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Pilot study on ascension-pipe heat exchanger used for waste heat recovery of coke oven gas

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Abstract

Coke oven gas (COG) is syngas with abundant waste heat generated from coke-making process. Waste heat recovery of COG can be a useful solution to address issues of energy shortage and environmental protection. Empirical approaches to recover waster heat from COG are to re-combust residual heat, purify hydrogen and synthesize methane for energy generation. However, sensible heat of COG cannot be recovered in efficient manner. Ascension-pipe heat exchanger (APHE) as one of heat pipe heat changer is considered to mitigate such issues. However, few studies were implemented to analyze the thermal performance of APHE for waste heat recovery of COG. It might restrict the development of APHE used in coke oven plant. As a result, this pilot study aims to evaluate the overall heat transfer coefficient with different mass flow rate of working fluid and effectiveness of APHE in one period of coke-making process. The findings showed that overall heat transfer coefficient rises with the increase of mass flow rate of working fluid. The average effective of APHE in one period can reach around 69%. These can demonstrate that APHE is a promising choice to recover the sensible heat from COG. In addition, the temperature variation of COG during entire coke-making process needs to be concerned for accurate thermal performance evaluation of APHE.

Keywords: Coke oven gas, waste heat recovery, sensible heat and ascension-pipe heat exchanger

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1. Introduction

As the solid carbonaceous fuel with few impurities and high carbon content, coke has been widely used as raw material for steel production in China. In 2007, the annual coke output was approximately 225 million tons in China, accounting for 60% of the total global coke production [1]. Coke oven gas (COG) is generated from the coke-making process as by-product. Usually 80% of generated COG is directly discharged into surrounding environment resulting in lots of environmental issues and energy waste. If waste heat of COG is recovered efficiently, this will be significantly useful to mitigate energy crisis and environmental pollution. Numerous research have proposed several methods to recover waste heat from COG, such as combustion of COG for energy generation [2], extracting hydrogen from COG [3] and assisting COG to synthesize methanol [4][5]. However, these ways of recovering COG waste heat do not focus on reusing sensible heat of COG. As an effective manner to recover sensible heat, ascension-pipe heat exchanger (APHE) is considered to perform its function directly to transfer sensible heat from COG to working fluid [6]. To best of my knowledge, few research have been conducted to investigate thermal performance of APHE for waste heat recovery of COG. Due to lack of such reliable analysis, this might be the challenge for APHE to be widely applied into coke-making industry. In order to bridge aforementioned gap, this pilot study seeks to carry out an experiment for evaluating thermal performance of APHE at a coke oven plants in China. Research findings and some issues in the experiment may provide useful suggestions for researchers to improve heat recovery of COG which can significantly support China's targets in relation to reduction of CO_2 emission and energy shortage.

Nomenclature

Abbreviations

APHE	Ascension-pipe heat exchanger	COG	Coke oven gas

Symbol

Q	Heat transfer rate	m_{ss}	Mass flow rate of saturated steam
h_{ss}	Enthalpy of saturated steam	h_{cw}	Enthalpy of cold water
$T_{cog,in}$	Temperature of coke oven gas at inlet	$T_{cog,out}$	Temperature of coke oven gas at outlet
$T_{cw,in}$	Temperature of cold water gas at inlet	$T_{cw,out}$	Temperature of cold water gas at outlet
u	Overall heat transfer coefficient	A	Overall heat transfer area
ΔT_{lm}	Logarithmic temperature difference	Q_{max}	Maximum heat transfer rate
V_{cog}	Volume flow rate of COG	C_{vcog}	Volumetric heat capacity of COG

