression stations. Within the article research method, modelling environment's block diagram, proposed algorithms and results are described. For surge cases control and prediction, Anti-surge control block implemented which based on practical experience and centrifugal compressor theory. To avoid complicated energy balancing differential equations the volumetric flow calculation algorithm proposed which is used in combination with Redlich-Kwong equation of state. Developed software's adequacy test performed through modeling of one-stage gas compression scheme at rated speed with comparison of parameters with reference commercial software and verification of the anti-surge control system.

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1. INTRODUCTION

Gas compressors are represented by two common types-dynamic gas compressors and positive displacement ones. In a positive displacement compressor work is performed by reducing the volume of gas which increases its pressure. In a dynamic compressor work is done transferring movement kinetic energy to the gas. By the velocity reduction occurs conversion of kinetic energy into the potential energy or pressure. Centrifugal and axial compressors are two main types of dynamic compressors. By the series of rotors, the axial compressors transferring energy of movement to the gas in the axial direction. On the other hand, centrifugal compressors are performing work by an impeller which transfers movement energy in radial direction. Then this velocity in a diffuser is converted into pressure.

The instability of a centrifugal gas compressor can appear in two main forms: surging and stalling. Stalling is a disruption of flow, does not usually damage the centrifugal compressor. In fact, in industrial environments it can be difficult to identify a stall. The term of compressor surge can be described as audible thumping and honking at frequencies as low as 1 hertz, severe mechanical vibration, and pressure pulsations throughout the machine [1]. Surging is an unstable compressor operation mode in which the pressure at the compressor discharge is large relative to the flow through the compressor. Surging can destroy a compressor, and most industrial compressors have some form of surge protection. An anti-surge control system protects compressor from surging, by controlling the suction flow rate of gas to the compressor [2]. Effective anti-surge control depends on various factors, such as measuring devices accuracy, the type of control valves, and dynamic response of the process [3]. The surge region is the area to the left of the surge limit line (SLL) as shown in Figure 1, and it should be given in the compressor performance curves and datasheets.

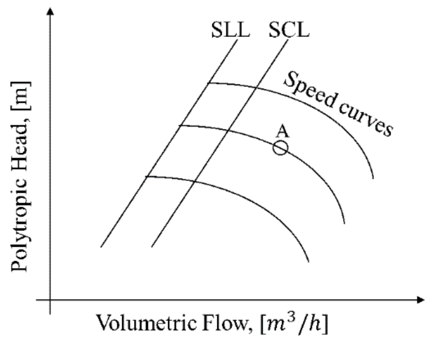

Figure 1. Operating point position control by anti-surge regulator

The anti-surge control system prevents reaching the “SLL” curve by the operating point “A” as shown in Figure 1. This is achieving by an additional line of defense called surge control line (SCL) which is located to the right of “SLL”. Suction gas flow is increasing with the anti-surge valve’s opening, whose purpose is maintain the operating point in the stable operating area along with the velocity curve.

Speed and anti-surge control circuits are one of the important protection systems for the compressors. Over the past decades significantly has changed design philosophies for these control systems. In the mid-seventies, the first analog based electronic control systems appeared on the market. In the eighties appeared microprocessor systems. In recent years, significant changes have occurred in the market of microprocessor-based anti-surge systems and speed control systems due to the transition to 32-bit and 64-bit processors [4], [5]. Different modelling approaches have been proposed in recent years [6]–[15]. Over the years, to determine more precise operational parameters of the transmission lines, it have been carried out different numerical simulations of pipeline network systems [16]–[19]. The methods for developing of gas compression system simulator are described in [20], [21].

As described above, anti-surge regulator maintains the compressor in the stable operating ranges [22]–[26]. Any regulation basically is based on measurement of flow through the machine and should meet the basic requirements: i) machine must be protected by the system under all operating conditions, where included start and stop sequences; ii) surge control line should be as close as possible to a parallel displacement of the surge limit line considering the safety and efficiency requirements; iii) for the efficient operation of compressor, surge control line must not get closer to the surge limit line more than it is necessary.

Surge and high vibration cause emergency shutdown of the gas compressor unit in 20-25% of cases [27]. The assessment and consequences of surge based on empirical analytical models have been investigated in various works [28]–[30]. Surge studies and risks, however, need to be studied on a case-by-case basis, since each gas compressor has its own surge characteristics.

