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COMPARATIVE ANALYSIS OF AN ORGANIC RANKINE CYCLE FOR WASTE COGENERATION PLANTS

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Abstract: *For low, moderate and high temperature Organic Rankine Cycle (ORC) used in waste heat recovery, it is necessary to select a fluid with high working temperature. In plastic waste power and heat plants the ORC is used for cogeneration. The analysis of the cycle has been carried out considering evaporation temperature and condensation temperature of pure ecologic HFC working refrigerants R134a, R245fa, R227ea, R600a, R152a and R123 CFC fluid. Based on the Helmholtz thermodynamic mathematical models for working fluids, the effects of design parameters, including that of turbine inlet pressures, mass flow rates of working fluids and outlet steam fractions of boiler 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 use of the energy from recoverable resources is a modern method on energy saving and decreasing the CO_2 emissions. These resources came from the most technological processes. Also, the requirements for energy use purposes such as: producing hot-water, heating and air conditioning are based on electrical energy. The basic Rankine cycle converts high energy streams, came from coal burning, into electrical energy using water as working fluid. The ORC allows energy recovery of waste heat streams that are low in temperature to be converted into electrical power by conventional vapor cycles using organic fluids, which are basically working fluids in refrigeration technology. The use of organic fluids enables cost-effective electrical power recovery of waste heat. The management of plastic wastes supposes feedstock recovery, mechanical recycling and landfilling which is the last option, more and more avoided. Other options are the energy recovery by waste incineration. A promising way is the use of the plastic waste energy to obtain electricity combined with heating and/or cooling with ORC.

The thermodynamic cycle efficiency of the ORC is influenced by the choice of working fluid. The Montreal protocol forced industry to use thermodynamically less efficient refrigerants which are not containing chlorine, such as ChloroFluoroCarbon compounds (CFC's) and HydroChloroFluoroCarbon compounds (HCFC's). The non-toxic refrigerants

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used in the past as working fluids [1], i.e. Dichlorotetrafluoroethane (CFC114), Trichlorofluoromethane (CFC11) and Dichlorotrifluoroethane (HCFC123), were outlawed since are not chlorine free. Chlorine based refrigerants and also other categories of refrigerants have higher ozone depletion potential (ODP) and are also disregarded.

This paper considers ecologic refrigerants based on near to zero ODP and low Global Warming Potential (GWP), i.e. Tetrafluoroethane (R134a), Pentafluoropropane (R245fa), Heptafluoropropane (R227ea), isobuthane (R600a), Difluoroethane R152a and HCFC-R123 in ORC system efficiency. The choice of a HCFC non-ecologic refrigerant was made for comparison reasons. The study considered the basic ORC with different evaporation and condensation temperatures.

2. Basic Organic Rankine Cycle

2.1. Thermodynamic Cycle

A schematic description of the basic ORC is shown in Figure 1 and consists of four major components: pump, evaporator, turbine and condenser [3-6].

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 superheatead to state point 5 which is the entering state to the turbine. The expansion to low-pressure vapor in the turbine at state point 6 enters in the condenser where heat is rejected from the system during condensation.

In the turbine the mechanical energy is recovered through expansion from high-pressure vapor to low-pressure vapor and converted into electrical energy through an electrical generator. The temperature entropy diagram of the baseline Organic Rankine cycle is shown in Figure 1.

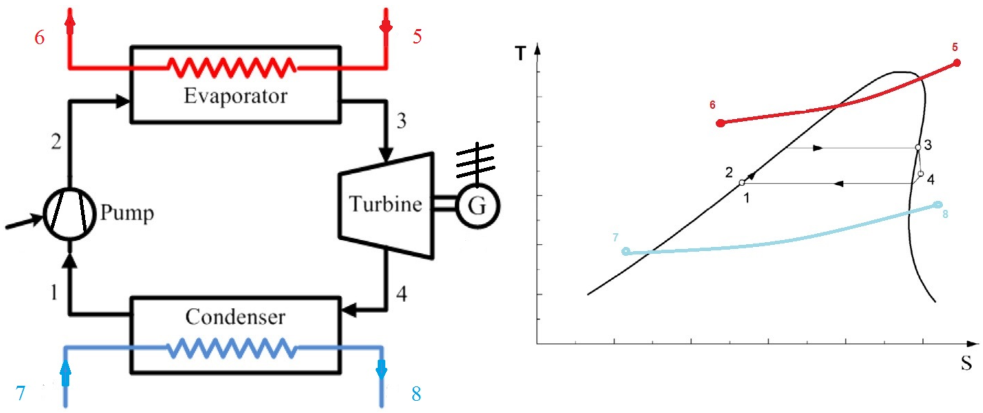


Fig. 1. *Rankine schematics and T-S thermodynamic cycle*

2.2. Thermodynamic Model

The ORC cycle modeling 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 component in Table 1.

The exhaust gases from plastic waste incinerators vary between 350 and 550 °C depending on the plastic waste composition. The presence of polyolefines such as polypropilene, polyethilene, etc., which have a high heat of combustion and flame temperature determines that the exhaust gas temperatures are even higher. This was considered in the study as superheated temperature of the refrigerant between 105 and 150 °C.

