Renewable and Sustainable Energy Reviews 79 (2017) 50–60

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of the optimum operation conditions on a heat pipe heat exchanger for waste heat recovery in steel industry

Hongting Ma[a,b], Na Du[a,b], Zeyu Zhang[a,b], Fan Lyu[a,b], Na Deng[a,b,*], Cong Li[a,b], Shaojie Yu[a,b]

[a] Tianjin Key Lab of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[b] MOE Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Keywords:
Heat pipe heat exchanger
Waste heat recovery system
On-line cleaning device
Steel industry
Energy-exergy analysis
Optimum operation condition

ABSTRACT

In order to investigate the characteristics of a heat pipe heat exchanger (HPHE) used for recovering the waste heat in a slag cooling process in steel industry, a waste heat recovery experimental system has been designed and established. Main parameters representing the HPHE are investigated experimentally and theoretically, the optimum operation conditions are determined by integrating the first and the second law of thermodynamics. The results indicate that the heat transfer ratio and heat transfer coefficient increase with waste water mass flow rates increasing at constant cold water mass flow rate. As the waste water mass flow rate varies between 0.8 and 1.9 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the HPHE have the values from 0.277 to 0.510 kW; from 66.1% to 42.9% and from 0.085 to 0.192, respectively. The optimum waste water and cold water mass flow rate are deduced as 1.40 and 2.90 m^3/h, respectively. In addition, the effect of on-line cleaning device on the heat transfer and fouling cleaning has been verified by experiments in this study. It is concluded that the heat transfer performance has been significantly improved after using the on-line cleaning device.

1. Introduction

Waste heat recovery is indispensable in saving energy, which is an important goal of the world economy and in the future will continue to be one, lowering energy consumption and reducing pollutants. As the world resources decreasing and energy costs increasing, highly efficient heat transfer plays a more important role in energy utilization [1]. The loss rate of global primary energy consumption after the conversion is 72%, and the heat below 100 ℃ in the proportion of 63%, among which, power generation has the largest portion followed by transportation and industry [2]. Industrial waste heat resources are abundant in China, which account for 17–67% for the total amount of fuel consumption. 60% of the waste heat can be recovered and utilized, and then the energy utilization efficiency would be improved significantly [3].

China is a large country of producing steel and steel consumption. The steel producing has an important strategic position in the national economic development. There are abundant hot waste gases and liquids in many steelmaking processes. These waste gases and liquids have huge potential and space in energy saving, particularly for steel slag cooling process. The amount of waste heat resources is 455.1kgce per ton of steel. Presently, the recycling rate is only 45.6%. By the application of advanced recycling technology and strengthening the popularity rate of mature technology, the utilization of waste heat in China's steel industry can be increased to 63.6% [4]. It is possible to use the waste heat recovery system (WHRS) to achieve energy saving. Also there are numerous advantages of WHRSs for steel industry: (a) decreasing overall production cost, (b) reducing water loss, (c) providing heat source for heating system, and (d) decreasing energy cost.

There are many literatures about waste heat recovery systems. Hao Fang et al. [5] shows recovering industrial waste heat for use in district heating (DH) can improve the efficiency of industrial and DH system. Due to the high rate of utilization in the waste heat recovery system, a cross-flow plate heat exchanger has been investigated in laboratory conditions [6]. Conde [7] points out that it is susceptible to optimize the conventional tumbler dryer technology by using of heat recovery heat exchangers and demonstrates that the heat recovery heat exchangers enables the energy recovery potential to reach 20% of that required for heating the drying air. Wang et al. [8] construct an experimental prototype, a new type of open-cell metal foam-filled plate heat exchanger, to utilize low grade waste heat. It is found that the heat exchange efficiency between heated air and cold water can reach 83.56%. Larsen et al. [9] investigate the Split-cycle for the exhaust heat recovery from large marine engines. A multi-variable optimization

* Corresponding author at: Tianjin Key Lab of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China.

E-mail address: denglouna@tju.edu.cn (N. Deng).

http://dx.doi.org/10.1016/j.rser.2017.04.122
Received 7 March 2016; Received in revised form 12 March 2017; Accepted 30 April 2017
1364-0321/

