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Theoretical and experimental research of organic Rankine cycle steam turbine plants

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Abstract. Currently steam power cycles using organic actuation fluid - Freon, ammonia, ethanol, isobutene, etc are becoming increasingly important. Such cycles are called Organic Rankine Cycle (ORC). With the help of such cycles it is possible to use low-grade heat sources in the production of mechanical and electrical energy.

The modern energy crisis is problem area in the supply of energy resources to an economy. This calls for giving more emphasis on the development of alternative energy sources. One of the common approaches to obtain the mechanical and electrical energy is the application of the heat engines.

According to the analysis of domestic and foreign publications it is possible to indicate four types of heat sources that are promising for further development and they require to design a specific approach to their use as energy resource [1-4]:

- geothermal heat;
- thermal output of solar radiation;
- thermal industrial emissions;
- heat flow from the engines and airborne equipment transport systems, including vehicles, marine transportation, spacecraft.

The particular feature of the above sources means the presence of non-ambient temperature that is not sufficient to organize the traditional steam cycles in water vapor. Temperature difference for these sources, the difference in temperature between the heat source and the environment, is in the range 60-200 C. In the papers, such sources are called low-temperature [5-6].

The most promising and the most common methods to transform thermal energy into mechanical and electrical ones are the steam power cycle in turbo machines. Such cycles function on the principle of heat transfer from the source to the field of warm reset producing the energy. At these temperature differences steam power cycle can be realized only through specific actuation fluids - organic (ethanol, Freon, isobutene, etc.) [7].

The research and development of energy resources are important because there are still no adequate and optimal methods for their use.

Engineering development of these steam turbines plants (STP) on organic acuation fluids (OAF) presented on the world market (Turboden (Italy), Infinity Turbine LLC (USA)), have effective coefficiency in the range of 10-12% and limited application spheres. Powerful methods for design and optimization of such systems have not been developed yet.

Connecting with the above material the need for analysis, calculation and design of such plants appear. The urgency of the work to create steam turbines plants on organic actuation fluids causes the need to simulate cycles to describe the plant and optimize its processes [8].

Creation of mathematical models is a challenging direction in modern research [9-11]. The model allows calculating the main parameters of the process under certain initial conditions, to get them modified by varying the input data, to assess the impact of various factors on the plant functioning.

The mathematical model defines the joint work of constituent elements of stream turbine plants on organic actuation fluids. Block diagram of the plant (Fig. 1) includes the following elements:

1. Turbine: an active axial turbine is used to convert the energy of the actuation fluid into the work.
2. Circulation pump: it is designed to increase the pressure of the actuation fluid and feed it into the evaporator.
3. Evaporator: it is assigned to transfer heat from the source to the actuation fluid.
4. Capacitor: it is used to transfer the heat of the actuation fluid source to cold working fluid and to change the actuation fluid to the liquid phase.
5. Electricity generator.

The principle of operation of the plant is the following. A working body receives heat from a source in the evaporator, where it is vaporized and heated. After that, the actuation fluid enters the turbine where it emits energy. Pressure and temperature of the actuation fluid is reduced at the same time. Further, the working fluid enters the condenser, where it is condensed due to the interaction with the source of the cold. The liquid actuation fluid goes to the receiver, after it is evacuated by the circulating pump and is fed to the condenser.

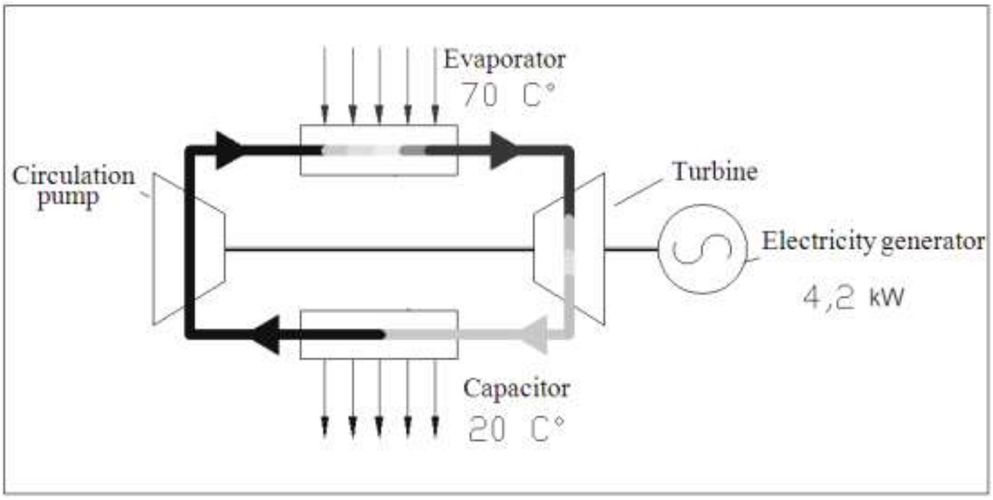

Figure 1. Block diagram of the plant

The model plant incorporates mathematical models of its constituent elements to define the basic parameters of the actuation fluid that allow estimating the reaction of equipment to both internal and external influencing factors. In the model plant there are some main parameters to provide the required mode of operation such as: pressure p, consumption V, temperature T and angular speed of turbine rotor motion w.

