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Evaluation of external heat loss from a small-scale expander used in organic Rankine cycle

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ABSTRACT

With the scaling down of the Organic Rankine Cycle (ORC), the engine shaft power is not only determined by the enthalpy drop in the expansion process but also the external heat loss from the expander. Theoretical and experimental support in evaluating small-scale expander heat loss is rare. This paper presents a quantitative study on the convection, radiation, and conduction heat transfer from a kW-scale expander. A mathematical model is built and validated. The results show that the external radiative or convective heat loss coefficient was about 3.2 or 7.0 W/K·m^2 when the ORC operated around 100 °C. Radiative and convective heat loss coefficients increased as the expander operation temperature increased. Conductive heat loss due to the connection between the expander and the support accounted for a large proportion of the total heat loss. The fitting relationships between heat loss and mean temperature difference were established. It is suggested that low conductivity material be embodied in the support of expander. Mattress insulation for compact expander could be eliminated when the operation temperature is around 100 °C.

1. Introduction

Among many well-proven technologies, organic Rankine cycle (ORC) is one of the most favorable and promising ways in low to medium-temperature applications. Substantial improvements have been made in ORC technology in the past decade. Moreover, there is mounting interest for kW-scale ORC applications, such as small-scale solar ORC for rural cogeneration, biomass-fired combined heat and power (CHP) system, and small ORC for waste heat recovery. The interest for small-scale ORC is reinforced by the following aspects: 1) Small-scale production of electricity at or near customers' homes and businesses could improve the reliability of power supply. 2) Local generation leads to smaller scale power plants which exclude traditional steam cycles that are not cost-effective [1]. And heat demand can be fulfilled by domestic heating, which results in an increase in the overall energy conversion efficiency of ORC. 3) The size of the ORC plant is limited by the low energy density of heat sources. Biomass typically contains more than 70% air and void space and is difficult to collect, ship, and store. Solar radiation is generally less than 1000 W/m^2, and a large area to gather an appreciable amount of energy is difficult to obtain. Yet more than 90% of the availability of waste heat worldwide is available to the 10–250 kW system size [2]. 4) The size of the ORC plant is also limited by the availability of energy consumers. Many applications in residential areas only require several to tens of kWe for pumping, refrigerator, air conditioning, and so on. The market potential for small ORC is becoming more and more significant as the environmental protection, economical development and climate change control become more and more urgent [3].

Both theoretic and experimental works have been done on small-scale ORC. And the research on this topic is growing fast. Riffat et al. designed and tested a 1.34 kW ORC-based CHP system assisted by fuel gas. The electrical efficiency was 16% and the overall efficiency was about 59%. Further analysis showed that the proposed system would save primary energy of approximately 3150 kWh per annum compared with conventional electricity and heating supply systems, which would result in reduced CO_2 emission of up to 600 tons per annum [4]. Peterson et al. presented a study on the performance of a small-scale regenerative Rankine power cycle employing a scroll expander. The system efficiency was about 7.2% [5]. Manolakos et al. presented the detailed laboratory experimental results of a low temperature ORC engine couple with a reverse osmosis desalination unit. The results indicated that the efficiency of the Rankine cycle fluctuated from 3.5% to 5.0% [6]. Liu et al. developed and evaluated a biomass-fired micro-scale CHP system. The system generated 284 W electricity, corresponding to

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1.34% electric efficiency and 88% overall CHP efficiency [7]. Gang et al. examined the innovative solar ORC system with two-stage collectors and a regenerative cycle suitable for domestic applications. System performance was estimated based on the commercial collector and expander. The heat collection efficiency could be improved by using two-stage collectors, and ORC efficiency could be increased by the regenerative cycle [8]. Wang et al. designed, constructed, and tested a prototype low temperature solar ORC system. With a 1.73 kW rolling-piston expander, the overall power generation efficiency was estimated at 4.2% or 3.2% for evacuated or flat plate collectors, respectively [9]. Yamada et al. proposed a new pumpless micro-ORC for power generation from low temperature heat sources. Switching valves and expander emulated by expansion nozzle were employed. The experimental results confirm that this cycle works and that it has the potential to produce power [10].

