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Research Paper

Investigation of the organic Rankine cycle (ORC) system and the radial-inflow turbine design

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HIGHLIGHTS

- The thermodynamic analysis of an ORC system is introduced.
- A radial turbine design method has been proposed based on the real gas model.
- A radial turbine with R123 is designed and numerically analyzed.

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ABSTRACT

Energy and environment issue set utilizing low-grade heat noticed. Organic Rankine Cycle (ORC) has been demonstrated to be a promising technology to recover waste heat. As a critical component of ORC system, the turbine selection has an enormous influence on the system performance. This paper carries out a study on the thermodynamic analysis of ORC system and the aerodynamic design of an organic radial turbine. The system performance is evaluated with various working fluids. The aerodynamic design of the organic radial-inflow turbine is focused due to the high molecule weight and the low sound speed of the organic working fluid. An aerodynamic and profile design system is developed. A radial-inflow turbine with R123 as the working fluid is designed and the numerical analysis is conducted. The simulation results indicate that the shock wave caused by the high expansion ratio in the nozzle is well controlled. Compared with the one-dimensional design results, the performance of the radial-inflow turbine in this paper reaches the design requirements.

1. Introduction

Energy development strategies demand energy conservation and emission reduction. Industrial sector consumes a large amount of energy, while at least 50% of the fuel energy is lost through the industrial waste heat. It not only causes enormous loss of energy, but also causes serious environmental heat pollution. Therefore, it is essential to recover the heat from industrial low temperature exhaust heat.

One of the main technologies to utilize the low temperature heat is based on the organic Rankine cycle (ORC), in which the water is usually replaced with the organic working fluid on account of high efficiency, simple system and low cost in operation and maintenance.

Many studies have been done on the working fluid property and its influence on the cycle to select an appropriate working fluid. Badr et al. [1] studied the ORC thermal performance of about 70 organic working fluids, including the system operation, security, high efficiency expander design and the economic efficiency of heat exchanger. Papadopoulos et al. [2] developed a method to select organic working fluid based on many related criterions. Liu et al. [3] found that the organic working fluid which has the hydrogen bonds in the molecule, such as water, ammonia water and alcohol, tends to be the wet fluid with a high latent heat of vaporization and unfit to be the organic working fluid for the power system with a low-grade heat source. Mago et al. [4] found out that it is more economical to replace the vapor with an organic working fluid in the ORC system utilizing heat sources below 370 degree centigrade; in view of the thermal efficiency of the system, it is better to utilize a dry fluid than a wet fluid and no use of overheating at the inlet of turbine; it also showed that improving the inlet temperature would reduce the system efficiency at a constant evaporating pressure. Song and Gu [5] examined the potential of using mixtures of a hydrocarbon and a retardant in an ORC system for the engine exhaust gas and the jacket cooling water heat recovery, and solved the matter of flammability of hydrocarbons as the working fluid. Meanwhile, the character of non-isothermal phase change was considered to promote the performance of the system. In the subsequent

Abbreviations: ORC, Origanic Rankine Cycle; GWP, Global Warming Potential; ODP, Ozone Depletion Potential.

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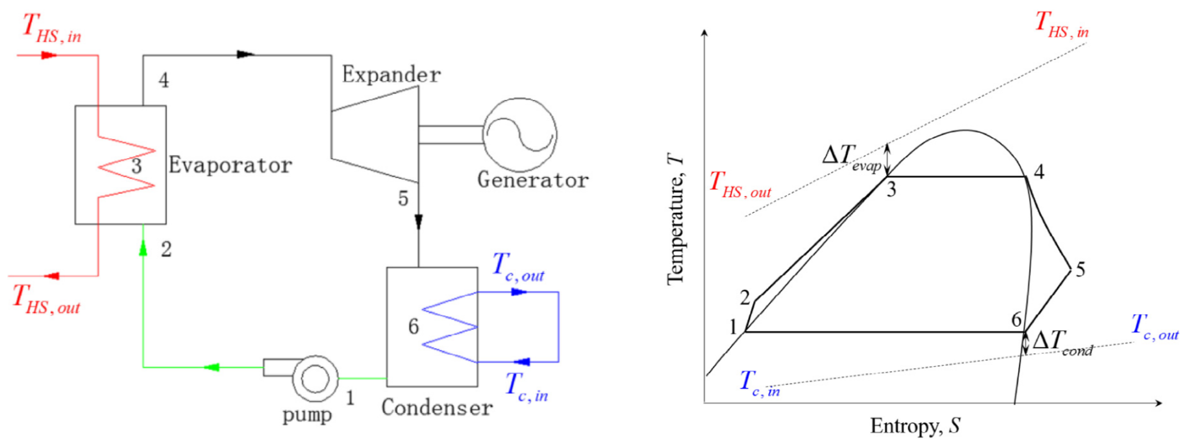

