Applied Thermal Engineering 69 (2014) 143–154

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Power generation with ORC machines using low-grade waste heat or renewable energy

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HIGHLIGHTS

- A laboratory-scale beta-prototype Organic Rankine Cycle machine has been studied.
- Cycle efficiency with feed pump at variable full range speed has been determined.
- Energetic and exergetic conversion efficiencies have been experimentally evaluated.
- Various effects of evaporator superheating on the cycle efficiency have been analysed.
- Several cycle improvements and potential industrial application were identified.

ARTICLE INFO

Article history:
Received 10 February 2014
Accepted 19 April 2014
Available online 28 April 2014

Keywords:
Industrial waste heat recovery
Renewable energy
Power generation
Organic Rankine cycle
Energy efficiency

ABSTRACT

By 2030, global energy consumption is projected to grow by 71%. At the same time, energy-related carbon dioxide emissions are expected to rise by more than 40%. In this context, waste and renewable energy sources may represent alternatives to help reduce fossil primary energy consumption. This paper focuses on the technical feasibility, efficiency and reliability of a heat-to-electricity conversion, laboratory beta-prototype, 50 kW Organic Rankine Cycle (ORC) machine using industrial waste or renewable energy sources at temperatures varying between 85 °C and 116 °C. The thermodynamic cycle along with the selected working fluid, components and control strategy, as well as the main experimental results, are presented. The study shows that the power generated and the overall net conversion efficiency rate of the machine mainly depends on such parameters as the inlet temperatures of the waste (or renewable) heat and cooling fluid, as well as on the control strategy and amount of parasitic electrical power required. It also indicates that after more than 3000 h of continuous operation, the ORC-50 beta-prototype machine has shown itself to be reliable and robust, and ready for industrial market deployment.

1. Introduction

In Canada, eight major manufacturing sectors account for over 91% of the energy input to the manufacturing industries and about 71% of the input energy is released to the environment via four classes of identifiable waste heat streams at relatively low temperatures (i.e. up to 370 °C) in the form of stack gases, vapour or liquid effluents [1]. Such energy rejections along with power generation from fossil fuel combustion lead to global warming and ambient air pollution. Generally, heat recovery below 370 °C is not economically feasible for producing electricity with conventional steam-based power generation cycles such as Diesel, Stirling, or basic Clausius–Rankine. The last of these, for example, converts heat into work at higher temperatures by using water as a working fluid, but it becomes inefficient at input temperatures below 370 °C [2]. Consequently, different energy conversion techniques are required to efficiently use low-grade "free" waste heat resources for power generation [3–6]. Among these alternatives, Organic Rankine Cycle-based (ORC) machines, similar to basic Clausius–Rankine power plants, do not use water, but rather vaporize high-molecular-mass fluids (also known as *organic* fluids) with boiling points below that of water [7,8]. ORC machines can use various types of low-grade industrial waste heat or renewable (solar, biomass, geothermal) energy sources. But, in spite of their well-known advantages over conventional high-temperature water steam cycles (e.g. lower operating pressures and temperatures, smaller size, and lower complexity and costs), ORC machines have not been widely used so far, mainly because of concerns about their economic feasibility, lower heat-to-power conversion efficiency, and, in certain cases, parasitic energy consumptions.

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http://dx.doi.org/10.1016/j.applthermaleng.2014.04.054
1359-4311/

2. Experimental set-up

A 50 kW beta-prototype ORC machine was designed, built [9], and installed on a laboratory test bench [10–12]. The prototype includes a single-stage twin screw expander, a stainless steel condenser and pre-heater/evaporator heat exchanger assembly, a liquid receiver, and a working fluid variable speed circulation pump (WFP) (Fig. 1). The machine is scalable, allowing for the connection of multiple similar units to a single heat source if enough energy is available. If these units are installed in parallel, enough hot water flow rate for each machine is needed. If they are connected in series with one using hot water from the pre-heater outlet of the other, the heat source entering temperature will need to be high enough, as well.

Routine maintenance is easy, and with a basic set-up, technicians with an HVAC and mechanical background can handle required maintenance. Additionally, the control system is fully automated, allowing for remote control and monitoring via an Internet connection, as well as off site maintenance. The small footprint, skid-mounted ORC-50 machine has been connected to a 700 kW electrical boiler, simulating the waste (or renewable) heat source, to an air-cooled liquid cooler, and to the Hydro-Québec electrical grid. The machine converts into electrical power the thermal energy recovered from the waste (or renewable) heat entering the machine in a liquid form (water) at temperatures varying from 85 °C up to 125 °C. The ORC-50 machine's output power ranges from 20 to 50 electrical kW, depending on the inlet temperatures and flow rates of the source and sink heat sources, respectively.

The system was comprehensively instrumented with thermocouples, power and pressure transducers, flow meters for the working fluid, and both organic fluid, heat source, and sink thermal carriers. A data transmission system and associated analysis software were set up to monitor system operation. All parameters were scanned at 15 s intervals, then averaged and saved every minute, to help determine the cycle's instantaneous and overall thermodynamic performance.

