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WASTE HEAT RECOVERY USING DIRECT THERMODYNAMIC CYCLE

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Abstract: *For waste heat recovery the thermodynamic cycles is a solution by selecting a fluid with corresponding working temperature. The waste energy is used for cogeneration of heat energy and electrical energy. The analysis of the thermodynamic cycle has been carried out considering evaporation temperature and condensation temperature of pure ecologic working refrigerant R245fa. Based on the thermodynamic mathematical model with equation of state for working fluid, the effects of design parameters on the system performance are investigated from the view of both thermodynamics efficiency and exergetic efficiency.*

Key words: *Rankine Cycle, refrigerants, waste heat recovery, cogeneration, thermodynamic analysis.*

1. Introduction

The recovery of the energy from waste resources is a modern method for energy conversion that came from the all most technological processes. Chang et al. [2] have highlighted that the 60% of low-temperature waste heat is not recovered in US and the Rankine cycle is a promising thermodynamic cycle for energy conversion. The direct thermodynamic cycle, called also Rankine cycle, allows energy recovery of waste heat streams that are moderate in temperature to be converted into electrical power by conventional steam cycles. The use of organic refrigerants with high molecular mass enables cost-effective electrical power recovery of waste heat, and these thermodynamic cycles are called Organic Rankine Cycles, ORC. A promising way to increase the cycle efficiency is the use of the waste energy to obtain electricity combined with heating and/or cooling as has studied in [2-5].

The thermodynamic cycle efficiency of the Rankine cycle is influenced by the choice of the working refrigerant. The Montreal protocol forced industry to use thermodynamically less efficient refrigerants which are not containing chlorine in their composition, named HFC refrigerants. The non-toxic refrigerants used in the past, i.e. CFC114, CFC11 and HCFC123, were outlawed since are not chlorine free.

This paper investigates the ecologic working refrigerants R245fa and R600a (isobuthane) in a Rankine cycle system to produce work to a turbine which is directly connected to an electrical generator. The waste energy came from gas exhaust of an automotive engine. The temperatures of

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exhaust gases depend on the functioning regime of the engine and have about 350 to 450 °C.

The study considered the basic Rankine cycle with different evaporation and condensation temperatures which are determined by the heat source and the heat sink.

2. Basic Thermodynamic Cycle

The working fluid, in liquid state, is pressurized and circulated through the system by a pump. On the discharge side of the pump, the highly pressurized liquid is heated in a heat exchanger, called evaporator or boiler, until it absorbs the waste heat and boils at high pressure and moderate temperature. The vapor state refrigerant then passes through a pressure lowering device also called an expansion device. This may be an expansion valve, or commonly used a work-extracting device such as a turbine. The low pressure vapor refrigerant then enters to another heat exchanger, the condenser, in which the fluid release heat and condenses. The condensed liquid refrigerant then returns to the pump and the thermodynamic cycle is repeated.

The temperature entropy diagram of the basic Rankine cycle is shown in Figure 1.

The correlation between thermodynamic state points and the functioning cycle presented in Figure 1 is: the saturated liquid refrigerant leaves the condenser at low-pressure with thermodynamic state point 1. The pump raises the pressure of the liquid to state point 2 and feeds the evaporator/boiler. In the evaporator the refrigerant is heated in liquid state to state point 3, evaporated to state point 4 and super-heated to state point 5 which is the entering state to the turbine. The adiabatic expansion to low-pressure vapor in the turbine at state point 6. After that the vapor enters in the condenser where heat is rejected from the system during condensation. The turbine is usually connected to electric generator.

2.1. Thermodynamic Modelling

The Rankine cycle modelling is based on the conservation equations for energy and mass. To analyze this thermodynamic system, the mass and energy balance must be performed for each plant component. Because this plant is a closed system and the turbine has one inlet and one outlet port, the mass flow circulating in the plant is the same for all devices. For energy balance for all devices the specific enthalpy difference of inlet and outlet state defines the rate of specific energy exchange at given pressure and temperature using the equation of state model.

