IMPLEMENTATION OF AN ENERGY SEPARATION DEVICE BASED ON THE HARTMANN-SPRENGER EFFECT IN A PRESSURE REDUCTION UNIT OF A GAS DISTRIBUTION STATION

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ABSTRACT. Energy efficient management of main pipeline transportation and distribution of natural gas is one of the priorities of sustainable development and cost optimisation in the gas industry. The study is devoted to solving the problems of energy and resource saving by introducing an energy-separation device based on the Hartmann-Sprenger resonance effect into the gas distribution station (GDS) pressure reduction unit. When the gas pressure is reduced at the GDS, due to the Joule-Thomson effect and the work done by the gas, a significant drop in its temperature occurs. To prevent a drop in temperature and the possible formation of hydrates, special measures are applied. All of them require significant investments and resource costs (gas for combustion, electricity, and methanol). Introduction of energy-separating devices to the reduction unit is a rational solution that will allow to carry out the general or partial gas heating by utilising the energy of its pressure. There are many types of energy-separating devices based on different effects. Among them are: Ranque-Hilsch vortex tubes, ejection with a negative ejection coefficient, an energy separation device with a phase transition, pulsation tubes, energy separation in gas flows in the flow around various obstacles and in a free flowing stream of gas. Using the analysis of existing methods of energy separation and numerical simulation, justification of the effectiveness of the energy separation device of the resonant type is given. Hartmann-Sprenger effect is based on the principle of aerodynamic resonance and thermal energy separation in the case of non-linear gas oscillations in a pipe plugged from one end. An energy-separation device has been developed with a non-fire gas preheating to provide a predetermined temperature at the outlet of the gas distribution station and a warning of possible hydrate formation at the station pipelines. The proposed technology will make it possible to partially or completely exclude the generation of thermal energy at the gas distribution station by gas combustion.

Keywords: Natural gas, gas pipeline, energy saving, energy separation, Hartmann-Sprenger effect, pressure reduction, gas distribution station

ВЪВЕЖДАНЕ НА УСТРОЙСТВО ЗА ОТДЕЛЯНЕ НА ЕНЕРГИЯТА, ОСНОВАНО НА ЕФЕКТА НА HARTMAN-SPRENGER, В РЕДУКТОРА НА ГАЗОРАЗПРЕДЕЛИТЕЛНА СТАНЦИЯ

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РЕЗЮМЕ. Енергийно ефективното управление на магистрални тръбопроводи и разпределението на природен газ е един от приоритетите за устойчиво развитие и оптимизиране на разходите в газовата промишленост. Докладът е посветен на решаване на проблемите за спестяване на енергия и ресурси чрез въвеждане на устройство за отделяне на енергията, основано на резонансния ефект на Hartmann-Sprenger, в редуктора на газоразпределителната станция. Когато налягането на газа се понижи в газоразпределителната станция поради ефекта на Джоул-Томсън и работата, извършена от газа, настъпва значителен спад в температурата му. Използват се специални мерки за предотвратяване на спада на температурата. Всички те изискват значителни инвестиции и разход на ресурси (газ за горене, електричество, метанол). Инсталирането на устройства за отделяне на енергията в редуктора е рационално решение, което ще позволи общо или частично загряване на газа чрез използване на енергията от налягането му. Съществуват много видове устройства за отделяне на енергия, основани на различни ефекти. Сред тях са: вихрови тръби Ranque-Hilsch, изхвърляне с отрицателен коефициент на изтласкване, устройство за отделяне на енергията с фазов преход, пулсационни тръби, енергийно разделяне на газовите потоци при преминаване покрай различни препятствия и в свободно течащ газов поток. На базата на анализа на съществуващите методи за отделяне на енергията и числената симулация е дадена обосновка за ефективността на работата на устройство от резонансен тип за отделяне на енергията. Принципът на отделяне на аеродинамичния резонанс и топлинната енергия при нелинейни колебания на газ в тръба, включена в единия край, е в основата на ефекта на Hartmann-Sprenger. Разработен е термоакустичен газов подгревател за поддържане на зададената температура на изхода на газоразпределителната станция и предотвратяване на възможно образуване на хидрат в тръбопроводите на станцията. Предложената технология ще позволи частично или напълно да се изключи генерирането на топлинна енергия от газоразпределителната станция чрез изгаряне на газ.

