CONCERNING UTILIZATION OF HEAT FROM LOW-POTENTIAL SOURCES

by

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The possibility of using R245fa and n-pentane in the Rankine cycle to convert the heat of low-potential sources into electrical energy is analyzed. A multistage axial-type turbine is considered as a drive of an electric generator. The influence of initial pressure of working fluids on the efficiency of the expansion process is determined. The algorithm and characteristics of thermal calculation of the turbine are given.

Key words: *Rankine cycle, axial-type turbine, thermodynamics, power*

Introduction

Today, production of electric energy from hot water of low-potential heat sources with a temperature of less than 120-130 °C is real, and this technology has been developed [1, 2]. However, in order to convert efficiently thermal energy of low-potential hot sources into electricity, it is necessary to search for an intermediate substance that meets the requirements of the working medium of power plants. It was previously shown [2] that obtaining the low-potential heat in the Rankine cycle makes it possible to provide consumers with electrical and thermal energy (cogeneration) and creates favorable prerequisites for the technical and economic efficiency of such installations, despite the low density of the thermal energy used. The traditional use of steam as a working fluid for power generation is limited by the increase in steam moisture at the end of the process of its expansion in the turbine, which does not allow the maximum use of the thermal potential of the energy source.

Currently, in the USA, Germany, Italy and some other countries research and commercial production of power plants operating by the organic rankine cycle (ORC) are being studied and produced. Energy-saving technology using the Rankine cycle allows generating electricity with efficiency of up to 18% depending on the temperature of the heating low-potential source. This means a significant increase in the efficiency of the energy complex, especially the steam-water cycle, when two cycles are combined into a single binary cycle, using the heat of sources with the temperature of ~200 °C [3].

An overview of the state of the steam-turbine units operating by the ORC since 1995 is presented in tab. 1 [4]. Analysis of data presented shows the ambiguity of the use of low-boiling substances as the working medium in the Rankine cycle. The producers of low temperature power installations use the low-boiling substances with zero ozone-depleting potential and minimal potential of global warming as the working fluids.

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Table 1. Characteristics of steam power plants with low-boiling working fluids [4]

Manufacturer	Consumer	Power of installation, [kW]	The working fluid	The use of instalation	Turbine type	The parameters at the entrance		Units	Year of sale
						T, [°C]	*P*, [MPa]		
Atlas Copco (Sweden)	Canada	2100	R134a	Utilization	Radial	no data	no data	1	2012
	Turkey	22 500	n-Butane	Geothermics				4	2013-2015
	Germany	3600	iso-Butane	Geothermics				1	2014
Exergy (Italy)	Turkey	1000	Fluorocarbons	Biomass				2	2012
	Italy	1000	Hydrocarbons	Geothermics, Biomass				2	2013
	Italy, France	100-1000	Fluorocarbons, siloxans, refrigerants	Utilization, Biomass				4	2014
	Italy, Turkey	1200-12000	Hydrocarbons	Utilization, Geothermics	Rad./Axial.			7	2015
General Electric Energy (USA)	different	125	R245fa	Biomass	Radial	121	1.72	>100	2009-2011
General Electric Oil&Gas (Italy)	Canada	1700	Cyclo-pentane	Utilization	Radial	250	no data.	1	2012
Ormat (USA)	USA, different	400-3500	n-Pentane	Geothermics	Axial	105-170		67	1995-1999
		2000-15 000		Geothermics, Solar energy		140-180		144	2000-2013
		300-6500		Utilization		110-180		19	1999-2013
Tri-O-Gen (Holland)	different	80-160	Toluene	Utilization	Radial	325	3.2	21	2009-2013
		135-160		Biomass		325	3.2	6	2012-2013
Capstone Turbine Corporation (USA)	different	50-125	R245fa	Utilization, Biomass, Solar energy	no data	88	0.96	>10	no data
Turboden (Japan)	Russia, Germany, Austria, different	200-15 000	no data	Utilization, Biomass, Geothermics, Solar energy	no data	100-200	no data	>200	1998-2015

Among them we can emphasize butane (R600), pentane (R601) with their isomers, and pentafluoropropane (R245fa). Pentafluoropropane (R245fa) is used to convert the low potential heat (80-120 °C) in installations of small unit power (50-125 kW) [4, 5]. The use of natural flammable n-pentane, tab. 1, which does not meet the classical requirements of the working fluid of power plants, as a working fluid is of interest. However, the task of creating a sealed thermal power circuit is a technical one, which is solved by the American company Ormat, tab. 1.