Nowadays there are exists various commercial gas industry simulation programs that can simulate with high accuracy. Such software packages are very accurate, but they are created through complicated calculations and material and energy balancing differential equations and may not reflect the entire logic of the gas compression unit control system in the field. They are widely used to obtain accurate calculations when simulating various technological processes. But in the tasks of optimal and operational control of the gas compression unit, the modeling system should be more flexible to the implementation of changes, depending on the requirements of the technological process, and the speed of calculations is also important. Most of the simulation programs are based on solving n-order differential equations, which favorably affects the accuracy of calculations, but at the same time requires more system time than in cases of using simple algebraic dependencies. Therefore, it is advisable to develop own modeling package that meets these requirements.

This article provides a description of the anti-surge regulator implemented in the developed gas compression system simulation software. Implemented anti-surge control strategy used for predicting and simulating cases of surge and based on practical experience and centrifugal gas compressor theory. Checking the adequacy of the regulator was done on the basis of the created mathematical model with further implementation in the simulation application. To check the adequacy of developed simulation software to changes in suction and discharge conditions it has been used the one-stage gas compression model. The proposed method includes the developed flow formation algorithm, modeling of the main equipment of the gas compressor station and a developed anti-surge control system.

The paper continues in section 2 where described the proposed algorithms and the method of research. In section 3 modeling results obtained from the software are provided. The conclusion of the paper is given in section 4. Future work outlined in section 5.

2. RESEARCH METHOD

An anti-surge control circuit consists of a line of recirculation with valve which connects compressor's discharge with suction sides. Depending on the degree of opening of the anti-surge valve, the recirculation line allows to transfer of the outlet gas flow to the compressor inlet, which leads to an increase in the inlet flow rate and a decrease in the pressure at the compressor discharge. Within this section described developed software's modeling environment block diagram, modeling and parameters calculation flowchart algorithm and an implemented anti-surge control strategy.

2.1. Modeling environment block diagram

One of the first stages in solving the problem of modeling the technological process of gas compression is the development of the structure of the modeling environment and its further software implementation. The technological process of gas compression is not static, as a result it is necessary to develop a software environment for simulating dynamic processes. The block diagram with steps of the modeling process is shown in Figure 2. According to this structure, the software environment consists of three main modules: A model generation module, a simulation module, and an execution module. The structure also takes into account the requirements for the control system, requirements for the list of equipment, and simulation results.

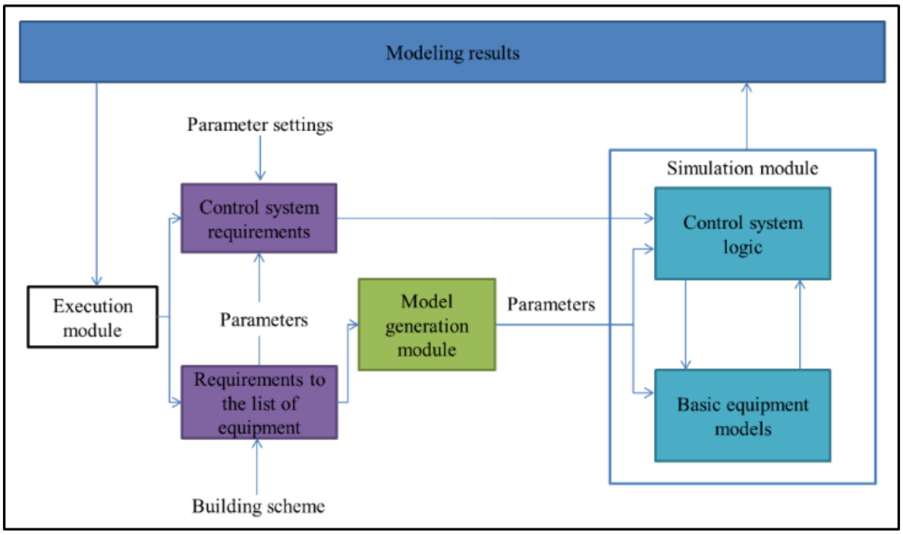

Figure 2. Block diagram of the modeling process in the developed software package

Before proceeding with direct modeling, it is necessary to build a gas compression scheme, set the gas parameters at the inlet to the model (gas pressure, gas temperature, component composition) and all the necessary parameters for the selected list of equipment, for example, gas compressor performance curves, anti-surge protection lines, capacity of valves, and parameters of the cooler. It is necessary to set the requirements for the control system: the choice of control parameters, the settings of control criteria. After that, the model generation module will create a simulation scheme and transfer all parameters to the simulation module.

