Досліджено умови формування режимів протікання потоку через дросель, що використовується для сепарації вологи із потоку повітря або газу. Проведено ідентифікацію параметрів дроселя шляхом порівняння експериментальних даних, отриманих на експериментальній установці, із чисельними розрахунками по відомим математичним моделям дроселя. Створена статична модель дроселюючого пристрою установки відбору вологи. Проаналізовано вплив значення площі поперечного перерізу дроселя на всі параметри потоку, що дроселюється, та оцінена можливість керування цим потоком

Ключові слова: докритичний режим, моделювання потоку, дросельна заслінка, витрати газу, гідравлічний опір трубопроводу, температура точки роси

Исследованы условия формирования режимов протекания потока через дроссель, который используется для сепарации влаги из потока воздуха или газа. Проведена идентификация параметров дросселя путем сравнения экспериментальных данных, полученных на экспериментальной установке, с численными расчетами по известным математическим моделям дросселя. Создана статическая модель дросселирующего устройства установки сепарации влаги. Проанализировано влияние значения площади поперечного сечения дросселя на все параметры дросселируемого потока и оценена возможность управления этим потоком

Ключевые слова: докритический режим, моделирование потока, дроссельная заслонка, расход газа, гидравлическое сопротивление трубопровода, температура точки росы

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MODELLING A THROTTLING DEVICE DURING SEPARATION OF MOISTURE FROM GAS FLOW

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1. Introduction

The main task of the preparation of natural gas for transportation is the separation of moisture and various additives that it contains. Traditionally, in the units of complex processing of gas (UCPG), the process of low temperature separation (LTS) is used, which occurs as a result of throttling of the flow of natural gas. A throttle effect (by Joule-Thomson) leads to the cooling of natural gas but the condensation of moisture and hydrocarbons in the separator is observed only when the temperature of gas mixture overtakes the dew point (DP).

It should be noted that the DP for water is different from that for hydrocarbons contained in natural gas. Accordingly, optimal conditions of separation for carbohydrate additives cannot simultaneously provide efficient selection of water from gas. Additional difficulties during moisture separation during the LTS are the influence of the flow rate of gas on the process of separation because, under certain values of the flow velocity, an unwanted removal of condensed droplets from the separator occurs [1]. These difficulties are caused by joint influence of a cross-sectional value of a throttle valve on the gas rate (flow velocity) and the pressure drop in the throttle.

Attention to the value of the flow rate of gas is predetermined also by the parameters of the productivity of this flow, since at certain minimal values of the flow the transportation of gas does not make any sense.

Different approaches for the measurement of gas rate, which are valid for certain terms of the gas flow, lead to substantial errors when the conditions of formation of the mode of throttling change. Additional components of the measurement error form as a result of neglecting a nonlinear nature of the relationship between the pressure and the flow rate during functioning of a throttle device in the working range of pressures and rates.

Depending on the pressure drop, laminar or turbulent flows form in the throttle [2]. In accordance with the pressure drop, subcritical or supercritical modes of the flow through the throttle are formed, which is usually not taken into account in determining the real flow rate.

Thus the relevance of the work is determined by the objective to obtain an adequate definition of the parameters of a throttling process, since an adequate model allows developing the criterion of efficient control over the process and creating a control system based on it.

2. Analysis of scientific literature and the problem statement

Software methods of gas flows simulation known at present, for example, HYSYS, are widely used not only for the design calculations but also in the management of the production process in the mode of “advisor” [3]. As a result of comparisons of the calculated data by Aspen-HYSYS simulator and the performance specifications of existing equipment, operation control of the flows of natural gas makes it

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possible to overtake optimal modes faster and to improve economic specifications of the processes of preparation gas for transportation.

However, more efficient specifications of control are achieved while building up specialized technological modelling systems [4]. Such systems allow receiving data that characterize the dynamics of the process of the LTS and adapting to the specifics of a particular technology of gas processing. In this case, optimization of the process is carried out as a result of processing of large arrays of collected data. In the research into the process of LTS by a modelling system [4], it is believed that the flow rate Q is associated with the drop of pressure in the throttle ΔP by the ratio:

$$Q = K_V\sqrt{\Delta P\frac{1000}{\rho}}, \quad (1)$$

where K_V is the throttle characteristic; ρ is the density of the flow.