The main direction of Russian research is the practical increase in the energy efficiency of geothermal and gas-steam plants by creating the combined power units with organic working fluids [3, 6-8]. In [6], the creation of an experimental-industrial geothermal pilot power unit with a capacity of 2.5 MW at the Pauzhetskaya GeoPP (Kamchatka), operating in a binary cycle, is analyzed. The main idea of the authors' innovative concept [3] is the combination of a traditional steam-water turbine with back pressure with the ORC.

Most of the works in recent years [9-17] are aimed at increasing the efficiency of the Rankine cycle on organic working fluids with a capacity of up to 500 kW, including optimization studies related to the choice of the process equipment and evaluation of technical and economic indicators. It is shown that ORC with n-pentane seems to be the most profitable cycle [9]. The structural distribution of investments in plant equipment has been determined [9-11].

The studies conducted by the authors [18] on the development of a new RES are connected with determination of the technical and economic feasibility of using the heat energy of dry hot rocks of the Earth to produce electricity. This direction is attractive because it is not associated with volcanic activity and its implementation is possible in an industrialized region.

Problem statement

The object of research is a power plant with an axial three-stage turbine with a unit capacity of 4 MW and turbine shaft rotational speed n = 3000 rpm for generating electricity in the ORC cycle using R-245fa and n-pentane (R-601) as the working fluids. The construction versions of various types of turbines (axial turbine in single-stage and multi-stage design, radial and radial-axial turbine using freons with small thermal gradient as the working bodies) are considered in [19]. These approaches are valid now [11]. The coefficient of specific speed, n_s, which takes into account the total performance of the workflow, is taken as a criterion for comparative evaluation of thermodynamic efficiency of turbines of these types:

$$n_s = \frac{nV_f^{0.5}}{\Delta h_{ad}} \tag{1}$$

where Δh_{ad} [kJkg^{-1}] is available heat drop, V_f [m^{3}s^{-1}] – the volumetric flow rate of the working fluid at the end of the expansion process, and n [rpm] – the rotational speed. The study by the authors of [19] of an axial multistage turbine with a capacity of 1500-6000 kW for the generator drive (n = 3000 rpm) when operating on R21 freon showed that the value of the internal relative efficiency is 85%, which is higher as compared to other types of turbines. The high energy efficiency of a multistage axial-type turbine is achieved by using returnable energy losses of the previous stages in subsequent ones and reducing energy losses with an output speed. Despite the relative complexity of manufacturing and the increased cost of an axial multi-stage turbine in comparison with the radial-type turbines, capital costs in the extraction and transportation of underground thermal energy are likely to be major. In such an energy complex with a universal renewable source of thermal energy, the factor of efficient conversion of thermal energy into electricity, conditionally speaking *expensive* fuel, is decisive. Since the technology of heat extraction of underground hot dry rocks affects the cost of thermal energy, the resulting energy must be converted to electricity with maximum efficiency.

When developing a new renewable source of thermal energy of dry hot rocks with exploitation of this source in the center of the region energy loads, the problem of determining the maximum unit turbine power with a standard electric generator arises. The potential for the use of the initial vapor temperature of organic liquid n-pentane (R-601) in the subcritical region is higher than that of R-245fa, and this will contribute to greater thermal efficiency. In this regard, to implement large turbine capacities (more than 10 MW) with high consumption of organic liquid, the orientation to n-pentane is justified. However, it is required to determine the technical capabilities of a high-tech and more cost-effective axial turbine working on vapors of selected working fluids.

In this paper, R245fa and R601 are considered as the working fluid. When choosing R245fa as a working medium of a power plant, its ozone-safety, approbation [4, 7-17] and previously performed cycle of works on the use of energy-efficient freon R21 [20] were taken into account tab. 2. The choice of natural environmentally friendly R601 is due to its physical properties, allowing the expansion process in the subcritical region with a high upper temperature of the cycle.

