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超临界参数低沸点工质ORC汽轮机组技术经济指标计算
CALCULATION OF TECHNICAL AND ECONOMIC INDICATORS OF TURBINE UNITS AT ORC WITH LOW-BOILING WORKING FLUIDS AT SUPERCRITICAL PARAMETERS

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注释。 评价超临界参数低沸点工质ORC透平机组的技术经济性能指标，研究低沸点工质热力学最优压力下热能再生透平机组的火用效率与其热物理性质的关系（ 临界压力和冷凝比热），以及涡轮机前工作流体在 100 至 300 oC 温度范围内的初始温度。 获得的相关性还使得可以评估低沸点工作流体的热力学效率，以供其在超临界参数下的涡轮机装置中进一步使用。 本文提出了一种工质中间过热和超临界参数的汽轮机组成本估算方法，使得预测此类汽轮机组的经济性能指标成为可能。 为此，提出了一种利用低沸点工质超临界参数确定汽轮机组技术经济效率指标的方法，无需经过复杂的计算和软件求解即可对其效率进行初步评估。 这样的问题

关键词：有机朗肯循环、二次能源回收、低沸点工质、透平机组、火用效率、技术经济指标。

Annotation. *To assess the technical and economic performance indicators of ORC turbine units with low-boiling working fluids at supercritical parameters, the dependence of the exergy efficiency for turbine units with thermal energy regeneration at thermodynamically optimal pressures of low-boiling working fluids on their thermophysical properties (critical pressure and specific heat of condensation), as well as the initial temperature of the working fluids in front of the turbine in the temperature range from 100 to 300 ^{o}C. The obtained dependence also makes it possible to evaluate the thermodynamic efficiency of low-boiling working fluids for their further use in turbine units at supercritical parameters. The paper proposes a method for estimating the cost of turbine units with intermediate overheating and supercritical parameters of the working fluid, which makes it possible to predict the economic performance indicators of such turbine units. Thus, a methodology has been proposed for determining the technical and* *economic efficiency indicators of turbine units using supercritical parameters of low-boiling working fluids, which allows for a preliminary assessment of their efficiency without the use of complex calculations and the use of software to solve such a proble*

Keywords: *organic Rankine cycle, recycling of secondary energy resources, low-boiling working fluids, turbine unit, exergy efficiency, technical and economic indicators.*

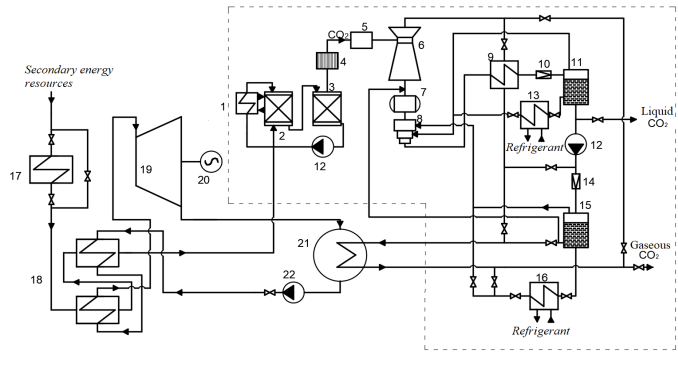
Introduction

In the context of the development of low-carbon energy, ORC turbine units (Figure 1), using freons and carbon dioxide as working fluids, are increasingly used. Turbine plants using low-boiling working fluids are used as part of polygeneration plants, for the utilization of gas turbine exhaust gases, for the combustion of fuels with low calorific value, and for the utilization of high-temperature water and energy resources [1-6].

In [7-9], in order to increase the efficiency of turbine units, it was proposed to use supercritical, thermodynamically optimal parameters of a low-boiling working fluid. However, to determine the thermodynamic efficiency of such installations it is necessary to perform complex calculations or use specially developed programs. The lack of operational turbine units with supercritical parameters of low-boiling working fluids makes it difficult to determine the cost of such units, and, consequently, to calculate the technical and economic indicators of their operation.

Scheme

In works [1,5], for the simultaneous production of electrical energy, heat, cold and carbon dioxide, a polygeneration unit was proposed, which includes a turbo unit for ORC (Figure 1).



