Comparative analysis of working fluids for efficient waste heat recovery

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Abstract. The paper analyzes the implementation of plants with an organic Rankine cycle (ORC) on the example of the circuit of the regenerative gas turbine unit and exhaust gas recovery system of the compressor system of the gas-compressor unit. The theoretically achievable values of power generated by the ORC-installations are determined. A criterion is presented for comparing the working fluids according to the efficiency of use in ORC-installations. To evaluate the overall characteristics of the system, the parameters of heat exchangers for air and water cooling were determined. As a result, it is concluded that the use of ORC-installations allows to utilize up to 23% of the heat of exhaust gases (convert into useful work).

1. Introduction

One of the most relevant solutions aimed at implementing the efficient use of fuel combustion energy is the use of Organic Rankine Cycle (ORC) plants for the utilization of low-grade heat [1]. But it happens that due to the large sizes, the use of a heat recovery power plant is impractical [2].

The range of applications of heat recovery power plants is very wide: utilization of heat from exhaust gases of internal combustion engines with a further increase in its thermal efficiency [3], application in geothermal energy [4], in solar energy [5], utilization of biomass at agricultural enterprises [6].

Work is being carried out on the selection of an effective working body of ORC-installations [7] and equations of state of working bodies for calculating cycles and processes are being developed [8].

In this paper, the efficiency of the use of ORC-installations for regenerative gas turbine unit with a capacity of 250 kW and gas-compressor unit is evaluated. To increase the efficiency of these units, it is proposed to use ORC-installation, for which the choice of the working fluid is analyzed. The scheme of the heat recovery power plant is shown in Fig. 1. Pentane and freon R141b are considered. This choice of substances is due to the widespread use of pentane in ORC-installations, and freon R141b, according to thermodynamic estimation, has good efficiency indicators [9].
2. Waste heat utilization by the example of gas turbine unit and gas-compressor unit

The lowest temperature head for exhaust gas heat recovery is at the so-called pinch point [5]. When the temperature difference varies at this point, the generated power of the ORC-installation and its dimensions will change. A significant part of the heat recovery power plant will be heat exchangers. As an example, an evaporator and a condenser of the tube-in-tube type with a countercurrent flow mode of heat carriers are proposed as an example.

To determine the weight and size characteristics of tube-in-tube heat exchangers, a standard method [10] is used with a number of assumptions:

- during the phase transition, the temperature of the working fluid is unchanged;
- the influence of pollution on heat exchange is not considered;
- the specific heat capacity of the gas varies negligibly;
- the temperature change during pump operation is negligible.

The working fluid is heated and evaporates in the evaporator during the transfer of heat from the outgoing exhaust gases. Fluid is cool and condenses in a condenser, where the pressure of the working fluid is assumed to be equal to atmospheric pressure. There are two cooling options available: water and air.

The calculations are carried out for the case when the gas turbine unit and gas-compressor unit operate at the nominal mode. The supplied heat output of the ORC-installation takes a fixed value.

3. Heat recovery of gas turbine unit exhaust gases

The exhaust gases at the nominal operating mode of the gas turbine have a temperature of 275 °C and a mass flow rate of 1.41 kg/s. The specific heat capacity of the gases is assumed to be equal to the specific heat capacity of the air.

The dependences of the heat transfer area in the evaporator on the temperature difference at the pinch point are obtained for two working fluids (pentane and R141b), shown in Figure 1. In the case of pentane, the heat transfer areas are calculated in a certain range of temperature values, and two values of the heat transfer area can correspond to one temperature difference. This is due to the fact that at a given temperature difference at the pinch point, two cases of the Rankine cycle with different evaporation temperatures at the upper pressure are possible.
Figure 2. Dependence of the evaporator area on the temperature difference at the pinch point for R141b (1) and pentane (2).

Figure 3a illustrates the effect of the temperature difference at the pinch point on the heat transfer area in the condenser, where air a cooling fluid. As in the case of a pentane evaporator, a condenser can take two values of the heat exchange area at one value of the temperature difference.

The calculation of the water-cooled condenser has shown a significant reduction in size compared to the air one (Figure 3b).

Figure 3. Dependence of the air condenser area (a) and the water condenser area (b) on the temperature difference at the pinch point for R141b (1) and pentane (2).

4. Heat recovery of gas-compressor unit exhaust gases

For the case of waste heat recovery gas-compressor unit, at the nominal operating mode, the exhaust gas temperature at the inlet to the evaporator is 507°C, and the mass flow rate is 55 kg/s [11].

Figure 4 shows the dependence of the heat transfer area of the evaporator on the temperature difference at the pinch point.

