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Evaluation of ejector performance in an organic Rankine cycle

Kun Zhang [a,b,*], Xue Chen [c], Christos N. Markides [b], Yong Yang [c], Shengqiang Shen [c]

[a] School of Ocean and Civil Engineering, Dalian Ocean University, Dalian 116023, China
[b] Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, United Kingdom
[c] School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, China

HIGHLIGHTS

- An organic Rankine cycle system featuring an ejector (EORC) was introduced to provide both power and a cooling capacity.
- The energy losses of an ejector in the EORC system were discussed.
- Improved ejector and EORC designs were made.

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ABSTRACT

Power-generation systems based on organic Rankine cycles (ORCs) are well suited and increasingly applied to the conversion of thermal energy from low temperature heat sources to work. These systems can be driven by waste heat, for example from various industrial processes, as well as solar or geothermal energy. In this paper a combined ORC and ejector refrigeration cycle is considered that is capable of producing useful power while having a simultaneous capacity for cooling. The main energy loss in the combined system takes place in the ejector due to unavoidable losses caused by irreversible mixing. This paper concentrates on the flow in the ejector in order to understand quantitatively the underlying reasons for these energy losses. An appreciation of these mechanisms of loss can be harnessed to propose improved designs for more efficient systems, which would greatly enhance this technology's economic and environmental potential. It is found that some operating conditions, such as a high pressure of the secondary and discharge fluid, lead to higher energy losses inside the ejector and limit the performance of the entire system. Based on the ejector model, an optimal design featuring a smoothed nozzle edge and an improved nozzle position is found to achieve an improved entrainment ratio, significantly better performance and reduced energy losses in the ejector.

1. Introduction

Energy is essential to sustaining life and its careful use is increasingly recognized as playing a critical role in the vast majority engineering, physical and environmental processes. Recovering and utilizing low- and medium-grade heat (typically thought of as heat at temperatures ranging from 60 °C to 300 °C), which includes industrial waste heat but also geothermal energy and solar energy when using non-concentrated or low-concentration collectors, amongst other, is a compelling, significant and promising way to solve the global energy-related challenges sustainably [1,2]. In particular, organic Rankine cycle (ORC) systems are highly suitable for generating power from these low- and medium-temperature heat sources at scales which are most appropriate to distributed power generation up to an order of about 10 MW, and their use has been increasing exponentially in recent years [3,4]. High reliability and flexibility also contribute at making the value proposition of ORC attractive [5–9]. Currently, more than 600 such units are installed worldwide with a cumulative capacity in excess of 2000 MW.

Unfortunately, the current economic proposition offered by ORC systems in many applications is still acting to limit their even greater use in the industrial, but also commercial and domestic sectors. In addition, it is often and increasingly the case that cooling is required due to advancements and an increasing penetration of insulation in many applications. In order to increase the power output capacity and overall efficiency of relevant systems, and to supply a simultaneous cooling capacity, some combined power and refrigeration systems have been proposed in recent years. These systems can improve the overall efficiency of the energy utilization compared to conventional standalone power-generation

* Corresponding author at: School of Ocean and Civil Engineering, Dalian Ocean University, Dalian 116023, China.

E-mail address: cruiseer@hotmail.com (K. Zhang).

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systems. Relevant systems can be classified as belonging to two categories, depending on whether they are based on: (i) absorption combined cycles [10]; or (ii) the ejector combined cycle [11–13].

The former (i.e. absorption combined cycles) have been in use for several decades but the latter are simpler and have been attracting increasing attention in the recent literature. In 1995, Goswami [14] proposed a combined power and refrigeration cycle for use with low-temperature heat sources (<200 °C). This cycle combines a Rankine heat-engine cycle and an absorption- refrigeration cycle using an ammonia-water mixture as the working fluid, as shown in Fig. 1. Many researchers [15–17] have analyzed the proposed cycle both theoretically and experimentally. It is found that the combined cycle proposed by Goswami can utilize low temperature heat sources efficiently. However, the refrigeration capacity of the proposed cycle is relatively small, because the phase of the working fluid does not change during the refrigeration process.

Other investigators have suggested new configurations based on the concept of a combined power and ejector refrigeration cycle, which can supply power and refrigeration simultaneously. The ejector was invented by Sir Charles Parsons in 1901 for removing air from a steam engine's condenser. In 1910, an ejector was used by Maurice Leblanc in the first steam jet refrigeration system [18]. Since energy crisis, ejectors are focused either to totally replace mechanical compressors or simply for cycle optimization, in an attempt to develop energy efficient and environment-friendly techniques, responsible for environmental damages such as ozone depletion or global warming. The basic theory of ejector performance was formulated by Keenan [19,20] who used perfect gas relations. Many theoretical and experimental studies were performed in order to understand not only the fundamental mechanisms in terms of fluid dynamics and heat transfer, but also ejector operational behavior [21–24]. Recent studies [25–27] use real fluid properties since the operating conditions are usually close to saturation. Some studies of combined power and ejector refrigeration cycles are summarized in the next paragraph.

