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Biomass Based Organic Rankine Cycle: Thermodynamic Modeling for 20 kW Power Output Electricity Using R227ea and Toluene as Working Fluids

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ABSTRACT

The bio*mass based organic Rankine cycle of the 20 kW power output has been investigated and thermodynamically modeled with the basic laws of thermodynamics. The two working fluids selected for modeling which are R227ea and Toluene. The ORC system has efficiency 10.9 % and 11.1 % in addition to the heat input to the boiler is 186.1 kW and 178.45 kW when boiler inlet temperature is 85 °C with R227ea and Toluene respectively. The thermal efficiency, pressure ratio, mass flow rate of working fluids and boiler heat input varies according to the boiler input temperature. This paper examines the variation in thermodynamic parameters when subjected to change in temperature of working fluids.*

Keywords: Biomass, Thermal efficiency, boiler heat input, working fluids.

INTRODUCTION

The importance of energy in the world has become higher as we have developed new technologies which help make our lives easier and more productive. Energy is needed everywhere from transportation to housing and plays a fundamental role in how the world is today. Currently, much of the world's energy is derived from fossil fuels which are an unsustainable resource. As it becomes harder to exploit oil and gas deposits in the world, the price of energy is increasing. Coupled with increasing demand due to increased technology implementation and population, sustainable alternatives are becoming more important as time goes on. According to the International Energy Agency energy, coal accounts for nearly half of the increase in global energy use over the past decade. The bulk of this growth is due to the power sector in emerging economies [1]. This has adverse effects on the environment due to increased $CO_2$and other harmful emissions.

The ORC technology is based on a long term development with the aim to efficiently use solar energy, geothermal energy as well as energy from biomass in decentralized units. The principle of electricity generation by means of an ORC process corresponds to the conventional Rankine process. The substantial difference is that an organic working medium (hydrocarbons such as isopentane, iso-octane, toluene or silicon oil) with favorable thermodynamic properties at lower temperatures and pressures is used instead of water - hence the name Organic Rankine Cycle (ORC). The right choice of the organic working medium used is very important for an optimized operation of the ORC process [2-3]. The energy produced by biomass combustion is transferred from a thermal oil boiler via a thermal oil cycle to the ORC process. Thermal oil is used as a heat transfer medium because the temperature required for operating the ORC process can be achieved while operating the thermal oil boiler practically at atmospheric pressure .The pressurized organic working fluid is vaporized in the evaporator by the energy supplied from the thermal oil cycle. The vapor is then condensed in the condenser. In this way the cycle is completed. The working fluid for biomass ORC plays important role .The working fluids for ORC method should be first recognized by its applications. octamethyltrisiloxane (OMTS) has been chosen as a working fluid. For OMTS, thermal as well as total heat recovery efficiency is comparatively low for a high temperature ORC process [7]. This is the incentive to search for fluids adapted specially to biomass application which differs from other ORC.

In order to identify the most suitable organic fluids, several general criterions have to be taken into consideration, including: thermodynamic properties ,stability of the fluid and compatibility with materials in contact, safety, health and environmental aspects, availability and costs [4-6]. Biomass based Organic Rankine Cycle (ORC) is one of the power generation ideas which have recently been applied to biomass based ORC. Biomass-based ORC could be economical feasible within the size in the range of 200 kW–1.5 MW which have been successfully demonstrated and now they are commercially available from several manufacturers with typical electrical efficiency of in the order of 15–20% [7].

MATERIALS AND METHODS

The proposed 20 kW biomass based ORC system

The proposed 20 kW biomass- based ORC system is schematically shown in Fig. 1. It consists of boiler, turbine, condenser and pump. The heat released from the combustion of biomass inside the biomass boiler is used to heat the water via the boiler heat exchangers, while the hot water is used as the heating source of the organic Rankine cycle. The ORC working fluid is closely circulating within the organic Rankine cycle: the condensed ORC working fluid is pumped through the evaporator where it is heated by the circulating hot water to generate organic working fluid vapor which expands in the turbine to generate electricity; the working fluid at the turbine exhaust is condensed in the condenser and flows back to the circulation pump to begin a new cycle.

