Using energy of compressed natural gas as an environmentally safe source of heat energy of the heating system of the industrial premises

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Abstract. The housing and utilities system is extremely energy-intensive and currently impedes the implementation of energy efficiency policies. In this regard, the development of science-based technology for environmentally friendly resource-saving consumption of compressed natural gas, as a source of thermal energy, is becoming relevant. The article describes the technical solution for using the energy of compressed natural gas as a source of thermal energy, which consists in using a vortex heat exchanger in the heating system of a gas control station, which allows you to generate thermal energy due to technologically unused energy, which is the pressure drop between high and medium gas pipelines as well as medium and low pressure natural gas. This technical solution is aimed at reducing energy costs and ensuring environmental safety when using compressed natural gas as a source of thermal energy. To determine the possibility of practical use of this technical solution in the production room for installing gas control equipment, an analytical expression of the temperature of the wet gas mixture after the process of condensate-evaporative heat and mass transfer in a vortex heat exchanger has been obtained, which allows us to predict the parameters of the coolant in the heating system of the production room.

1. Introduction
Currently, much attention is paid to environmental safety and energy saving in all areas of the fuel and energy complex related to the generation, transportation and consumption of energy resources, including the reduction of the energy intensity of heating systems, especially small industrial buildings [1 - 5].

The production of thermal energy for communal needs is invariably associated with a negative impact on the environment. This problem is especially relevant in the face of a tense environmental situation in most large cities of Russia. The introduction of autonomous heat supply can improve the current environmental situation and increase the efficiency of thermal energy production up to 85 - 97%. The total yield of combustion products during autonomous heat supply is significantly less and safer than emissions from existing heat and power plants (TPP).
The most widespread in the case of autonomous heat supply are capacitive water heaters of the AOGV series, which provide hot water of a given temperature and in sufficient volume for room heating systems. This quality has become the basis for the predominant use of AOGV for heating an industrial building, in particular a gas control unit (GCU), however, this heat exchanger requires fuel consumption for burning gas when heating water in a heating system.

A feature of the operation of the GCU room is the regulation of the pressure of the gas coming from the pipeline to consumers. At the same time, pressure regulators operate at a sufficiently high (from 3.5 and more times) differential pressure of the input and output pressure values with unclaimed repayment of excess energy. Due to the significant energy potential of natural gas, which consists in the need to reduce its pressure before the consumer by 0.35 MPa or more, the article proposes one of the technical solutions to the problem of reducing energy consumption for heating a gas distribution building.

The proposed technical solution consists in the use of a vortex heat exchanger in the heating system of a gas control station, which allows you to generate thermal energy due to technologically unused energy, which is the pressure drop between the high and medium, as well as medium and low pressure natural gas pipelines.

2. Materials and methods
An analysis of the known works [6, 7] shows that the heat transfer coefficient or the degree of heat transfer intensity of a heating and heated medium in a heat exchanger depends largely on the largest of the thermal resistances of the heat exchange surface. Of particular urgency is the task of intensifying heat transfer when using gaseous working media, which are characterized by a reduced intensity of metabolic processes and high energy costs to overcome hydraulic resistance during gas movement.

In addition, the decrease in the intensity of heat exchange of the heating surface with the heated room air [8, 9] is affected by the corrosion of heat exchange surfaces, which refers to the processes of chemical and electrochemical corrosion and leads to damage to their heating surface.

The most common and widely used in heating systems of industrial buildings is a tubular heat exchanger-air heater. It is easy to use and operate, but has a large mass and a large volume. In tubular heat exchangers made of steel tubes, significant low-temperature corrosion is observed. When exposed to a cold coolant flow on a metal surface, a sharp decrease in the intensity of heat transfer occurs. This is due to the transition of the “cold” flow to the “hot” one, which reduces the heat exchange between swirling gas and the air of the heated room [10].