2. Waste heat recovery of COG

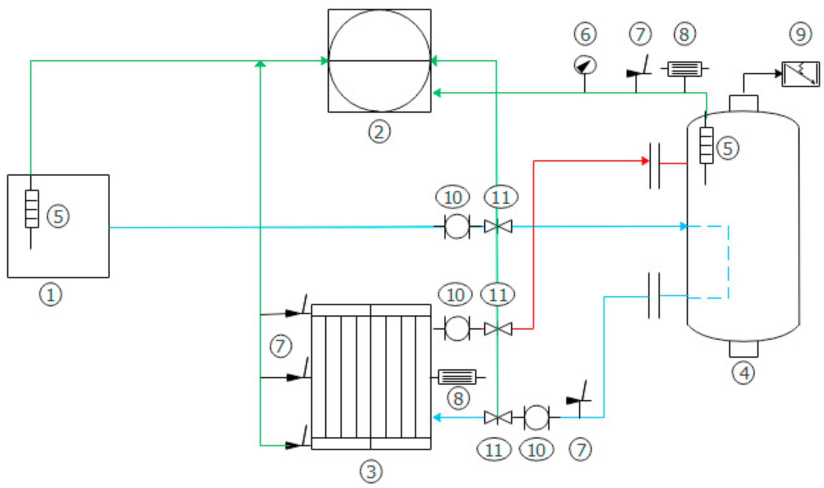
In 2015, annual COG was produced at approximately 210 billion Nm^3 in China [7]. Only around 20% of them can be recovered to for energy supply. Recovering waste heat from COG is gaining importance in environmental protection and reduction of energy shortage [1]. For example, COG can serve as feed stocks to be mixed with blast furnace gas for power generation [2]. The first COG-based heat and power plants in China were established since 2006 which can provide for power generating capacity of around 1.6 kWh/m^3 [8]. Due to high content of H_2 in COG (50%-60%), COG is regarded as potential feedstock to purify hydrogen for energy generation [9]. According to analysis in U.S. steel mills, it reported around 370000t H_2 can be produced annually from discharged COG, and per m^3 of COG was estimated to generate 0.043kg H_2 [3]. In addition, a study has examined COG satisfies the requirement of the methane reforming process because of its composition (e.g. H_2 and CO) and high temperature 800 to 1200°C [10]. In order to reform methane efficiently, some studies have successfully integrated CO_2 into process of conversion from COG to methane. They found such way seems to have great advantages in terms of energy efficiency, economic factor, CO_2 emission and raw material exploitation [4][5].

As syngas with high temperature from 800 to 1200°C, COG has abundant sensible heat that can be further exploited. Aforementioned waste heat recovery are to combust residual energy of COG for power generation, purify hydrogen and synthesize methane as energy source, which cannot fully extract sensible heat efficiently. Accompanying with development of heat exchanger technology, it has the potential to recover sensible heat depending on heat transfer principle. Installed heat exchanger on ascension pipe (APHE) where COG exits through, is thus identified to be another alternative [6]. The working principle of APHE mainly relies on temperature difference between COG and working fluid rather than chemical reaction. As a result, it is relatively easier to be controlled and faces with less safety problems. Due to lack of on-site experimental analysis, there are few investigations regarding thermal performance of APHE for waste heat recovery of COG. Therefore, the goal of this present study is to conduct a pilot study at a coke oven plant for evaluating overall heat transfer coefficient and effectiveness of APHE. Research findings from this study can offer best practice and useful suggestions to operate and optimize APHE for better performance of COG waste heat recover.

3. Experimental design

3.1. Experimental apparatus

In order to investigate the heat transfer performance of APHE effectively, this study sets out an experiment in a coke oven plant located at Handan, Hebei province, China. The coke oven plants aims to provide coke for steel making, and discharged coke oven gas was measured at approximately 1123K. The experimental apparatus mainly consisted of ascension-pipe, water tank, data acquisition system and circulation system as shown as Fig.1. The cold water firstly at first is driven from water tank to circulation system by circulating water pump as blue line. Then the cold water (25℃) was forced through the APHE where located at outlet of coke oven gas for heat transfer. After heat transfer process, mixture of water and steam returns back to circulation system as red line. In the circulation system, saturated steam is extracted from mixtures to be used for end-users (e.g. heating system or hot water supply system). The rest of mixture will be released to APHE again for repeated heating until they becomes saturated steam. The heat of saturated steam is regarded as useful heat that used for calculating overall heat transfer coefficient and effectiveness. It usually takes approximately 19 hours as one period to converse coal into coke. The entire system is operated under pressure condition of 0.4Mpa.