Ключови думи: природен газ, газопровод, енергоспестяване, отделяне на енергия, ефект на Hartmann-Sprenger, редукция, газоразпределителна станция

Introduction

Energy efficient management of main pipeline transportation and distribution of natural gas is one of the priorities of sustainable development and cost optimisation in the gas industry. At present, Gazprom's gas transmission companies pay serious attention to the problems of rational use of natural gas for their own technological needs, observing the conditions for ensuring industrial safety and optimal control of the gas transmission system, and improving the energy efficiency of production processes (*Gazprom PJSC*, 2011; 2016).

One of the most important problems in the operation of gas pipelines is the formation of gas hydrates. In the process of reducing the gas pressure on the GDS, due to the Joule-Thompson effect, a significant drop in the gas temperature occurs. This leads to the formation of condensate in the form of gas hydrates, a solid snow-like mass that can accumulate inside the gas pipelines, reducing their flow cross-section, and affect the efficiency of the valves (Kitaev, 2011). Most often, the blockage of the pipeline can occur in the winter period due to the significant cooling of the gas flow moving in the pipeline. As a result, an emergency stop of the pipeline operation may occur. The costs of oil and gas companies to prevent and eliminate gas hydrate plugs constitute a significant part of the cost of transport and distribution of gas.

The paper presents the topical problem of resource and energy saving in the system of transport and distribution of natural gas and a method is proposed for its solution based on the introduction of an energy separation device (ESD) at the reduction unit of gas distribution station.

The traditional methods for reducing hydrate formation in the GDS include: general or partial heating of the gas, local heating of the regulator housing, and the introduction of methanol into the gas pipeline. All of them require either significant investment or resource costs: gas for combustion, electricity for local heating, methanol.

In order to minimise the transportation costs of gas, the urgent task is to develop new ways to carry out gas heating during the reduction, taking into account energy saving requirements.

One of the solutions is the introduction of alternative sources that use the energy of wind, water, sun, etc. However, the effectiveness of these methods strongly depends on the climatic conditions.

To prevent frosting of gas equipment and gas preheating, the introduction of a machine-free power separation unit is proposed. The term “energy separation” or “machine-free energy separation” means the redistribution of total enthalpy (stagnation temperature) in a gas stream without external work and without heat exchange with the environment.

The reasons for the energy flow separation may be different. In some cases, these are vortex flows, in others – pressure pulsations and shock waves. These effects form the basis of devices for the energy separation of gases.

Analysis of existing methods of energy separation

Energy separation is the process of the emergence of “hot” and “cold” regions in a gas flow without the supply/removal of energy from outside. The implementation of this process is possible in special devices without a machine power separation. Due to its geometry, these devices allow the redistribution of thermal energy of the gas flow, utilising its pressure (Gurin, 2008).

There are many types of energy-separating devices (ESD) based on different effects. Among them are: Ranque-Hilsch vortex tubes, ejection with a negative ejection coefficient, an energy separation device with a phase transition, pulsation tubes, energy separation in gas flows in the flow around various obstacles and in a free flowing stream of gas.

ESD are multifunctional: with different designs it is possible to obtain both ultra-low and ultra-high temperatures. A distinctive feature of these devices is their simplicity, the absence of moving parts, low inertia, low weight and reliability of structures (Parfenov, 2018).

With regard to the working conditions of the GDS, the following methods of energy separation can be distinguished: temperature stratification in supersonic flow; the vortex effect of the Ranque-Hilsch; Hartmann-Sprenger effect (H-S).

