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Main parameters optimization of regenerative organic Rankine cycle driven by low-temperature flue gas waste heat

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ABSTRACT

Thermodynamic analyses of regenerative ORC (organic Rankine cycle) driven by low-temperature flue gas waste heat are performed. The heat transfer and flow analyses of a regenerator are also analyzed. A simplified optimal design method to optimize main thermodynamic parameters is proposed for the regenerative ORC driven by flue gas waste heat under different temperature conditions. Results reveal the existence of two characteristic temperatures, namely, $T_{w1}(1)$ and $T_{w1}(2)$. If the flue gas inlet temperature T_{w1} is lower than $T_{w1}(1)$, then the regenerator should not be equipped, the optimal pinch point temperature difference is the lowest limit value, and the optimal evaporation temperature increases with the increasing flue gas inlet temperature. If $T_{w1}(1) \le T_{w1} \le T_{w1}(2)$, then the regenerator should be equipped, the optimal regenerator effectiveness increases with the increasing flue gas inlet temperature, the optimal pinch point temperature difference is the lowest limit value, and the optimal evaporation temperature is the highest limit value. If $T_{w1} \ge T_{w1}(2)$, then the regenerator should be equipped, the optimal regenerator effectiveness is the highest limit value, the optimal pinch point temperature difference increases with the increasing flue gas inlet temperature, and the optimal evaporation temperature is the highest limit value.

1. Introduction

Large amounts of waste heats are exhausted into the environment in numerous industrial processes. Statistics show that over 50% of waste heats are low-temperature heat energy and are mostly discharged in the form of flue gas [1]. Flue gas waste heats not only cause a substantial waste of energy but also pose serious environmental thermal pollution. Generally, flue gas waste heats are much more desirable to be recovered for power generation than for other utilizations. Unfortunately, not many solutions exist for recovering low-temperature waste heats for power generation because of the low temperature of the heat source and the limit of the heat sink temperature. Numerous theoretical analyses and engineering practices show that the ORC (organic Rankine cycle) technology is an effective method for low-temperature waste heat recovery. Many researchers have conducted numerous studies on ORC working fluid selection [2–8], simulations and thermodynamic analyses of the effects of main parameters on ORC performance [9–12], and ORC prototype testing and engineering [13–16]. Some researchers have studied the parameter optimization of ORC for a given low-temperature waste heat resource. Wei et al. [17] conducted a simulation for ORC driven by industrial waste heat using R245fa; the authors examined the influence of waste heat inlet temperature, ambient temperature, waste heat flow rate and cooling air flow rate on system power output and efficiency, and subsequently determined the optimal cyclic parameters. Dai et al. [18] studied the effects of thermodynamic parameters on the performance of low-grade waste-driven ORC using different working fluids; the authors selected exergy efficiency as the objective function and optimized the thermodynamic parameters of the ORCs using a genetic algorithm. Madhawa Hettiarachchi et al. [19] investigated the optimization of evaporation temperature, condensation temperature, cooling water flow rate, and geothermal water flow rate for ORC driven by geothermal water; in

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this work, the ratio of the total heat exchanger area to the net power output was selected as the objective function, and the main ORC performances given the working fluids of ammonia, R123, and PF5050 were compared. Ma et al. [20] performed a theoretical calculation of the thermal performance of ORC driven by geothermal heat using the EES (Engineering Equation Solver); in this work, the effects of refrigerants, condensation temperature, geothermal fluid temperature, and dryness on optimal evaporation temperature and power output were analyzed. Roy et al. [21] investigated the optimization of turbine inlet pressure for low-temperature waste heat-powered ORC by selecting output power or exergy efficiency as the objective function; R12, R123, and R134a were used as the working fluids. He et al. [22] analyzed the optimization of simple, single-stage regenerative, and two-stage regenerative ORCs driven by low-temperature waste heat; the authors selected exergy efficiency as the objective function and adopted a genetic algorithm. Liu et al. [23] proposed a theoretical formula to calculate the optimal evaporation temperature of subcritical ORC on the basis of thermodynamic theory by selecting net power output as the objective function; the authors determined the optimal evaporation temperatures of 22 working fluids. Xiao et al. [24] put forward a multi-objective optimization method to calculate the optimal evaporation and condensation temperatures for subcritical organic Rankine cycles; single-objective functions including net power output, exergy drop of the exhaust gas from inlet to outlet, total exergy destruction rate, and system total cost C_{2013} were selected as the subcritical ORC performance indicators, and the multi-objective optimization was solved with the method of linear weighted evaluation function. Based on a sub-critical ORC process, Liu et al. [25] introduced a new term OHST (Optimal Heat Source Temperature) with consideration of a suitable thermal match between heat source and working fluid, and developed a theoretical formula to predict the OHST; the authors demonstrated that OHST could be regarded as an important performance indicator to optimize ORC systems.