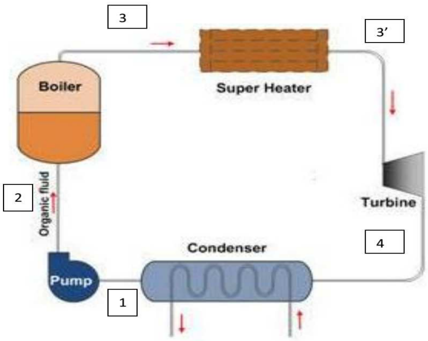

Fig. 1 Schematic diagram of biomass based ORC system.

Thermodynamic modeling of the proposed 20 kW biomass-based ORC system

The proposed 20 kW biomass based ORC shown in fig. 1 will only use environmentally friendly ORC fluid. The T-s diagrams of these two pure compounds are shown in figs. 2 and 3 respectively. The main thermodynamic properties of the selected ORC fluids are summarized in Table 1.

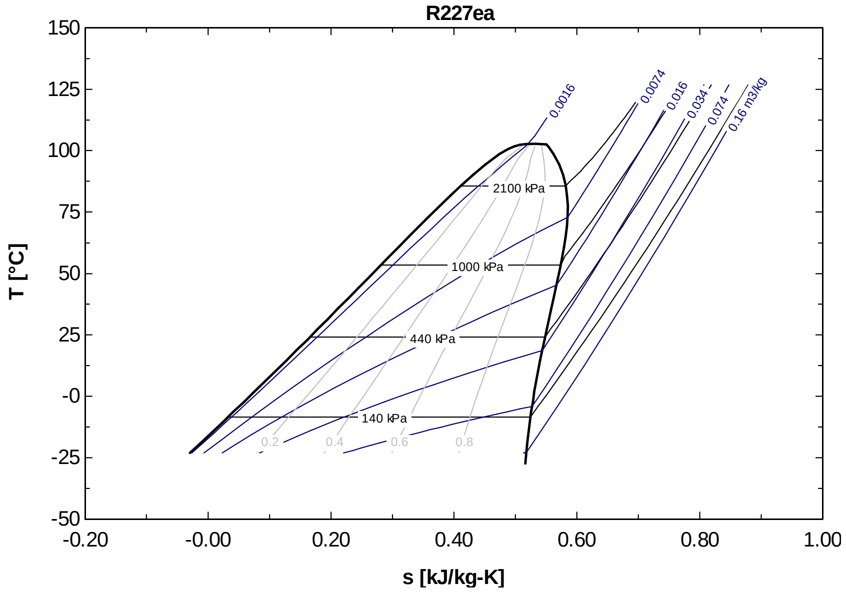

Fig. 2 T-s diagram for R227ea working fluid.

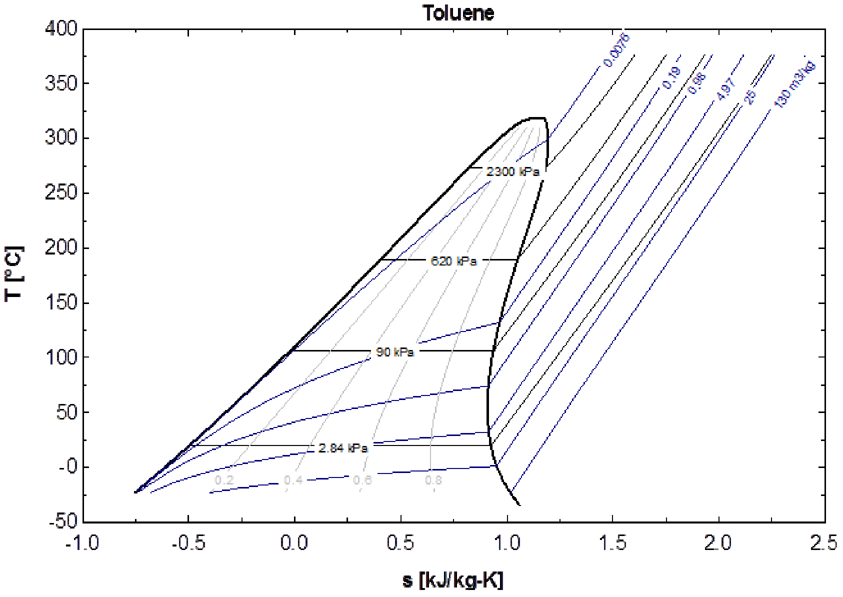

Fig. 3 T-s diagram for Toluene working fluid.