The simulation module consists of two main blocks: Mathematical models of the main equipment and logic of the control system. The main equipment block includes models of such elements as a single-stage gas compressor, a gas-liquid separator, a cooler, a gas valve, a pipe model, a flow mixing unit, a flow separation unit, an anti-surge valve. Models of the main equipment are implemented in the form of library elements, including the necessary mathematical calculations for gas parameters. The runtime module is the main engine of the application, whose task is to update the simulation results and transfer them to the simulation module, considering the requirements for the control system and the simulation scheme.

2.2. One-stage compression system modeling and parameters calculation flowchart

Figure 3 shows the one-stage gas compression stage with anti-surge valve. The circuit contains the following elements: gas inlet and outlet points, valves, gas flow collection unit, gas flow dividing unit, centrifugal compressor, recirculation line with anti-surge valve. At every element's inlet, gas pressure, temperature, volumetric flow, and gas composition are known parameters. At the input to the system user through the dialog box must set the initial values of pressure, temperature, and gas composition. The value of the volumetric gas flow rate is an unknown parameter and need to be calculated every program cycle.

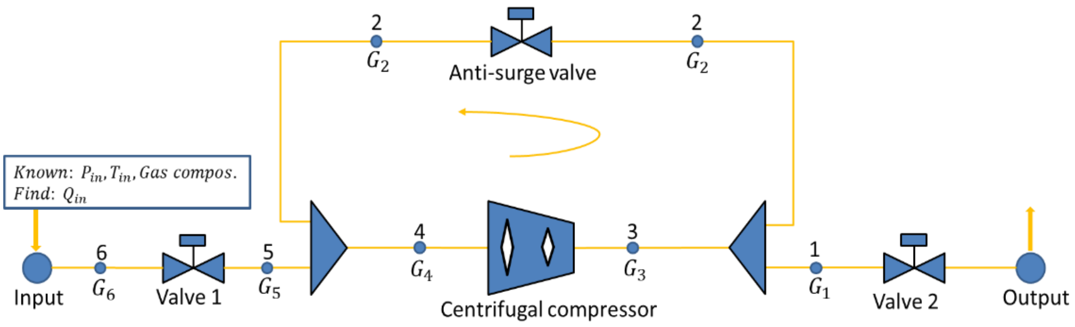

Figure 3. The main components of the one stage gas compression scheme

The volumetric flow rate in the gas compression scheme depends on each of the element's capacity (points $G_1 - G_6$). To find out the volumetric flow rate at the inlet, it is required in the created scheme to determine the element with the minimum mass flow and divide this mass flow to the gas density at the inlet. The volumetric gas flow calculation algorithm is described in 7 steps.

Step 1. Searching the minimum capacity of the scheme is starting from the end and move to the beginning of the circuit. From Figure 3 it can be seen that the last element in the scheme that affects the capacity is "Valve 2". Therefore, the capacity at point G_1 will be defined as the capacity of "Valve 2":

$$G_1 = Vlv\_2_{cap} \tag{1}$$

where, G_1-gas mass flow rate, [kg/sec]; Vlv_2_{cap}-the valve's mass flow rate which depends on size and properties of the valve.

Step 2. Determination of the recirculation line capacity, which is equal to capacity of the anti-surge valve (ASV).

$$G_2 = ASV_{cap} \tag{2}$$

Step 3. The capacity at the entrance of the branching point (G_3) is the sum of the capacities of each of the outgoing branches:

$$G_3 = G_1 + G_2 \tag{3}$$

Step 4. Depending on the speed of the centrifugal compressor, it's capacity also changes. Therefore, the mass flow at point G_4 is defined as the minimum value of the capacity at point G_3 and the flow through the centrifugal compressor:

$$G_4 = \min(Compressor_{cap}, G_3) \tag{4}$$

Step 5. The capacity at the inlet of the flow mixing unit (point G_5) is determined by subtracting the flow rates of the remaining inlet branches from the mass flow rate at its outlet:

$$G_5 = G_4 - G_2 \quad (5)$$

Step 6. The flow rate at point G_6 is calculated as the minimum value between the flow rate at point G_5 and the capacity of "Valve 1":

$$G_6 = \min(Vlv\_1_{cap}, G_5) \quad (6)$$

Step 7. The volumetric gas flow rate at the inlet of the gas compression scheme is defined as the ratio of the mass flow rate at point G_6 and the gas density at the inlet:

