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Experimental investigation on a flat heat pipe heat exchanger for waste heat recovery in steel industry

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Abstract

The majority of the energy demand in industrial application is primarily used for heating purposes. Recovering waste heat could contribute to significant reduction of production cost and greenhouse gas emission. In this paper, an innovative heat recovery system was designed, manufactured and tested. The Flat Heat Pipe (FHP) is designed to recover the heat by radiation from hot steel rods during the manufacturing cooling process. The FHP system is composed of stainless steel heat pipes linked by a collector at the bottom and a shell and tube top header. The thermal performance of the FHP was investigated by testing the system at two positions from the barrier of the wires conveyor. The amount of the energy recovered and the working temperature of the FHP is also reported. The experimental results show that the heat transfer capability of the FHP is strongly influenced by the hot source temperature. It was observed from the results that the FHP is an innovative technology for waste heat recovery from industrial applications with high efficiency.

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Keywords: Flat heat pipe, heat exchanger, Waste heat recovery

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1. Introduction

The iron and steel industry is the largest energy consuming production process. Energy cost represents about 30 % of the total production cost. Recovering the heat from the steel manufacturing process is a huge challenge. Recovering the excess heat from those processes could reduce the greenhouse emissions and significantly reduce the production costs. A significant amount of investigations within waste heat recovery has been conducted over the past decade, with significance on molten slag. The majority of innovation has been focused on molten slags heat recovery as discussed by *Zhang et al.* [1], *Liu et al.* [2], and *Gutiérrez-Trashorras et al.* [3]. Four waste heat recovery systems have been investigated: Air blast, Single Drum, Twins Drums, and the spinning cup methods, typically these systems have an average efficiency of approximately 50%. *Kaşka* [4] proposed an Organic Rankine Cycle for power generation using the excess heat of a walking beam slab reheat furnace. The system proposed was tested with different working fluids in two working conditions. The first case was with a gross power production of 262.2 kW. The second case was with a gross power production of 203 kW. The ORC designed has an energy and exergy efficiencies of 10.2%, 48.5% and 8.8%, 42.2%, respectively.

Waste heat recovery using heat pipe technology has been investigated on many different applications. *Tian et al.* [5] investigated a new type of heat pipe based heat exchanger applied on waste heat recovery of flue gas. The heat pipe is composed of a condensing shell and tube chamber and finned pipe evaporator. The clean air is used to pre heat the burner air supply. This lead to a reduction of 15% of natural gas consumption and therefore a reduction of greenhouse gas emissions. *Jouhara et al.* [6] developed and validated a novel flat heat pipe based photovoltaic thermal (PV/T) system called ‘heat mat’. The new design performs as a building envelope. Three heat mats were tested in real application scale as follows: two PV/T system configurations, one with a cooling cycle and one without, and a third heat mat without a PV layer, which was using a mixture of water/glycol as cooling fluid. The experiments examined the effects of cooling cycles on the electrical output and the temperature of the heat pipe PV/T panels. The electrical efficiency was increased by 15% with the use of an active cooling cycle in the panels. Moreover, the temperature range was decreased from the range of 40 to 58°C to the range of 28 to 33 °C. The thermal efficiency of the heat mat without PV layer was around 64%, while the efficiency of the heat mat with the PV layer was around 50%. The ability of the heat mat to absorb heat from the ambient was studied as a function of air speed and the temperature difference between the ambient and cooling water. *Yang et al.* [7] proposed a design of high temperature flat heat pipe receiver in solar power tower plant. The start-up and the thermal performance were experimentally investigated. The flat heat pipe consisted of a stainless steel vapour chamber charged with liquid sodium, water jacket, and serrated fins. The FHP was tested at constant heat input to examine the start-up response and the isothermal characteristics. In addition, the impact of inclination angle and heat input on the start-up time and temperature distribution was tested and the best performance was obtained angle of 45°. The effective thermal conductivity, thermal resistance, and heat transfer efficiency of the FHP were calculated at various inputs. It was noted that the thermal resistance decreases as the heat input increase, whilst the efficiency is enhanced as the heat input increase. Furthermore, the stability performance was studied and the FHP exhibited the potential of long term, safe and uniform temperature distribution.

In this paper a flat heat pipe is designed to recover the heat by radiation and convection from hot steel in steel industry with temperatures higher than 500°C. The design of the FHP is presented and experimentally investigated. The experimental results of the performance of the FHP are reported.

