Method of calculation and selection of design parameters and operational characteristics of the spiral expander

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Method of calculation and selection of design parameters and operational characteristics of the spiral expander

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Abstract. The paper proposes a method for calculating the main design parameters and operational characteristics of the HPEC using the Helmholtz equations of state. N-pentane, freon R11, and acetone were considered as the working fluid. The calculations were performed using the CoolProp 6.3.0 library. It was found that the most profitable for HPEC operating on the Rankin cycle with low-potential sources is n-pentane. L_D expander operation and mass flow rate of the working fluid are calculated. The calculations were performed using the freely distributed open source library CoolProp 6.3.0. The calculations show that the most profitable WF for HPEC running on the Rankin cycle with low-potential sources is n-pentane. It is determined that the increase in costs when the temperature decreases before the SD is due to a decrease in the level of operation of the Lд expander, which in turn depends on the value of the steam enthalpy at the entrance to the ex-pander.

1. Introduction

Taking into account the accumulated world experience in the design and operation of thermal machines operating on the organic Rankin cycle (ORC) [1-3], as well as the high level of development of some elements of such machines, it is appropriate and reasonable to use some ready-made solutions [4-6]. In this paper, the main attention will be paid to the method of calculating and selecting the design parameters of the drive of the generator of heat and power energy converters (HPEC), which is a spiral expander.

Spiral machines have recently gained popularity primarily as compressor units, including oil-free ones [7]. However, a number of studies have appeared on the use of spiral machines as expanders, including in ORC cycles [8-11]. Despite the significant similarity, expanders have completely different requirements, which must inevitably affect both the method of their calculation and design, as well as their design.

First of all, to do this, it is necessary to select and justify the applied structural materials and coverings with special properties. The solution of this issue will allow determining the design standards in terms of the permissible speeds of movement of parts and components of the expander, and the permissible loads on them, determine the rational pairs of friction materials, take into account the thermal impact of the environment on the deformation of elements, and create a basis for predicting the product life.

The second, no less important issue is the development of a method for selecting the optimal parameters of the thermodynamic cycle of HPEC, taking into account the possibility of its implementation in its individual elements. In addition, it is necessary to develop mathematical models of the main components of the HPEC, such as pump; recuperator; heater; expander; condenser; generator.

As a result of solving these problems, it is possible to create an optimal heat engine with the highest possible efficiency.

2. Materials and methods

2.1. Method for calculating the main design parameters of the HPEC

As the optimal WF for low-potential energy sources, liquids should be selected that, on the one hand, should boil at the minimum temperature, but not below the possible ambient temperature, and on the other hand, it is necessary to ensure effective condensation of WF. Three liquids meet these requirements: n-pentane (boiling point 36.074 °C), Trichlorofluoromethane (freon R11, boiling point 23.77 °C), and acetone (boiling point 56.1 °C).

The calculations used fundamental equations of state of substances in terms of Helmholtz energy [12]. A similar approach to the description is also presented in [13-14], devoted to the development of the fundamental equation of the normal pentane state.

These equations are implemented in the freely distributed open-source library CoolProp, where fluid models are based on Helmholtz energy formulas. The equations of state used to calculate the thermodynamic properties of substances are presented in [15].

Let us consider two variants of the Rankin cycle: a simple cycle and a cycle with heat recovery in order to determine the possible efficiency of the process in both variants and then compare them.

Comparison of cycles with and without recuperation, as well as comparison of application options for different WF was carried out by the value of the cycle efficiency:

$$\eta_t = \frac{q_1 - q_2}{q_1},\qquad(1)$$

where q_1 – heat supplied in the cycle; q_2 – the heat rejection in the cycle.

As heating and heat removal in this cycle are Isobaric processes, the input heat is the difference between the enthalpy at the output and input to the heater, and the output heat is the difference between the enthalpy at the input and output of the condenser [16]:

$$q_1 = h_{\text{н } out} - h_{\text{н } in} \;; \qquad q_2 = h_{\text{к } in} - h_{\text{к } out} \;; \qquad(2)$$

$$\eta_t = \frac{(h_{\text{н } out} - h_{\text{к } in}) - (h_{\text{н } in} - h_{\text{к } out})}{(h_{\text{н } out} - h_{\text{н } in})} = \frac{L_{\text{Д}} - L_P}{Q_H},\qquad(3)$$

where $L_{\text{Д}} = (h_{\text{н } out} - h_{\text{к } in})$ – the work of expander; $L_P = (h_{\text{н } in} - h_{\text{к } out})$ – work performed by the pump; Q_H – energy supplied in the cycle by the heater.

