Using compressor's secondary energy resources (SER) for heat supply of industrial buildings

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Abstract. This article gives an assessment of the energy potential of secondary energy resources (SER) generated by cooling compressed air in centrifugal compressors. The possibility of using thermal (SER) for the needs of heat supply of industrial buildings is considered. The authors developed an energy-saving heat supply scheme. The mathematical simulation of heat exchange processes in separate elements of the scheme has been made. It allows to evaluate the areas of heat-exchange surfaces for heating fire-fighting water and air for ventilation systems, depending on the operating condition. This model allows you to design the proposed scheme of heat supply for any industrial building in the presence of centrifugal compressors.

1. Introduction
Nowadays, the problem of heat energy saving becomes more acute. According to most experts, the lack of fuel in all industrialized countries will increase. According to the Ministry of Energy of the Russian Federation, about 2.1% of GDP [1] or 400-440 million tons of fuel is spent on heat supply every year [2]. One of the ways of rational consumption of thermal energy is the use of secondary energy resources (SER) [3,4]. With a total consumption of 2 billion tons of conventional fuel per year, about 1.5 billion GJ of SER are generated in the country [5]. The presence of large steelworks of a full circle is typical for the Chelyabinsk region, which include oxygen shops with centrifugal compressors. There is a three-stage compression with air-cooling in intermediate water-cooled refrigerators in compressors. It should be noted that only 10-15% of the energy is used for compression, and the rest is lost with cooling water, so it is better to use the heat of the cooling water in heat supply systems [6].

2. Modernization of oxygen station
To use the heat from the compressor, a schematic diagram of the heat supply of the station has been designed [7], is presented in Figure 1.
3. Mathematical modeling of heat exchange processes in elements of energy-efficient heat supply scheme

A mathematical model was designed to determine the qualitative and quantitative characteristics of the considered scheme for heating fire-fighting water and ventilating air [8-10].

The structural-mathematical model is divided into four blocks. The K-1500 compressor (a six-stage compressor squeezing 1500 Nm3/min of air to 0.6 MPa), with two intermediate gas-coolers (after the second and the fourth-stage squeezing stage) and one filum cooler was considered as a source of thermal SERs. We propose to use the coolant from the second intermediate and filum gas-coolers for heat supply. Chemically treated water was chosen as the most suitable coolant [11]. The modeling took into account the thermodynamic and thermophysical properties of relevant substances [12-15].

The first and second units include the calculation of the air compression process in the compressor and the calculation of the heat exchange between the compressed air and water in the intermediate gas-cooler. The results of investigations on these blocks are given in [16, 17]. The baseline data for the calculation are compressor-capacity curve, environmental temperature and cooling-water temperature entering and leaving the gas-coolers. The cooling water flow (hereinafter the coolant) and the cooling area are the result of the modeling.

In the third block, there is a calculation between the coolant and fire-fighting water in a tubular heat exchanger. The baseline data for the calculation are the temperature of the coolant and fire-fighting water entering and leaving the heat-exchange unit, coolant rate. The consumption of heated fire-fighting water, the heat-exchanging surface, expenditure on circulation are the result of the modeling.

Heat transfer coefficient to fire-fighting water inside the tubes was calculated according to [18], W/(m²·K):

$$\alpha = \frac{Nu \cdot \lambda_{water}}{d_{in}}$$

(1)

Nu number in accordance with [19]:

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**Figure 1.** Schematic diagram of heat supply:
1-compressor; 2-gas cooler; 3-intermediate coolant cooler (cooling tower); 4-heater for preheating air for heating and ventilation; 5-water heater for hot water supply (DHW).
\[ \text{Re}_d \geq 10^4 : \]

\[ Nu = \frac{\varepsilon \cdot Pe}{8 \left( 1 + \frac{900}{\text{Re}_d} + 12.7 \sqrt[3]{\frac{\varepsilon}{8}} \cdot (\text{Pr}^2 - 1) \right)} \quad (2) \]

Heat transfer coefficient from the intermediate coolant to the tubes was determined according to [18], W/(m²·K):

\[ \alpha_{\text{water}} = \frac{0.6 + 0.7 + (b - 2) \cdot 0.41 \cdot \text{Re}^{0.6} \cdot \text{Pr}^{0.33} \cdot 1.12 \cdot \frac{\lambda_{\text{water}}}{d_{\text{ex}}} \cdot \varepsilon}{b} \quad (3) \]

The loss of pressure during water circulation in accordance with [19], Pa:

\[ \Delta P = \frac{\varepsilon \cdot w^2 \cdot \rho_{\text{water}}}{2 \cdot d_{\text{in}}} \cdot L \quad (4) \]

where \( \lambda_{\text{water}} \) is the thermal conductivity of water, W/(m²·K); \( d_{\text{in}} \) and \( d_{\text{ex}} \) – internal and external diameters of tubes, m; \( \text{Re}_d \) – the Reynolds number, \( \text{Pr} \) – the Prandtl number, \( \text{Pe} \) – the Peclet number, \( \varepsilon \) - pipe friction number, \( b \) - number of rows of pipes along the coolant path, \( w \) – coolant velocity m/sec; \( \rho_{\text{water}} \) - coolant density, kg/m², \( L \) - run of pipe, m.

According to the data obtained of mathematical modeling for Magnitogorsk conditions, it is possible to heat 16.47 kg/s of water for hot-water supply from 5 to 55 °C.

