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A review on thermodynamic analysis of organic Rankine cycle with different working fluids

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ABSTRACT

The development of the world today has largely been achieved through the increasingly efficient and extensive use of various forms of energy. Over the past decades, the growth in energy consumption around the world has shown that fossil fuel energy source alone will not be capable of meeting future energy demands. With the increase in fossil fuel consumptions, more and more industrial activities produce an increasing amount of waste heat. Energy generated as a result of industrial activities that are not practically utilized is referred to as industrial waste heat. Several studies have shown that the specific amount of industrial waste heat is poorly measured, it is estimated that 25 to 55% of the input energy in industries are actually used while the remaining are discharged as waste heat

Keywords— *ORC, EES, Simulation model, Rankine cycle, First law efficiency, Second law efficiency, The turbine size factor*

1. INTRODUCTION

The increase in energy consumption by the burning of fossil fuel has led to several conflicts around the world, global warming and environmental pollution such as soil, water, air and acid rain pollution. Besides the adverse environmental effects, the prices of fossil fuels are not consistent but usually going up most of the time.

Petroleum and natural gas and coal are fossil fuels and are non- renewable. Several countries today have been investing money to get new and efficient energy technologies that are alternative to fossil fuels to generate power. Low-grade heat is largely available in renewable energy sources and in industrial waste. Utilizing this type of sustainable energy could help reduce the use of non-renewable energy, thus reducing the environmental impacts of non-renewable energy sources. Development of efficient and effective technologies is required to generate useful work by using these low-grade heat sources. An ORC is a suitable means of carrying out this purpose. The ORC works with a high molecular mass organic working fluid with the characteristic of having a phase change of liquid to vapour occurring at a temperature which is lower than the phase change of water to steam for a given pressure. The recovery of low-grade heat can be achieved using organic fluids. These low-grade heat sources can be from biomass energy, solar energy, geothermal energy and industrial waste. The ORC converts the low-grade heat into work and finally into electricity.

2. LITERATURE REVIEW

2.1 Organic Rankine cycle based hybrid systems

Growing interest in low-grade heat recovery for power generation or cogeneration has given more attention to ORC due to its lower evaporation temperature and simplicity (Lee et al., 2014; Yu et al., 2016). An Organic Rankine cycle performs better than a steam turbine in the typical range of 150-200°C source temperature and small scale systems (Tsoukpoe et al., 2016). The combined generation of heat and power using an ORC enhances the utilization of energy and reduces the carbon emission (Peris et al., 2015). Moreover, ORCs (using dry working fluids) are better suited for the micro-scale applications due to lower operating pressures, intake of saturated vapour at the expander inlet, dry expansion, positive gauge pressure in the cycle, improves expander life, reduces mechanical stress, and reduces operation and maintenance cost, etc. (Hung, 2001; Algieri and Morrone, 2012). Organic Rankine cycle, which uses organic working fluid instead of water in the conventional Rankine cycle, efficiently utilizes low-medium temperature energy sources (Uusitalo et al., 2016), like waste heat (Liu et al., 2016), solar thermal (Desai and Bandyopadhyay, 2016), geothermal (Coskun et al., 2012), biomass combustion (Al-Sulaiman et al., 2012), ocean thermal energy (Yang and Yeh, 2014), etc. For <1 MWe scale low-temperature operations ORC is a promising option compared to steam Rankine cycle (Desai and Bandyopadhyay, 2016).

Commercial manufacturers of ORC power block have installed a significant number of plants with waste heat, biomass, or geothermal as an energy source (Quoilin et al., 2013). Organic Rankine cycle based cogeneration systems, using different energy sources, have been analyzed by many researchers.

Integration of an ORC in a small-scale hybrid system (electric output 1–200 kWe) is a promising option due to superior thermodynamic and economic performance (Maraver et al., 2013a). Extensive investigations on organic Rankine cycle based hybrid systems powered by waste heat (Wang et al., 2011), solar thermal energy using parabolic trough collector (PTC) (Al-Sulaiman et al., 2011) and flat plate collector (Wang et al., 2012), solid oxide fuel cell (SOFC) (AlSulaiman et al., 2011), biomass (Al-Sulaiman et al., 2012), gas turbine exhaust (Ahmadi et al., 2012), combined biomass and solar thermal energy (Karellas and Braimakis, 2016), combined geothermal and solar thermal energy (Buonomano et al., 2015) have been reported in literature. Many researchers have analyzed ORC based hybrid system using VARS (Al-Sulaiman et al., 2011), VCRS (Wang et al., 2011) and other cooling system, like, liquid desiccant cooling system (Jradi and Riffat, 2014) and ejector cooling system (Wang et al., 2012), a cooling unit.

