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Review

Review of organic Rankine cycle for small-scale applications

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The ever-increasing demand for energy, scarcity of traditional energy sources and severe environmental issues are, perhaps, the biggest global challenges that need immediate actions. In this regard, harnessing the renewable energies and waste heat recovery are considered as potential solutions that can effectively address these issues. Organic Rankine cycle (ORC) is proved to be reliable technology that can efficiently convert these low to medium-grade heat sources into useful power. This paper is a comprehensive review of literature about the ORC that contains the ORC configurations, ORC applications, ORC working fluid selection and modelling and experimental study of the ORC expansion devices.

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1. Introduction

Nowadays energy is a key factor in the global economy and is considered as a crucial input for all industrial and production processes. The effectiveness of energy generation and consumption processes has remarkable impacts on our society and environment. Following the international energy agency (IEA) report [1], extending the current trend of energy consumption and energy efficiency to 2050 yields a growth of 70% and 60% in the global energy demands and emissions respectively compared to 2011. The associated emissions result in a long-term global average temperature rise of 6 °C by 2050 which can result in potentially devastating consequences such as climate change, energy security and unsustainable future. IEA (2014) suggested an effective scenario called "2DS" which offers a vision for a sustainable energy system that reduces carbon dioxide (CO_2) emissions to maintain the global temperature rise within 2 °C by 2050. The "2DS" scenario offers drastic actions to industry, energy sector key players and policy makers to substantially improve the energy efficiency of systems in order to limit increases in the energy demand by 25% and cut emissions by 50% during the next 40 years. This strategy creates a framework that can simultaneously deliver secure, affordable and environmentally sustainable energy systems and shifting the energy landscape as a whole. Such scenario requires necessary actions in all aspects as there is no single technology, energy source or policy that can be solely employed to decarbonize the energy systems in line with the "2DS". In contrast, it demands a mix of actions including utilization of renewables such solar, wind and geothermal energies, smart transmission and distribution of electricity, electrification of transportation sector, enhanced international and regional cooperation [1]. In essence, the future sustainable energy systems are expected to be smarter, renewable oriented, integrated, well regulated and more distributed.

Improvements in energy efficiency have significant contribution to the "2DS" scenario. For example, power in the traditional electrical grid (or centralized power generation) followed one way from the generation station to the load. The traditional grid uses the highest possible voltage level to transmit and distribute large quantities of power. During this transport there are associated losses that accounts for 12% of power and 30% of delivered electricity cost as reported by [2]. In addition, there are implicit costs in terms of carbon emissions in which the fuel that is consumed to generate electricity is not fully used by the end user. Therefore, it is necessary to minimize these losses in order to increase the energy efficiency of the system. Moreover, centralized power generation (CPG) requires large capital investment cost for electrification of remote areas where the infrastructure requires the electricity but at low quantities. Moreover, CPG suffers from costly investment of about 3500 billion dollars for OECD counties for upgrading the transmission and distribution network [3], high cost of electricity deregulation and control devices and harmful environmental impacts due to the use of fossil fuels.

In this regard, distributed (on-site) power generation (DPG) is a promising alternative that overcomes all the deficiencies of the CPG. Distributed power generation is an independent electric source connected directly to the distribution network or to the customer site with the power ratings shown in Table 1 [4]. DPG is becoming a new trend in the world's ever-increasing demand for energy as it exhibits unique advantages such as reduced transmission and distribution losses, emergency backup power in the case of power outage for hospitals, telecommunications centres and data storage centres, lower damages and economic losses in the case of natural disasters, environmentally friendlier than CPG, versatility for suppling the power demand into remote areas (i.e. sub-Saharan Africa) and security and reliability due to its compatibility with wide range of fuels. In fact DPG can utilise any source of energy including solar, geothermal or waste heat.

Table 1
Power rating of DPG systems [4].

Category	Power rating
Distributed micro power generation	1 W to 5 KW
Distributed small power generation	5KW to 5 MW
Distributed medium power generation	5 MW to 50 MW
Distributed large power generation	50 MW to 300 MW

About 50% of the world's energy consumption is wasted as heat due to the limitations of energy conversion processes [5]. This waste heat can be from variety of sources such as industrial and household waste heat, gas and steam turbines exhaust heat, internal combustion engines exhaust heat, solar radiation, geothermal heat and biomass heat. Adopting waste heat recovery (WHR) with distributed power generation (DPG) systems has a great potential in increasing the system efficiency while reducing the fuel consumption, lowering the CO_2 emissions, reducing demand on the primary fuel because more power can be generated with the same amount of fuel thus enhancing sustainability by increasing the power cycle conversion efficiency [5]. This efficiency gain can be achieved through the implementation of the best available technologies. Compared to the steam Rankine cycle's need for superheating device, Kalina cycle's complex systems structure, Tilateral's flash cycle's difficult two-phase expansion, supercritical CO_2 cycle's high operating pressure and thermoelectric generator's expensive material and low efficiency, organic Rankine cycle (ORC) has the favourable characteristics of simple structure, high reliability, low cost and easy maintenance. ORC technology proved to be one of the most reliable and efficient solutions that utilizes the waste heat of the above-mentioned thermal heat sources for supplying the electricity demand using the DPG systems. In other words, ORC units utilise the otherwise wasted energies and convert them into useful power in the range of few kW_E to tens of MW_E. The ORC is similar to the steam Rankine cycle, however, it utilizes organic compounds such as hydrocarbons and/or refrigerants that boil at low temperature and pressure compared to the water. This facilitates the ultimate versatility of the ORC to capture almost any low to medium temperature (from 60 °C up to 350 °C) heat sources to generate power. Compared to steam Rankine cycle, the ORC exhibits unique advantages such as small size, low capital and maintenance cost, simplicity, high reliability and low environmental impacts when combined with renewables. Due to this, the ORC technology has been deployed at fast pace during the past few years across the globe and experienced remarkable advances due to the extensive academic research.

This paper reviews the reported work about the ORC which is mainly categorized as thermodynamic modelling of the ORC, optimization of the ORC overall performance metrics such as thermal and exergy efficiencies, selection of appropriate working fluid for a specific type of low-grade heat source such as geothermal heat, solar radiation and biomass heat and modelling and experimental study of the expansion machines (both volumetric and velocity types). Fig. 1 outlines the content of this paper.

2. ORC background

Organic Rankine cycle (ORC) is analogous to the steam Rankine cycle (SRC) as it contains all the main components of the SRC such as evaporator, expansion device, condenser and pump with the only difference that the water is replaced by an organic compound (i.e. hydrocarbons, refrigerants, ethers and siloxanes). In fact the ORC technology is rather old perhaps as old as the SRC. The first patented concept of an engine using ether as the working fluid is