Table 2 Physical properties of working fluids R245fa, R21, R601 [21-23]

Characteristics		R245fa	R21	R601
Normal boiling temperature T_0, [K]		288.05	281.9	309.2
Critical point	temperature T_c. [K]	427.16	451.61	469.78
	pressure p_c . [Mpa]	3.651	5.190	3.37
Critical density ρ_c, [kgm^{-3}]		517.0	528.0	232.0
Ozone-depleting potential, ODP		0	0.04	0
Global warming potential, GWP		930	0.4	20 [11]
Molecular mass, [gmol^{-1}]		134	102.9	72.2

Calculation method

Considerable vapor density of low-boiling working fluids, low sound velocities with relatively low vapor parameters, low available heat drop (~40-50 kJ/kg) predetermine turbine operation at expirations of freon vapors close to the critical ones. The specific properties of low-boiling working fluids make it necessary to model the thermal process in a refrigerant turbine, whose purpose is to determine the degree of influence of the initial and final parameters of vapor on the process of expansion of low-boiling working fluids in the turbine. This allows determination of the expansion parameters of low-boiling working fluids in the turbine, as in a non-standard element of equipment of the low-temperature power plant. So, it is possible to find the parameters of the working fluid at the end of the expansion process before entering the condenser, individual components of the energy loss and determine the configuration (focal points) of the Rankine cycle.

To solve this problem, the traditional method of thermal calculation of a steam turbine was used [24]. The block diagram of the algorithm for thermal calculation of the turbine on the low-boiling working fluids is shown in fig. 1. The initial parameters of the working fluid (pressure and temperature) before the process of its expansion in the turbine are independent and they are selected taking into account the potential of utilized heat source. The working fluid parameters at the outlet from the turbine and total available heat drop, Δh_a, during adiabatic expansion determined by the given (in the first approximation) final pressure, p_f, and the value of entropy corresponding to the initial point of the expansion process. Features of the presented calculation algorithm are: iterative determination of the vapor flow rate per turbine (2), subsonic regime for the expiration of the low-boiling working fluid vapor from the nozzle array (3), limitation on the fan speed of the last turbine stage (4):

$$D = \frac{N_{\text{inst}}}{\Delta h_a \eta_{\text{oi}} \eta_{\text{m}} \eta_{\text{g}}} \tag{2}$$

$$M < 1 \tag{3}$$

$$\frac{d_{av}}{l} > 2.5 \tag{4}$$

where N_{inst} [kW] is installed power of electric generator, Δh_a [kJkg^{-1}] – the adiabatic heat drop per a turbine, η_{oi}, η_{m}, η_{g} – are inner relative efficiencies of a turbine, mechanical one and generator efficiency, respectively, M – the Mach number, d_{av} [m] – the average diameter of a stage, l [m] – the length of turbine blade.

$$M = \frac{C_{1t}}{C_s} \tag{5}$$

$$C_{1t} = \sqrt{2\Delta h_c + æC_o^2} \tag{6}$$

$$C_s = \sqrt{kp_{c2}v_{1t}} \tag{7}$$

$$d_{av} = \frac{60U}{\pi n} \tag{8}$$

$$l = \frac{Dv_1}{\mu_1 \pi d_{av} C_{1t} \sin\alpha_1 \cdot e} + \Delta \tag{9}$$

where C_{1t} [ms^{-1}] is theoretical flow rate of vapor from the nozzle array, C_s [ms^{-1}] – the velocity of sound in the medium where the outflow occurs, Δh_c [kJkg^{-1}] – the adiabatic heat drop per a stage, C_0 [ms^{-1}] – the initial vapor velocity at the inlet, æ is a share of kinetic energy of the vapor flow, which can be used in the turbine, k is adiabatic exponent, p_{c2} [bar] – the pressure of vapor behind the nozzle, v_{1t} [m^{3}s^{-1}] – the specific vapor volume at isentropic expansion, U [ms^{-1}] – the circumferential velocity at medium diameter of stage, μ_1 is flow rate coefficient, α_1 [°] – the angle of vapor outflow from the nozzle array, e is admission degree, Δ [m] – the total overlap (at the root and at the top).

