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HEAT RECOVERY UNIT DEVELOPMENT BASED ON ORGANIC HEAT-CARRYING AGENTS

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ABSTRACT

To realize the energy savings potential of thermal emissions, a heat recovery power plant is constructed based on the Rankine cycle using organic working fluid agents. The analysis of the main technical problems on the way of creating such installations is given: the choice of the perspective working fluid and the type of the turbine unit, experimental studies of heat and mass transfer processes, including boiling crises. Directions of perspective scientific research are designated.

Key words: working fluid, heat-carrying agents, organic fluid agents.

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1. POTENTIAL FOR ENERGY SAVINGS

Potential for energy savings in the world is comparable with the extraction of organic fuel. In Russia, this potential is estimated at 300-315 million tons of oil equivalent per year (oil production in 2017 equal to 547 million. tons). Industry and fuel-energy sector account for 60 to 65 % of this potential. Since energy saving, it is advisable to organize the production of electricity.

The classic Rankine cycle for its production has not yet exhausted its capabilities [1]. An example is the power unit at the CS "Chaplygin" (Figure 1), this is a typical solution for a high-potential heat source with a water heat-carrying agent. For low-potential sources with a heating fluid temperature up to t_{gr} =250÷300 °C a cycle on the organic heat-carrying agent (refrigerant, organosilicon, fluorocarbons) is preferable [2-6]. For northern regions water cycle is not generally desirable, and temperature boundaries expand to higher values $t_{гр.}$

Figure 1. Heat recovery unit with a capacity of 500 kW at the Chaplygin compressor station LLC 'Gazprom transgaz Moscow'

JSC Scientific production company "Turbocon" develops heat recovery units on organics of two versions:

- for compressor stations of gas pipelines with a temperature of $t_{cr.}$ =350÷500 °C;
- for geothermal sources with a temperature of 90 ÷ 170 °C [7, 8] .

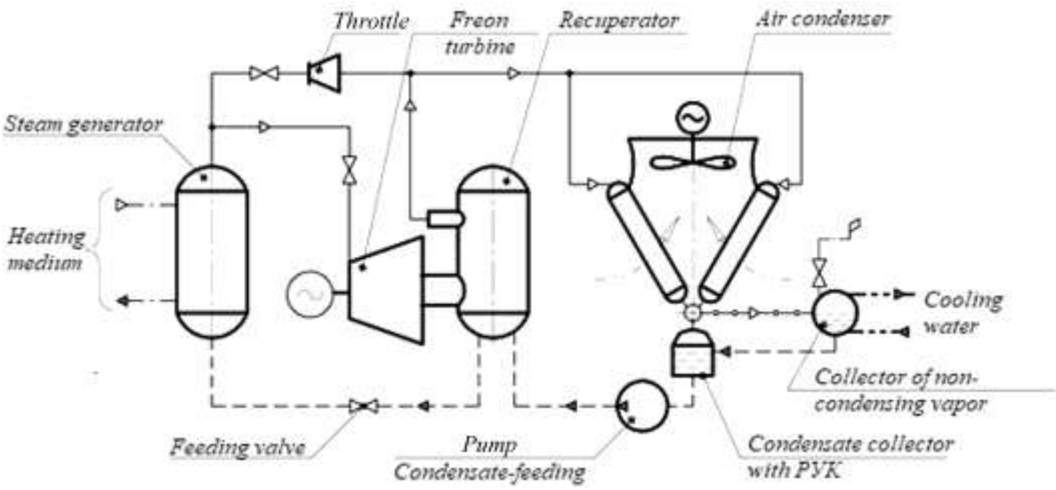
The schematic diagram and thermodynamic cycle of such installations does not change (see Figure 2), but the working fluid can be different.

The installation includes a steam generator, a freon turbine with a generator, a recuperator, a freon vapor condenser, a feed pump and a throttle-humidifier.