In any simulation and modeling analysis it is necessary to assume different criteria and conditions for carrying of the simulation process. In this regard, the various assumptions relating to thermal behavior of properties and mechanical conditions are described below:

I. Boiler Efficiency

The boiler efficiency is assumed to be 80%. This is because of the current technological status from the various literatures [8-9]. In few ORC industries the efficiency of boiler goes up 90%.

II. Turbine Efficiency

According to the different types of turbine available in the market, the turbine efficiency ranges from 50-70% [8]. The present paper assumption for turbine efficiency is 70%.

III. Pumping system Efficiency

The working fluid pump efficiency is assumed to be around 70%. Various authors estimated the pump efficiency to be in between 60-80%[8].

IV. Piping Losses

The pressure losses along the pipes and bents are neglected in this present study. Though there are few losses in the pipes and bent as compared to other losses, it is ignored.

V. Loss in Heat Exchangers

The losses in heat exchangers include fouling and pressure drop. In the present study losses are also neglected.

As it can be seen from fig. 1that from point 2 to point 3, the heat gain of the working fluid is given by the following equation

$$q_{in} = h_3 - h_2 \qquad (1)$$

From point 4 to point 1 is a constant pressure process, the heat rejected from the working fluid is expressed by this equation

$$q_2 = h_4 - h_1 \qquad (2)$$

During the adiabatic expansion process (from point 3 to point 4), the work that has been done by the working fluid in the turbine is equation

$$W_t = h_3 - h_4 \qquad (3)$$

From point 1 to point 2 is an adiabatic compression process; the consumption of power by the pump is equation

$$W_p = h_1 - h_2 \qquad (4)$$

In this cycle, the net work done by the working fluid should be equivalent to the power output from the turbine minuses the power consumption of the pump which is expressed as equation below:

$$W_{out} = (h_3 - h_4) - (h_2 - h_1) \qquad (5)$$

Therefore, the thermal efficiency of the ORC can be calculated as follows equation

$$\eta_{ORC} = W_{out} / q_{in} = (h_3 - h_4) - (h_2 - h_1)/(h_3 - h_2) \qquad (6)$$

where h_1, h_2, h_3 and h_4 are the specific enthalpies of the working fluids.

RESULTS AND DISCUSSION

The two pure working fluids compounds R227ea and Toluene are analyzed for biomass ORC system. The physical and chemical properties of working fluids best described the behavior of the ORC system. The different parameters such as thermal efficiency, boiler heat input, pressure ratio and mass flow of working fluids are analyzed.

System efficiency

The thermal efficiency of biomass ORC is the most important characteristic feature of ORC system. This parameter determines the thermal heat conversion from the input heat. Generally the thermal efficiency ranges from 10-15% in real ORC plants. In the present study, the thermal efficiency of R227ea and Toluene are 10.9 % and 11.1 % respectively. The thermal efficiency of ORC varies when the boiler input temperature changes. Higher the temperature, the higher is the thermal efficiency of the system. In addition to the variation in pressure in rotating turbine also affects its thermal efficiency. The pressure raised in the system helps in increasing the thermal efficiency. The boiler point of working fluids in the ORC system helps in maintaining the thermal efficiency. The critical temperature of the organic working fluids is also another factor of increase in thermal efficiency. If the working fluids are heated above the critical temperature for getting of higher efficiency in the system, the cost could be increased. But if the system efficiency should be increased the working fluids should be heated up to supercritical stages. In case of supercritical stages, an introduction of super-heater is needed. In this study, the working fluids are heated only within the fluids critical temperature or below. Fig. 4 illustrated that thermal efficiency increases with increase in temperature of boiler heat input. This increased heat exchanges heat with the oil from heat exchanger and expands adiabatically with the turbine that is coupled with generator. The variation in thermal efficiency occurs when the vaporized working fluid is pressurized from the lower to higher. The high pressure drives the vapor into turbine thereby increasing the thermal efficiency.

Pressure Ratio

The pressure ratio is the ratio between turbine inlet pressure to outlet pressure. Generally speaking higher is the pressure ratio implies higher system efficiency but the turbine will usually weigh more, so there is a compromise. A high pressure ratio helps in expanding more heat energy for conversion and energetic efficiency improves. So this is advantageous in biomass ORC system.