Another common structural type of heating apparatus-air heaters is represented by a plate heat exchanger. It consists of steel sheets 1.5–2.0 mm thick. Such a heat exchanger is difficult to manufacture due to the formation of a laminar layer. When the temperature gradient is observed warpage of the sheets, which reduces the reliability of the air heater.

An effective way to protect low-temperature heating surfaces from corrosion is to make them from corrosion-resistant materials, namely low-alloy steel with copper additive 10xndp, oh23n28m3d3t, nickel alloy om70m27f.

However, the use of these materials significantly increases the cost of heat exchange equipment. This necessitates the use of new, cheaper, corrosion-resistant materials. For example: the use of non-metallic materials and coatings, such as organosilicon varnishes and enamels based on furan, epoxy and other resins, as well as the use of polymeric materials. However, these materials have low heat resistance.

In this regard, an original design of an air heater in the form of a vortex tube was developed, which provides the conditions for intensive and reliable heat transfer under the corrosive effect of a heat carrier [11, 12].

The determination of the possibility of the technological use of this constructive expansion in the production room for the placement of the gas control equipment leads to the need to formulate the
problem of mathematical modeling of the heat exchanger with maintaining the initial temperatures. For example: at the inlet = 100°C and at the outlet = 70°C, which is the closest with the standard in heating systems.

In a vortex tube, the thermodynamic separation of the moving gas proceeds from the well-known theoretical assumption that the energy exchange process at the exit of the swirl is complete, the result of which is the adiabatic distribution of temperature gradients along the radius of the heat exchanger [13].

Currently, the resource-saving policy pays special attention to the development and use of both energy-saving technologies and equipment that ensures the implementation of processes with minimization of costs, including heat, for the heating system of industrial premises [14].

The ratio between the heat transfer rate and the hydraulic resistance of the apparatus near the wall of the heat exchanger enclosure is more favorable in that case, the more significant is the difference in the temperature distribution and the velocity of the coolant particles [15].

When using a vortex tube heating system as a heat exchanger, one of the effective solutions to intensify heat transfer is to make swirlers in the form of blades.

We study the nature of the movement at the place of rotation of the swirl blade at the entrance to the vortex tube of the elementary volume of the coolant in the form of compressed natural gas moving at a speed \(\omega_{v,g}\) revolutions per second, whose mass is equal:

\[
d m_{v,g} = \rho d_f dz,
\]

where \(d_f\) – cross-sectional area of elementary volume, \(m^2\);

\(dz\) – direction of movement at the moment, \(m\);

\(\rho\) – heat carrier density, \(kg / m^3\).

The elementary centrifugal force acting on this object is:

\[
\frac{\delta d_f dz \omega_{v,g}^2}{z}
\]

where \(z\) - is the radius of rotation of the spinning blade, \(m\)

This force is balanced by the pressure difference on the faces of the volume in question:

\[
d_p = \left(\frac{dp}{dz}\right) d_f dz
\]

Based on the d’Alembert principle, we design all the forces in the Z direction in the direction of the moving coolant, write:

\[
d_f dz \omega / z = dp / dz d_f dz = 0,
\]

where does it come from:

\[
\frac{\rho \omega_{v,g}^2}{z} = \frac{dp}{dz}
\]

A change in static pressure based on the Bernoulli equation can occur only as a result of a change in the speeding pressure head [16]:

\[
p + \frac{\rho \omega_{v,g}^2}{2} = \text{const}
\]

Differentiating (5), we get:

\[
\frac{dp}{dz} = -\frac{\rho \omega_{v,g} \omega_{v,g}}{dz}
\]
Substituting (6) in (4), we obtain:

\[-\frac{\rho \omega \nu \omega^2 g d\omega}{dz} + \frac{\rho \omega^2 \nu \omega g d\omega}{dz} = 0\]  

(7)

Integrating (7), we arrive at the result:

\[z \omega \nu \omega = \text{const}\]  

(8)