The upper limit of the $T_{\text{г}}$ cycle temperature for all WF was assumed to be the same in order to ensure comparison of efficiency under equal conditions with respect to the heating source. The operating pressure at the inlet to the expander was assumed to be 10 bar, which according to preliminary calculations is an acceptable value for a spiral expander, and is not the limit for other elements of the HPEC. The calculation scheme is shown in figure 1, a.
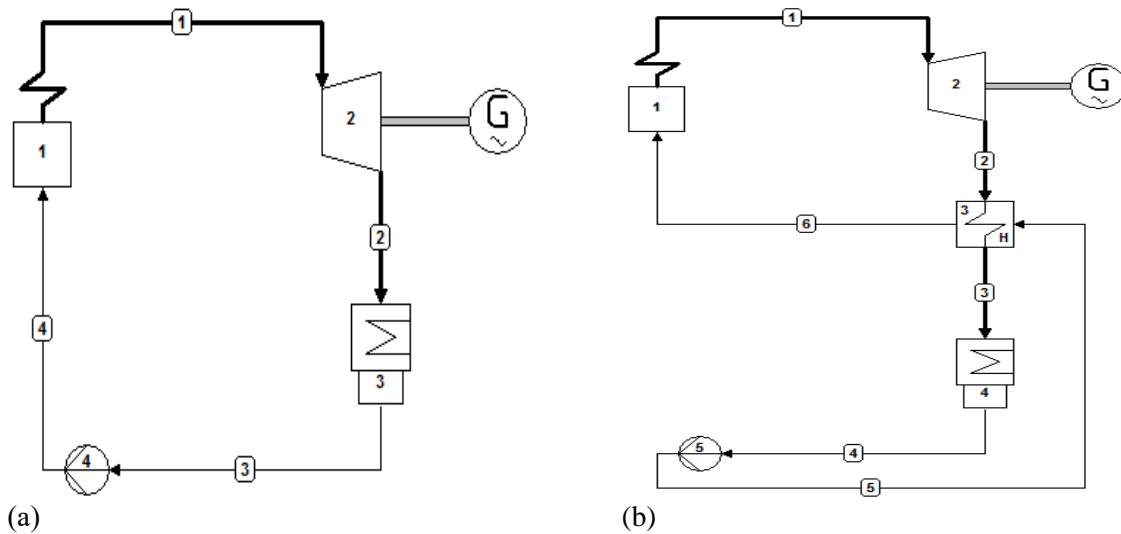
(a)   (b)

Figure 1. A design scheme of HPEC, (a) – working on a simple Rankin cycle, (b) – working on the Rankine cycle with energy recovery.

The simple Rankin cycle is characterized by the following successive stages: isentropic compression – Isobaric heating – polytropic expansion – Isobaric condensation.

3. Results
Results of calculation of the main design parameters of the HPEC.
The calculations were performed using the CoolProp 6.3.0 library. Temperatures, pressures, density, specific volume, enthalpy, and entropy were obtained at the calculated points of the cycle. Then we performed calculations of Rankin cycles with heat recovery for the same WF under equal conditions of heating and condensation. The diagram of the simulated device is shown in figure 1, b.