Figure 5a shows the heat transfer area of the air condenser. It is worth noting that the mass flow rate of air in the condenser can reach 2600 kg/s. This is due to the fact that when the working fluid condenses at atmospheric pressure with air from the environment, there is a small value of the average temperature head in the condenser. To remove a large amount of heat at such a temperature head and a small value of the heat power of the air, a large value of the mass flow rate of the coolant is required.
The heat exchange area of the water-cooled condenser of the ORC-installation that recovers the exhaust gases of the gas-compressor unit is shown in Figure 5b. The mass flow rate of water in the condenser reaches 650 kg/s.

![Figure 4. Dependence of the evaporator area on the temperature difference at the pinch point for R141b (1) and pentane (2)](image-url)

![Figure 5. Dependence of the air condenser area (a) and the water condenser area (b) on the temperature difference at the pinch point for R141b (1) and pentane (2)](image-url)

5. Discussions

When using tabular data on the thermodynamic properties of substances, the calculation of the useful power generated on the turbine shaft of the heat recovery power plant was made [12]. Moreover, the efficiency of the turbine 0.8 and the pump 0.6 were considered.

Since it is not possible to make a full economic calculation, the ratio of the useful power to the mass and size characteristics of heat exchangers (specific power) was adopted as a criterion for determining the efficiency of using a particular working fluid in ORC-installation. It is assumed that the weight and size characteristics are proportional to the total heat exchange area of the evaporator and the water condenser.

The dependence of the introduced criterion on the temperature difference at the pinch point for the working fluids used in the ORC-installation for the disposal of exhaust gases of the gas turbine unit is shown in Figure 6a.

For the utilization of gas-compressor unit exhaust gases, the dependence of the criterion on the temperature difference at the pinch point is shown in Figure 6b.
In the case of utilization of waste heat of the gas turbine unit, the temperature head for freon is determined in the range from 1 to 30, while with an increase in the temperature difference at the pinch point, the value of the highest temperature in the cycle decreases, and consequently, the efficiency of the cycle. The effective efficiency varies from 0.18 to 0.14.

In the case of using pentane as a working fluid in an ORC-installation for the disposal of exhaust gases of gas turbine unit, the temperature difference at the pinch point is determined in the range from 54 to 62, and the highest temperature in the cycle decreases with an increase in the temperature difference. The effective efficiency takes values from 0.19 to 0.11.

In the case of utilization of gas-compressor unit exhaust gases by a plant where freon is used as a working fluid, the temperature head at the pinch point varies from 35 to 100, the highest temperature in the cycle also decreases. The effective efficiency in this range takes values from 0.23 to 0.13.

For pentane, as the working fluid used in the ORC-installation for the disposal of waste heat from the gas-compressor unit, the temperature head at the pinch point varies from 145 to 250. In this case, with an increase in the temperature difference at the pinch point, the maximum temperature in the cycle increases, and the effective efficiency has values from 0.11 to 0.21.

It is worth noting that pentane and freon R141b have almost the same boiling points and critical temperatures. Both substances have different slopes of the saturated vapor line. The specific heat capacity of the liquid phase of freon in the temperature range from the boiling point to the critical one varies from 1200 to 2100 J/(kg*K), and the average thermal conductivity coefficient of the liquid phase takes an average value of 0.088 W/(m*K). For the gaseous phase, the average thermal conductivity coefficient is 0.012 W/(m*K). In pentane, the specific heat capacity of the liquid phase takes values in the temperature range from the boiling point to the critical 2500-4500 J/(kg*K), the average thermal conductivity of the liquid phase takes the value 0.11 W/(m*K), and in the gas phase - 0.15 W/(m*K).

From the above data, it can be concluded that the generated power of the ORC-installation, where freon is used in a certain temperature range, slightly exceeds the generated useful power of the same ORC-installation than on pentane, but in a different temperature head range. However, the specific heat capacity of the liquid phase and the coefficient of thermal conductivity of pentane are much different from the same properties of freon, which affects the smaller dimensions of the heat exchangers of pentane. This means that less occupied area of the installation itself is required per unit of generated power of the power plant on pentane than on freon, as can be seen in Figure 6.

![Figure 6](https://via.placeholder.com/150)

**Figure 6.** Dependence of the specific power on the temperature difference at the pinch point in the case of heat recovery of gas turbine unit (a) and gas-compressor unit (b) for R141b (1) and pentane (2).
Conclusions
Comparing the two working fluids according to the proposed criterion (the ratio of the useful power generated to the weight and size characteristics) we may conclude that pentane is preferable to freon R141b for the disposal of exhaust gases of both gas turbine unit and gas-compressor unit, in order to increase the efficiency of fuel combustion. The final conclusion, which working fluid is preferable for use in ORC-installations, requires a technical and economic calculation.

The use of water to remove heat in the condenser significantly reduces the heat exchange area, compared to air. However, it is worth considering the power spent on the movement of the coolant in the condenser to select the optimal cooling option.

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