This statement is true only for the incompressible components of the flow, such as water or gas condensate. For the gas itself, depending on the modes of the flow of the mixture, the connection between the flow rate Q and the drop of pressures takes a more sophisticated form.

To study the effects of gas flow modes on its parameters, software simulation environment is used [5] that allows obtaining a distribution of the fields' pressures, flow velocity and the temperature of a well, depending on the diameter of a throttling hole of the well. However, the equations in partial derivatives, on which the results of the simulation are based, do not answer the question of building the tools to control the process and this problem becomes even more complicated when the flow parameters change in the time.

The peculiarities of controlling the process of moisture separation are in the fact that the flow parameters of natural gas supplied from a well arbitrarily change in the time. By enhancing the research into analysis of material flows of the LTS unit, a linear mathematical model of static and dynamic was created [6], which allows formulating requirements to the regulator of material balance of liquid and gas phases in the separator. Efficient control of the LTS process is possible only while tracking parameters of gas flow – pressure and temperature. However, to construct an optimal management system or a system that adapts in a given range of changes of the flow parameters, based on the linearization of equations around one working point of the model, is quite difficult.

The objective to describe a throttling model of the flow by simplified equations or universal formulas leads under real conditions to errors in the control process of moisture separation. That is why it is only natural to take into account subcritical and supercritical modes of the flow, with modern trends of control systems design enabling their implementation based on microprocessor tools.

Passing over to the study of the modes under direct control of a throttle valve, one has to pay attention to the character of distribution of the air flow through the throttle. An example of such a study in the Wankel engine [7] allows assessing the dynamics of the device's processes and determining the ratio of the mass flow depending on the opening angle of a throttle valve. The results of the research, taking into account the values of pressure drop and the design of a throttle valve, cannot be directly used in the modelling of LTS processes.

The development of this approach for the modelling of a throttling device that is used in the LTS processes is based on considering the Joule-Thomson effect. This is necessary with regard to the fact that during the changing of the area of a throttle cross section, not only the pressure and gas rate change, but also the temperature of the flow. It is the objective to reduce the temperature of the flow to the DP, which predetermines the task of increasing a pressure drop by the reduction of pressure after the throttle, but in this case the flow rate falls down, and the well's productivity decreases accordingly. On the contrary, the increased rate due to a pressure rise after the throttle reduces the amount of removed water and condensate because carrying out of formed water droplets into the pipeline increases.

Thus, a model of the throttling process, which is used for the removal of moisture by the LTS method, must reflect relationship between pressure, flow temperature and its rate.

Taking into account the influence of the phase composition of the mixture of gas flow [6] under throttling complicates simulation of the LTS process. Implementation of the approach [8], which defines the conditions of simplification of the estimates of the flow down to a single phase system, allows simplifying assessment of the indicator of criticality of the mode of the flow.

If we accept that the drop in gas pressure at a throttle does not overtake critical values, then in a settled throttling mode, considering insignificant deviation of gas pressure from the nominal, in the case of ideal uncompressed gas, the errors in determining the rate can be neglected. Then the change in the flow rate Q, which depends on the pressure difference before and after the throttle, is described by the formula (1).

At the same time, for a supercritical mode, which is characterized by a significant drop of gas pressure, the flow rate is determined:

$$Q = \mu \times f\frac{P_1}{\sqrt{RT_2}}, \quad (2)$$

where μ is the coefficient of gas flow rate, f is the cross-sectional area of a throttle, P_1 is the gas pressure before the throttle, R is the gas constant, T_2 is the gas temperature.

So, given the parameter of adiabat for real gas k=1,3, in accordance with the need to obtain maximal pressure drop that provides a proportional decrease of temperature, the estimate of the flow rate is carried out based on the equation of Saint-Venant-Wantzel [9].