2. Mechanical design

The flat heat pipe is designed to recover the heat by radiation and convection from hot sources with temperatures higher than 500°C. The radiative heat is transferred through the heat pipe evaporator wall to inner surface of the evaporator by conduction. When the working fluid reaches the saturation temperatures, it vaporizes and flows upward to the condenser. The heat is then transferred to the cooling fluid via shell and tube heat exchanger and condenses the working fluid. Finally the condensate flows back to the evaporator section with the assistance of gravity.

The flat heat pipe prototype presented in Fig. 1. (a) is composed of 14 stainless steel pipes linked by a bottom collector pipe and atop header. The top header is a shell and tube heat exchanger consists of 8 stainless steel smooth tubes within a stainless steel pipe. A stainless steel sheet is fixed at the back of the evaporator section to increase the overall heat transfer area. The dimensions of the flat heat pipe are 1 m height × 1 m width. A stand has been designed and manufactured to hold the system in place presented in Fig. 1. (b). It allows the system to be tested at different inclinations and heights.

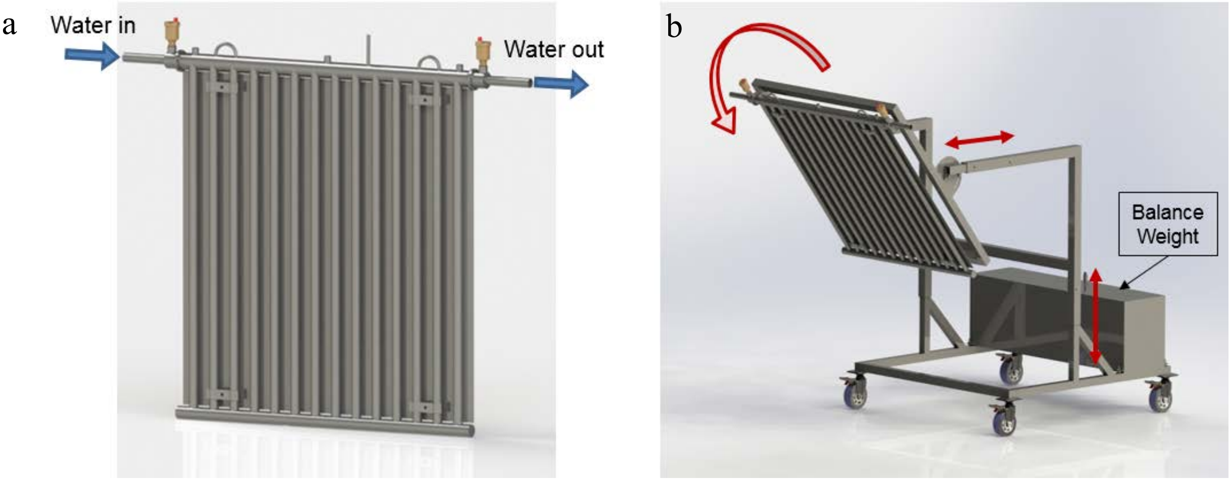

Fig. 1. (a) The mechanical design of the FHP; (b) The stand of the FHP

3. Experimental setup

The flat heat pipe was tested on the hot wire cooling process of the production line. The production line length is 70m. The FHP was placed 575 cm from the beginning of the production line, at the hottest point of the cooling zone. The temperature was measured using K type thermocouples, while the flow rate was measured using a flow meter. These instruments were eventually connected to a data logging system. The thermocouples' positions and the flat heat pipe set up are presented on Fig. 2. (a). Three thermocouples were installed on the bottom collector (EV 1-3), an additional nine on the vertical heat pipes (HP 1-9), three on the top header to measure the saturation temperature of the working fluid (AD 1-3), one on the back panel of the FHP, and two thermocouples on the inlet and outlet water temperatures. The speed and temperature of the air used to cool the wire was measured using a Testo 425 portable anemometer. The FHP testing on-site is presented in Fig. 2. (b). The flat heat pipe was charged with water, with an initial inclination angle of 12.5°. High temperature thermal insulation was used to insulate the top header of the FHP and the back panel to minimize the heat loss to the ambient surroundings. The water supply pipe was also insulated to avoid any radiative heat transfer with the water and 3.

