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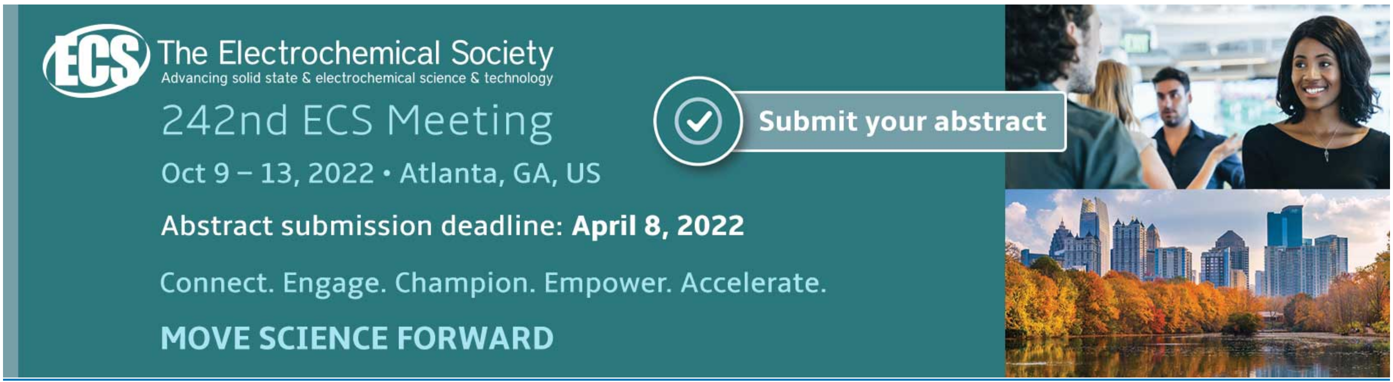

Improving the technology of using freon-steam turbines in mine power complexes

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Abstract. Mining power complexes can significantly reduce the cost of production of mining enterprises and increase their competitive position in the relevant market. To solve the urgent problem of further improving the operation of mine energy complexes, it is proposed to include in their composition installations for the useful use of energy from low-potential sources with a freon-steam turbine, which implement the thermodynamic Rankine cycle. The article considers the features of the organization of the Rankine cycle depending on the properties of freons. When choosing freons, the emphasis is placed on the use of strictly ozone-safe freons that meet modern requirements for normalizing the value of the global warming potential. The previously proposed method for calculating the thermodynamic parameters necessary for evaluating useful action's coefficient of using specific freons in a useful energy recovery equipment has been improved. The calculation of the energy efficiency of the equipment with a freon-steam turbine for the selected options for the use of freons is performed. The analysis of the obtained results showed that the use of ozone-safe freons with low values of the global warming potential in installations for the utilization of energy from low-potential sources will improve the operation of mine energy complexes.

1. Introduction

Thermodynamic analysis [1] of the use of freon-steam turbines for the utilization of energy from low-potential sources of mine energy complexes (MEC) showed a fairly high level of efficiency. To evaluate the efficiency of the Rankine cycle, the thermodynamic useful action's coefficient (UAC) Rankine's cycle was calculated with a heating temperature $T_2 = 323$ K (50°C) and a cooling temperature $T_1 = 293$ K (20°C) when the turbine was operated on ozone-safe freons R-125 and R-236ea. These freons, as an example, are recommended for use on the basis of the developed principles [1] for the selection of freons for installations for the utilization of thermal energy from low-potential sources. However, taking into account the current additional requirements [2] for rationing the global warming potential of freons in the fairly near future, it is necessary to continue the work on selecting the optimal working bodies for secondary low-potential energy utilization plants in the MEC. In the article [1], a method for calculating the efficiency of a secondary heat energy utilization plant is developed, the operation of which is based on the thermodynamic Rankine cycle using freons as working bodies.

The Rankine's cycle consists of heating the working fluid in the heat exchanger, adiabatic expansion in the turbine with the return of useful mechanical work to the electric generator and subsequent condensation of freon to the state of a saturated liquid, which is then returned to the heat exchanger by a pump. Depending on the properties of freons in the Rankine cycle diagram in the coordinates "pressure p − specific volume υ", the line of adiabatic expansion in the turbine can be located in two ways. In the article [1], the method for calculating the cycle's useful action's coefficient (UAC) is developed for the variant of the location of the freon expansion line "5-6" on the Rankine cycle diagram (figure 1), when it is necessary to overheat the freon to close the cycle loop on the line "4-5".