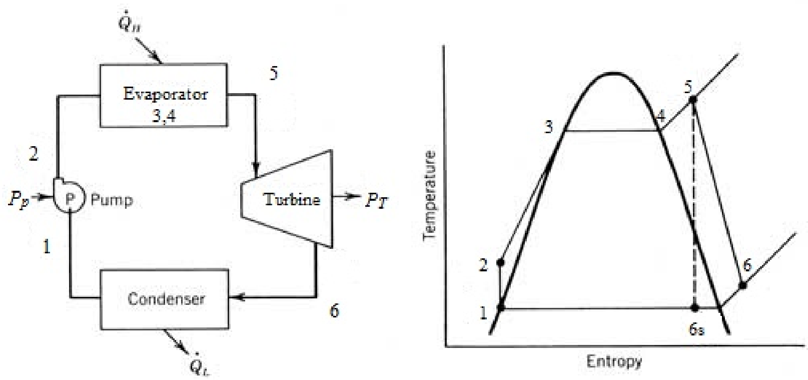

Fig. 1. *Rankine schematics and T-S thermodynamic cycle*

- **Pump modelling**

Mass balance: $\dot{m}_{ref} = \dot{m}_2 = \dot{m}_1$, (1)

Energy balance: $P_p = \dot{m}_{ref}(h_2 - h_1)$, (2)

where $\dot{m}_{ref}$ is the mass flow [kg/s], P_p is pump power [kW], h_1, h_2 are the inlet and outlet enthalpies.

- **Boiler/Evaporator modelling**

Mass balance: $\dot{m}_2 = \dot{m}_5$, (3)

Energy balance: $\Phi_e = \dot{m}_{ref}(h_5 - h_2)$, (4)

where Φ_e is the boiler heat flow [kW], h_2, h_5 are the inlet and outlet enthalpies.

- **Turbine modelling**

Mass balance: $\dot{m}_6 = \dot{m}_5$, (5)

Energy balance: $P_T = \dot{m}_{ref}(h_5 - h_6)$, (6)

where P_T is the turbine power [kW], h_5, h_6 are the inlet and outlet enthalpies.

- **Condenser modelling**

Mass balance: $\dot{m}_6 = \dot{m}_1$, (7)

Energy balance: $\Phi_c = \dot{m}_{ref}(h_1 - h_6)$, (8)

where Φ_c is the condenser heat flow [kW], h_6, h_1 are the inlet and outlet enthalpies.

The overall energy balance is:

$$\Phi_e + P_p = \Phi_c + P_T. \quad (9)$$

Thermodynamic efficiency or coefficient of performance is defined as the ratio of useful energy or power and consumed energy or power and computed with the relation:

$$COP = \frac{P_T - P_p}{\Phi_e} = \frac{P_{net}}{\Phi_e}. \quad (10)$$

Exergetic efficiency is:

$$\eta_{ex} = \frac{Ex(P_{net})}{Ex(\Phi_e)} = \frac{P_{net}}{\Phi_e} \cdot \frac{T_{Fm}}{T_{Fm} - T_{amb}}, \quad (11)$$

where T_{amb} is the ambient temperature and T_{Fm} is the average temperature in the evaporator calculated with:

$T_{Fm} = \dfrac{(h_5 - h_2)}{(s_5 - s_2)}$ as ratio of enthalpy and entropy difference for boiler.

- **Refrigerant modelling**

The thermodynamic properties for pressure, enthalpy, entropy at saturation state, subcooled or superheated states are calculated using CoolProp precision Helmholtz thermodynamic mathematical model for working fluid presented in [1].

This model was implemented for simulation in EES (Equation Engineering Solver) [7] resulting a system with 52 algebraic equations, 11 equations for mass and energy balance and 41 equations for pressure, specific volume, temperature, enthalpy and entropy of the state points.

The thermodynamic properties used for R254fa and R600a refrigerants according ASHRAE [6] are: R245fa - the molecular mass M = 134.05 kg/kmol, boiling temperature at normal pressure t_{bp} = +14.9 °C, critical temperature t_{crit} = +154.05 °C, critical pressure p_{crit} = 3.6 MPa, and for R600a the molecular mass M = 58.12 kg/kmol, boiling temperature at normal pressure t_{bp} = -11.7 °C, critical temperature t_{crit} = +134.7 °C, critical pressure p_{crit} = 3.6 MPa.

