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Energy Analysis of Solid Waste Fueled Cogenerative Organic Rankine Cycle for Different Working Fluids

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Abstract
The change of living conditions have been increased the energy need and its consumption significantly. Besides, reducing the primary energy source, increasing fuel price and the negative effects of fossil fuels to ecosystem and human health has obligated the developing and developed countries to find out alternative ways. Utilization of the solid waste as a hear source is an important solution for disposal of waste and to decrease the dependency of the countries to limited amount of primary energy source. In this study, the feasibility of a combined heat power (CHP) module using the Organic Rankine Cycle (ORC), with different calorific values as heat source in various working fluids (R600, Isopentane, R141b, R123, R134a, R32) was examined. Energy analysis was carried out in Engineering Equation Solver (EES) Program. The first law of thermodynamic was applied to Cogenerative Organic Rankine Cycle. The results showed that the wet fluids have the best performance while that of the dry fluids were comparatively low. The highest values of the thermal efficiency were seen in the case of wet fluid, R32 and followed by R134a for the overall system performance.
Keywords: Solid waste, Organic rankine cycle , Cogeneration system ,Working fluids, Calorification

INTRODUCTION

In order to reduce the adverse effects of chemical, biological and physical aspects of the increase in the amount of solid wastes, starting with the use of fossil resources and increasing day by day, researchers have focused on getting cleaner energy in their work , benefiting from the rapidly developing technology. Nowadays, the increase of energy consumption is not sufficient enough to meet this need, and the high energy production costs have made it necessary to use the energy efficiently, in addition to getting clean energy. Energy efficiency is especially important in heating and cooling systems where we use almost every area in our times.

As a result of their awareness of the importance of efficient use of energy, researchers have turned to renewable energy sources that have both a high rate of energy use and less adverse ecological impact (such as greenhouse gas emissions) compared to fossil fuels [1].

Up to now, studies have shown that the development of energy systems, that can be integrated into small scales reduces the investment and operating costs of the facility as well as an important factor for the sustainability of energy [2],[3].

Anders N. Andersen et al. [4] presented several solutions for integrating renewable energy sources (such as biomass energy) into combined heat and power (CHP) systems in small and medium measurement.

Unlike studies evaluating Organic Rankine Cycles for energy efficiency in the literature, this research utilized various solid wastes with different thermal values, which are adverse ecological effects as heat source, the applicability of the designed system for individual use has been examined. In addition to the study, the effect on the system performance of the use of different working fluids in the solid waste fueled Organic Rankine Cycle will be examined and energy analysis of the system will be performed to determine the most suitable working fluid for the cycle.

MATERIALS AND METHODS

A.System Description

Ideal cogeneration systems using steam turbines can’t be integrated into process heat and power changes, are not suitable for combined heat-power generation. The general schematic of the combined heat-power generation system used in applications and including a more complex process is shown in Figure 1.

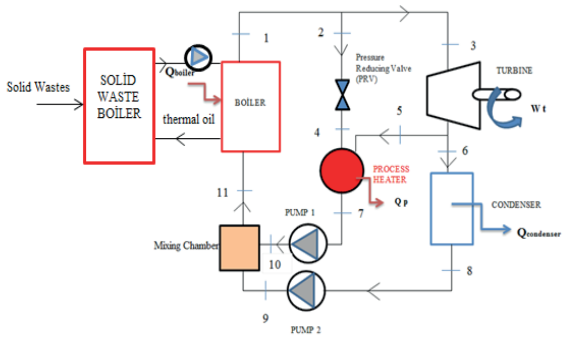

Figure 1. Real combined heat-power system (cogeneration)

During normal operation, a portion of the vapor is separated from the turbine by an interval pressure of a predetermined P5 value .Extend the rest of the steam to the condenser pressure (P6) and cooled to constant pressure in the fluid condenser. The heat given to the surroundings during cooling is lost as waste heat.

When the process needs more heat, all of the steam is sent to the process heater. Steam passes through the condenser ($\dot{m}_6 = 0$) and waste heat losses do not occur ($Q_{waste\ heat} = 0$). If this is not enough, some of the vapor formed in the boiler is directed to the process heater via a throttling valve or a pressure reducing valve. The highest value of the process heat is obtained by passing all the vapor obtained from the boiler to the pressure reducing valve ($\dot{m}_{1,2,3} = \dot{m}_4$). Power generation does not happen in this case. If the process does not have a heat load, all the steam is passed through the turbine and the condenser ($\dot{m}_4 = \dot{m}_5 = 0$). The system works like a steam power cycle.