The calculations assumed that the temperatures of both flows at the outlet of the recuperative heat exchanger will be equal, i.e. the maximum possible heat exchange characteristic of a shell-and-tube heat exchanger will be provided. Figures 2-4 show the results of calculations of the Rankine cycle with energy recovery for n-pentane, acetone, and freon R11.
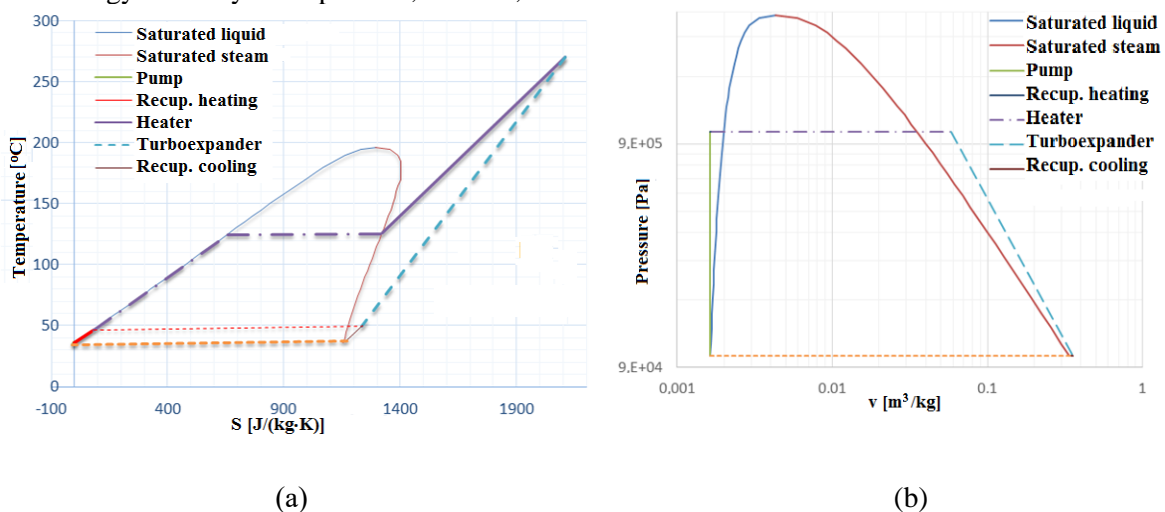

(a)   (b)

Figure 2. T-s (a) and P-v (b) diagrams of the Rankine cycle with recuperation
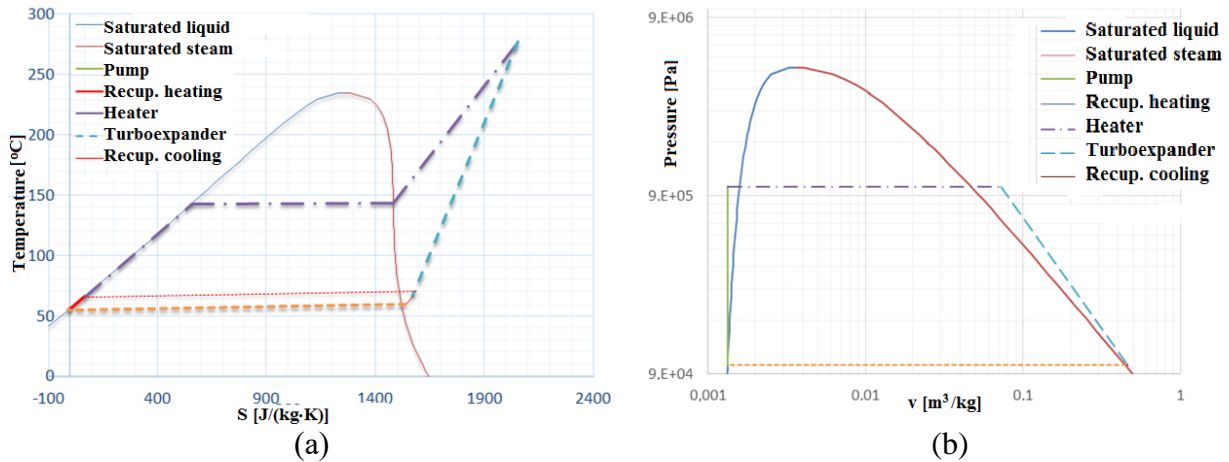(n-pentane).

