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Experimental study on heat pipe assisted heat exchanger used for industrial waste heat recovery

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HIGHLIGHTS

- A heat pipe heat exchanger (HPHE) was used to recycle the waste heat in a slag cooling process of steel industry.
- An specially designed on-line cleaning device was construed and used to enhance the heat transfer of HPHE.
- The performance characteristics of a HPHE has been assessed by integrating the first and second law of thermodynamics.
- The optimum operation conditions was determined by integrating the first and the second law of thermodynamics.

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ABSTRACT

Steel industry plays an important role economically in China. A great amount of hot waste liquids and gases are discharged into environment during many steelmaking processes. These waste liquids and gases have crucial energy saving potential, especially for steel slag cooling process. It could be possible to provide energy saving by employing a waste heat recovery system (WHRS). The optimum operation condition was assessed by integrating the first and the second law of thermodynamics for a water–water heat pipe heat exchanger (HPHE) for a slag cooling process in steel industry. The performance characteristics of a HPHE has been investigated experimentally by analyzing heat transfer rate, heat transfer coefficient, effectiveness, exergy efficiency and number of heat transfer units (NTU). A specially designed on-line cleaning device was used to clean the heat exchange tubes and enhance heat transfer. The results indicated that the exergy efficiency increased with the increment of waste water mass flow rate at constant fresh water mass flow rate, while the effectiveness decreased at the same operation condition. As the waste water mass flow rate varied from 0.83 m^3/h to 1.87 m^3/h, the effectiveness and exergy efficiency varied from 0.19 to 0.09 and from 34% to 41%, respectively. In the present work, the optimal flow rates of waste water and fresh water were 1.20 m^3/h and 3.00 m^3/h, respectively. The on-line cleaning device had an obvious effect on the heat transfer, by performing the device, heat transfer rate, heat transfer coefficient, effectiveness and exergy efficiency were improved by 6.11%, 9.49%, 7.19% and 7.93%, respectively.

1. Introduction

Energy consumption in industrial field accounts for about 70% of the total energy consumption in China [1], but the energy utilization ratio is only about 33%, which is 10% lower than that in developed countries. Large quantities of energy are directly discharged into environment as forms of waste heat during industrial processes without any recycle. Therefore, recovery and utilization of industrial waste heat is of substantial importance for energy saving and emission reduction.

Different kinds of recovery and utilization of waste heat can effectively reduce energy consumption, and there have been a number of studies focusing on the recovery and reuse of industrial waste heat. Fang et al. [2] proposed a holistic approach to the integrated and efficient utilization of low-grade industrial waste heat. It showed that the reuse of low-grade industrial waste heat to district heating system was practical with regards to thermal energy efficiency and environmental protection. In another study, a new type of open-cell metal foam-filled plate heat exchanger

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Nomenclature

Abbreviations

HPHE	heat pipe heat exchanger
NTU	number of heat transfer units
WHRS	waste heat recovery system

Symbols

Q	heat transfer rate (kW)
m	mass flow rate (kg/h)
m_{ww}	hot waste water mass flow rate (kg/h)
m_{cw}	cold fresh water mass flow rate (kg/h)
C_p	specific heat (kJ/(kg K))
C_{pww}	specific heat of hot waste water (kJ/(kg K))
C_{pcw}	specific heat of cold fresh water (kJ/(kg K))
T	temperature (K)
T_0	ambient temperature (K)
$T_{ww,in}$	inlet temperature of hot waste water (K)
$T_{ww,out}$	outlet temperature of hot waste water (K)
$T_{cw,in}$	inlet temperature of cold fresh water (K)
$T_{cw,out}$	outlet temperature of cold fresh water (K)
u	overall heat transfer coefficient (W/(m^2 K))
A	overall heat transfer area (m^2)
ΔT_{lm}	logarithmic temperature difference (K)
C	heat capacity (kJ/K)
C_{ww}	heat capacity of hot waste water (kJ/K)
C_{cw}	heat capacity of cold fresh water (kJ/K)
R	ratio of the minimum and maximum heat capacity rates
E_X	exergy rate (kW)
Ex_{in}	inlet exergy rate of hot waste water (kW)
Ex_{out}	outlet exergy rate of cold fresh water (kW)
$e_{ww,in}$	inlet specific exergy of hot waste water (kW/kg)
$e_{ww,out}$	outlet specific exergy of hot waste water (kW/kg)
$e_{cw,in}$	inlet specific exergy of cold fresh water (kW/kg)
$e_{cw,out}$	outlet specific exergy of cold fresh water (kW/kg)
h	specific enthalpy (kJ/kg)
h_0	specific enthalpy at ambient temperature (kJ/kg)
s	specific entropy (kJ/(kg K))
s_0	specific entropy at ambient temperature (kJ/(kg K))