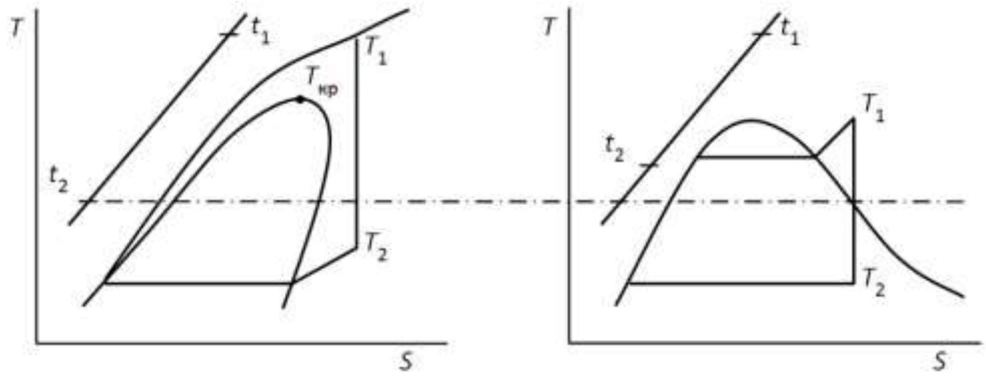
The peculiarity of the thermodynamic cycle of organic heat-carrying agents - $\frac{dT}{dS} > 0$ for the right boundary curve. A consequence of this is an increase in steam superheating as it expands in the turbine (see Fig. 2b). In addition, for most part of the cycle, units of this type operate either in the supercritical zone or near the critical point for small values of the phase transition heat. This makes it possible to cool the heating fluid more deeply and provides a higher efficiency in comparison with water (Fig. 2c).

2. THE STRUCTURAL DIAGRAM OF THE PROJECT

The structural diagram of the project scientific and technical components is given in Table 1. The main problems, the solution of which accompanies the project, are identified in it as well.



a)



b) c)

Figure 2. Scheme of heat-recovery energy complex (HRC) and thermodynamic cycles: a) schematic diagram of HRC, b) thermodynamic cycle (TC) based on organic heat carrying agents, c) - TC based on water

3. SELECTION OF WORKING FLUID

The choice is based on safety, as well as technical, environmental and economic parameters of working fluids (WF). Table 2 shows the characteristics of WFs, suitable for solving the assigned tasks of creating heat recovery units. The choice of working fluid is carried out against the background of the future tightening of environmental requirements and the prospect of prohibiting the use of some of them soon. The search for an ideal working fluid is a task that leading firms are actively solving.

Table 1 Structural diagram of the project scientific and technical components

An object	Implementation Options	Thermophysical, gas-dynamic problems
Working fluid	Freons	- Thermophysical properties - thermodynamic properties - safety - environmental indicators - availability
	Silicon-based compounds	
	Fluorocarbon compounds	
Steam Generator	Vertical	- heat transfer at boiling in vertical channels - boiling crises in the pipe
	Horizontal	- heat transfer during boiling in a tube bundle - boiling crisis in the tube bundle
Turbine generator	Axial	- supersonic flow of high-molecular compounds vapor around profiles - compaction of penetrations - creation of capsular turbogenerators
	Centripetal	
Recuperator	Longitudinally streamlined Cross-flow	- Unit Parameters Optimization based on the heat exchanger variant
Condenser	Water	- condensation on a bundle of horizontal and inclined tubes - influence of flooding
	Air	- freon vapor condensation in the channels
Condensation system	-	- compaction of penetrations - creation of block pumps in a single casing
Control system	Hydromechanical	- work for an isolated power system - work in an integrated power system.
	Electrohydraulic	

For further consideration, take the following working fluids: n-pentane, freons R134a and its analogue R245FA, widely used freons R21, R114 and R113, allowed for space programs until 2020, fluorocarbons C_4F_{10} and C_6F_{14} - the characteristics of which are summarized in Table 2.

Table 2 Technical characteristics of working fluids

Working fluids	***p* = 1 bar temperature of normal boiling, ° C**	**surplus. pressure at *t*= 25 °C bar**	**Interaction with metals and gaskets**	**Explosion-danger**	**Class of toxicity**	***T* cr . °C**
n-pentane C_5H_{12}	+35.7	-	-	fire - explosion-dangerous	4	197
R 134a CF_2H -CF_2H	-26	6.0	Mg, Pb, Zn	-	4	100
R21 $CHFCl_2$	+9	1.0	-	not flammable	4	178
R113 CF_3 -CCl_2	+46	-	constraint on gaskets	difficult-combustible	4	214
R114 CF_2Cl-CF_2Cl	+3	2.5	special gaskets	difficult-combustible	5	146
R245FA $CF_3CH_2CHF_2$	+15	0.48	-	difficult-combustible	4	154
PP-1 C_6F_{14}	+57	-	does not oxidize	not flammable	5	184
C_4F_{10}	-2.6	3.9	-	not flammable	5	113

