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Energy and exergy analysis of an organic Rankine for power generation from waste heat recovery in steel industry

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ABSTRACT

Energy, in conjunction with exergy, analysis of a waste heat driven Organic Rankine Cycle (ORC) is performed. Using actual plant data, performance of the cycle and pinpoint sites of primary exergy destruction are assessed. Furthermore, variations of energy and exergy efficiencies of the system with evaporator/condenser pressures, superheating and subcooling are illustrated. It is observed from the analysis that, the energy and exergy efficiencies of the system are 10.2%; 48.5% and 8.8%; 42.2%, respectively, for two different actual cases. Exergy destruction of subcomponents is also quantified. The components with greater exergy destructions to lower one can be listed as evaporator, turbine, condenser and pump. Evaporation pressure has significant effect on both energy and exergy efficiencies. Pinch-point analysis is, also performed to determine effects of heat exchange process, in the evaporator, on the net power production.

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1. Introduction

Heat is one of the unavoidable requirements of many applications in the industry. However, this crucial requirement is usually produced excessively and often the excess amount cannot be reused entirely on-site. For instance, steel industry needs high temperature heat, and thus many furnaces, to make steel slabs soft enough to roll. One of the heat rejection process in the furnaces is cooling of walking beams that are used to carry slab through the furnaces. Water is used to cool these walking beams and the temperature of the cooling-water leaving the furnace is generally between 90 and 150 °C. This waste hot water at moderate temperature level (between 90 and 150 °C) is one of the appropriate source for heat recovery process. It can be used for heating offices, buildings or for preheating of any other process if necessary. Furthermore, this moderate temperature level hot water can also be used to produce electricity.

Utilizing moderate temperature steam in a conventional Rankine cycle to produce electricity is not a good choice technologically and economically. However, Organic Rankine Cycle (ORC) is a promising technology for conversion of low-grade heat into electricity. The operational principle of the ORC is the same as of conventional steam Rankine cycle. The only difference is an organic working fluid with lower boiling temperature is used to the expander (turbine) in ORC instead of water. ORC exhibits great flexibility in utilization of moderate temperature heat source [1]. The heat source of an ORC can be solar radiation [2–4], geothermal energy [5–7], biomass combustion [8–10] and industrial waste heat [1,11–13], etc.

Many studies on ORC have been presented in the literature. For example, Quoilin et al. [14] have presented techno-economic survey of various ORC applications. In this study, a market review has been proposed, technological constraints and optimization methods have been described and discussed.

Several researches on the characteristic of different working fluids in an ORC application have also been presented in the literature [15–18]. Wang et al. [1] have proposed a double Organic Rankine Cycle for discontinuous waste heat recovery. The study includes calculation of optimal operation conditions of several working fluids. Pinch point analysis has also been employed to analyze the ORC performance. Pinch point analysis is an important tool to establish basic design criteria of heat exchangers used in ORC. The results of the study have shown that dry and isentropic fluids offer attractive performance. Hung et al. [19] have presented another study, which assist the results given in [1], to determine best fluids to be used in ORC for low temperature waste heat recovery. They have also stated isentropic fluids as the best choices for low temperature heat recovery. Wei et al. [11] have studied performance analysis and optimization of ORC for waste heat recovery. Guo et al. [20] have presented thermodynamic analysis of a waste heat power generation system. They have proposed two approaches to analyze and improve ORC performance; first is to improve availability of heat source and the second is to enhance the heat-work conversion of the system.

Thermodynamic characteristics and performance of power plants are usually investigated to assist in improving their

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efficiencies. Energy analysis is a traditional tool used to examine power plants. However, a better understanding is attained when a more expanded and detailed thermodynamic view is taken, which uses the exergy analysis in conjunction with energy analysis. Exergy analysis has been proven to be a more powerful tool than energy analysis for power cycles because of the fact that it helps to determine the true magnitude of losses and their causes along with locations. Some applications of exergy analysis of power plants using Organic Rankine Cycle may be found in [21–24]. Roy et al. [21] have presented a parametric optimization of a non-regenerative Organic Rankine Cycle, using different working fluids. In another study, the performance of an ORC system has been investigated, evaluating various working fluids with a genetic algorithm to optimize the system [23]. Wang et al. [24] have proposed a more intuitive approach to calculate the performance of an exhaust gas waste heat powered Organic Rankine Cycle. The method described in the paper can also be useful in thermodynamic analysis, optimal selection of working fluids, sizing of systems and assessing the configuration of exhaust gas waste heat driven ORC. Wu et al. [25] proposed a model of evaporator in ORC, recovering waste heat, based on exergy recovery. The study contribute an original approach, that can be useful in the design of evaporator for waste heat recovery based power generation systems, on the basis of the viewpoint of exergy recovery.

In this paper, an exergy analysis in conjunction with energy analysis is performed on an ORC. The cycle is driven by waste heat from reheat furnaces used in the steel industry and the analyses are based on actual plant data obtained recently. The study describes an easy to follow procedure for exergy analysis of waste heat driven Organic Rankine Cycles. Energy and exergy efficiencies are calculated for two different cases. The locations and magnitudes of exergy destruction are identified and quantified. The effects of evaporator/condenser pressures, superheating in evaporator, subcooling in condenser on exergy and energy efficiencies are investigated. Pinch-point analysis is also performed to determine effect of heat exchange process in the evaporator on the net power production.