$$Q_{in} = \frac{G_6}{\rho_{in}} \quad (7)$$

where, Q_{in} is the desired value of the volumetric gas flow rate at the inlet to the system, [m^3/sec]; G_6-gas mass flow rate at point G_6, [kg/sec]; ρ_{in} is the gas density at the inlet, which is calculated by the standard equation for density calculation:

$$\rho = \frac{P \cdot MW}{Z \cdot R \cdot T} \quad (8)$$

where, P is the pressure, [Pa]; MW is the molecular weight of the gas, [kg/mol]; T is the gas temperature, [°K]; R-Universal gas constant, [J/(mol · K)]; Z-gas compressibility factor, [-]. The Redlich-Kwong equation of state (EOS) is used to perform a mass balance and calculation of the compressibility factor Z [31].

2.3. Anti-surge controller development

The surge curves are necessary component of the anti-surge control system and should be given in the datasheet of the compressor. Figure 4 shows surge curves used in the developed software. The compressor's operating point is determined by suction gas flow rate ["Q"] and polytropic Head ["H"]. Below are described main curves of the anti-surge controller.

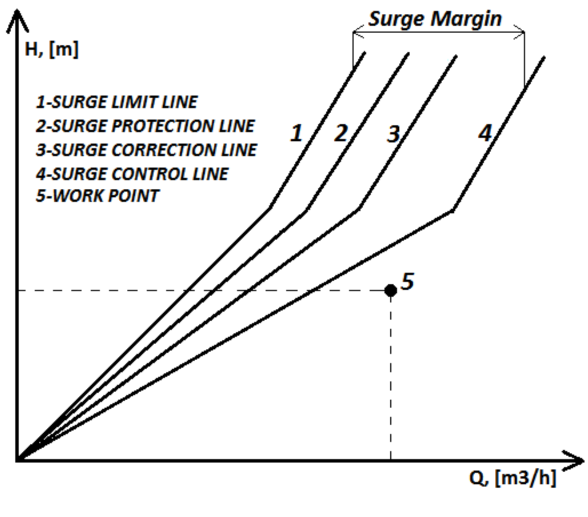

Figure 4. Anti-surge regulator curves

Surge limit line-is the curve, where a set of volumetric flow values with the corresponding values of polytropic pressure determines the limit beyond which the compressor will be in surge and must be presented in the compressor datasheet. The software application allows to enter this curve through a custom dialog box window. Surge protection line-is the protection line prior of reaching SLL by operational point. The "SPL" coordinates are defined as (9).

$$SPL = SLL \cdot K_{SPL} \quad (9)$$

Where, K_{SPL} is the SPL coefficient, by default setpoint is 1.0404 and could be adjusted by user through the dialog box. If the "SPL" curve is activated in the anti-surge control panel and the operating point of the compressor reaches "SPL", after defined delay the compressor protection logic is activated, the logic immediately opens anti-surge valve to 100% to protect compressor from surge.

Surge correction line-is the line which allows to increase the surge margin and quick opening of anti-surge valve once the position of the operating point is between "SPL" and "SCrL". Surge control line-is the curve along which anti-surge regulator keeps the compressor's operating point position. If the operating point for flow rate is less (to the left of the curve) than the "SCntL", regulator opens the anti-surge valve. Once the operating point for the flow is larger (to the right of the curve) than "SCntL", then the regulator will start closing the anti-surge valve. The "SCntL" position during the normal operation, is defined by (10).

$$SCntL = SLL \cdot \left(1 + \frac{Surge\ Margin}{100}\right), \tag{10}$$

Where the value of surge margin could be adjusted by user from the anti-surge control dialog box. In our test cases we selected surge margin equal to 30%. On real gas compression sites this value could be vary depending on the specified centrifugal compressor's anti-surge write-up document.

Anti-surge valve's position is controlled by a standard proportional-integral-derivative controller (PID) as it is done on real gas compression sites. The setting of the SP (Set Point) of the controller is defined by (11).

$$SP = 1 + \frac{Surge\ Margin}{100\%} \tag{11}$$

The value of the Process Value (PV) is calculated by the (12).

$$PV = \frac{Q_{in}}{RO\_SET} \tag{12}$$

Where, RO_SET is the volumetric flow which corresponds to the polytropic head's current value, Q_{in} is the gas flow at the compressor suction. The RO_SET parameter defined by linearly interpolating the polytropic pressure to the "SCntL" curve.

