Energy and exergy analysis of Organic Rankine cycle fed by Electric Arc furnace waste heat

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ABSTRACT

In this study, the hybrid of Organic Rankine cycle with heat recovery system of low temperature gases in Electric Arc furnace has been investigated. Moreover, the effect of steam accumulator on stabilizing the mass and heat of exhaust gases of the heat recovery boiler is shown. Hence, constant thermal power has been achieved for a longer period of time for the Organic Ranking cycle. The steam accumulator thermodynamic model is simulated based on the non - equilibrium thermal model for the liquid and vapor phases. Furthermore, the steam accumulator pressure variations with different mass outflow rates have been investigated. Constant and continuous thermal power has been reached with an output mass flow rate of 2.84 kg/s during four processes of the electric arc furnace. The transient state of the aforementioned hybrid system has been studied from the energy and exergy point of view. The energy and exergy efficiencies of the whole system are calculated with three working fluids MM, Toluene and R245fa of the Organic Ranking cycle. Toluene with thermal and exergy efficiencies of 16.4% and 27.1%, respectively, is suitable for using in the Organic Ranking cycle compared with the other two fluids.

KEYWORDS

Waste heat recovery, Organic Rankine cycle, Electric Arc furnace, steam accumulator, Exergy

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1. Introduction

In the past few decades, the growing fuel prices and global warming have led scientists and engineers to reduce greenhouse gas emissions and improve site efficiency. In this regard, the application of waste heat recovery systems (WHRS) in the industry is one of the most important fields of research to reduce fuel consumption, greenhouse gas emissions, and improve production efficiency. One of the main technical limitations of adopting WHRS is the intermittent and periodic nature of heat loss. These fluctuations in industrial processes incur inherently due to non-uniform production rates.

In this study, the steam accumulator's behavior in reducing heat fluctuations and heat storage in the heat recovery system to achieve a continuous and stable in organic ranking cycle's output power is investigated. The thermal fluctuations of the output saturated steam from the boiler, due to the thermal fluctuations of the exhaust gases from the electric arc furnace, are recovered by a steam accumulator. By storing steam inside the steam accumulator, its delivery time to the Organic Rankine cycle (ORC) is increased. The steam accumulator is simulated based on a non-equilibrium thermodynamic model of two phases, liquid and steam. Also, the heat recovery system and the organic ranking cycle with three operating fluids, Hexamethyldisiloxane (MM), Toluene, and R245fa, have been studied from the energy and exergy viewpoint.

2. Methodology

Error! Reference source not found. represents the layout of the process involved in electricity production through the use of Organic Rankine cycle in a combination of waste heat recovery system. As has been indicated by [1], about 25 - 30% of the power input to the EAF might be wasted through the flue gases.

First, the EAF flue gases pass through the heat recovery unit, which is considered as a heat exchanger, the gases' thermal energy is given to water. This produces saturated steam with the pressure of 2000 kPa. Steam as a heat conveyor is employed to transfer the thermal energy from the low-grade heat source (the Electric Arc furnace flue gases) to ORC's evaporator. However, care shall be exercised that the rate of the flue gases' mass and temperature varies in a specific range. Hence, smoothing of the available steam fluctuations and generating continuous thermal power are the main challenges.

The produced saturated steam enters the steam accumulator to reduce its fluctuations. In the next step, this steam exits the steam accumulator by constant mass flow rate for a longer time. The accumulator initially has been filled by two-phase saturated steam and water with a pressure of 800 kPa. It should be noted that charging and discharging of the steam accumulator takes place simultaneously. Moreover, the pressure inside the accumulator changes in the range of 800 to 2000 kPa depending on the outlet mass flow rate. The pressure of the outlet saturated steam from the steam accumulator does not go beyond 800 kPa by using a pressure reducing valve, which causes superheated steam. The output stream with a specific mass flow rate and pressure is directed to the ORC's evaporator. The superheated steam in the evaporator turns into saturated water by losing heat at 800 kPa, then exits from the evaporator and feeds the FW tank (showed as point 3). The saturated water pumps toward the heat recovery unit at the pressure of 2000 kPa (indicated as point 5) to recover the EAF flue gases waste heat.

In the ORC's evaporator, the working fluid is heated and evaporated by the heat released from the superheated steam of the accumulators. Then, the working fluid passed through the turbine, and after generating electricity, the low pressure working fluid is sent to the recuperator (showed as point 8). The working fluid loses its heat in the recuperator and turns into liquid in the condenser (showed as points 10). In the end, the working fluid is pumped to the recuperator in high pressure (showed as point 11) for preheating; afterward, it is conducted to the evaporator (showed as point 7) and the cycle is closed.