Greek letters

ε	heat exchanger effectiveness
η_e	exergy efficiency
ε_{sde}	system device error
ε_t	temperature measurement error
ε_m	mass flow rate measurement error
ε_p	pressure measurement error
ε_d	data acquisition error

Subscripts

ww	hot waste water
cw	cold fresh water
in	inlet
out	outlet
min	minimum
max	maximum
des	destruction

based thermoelectric generator system (HE-TEG) was proposed to utilize low-temperature waste heat, during which the metal foams played an important role in enhancing the heat transfer process [3]. Pierobon et al. [4] studied on the most suitable waste heat recovery technology for off-shore facilities. The steam Rankine cycle, the air bottoming cycle and the organic Rankine cycle were applied to recover part of the waste heat from the gas turbines-based power system of an offshore oil and gas platform. Brückner et al. [5] presented that using industrial waste heat as heat source for residential heating system could postpone or even avoid the costly energy-efficiency refurbishing of the building stock. Pulat et al. [6] assessed the potential of waste-heat obtained from particularly dyeing process at textile industry by using of waste-heat recovery systems. It found that the payback period was less than six months, and waste-heat recovery systems had a better economy. Khosrow investigated the technical and economic issues associated with waste heat recovery in data centers [7].

It should be noted that iron and steel industry waste heat is abundant; therefore taking advantage of these waste heat is of great significance for reducing energy consumption and emissions. Guang-yu et al. [8] studied the quality and source of waste heat in Chinese iron and steel industry. It pointed out that low-grade waste heat, basically, has not been fully used, which had great potential to be recovered and utilized in the future in China. Xiong et al. [9] established a physical and numerical model of two-stage thermoelectric energy harvesting system driven by blast furnace slag water waste heat. It showed that the maximum power output of 0.44 kW and maximum efficiency of 2.7% were available with inlet temperature of blast furnace slag water at 100 °C if load resistance was matched. A physical and numerical model of thermoelectric power generation was established by Meng et al. [10]. It showed when blast furnace slag flushing water was at 100 °C, water temperature dropped by 1.5°C per meter. Approximately, 0.93 kW electrical energy could be produced per area and conversion efficiency of 2% could be achieved. It was also indicated that the average recovery of waste heat resources was only 25.8% while low temperature waste heat recovery rate was less than 1%. Therefore it is necessary to study the waste heat recovery of blast furnace slag water, which is expected to achieve the goal of energy saving and emission reduction in the iron and steel industry.

In previous studies, it demonstrated that HPHE has high heat transfer efficiency with simple structure. The waste heat recovery by HPHE is accepted as an excellent way of saving energy and preventing global warming [11]. HPHE has been widely used in chemical industry, electric power, metallurgy, petroleum and other industrial fields, and a number of investigations on the HPHE for waste heat recovery have been reported. Some typical applications of HPHE in industrial waste heat recovery, such as chemical reactors and high-temperature hot air generators, had been reported [12–15]. Tipton proposed that setting the HPHE in the power plant boiler could preheat the air and reduce the consumption of coal, and decrease the exhaust gas temperature [16]. Simple experiments were carried out to examine the performance of the heat exchanger for heating a large bus using automotive exhaust gas [17]. In another study, the waste heat recovery using HPHE for surgery rooms in hospitals was examined. The HPHE was designed, constructed and tested under low temperature operating conditions (15–35 °C), and the study found that the effectiveness of the heat exchanger was 0.16 [18]. Heat recovery between two streams of fresh and return air in an air conditioning system using HPHE has been investigated by Abd El-Baky et al. [19], and the ratios of the mass flow rate between the return and fresh air (1, 1.5, and 2.3) were tested to validate the heat transfer and the temperature change of the fresh air. During the tests, the fresh air inlet temperature was controlled in the range of 32–40 °C, while the inlet return air temperature was kept constant at