Expander is the key issue of small-scale ORC system. James et al. presented an experimental test of relatively cost-effective gerotor and scroll expanders, which produced 2.07 and 2.96 kW, and had isentropic efficiencies of 0.85 and 0.83, respectively. Both expanders had significant potential to produce power from low-grade energy [11]. Lemort et al. performed an experimental study on the prototype of an open-drive, oil-free scroll expander integrated into an ORC working with refrigerant R123. The maximum delivered shaft power was 1.82 kW, and the maximum achieved overall isentropic effectiveness was 68%. Internal leakages and, to a lesser extent, supply pressure drop and mechanical losses, were the main losses affecting the performance of the expander [12,13]. Liu et al. presented simulation and experiment research on wide ranging working process of scroll expander driven by compressed air. The maximum volumetric efficiency is 0.69 with the clearance of 0.04 mm [14].

A summary of recent experimental work on small-scale expanders is shown in Table 1. The studies on expanders with capacity ranging from a few to tens of kW are beginning to accumulate. However, little attention has been paid to external heat loss from low power expanders. An assumption of adiabatic expansion process was generally adopted in previous works. In order to get a better understanding of the significance of evaluating the external heat loss, four considerations are made as follows.

1) Unlike traditional MW turbines that may need to operate above 500 °C, small-scale ORC can operate off a heat source of around 100 °C. Although it was once a reasonable concern that inadequate steam turbine insulation could cause uneven or rapid temperature changes in turbine shells, thus resulting in contact and damage to packing seal teeth, this concern seems unnecessary for ORC expanders due to the low temperature difference between the expanders and the environment. And small-scale expander together with generator, is generally rooted on a solid support to ensure reliable transmission of the shaft power. Due to the irregular expander shape and the connections between the expander and pipes, thermal insulation would be quite complicated. And repair and maintenance are frequently needed, such as adding oil to the expander. Outer cladding would be wasteful or would make the work inconvenient.

The elimination of outer cladding offers advantage from both the economic and operational points of view. On the other hand, convective and radiative heat loss from the expander will become larger without thermal insulation. An evaluation should be made first to provide reference information about the convective and radiative heat loss.

2) The expander will undergo conductive heat transfer due to the connection between the expander and the support in the ORC practical operation. A calculable amount of heat loss in comparison with the enthalpy drop through the expander might proceed even though it is well clad. A revealing study into the conductive heat loss is therefore necessary.
3) With the scaling down of expanders, both the heat transfer coefficient and the ratio of expander surface over power output increase. The expander shaft power output is then determined by the enthalpy drop in the expansion process and the external heat loss from the expander. The latter might be appreciable and might alter the net power of the small-scale engine [15].
4) Previous studies on small-scale ORCs were inclined to assume zero heat loss in the expansion process, regardless of the possibility that heat loss might be appreciable in a non-adiabatic operation. The expander or ORC efficiency according to the non-rigorous assumption may deviate from the true value.

Considering the above mentioned points properly evaluating the expander external heat loss is the matter in question. To our knowledge, experimental work on this topic has not been reported yet. This paper presents a close examination of external heat loss from a kW-scale ORC expander. A quantitative study is carried out. The mathematic model of the convective and radiative heat loss to the environment, and conductive heat loss through the support is built and validated. Heat transfer coefficients at various ORC operation temperatures are obtained.

2. A brief system description

A small-scale turbine expander was especially designed and fabricated by the University of Science and Technology of China and Aero-Technology Applying Co., Ltd. for the application in the ORC. Some parameters for the turbine on the normal conditions are as follows.

1. Working fluid: R123
2. Mass flow rate: 500 kg/h

Table 1
Non-exhaustive list of recent experimental work on small-scale expanders.

Participant	Working fluid	Type of expander	Expander efficiency	Cycle electric efficiency
Peterson et al.	R123	Scroll expander	0.40–0.50	7.2%
Yamada et al.	R245fa	expansion nozzle	unavailable	0.24–0.62%
Liu et al.	air	Scroll expander	0.69	unavailable
Jame et al.	R123	Gerotor/Scroll expander	0.85/0.83	7.7%
Manolakos et al.	R134a	Scroll expander	0.30–0.50	3.5–5.0%
Liu et al.	HFE-7000 HFE-7100	turbine expander	unavailable	1.34% (CHP system)
Wang et al.	R245fa	Scroll expander	0.45	5.8%
Lemort et al.	R123	Scroll expander	0.42–0.68	unavailable

Refs. [5–7], [9–12]; [14].