2. System description

The ORC system under examination is installed to produce electricity by using excess heat of a walking beam slab reheat furnace. The furnace is a natural gas burning furnace with 250 tons/h maximum cold charge slab capacity. A semi-closed loop evaporative cooling system is used to cool the skids of the furnace. Water is in liquid form in ORC inlet water collector. Water is circulated through the furnace to cool the walking beam skids, which leaves the furnace as a saturated liquid–vapor mixture (wet steam). ORC units use the water from the furnace as the heat source. Four ORC units, with around 250 kW net power capacity, are installed for waste heat recovery from the reheat furnace. Maximum power generated by ORC units is limited on control panel to prevent ORC units from removing too much heat and inducing cold spots in to the slabs that are resting on skids.

The picture and schematic representation of the ORC is shown in Fig. 1. The properties at various states for two different running conditions are given in Tables 1 and 2. Dead state properties of the water and R245fa are calculated at 1 bar and 25 °C. Mass flow rate of the condenser cooling water is measured by ultrasonic flow meter. Inlet and outlet temperature of the condenser cooling water is read from control panel. Mass flow rate of the R245fa is calculated from the energy balance at condenser. *T–s* diagram of the cycle for Case 1 given in Table 1 is shown in Fig. 2. R245fa is in saturated liquid condition at condenser exit and compressed liquid at evaporator inlet. Evaporator and condenser pressures are also read from control panel. It is accepted that R245fa leave the evaporator as saturated vapor. There is a water collector at ORC inlet to collect water coming from different section of the furnace and distribute it to ORC units. Pressure and temperature sensors are replaced on this collector to detect water. Pressure and temperature of the water at evaporator exit are also measured and monitored on control panel. Mass flow rate of the water through the evaporator are estimated by applying the first law of the thermodynamics.

3. Energy and exergy analysis

According to data in Table 1, working fluid R245fa is circulated by the pump, enters the evaporator as compressed liquid at 10.8 bar and leaves as saturated vapor at evaporator pressure. Working fluid R245fa leaves the turbine as superheated vapor at condenser pressure of 2.1 bar and leaves the condenser as saturated liquid. Condenser is a water-cooled condenser. Water enters and leaves the condenser at 32.1 °C and 27 °C, respectively. Mass flow rate of the water is 104 kg/s. Mass flow rate of the R245fa is calculated as 11.06 kg/s from mass balance. Pressure drops of R245fa in the evaporator and condenser is neglected. The heat exchange process in the evaporator is shown in Fig. 3. An energy balance can be written from Fig. 3 for the evaporator as:

$$\dot{m}_s(h_1 - h_{pp}) = \dot{m}_r(h_3 - h_f) \quad (1)$$

and

$$\dot{m}_s(h_{pp} - h_2) = \dot{m}_r(h_f - h_6) \quad (2)$$

where $\dot{m}_s$ and $\dot{m}_r$ are the mass flow rate of the water from furnace and R245fa respectively. h_f is the saturated liquid enthalpy of R245fa at evaporation temperature of 92.9 °C. h_{pp} is the pinch-point enthalpy of the furnace cooling water. Solving above equations for, corresponding pinch point temperature of the furnace cooling water is determined to be 99.7 °C. The pinch-point temperature difference ΔT_{pp} is the difference between pinch-point temperature of the furnace cooling water and the vaporization temperature of R245fa. Thus, is 6.8 °C. The ORC systems consist of several steady state control volumes. General expressions of mass, energy, and exergy balances of any steady state control volume, by neglecting the potential and kinetic energy changes, can be given, respectively, as

$$\sum \dot{m}_{\rm in} = \sum \dot{m}_{\rm out} \quad (3)$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_{\rm out} h_{\rm out} - \sum \dot{m}_{\rm in} h_{\rm in} \quad (4)$$

$$\dot{E}_{\rm heat} + \dot{W} = \sum \dot{E}_{\rm out} - \sum \dot{E}_{\rm in} + \dot{I} \quad (5)$$

where, subscripts in and out represent the inlet and exit states, $\dot{Q}$ and $\dot{W}$ are the net heat and work inputs, $\dot{E}$ is the exergy rate and $\dot{I}$ is the irreversibility rate. If the specific the flow exergy is given by $e = h - h_0 - T_0(s - s_0)$, then the exergy rate is

$$\dot{E} = \dot{m}e \quad (6)$$

Net exergy transfer by heat at the temperature T is given by

$$\dot{E}_{\rm heat} = \sum \left(1 - \frac{T_0}{T}\right) \quad (7)$$

Heat transfer rate in the evaporator, by neglecting heat loss to the surroundings, can be expressed as

$$\dot{Q}_{\rm ev} = \dot{m}_s(h_1 - h_2) = \dot{m}_r(h_3 - h_6) \quad (8)$$

Exergy balance for the evaporator and the condenser can be defined as

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