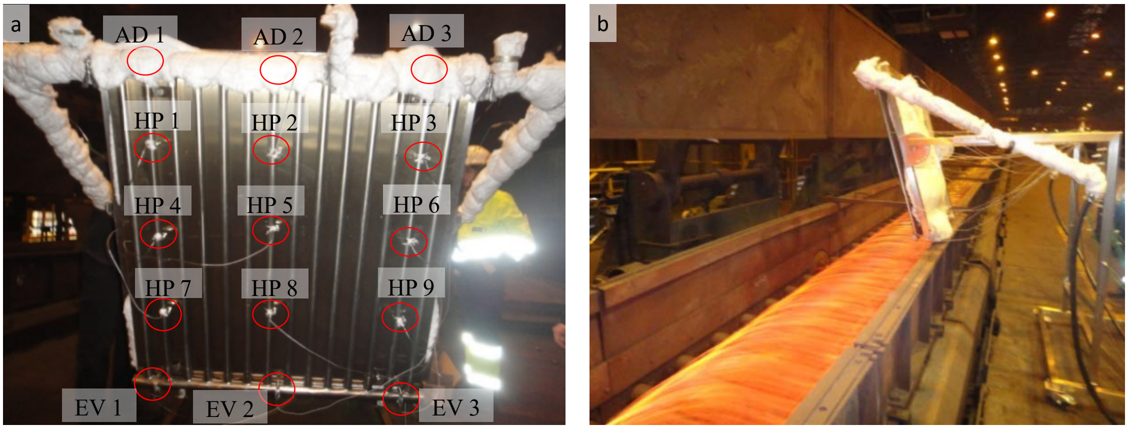

Fig. 2. Heat pipe experimental set up (a) Thermocouple positions; (b) FHP testing

The experimental conditions including FHP positioning and water parameters are presented in Table 1.

Table 1. Experimental conditions.

Experiment Conditions	Test 1	Test 2
Air temperature above the hot wires	136 °C	
Air cooling velocity	6.75 m/s	12 m/s
hot wires temperature	450 °C	450 °C
Distance between the FHP and the edge of the barrier	65 cm	6 cm
Distance between the FHP and the beginning of the production line	575 cm	
FHP inclination angle from the vertical	12.5°	
Water flow rate	23 L/min=0.38 kg/s	
Water inlet	26.2 °C	34.7 °C