Accept \(c_p = \text{const}\), since the process of heat and mass transfer occurs in a particular element under study, moving under the action of centrifugal forces, on stain of a fluid at a constant pressure for these conditions:

\[M_{\text{CM}} h_{\text{CM}} = m_{\nu \omega} h_{\nu \omega} + m_{\text{cb}} h_{\text{is}},\]  

(9)

\[h_{\text{cm}} = g_1 h_{\nu \omega} + g_2 h_{\text{is}},\]  

(10)

where \(g_1, g_2\) – mass fractions of wet gas at the exit of the tapering nozzle and in the boundary layer of the swirl blade during the evaporation process, %:

\[h_{\nu \omega} = C_{\nu \omega} T_{\nu \omega},\]  

\[h_{\text{is}} = C_{\text{is}} T_{\text{is}},\]  

\[c_{p_{\nu \omega}} T_{\nu \omega} = g_1 c_{p_{\nu \omega}} T_{\nu \omega} + g_2 c_{p_{\text{is}}} T_{\text{is}},\]  

(11)

Then, at \(c_p = \text{const}\), we have the temperature of the wet gas mixture after the process of condensate-evaporative heat and mass transfer:

\[T_{\text{CM}} = \frac{g_1 c_{p_{\nu \omega}} T_{\nu \omega} + g_2 c_{p_{\text{is}}} T_{\text{is}}}{g_1 c_{p_{\nu \omega}} + g_2 c_{p_{\text{is}}} T_{\text{is}}}\]  

(12)

For the temperature of thermodynamic separation of the mixture of “cold” and “hot” flows of wet gas, the obtained analytical expression of the temperature of the mixture of wet gas after the process of condensate-evaporative heat and mass transfer in a vortex heat exchanger allows predicting the parameters of the heat carrier in the heating system of the industrial building [17]. The resulting equation allows you to get the parameters of the heat carrier of the heating system of the production room closest to standardized. The experimental examination of the analytical dependencies was carried out in laboratory and industrial conditions on the installation simulating the heating element of the heating system of an industrial building, in particular a gas control station (GCU).

The developed mathematical model for the process of heat transfer in a vortex heat exchanger from a swirling flow of natural gas to the air of a heated room became the basis for creating the concept of a vortex heat exchange element [18].

3. Results

The operation of the gas control station is carried out under conditions when the pressure regulators operate at a sufficiently high (3 - 5 times or more) differential pressure input and output values in gas pipelines with unclaimed discharge of excess energy [19] before supplying the consumer. The use of this energy of a moving gas stream is possible when using an excess pressure of a vortex tube as a partial absorber.

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The vortex heat exchange element operates as follows (figure 1). Depending on the place of extraction and production conditions, the compressed natural gas used in the vortex method of heat transfer (without preliminary drying) is always saturated to a certain concentration with moisture vapor,
both atmospheric and technological, therefore, as shown by the analysis of known vortex heat exchangers, in a cold stream after thermodynamic separation of natural gas, condensation of moisture vapor with the release of heat of condensation is observed.

Figure 1. Vortex heat exchange element: a) - a schematic diagram of a vortex heat exchange element; b) - the inner surface of the cold coolant supply pipe with a round groove connected to both the contaminant removal device and longitudinally placed curved grooves; c) - a profile of a helical groove in the form of a “dovetail”; 1 - inner pipe; 2 - pipe of larger diameter; 3 - swirl; 4 - input section; 5 - peripheral zone of the flow of cold coolant (CC); 6 - the inner surface of the pipe 2 of larger diameter; 7 - the outer surface of the inner pipe 1; 8, 9 - pipe sections 2, equipped with cold coolant supply pipes; 10, 11 - nozzles supply cold coolant; 12, 13, 14 - swirlers; 15 - input section; 16 - swirl; 17 - the inner surface of the inner pipe 1; 18 - narrowing nozzle; 19 - curved groove; 20 - inlet; 21 - groove; 22 is a device for removing contaminants.
The heat of condensation obtained in conjunction with the heat of the “hot layer” of an additionally stratified cold stream acts on the cylindrical wall of the inner pipe 1. As a result, the thermal ratio of the counter-directed heat flows of the “hot” and “cold” heat carriers transferred by the thermal conductivity through the bimetallic fence in the form of a cylindrical the walls of the inner pipe 1. This virtually eliminates the possibility of efficient use of the vortex method of heat transfer, because the condensation process, especially drip, has a random nature of the release of condensation heat over the heat exchange surface.