For a subcritical mode, when $Y>Y_{cr}$, the formula is valid:

$$Q_{Th} = \varepsilon \times A \times P_1\sqrt{\frac{2k}{(k-1)RT_1}\left(Y^{\frac{2}{k}} - Y^{\frac{k+1}{k}}\right)}. \quad (3)$$

For a supercritical mode, at $Y \le Y_{cr}$, the Saint-Venant-Wantzel equation takes the form:

$$Q_{Th} = \varepsilon \times A \times P_1\sqrt{\frac{k}{RT_1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}, \quad (4)$$

where ε is the coefficient of rate of a throttle hole; T_1 is the temperature in the pipeline; k is the adiabat parameter. $Y_{cr} = \frac{P_2}{P_1} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = 0{,}546,$ – indicator of criticality of gas flow, where P_1 and P_2 are the pressure before and after a throttle.

In addition to the necessity of assessing the adequacy of the equations (1)–(4) of the flow throttling, a priority task of the research is the conditions of transition of a subcritical mode of throttling into a supercritical one because under conditions of a supercritical mode the manageability of a flow rate takes on a special meaning.

Nonlinearity of the connections of the flow parameters, as is evident from the formulas (1)–(4), with regard to the presence of only one channel of a throttling process management, complicates efficient control of the process of moisture separation.

Proceeding from the task of ensuring efficient management of the process of LTS of moisture from the gas flow under throttling to build a model of a throttle device, it is necessary to obtain an adequate description of this process.

Modern software tools allow reconsidering the concepts of building control systems of the LTS processes, which is why a mathematical model of a throttling device of the LTS process must match the level of the development of control systems.

3. The purpose and objectives of the study

The aim of the work is to create a model of a throttling device, which is used at the LTS of water and other carbohydrates from a gas flow.

To achieve the set goal, the following tasks were to be solved:

– to explore the conditions of formation of turbulent or laminar flows through a throttle depending on the position of a throttle valve, since under conditions of a supercritical mode the manageability of a flow rate takes on a special meaning;

– to identify parameters of an experimental installation of throttling the flow through the clarification of the transfer function of the throttle, using its physical model;

– to analyze the nature of the influence of the value of a cross-section throttle valve area on the flow parameters during the water and other carbohydrates LTS.

4. Analysis of distribution of the field of the flow under throttling

Given the fact that the present of the adequacy of the model on a real object is problematic, let us consider a spatial model of the flow under throttling in an experimental unit of separation of moisture from compressed air, to compare the result of the simulation with the data of measurements.

For the implementation of the model, a geometric simulation of a throttling device is built in the Solid Works package and it is exported to the ANSYS environment [10].

At the input of the model, the parameters of the incoming air stream are set: the pressure P=8 atm, the flow rate Q=19 m^3/h.

An element of the research is the measure of the degree of changes in the flow modes depending on the position of the throttle valve. That is why, by changing the values of a throttle cross section area A_{1m}=0,5 cm^2; A_{2m}=0,6 cm^2; A_{3m}=0,8 cm^2, corresponding to the values of parameter of criticality Y_{1m}=0.125; Y_{2m}=0.5; Y_{3m}=0.7, we receive a distribution of velocities (rates) presented in Fig. 1.

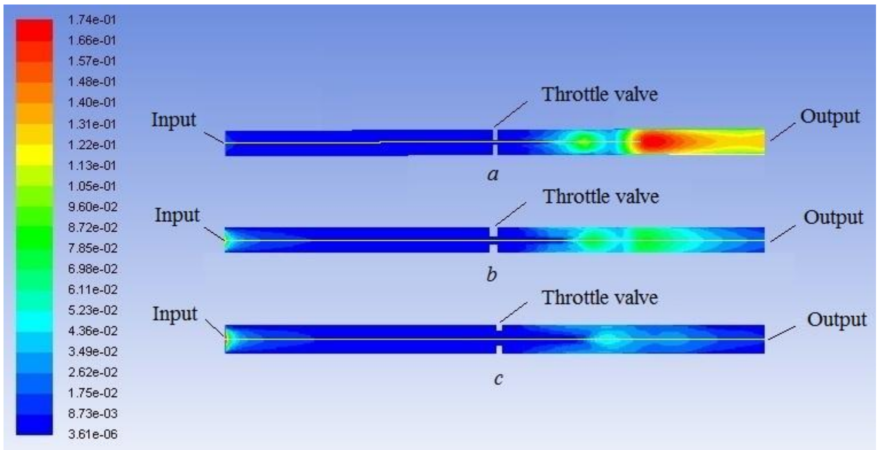

Fig. 1. Model of distribution of the flow passing through the throttle: *a* – Y_{1m}=0.125; *b* – Y_{2m}=0.5; *c* – Y_{3m}=0.7