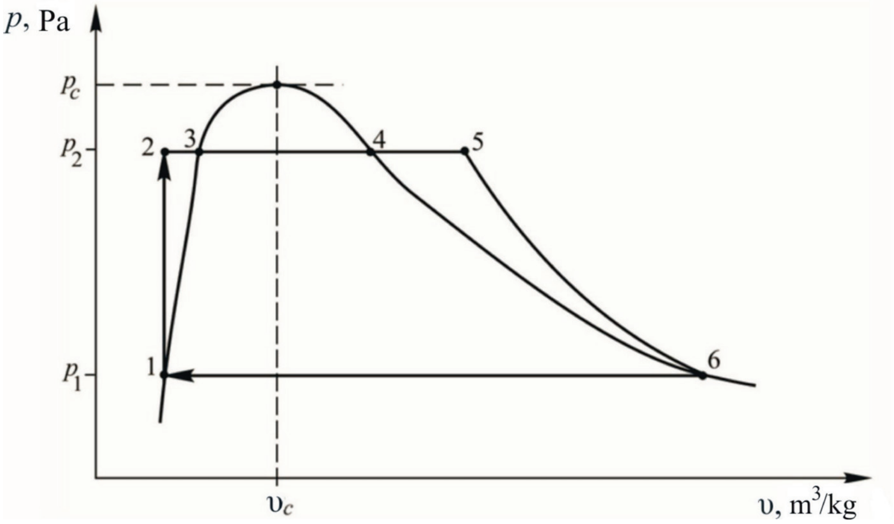

Figure 1. Rankine cycle in coordinates "pressure p − specific volume υ", where p_1, p_2 are pressure freon on lines "6-1" и "2-5", Pa; p_c, υ_c are pressure (Pa) and specific volume (m^3/kg) in critical point, respectively.

Freon overheating occurs from the temperature T_2, which is kept constant on the line "2-4", to the temperature T_5 at the point "5". Freon or other working fluid (water, carbon dioxide), for which the Rankine cycle in the coordinates "pressure p - specific volume υ" is shown in figure 1, is characterized by the following property. The entropy of the saturated freon vapor (working fluid) decreases with increasing temperature. Let such working bodies, including freons, be called working bodies (freons) of the first type. The first type of freons includes R-125 and R-236ea, the properties of which were analyzed in [1] for the purpose of application in MEC equipment. The first type of freons also includes R-32, R-152a, which have a significantly lower global warming potential value compared to the above-mentioned substances. Freon overheating occurs from the temperature T_2, which is kept constant on the line "2-4", to the temperature T_2 at the point "5". Freon or other working fluid (water, carbon dioxide), for which the Rankine cycle in the coordinates "pressure p-specific volume υ".

But working bodies are possible, let's call them working bodies of the second type. In them, the above-mentioned property with respect to the change in entropy is formulated in the opposite way. Namely, the entropy of the saturated vapor of freon (working fluid) increases with increasing temperature. Such freons include, for example, R-1234yf with a very low global warming potential.

The geometric shape of the Rankine cycle diagram for freons of the second type will differ from the diagram shown in figure 1. The possibility of using R-1234yf for thermal energy utilization plants of low-potential sources produced in mine power complexes is not considered in this paper.

This article is devoted to the evaluation of the thermodynamic efficiency of the use of R-32 and R-152a in installations for the use of secondary energy resources for the generation of additional electricity as part of the MEC. In the course of further work on the general problem of utilization of secondary energy resources (SER), which are produced in the MEC, the possibility of a significant simplification of the mathematical apparatus of the methodology previously presented in [1] was established.

Therefore, the purpose of this article is to improve the methodology for evaluating the efficiency of installations with a freon-steam turbine in mine power complexes, when freons of the first type are used as working bodies.