The Rankine cycle system calculation was made under the following conditions:

- the maximum boiling temperature in the evaporator $t_{e,max}$ = +100 °C;
- the ambient temperature t_{amb} = +25 °C;
- the condensing temperature $t_c = t_{amb}$ + 10 °C;
- the waste heat source temperature t_{ws} = 350-450 °C;
- the turbine efficiency η_T = 0.85;
- the pump efficiency η_p = 0.80.

The variable parameter is considered the entering refrigerant temperature in the turbine t_5 = +100...+155 °C.

3. Results and Discussions

The performance evaluation of the Rankine system resulting from simulation for the 2 refrigerants investigated is presented in function of inlet turbine temperature for:

- the coefficient of performance, COP, the exergetic efficiency, $\eta_{ex,}$ in Figure 2 and Figure 4;
- boiler heat, Q_{in}, condenser heat, Q_{out} and turbine work, $W_{T,}$ in Figure 3 and Figure 5.

The COP variation for R245fa depending on the turbine inlet temperature is decreasing since turbine inlet temperature is increasing, while for R600a the COP have a maximum around 110 °C (see Figure 4). The behavior for R245fa and R600a of the exergetic efficiency (see Figure 2 and Figure 4) is the same as the thermal efficiency.

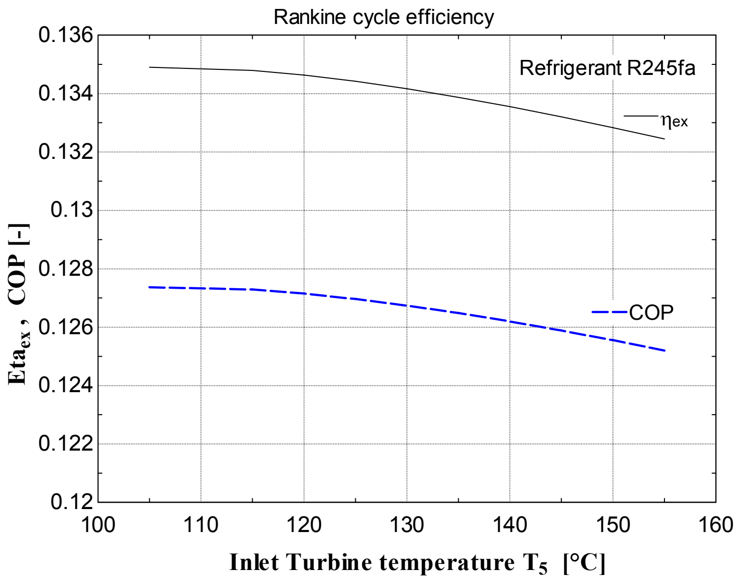

Fig. 2. *COP and* η_{ex} *vs. temperature*

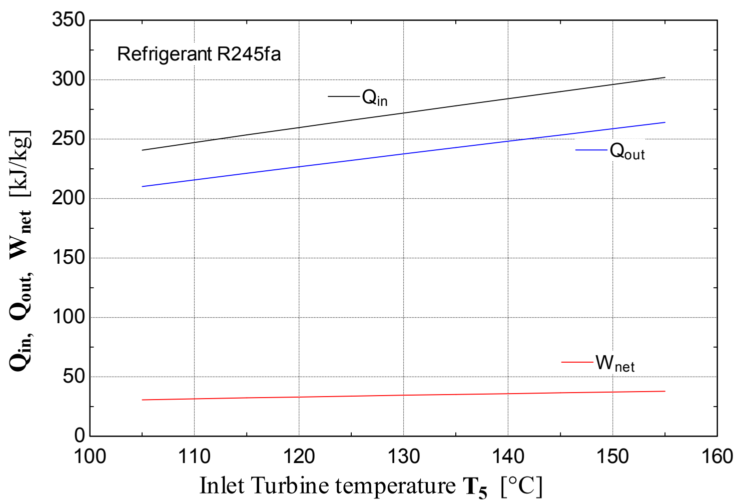

Fig. 3. Q_{in}, Q_{out}, W_T *vs. temperature*

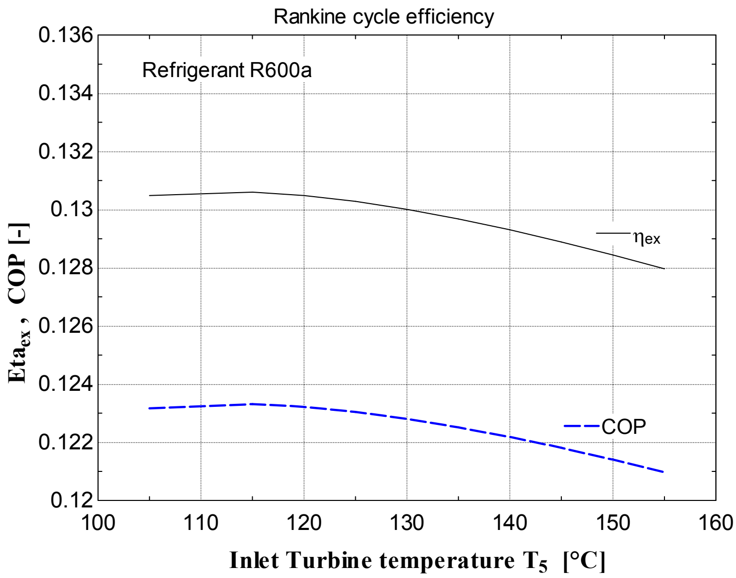

Fig. 4. *COP and* η_{ex} *vs. temperature*

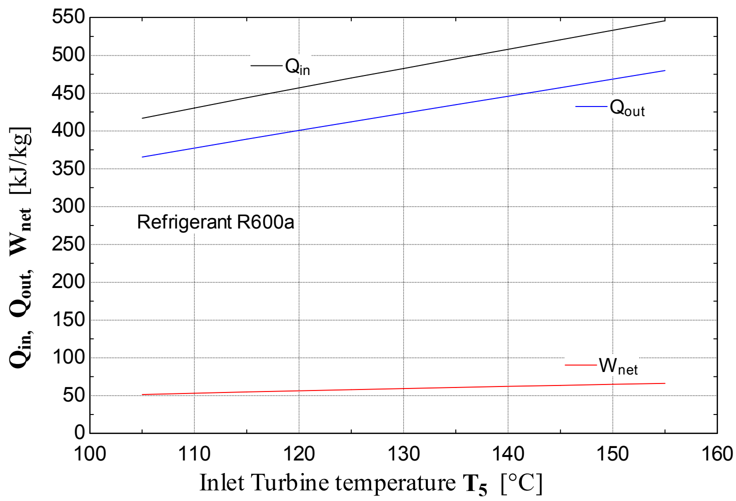

Fig. 5. Q_{in}, Q_{out}, W_T *vs. temperature*