Fig. 1 displays various positions of a throttle valve corresponding to different levels of the flow turbulence. For the largest values of a throttle cross section area, the character of the flow approaches laminar, but with the transition of the flow into a subcritical mode an increase in the turbulence is observed.

Analysis of the level of turbulence of a throttling flow allows forecasting a distribution of temperatures of this flow, and the trajectory of the moisture droplets, respectively, formed under throttling. The results of the analysis make it possible to calculate mode parameters of the flow, which provides conditions for sustainable droplet formation, to optimize the design of a moisture separator and the possibilities of controlling the value of the gas (air) flow rate.

For a purposeful management of the process of precipitation of the moisture contained in gas, a subcritical mode is acceptable, which allows minimizing the carrying out of moisture drops into the pipeline as a result of the control.

5. Identification of parameters of a throttle

To identify the parameters of an experimental unit of water removal from the flow of compressed air that is injected by compressor, the scheme shown in Fig. 2 is used.

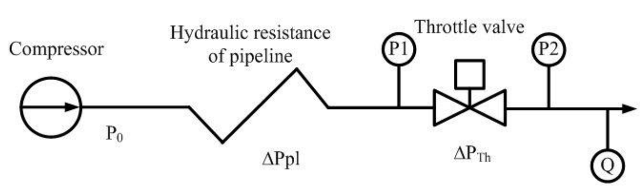

Fig. 2. Scheme of an experimental installation: P_1 and P_2 are the pressure before and after the throttle; Q – flow rate

In operating mode, as a result of controlling the pressure value by changing the area of the throttle cross section, we obtained experimental data that reflect the relationship between the flow rate Q and the pressure drop in the throttle (Fig. 3). As the pressure after the throttle does not practically change, then the mentioned connection presented in Fig. 3 corresponds to the function:

$$Q=f(P_1).$$

The same figure displays the data obtained by numerical calculation of rate function, depending on the area of cross section of the throttle (which determines the value of pressure P_1 before the valve) by the ratios (1)–(4), by technical parameters of the experimental unit. These functions differ on the characteristics by different type of lines. Certain areas of cross section correspond to the indicators of criticality $Y_{1m}=0.125$; $Y_{2m}=0.5$; $Y_{3m}=0.7$. In this case, a family of curves is created as the result of using the mentioned ratios for each indicator Y:

Y_{1m} – (2), (4); Y_{2m} – (2), (4); Y_{3m} – (1), (3).

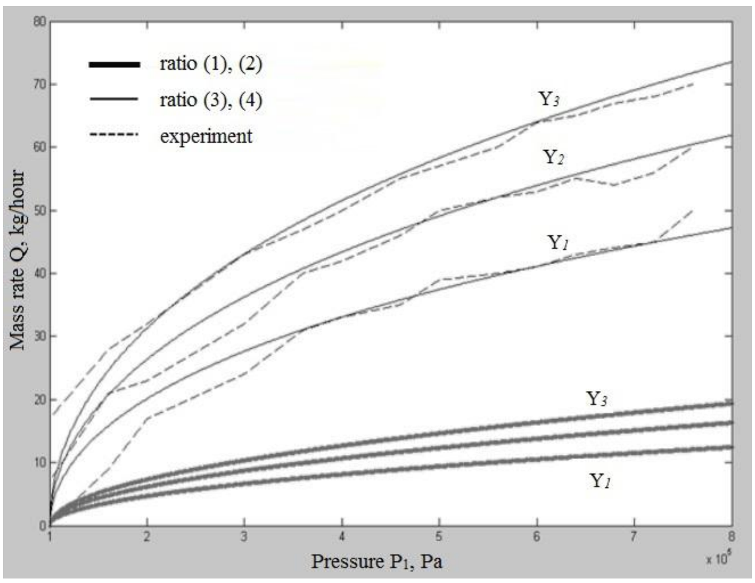

Fig. 3. Throttle characteristics

It follows from the analysis of experimental and calculated data that the drop of pressure on a throttle is determined by the pressure of the flow, which is supplied to the throttle, because the pressure after it does not practically change – under industrial conditions, this is the pressure of a pipeline while under conditions of experimental laboratory installation performance, this pressure corresponds to atmospheric.