2. Methods

In figure 1 of the Rankine cycle diagram, the adiabatic expansion of the freon vapor in the turbine along the "5-6" line can be considered isentropic in disregard of friction. In figure 1, the isentrope "5-6" of steam expansion in the turbine is preceded by the process of its overheating on the line "4-5". The thermodynamic efficiency of the freon application is evaluated by calculating the thermodynamic efficiency of the Rankine cycle. The efficiency is determined by the ratio of mechanical work, which is numerically equal to the area of the figure formed by the lines "1-2-3-4-5-6-1" of the cycle, to the amount of heat that the working fluid gives to the cooling medium in the condenser on the line "6-1". The temperature of the freon on the line "6-1" in the condensation process is constant and is equal to T_1.

Since the cycle efficiency is calculated for 1 kg of the working fluid, the heat given off on the line "6-1" is numerically equal to the specific heat of the phase transition. Thus, the general expression for the efficiency of the Rankine cycle is determined by the formula [3]

$$\eta_R = \left(\frac{p_2 - p_1}{L(T_1)}\right) \cdot \left[(\upsilon_5 - \upsilon_1) + 0.5 \cdot (\upsilon_6 - \upsilon_5)\right], \tag{1}$$

where p_1, p_2 are the freon pressure on lines "6-1" and "2-4" (figure 1), respectively, Pa; υ_1, υ_5, υ_6 are specific volume freon at points "1", "5" and "6" (figure 1), respectively (m^3/kg); $L(T_1)$ is specific heat of boiling of freon on line "6-1" at temperature T_1, (J/kg).

For calculations using the formula (1), the value υ_1 (specific volume in the state of saturation of the liquid phase) of a particular freon is found according to reference data [3]. At point "5", the freon pressure is known to be p_2. The steam expansion isentrope in the turbine starts at point "5". The process of isentropic expansion ends at point "6". At point "6", the parameters of the freon vapor correspond to the temperature T_1 and are found according to the reference data [4]. The temperature value T_1 is determined by the temperature of the cooling medium in the condenser where the freon is liquefied. At point "5", the freon pressure equal to p_1 is known, but the specific volume υ_5 of the freon and its temperature T_5 are unknown .

Therefore, for the effective use of formula (1), the task of the methodology is to determine υ_5 and T_5. To solve this problem and determine the thermodynamic efficiency of the Rankine cycle, we use the Redlich-Kwong thermal equation of state [5]:

$$p_{RK}(\upsilon, T) = \frac{R_{gf} T}{\upsilon - b} - \frac{a}{\upsilon(\upsilon + b)\sqrt{T}}, \tag{2}$$

$$R_{gf} = \frac{R_{gu}}{M_f}, \tag{3}$$

where R_{gu} = 8.314 J/(mol·K), universal gas constant; M_f – is molecular mass of freon, kg/mol; T is a температура, K; υ is a specific volume, m^3/kg; b is a constant of the Redlich-Kwong equation, which characterizes the forces of intermolecular repulsion, m^3/kg; a is a constant of the Redlich-Kwong equation, which characterizes the forces of intermolecular attraction, Pa·m^6·K$^{0.5}$/kg^2, R_{gf} – is gas's constant of freon, J/(kg·K).

To estimate the efficiency and efficiency of the thermodynamic cycle, it is necessary to have an expression for the entropy of freon, the thermal properties of which are given by the Redlich-Kwong equation. In the article [1], an expression for the entropy of the working fluid according to Redlich-Kwong is obtained

$$S_{RK}(\upsilon, T) = A_S(\upsilon, T) - A_S(\upsilon_0, T_0), \tag{4}$$

$$A_S(\upsilon, T) = R_{gf} \ln(\upsilon - b) + \frac{a}{2bT^{1.5}} \ln\left(\frac{\upsilon}{\upsilon + b}\right) + c\ln(T) + dT + \frac{kT^2}{2}, \tag{5}$$

where $S_{RK}(\upsilon,T)$ is specific entropy of freon, the thermal properties of which are modeled by the Redlich-Kwong equation, J/(kgK); $A_S(\upsilon,T)$ is the function whose unit coincides with the unit of the specific entropy of freon, J/(kgK); υ_0 is specific volume at some point, which is taken as the initial state of the adiabatic process, m^3/kg; T_0 is temperature at some point, which is taken as the initial state of the adiabatic process, K; *c, d, k* – the polynomial approximation constants of the dependence of the isochoric heat capacity (in the ideal gas state) of freon on the temperature [6], which have dimensions, respectively, J/(kg·K), J/(kg·K^2), J/(kg·K^3).