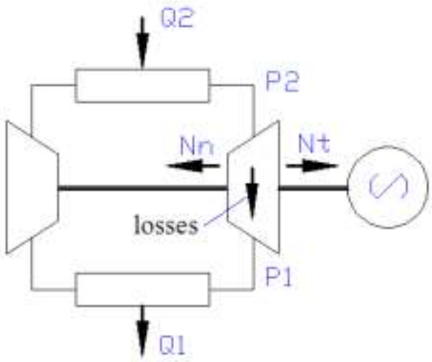

Figure 2. The energy balance of the system.

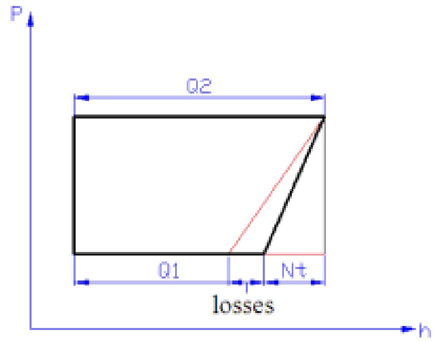

Figure 3. Diagram of the working cycle of the plant.

The energy balance of the model is as follows (Fig. 2). In the adiabatic turbine power N_{ad} is produced, that depends on the parameters of the actuation fluid at the inlet and outlet position and the mass flow rate.

$$N_{ad} = L_{ad} \cdot \dot{m} = \frac{k}{k-1} RT_0 \left[1 - \left(\frac{P_2}{P_1} \right)^{(k-1)/k} \right] \cdot \dot{m} \qquad (1)$$

where L_{ad} - adiabatic work of gas; $\dot{m}$ - gas flow in the turbine; k - rate of adiabatic line; P_2 - gas pressure at the turbine inlet; P_1 - gas pressure at the turbine outlet;

Adiabatic power is used for the technical capacity of the generator *Nt*, pump power *Nn* and losses in the turbine itself N_{loss}.

$$N_{ad} = Nn + Nt + N_{loss} \qquad (2)$$

The balance of power can be seen in the diagram of the working cycle (Fig. 3).

$$Q_2 - Q_1 - (Nn + Nt + N_{loss}) = 0 \qquad (3)$$

where Q_1 - Heat flow in the condenser; Q_2 - Heat flow in the evaporator.

As the all parameters are determined based on the actuation fluid flow in the system, respectively it sets the condition of continuity in the system.

In addition to establishing energy balance and expenditure, the system determines the angular velocities of the components – rotors of turbines, pumps, generators. Angular velocity determines the disk friction losses, mechanical losses, etc. In general, the power generator and pump losses in the turbine can be introduced with a function of angular velocity, the following equation is possible to obtain

$$N_{ad}(P_1, P_2, T_0) = Nn(\omega) + Nt(\omega) + N_{loss}(\omega) \qquad (4)$$

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This condition furnishes the angular velocity of the system.

The model allows calculations in two directions, solving forward and inverse design tasks.

The forward task is to design a steam turbine, if you know the input parameters of evaporator and condenser.

Initial data for the forward problem are the characteristics of the source; characteristics of the refrigerator; useful power of turbine; rotor angular velocity; organic actuation fluid (Freon) and its chart.

The solution of the forward task is the following algorithm:

1. The working cycle of plant is created based on the known parameters of the source and the refrigerator; its specific parameters are defined.
2. The specific parameters of the turbine are calculated: the adiabatic work L_{ad}, useful work Ln, losses and efficiency.
3. The specific parameters of the pump are determined: expended power N_z, useful power Nn, losses and efficiency.
4. The specific parameters of heat exchangers and their geometry are defined.
5. The mass flow output at the evaporator based on the known thermal power source Qist, mass and energy parameters of the cycle are calculated.
6. The type and geometry of the turbine, pumps, heat exchangers are selected.

The result of solving the forward task is defined by the geometry of the device, its energy balance, the power output and efficiency.

The inverse task is to obtain parameters of different modes, features of the stream turbine plant if its geometry is known, then it is possible to optimize cycle of this plant based on the parameters obtained.