4. Results and discussion

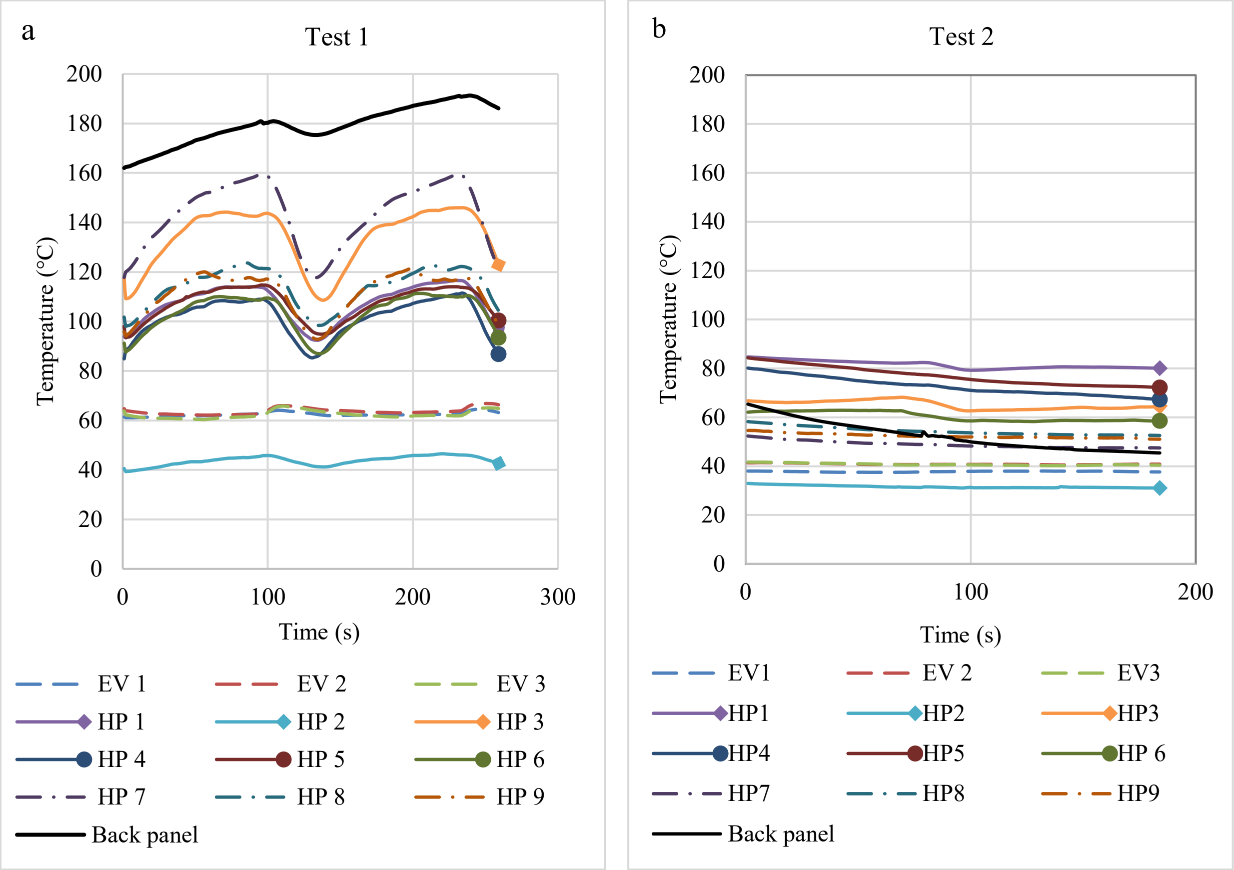

Fig. 3. Heat pipe temperatures (a) Test 1; (b) Test 2

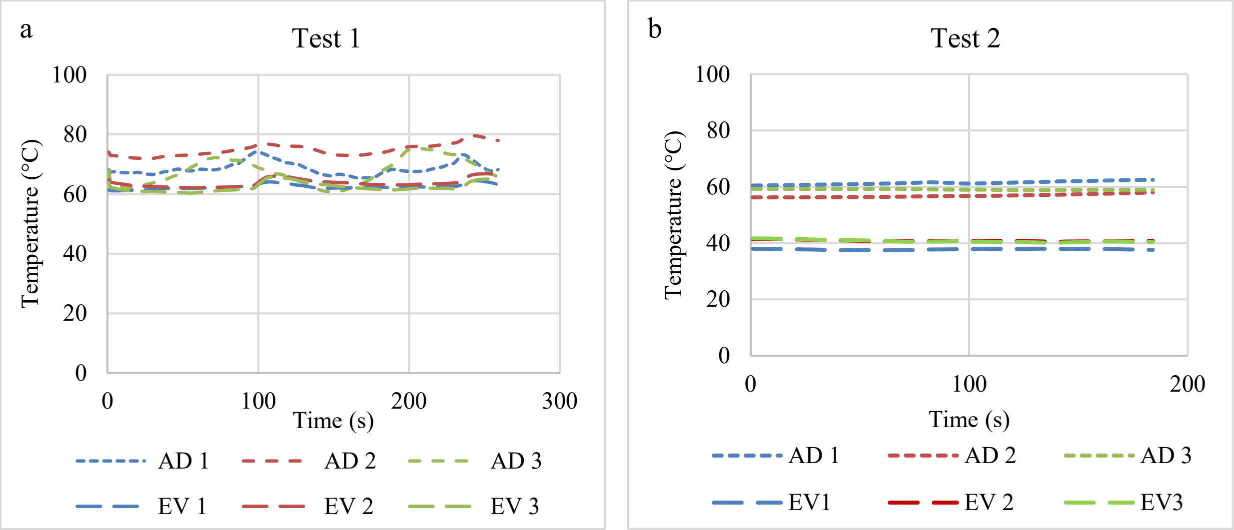

Fig. 4. Bottom collector and adiabatic temperatures of the FHP (a) Test 1; (b) Test 2

The tests were conducted for two production processes. The first test was achieved during a high density wire production process. Fig. 3. (a) presents the temperatures of the FHP surface in test 1. The fluctuation of the results in the experiments is due to the steel production process where the steel is produced for about 120 seconds and paused for 40 seconds. It was observed that the temperature of thermocouple HP7 was the highest due to the location, the position reflected the maximum temperature (160°C) during the process. The surface temperature of the FHP during the hot wires production varied between 111 °C and 160 °C while it decreased to the range of 84.9 to 117.7 °C when the steel production was off. The back panel temperature ranged between 162 °C and 191.3 °C which is expected to be higher than the temperature of the FHP surface since the thermal conductivity of the stainless steel sheet is low. The second test was performed during a low density wire production process. The heat pipe temperatures for test 2 are presented in Fig. 3. (b). The surface temperatures of the flat heat pipe varied between 80°C and 51°C. It can be observed from the results that the temperature of the thermocouples 7, 8, 9 was higher than the temperature of the bottom collector. The film boiling present is reflected as an incremental increase as shown in thermocouple positions 4, 5, 6, 1, and 3. Thermocouple 2 had the lowest temperature value, this temperature could be explained by a failing thermocouples or a bad installation.