It should be noted that the given throttle characteristics are similar in form, while the character of behavior of the function indicates that the flow passes in a supercritical mode.

Fig. 3 also shows that the rate function, which is described by the Saint-Venant-Wantzel equation (3), (4), with the practically acceptable accuracy matches the data obtained experimentally. At the same time, the calculated data, obtained on the basis of dependencies (1), (2) with the assumption that the gas is incompressible, give a large error in determining a flow rate. The magnitude of the error does not make it possible to use these dependencies for modelling the work of a throttling device in the range of pressures that are in the zone of critical modes. Accordingly, setting on the optimum of a regulator of moisture removal, which is built based on the ratio – rate of gas/DP, is problematic.

Thus, to construct a mathematical model of a throttle that works at significant pressure drops of the flow, it is expedient to apply the ratio of Saint-Venant-Wantzel.

6. Implementation of the model in MatLab software

A necessary prerequisite for moisture removal in the process of throttling of the flow is the DP in the separator. The degree of reduction of this temperature determines the speed of growth of the size of the drops of moisture found in gas. Accordingly, the size of the droplets determines the speed of subsidence of moisture in the separator.

The change in temperature after a throttle occurs due to the effect of Joule-Thomson, which is described by the appropriate ratio:

$$T_2=T_1+\mu(P_1-P_2)=T_1+\mu\times\Delta P_{Th}, \quad (5)$$

where T_1, T_2 are the temperature before and after a throttle, respectively, P_1, P_2 are the pressure before and after a throttle, respectively, μ is the Joule-Thomson coefficient.

Pressure drop on a throttle is a component of pressure losses in the flow-source (compressor or a well) P_{sr}, can be found by the ratio:

$$P_{sr}=P_{pl}+\Delta P_{Th}+P_2, \quad (6)$$

where P_{pl} is the pressure losses in the pipeline, ΔP_{Th} is the pressure loss on a throttle.

Pressure losses in the pipeline are caused by the flow friction. According to the Darcy-Weisbach equation, the losses from the friction ΔP_{pl} are proportional to the speed pressure of gas medium [11]:

$$\Delta P_{pl}=\lambda\frac{\rho}{d}\frac{v^2}{2}L=\frac{\lambda}{2dA^2}\frac{Q^2}{\rho}L, \quad (7)$$

where λ is the coefficient of hydrodynamic friction losses; d is the diameter of the pipeline; v is the flow rate; A is the area of the cross section of the pipeline.

Therefore, pressure losses on the throttle in the model being considered in the work, have the form:

$$\Delta P_{Th}=P_{sr}-P_{pl}-P_2. \quad (8)$$

A scheme of simulation of these losses in the Matlab Simulink software is presented in Fig. 4.

In accordance with the objectives of the research, the next step of the implementation of the model of a throttling device is the reflection of the connections of flow parameters in the MatLab Simulink software with consideration of the equations (3), (4) of Saint-Venant-Wantzel. The availability of fractional values of the parameters of criticality of the gas flow Y in the rate function forces to use approximation of this function by a polynomial of the 3rd order [12]. The error of approximation of power function is 3 %, which lets make this an acceptable approach for implementation of the model of a throttling device.

The input parameters for the block of the model (Fig. 5) that reflects the connection of the flow parameters to the characteristic of a throttle device are pressure before and after the throttle, the output parameter is the flow rate. The parameters that influence the output parameter, which indirectly determines the pressure of the flow before the throttle, are the cross-sectional area of the throttle and coefficient of the rate of the hole ε. The coefficients of approximation of the model's polynomial are set by the multipliers Gain1... Gain3.