Figs. 2–4 illustrate 3 types of ORC with ejector system, the differences of which are where primary fluid comes from. Oliveira et al. [28] proposed a combined ejector and rankine system, in Fig. 2, which supply electricity and cooling capacity at the same time with only one heat source. The power from generator was divided into two parts to drive turbine and ejector separately. When heat source is 95 °C, COP (coefficient of performance) of refrigeration system achieves 0.3 and power generation efficiency is 3–4%. However, it is difficult to balance pressure from the exit of turbine and ejector.

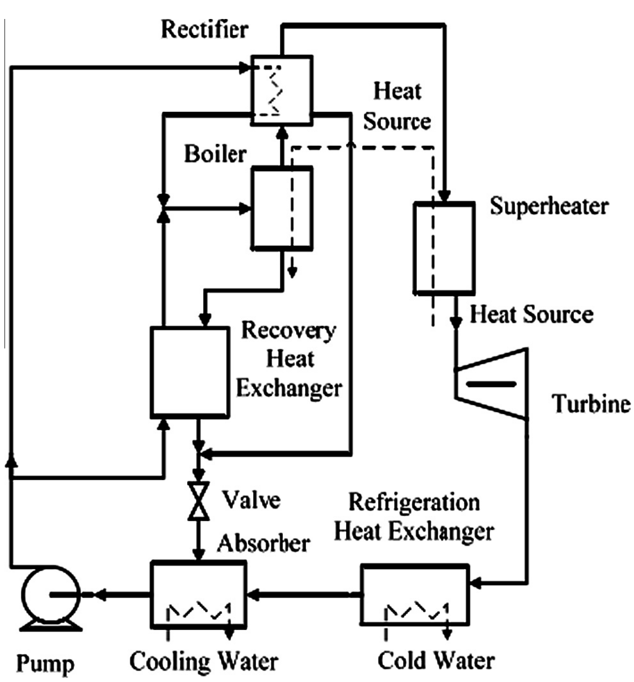

Fig. 1. Schematic of the combined ORC and absorption refrigeration system.

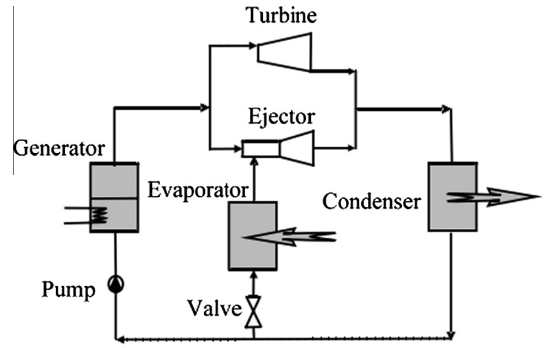

Fig. 2. Schematic of ORC with ejector of primary fluid from generator [28].

Fig. 3 is a schematic of an organic Rankine cycle with ejector (EORC) proposed by Li et al. [29] and Yari et al. [30], which vapor from the second-stage evaporator works as the primary fluid for the ejector to induce the exhaust from the expander so as to decrease the expander backpressure and increase the pressure difference in the expander. It results in an increase of the power output of the ORC, but few cooling capacity is obtained.

In order to utilize the advantages of the ejector-refrigeration cycle and recover low-grade heat effectively, a new system using R123 was proposed by Dai et al. [31]. It combined the Rankine cycle and the ejector-refrigeration cycle by adding a turbine between the generator and the ejector, as in Fig. 4. Thus the fluid expanded in the turbine entered the converging-diverging nozzle of the ejector and mixed with the fluid coming from the evaporator of the refrigeration cycle. The results show that the condenser temperature, the evaporator temperature, the turbine inlet pressure and the turbine outlet pressure have significant effects on the turbine power output, the refrigeration output and the energy efficiency of the combined cycle. They also show that the biggest energy loss occurs in the heat addition processes followed by the ejector. Wang et al. [32] studied a modified version of this combined cycle with the same working fluid and conditions. In this version a part of the fluid flowing through the turbine is bled and enters the converging-diverging nozzle of the ejector. The rest expands further in the turbine and is mixed with the stream coming from the ejector (the latter is the sum of the primary stream coming out of the converging-diverging nozzle and the secondary one from the evaporator). In addition to the conclusions of [31], the new results show that the turbine extraction pressure and extraction ratio have significant effects on the turbine power output, the refrigeration output, the exergy efficiency and exergy destruction in each component of the combined cycle. They also show that the biggest exergy destruction occurs in the vapor generator followed by the ejector and the turbine. This finding is particularly interesting, and important, as it confirms the role of the ejector as a crucially important component whose losses must be considered with particular care if a high overall system efficiency is to be achieved.

Zheng and Weng analyzed the performance of the cycle studied by Dai et al. [31] using R245fa as the working fluid. Their simulation results show that this cycle has considerable potential to pro-