Initial data for the inverse task are the geometry of the turbine, pump, heat exchanger, the actuation fluid and its properties; angular velocity of motion of the rotor, the characteristics of the source and refrigerator, range and a step change in controlling parameters.

The solution of the inverse problem requires the following algorithm: the adiabatic gas work and loss in the nozzle unit is determined according to the given pressure and mass flow at the inlet of the nozzle unit. Next for the Freon flow in the impeller channels of the rotor wheel the velocity triangles are constructed, the velocity at the outlet of the working grid and losses are defined. Taking into account the pressure and temperature at the outlet of the turbine together with the characteristics of the refrigerator the parameters in the condenser are evaluated. The pumping capacity and its efficiency is measured based on the flow rate and pressure drop.

The result of solving the inverse problem is sets of design parameters for different combinations of controlling factors which are the basis to determine optimal modes of the plant operation and critical situations.

The inverse problem can be solved only by taking into consideration the actual losses in the plant, which are in most cases found experimentally. Loss imbalance is necessary to determine the components' effectiveness.

Determination of losses due to the complexity of their analysis is possible only by experiment. The algorithm if there is a shortage of experimental data is designed to meet the recommended values of loss coefficients for typical steam turbines plants: in the turbine nozzle apparatus φ; in the rotor ψ. Losses with output speeds are determined by the triangle of velocities. Ventilation losses and losses from the disk friction are found out with the help of friction in the spatial boundary layer. Mechanical losses are determined with the speed and pressure in the system.

Based on the above equations of the mathematical model of the STP OAF the calculation algorithm was set up and the numerical study of the operating modes of the plant and energy balance of the turbine was carried out. The variable parameter is pump thrust that gives the pressure difference between the heat exchangers. In this system two parameters are changed, they are specific work and the mass flow rate.

Calculation algorithm is characterized by the following parameters: the original data are the heater temperature, the refrigerator temperature, the working elements geometry (profile of nozzle block, the area of heat exchange evaporator and condenser, the diameter of the turbine wheel, the typical angles of the nozzles, inlet and outlet vanes). The calculated parameters are mass flow rate of the actuation fluid, adiabatic turbine capacity, the losses in the turbine, the thermodynamic parameters of the actuation fluid at the inlet and outlet of the turbine, the speed of the actuation fluid in the turbine wheel, the required pump power, the efficiency of the turbine.

The solution is as follows: the basic thermodynamic parameters of the cycle - pressures and flows, temperatures of boiling and condensation are determined the original data. Further, the parameters of the turbine are calculated. The adiabatic operation of gas and loss in the nozzle are determined with the calculated pressure and specific volume at the inlet of the nozzle unit. The velocity triangles are designed the velocity at the outlet of the working grid, the loss of a wheel and the output speed are determined for steam in the impeller channels of the rotor wheels. The angular velocity and mechanical ventilation losses are evaluated next. To calculate them the parameters of the working body are taken from a database of properties that represent a mathematical surface in a formal way.