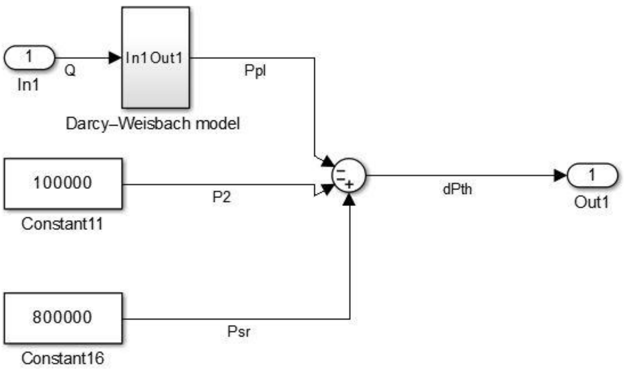

Fig. 4. Scheme of simulation of pressure loss in the Matlab Simulink environment

A defining factor of the control process is formulated as the difference between the DP and the temperature of the flow under throttling. Therefore, it is necessary, depending on the value of the area of a cross-section of a throttle, to track the difference between the received temperature of the flow T_2 and the DP. To do this, a block is introduced to the model that allows simulating arbitrary initial settings of the gas flow under throttling. The variable parameters of the flow are its temperature T_1 and humidity ψ. Then the value of the DP can be identified by the simplified formula [13]:

$$T_{Th} = T_1 - \frac{1-\psi}{0.05}, \qquad (9)$$

where ψ is the relative humidity of the input flow, T_1 is the temperature of the input flow.

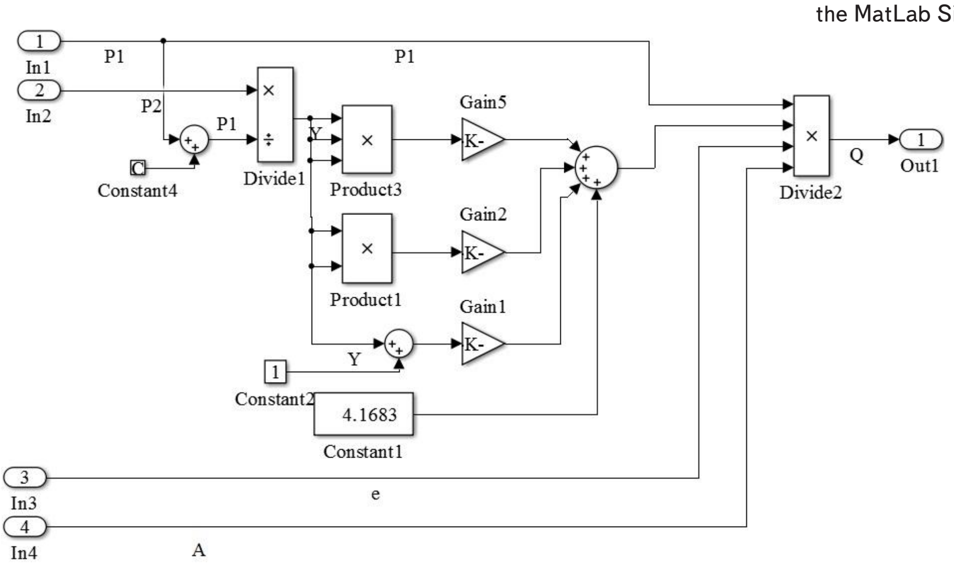

Fig. 5. Scheme of the block of simulation of the Saint-Venant-Wantzel equation

It is the difference between the value of the temperature of the flow T_2 and the DP that allows specifying the required position of the throttle valve, i. e. the required area of the cross-section of the throttle, which will provide conditions for the condensation of water or carbohydrates contained in the flow of air or natural gas.

As a result of combining described blocks of modelling a throttling device, one can receive its static model, the scheme of which is depicted in Fig. 6.

Constructing a dynamic model of the considered object requires taking into account the inertia of the processes that occur in the volume of a throttling device, a connecting pipeline and the separator. However, estimating the volume of the throttle, compared to the volume of the unit's separator, a connecting pipeline and the pipes of a heat exchanger, one can neglect the influence of the throttle parameters on the dynamics of the moisture separation installation in general.