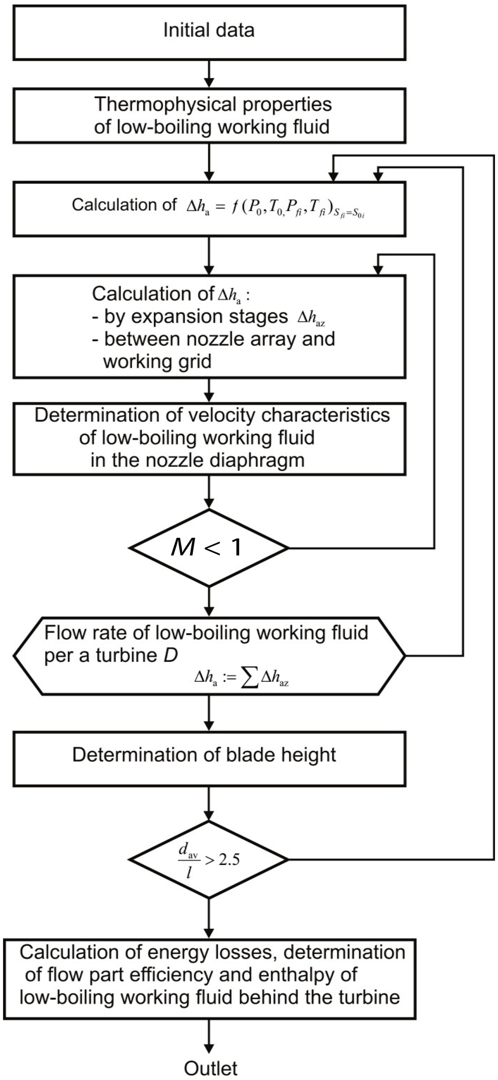

Figure 1. The block diagram of the algorithm for thermal calculation of the turbine on the low-boiling working fluids

Calculation results

In accordance with the calculation algorithm, fig. 1, using the database of [21] for the thermophysical properties of R245fa vapor, the adiabatic heat drop for a turbine was determined for independent initial and final pressures at the initial temperature of 110 °C. This temperature level was worked out by the Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences for the binary power unit of the Verkhne-Mutnovskaya geothermal power station in Kamchatka (on Freon R21) on the instructions of developers. The obtained dependences are shown in fig. 2.

An increase in the initial vapor pressure is always accompanied by an increase in the adiabatic heat drop. For other fixed parameters of the heat-power circuit, the latter allows a decrease in vapor flow rate per turbine and, as a consequence, the flow rate of the working medium of a condensate-feed pump, but causes an increase in power consumption for auxiliaries of the power plant. However, as the initial vapor pressure in front of the turbine increases at a fixed temperature, an increase in adiabatic heat drop slows down regardless of

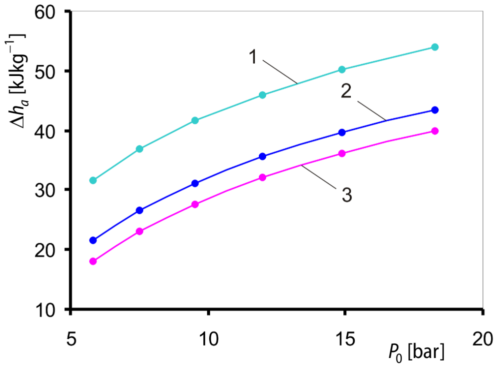

Figure 2. Effect of initial pressure of expansion P_0 of R245fa vapor on adiabatic heat drop Δh_a in the turbine at t_0 = 110 °C and different condensation pressures P_f spent vapor; 1 – P_f = 1.02 bar, 2 – P_f = 1.18 bar, 3 – P_f = 2.17 bar

the value of the final pressure of expansion. An analysis of results obtained suggests that when the temperature of R245fa vapor in front of the turbine is 110 °C, the initial pressure is ~13 bar, tab. 3.

Table 3. Initial parameters of R245fa and n-pentane (R601) in front of nozzle unit

Characteristics	R245fa	R601
Pressure p_0, [bar]	13	25
Temperature t_0, [°C]	110	186
Enthalpy h_0, [kJkg^{-1}]	488.35	1164
Specific volume v_0, [m^{3}kg^{-1}]	0.014257	0.01307

When using pentafluoropropane and pentane in the ORC, the adiabatic expansion process ends in the region of superheated vapor in a wide range of final pressures exceeding the ambient pressure (fig. 3, where the saturation curves are taken according to [7]). This makes it possible to consider various condensation systems for cooling the vapor after the turbine.