3. RESULTS AND DISCUSSION

The result of the work is developed application for modelling of centrifugal compressor operation modes with anti-surge control under various dynamic operating conditions. The developed application allows to create different technological schemes with the elements like valve, gas compressor, cooler, gas-liquid separator, anti-surge line [32]. The functionality of compressor control system must meet all the requirements that are necessary to control and regulate the parameters of the main compressor: regulation of pressure of the compressor on an inlet and discharge sides, flow control, operation of the cooling system, speed control, control and management of operator alerts, compressor start/stop sequences. Developed software adequacy test performed through two types of tests: modeling of compressor at rated speed with comparison of parameters with reference commercial software and verification of the anti-surge control.

3.1. Modelling of compressor control mode at rated speed

In this mode, the compressor operates at steady-state speed without transients. To determine the adequacy of the model, a comparison was made at compressor nominal speed for developed software and the reference one (Aspen hysys) with the same compression scheme and properties of the elements. The centrifugal compressor speed was 3,000 rpm. The comparison was done for seven main parameters at compressor suction and discharge sides: temperature (T), pressure (P), process gas mass flow rate (F_{mass}), gas density (ρ), process gas volumetric flow rate (F_{vol}), power (Pow), polytropic head (H_{polyt}). The corresponding results are shown in Table 1.

As it is seen from above table, the difference between the modelling parameters for the developed software and the reference one is less than 0.6%, which means that proposed methods and algorithms in the developed software performs adequate calculations. Considering this, developed software could be used for further anti-surge regulator verification.

Table 1. Comparison of compressor suction/discharge modeling parameters at rated speed for developed and reference software

Parameters	Developed software		Reference software	
	Suction	Discharge	Suction	Discharge
T, [C]	22.33	87.68	22.23	85.97
P, [bar]	17.71	37.71	17.61	37.57
F_{mass}, [kg/h]	390030	390030	389400	389400
ρ, [kg/m3]	13.93	24.28	13.88	24.39
F_{vol}, [m3/h]	28005	16064	28050	15970
Pow, [kW]	14113	14113	14045	14045
H_{polyt}, [m]	10661	10661	10630	10630

3.2. Anti-surge regulator verification

The simulator interface for anti-surge control is shown in Figure 5. The interface allows to configure the surge curve, set the parameters of the PID controller, as well as see the parameters of the anti-surge regulator. As a process of the gas compression, a single-stage scheme with one input and one output was chosen. According to this scheme, one centrifugal gas compressor with one drive participates in the gas compression process. This scheme also includes such elements as cooler, gas-liquid separator, valves, pipes. Anti-surge control line is one of the significant elements of compressor. The system parameters initialization is an important part. Within this phase is setting inlet gas pressure, temperature, gas composition, valves' properties, compressor curves (performance curve, efficiency, anti-surge curve), and pipe properties. Correct operation of the anti-surge regulator is important in the entire process of compressor operation from the moment of start up to a complete stop. Compressor shutdown is the critical event for the anti-surge regulator because it should react immediately to prevent the compressor's operating point from entering to the surge zone.