Based on the first method, the author (Popovich, 2016) developed an energy separation device in the main pipeline for organising a supersonic flow in an internal or external channel (Fig. 1). Its principle of operation is the following: high-pressure gas is divided into two parts, one of the streams accelerates in a Laval nozzle to supersonic speeds, and the other – subsonic high-pressure flow – is directed through the inner pipe. For a supersonic flow, the stagnation temperature diagram is redistributed. For a subsonic flow, the wall temperature is almost equal to the stagnation temperature. As a result of interaction through the heat-conducting wall in the energy-separation device, the supersonic flow is heated, and the subsonic is cooled using a gas with a Prandtl number less than one. If the Prandtl number of the working substance is greater than unity, the effect is reversed — the supersonic flow is cooled and the subsonic flow is heated up.

Fig. 1. The energy-separation device in the pipeline during the organisation of a supersonic flow in the internal channel

The disadvantages of this technology are: the need to maintain a supersonic gas flow rate; cooled subsonic flow is sent back to the gas pipeline.

The main principle of the vortex effect is the separation of gas when twisting in a cylindrical or conical chamber into two fractions. At the periphery of the chamber, a swirling flow is formed with a higher temperature, and in the centre – a swirling cooled flow, and rotation in the centre occurs in a different direction than at the periphery.

On the basis of the vortex effect, a device is known, the gas pressure regulator RDU-T with a heat generator, produced by PJSC “Plant Staroruspribor”. Energy separation occurs due to the presence of the Ranque-Hilsch vortex tube (VT). The cold component is removed and discharged into the rear flange of the regulator, which helps to heat the heat generator to a temperature of +40–50°C for 6–8 minutes. The heating temperature of the heat generator is sufficient to prevent frosting of the valve.

It was experimentally established that the preheating of the inlet gas due to the hot wall of the VT allows the gas temperature to rise before entering the vortex tube by 3–5°C (Gurin, 2008.). The tests of the developed device showed that in the design mode with absolute inlet pressure P=0.4 MPa and pressure decrease of natural gas to absolute pressure of 1.003 MPa, the heated air at the outlet of the HT (when mixing cold and hot streams) at the maximum flow rate is 5.5°C, with a minimum flow rate of 2.7°C (about 10% of the maximum value). The tests of the developed device showed that in the design mode with absolute inlet pressure P=0.4 MPa and pressure decrease of natural gas to absolute pressure of 1.003 MPa, the temperature of heating the air at the outlet of the HT (when mixing cold and hot streams) at maximum flow rate is

5.5°C. The amount of heating of natural gas in the design mode is equal to 2.0°C and 1.0°C for maximum and minimum flow. Despite such an advantage as the possibility of carrying out several processes at the same time (cooling, heating, phase separation), this device has low energy efficiency.

The principle of aerodynamic resonance and thermal energy separation in nonlinear oscillations of a gas in a dead-end pipe is the basis of the Hartmann-Sprenger energy separation effect (Fig. 2).

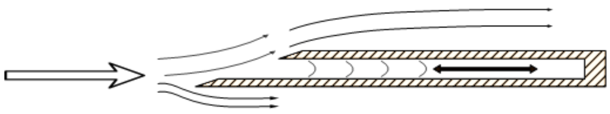

Fig. 2. The flow of gas inside the dead-end cavity

The Hartmann-Sprenger (H-S) effect is the following: breaks in the jet of high-speed gas flow at the entrance to the dead-end cavity cause pressure pulsations, the waves of which propagate in the direction of a dead end, reflect and move in the opposite direction, entering with subsequent waves in resonance with a sharp temperature rise. Inside the dead-end tube it is possible to create temperatures up to several hundred degrees. At the same time, the gas flow loses energy and comes cooled to the exit of the installation.

The H-S effect was not previously considered as a way to preheat the gas at the GDS. The following applications are known: in aircraft industry, as a heating element of the anti-icing system in the air intake of the aircraft; gasdynamic igniter for sparkless burning of combustible gases; a device for pulsating impact on the bottom hole formation zone; rotary wave cryogenerator for low-tonnage production of liquefied natural gas.

The following advantages of the effect H-S can be identified: a simple theoretical description of the physical meaning of the effect; shared hot and cold streams do not come in direct contact and are separated by a wall; ease of obtaining high temperatures: in certain situations, the actual overheating temperature can reach values of ~ 500–1500 K.