In this article, solid wastes different thermal properties obtained from the Aladağ district of Bartın province were used as the working fluid as the heat source of the CHP system and energy analysis were made by using 6 different fluids in the isentropic, wet and dry properties as the working fluid (R600, Isopentane, R141b, R123, R134a, R32) in order to find the optimum fluid for the system. In addition, steam turbine (Organic Rankine Cycle) is used for power generation in the system. Cooling fluids with a flow rate of 5 kg/ s were used in the system and the calculations were taken into account when 10% of the steam obtained from the boiler was expanded before the turbine and 70% was expanded to a predetermined pressure of 500 kPa in the turbine before being sent to the process heater.

B. Working fluid selection for system

One of the important variables in thermodynamic systems is the determination of the refrigerant that provides energy transfer in the system.The determination of the fluid is to simulate different fluids for the cycle by some factors.A total of 6 different refrigerant fluids (R600, Isopentane, R141b, R123, R134a, R32) were selected for dry, isentropic, wet properties to be used as working fluid in the system. Parameters such as fluid availability, chemical stability, safety, toxicity, flammability, ecological effects (global warming potential GWP, ozone depletion potential ODP) were taken into account in selecting the fluids and their requirements coverage rates were examined.

As a result of the examination, the optimum fluid with the most suitable features for the system was determined. The thermodynamic parameters obtained and used in the study are obtained from the Engineering Equation Solver (ESS).

The properties of the refrigerants used are shown in Table 1.

Table 1. The properties of the refrigerants [5]

Property	Component	Molar mass (g/mol)	Critical temperature (°C)	Critical pressure (MPa)	ODP	GWP (100year)
Dry	R600	58.12	152.0	3.80	0	~20
Dry	Isopentane	72.15	187.2	3.38	0	~20
Isentropic	R141b	116.95	204.4	4.21	0.120	717
Isentropic	R123	152.93	183.7	3.66	0.010	77
Wet	R134a	102.03	101.1	4.06	0	1370
Wet	R32	52.02	78.1	5.78	0	716

C. Thermodynamic equations for the energy transfer

All of the equipment forming the cogeneration system using the Organic Rankine Cycle includes continuous flow-open thermodynamic processes. In continuous flow-open systems, heat and work transition between environment and system do not change with time. At the same time, all fluid properties at the inlet and outlet of the control volume are stable.

Mass conservation in continuous flow-open systems;

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

As the energy change in the control volume is constant ($\Delta E_{Cv} = 0$),the amount of energy (mass, heat, work) entering the system at that time should be equal to the amount of energy generated.

Energy conservation in continuous flow-open systems;

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{sys}}{dt} = 0 \tag{2}$$

$$\dot{E}_{in} = \dot{E}_{out} \tag{3}$$

Energy from the unit mass of the fluid;

$$E_{mass} = (u + PV) + ke + pe = h + ke + pe \tag{4}$$

if it is written in the equation;

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}E = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}E \tag{5}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}_{in}(h + V^2/2 + gz) = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out}(h + V^2/2 + gz) \tag{6}$$

$$\dot{Q} - \dot{W} = \dot{m}(h_{out} - h_{in} + \frac{V_{out}^2 - V_{in}^2}{2} + gz_{out} - gz_{in}) \tag{7}$$

Kinetic and potential energy changes in the system are often neglected because they are small compared to heat and work transitions. ($\Delta ke \cong 0, \Delta pe \cong 0$)

$$\dot{Q} - \dot{W} = \dot{m}(h_{out} - h_{in}) \tag{8}$$

A part of the heat energy entering the heat machines can be transformed into work. The part of the thermal energy entering the system that can be converted to net work is a parameter of system efficiency and is called thermal efficiency (η_{th}).

The desired result in the heat engines is the net work, the required value, the net amount of heat given to the system working fluid.

The thermal efficiency defined as;

$$\text{thermal efficiency} = \frac{\textit{net work} \text{ obtained}}{\text{total incoming heat}} \quad (9)$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{incoming\ heat}} \quad (10)$$

D.Conditions for the CHP Calculation

Table 2. Input parameters to the system

Parameters	Values
Inlet temperature of heat source	150 °C.
Ambient temperature	25 °C.
Cooling water temperature at the condenser	25 °C
Mass flow of the heating fluid (Therminol55)	10 kg/s
Isentropic efficiency of the pump1,2	0.85
Isentropic efficiency of the turbine	0.85
Efficiency of the boiler	0.95
Mass flow of the working fluid	5 kg/s
Isobaric heat capacity (Therminol55)	2.17 kJ/kg.K
Isobaric heat capacity cooling water	4.179 kJ/kg.K
Boiler pressure	10 MPa
Interval pressure	500 kPa
Condenser pressure	10 kPa
System runtime	12 hour

RESULTS AND DISCUSSION

The Engineering Equation Solver (EES), which is useful when analyzing the system, is taken from the written program. The parameters used in the cycle energy analysis are shown in Table 2.