Working fluids	*R* cr. bar	Heat transfer parameter at *t* = 110 ° C		Price, rubles / kg	ODP *	GWP **
		P	F			
n-pentane C_5H_{12}	33	43.4	206.6	110	0	0
R 134a CF_2H -CF_2H	40	34.5	157.9	350	0	1300
R21 $CHFCl_2$	52	20.0	111.5	700	0.04	0.4
R113 CF_3 -CCl_2	34	18.3	75.1	1100	0.8	0
R114 CF_2Cl-CF_2Cl	33.4	23.6	104.5	2800	0.85	9200
R245FA $CF_3CH_2CHF_2$	3.65	29.8	128.6	1800	0	1030
PP-1 C_6F_{14}	18	52.1	200.6	2000	0	0
C_4F_{10}	23	48	180	15,000	0	0

Notes:

* ODP - Ozone - Depleting Potential;

** GWP - Global Warming Potential

For R134a, the critical temperature is lower than 110, so the parameters are given for it at 80 ° C.

It follows from the table that the best indicators for all parameters is shown by n-pentane, which is actively used by such firms as ORMAT, Turboden, and others. At the same time, it has one, but a very important, drawback:

n-pentane is explosive and flammable .

In connection with this, it was decided to carry out the experimental work at the first stage with the R-113 freon, which is more expensive, but with close thermophysical characteristics, followed by a transition to n-pentane.

At the same time, fluorocarbons, for example C_6F_{14} , are of interest, as well as working fluids based on liquids containing Si, the properties of which can provide an advantage against the relatively high cost of their production.

4. TURBINES FOR WORKING ON ORGANIC FLUID AGENTS

The properties of various working fluids that are promising for use in the organic Rankine cycle (ORC), such as the adiabatic exponent k , the specific heat at constant pressure cp , the specific volume v, etc., differ significantly both among themselves and similar characteristics of water vapor. Significantly different values of the pressure in the condensers and, respectively, the initial pressure of the cycle. For most WFs, the sound velocity is much less than that of water vapor, and with expansion in the turbine the specific volume increases more intensively, which leads to an increase in the degree of opening of the flow part.

Table 3 presents the characteristics of some WFs, illustrating the foregoing.

Table 3. Gas-dynamic characteristics of working fluids

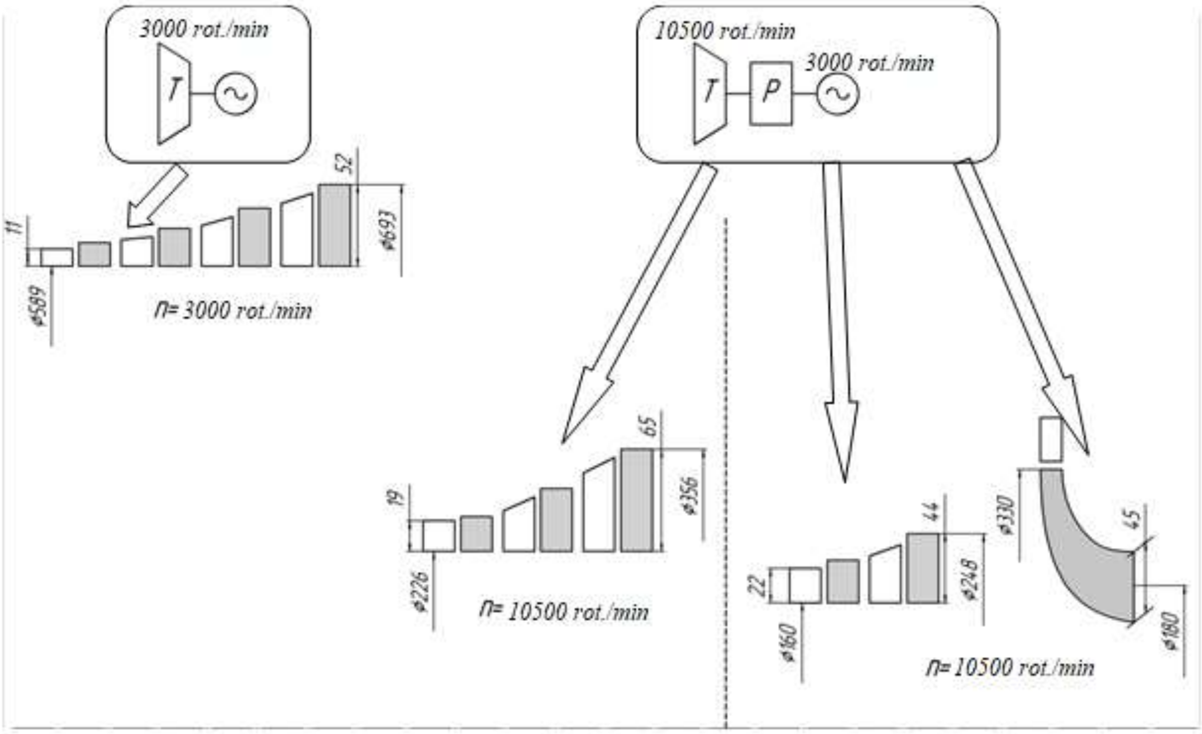
Type of WF	n-pentane	R134a	R21	R113	PP-1	H_2O
Pressure in the condenser at t = 40 °C , kPa	115.7	1017	296	78	53.6	7.4
The speed of sound at = 150 ° C and p = 1 MPa, m / s	191	185	184	117	-	510 p = 0.2
The adiabatic exponent c_p / c_v at t = 150 ° C and p = 1 MPa	1.12	1.11	1.19	1.15	-	1.33
The specific heat at p= const (at p = 1 MPa), kJ / kg	2.4	1.09	0.77	0.86	1.228	p = 0.2 t = 1.5 °C