1,13,16 – heat exchanger; 2 – absorber; 3 – desorber; 4 – splash separator; 5 – dehumidifier; 6 – injector; 7 – receiver; 8 – compressor; 9 – capacitor;

10.14 – control valve; 11.15 – separator; 12.22 – pump; 17 – network water heater; 18 – waste heat boiler; 19 – turbine at NKRT; 20 – generator; 21 – capacitor

***Figure 1.** Scheme of a turbine unit with thermal energy regeneration [1, 5]*

Thermodynamic efficiency of turbine units

One of the most important indicators of the efficiency of turbine plants is exergy efficiency. The studies carried out [8,9] showed that for each initial temperature of a low-boiling working fluid there is its own thermodynamically optimal pressure. Having plotted the dependences of exergy efficiency on temperature for various low-boiling working fluids at optimal pressures of the working fluids (Figure 2), it is clear that these curves have a similar shape and slope. These dependencies can be represented mathematically in the form of a polynomial:

$$y(x) = A \cdot x^2 + B \cdot x + C, \qquad (1)$$

where A, B, C – are the coefficients of the polynomial.

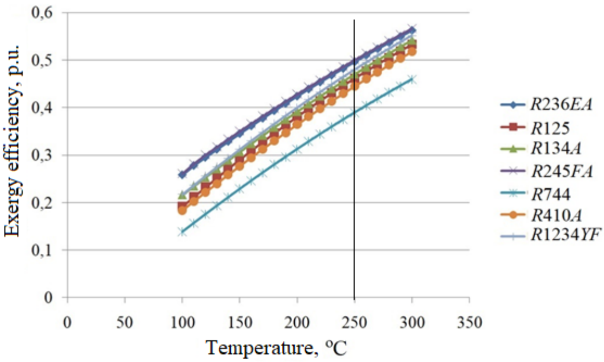


***Figure 2.** Exergy efficiency of turbine units at different temperatures of low-boiling working fluids*

The studies carried out in [8] indicate the influence of critical pressure and specific heat of condensation on the operating efficiency of turbine units. This relationship can be described by the formula:

$$\eta = A \cdot P_{\text{кр}}^{x} \cdot L_{\text{к}}^{y}. \qquad (2)$$

where A, B, C – are the coefficients.

For a working fluid temperature in front of the turbine of 250 °C, formula (3) according to [8] will take the form:

$$\eta = 47{,}5 \cdot P_{\text{кр}}^{-0{,}27} \cdot L_{\text{к}}^{0{,}072}. \qquad (3)$$

Coefficients A and B of equation (1) can be determined from the results obtained (Figure 2), and coefficient C can be obtained based on formula 3. Then formula (1) will take the form:

$$\eta = -1{,}75 \cdot 10^{-4} \cdot t^2 + 0{,}229 \cdot t + 47{,}5 \cdot P_{\text{кр}}^{-0{,}277} \cdot L_{\text{к}}^{0{,}072} - 46{,}0. \qquad (4)$$

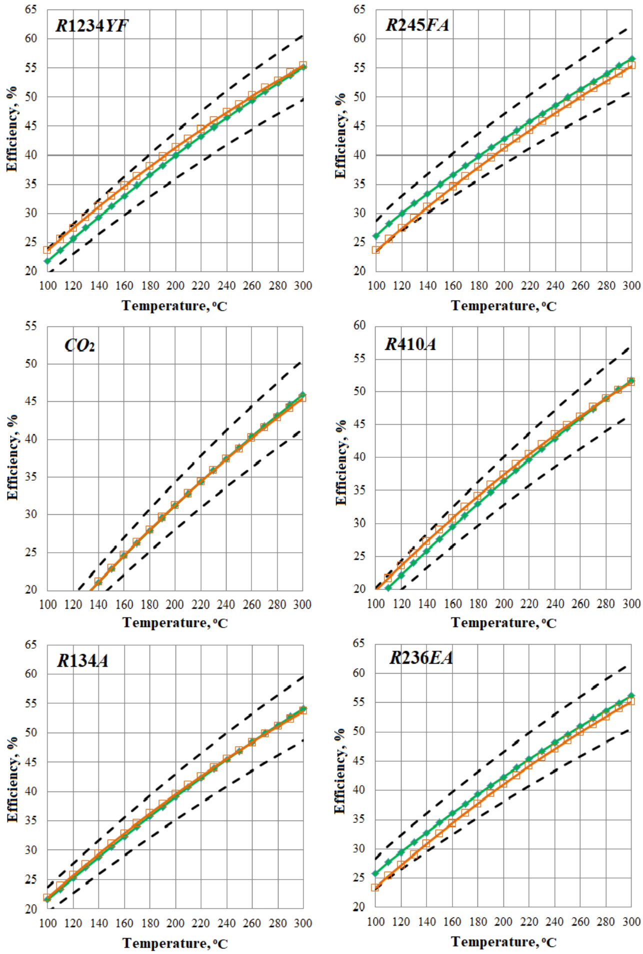


Figure 3. *Graphical representation of the dependence of exergy efficiency on the temperature of low-boiling working fluids*

The results obtained using dependence (4) are presented in Figure 3, the error of the obtained results did not exceed 10%. The obtained dependence can be used to determine the operating efficiency of turbine units at ORC using supercritical thermodynamically optimal parameters of low-boiling working fluids, as well as for a preliminary assessment of the amount of generated electrical energy when calculating the economic indicators of the operation of turbine units.