The named polynomial approximation is given by the expression [6]:

$$C_\upsilon^0(\upsilon,T)=c+dT+kT^2\,, \tag{6}$$

where $C_\upsilon{}^0(\upsilon,T)$ is the specific heat capacity of freon in the ideal gas's state, J/(kg·K).

The task of the methodology is to determine υ_5 and T_5. We will improve the previously developed method for finding the specific volume of freon υ_5 at point "5" and its temperature T_5 in the case when the line "5-6"of the isentropy in figure 1 ends at point "6", for which all the parameters of the freon are known. Based on the obtained expression (4) for $S_{RK}(\upsilon, T)$, we can write a nonlinear equation with respect to υ_5 and T_5

$$A_S(\upsilon_5,T_5)=A_S(\upsilon_6,T_1)\,. \tag{7}$$

To exclude T_5 from equation (7), we find the temperature for point "5" according to the Redlich-Kwong equation at the freon pressure p_2.

The Redlich-Kwong equation with respect to $(T_5)^{1/2}$ is a cubic equation

$$x^3-\theta x-1=0\,, \tag{8}$$

where the dimensionless complexes x and θ are defined by the expressions

$$x=\left(\frac{\upsilon_5 R_{gf}}{a}\right)^{1/3}\left(\frac{\upsilon_5+b}{\upsilon_5-b}\right)^{1/3}\sqrt{T_5}\,, \tag{9}$$

$$\theta=\left(\frac{p_1}{\sqrt[3]{R_{gf}}}\right)\left(\frac{\upsilon_5}{a}\right)^{2/3}(\upsilon_5+b)^{2/3}(\upsilon_5-b)^{1/3}\,. \tag{10}$$

The solution (8) was obtained in [1] using the trigonometric Vietta's formula for the roots of a cubic equation. Note that formally, the solution (8) is a function

$$x=K(\theta)\,, \tag{11}$$

This function actually determines the temperature value of T_5 as a function of υ_5. Further, this function, being used in (7), turns the latter into an equation with respect to a single unknown υ_5. To simplify the algorithm for solving the newly obtained equation (7) using (11), the following approximation for (11) is proposed.

The function (11) itself, which needs to be approximated, is obtained as a Cardano's solution of the cubic equation (8). The real root of equation (8) according to J. Cardano [7] has the form

$$x=K(\theta)=\left(\frac{\theta}{3\sqrt[3]{f(\theta)}}+\sqrt[3]{f(\theta)}\right), \tag{12}$$

where

$$f(\theta)=\left(\sqrt{\frac{1}{4}-\frac{\theta^3}{27}}+\frac{1}{2}\right). \tag{13}$$

To simplify (7), when substituting (11), the last expression is suggested to be approximated by the following rather simple expressions [7]. Namely, for the values of θ in the range from 0 to 1, the dependence is linear

$$x=K_1(\theta)=0.3162\cdot\theta+1. \tag{14}$$

For values of θ in the range from 1 to 2.5, the dependence is

$$x=K_2(\theta)=0.3162\cdot\theta^{0.95}+1. \tag{15}$$

After substituting (14) or (15), depending on the value of θ for a particular freon in (7), the last equation is converted into equations with respect to υ_5. Taking into account the proposed approximations, the form of this equation is much simpler compared to (7), which would use the full solution of (12). It is advisable to solve the resulting equation by the Newton method. After determining υ_5 and T_5, we find by calculating the value of the expression

$$T_5=\left\{K_i(\theta)\cdot\left[\sqrt[3]{\frac{a\cdot(\upsilon_5-b)}{R_{gf}\cdot\upsilon_5\cdot(\upsilon_5+b)}}\right]\right\}^2. \tag{16}$$

where $i = 1, 2$, which corresponds to the numbers of approximations (14) or (15).

Thus, equations (7), (8), approximations (14) (15) are obtained to simplify the analytical form of the solution of equation (8) and the expression (16). These equations and expressions determine the parameters of the first type of freon at point "5" of the Rankine cycle for an installation with a freon-steam turbine.