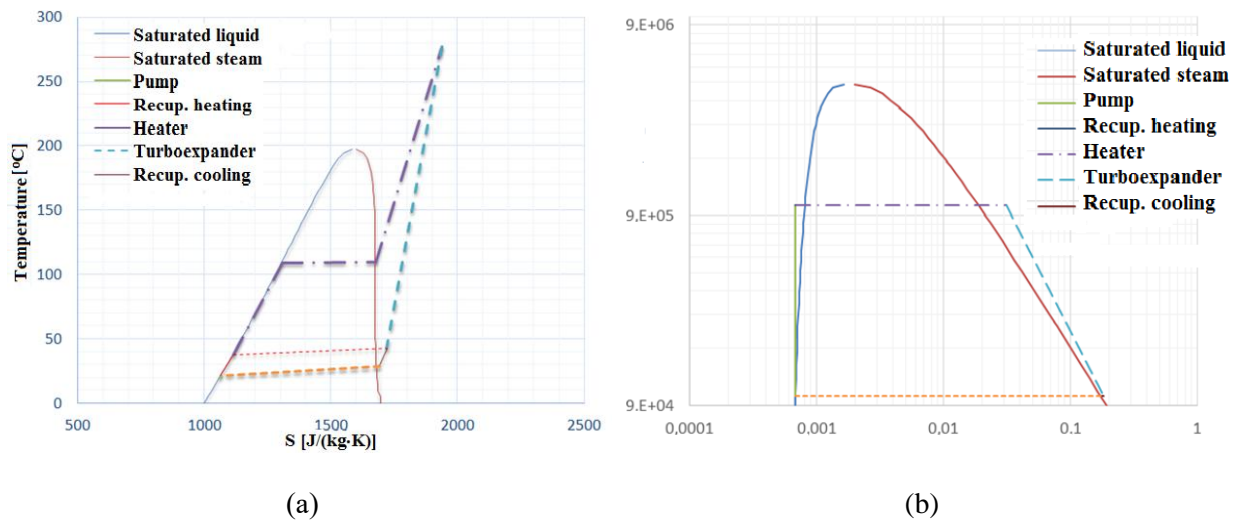**Figure 3.** T-s (a) and P-v (b) diagrams of the Rankine cycle with recuperation (acetone).

Figure 4. T-s (a) and P-v (b) diagrams of the Rankine cycle with recuperation (freon R11).

The results of calculations show that almost half of the heat previously spent on cooling the condenser (direct heat loss in the system) during heat recovery is returned back to the circuit, and the heat loss in the refrigerator reduced by almost half.

To compare the effectiveness of the three listed WF, the maximum temperature for acetone is selected as the upper limit. In the temperature range from 150 °C to the maximum temperature for acetone, the thermal efficiency of the process was calculated for three types of WF for modifications of Rankin cycles with and without regeneration. The results of the calculations are shown in figure 5.

Calculations show that n-pentane is the most profitable WF for HPEC operating on the Rankin cycle with low-potential sources. The theoretical efficiency of the cycle on n-pentane with heat recovery (without taking into account irreversibility) at the temperature before the expander 573 K reaches 64%, and at the maximum WF temperature of 650 K reaches the value of 70.8%. Based on the performed calculations, the main parameters of cycles with and without heat recovery are determined.

The calculations assumed that the indicator efficiency of the spiral expander η_i is 85%, and the conversion efficiency of the synchronous generator η_e is 98%. According to these assumptions, when the rated electrical power N_e =9000 W, the rated mechanical power of the SD should be $N_{Д} = \dfrac{N_e}{\eta_e} =$ 9183.67 W.
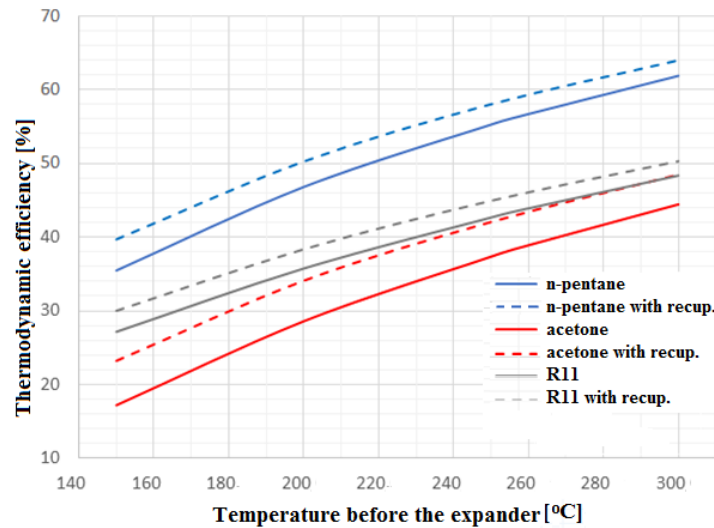
Figure 5. Results of comparative calculations of the thermal efficiency of the Rankin cycle for n-pentane, acetone and freon R11 with and without regeneration.