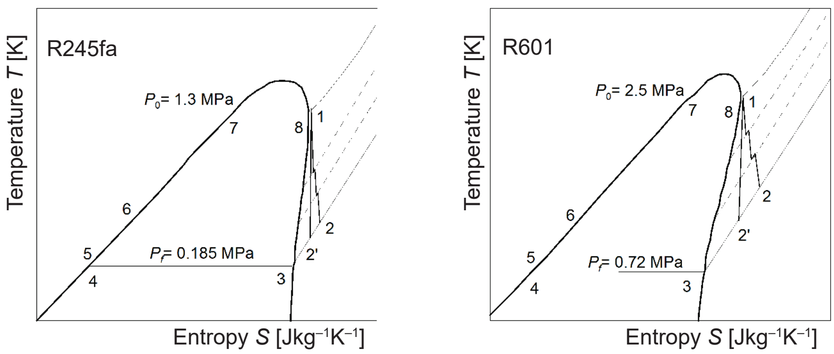

Figure 3. The ORC in *T-S* diagram for pentafluoropropane (R245fa) and pentane (R601); *(1-2') – available adiabatic heat drop, (1-2) – vapor expansion in the turbine, (2-3) – heat removal in recuperator, (3-4) – heat removal in condenser, (4-5) – pressure increase in feed-pump, (5-6) – heating the working fluid with the heat of vapor after the turbine, (6-1) - heating the working fluid from an external heat source, including heat exchange zones: economizer (6-7), boiling (7-8), overheating (8-1), --- - intermediate expansion stages with constant pressure*

A version of a three-stage turbine on R245fa and R601 vapor is considered. The results of the estimates for the last (third) stage of the turbine are presented in tab. 4.

The performed thermal calculation shows that for a turbine of the reactive type at a low sound velocity of the working fluid (146 ... 149 m/s), subsonic velocities of freon vapor, discharged from the nozzle array, can be achieved. Vapor is supplied along the entire circumference of the nozzle array. Lowering the degree of reactivity of the last stage allows reducing the output velocity of freon vapor from the turbine. An increase in the number of turbine stages

Table 4 Design characteristics of the output stage of the ORC turbine

Characteristics	R245fa	R601
Final pressure of expansion process p_f, [bar]	1.85	7.2
Circumferential velocity U, [ms^{-1}]	82.16	85.3
Mach number M	0.93	0.65
Energy loss with output velocity $\Delta h_{\mathrm{o.v}}$, [kJkg^{-1}]	0.586	0.63
Enthalpy at the end of the expansion process h_f, [kJkg^{-1}]	456.4	1125.9
Adiabatic heat drop on the turbine Δh_{a}, [kJkg^{-1}]	38.1	48.54

with a decrease in the final expansion pressure to p_f leads to a sharp opening of the flow part. This is due to an increase in the specific volume of pentafluoropropane and height of the working blades, which does not allow for available heat drop on the turbine with a decrease in the final pressure of the expansion process to possible $p_f = 1.1$ bar. These design features limit the installed unit capacity of the turbine to 3 ÷ 3.5 MW by the conditions of the last-stage fanning and do not allow R245fa to be used for the achievement of high unit capacities.

When considering flammable *n-pentane*, the thermophysical properties were taken according to [23]. Comparative analysis of *n-pentane* and R245fa in the ORC shows that the use of n-pentane ensures a relatively large adiabatic heat drop on the turbine, lower flow rate of the working fluid in the heat-power circuit and ability to increase the unit power of installation.

When analyzing the results of the research performed, the following should be noted.

The potential of using R245fa in the ORC is wider ($T_c = 427.16$ K) in the current work. However, regardless of the type of expansion device, the growth of the specific vapor volume of the output expansion stage and the flow rate of the working fluid ($v_{1t}D$) are the limiting factors for reducing the final pressure. In these studies, it was $p_f = 1.85$ bar, what is consistent with [5], where $p_f = 1.8$ bar.

Concslusions

- Pentafluoropropane (R245fa) and n-pentane (R601) make it possible to achieve the subsonic flow rates of vapors out of the nozzle array of an axial-type turbine.
- R245fa and *n-pentane* provide full vapor supply to the nozzle plate.
- When using pentafluoropropane (R245fa), it is possible to achieve a unit electrical power of up to 3-3.5 MW in an axial turbine. For turbine generators with an installed unit capacity of more than 3-3.5 MW, it is advisable to use *n-pentane* as the working medium of the organic Rankine cycle.

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