To eliminate this phenomenon, i.e., to remove contaminants from the cold coolant (CC) in the form of condensed moisture vapor, the CC is sent to the supply pipes 10 and 11, made in the form of tapering nozzles 18, where it increases its speed and moves along curved grooves 19 and twists. As a result, the particles of contaminants (droplet-like moisture) fill the cavities of the curved grooves 19 and under the action of centrifugal forces move, enlarging, towards the groove 21 located at the inlet 20 of the nozzles 10 and 11, from where they accumulate into the pollution removal device 22 for discharge into environment manually or automatically.

The resulting natural gas or compressed air as a result of separation of droplet-like moisture at the outlet of the swirl 14 is stratified into layers: “hot” peripheral and “cold” axial. The heat is transferred by convection from the “hot” layer of the HC to the inner surface 17 of the inner pipe 1 and then, through the thermal conductivity, the thickness of the material of the inner pipe 1 is heated.

At the same time, CC passing through swirlers 3, 12, and 13 also stratifies into a “hot” peripheral layer located in zone 5 and a “cold” axial layer, while the “hot” layer contacts the outer surface 7 of the inner pipe 1, giving it its heat convection and, further, thermal conductivity.

The flows of hot coolant (HT) and cold coolant (HT) are twisted and mixed in the axial direction, while simultaneously performing a rotational movement. Due to the intense heat exchange between the rotational flow CC in the pipe 2 and the outer surface 7 of the inner pipe 1, an even greater heating of the peripheral layer of CC in zone 5. This results in the formation of CC with an inhomogeneous density field, which leads to the continuous replacement of less heavy particles of CC heavier and this process continues until the rotational motion of the flow attenuates.

From the peripheral "hot" layer of HC, thermal energy is transferred to the inner surface 17 of the pipe 1 with convection. Further, the thermal conductivity of the bimetal material with an increased value of the coefficient of thermal conductivity and has a higher temperature gradient than the heat transferred from the peripheral flow of CC to the outer surface 7 of the inner pipe by the thermal conductivity of the material of the bimetal with a lower value of the coefficient of thermal conductivity.

The contact area of the counter-directed heat flows in this case is shifted towards the outer surface 7 of the inner tube 1 and is about 20% of the distance from the outer surface 7 (see figure 1). As a result, heat losses caused by the movement of heat energy along the thickness of the inner tube 1 are significantly reduced, which allows to significantly increase the efficiency of using the method of heat transfer in recuperative heat exchangers, for example, with the location of swirlers inside the cavity of both the pipe 2 with a large diameter, and inside the inner tube 1. The novelty of the developed technical solutions applicable for the constructive calculation of environmentally safe and resource-saving equipment for technological systems for transportation and consumption of natural gas is protected by a number of patents of the Russian Federation for inventions and utility models [20, 21].

4. Conclusions
The developed technical solution allows you to: save gas as fuel in the heating system of the gas control point, eliminating the need to install GCU in which water heating in the heating system is carried out by gas combustion; provide more comfortable working conditions for the pressure regulator due to a decrease in the differential controlled pressure of gas entering the consumer, since there is a significant decrease in the output pressure due to the operation of the vortex tube as a heat exchanger in the heating...
system of the production building; increase environmental safety in the production of thermal energy, since there is no need to burn natural gas for heating the production premises. Production of heat energy to maintain a microclimate in the production room is carried out by a regulated pressure drop of natural gas.

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