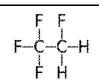
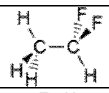
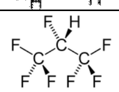
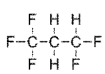
Thermodynamic analysis of the ORC Table 1

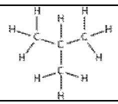
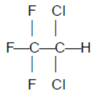
Component	*Mass flow*	*Energy*
Boiler/Evaporator (2 →3)	$\dot{m}_2 = \dot{m}_3 = \dot{m}_{ref}$	$\Phi_e = \dot{m}_{ref}\left(h_3 - h_2\right)$
Tubine (3 →4)	$\dot{m}_3 = \dot{m}_4$	$P_T = \dot{m}_{ref}\left(h_3 - h_4\right)$
Condenser (4 →1)	$\dot{m}_1 = \dot{m}_4$	$\Phi_c = \dot{m}_{ref}\left(h_4 - h_1\right)$
Pump (1 →2)	$\dot{m}_2 = \dot{m}_1$	$P_p = \dot{m}_{ref}\left(h_2 - h_1\right)$
Hot fluid (5 →6)	$\dot{m}_{hf}$	$\Phi_{hf} = \dot{m}_{hf} \cdot c_p\left(T_5 - T_6\right) = \Phi_e$
Cold fluid (7 →8)	$\dot{m}_{cf}$	$\Phi_{cf} = \dot{m}_{cf} \cdot c_p\left(T_8 - T_7\right) = \Phi_c$
Thermodynamic efficiency	$COP = \dfrac{P_T - P_p}{\Phi_e} = \dfrac{P_{net}}{\Phi_e}$	
Exergetic efficiency	$\eta_{ex} = \dfrac{Ex(P_{net})}{Ex(\Phi_e)} = \dfrac{P_{net}}{\Phi_e} \cdot \dfrac{T_{Fm}}{T_{Fm} - T_{amb}} \cdot$	
T_{Fm} is the average temperature in the evaporator: $T_{Fm} = \dfrac{\left(h_3 - h_2\right)}{\left(s_3 - s_2\right)}$ T_{amb} is the ambient temperature.		

The thermodynamic properties for pressure, enthalpy and entropy at saturation state, subcooled or superheated states are calculated using CoolProp [2] software routines using precision Helmholtz thermodynamic mathematical models for working fluids used in this paper. The routines are used in EES [8] software with ORC model.

The Table 2 presents basic properties of the selected refrigerants.

Refrigerant properties [7], [8] Table 2

	Chemical data			*Thermodynamic and environmental data*					
Refrigerant	*IUPAC name*	*Formula*	*Structure*	*M [g/mol]*	*T_{bp} [°C]*	*T_{crit} [°C]*	*P_{crit} [MPa]*	*ODP*	*GWP*
R134a	1,1,1,2-Tetrafluoro-ethane	CH_2FCF_3		102.03	-26.07	101.06	4.0	0	1430
R152a	1,1-Difluoro-ethane	$C_2H_4F_2$		66.05	-25.0	114	4.7	0	124
R227ea	1,1,1,2,3,3,3-Heptafluoro-propane	C_3HF_7		170.03	-16.45	101.65	2.9	0	3320
R245fa	1,1,1,3,3-pentafluoro-propane	$C_3H_3F_5$		134.05	14.9	154.05	3.6	0	1030

	Chemical data			*Thermodynamic and environmental data*					
Refrigerant	*IUPAC name*	*Formula*	*Structure*	*M [g/mol]*	T_{bp} *[°C]*	T_{crit} *[°C]*	P_{crit} *[MPa]*	*ODP*	*GWP*
R600a	Methyl-propane	C_4H_{10}		58.12	-11.67	134.67	3.6	0	20
R123	2,2-Dichloro-1,1,1-trifluoro-ethane	$C_2HCl_2F_3$		152.93	27.85	183.68	3.67	0.06	77

M - molar mass
T_{bp} - normal boiling point
T_{crit}, P_{crit} - critical temperature and pressure
ODP - Ozone Depletion Potential (ODP=1 for Trichlorofluoromethane (CCl_3F)=R11)
GWP - Global Warming Potential for 100-year time horizon (GWP=1 for CO_2)

The ORC 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}=350-550 °C;
- the turbine efficiency η_T = 0.85;
- the pump efficiency η_P = 0.80;
- the expansion imposed turbine power of the system $P_T = 100\ kW$.

The following variable parameter is considered: the entering refrigerant temperature in the turbine t5 = +105 ...+150 °C.

3. Results and Discussions

The advantage of this model is given by the high evaluation accuracy of the state points, compared with the common method, with the lnp-h diagram were the reading accuracy of the values is relative.

The performance evaluation of the ORC system is presented in function of inlet turbine temperature for each refrigerant for:
- the performance coefficient or thermal efficiency, COP - in Figure 2;
- the exergetic efficiency, $\eta_{ex,}$ in Figure 3;
- turbine work, W_{T}, in Figure 4.