According to Figure 3 the turbine work which can be converted in electrical work is increasing with inlet turbine temperature increasing for both refrigerants. At maximum turbine inlet temperature the work produced by R245fa is about 37.8 kJ/kg and heat introduced in boiler is 301.8 kJ/kg since for R600a the work produced is 66 kJ/kg and heat introduced in boiler is 545.7 kJ/kg. If one consider a mass flow about 1 kg/s in plant an amount of 37.8 kW turbine power is produced from 301.8 kW of heat introduced in the system for R245fa and 66 kW turbine power is produced from 545.7 kW of heat introduced for R600a. So, the turbine power produced by R600a is 57% higher than power produced by R245fa in the same simulation conditions.

The efficiency of the investigated Rankine cycle using recoverable energy wastes is similar with other plants i.e.

using solar absorption thermodynamic cycle as presented in [2], [3] or exhaust gas recovery from diesel engines in [4], [5]. Even the value of thermal efficiency is about 13% the value of produced turbine power is not negligible.

3. Conclusions

1. This paper has presented the Rankine cycle simulation using organic refrigerants R245fa and R600a.
2. The analysis has been made for thermodynamic efficiency, exergetic efficiency and turbine resulted work using high accuracy equation of state using Helmholtz thermodynamic mathematical model.
3. The paper has demonstrated that the energy waste recovery can be used for electrical energy production.

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