Fig. 1. Schematic diagram of an ORC system (*left*) and *T*–*S* diagram (*right*).

optimization [6], a dual-loop system was proposed, in which the high temperature part was used to recover exhaust gas heat while a low temperature part is employed to recover heat from the cooling water and the cooling unit. Hung et al. [7] compared the performances of ORC systems with different working fluids, i.e., benzene, methylbenzene, p-xylene, R113 and R123, and figured out that p-xylene is the best one for the ORC system recovering heat from 300 degree centigrade heat sources due to a low irreversible loss. R123 and R113 do better in the system recovering heat from 200 degree centigrade heat sources. Maizza and Maizza [8], Borsukiewicz-Gozdur and Nowak [9] and Saleh et al. [10] did research about the output power and thermal efficiency of the ORC system with alkane, ether and its fluoride, or non-azeotropic mixtures as the working fluid to recover heat from 80 ~ 115 degree centigrade geothermal resources or the hot water. It showed that the supercritical working fluid was better than the subcritical working fluid in the heat transfer, and R134a, R152a, R245fa and R227ed are proper choices.

The aerodynamic performance of turbomachinery mainly depends on the aerodynamic design [11–15], and is also influenced by the nozzle, vane and flow path. The Lewis Research Laboratory from National Aeronautics and Space Administration (NASA) did a large amount of research about the aerodynamic design [16,17], performance analysis, performance prediction [18,19] and loss models [20]. Suhrmann et al. [21] surveyed loss models for the high-power radial-inflow turbine and verified their capacity on the small-size turbine (the impeller inlet diameter is less than 40 mm). Based on the comparison between the numerical simulation and the predicted one by the loss model, the modification of the model had been done and their predication capacities were improved. Artt and Spence [22] and Doran et al. [23] did experiment research on a 99.0 mm radial turbine with different nozzle throat areas, and different loss models were analyzed and verified.

In this paper, the thermodynamic design of the ORC system with the given temperature and mass flow rate is presented and its performance with several working fluids is evaluated. The aerodynamic and profile design method for the critical component of the ORC system, meaning the radial-inflow turbine, is focused on the condition that the organic working fluid has a high molecule weight and a low sound speed. Then, a radial-inflow turbine with R123 is designed, containing the aerodynamic design, the profile design and numerical verification. The results indicate that the proposed design method for the radial-inflow turbine in the ORC system has a good capacity and can be applied to the ORC system for the waste heat recovery.

2. ORC system

A basic ORC system consists of a working fluid pump, an evaporator, an organic expander and a condenser. Fig. 1 shows the schematic diagram of a basic ORC system and its *T*–*S* diagram.

The working fluid has an enormous influence on the thermal performance of the ORC recovery system under different heat source conditions. Generally, the organic working fluids can be divided into three categories: dry, isentropic and wet according to the saturation vapor curve slope, as shown in Fig. 2. Here we select the working fluid candidates according to the following principles:

- Proper thermal properties during the cycle;
- Chemical stability under the operating condition;
- Slight impact on the environment – low GWP (Global Warming Potential) and low ODP (Ozone Depletion Potential);
- Security in the system (non-flammable, non-explosive and non-toxic);
- Availability and low cost.

Table 1 shows the primary working fluid candidates. To select the optimal working fluid, thermodynamic analysis of the ORC

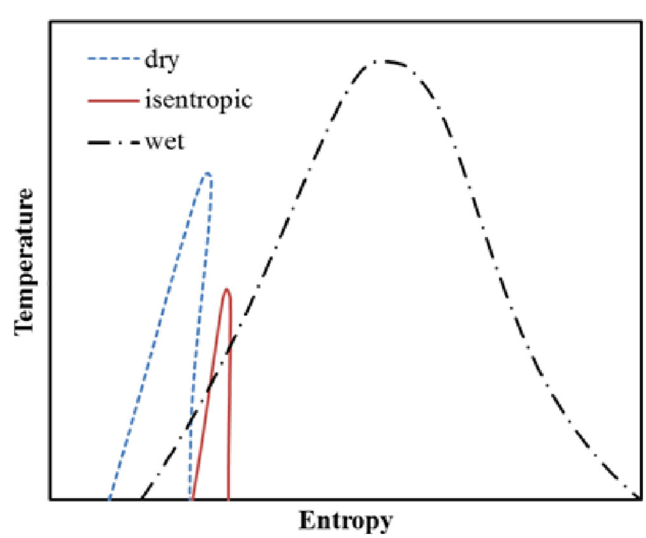

Fig. 2. *T*–*S* diagrams for different working fluids.