In the gas transportation system, the H-S effect was considered only as negative. In (Parfenov, 2018), cases of heating of individual elements of the block valve station during the filling of the sections of the gas pipeline with melting of outer insulation, emitting acrid smoke and loss of tightness of the shut-off and control valves were considered.

Thus, the analysis of the devices proves the limited effectiveness and application of the effect of temperature stratification in supersonic flow and the vortex effect of Ranka-Hilsch for heating the gas in the GDS.

Justification of the efficiency of energy separation on the Hartmann-Sprenger effect by numerical simulation in ANSYS FLUENT

The simulation of the effect of resonant energy separation is a complex mathematical problem that requires large computing resources and time. In this paper, a simplified 2D model is proposed to provide a qualitative representation of energy separation processes in a dead-end cavity.

The description of the gas movement under arbitrary conditions is made using the Navier-Stokes equations. For the solution, numerical methods implemented in various software products are used. In this paper, the ANSYS FLUENT package is used to solve this problem. It is applicable for solving various problems of gas dynamics.

The turbulent flow is characterised by the presence of vortex structures. Special models of turbulence are used to solve practical problems in order to reduce the calculation time. RANS models (Reynolds Averaged Navier–Stokes) are most prevalent today. In these models, the following approach is used: for all desired parameters (velocity, pressure, temperature, etc.), the value is represented as two terms — the averaged and the pulsation value (Savchenkov, 2013; Voronin, 2014).

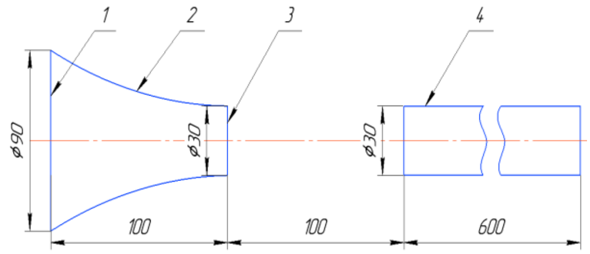

Fig. 3. The scheme of the resonant tube: *1*, gas inlet; *2*, nozzle; *3*, exit from the high-speed flow nozzle; *4*, resonant tube

Modelling is carried out in the software package ANSYS FLUENT. Air is accepted as a gas mixture and is described by the Redlich-Kwong real gas law. At the entrance to the nozzle, the speed is set at 15 m/s and the temperature is 300 K. The outlet pressure is set to 0 Pa. To determine the initial conditions, the problem is solved in a stationary formulation. For this purpose, the Menter turbulence model is chosen — shear stress transfer SST. The calculation is based on the DES-model of turbulence with a time step of 1·10-5 s. The pulsation effects are stabilised in 0.2 s. Visualisation of the simulation results is presented in Figure 4.

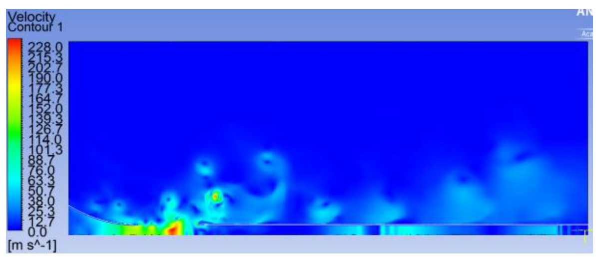

Fig. 4. Speed contours in the case of a steady-state oscillatory process

In the case of oscillation due to flow interruptions at the entrance to the dead-end cavity without using artificial pulsators (for example, pistons), the frequency of pressure oscillations will depend only on the cavity length (l_T) and the speed of sound in the medium (c) and will be $f = c/2l_T$. The frequency in the process of resonance is half as much, because the wave changes sign when reflected from the open end, and the rarefaction wave passes through the pipe instead of the reflected shock wave. Therefore, the theoretical frequency of oscillations in resonance is equal to:

$$f = {}^{c}\!/_{4l_T} .$$

The resonant frequency of pressure oscillations is within the range f_{calc}≈150÷160 Hz. According to the formula (1), the theoretical frequency of pulsations in resonance is (the speed of sound in the air is 340 m/s):

$$f_{theor} = \frac{340}{4 \cdot 0,6} = 142\ Hz$$

The deviation of the received frequency from the theoretical frequency is 5.9–12.9%, which is within the normal range. The range of amplitudes of pressure pulsations at the bottom of the cavity is 30–70 kPa.