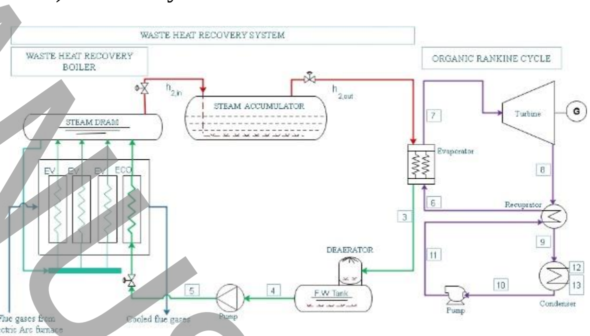

Figure 1 The layout of hybridization of Waste heat recovery system with Organic Rankine cycle

For numerical modeling of the aforementioned system MATLAB [2] was employed. The thermodynamic properties of fluids were derived from the COOLPROP [3] library function. The changes in pressure, enthalpy and mass inside the steam accumulator have been calculated using the Rong-Kuta numerical solution.

3. Results and Discussion

To validate the steam accumulator model and ORC, the experimental data of Kaska [4] and Stevanovic et al. [5] were used, respectively. In this study, the steam accumulators were modeled with an initial condition by which 30% of the total volume of the accumulator was filled by water without inlet and outlet water flow. The initial conditions of water and steam inside the accumulator were at the thermodynamic equilibrium state with an initial pressure of 800 kPa. The volume of WHRS's accumulator is 104 m3. The saturated steam outlet from the heat recovery unit varied intermittently with maximum value of 6.7 kg/s in each EAF process, which is the only input to the WHRS' accumulator. The inlet saturated steam covers 2814 s (47 minutes) in each process. However, it should be noted that the case with the outlet mass flow rate of 2.84 kg/s tended to output mass flow rate among the three cases (2.84, 3.00, and 3.5 kg/s) with respect to the four EAF processes. Furthermore, with the output 3 and 3.5 kg/s mass flow rates, a constant mass flow rate output was provided for only 3451 s (57 minutes) and 2990 s (50 minutes), respectively, for each process. This leads to discontinuity in the available thermal power of the ORC for specific time intervals.

The Organic Rankine cycle system's net power with the Hexamethyldisiloxane (MM) as the working fluid and different discharging mass flow rate from the WHRS's accumulator was given in Figure 2. The accumulator outlet mass flow rate of 2.84 kg/s led to an almost constant net power of 1005 kW during four EAF process. However, for an output mass flow rate of 3 and 3.5 kg/s, the net power of the ORC is equal to 1048.5 and 1210 kW in each process, respectively. Even though a higher net power value is available for the outlet mass flow rate of 3 and 3.5 kg/s, the output net power is not continuous during the four processes. The amount of the furnace off gas's recyclable energy is equal to be 24120 kWh approximately for each of the mass outflow rate from the WHRS's steam accumulator during a full day.

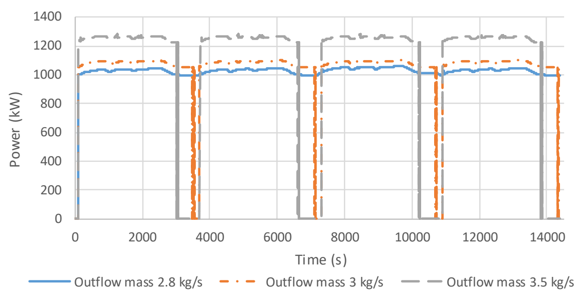

Figure 2 The net power of ORC with different mass flow rate from steam accumulator

4. Conclusion

One of the processes for converting waste heat to power is through the use of the EAF flue gases which have variable temperature and mass flow rate along with its batch operational nature. In this study, the waste heat recovery system with steam accumulator was adopted to generate a continuous heat source for the Organic Rankine cycle. The energy and exergy efficiencies of the organic Rankine cycle with three different working fluids, Hexamethyldisiloxane (MM), Toluene, and R245fa, have been studied in both critical and subcritical transitions. Steam accumulators play a vital role in stabilizing the thermal power fluctuations and saving thermal power to deliver it to the Organic Rankine cycle in a long time with a specific mass flow rate. Moreover, the behavior of the steam accumulators was investigated. A steam accumulator with a volume of 104 m3 was employed, moreover, WHRS could provide continuous heat load for one day with a mass flow rate of 2.84 kg/s and an average net power of 1005 kW. Even though a higher net power value is available for the outlet mass flow rate of 3 and 3.5 kg/s, the output net power is not continuous during the four processes. The amount of the furnace off gas's recyclable energy is equal to be 24120 kWh approximately for each of the mass outflow rate from the WHRS's steam accumulator during a full day. Also, the study of the three working fluids shows that Toluene can be a suitable alternative to working fluid MM in terms of energy and exergy efficiencies viewpoint. The maximum to minimum exergy destruction rates of the aforementioned system's components were detected to be heat recovery's heat exchanger, steam accumulator, condenser, evaporator, turbine, recuperator, ORC's pump, and WHRS's pump, respectively.

5. References

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