But another disadvantage of high pressure ratio is material failure risk so it should be also considered. In this study the pressure ratio for two different working fluids are compared and recommended for biomass ORC system. The variation in pressure ratio with respect with boiler inlet temperature can be shown in figure 5. In the present study, the pressure ratio for R227ea is 7.71 and Toluene is 12.22 respectively.

Working fluids mass flow rate

The working fluids mass flow rate is determined by the boiler heat input temperature. The variation of the mass flow rate can be demonstrated with figure 6. The generated simulated result is obtained by keeping the constant power output of 20 kW with the same assumptions as described in the early section. The figure 6 shows that increment in temperature in boiler requires low working fluid mass flow rate. This concept can be applied in operating pressure. In other words, the boiler inlet temperature and turbine inlet pressure are inversely proportional to its mass flow rate of working fluids. This is because of the increase in the net workdoneof the cycle with the increase of the turbine temperature and pressure in the biomass ORC system. In the present study R227ea has high flow rate as compare to Toluene which is 1.18 kg/s and 0.37 kg/s respectively. It should be taken into consideration that Toluene working fluids is toxic in nature so proper handling of the ORC system requires.

Boiler heat input

The boiler heat input is given by the biomass products such as wood, straw and pellet as literature shows [9]. In the proposed 20 kW biomass ORC system, the maximum heat input to the boiler is 186.1 kW. This heat is necessary for the getting for work done for given output power. When the boiler heat input temperature is changed then, the biomass ORC system thermal efficiency also changes. The variation in thermal efficiency according to the boiler input temperature is shown in fig 7. It is well know that the combustion process in this ORC plants emits some pollutants which is very harmful for the community living nearby. So it is necessary to take early precaution measurement must be taken [9].

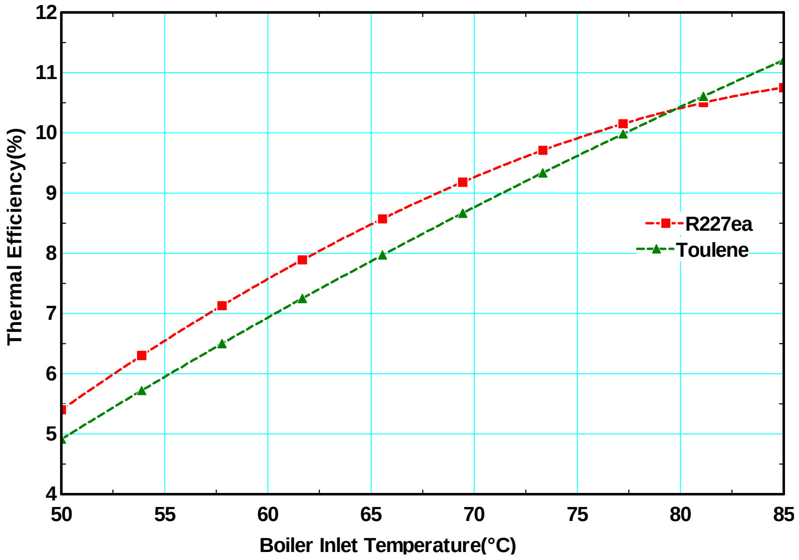

Fig. 4 Variation in thermal efficiency due to boiler inlet temperature.

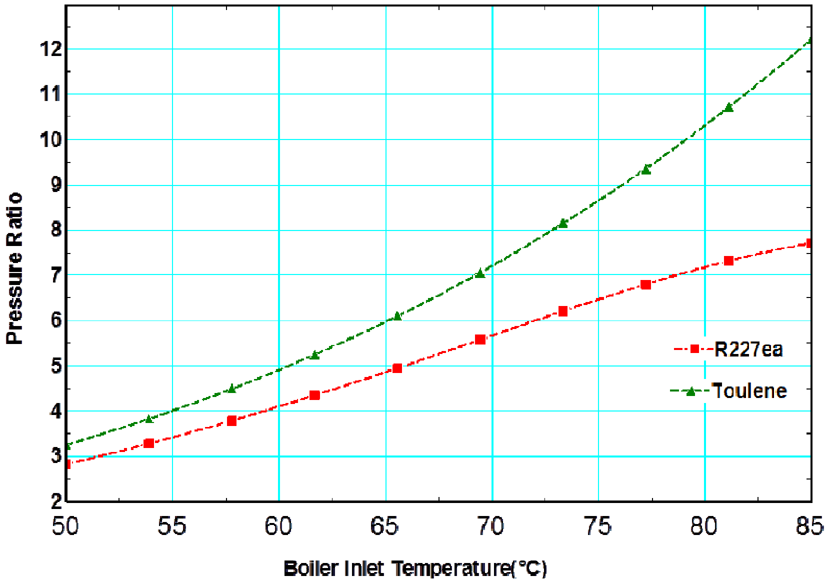

Fig. 5 Variation in pressure ratio due to boiler inlet temperature.