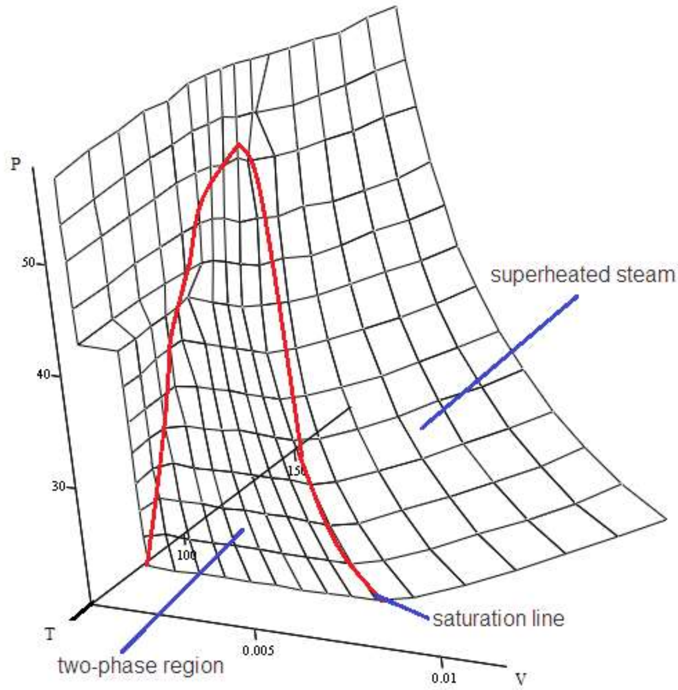

Figure 4. The surface condition of refrigerant R22

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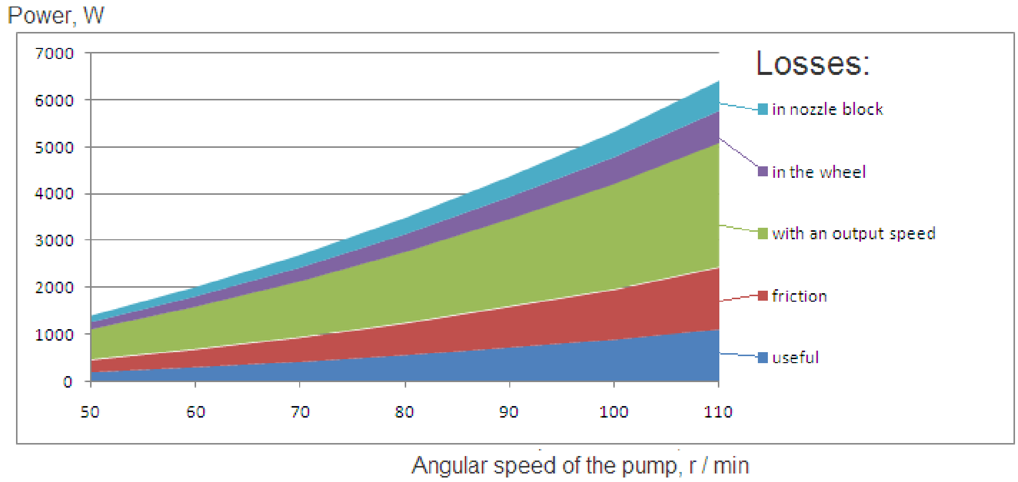

Figure 5. The balance of power turbine

The mathematical surface of the state (Fig. 4) of low-temperature boiling actuation fluid within the pressure P, specific volume V and temperature T allows calculating cycle power plants by numerical methods taking into account the continuous changes in the properties. In addition, using the surface it is possible to obtain the basic parameters of the body (enthalpy, entropy, heat capacity, sound velocity, etc.) applying the differential equations of thermodynamics. Representation of the surface is constructed on the state of refrigerant tables.

The results of calculation of the turbine balance are based on the model shown in Fig. 5. There is a tendency to increase the efficiency with the increased power adiabatic turbine. This is due to rearrangement of the velocity triangles and the decrease of losses with the output speed. Optimal solutions for the efficiency are obtained with greater pump thrust.

To verify the model test setup was designed. Measurement of the effective turbine capacity is done with pneumothermometric method on the consumer that is hydraulic brake. A centrifugal pump pumping the water is used as an alternative to the hydraulic brake. To assess the turbine capacity the parameters of energy imparted to the water are required, which is estimated by the data connected with pressure and water temperature at the inlet and outlet of the pump.

The main element of the laboratory installation (Fig. 6) is the steam turbine. Such autonomous turbines are always performed active, with a supersonic gas flow. Supply of the actuation fluid to the turbine blades is through a single profiled nozzle.

Experimental studies in the pilot plant, processing and analysis of experimental results and model verification during the experiment have not been done by the authors yet.

In addition, the revision of the mathematical model of steam turbine is being planned. The coefficients of estimated losses are going to be corrected; they are determined by the analysis of experimental data. As a result, on the basis of the model it is intended to optimize steam turbine.

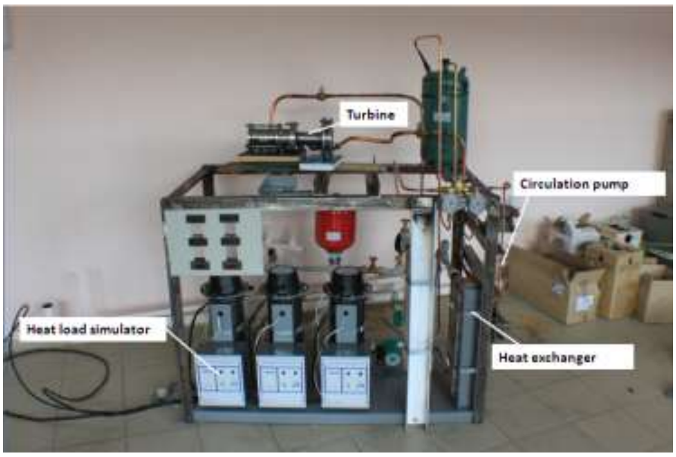

Figure 6. Testing stand of steam turbine plant.

Optimization of the organic steam turbine cycle can be based on a mathematical model using the energy equation and it describes the system components parameters. Depending on the type of problem being solved the model allows calculations in two directions, they are the definition of the geometry of the plant elements according to the given parameters of operating temperatures and the calculation of the energy parameters of the plant based on the given geometry. A mathematical model is an effective tool for the design of such plants.

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