2.2 Waste heat/Thermal energy powered orc based hybrid systems
Energy sectors use conventional fuels and wasting enormous energy. In this regard, researchers have been trying to use waste heat as an alternative energy source to produce useful commodities (Javan et al., 2016). Hybrid systems enable the recovery of the waste heat in the thermal systems and improve efficiency as well as make systems cost-effective. Hybrid systems that produce heating, cooling and/or power simultaneously have become a potential alternative to overcome environment problem. Many researchers have used waste heat as an energy source and analyzed ORC integrated VARS based hybrid. Ahmadi et al. (2012) used waste heat energy of gas turbine to run the ORC integrated VARS and reported 89% and 55% energy and exergy efficiency, respectively. Chaiyat and Kiatsiriroat (2015) focused on feasibilities of energy, economic and environmental aspects of diesel burner based waste heat powered ORC with absorption cooling system and reported 10 years of the payback period. Fang et al. (2012) recovered waste heat based combine ORC, VARS, and coil based heating system for dynamically adjustable electricity to thermal energy ratio.

Few researchers have also analyzed waste heat ORC system with VCRS. Wang et al. (2011a) integrated micro scale ORC with VCRS and reported overall COP about 0.48. Wang et al. (2011) analyzed hybrid ORC-VCRS with subcooling as well as with subcooling and recuperation. The reported overall COP is 0.54 with basic VCRS, 0.63 with subcooling, and 0.66 with subcooling and recuperation (Wang et al., 2011b). Moles et al. (2015) analyzed low-temperature ORC powered VCRS based hybrid system for different low GWP working fluids and reported a payback period of 3.3 years. Dai et al. (2009) analyzed waste heat (composed of 96.16% N_2, 3.59% O_2, 0.23% H_2O, and 0.02% $NO+NO_2$ by volume) energy powered ORC integrated ejector refrigeration cycle and reported thermal and exergy efficiency about 13% and 22%, respectively. Javan et al. (2016) utilized waste heat of the diesel engine to run the ORC based ejector refrigeration cycle and carried out fluid selection optimization for residential applications. Yang et al. (2016) analyzed ORC integrated ejector cycle using zeotropic mixture isobutane/pentane with 0.4%, 0.7% and 0.8% mass fraction.

2.3 Solar-thermal energy powered orc based hybrid systems
In past years, researchers are involved in improving existing solar thermodynamic cycles and finding a newer one to reduce environmental problems. Various solar technologies, like parabolic trough collector (PTC), linear Fresnel collector (LFR), paraboloid dish, evacuated tube collector, flat plate collector, and central tower technology etc. are used in different thermodynamic cycles. Many researchers have integrated low-temperature solar technologies with the ORC as it has a lower evaporation temperature. Solar-ORC based hybrid systems use various cooling systems e.g. VCRS, VARS and ejector cooling system etc. For example, Al-Sulaiman et al. (2011a) integrated PTC, ORC and VARS to generate combined cooling, heating and power. Al-Sulaiman et al. (2011) reported overall efficiency for organic Rankine cycle based hybrid systems powered by solar thermal energy (90%), solid oxide fuel cell (76%), and biomass (90%). Suleman et al. (2014) analyzed integrated solar geothermal cycle where solar-powered ORC integrated with VARS for cooling along with the drying process and geothermal powered ORC for power generation. The overall energy and exergy efficiencies of the system/cycle are found to be 54.7% and 76.4%, respectively. Buonomano et al. (2015) performed a thermodynamic and economic analysis of microscale ORC powered VARS using combine source of solar-thermal and geothermal.

Karellas and Braimakis (2016) analyzed solar (using PTC)-biomass energy powered ORC integrated VCRS system with R134a, R152a, R245fa working fluids in the system. Chang et al. (2017) analyzed hybrid proton exchange membrane fuel cells (PEMFC) energy powered ORC with compression system. Bu et al. (2013) have done performance analysis and fluid selection of ORC integrated vapor compression chiller for ice making. R123 is revealed as the most suitable fluid among selected R123, R245fa, R600a and R600 working fluids for ORC-VCC pair.

Wang et al. (2012) analyzed flat-plate collector powered ORC integrated ejector refrigeration cycle for different modes, like combine power and cooling, combine power and heating and power mode. Boyaghchi and Heidarnejad (2015) analyzed solar evacuated tube collector based ORC integrated ejector cooling unit and reported 23.7% energy efficiency and 9.5% exergy efficiency during summer mode. Rostamzadeh et al. (2017) investigated the performance of solar energy powered ORC integrated ejector refrigeration cycle and reported R123/isobutene as most appropriated fluid pair among R123, R245fa, and isobutane ORC working fluids.