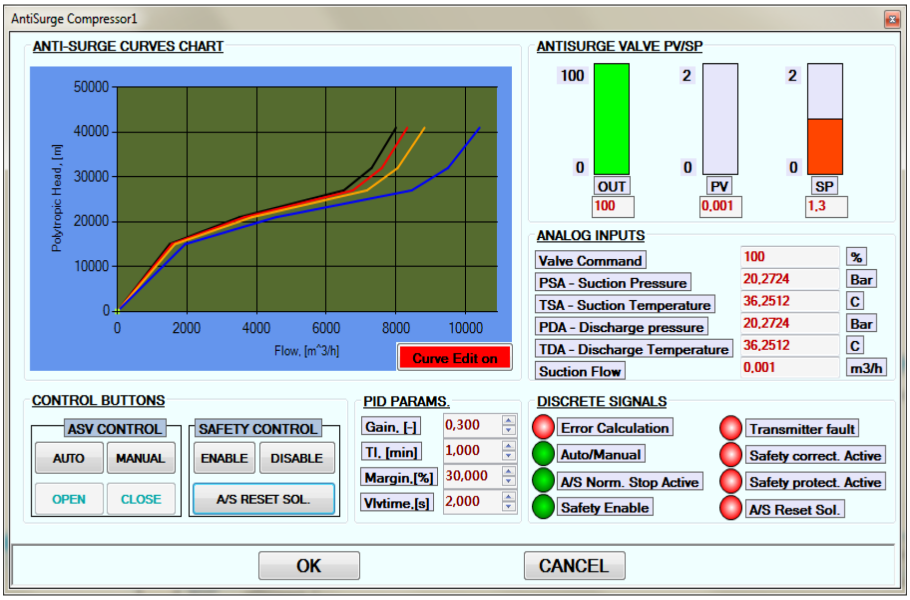

Figure 5. Anti-surge regulator dialog box

For test purpose it was selected the change in volumetric flow at suction side of the compressor, by closing the valve at the discharge ("Valve 2" from Figure 3) from 26% to 20% (decrease in flow) and opening the valve at the discharge from 20% to 26% (increase in flow). During the flow rate decreasing step, the compressor's operating point starts moving to the surge area, and regulator initiates anti-surge valve's opening, which leads to an increase in flow rate due to transferring part of the volumetric flow to the suction from the discharge side as shown in Figure 6. Accordingly, when the flow increases, the regulator initiates anti-surge valve's closing. As can be seen from the Figure 6, the anti-surge regulator smoothly controls the operating point without hesitation and aligns its position at the required for safe operation of the compressor flow rate. The compressor working point tracking during the suction flow change is also shown on Figure 6 (right). As the flow decreased, the working point moves to the left, the reaction of the anti-surge control regulator is as follows: at the beginning it tries to force the valve's command rate by moving the SCL to the right, if this does not help and work point reaches the SPL the regulator opens the anti-surge valve to 100% for protecting compressors from the surge.

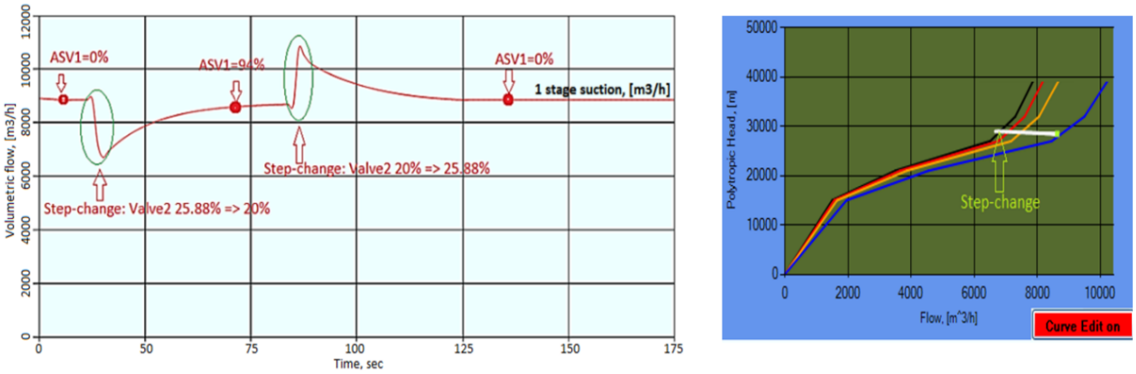

Figure 6. Anti-surge regulator reaction trend to flow change (left) and working point position tracking (right)

4. CONCLUSION

Within this article is described the software application, designed to simulate gas compression system's different operating modes with emphasizing on anti-surge control system and its model. The research method, modelling environment's block diagram and proposed algorithms are described. For prediction and investigate surge cases an anti-surge control block implemented which based on practical experience and centrifugal compressor theory. To tuning of the main anti-surge regulator parameters (PID regulator gains, anti-surge curves implementation, and auto/manual control selection) created the appropriate dialog box.

To determine the adequacy, a comparison was made at compressor nominal speed for developed software and the reference one with the same compression scheme and properties of the elements. The difference between the modelling parameters for the developed software and the reference one was less than 0.6%, i.e., the proposed methods and algorithms performs adequate calculations. Anti-surge regulator verification showed that it is reacts to system disturbance, protects compressor from surge occurrence and allows to simulate and analyze different cases which is not possible to test on real equipment. To avoid complicated energy and material balancing differential equations the volumetric flow calculation algorithm proposed which is used in combination with Redlich-Kwong equation of state. The developed application practically could be used in centrifugal gas compressor's operation modes study and analysis.

5. FUTURE WORK

Taking into account that compressor blades contamination leads to high fuel consumption, an increase in pressure and temperature of the discharge gas, and risks of earlier surge occurrence, the study of the compressor operating modes by modeling at the boundaries of the permissible operating regions of the speed and the surge limit line could be used to assess the permissible and critical values of the decrease in efficiency indicators, as well as the analysis of surge conditions.

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