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Thermodynamic and Thermo-economic Analysis of Integrated Organic Rankine Cycle for Waste Heat Recovery from Vapor Compression Refrigeration Cycle

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Abstract

In the present study, an integrated air-conditioning-organic Rankine cycle (i-AC-ORC) system which combines a vapour compression cycle and an organic Rankine cycle is proposed. An organic Rankine cycle system is applied to recover the waste heat rejected by the condenser of air-conditioning system. The selection of optimal fluid pairfor the air-conditioning subsystem and organic Rankine cycle subsystem is investigated. Based on thermodynamic (energy and exergy) and thermo-economic analysis, R600a-R123 is chosen as the fluid pair for this integrated air-conditioning-organic Rankine cycle system. The thermodynamic model has been programmed using Engineering Equation Solver (EES). The combined coefficient of performance (COP) of integrated system can be improved from 3.10 to 3.54 compared with that of the standalone air-conditioning subsystem. The organic Rankine cycle subsystem can yield1.41 kW of net electricity with a thermal efficiency of 3.05%. The organic Rankine cycle subsystem operates with an exergy efficiency of 39.30%. In addition, energetic and exergetic performances of the integrated system are studied with variable external conditions.

*Keywords:*Air conditioning;Vapor compression cycle; Organic Rankine cycle;Waste heat recovery;Working fluid;Thermodynamic and thermo-economic analysis*

1. Introduction

Global warming associated with burning fossil fuels is continuously driving the growth of electricity consumption in air-conditioning (AC) domains. According to Li et al.[1], AC applications surges 30-50% of the total electricity consumption in urban areas in summer. Consequently, AC applications have accelerated the deterioration of urban micro-climate due to the rejected waste heat. Therefore, itis of great importance to promote waste heat recovery (WHR) through AC applications to enhance micro-environmental protection and energy saving.

Many research works have been done on waste heat recovery using heat sources like exhausted gas from power plants, solar power and geothermal energy[2]–[7]. However, for recovery of low-grade waste heat through AC systems, little work has been done.Heating watermay be an applied method which realizes the production of hot water by utilizing rejected waste heat in the AC system[8]. In recent research, organic Rankine cycle (ORC) system has been proved to be effective to utilize and recover the waste heat for electricity generation. An idea of combined AC-ORC system has been proposed and presented in [9]. As stated by many studies, the selection of working fluids iscrucial to optimize the performance of the ORC system[10]–[13]. Wang et al. [14] investigated and found that

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isentropic and dry fluids like R245fa, R141b and butane show attractive performance for low-grade waste heat recovery.In these studies, the energetic and exergetic analyses were considered as effective approaches and key parametric indicators [15]–[17].

2. System configuration and fluids selection

2.1. System configuration

As shown in Fig.1, the proposed i-AC-ORC system is a combination of a vapor compression cycle (VCC) on the left side and an ORC on the right side. It can be seen that the sharing heat exchanger (SHX) between the VCC and ORC works as the condenser inthe VCC as well as the evaporator in the ORC. Through applying i-AC-ORC system, waste heat rejected by the VCC can be converted into electricity by the ORC subsystem.

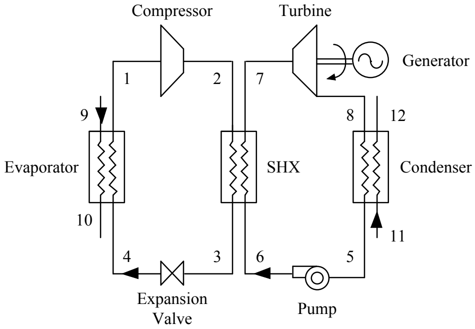

Fig.1. Schematic of i-AC-ORC waste heat recovery system.

2.2. Working fluids selection

Six refrigerants are selected as the potential working fuildsfor the ACsubsystem, which are R134a, R290, R404A, R407C, R600a andR410A. As mentionedabove, with growing interest in waste heat recovery, Bao et al.[18]presented the categoriesof the working fluids based on different heat source temperatures. Hence, six isentropic and dry fluids (butane, R123, R141b, R227ea, R245fa and R1233zd(e)) are chosen as the candidates for the ORC subsystem.

3. Modelling

Modelling equations on energetic, exergetic and thermo-economic analyses are developed and programmed in Engineering Equation Solver (EES). The computational modelling is based on the following general assumptions [19]. The system is considered under steady state. Friction, heat loss, changes inkinetic and potential energy are neglected.The pressure drops in heat exchangers and tubes are negligible. The working fluid in the VCC enters the compressor at saturated vapor state and exits the condenser at saturated liquid state. Expansion process in the VCC is adiabatic process. The designed condensation temperature of the AC subsystem is not affected by the ORC subsystem. The working fluid in the ORC exits the condenser at saturated liquid state and enters the turbine at saturated vapor state. Detailed design criteria are presented in Table 1.

3.1.Energy Analysis

Based on the aforementioned assumptions, the cooling capacity (Q_{evap}), the compressor work (W_{comp}), the rejected waste heat rate (Q_{waste}) and the initial COP of the AC subsystem (COP_{ini}) can be expressed as follows:

$$Q_{\text{evap}} = \dot{m}_{\text{AC}}(h_1 - h_4) \tag{1}$$

$$W_{\text{comp}} = \dot{m}_{\text{AC}}(h_2 - h_1) \tag{2}$$

$$Q_{\text{waste}} = \dot{m}_{\text{AC}}(h_2 - h_3) \tag{3}$$

$$COP_{\text{ini}} = \frac{Q_{\text{evap}}}{W_{\text{comp}}} \tag{4}$$

where $\dot{m}_{\text{AC}}$ is the mass flow rate of the refrigeration in the AC subsystem.