The use of a regenerator or internal heat exchanger can improve ORC performance under certain conditions; however, only a few researchers have studied the influence of regenerators on ORC performance [26–33], given that most of these studies have been conducted under given waste heat conditions and have ignored the flow resistance of regenerators that could cause turbine exit pressure to increase, the effect of flow resistance on ORC performance has not been considered yet. Some researchers have even offered conflicting views on the effects of regenerators on ORC. For example, Lai et al. [28] and Fischer [29] reported improvements in thermal efficiency but found that the output remains constant. Shu et al. [30] pointed out that the expansion ratio can be significantly decreased by regenerators when the evaporation pressure is below a certain value. Wang et al. [31] arrived at approximately the same result as that of Lai et al. and Fischer, that is, adding regenerators does not increase system output but increases thermal efficiency. The results of Li et al. [32] show that system power output slightly decreases when regenerators are equipped. Given that the temperatures of flue gas differ for numerous practical recovery applications, a generalized system optimization method for ORC driven by low-temperature flue gas waste heat with different temperatures should be studied.

Thermodynamic analyses of regenerative ORC driven by low-temperature flue gas waste heat are conducted in the present study, and the heat transfer and flow of regenerators are analyzed also. The calculation method for cyclic state parameters and performance is proposed to avoid the use of complex PVT equation of state and commercial fluid property calculation software and to display intuitively the effects of main parameters on ORC performance. The proposed method uses the correlations of saturation pressure, specific vaporization latent heat, specific heat capacity of saturated liquid at constant pressure, and specific volume. A mathematical model for calculating the optimal evaporation temperature, regenerator effectiveness, and pinch point temperature difference of regenerative ORC driven by low-temperature flue gas waste heat is developed by selecting power output as the objective function and by using an interior penalty function optimization algorithm. On the basis of the comprehensive analyses of the simulation results using the model, a novel piecewise optimal design method is proposed for ORC driven by flue gas waste heat with low-temperature corrosion under different temperature conditions. The complicated multiparameter parallel optimization problem with multiconstraint conditions is simplified to an equation-solving problem, and the difficulty of solving the optimization problem is reduced.

2. Thermodynamic analyses of regenerative ORC driven by low-temperature flue gas waste heat

The selection of working fluid could affect efficiency, operation conditions, and environmental and economic performance. Generally, working fluids should have excellent thermal properties and good chemical stability. Working fluids can be divided into wet, dry, and isentropic on the basis of the different shapes of saturated vapor lines [1–3]. When dry or isentropic fluid enters a turbine in a saturated vapor state, the turbine exit vapor is located in a superheated state. Vanes would not be endangered by droplet collision damage, but wet fluid must enter the turbine in a superheated state. Sufficient superheating areas must also exist in the vapor generator. Given that the thermal conductivity and the Prandtl number of working fluids in vapor state are significantly lower than those in liquid state, sufficient heat transfer temperature differences and heat transfer areas must exist; this requirement increases the investment in ORC vapor generators and results in irreversible losses, in which case dry and isentropic fluids are regarded as suitable for ORC [1–3,8].

As mentioned previously, the increasing superheat of the turbine inlet vapor increases both the investment in ORC vapor generators and irreversible losses. This effect causes a significant decrease in the technical and economic performance of ORC systems. Therefore, low-temperature flue gas waste heat-powered ORC using dry or isentropic fluid that enters the turbine in a saturated vapor state is discussed in this study.

Fig. 1 illustrates the process of ORC driven by low-temperature flue gas waste heat. The saturated vapor from the vapor generator enters the turbine to expand (4–5), and the turbine exit vapor enters the regenerator to preheat the feed liquid. It then enters the condenser and condenses to liquid (5–1). The liquid is then pressurized to feed the ORC vapor generator with the working fluid feed pump (1–2). The feed fluid then enters the regenerator to be preheated by the turbine exit vapor (2–3). It flows into the preheating area of the vapor generator to be heated to saturated liquid by the low-temperature flue gas waste heat (3–3′). The saturated liquid continues to be heated to saturated vapor in the evaporation area of the vapor generator by the low-temperature flue gas waste heat (3′–4). A whole Rankine cycle is then completed. The *T*–*s* diagram is shown in Fig. 2.

The following assumptions are made to simplify the model. (1) The flows of the flue gas waste heat and working fluid are steady. (2) The isentropic efficiencies of the pump and turbine remain unchangeable. (3) The heat losses of the pipes and equipment are all neglected. (4) The variations of the gravitational potential and kinetic energies of the working fluid between the feed pump outlet and the inlet are neglected.