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Analysis of a novel gravity driven organic Rankine cycle for small-scale cogeneration applications

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HIGHLIGHTS

- A novel gravity driven ORC is proposed.
- The necessity of the proposed ORC is discussed.
- The pressure loss of the novel system is estimated.

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ABSTRACT

A naturally-controlled organic Rankine cycle (ORC) without negative work is proposed. Compared with conventional ORCs, the novel system uses gravity instead of a pump to pressurize the working fluid, and hence the problems associated with the pump can be avoided. A possible application of the gravity driven ORC for combined heat and power generation is presented to outline the feasibility. Mathematical models are built. The required height for pressurization and the cycle efficiency varying with the condensation and evaporation temperatures are analyzed on using R123, R245ca, R113, PF5050 and PF5060. The results reveal that on the same condition of operating temperature, the required height for pressurization may vary drastically when the working fluid is different. Fluid of high liquid density and low saturation pressure offers a low height. The power efficiency of the novel ORC is adequate for low temperature applications. With an expander efficiency of 75%, evaporation temperature of 100 °C and condensation temperature of 40 °C, the highest efficiency is about 10.2% with fluid of R123, which is 0.9% higher than that of the pump driven ORC. And the lowest required height is only about 20.9 m with fluid of PF5060. The proposed ORC has both cost and efficiency advantages.

1. Background

The organic Rankine cycle (ORC) is one of the most promising technologies in low temperature applications. The latent heat of vaporization of ORC fluids is generally one to two orders of magnitude lower than that of water at temperature around 100 °C [1], which provides a larger flow rate and makes the design of expander easier at low power. By using dry fluids, superheat at the expander inlet can be avoided, which improves the cycle efficiency. Besides, the difficulty of maintaining a vacuum below 5 kPa in the steam condenser does not exist in the ORC when using a fluid of low boiling point, and adequate expansion and larger enthalpy drop are available for the fluid at low temperature. These advantages make the ORC suitable for distributed solar thermal power, waste heat recovery, biomass and geothermal power generation.

In particular, there is growing interest for small-scale ORC applications [2]. ORC units of several kWe to tens of kWe have great potential to meet the residential energy demands. Electricity and heat can be supplied near the point of use, and small scale ORCs are suitable for off-grid cogeneration. And the size of the ORC plant is limited by both the low energy density of heat sources and the availability of energy consumers. The energy density of most biomass feedstocks is generally low, which is between about 10% and 40% of that of fossil fuels. Biomass's low energy density and scattered sources push up the cost of logistics, and it will be very expensive for large scale collection, transportation and storage. Solar radiation has also relatively low energy density, and it is generally unavailable to harvest solar energy over large areas near residential buildings. Moreover, consumer demand is driving the growth of the small power market. Some major new growth opportunities are arising in small/mini power systems, stimulated by low carbon policies, an array of new products, energy efficiency trends and a brighter long-term outlook for gross margin as shown in recent research reports [3].

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Nomenclature

A	area, m^2
C	wetted perimeter, m
D	diameter, m
e	roughness, m
f	friction factor
g	gravitational acceleration, m/s^2
H	height, m
h	specific enthalpy, J/kg
L	length, m
m	mass flow rate, kg/s
p	pressure, Pa
Q	heat, W
Re	Renolds number
s	entropy, J/kg/°C
V	velocity, m/s
W	power, W
ε	machine efficiency
η	system efficiency
ρ	density, kg/m^3

Subscripts

1–5	state points
c	condenser
D	diameter
e	evaporator
f	friction
g	gravity
p	pump
in	input
l	liquid
s	isentropic
t	shaft power
v	vapor

On the other hand, the problems the ORC has to meet are also obvious. And one is that due to the low temperature difference between the hot and the cold sides, the heat to power efficiency of the ORC is much lower than that of fossil-fired steam plants. This problem is extremely critical for small-scale ORCs. For example, with a boiler outlet temperature of about 120 °C and a condenser outlet temperature of about 45 °C, the electricity generation efficiency of a demonstrated biomass-fired ORC CHP system was only 1.41% [4]. Most of the exergy was destroyed by low power mechanical devices including expander, alternator and pump which are characterized by relative low efficiencies. The low electricity efficiency of a practical solar ORC was also reported, which was about 3% [5]. And even net-energy negative ORC was demonstrated [6,7], for which more power was required to run the system than that produced.