For simultaneous tracking of the effect of changes in a throttle cross section area on the related parameters of the object, a "quasi-random" simulator of the throttle's sectional area was introduced to the designed model.

If necessary, one can imitate arbitrary changes in the parameters of the incoming flow of air or gas with other simulators.

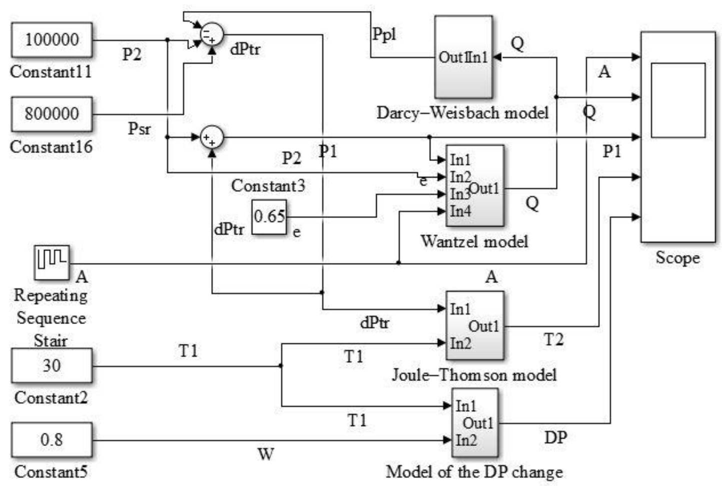

Fig. 6. Scheme of simulating the process of moisture selection in the MatLab Simulink

7. Results of modelling the process of throttling

If air enters the unit of moisture separation with random law of change in its parameters, then the conditions of moisture condensation change, too.

Fig. 7 displays that changing the incoming temperature of the flow T_1 leads to the change of the DP and temperature T_2, respectively, at unchanged temperature drop of a throttling device, which is determined by the difference of pressures (6), to restore the conditions of moisture removal it is necessary to adjust position of the throttle valve. This correction is aimed at achieving the values of the flow temperature that are lower than the DP.

Fig. 8 displays the influence of the value of a cross section area A on the flow rate after the throttle Q, the pressure before the throttle P_1 and the temperature after the throttle T_2. Fig. 8 shows that as a result of change in the value of a cross section area, with a decrease in the temperature of the flow T_2 (condensation conditions that provide maximum selection of moisture), the flow rate decreases, which is in contradiction with the task of maintaining maximal productivity of the flow.

It is clear that an optimal mode of throttling of the installation will be achieved when the amount of the selected moisture and the flow rate at the output of the unit will be maximal.

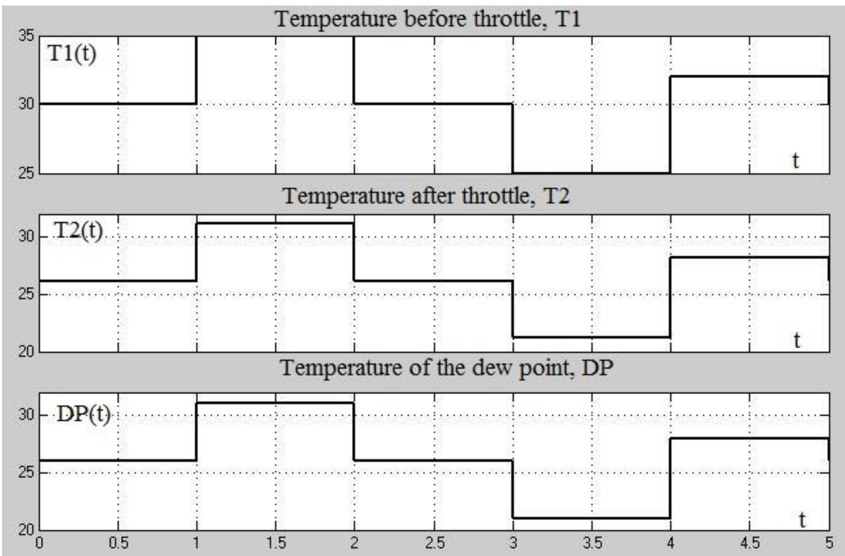

Fig. 7. Changes in the temperature of the flow and the DP when the position of a valve changes