2.4 Biomass energy powered ORC based hybrid systems
Biomass-based renewable energy can be utilized to reduce usage of fossil fuels and negative environmental impact. Numerous techniques and devices are available to extract energy from waste biomass. Biomass energy based systems hybrid systems enable low carbon footprint and a lower energy cost compared to conventional fossil fuel based systems. Due to the lower efficiency of the biomass-fueled power system, the system is mostly integrated with the heating and/or cooling systems to increase overall efficiency.

Many of the researchers have integrated biomass-powered organic Rankine power cycle with the different cooling cycle, like, VCRS, VARS, ejector system, dessicant unit etc.

Al-Sulaiman et al. (2012) analyzed 500 kW ORC integrated absorption unit for combined cooling, heating and power applications and reported 89% energy efficiency and 28% exergy efficiency. Huang et al. (2013) carried out a techno-economic analysis of small-scale biomass driven ORC integrated absorption cooling system. The variation in efficiency is within the range of 1% for power mode, 5% for combined heat and power mode, and 4% for trigeneration mode (Huang et al., 2013). Maraver et al. (2013) studied different organic working fluids for small and large-scale biomass assisted hybrid systems. Organic working fluids R245fa, R134a, and R152a are suitable for 20 to 35°C condensing temperature and small scale applications; however, npentane, toluene, and siloxanes are suitable for 60 to 80°C condensing temperature and large scale applications. Amirante et al. (2016) performed an energetic and economic analysis of biomass-based hybrid system which comprises commercially available 280 kWe organic Rankine cycle unit and absorption chiller for air conditioning of airport building. The reported payback period and internal rate of return are 6 years and 21%, respectively.

Karellas and Braimakis (2016) used combine biomass-solar energy source for ORC integrated compression unit for micro scale applications. The system is analyzed with R134a, R152a, R245fa working fluids and reported 7 years payback period. Jradi and Riffat (2014) experimentally investigated micro-scale biomass-based hybrid system using the liquid desiccant cooling system and reported an overall efficiency of 83% for combined heat and power mode and 85% for trigeneration.

2.5 Geothermal energy powered orc based hybrid systems

Based on the source temperature, geothermal energy has the potential to generate power, heating and cooling and used in various applications, like, industrial drying, distillation and desalination. Usage of low-temperature geothermal source with an organic Rankine cycle has great potential for power generation. Few researchers have integrated geothermal powered ORC with different cooling technologies.

Suleman et al. (2014) developed hybrid cycle based on two ORC units powered by solar energy (for power generation, drying process and VARS based cooling) and another ORC runs on geothermal energy for power generation. Zare (2016) performed thermodynamic optimization of ORC integrated absorption cycle for trigeneration application and reported isobutene as a promising working fluid compared to n-pentane, R245fa, and R152a. Akrami et al. (2017) carried out an energetic and exergo-economic assessment of geothermal ORC integrated absorption cycle and reported 35% energy efficiency and 49% exergy efficiency.

2.6 Micro scale organic Rankine cycle

Recent interest in small and micro scale organic Rankine cycle has coincided with increasing energy demand and carbon emission. Renewable thermal energy based ORC is also gaining importance due to the generation of decentralized power. Moreover, ORC plants avoid the requirement of an on-site operator. Medium and small-scale ORC unit manufacturers are not available in India. Therefore, there is no penetration of ORC systems in the Indian market. The development of indigenous ORC would serve as an economic solution as it reduces the levelized cost of energy and specific investment cost.

Small and microscale ORC units, with 0.5 to 30 kW capacity, have been successfully demonstrated in the literature. Different energy sources, like, geothermal, waste heat, biomass, solar thermal, and natural gas have been used in literature to achieve source temperature in a range of 70-200°C. Organic working fluids, like, n-pentane, R123, R245fa, HFE7100 and R134a have been used in small-scale ORC. The reported expander isentropic efficiency range is about 40-80% and as a result, the thermal efficiency of the cycle is in the range of 3-14%. The isentropic efficiency of the expander and the cycle efficiency are affected by different parameters, like, heat source temperature (66 to 165°C), working fluid, operating expander pressure ratio (2 to 6.5), expander type (scroll, screw, radial etc.), etc. Few researchers have experimentally investigated ORC test rig for the combined heat and power (CHP) mode and the reported CHP efficiency is in the range of 75-88%. Typically, in the theoretical analysis for different capacities of ORC systems, wide variations in the cost data are observed. The cost of the microscale ORC power block to be reported about 2264-4516 USD/kWe (Quoilin et al., 2011) and 1080-6360 USD/kWe (Maraver et al., 2013).

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