Given a low cycle efficiency, the pump may play an important role. To get a better understanding of this, a comparison between the ORC pump and the pump used in the steam Rankine cycle can be made.

First, the global pumping efficiency in a small ORC is expected to be much lower than that in the steam Rankine cycle. The reasons are given as follows: (1) The self-efficiency of the ORC pump, which is defined as the ratio of the theoretical power requirement to the power delivered to the pump shaft [7–9], is low. Centrifugal pumps are currently widely used to drive refrigerants [10–12]. The volumetric loss due to leakage of fluid between the back surface of the impeller hub plate and the casing, and the hydraulic loss caused by the friction between the fluid and the walls, acceleration and retardation of the fluid and the change of the fluid flow direction are usually more appreciable when the size of the pump decreases. Compared with the large centrifugal pump offering an efficiency of 90% in the steam Rankine cycle [13], the small centrifugal pump has a much lower efficiency, which is normally 50% in kW range [11,12,14]. The low efficiency is also reported for positive displacement refrigerant pumps [7]. (2) The shaft power of a pump is transmitted by a prime mover, which can be a diesel, gasoline engine or motor. Among the drivers for pumps, the induction motor is most popular due to its simple construction [15]. The motor is equipped with a pump and coupling, and its efficiency is defined as the ratio of the shaft output power to electrical input power [8,16]. Similarly to the pump, the motor friction loss, bearing loss, electrical and magnetic losses become larger at smaller sizes. An efficiency of 50–75% is common for small motors [11,15,17]. Aside from motor, frequency converter is preferably used to control the pump in an energy-saving way [15]. By converting a current with one frequency to a current with another frequency, a converter controls the speed and the torque of the motor, offering attractive energy conservation when the power requirement of the pump is not constant. However, power loss exists in this conversion. Regarding to these inefficiencies, the "wire-to-liquid" efficiency during pumping can be as low as 30% even at design operation (efficiency of 50% for pump, 65% for motor and 90% for converter, respectively). (3) Cogeneration of the ORC leads to energy savings compared with stand-alone systems. One challenge along with cogeneration is that consumers' demands for heat and power vary with time and season, and hence a flexible trade-off between the needs for heat and power should be allowed. Heat source properties of the ORC (e.g. the intensity of solar radiation, the heating value of biomass) also vary with time and season. The variable operation is generally unavoidable for small scale ORC systems [18]. The off-design operation will lead to further decrements in efficiencies of pump, motor and converter. And a global pumping efficiency of about 20% can be expected in the practical operation (efficiency of 45% for pump, 55% for motor and 85% for converter, respectively).

Second, the negative work done on the ORC pump is much more appreciable. In the steam Rankine cycle the power consumed by the pump is only 1–2% of the expander output work [19]. In approximating the cycle output, the power for water pumping is generally negligible. But this neglect will be not reasonable for the ORC. Suppose the ORC has a global pumping efficiency of 20%, expander efficiency of 75%, generator efficiency of 80%, evaporation temperature of 120 °C and condensation temperature of 50 °C, the ratio of the required power for pumping to the positive electricity generated is about 21% on using R245ca. The net cycle efficiency can even be zero or negative depending on the power consumption for pumping [6]. Among the components of the conventional ORC, the pump tends to cause the most critical decline in the net cycle efficiency [20].

Third, the technical requirement of the ORC pump is stricter. One common problem associated with the water pump is the leakage. Unlike water, most of ORC fluids are either toxic, flammable, ozone layer depleting or have global warming impact. The ORC pump must be very well sealed in order to prevent loss of the fluid to the atmosphere. And any inward leakage of air into the pump should be prevented. Great attention must also be paid to the