The performance coefficient, COP, depending on the turbine inlet temperature presents a maximum of 10% around the value of 122°C (Figure 2) for R227ea refrigerant, after which it uniformly decreases. For R152a and R134a the COP uniformly increases while inlet turbine temperature increases. The COP for R123, R245fa and R600a is decreasing since turbine inlet temperature is increasing.

The behavior for exergetic efficiency (Figure 3) is with maximum value of 69.7% for R152a and 67.3% for R134a around the turbine inlet temperature value of 120°C, and 115°C respectively. For R123, R245fa, R600a and R227ea the exergetic efficiency is decreasing since turbine inlet temperature is increasing. For temperature lower than 112°C the R245fa has best exergetic efficiency then other refrigerants, and R152a respectively for temperatures bigger than 112°C.

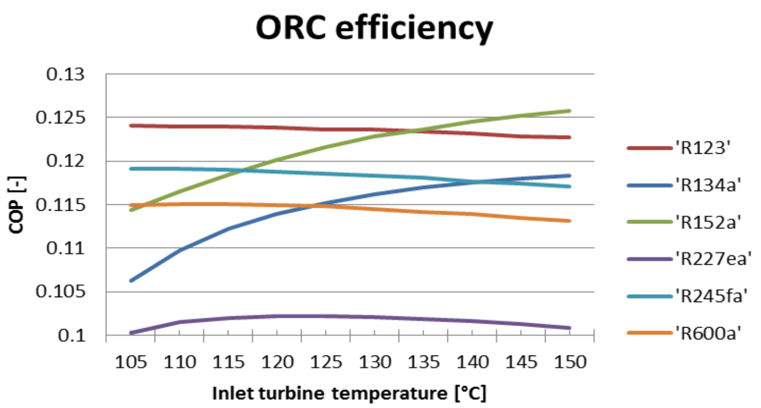


Fig. 2. *ORC thermal efficiency vs. inlet turbine temperature for selected refrigerants*

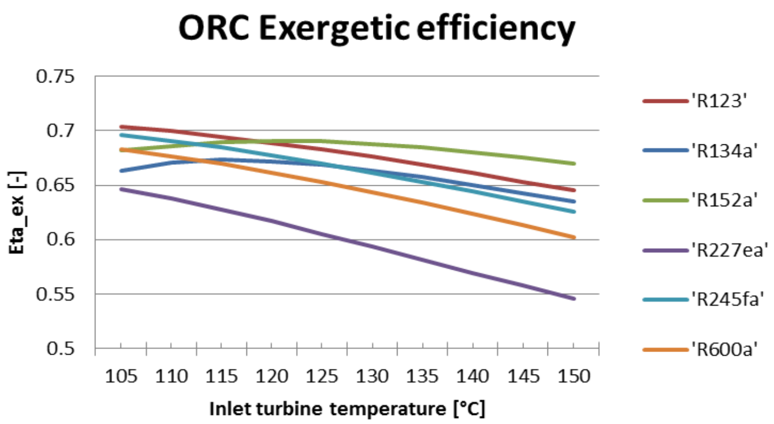


Fig. 3. *ORC exergetic efficiency vs. inlet turbine temperature for selected refrigerants*

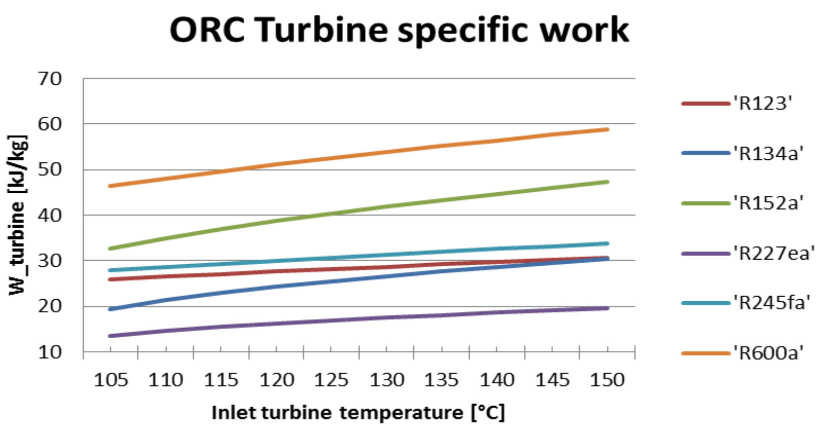


Fig. 4. *ORC turbine work vs. inlet turbine temperature for selected refrigerants*

According to Figure 4, the turbine work, which can be converted in electrical work, has increasing with inlet turbine temperature increasing. The best refrigerant according the maximum turbine work is R600a. The studied refrigerants can be selected for electrical energy production in the following order as: R600a, R152a, R245fa, R134a and R227ea.

The R123 was excepted because this is an HCFC refrigerant.

4. Conclusions

1. This paper has presented the Rankine cycle simulation using organic refrigerants R600a, R152a, R245fa, R134, R227ea and R123.
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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