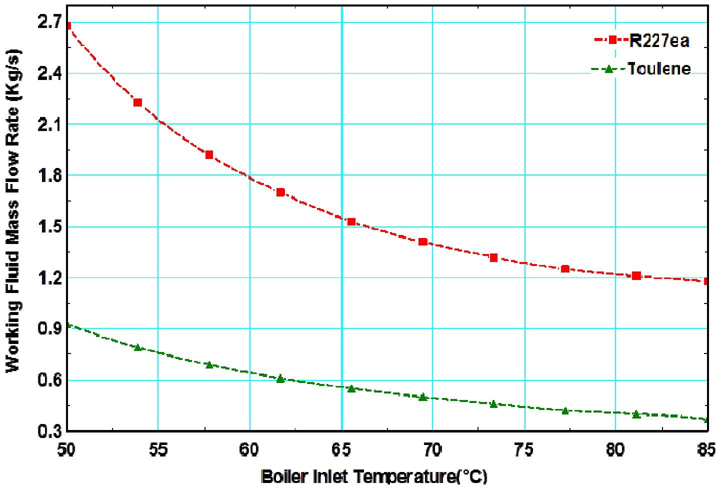

Fig. 6 Variation in mass flow rate due to boiler inlet temperature

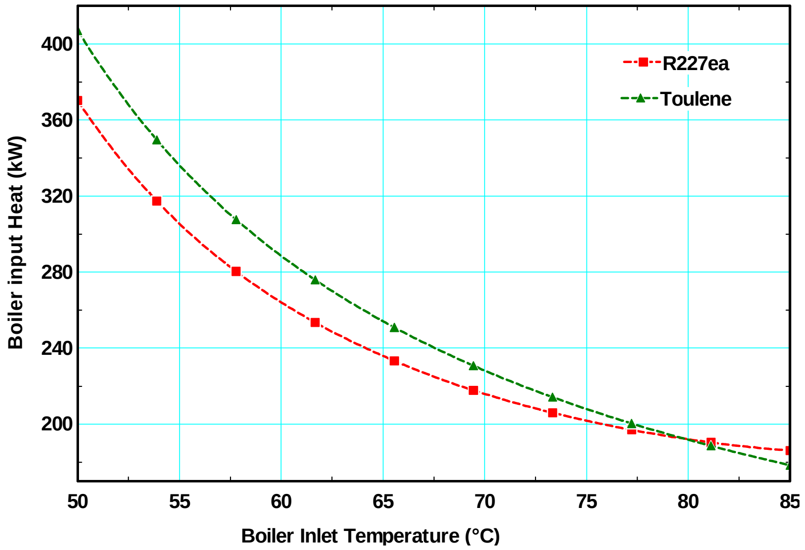

Fig. 7 Variation in boiler heat input due to boiler inlet temperature

CONCLUSION

A 20 kW biomass ORC system has been proposed and thermodynamically modeled with two selectedpure organic working fluids, namely R227ea and Toluene.

The following conclusions can be drawn from the results of thermodynamic modeling: under the simulated conditions,

1. The ORC efficiency depends on not only the modeling conditions but also the ORC fluid the highest predicted ORC efficiency is 10.9% and 11.1 % for R227ea and Toluene respectively.
2. The boiler heat input of the proposed 20 kW biomass ORC system with the selected ORC fluids is predicted and 186.1 kW and 178.45 kW for R227ea and Toluene respectively.

In order to improve the ORC efficiency, heat recuperating and super heater within the ORC should be considered, particularly when the inlet temperature of the ORC fluid to the condenser is much higher than that required by the heating application. The experimental results will be presented in the future and the thermodynamic modeling results will be compared with the experimental results.

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