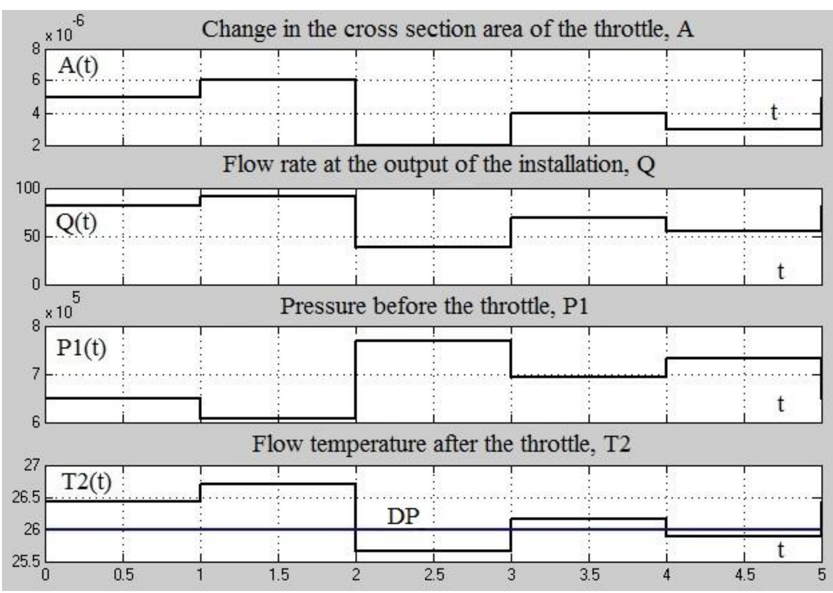

Fig. 8. Results of modelling the process of moisture selection

Using a constructed model (Fig. 6) allows tracking a possibility to achieve the conditions of condensation at different positions of a throttle valve. Fig. 8 displays that in the case of unchanged parameters of the input flow (e. g., constant DP) due to the change in a throttle cross section area, the temperature of the flow changes accordingly – either approaching or deviating from the required DP. Therefore, setting the model parameters allows determining directions of achieving optimal modes of the unit's performance.

The simulation results can be applied in the industrial units of complex processing of gas (UCPG), coordinating the time of parameters setting with dynamic parameters of the models of a heat exchanger and a separator.

In addition, it is necessary to consider that in the actual UCPG, parameters of pressure and rate by the order of magnitude exceed parameters of the considered experimental installation. This consideration is based on the principles of the theory of similarity and requires additional research.

A difficulty of the research into a throttling model of gas mixture flow in UCPG is explained by the presence of hydrocarbons, the DP of which differs from the DP of water. That is why these circumstances must necessarily be taken into account when designing a control system for the process of separation of natural gas.

8. Conclusions

As a result of the conducted studies we designed a model of a throttle device that reflects different modes of gas flow. Based on the obtained experimental data:

1. It was confirmed that the flow that passes through a throttle valve under conditions of significant pressure drops is more accurately described by the Saint-Venant-Wantzel equation. Simulation in the ANSYS environment of the flow under throttling confirms the change in the modes of passing flow at different initial settings of a throttle valve.

2. A throttle transfer function was specified, which is the object of the interconnected control by the channel "values of a throttle cross section area/flow temperature" and "the value of a throttle cross section area/flow rate". This allows identifying parameters of a throttling device in the aspect of formalization of the tasks of control.

3. A nonlinear nature of the influence of the value of a throttle valve cross-section area on the rate and the temperature of the throttling flow at the moisture LTS. In this case the capacities of efficient separation of moisture are limited by the conditions of transition into a supercritical mode of the passing flow.

Given the formed criterion of control of the process, which boils down to the support of the maximum gas flow rate, at acceptable parameters of the content of condensation and moisture in gas at the output of the installation, a designed model allows tracking the process of throttling in real time.

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