2.1. Thermodynamic cycle

The low-pressure (p_1) organic fluid leaving the condenser as a saturated or sub-cooled liquid (state 1) accumulates inside the receiver in equilibrium with its vapour phase (see Figs. 1 and 5). Then it enters the working fluid feed pump (WFP) where its pressure is adiabatically raised to the saturation (evaporating) pressure (p_2) (state 2s), prior to entering the pre-heater/evaporator heat exchanger assembly. The multistage feed pump is driven by a variable frequency drive (from 0 to 60 Hz) in order to supply the flow rate required to achieve a relatively small superheating effect (i.e. below 5 °C) at the evaporator outlet [13]. Also, between 10% and 15% of the organic fluid flow rate leaving the feed pump is injected into the expander at both the inlet and outlet ports.

Since the exergy destruction rate in the feed pump is relatively small, the 1–2s process is considered as isentropic (adiabatic), and the power input is expressed as

$$W_p = \frac{W_{p,ideal}}{\eta_p} = \frac{\dot{m}_{OF}(h_{2s} - h_1)}{\eta_p} = \frac{\dot{m}_{OF}(p_2 - p_1)}{\rho \eta_p} \quad (1)$$

where $W_{p,ideal}$ is the feed pump ideal power input (kW), η_p – the feed pump isentropic efficiency (90%), $\dot{m}_{OF}$ – the organic fluid mass flow rate (kg/s), h_1 and h_{2s} – the organic fluid mass enthalpies at the inlet and outlet ports of the feed pump in the ideal case, respectively (kJ/kg), p_1 and p_2 – the organic fluid pressures entering and leaving the feed pump, respectively, and ρ – the organic fluid average mass density (kg/m^3). On the other hand, the waste heat fluid carrier (water) enters the evaporator where it transfers heat to the working fluid during the evaporation and superheating processes (3–4–5). At the evaporator outlet, approximately 20% of the waste heat fluid (water) flow rate enters the pre-heater to partially or completely preheat the organic fluid from the sub-cooled liquid state (2s) up to (near) the saturated state (2a). The preheated organic fluid enters the evaporator at state 2a where it will vaporise and superheat at a constant pressure (process 2a–3–4–5). The pre-heater/evaporator thermal power recovered from the waste heat source is given by

$$\dot{Q}_{pre-heat/ev} = \dot{m}_{OF}(h_5 - h_{2a}) \quad (2)$$

where h_5 and h_{2a} are the organic fluid mass enthalpy leaving and entering the pre-heater/evaporator, respectively (kJ/kg). The pre-heater/evaporator assembly was designed and selected to optimally work with hot water flow rates in the range of 7.6–12 l/s (120–200 GPM). Its thermal efficiency versus size and cost was carefully analysed in order to achieve optimum pinch points defined as the differences between the corresponding waste heat (source) temperature and the temperature at which the organic fluid begins to vaporize [9].

The high-pressure saturated (state 4) or superheated vapour (state 5) leaving the evaporator enters the twin screw expander. It

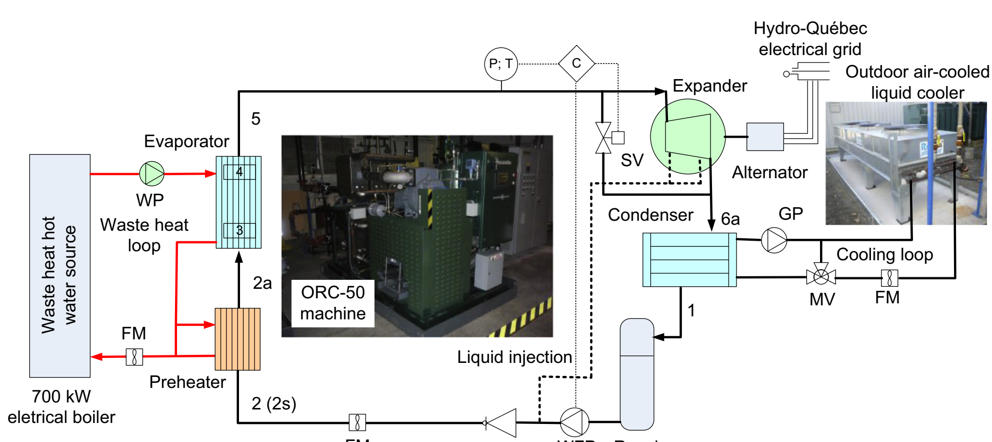

Fig. 1. Schematic representation of the experimental setup [9–11]. C – controller; FM – flow meter; GP – cooling fluid (water/glycol) pump; MV – mixing valve; P – pressure; T – temperature; WP – waste heat thermal carrier (water) pump; WFP – working fluid pump; SV – solenoid valve.