The temperature of the bottom collector and the adiabatic section of the FHP in test 1 and test 2 are presented in Fig. 4. (a), and (b). In test 1 the average temperature of the bottom collector was about 65.7 °C at the maximum and 61.2 °C at the minimum when the production is off. While the average temperature of the thermocouples placed on the top header which represents the adiabatic section varied between 76.4 °C and 66°C. However in test 2, the thermocouples on the adiabatic section displayed temperatures of 60°C while the three thermocouples placed on the bottom collector showed temperatures of 40 °C. It can be observed that the temperature of the bottom collector was lower than adiabatic section because the bottom collector was not receiving a sufficient amount of radiative heat.

Water inlet and outlet temperatures are illustrated in Fig. 5. (a) for the first and second experiment. The outlet temperature was varying by time as a result of varying the thermal performance of the heat pipe.

The water inlet temperature was nearly constant at 26.2 °C while the average temperature of the water outlet was 33.4 °C. In the second test the water inlet temperature varied between and 33.6 °C and 36.2 °C, whereas the average water outlet temperature was 41.4 °C and reached a maximum value of 45.3 °C.

The heat transfer rate obtained for both experiments is illustrated in Fig. 5. (b). In test 1, the heat transfer rate reached a maximum value of 15.6 (kW) and a minimum value of 9.1 (kW) and the average heat transfer during the test was 11 (kW), while the heat transfer in test 2 the heat rate varied between 14.8 (kW) and 8.4 (kW). The average heat transfer rate during 180 seconds is 10.7 (kW). It can be observed that results in test 1 were higher than test 2 due to a higher density of steel wires. The variation in results can be due to the variation in placement of the FHP alongside the rod conveyor.

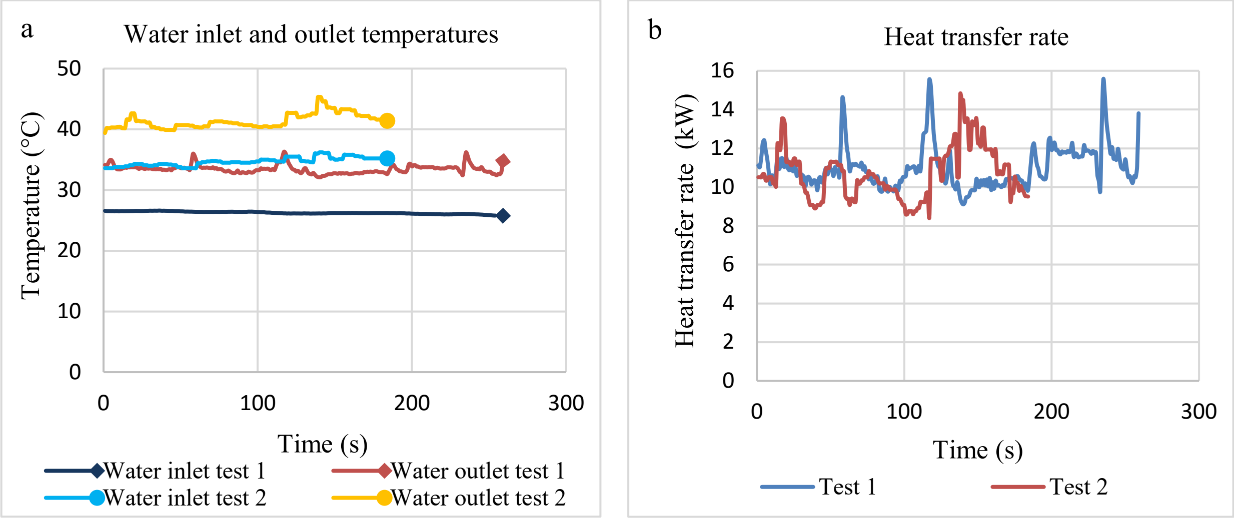

Fig.5. (a) Water inlet and outlet temperatures during Test 1 and Test 2; (b) Heat transfer rate in Test 1 and Test 2

5. Conclusion

A flat heat pipe (FHP) heat exchanger for waste heat recovery from high temperature steel production was presented and tested. The FHP was tested at two different distances from the edge of the steel conveyor at two different production density. The thermal performance of the FHP and the heat transfer rate was investigated. The working temperature of the FHP ranged between 80°C and 60°C while the surface temperature of the FHP reached a maximum value of 160 °C. The FHP was able recover heat up to 15.6 (kW) for a water flow rate of 0.38 kg/s and a hot source at 450°C. It can be observed from the results that the FHP is a promising technology for waste heat recovery in steel industry with many challenges such as high temperature source and limited available space on sites. More experiments should be carried out to investigate the performance of the FHP in various production process conditions and for different angle and position on the hot wire cooling line.

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