Analysis of the results, provided in figure 2, shows that with an increase in the rate of heating, the average of heat transfer coefficient is growing steadily. What is more, intensification of heat exchange occurs more intensively in the intertubular space. Thus, with the change in Re numbers from 10 000 to 100 000, heat-exchange coefficient of coolant increases from 2 807 W/(m²·K) to 11 180 W/(m²·K) and fire-fighting water from 4 008 W/(m²·K) to 27 930 W/(m²·K).

It can be seen from figure 3 that an increase in velocity leads to a decrease in the required area of the heat-exchange surface. Thus, with the change in Re numbers from 10 000 to 100 000 the area decreases from 54.28 to 19.83 m².

Figure 2. Change of heat transfer coefficients by intermediate coolant and hot water from Re numbers.
An increase in the velocity of water in the intertubular space leads to dramatically increasing the power consumption for circulation, which is clearly seen in Figures 4 and 5. Thus, with the change in Re numbers from 10 000 to 100 000, supplied power increases from 10 W to 4 500 W.

The fourth unit includes the calculation of the heat exchange between common air for ventilation and the coolant in the air heater. The baseline data for this block are the temperature of the coolant and common air on entering the heat-exchange unit, the required air temperature on exit the heat-exchange unit, coolant rate. The airflow rate, heat-exchanging surface area of the air heater, expenditure on circulation are the result of the modeling.
The heat transfer coefficient from air to tubes $W/(m^2 \cdot K)$ [20]:

$$\alpha_{gas} = c_1 \cdot c_2 \cdot \lambda_{air} \left( \frac{w_{air} \cdot \rho_{air}}{\mu_{air}} \right)^{0.6} \cdot Pr_{air}^{0.33}$$

(5)

The loss of pressure for the gas according to [20], Pa

$$\Delta P_{gas} = \rho_{air} \cdot w_{air}^2 \cdot n_h \left( \frac{S_p}{d_{ex}} \right)^{-0.72} \cdot Re_{air}^{-0.24}$$

(6)

where $c_1$ и $c_2$ - a coefficient depending on the degree of finning, $\lambda_{air}$ – the thermal conductivity of air $W/m \cdot K$; $w_{air}$ - air velocity in the narrowest section m/sec; $\rho_{air}$ - atmospheric density kg/m$^3$, $S_p$ - fin spacing m; $n_h$ - the number of horizontal rows of tubes in the bundle (vertically).

According to the data obtained of mathematical modeling for Magnitogorsk conditions, it is possible to heat 58.62 m$^3$/s of air for ventilation from -34 to +10 °C.

Analysis of the results shows that with increasing water velocity in the tubes of the air heater the heat-exchange coefficient increases continuously, figure 6. Thus, with the change in Re numbers from 10 000 to 100 000, the heat transfer coefficient changes from 5 558 $W/(m^2 \cdot K)$ to 36 950 $W/(m^2 \cdot K)$.

It can be seen from figure 7 that an increase in velocity leads to a decrease in the required area of the heat-exchange surface. Thus, with the change in Re numbers from 10 000 to 100 000, the area decreases from 258.54 to 252.49 m$^2$.

Figure 6. Change of heat transfer coefficient for coolant in pipes from Re numbers.

Figure 7. The change in the area of heat transfer surfaces of the Re numbers.
Figure 8. Changes in coolant and ventilated air circulation costs from Re numbers

The analysis of the power expenditure on the circulation of the coolant and the heated air showed that with increased speed of water in the tubes of the air heater, power expenditure on the circulation of the coolant increase. However, at the same time expenditure on the intake air, which is explained by the reduction of the required transfer surface, figure 8. Thus, with the change in Re numbers from 10 000 to 100 000, the expenditure on coolant circulation increases from 5 W to 14 730 W. The expenditure on moving air is reduced from 50 410 W to 6 126 W. At a coolant velocity of 0.7 m/s, these expenses become commensurable.

4. Conclusion

The use of thermal SER industrial production in heat supply systems is one of the most promising methods of energy saving. The authors have developed a heat supply scheme for industrial building due to thermal SER compressor plants. Separation of the intermediate refrigerator into two parts gives an opportunity of obtaining a coolant with a temperature of up to 90 °C; it is possible to use the heat of the compressed air for the needs of heat supply. A mathematical model of the heat exchanging process in the heat exchangers in the proposed scheme. This allowed an estimate of the area of heat-exchange surfaces for heating fire-fighting water and ventilation systems, depending on the movement modes, as well as energy expenditure on the circulation. Analysis of the results of mathematical modeling allows us to draw the following conclusions: for the conditions of Magnitogorsk at an outside temperature of -34 °C from one compressor K-1500, it is possible to heat 16.47 kg/s of water for the needs of hot water supply. The increase in the velocity of coolants in the heat-exchange unit for heating fire-fighting water leads to a significant increase in energy consumption, for circulation without a substantial reduction in the required heat exchange area. For the conditions of Magnitogorsk from one K-1500 compressor it is possible to heat 58.62 m³/s of air for ventilation from -34 to +10 °C; an increase in the velocity of the coolant to 0.7 m/s leads to a significant reduction in the power of the fan. The mathematical model allows to design the proposed scheme for the use of SER in heat supply systems for any industrial building with centrifugal compressors. The results of mathematical modeling can be used to automation of heat exchangers when using SERs from compressor plants.

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