Figure 2 shows the effect of the evaporator pressure on the overall thermal efficiency for system. As a result of the comparative analysis, the efficiency of dry (R600-Isopentane) fluids were lower than those of isentropic (R141b-R123) and wet fluids (R134a-R32) at the same evaporator pressure values.

When the evaporator pressure increases from 700kPa to 10MPa this ratio increased from 79.56% to 81.9% for R600a and from 78.52% to 80.13% for Isopentane.

The lowest values were observed for isentropic fluids at the same pressures after the dry fluids. As the pressure increased, efficiency of 141b and R123 increased by 2.22% and 2.19%, respectively and it was determined that the values and changes of two fluids are very close to each other under the same conditions.

The highest efficiency values were seen in wet liquids. The efficiency at maximum pressure is 84.86% at R134a and 85.17% at R32.

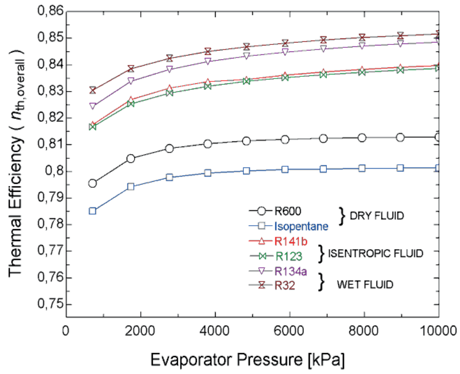

Figure 2. Exchange of overall thermal efficiency with Evaporator Pressure

Figure 3 shows the effect of the evaporator pressure on the thermal efficiency of ORC. The increase in pressure boosted the ORC efficiency and this increase was read at least in Isopentane (7.115% - 16.09%) and maximum in R32 (9.02% - 25.12%) .The highest efficiency values were recorded at R32 (9.02% at 700 kPa, 25.12% at 10 MPa).

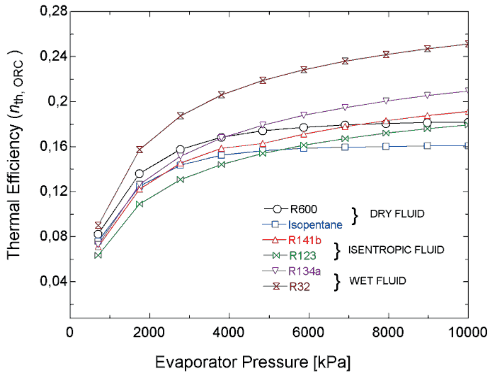

Figure 3.Exchange of ORC thermal efficiency with Evaporator Pressure

CONCLUSION

In this study, the energy analysis of the combined heat power systems (CHP) was carried out using EES. To evaluate the CHP program was written at EES.

The increase in evaporative pressure has increased system efficiency. This increase has more impact on overall efficiency than ORC efficiency.

The high overall efficiency values of the system have shown that the use of cogeneration systems provides a better utilization of energy than systems where heat and power are produced separately.

The use of solid waste fueled cogeneration system in this study is of great importance for clean and efficient energy production.

The cooling fluid to be used is selected for the system to work in optimum conditions. It has been observed that under the same conditions, the R32 refrigerant is advantageous over other refrigerants in terms of both ORC and overall thermal efficiency.

The resulting data and fluid properties (such as chemical, physical, biological properties) have shown that R32 fluid may be an important alternative to clean, sustainable energy in the future at the same time.

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Nomenclature			
cp	isobaric heat capacity, kJ/kg.K	$\eta_{turbine}$	isentropic efficiency of the turbine
h	specific enthalpy, kJ/kg	V	specific speed , m/s
$\dot{m}$	mass flow rate, kg/s	g	acceleration of gravity, m/s^2
P	pressure, kPa	z	reference height , m
s	specific entropy, kJ/kg.K	η_{th}	thermal efficiency
T	temperature , ^{O}C, K	t	time, s
$\dot{Q}$	heat input, kW	**Subscripts**	
$\dot{W}$	work, kW	1,2.3………11	state point
ϵ_{eu}	energy utilization rate	ke	kinetic energy, kJ
η	efficiency	pe	potential energy , kJ
$\eta_{pump1,2}$	isentropic efficiency of the pump	in	inlet
η_{boiler}	efficiency of the boiler	out	outlet

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