As a result of the simulation, we obtain the graphs of the pressure and temperature pulsations in the dead-end cavity (Figs 5, 6). In the first approximation, we assume that the temperature growth rate at the bottom of the dead-end cavity is described by a linear function (Fig. 7).

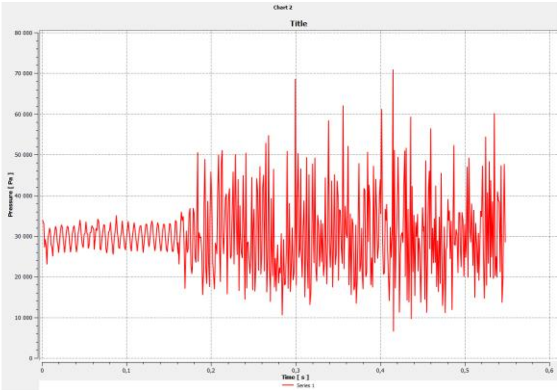

Fig. 5. Pulsations of pressure in the dead-end cavity for the time interval t= 0÷0.55 s

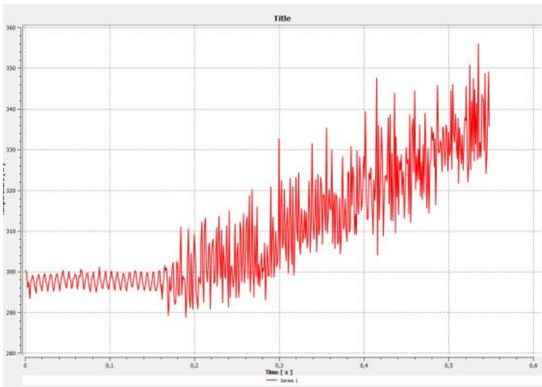

Fig. 6. Pulsations of temperature in the dead-end cavity for the time interval t= 0÷0.55 s

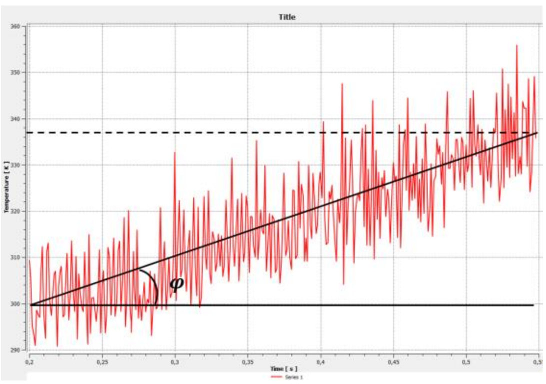

Fig. 7. The scheme for calculating the temperature growth rate at the bottom of the dead-end cavity

The temperature growth rate at the bottom of the dead-end cavity is:

$$\tan(\varphi) = \frac{337\text{-}300}{0,55\text{-}0,2} = 105,7\ \text{K/s}.$$

The temperature growth rate at the bottom of the dead-end cavity is 105.7 K/s. The calculation is made without taking into account the thermophysical properties of the wall material (without heat loss through the wall), therefore, the value of the final heating temperature is not considered.

Conclusion

A search study of existing devices without a machine power separation has been made. A wide range of their varieties is presented. The description of physical processes in ESD is given.

A numerical model has been developed that describes the processes of energy separation in a resonant tube.

Further research is aimed at applying the developed numerical model for more complex structures taking into account spatial phenomena (3D model) and physical properties of the resonator walls, comparing the results of numerical calculations with laboratory tests.

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