The thermal properties of freon were modeled by the Redlich-Kwong equation. Using this equation, the mathematical apparatus of the proposed improved method for determining the parameters of the first type of freon at the point "5" is developed. On the basis of these data, the estimate UAC of the use of a particular freon in the heat recovery equipment of secondary low-potential sources is evaluated.

3. Results and discussion

Taking into account the current additional requirements for normalizing the value of the global warming potential, freons R-32 and R-152a were chosen to illustrate the results of the application of the improved methodology. Experts estimate the global warming potential (GWP) for R-32 in the range of 550-675, for R-152a this indicator is 120-130 [3]. According to the above method, calculations were performed for freons R-32, R-152a, whose thermodynamic parameters are given in table 1 [4, 6].

Table 1. Constants of the Redlich-Kwong equation and isochoric heat capacity for R-32 and R-152a freons [5, 7].

Parameter, unit	Freon class	
	R-32	R-152a
a, $(\text{N}\cdot\text{m}^4\cdot\text{K}^{1/2})/\text{kg}^2$	4347	4390
b, m^3/kg	$8.42\cdot10^{-4}$	$9.359\cdot10^{-4}$
c, J (kg·K)	218.95	163.51
d, $\text{J}/(\text{kg}\cdot\text{K}^2)$	2.27	3.11
k, $\text{J}/(\text{kg}\cdot\text{K}^3)$	$-8.84\cdot10^{-4}$	$-1.23\cdot10^{-3}$

The data obtained using the above method for the thermodynamic parameters R-32 and R-152a at the calculated points of the Rankine cycle (figure 1) from the freon-steam turbine are presented in table 2.

Table 2. Parameters of R-32 and R-152a freons at the calculated points of the Rankine cycle.

№ point, condition working substance	Pressure, MPa		Specif. volume m^3/kg		Temperature °C	
	R-32	R-152a	R-32	R-152a	R-32	R-152a
1, saturated freon after condenser	1.505	0.527	0.00104	0.001	20.0	20.0
2, non-boiling freon	3.182	1.196	0.00104	0.0001	50.0	50.0
3, boiling freon	3.182	1.196	0.00099	0.0012	50.0	50.0
4, dry saturated freon’s steam	3.182	1.196	0.0105	0.0269	50.0	50.0
5, superheated steam or dry saturated steam	3.182	0.527	0.0127	0.0285	65.0	52.4
6, dry saturated freon’s steam	1.506	0.527	0.0248	0.0618	20.0	20.0

For equipments for the utilization of energy from low-potential sources using R-32, R-152a, the thermodynamic UAC of (1), calculated using the data in table 2, is 10%. This final result is explained by the close value of the properties of the considered freons (table 1). The temperatures T_2 and T_1 were also assumed to be the same for R-32, R-152a in order to compare the energy efficiency of using these two working substances under comparable conditions.

4. Conclusion

1. Improved the method of calculating the thermodynamic parameters necessary to evaluate the efficiency of the use of specific freons in the installation of useful energy recovery. The method is based on the solution of the Redlich-Kwong equation with respect to temperature and the selection of a power approximation for this solution, which allows the entire problem to be reduced to the solution of a single nonlinear equation by the Newton method. Approximations by power dependences (11) for solutions of the cubic equation (8), which, when used in (7), significantly simplify the final equation for determining

2. It is proposed to use freons R-32, R-152a with a sufficiently low value of the global warming potential for useful utilization of thermal energy generated in mine power comp

3. Thermodynamic analysis of the prospects for the use of freons R-32, R-152a in installations for the utilization of energy from low-potential sources by expanding the working fluid in the turbine showed their high efficiency. The UAC calculated by the improved method was 10%. This will allow additional utilization of thermal energy from sources with the lowest temperature, which is produced in large quantities in mine energy complexes.

4. When using R-32 and R-152a, the UAC of the equipment is almost the same and is 10%, the difference is in the first decimal place. But for R-32, T_5 = 65.0°C, and for R-152a, T_5 = 52.4°C. Therefore, R-152a is preferred. At the same UAC’s values, R-152a can be heated with a low-potential source with a temperature 12.6°C lower than R-32.

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