In this regard, the costs of WF, necessary to obtain the same power of 1000 kW, and, accordingly, the appearance and parameters of turbines for different options are also different.

For heat recovery energy complexes, both axial and axial turbines with direct or reducer drive of an electric generator can be used. They are characterized by speeds that are low in magnitude, but significantly higher than the speed of sound.

At optimal values (U/c_0) because of small heat drops in all cases, diametrical dimensions are small.

When using n-pentane, one can consider both a direct drive of a generator with a rotation speed of 3000 rpm, and a drive through a reducer. For fluorocarbons - only direct drive, for freon R134a - only through the reducer.



a) b)

Figure 3. Variants of a turbine (1000 kW capacity) flowing part: a) on n-pentane, b) on R134a

Figure 3 shows the meridian circumference of the flow part of an axial turbine on n-pentane, designed for a direct drive (3000 rpm) and a drive using a reducer (turbine rotation rotor speed 10500 rpm). The initial pressure p_0 = 1.5÷1.9 MPa, the temperature t_0 = 160 °C, the pressure in the condenser p_k= 120 kPa.

6. PERSPECTIVE DEVELOPMENTS ON THE TOPIC OF HEAT RECOVERY UNITS

Concerning the freon turbine and the condensate-feed pump, it is of great interest to develop sealed (capsule) versions of such units. Prototypes of such pumping units exist and are successfully operated. High-speed turbogenerators of low power are also known. Developments in this regard can radically change the appearance of heat recovery units.

Working fluids for utilization plants with their properties close to n-pentane but lacking in its principle disadvantages are one of the most promising studies. In this direction, fluorocarbon compounds are very interesting. Their ecological and thermophysical properties can become the basis for future projects, and then for existing installations.

The control system for heat recovery units also appears to be an important topic of analysis and research in relation to the isolated power system and when operating in an integrated power system. Modern IT-technologies in combination with high-speed executive mechanisms fit well into the process automated control systems of enterprises and compressor stations of gas pipelines. It is important to correctly substantiate the dynamics and reliability of a system consisting of large-sized and inertial heat exchange equipment and a dynamic and low-inertia turbine units.

7. CONCLUSIONS

The article outlines the range of problems, the solution of which will allow creating a modern heat recovery unit of a wide range of uses.

Other areas: the thermophysical properties of promising working fluids, the creation of hermetic freon turbines and pumps, the new automatic control systems, is the subject of innovative developments that will bring these products to a competitive world level .

LIST OF ABBREVIATIONS

FEC - fuel and energy complex;

PS - power station;

HRC - heat recovery complex;

CS - compressor station;

WF - working fluid;

IPS - an integrated power system.;

ODP - ozone - depleting potential;

GWP - the potential of global warming;

ORC - the organic Rankine cycle ;

IT - information technologies;

APCS is an automated process control system.

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