Economic efficiency of turbine units

Assessment of the economic efficiency of turbine units can be carried out according to the following indicators: static payback period, dynamic payback period, internal rate of return, net present value, etc. Determining the above-mentioned standard indicators is not difficult, but to determine them it is necessary to estimate the cost of turbine units on ORC. Due to the lack of implemented projects for turbo plants at the ORC with supercritical parameters of the working fluids, it is proposed to use the following formula to estimate the cost of such plants:

$$S = (1 + (\Delta t) \cdot k_t + (\Delta p) \cdot k_p + k_{\text{ПП}}) \cdot S_{\text{б}} \cdot (1 - k_{\text{ТП}}) + S_{\text{б}} \cdot k_{\text{ТП}}, \quad (5)$$

where Δt – temperature difference between the actual and basic versions of turbine units, °C;

Δp – pressure difference between the actual and basic versions of turbine units, MPa;

k_t– the coefficient taking into account the influence of temperature on the cost of installation is taken as k_t = 0,0005 units/°C;

k_p – the coefficient taking into account the influence of pressure on the cost of a turbine unit is taken as k_p = 15,0 units/kPa;

$k_{\text{ПП}}$ – the coefficient taking into account the influence of intermediate overheating on the cost of the turbine unit is taken as $K_{\text{ПП}}^{\text{ТУ}} = 0,06$ units. [11];

$k_{\text{ТП}}$ – coefficient taking into account the absence of influence of the working fluid parameters on the cost of the installation elements, $k_{\text{ТП}} = 0,07$ units [12].

Table 1.

Estimation of the cost of turbine units

Power, MW	**Pressure, kPa**	**Temperature, °C**	**Actual cost turbine units, million rubles**	**Price turbine units (formu. 5), million rubles**	**Error, %**
*R*410*A*					
0,03*	1100*	80*	0,111*	-	-
0,03	1400	130	0,115	0,118	2,8
0,1*	1000*	90*	0,372*	-	-
0,1	2200	130	0,403	0,391	10,2
0,5*	2200*	110*	1,776*	-	-
0,5	3700	200	1,773	1,886	6,4

3*	2600*	150*	10,860*	-	-
3	4000	220	12,573	11,430	9,1
Isobutane					
0,05*	1000*	105*	0,178*	-	-
0,05	1100	120	0,197	0,182	7,4
0,3*	900*	90*	1,050*		
0,3	11500	110	1,150	1,096	4,7
0,2*	100*	80*	0,718*	-	-
0,2	1100	160	0,998	1,104	10,7
0,8*	1500*	150*	2,880*		
0,8	2700	200	3,435	2,979	13,3
Carbon dioxide					
0,1*	2500*	110*	0,385*	-	-
0,1	3700	220	0,403	0,412	2,1
0,8*	2500*	180*	3,024*		
0,8	3300	250	3,535	3,156	10,7
1,5*	300*	250*	5,685*		
1,5	4200	300	5,730	5,913	3,2
* – turbine unit taken as the basic option					

Substituting the obtained values, formula (5) can be represented as:
- for a turbine unit with one-time overheating

$$S = (4650 \cdot 10^{-3} \cdot \Delta t \ \ + 1395 \cdot 10^{-3} \cdot \Delta p \ \ + 1) \cdot S_{б}, \qquad (6)$$

- for a turbine unit with double overheating

$$S = (4650 \cdot 10^{-3} \cdot \Delta t \ \ + 1395 \cdot 10^{-3} \cdot \Delta p \ \ + 110{,}56) \cdot S_{б}, \qquad (7)$$

Estimation of the cost of turbine units using the proposed formulas is presented in Table 1. The error of the results did not exceed 15%.

Conclusion

In the course of the research, a methodology was developed for determining the technical and economic indicators of the efficiency of ORC turbine units with supercritical parameters of the working fluids, which allows for a preliminary assessment of their efficiency without using software to solve this problem.

The dependence of the exergy efficiency for turbine units with thermal energy regeneration at thermodynamically optimal pressures of low-boiling working fluids on their thermophysical properties (critical pressure and specific heat of condensation), as well as the initial temperature of the working fluids in front of the turbine in the temperature range from 100 to 300 °C, was obtained. The obtained dependence allows us to make a preliminary assessment of the thermodynamic efficiency of low-boiling working fluids for operation in turbine units at supercritical parameters.

A method is proposed for estimating the cost of ORC turbine units with intermediate overheating and with supercritical working fluid parameters, which makes it possible to predict the economic performance indicators of such turbine units.

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