Knowing the difference between the enthalpy at the input and output of the SD, and thus determining the value of the expander $L_Д$, it is possible to determine the mass flow of the working fluid, which provides the mechanical and electrical power of the HPEC under specified conditions:

$$G_{mPT} = \frac{N_t}{L_Д} = \frac{N_e}{\eta_e \eta_i \eta_t L_Д}, \tag{4}$$

where η_t – thermal efficiency of the process.
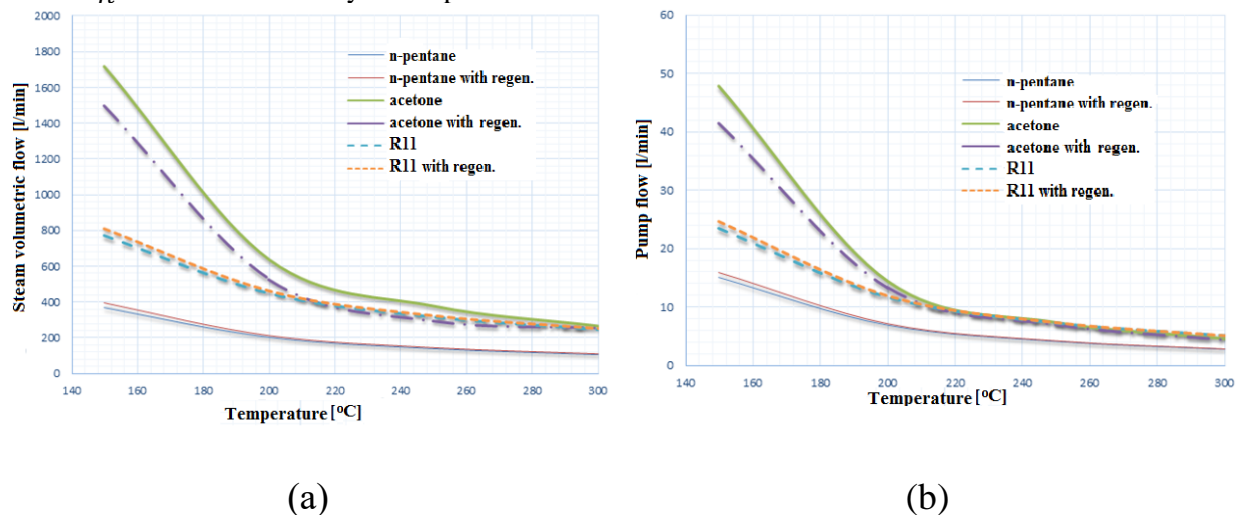

(a)

(b)

Figure 6. The dependence of the volume flow of various WF in ORC with and without recuperation, provided that a constant power is reached: before the SD (a); through the pump (b).

At a known mass flow rate, using the fundamental equation of state [12], it is possible to calculate important parameters for design: the volume flow rate of vapors at the entrance to the SD, as well as the volume capacity of the feed pump. Such calculations were performed for the three WF types under consideration and for ORC variants with and without recuperation. Figures 6 show the dependences of the volume flow of the working fluid through the SD and the feed pump.

It is obvious that the increase in costs when the temperature decreases before the SD is due to a decrease in the level of operation of the $L_Д$ expander, which in turn depends on the value of the steam enthalpy at the entrance to the expander. Taking into account the constancy of the indicator efficiency

of the SD and the efficiency of the generator, it can be argued that the mass flow rate of WF is inversely proportional to the thermal efficiency of the cycle, provided that the constant electric power of the HPEC is achieved.

4. Summary
The method of calculation and selection of the main design parameters and operational characteristics of HPEC is developed. The given method of calculation using equations of state of real substances allows determining the main design parameters of the HPEC. Three liquids were considered as optimal WF: n-pentane, freon R11, and acetone. The calculations were performed using the freely distributed open source library CoolProp 6.3.0. The calculations show that the most profitable WF for HPEC running on the Rankin cycle with low-potential sources is n-pentane. It is determined that the increase in costs when the temperature decreases before the SD is due to a decrease in the level of operation of the Лд expander, which in turn depends on the value of the steam enthalpy at the entrance to the expander.

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