Nomenclature

Abbreviations

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

Symbols

Q	heat transfer rate (kW)
m	mass flow rate (kg/h)
m_{ww}	waste water mass flow rate (kg/h)
m_{cw}	cold water mass flow rate (kg/h)
Cp	specific heat (kJ/(kg K))
Cp_{ww}	specific heat of waste water(kJ/(kg K))
C_{pcw}	specific heat of cold water (kJ/(kg K))
T	temperature (K)
T_0	ambient temperature
$T_{ww,in}$	inlet temperature of waste water (K)
$T_{ww,out}$	outlet temperature of waste water (K)
$T_{cw,in}$	inlet temperature of cold water (K)
$T_{cw,out}$	outlet temperature of cold water (K)
U	overall heat transfer coefficient (W/(m^2 K))
A	overall heat transfer surface area (m2)
$\triangle T_{lm}$	logarithmic temperature difference (K)
C	heat capacity (kJ/K)
C_{ww}	heat capacity of waste water(kJ/K)
C_{cw}	heat capacity of cold water (kJ/K)
R	ratio of the minimum and maximum heat capacity rates
Ex	exergy rate (kW)
Ex_{in}	inlet exergy rate of waste water (kW)
Ex_{out}	outlet exergy rate of cold water (kW)
Ex_{desc}	exergy destruction rate (kW)
ψ_{in}	outlet specific (flow) exergy (kW)
ψ_{out}	outlet specific (flow) exergy (kW)
h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/(kg K))
S_{gen}	entropy generation
IP	exergetic improvement potential (kW)

Greek letters

ε	heat exchanger effectiveness
η_{II}	the second-law efficiency
ε_{sde}	system device error
ε_t	temperature measurement error
ε_m	mass flow rate measurement error
ε_d	data acquisition error

Subscripts

0	the restricted dead state
ww	waste water
cw	fresh water
in	inlet
out	outlet
min	minimum
max	maximum
des	destruction

effort results suggest that the Split-cycle process using reheat can obtain a thermal efficiency of 23.2% higher than the value of 20.8% for a conventional reference Kalina cycle. Ebrahimi [10] focuses on the technical and economic problems of waste heat recovery from data centers using absorption cooling machines. Fergani et al. [11] propose an Organic Rankine using cyclohexane, benzene and toluene. It is used for recycling waste heat power generation system in cement industry and the exergy, exergoeconomic and exergoenvironmental analyses are carried out for achieve the system optimal operating conditions by the multi-objective optimization. Chaudhry et al. [12] evaluate the application of the common heat pipe system in the heat recovery and renewable energy sources. The investigation shows that the heat pipe with sorption phenomenon has a greater heat transfer capability. The working range of the tubular heat pipe is the highest; the average maximum operating temperature of the tube type heat pipe for all tests is 453 K.

Recently, a lot of attention focused on the application of thermodynamic analysis of various thermal units and systems. A performance evaluation criterion based on the second law has been proposed to evaluate the performance of the heat exchanger and the necessity for the system design of the heat exchanger using the second law based procedure has been discussed by Yilmaz [1]. Dincer et al. [13] perform exergy and energy analysis for a reheat Rankine cycle steam power plant and demonstrate that exergy analysis can help to make the best design decisions in a logical way. The heat transfer performance of a cross-flow serpentine heat exchanger for waste heat recovery is studied by San et al. [14,15], which shows that the effectiveness slightly decreases with an increase of the number of transfer units and the second-law efficiency value increases with the number of transfer units' value. Pulat et al. [16] perform the best running conditions of waste heat recovery systems with water-to-water shell and tube heat exchanger by thermodynamic analysis and exergy analysis, and obtain the potential of waste heat recovery in the dyeing process of the textile industry in Bursa. Kandilli et al. [17] obtain the optimal waste water flow rate and cold water flow rate for a countercurrent plate heat exchanger according to the analysis of the first and second laws of thermodynamics. Athari et al. [18] perform a thermodynamic assessment about the effect of fog inlet cooling and biomass fuel for gas turbine steam injection and combined power cycles, the results show that the efficiency of combined cycle is higher when the value for compressor pressure ratio is lower, but the efficiency of steam injection device increases with the increase of pressure ratio. Based on methane chemical-looping combustion to hot water, chilled water for cooling and produce electricity, Wang Jiangjiang et al. [19] propose a solar-hybrid trigeneration system. The thermodynamic performances of the system are analyzed, the results indicate that the best solar collector temperature is about 900 ℃, the pressure ratio of air compressor is 20, the energy efficiency is 67% and the exergy efficiency is 55%. Gakkhar et al. [20] make a complete review about exergetic analysis of solar assisted distillation systems. The general relations are presented for first and second law analysis, irreversibility and entropy generation of each subcomponent. Hamed Sadighi Dizaji et al. [21] make a comprehensive second law analysis for tube-in-tube helically coiled heat exchangers. The experimental study shows the impact of flow, thermodynamic and geometrical parameters on exergetic characteristics. The results demonstrate that the value of exergy loss increases with the increasing of the flow rates of hot or cold water, hot water temperature at the entrance and coil diameter. Song Jian et al. [22] reveal that the optimal operation condition for the engine waste heat recovery case of the ORC system is cyclohexane/R141b (0.5/0.5), thereby the net power output of the system increases by 13.3% than the pure cyclohexane. Chen et al. [23] analyze the impact of inlet temperatures of both heat resource and cooling water on ammonia-water Kalina-Rankine cycle system efficiencies based on the first and the second law of thermodynamics.

Numerous studies have been presented to show the effects of the