①: Water tank; ②: Data acquisition system; ③: APHE at outlet of coke oven gas ④: Circulation system; ⑤: Float level meter; ⑥: Pressure meter; ⑦: Temperature sensor; ⑧: Flow monitor; ⑨: End-user ⑩: circulating water pump; ⑪: Valve

Fig.1. Schematic diagram of the experimental apparatus.

The APAE in this study is the heat pipe in wick structure. Each unit of heat pipe is made of steel with inner diameter of 560mm and length of 2950mm. Since corrosion issue and conductivity are gaining importance in heat transfer process, the inner surface of APHE is attached by alloy steel with high conductivity and corrosion protection. During the experiment, the temperature of cold water were measured at outlet of water tank and circulation system respectively. In addition, the temperature was recorded at the inlet and outlet of heat exchanger. Recorded data are displayed by data acquisition system automatically. In order to obtain accurate data, there are nine periods of data collected to estimate thermal performance of APAE. Since coal is complemented continuously during coke-making process, state of COG will be in stable period. Thus, data of change in COG temperature and steam temperature during stable period is collected to predict thermal performance. Average COG temperatures in stable period at inlet and outlet are 850℃ and 510℃ respectively. Steam temperature is heated to saturated steam at pressure condition of 0.4Mpa (from 140℃ to 143.5℃).

Fig. 2. Photographic image of experimental apparatus: (1) Circulation system; (2) APHE at outlet of coke oven gas; (3) Control and data collection system

3.2. Thermodynamic analysis

The first law of thermodynamics is used to evaluate quantity of energy conversion, and energy during heat exchange process cannot be created or destroyed. Based on first law of thermodynamics, overall heat transfer rate and effectiveness of APHE is calculated by energy change from cold water to saturated steam as below equations:

$$Q = m_{ss}(h_{ss} - h_{cw}) \quad (1)$$

$$u = \frac{Q}{A * \Delta T_{lm}} \quad (2)$$

$$\Delta T_{lm} = \frac{(T_{g,in} - T_{cw,out}) - (T_{g,out} - T_{cw,in})}{\ln[(T_{g,in} - T_{cw,out})/(T_{g,out} - T_{cw,in})]} \quad (3)$$

$$\varepsilon = \frac{Q}{Q_{\max}} \quad (4)$$

$$Q_{\max} = V_{cog} C_{vcog}(T_{cog,in} - 773) \quad (5)$$

Where Q_{max} is the maximum amount of sensible can be extracted from COG as following. Since final carbonizing temperature of coke making is suggested as 773K [11], the minimum temperature of COG can only be reached at 773K.

4. Results and Discussion

The variations of COG temperature and steam temperature during entire period of coke-making process are indicated as shown as Fig.3. Due to high temperature in coal chamber, COG at first was generated with temperature of around 900 ℃ at inlet. During stable period (3h-15h) accounting for 2/3 of entire period, COG temperature kept at 850 ℃ steadily which reaches heat transfer balance between COG and coal chamber temperature. After 15h, its temperature decreased sharply to 530 ℃. This can could explain by absence of coal that no heat is supplied to coke-oven gas. Similar trend of COG temperature can be found after heat exchange process. As for steam temperature, there was slight increase by around 4 ℃ after absorbing sensible heat from COG. It is obvious that understanding coking-making process could contribute to thermal performance analysis of APHE. As a result, average effectiveness of APHE in one period is calculated in this pilot study, and overall heat transfer coefficient varied as change of mass flow rate of circulating is estimated according to data from stable period.

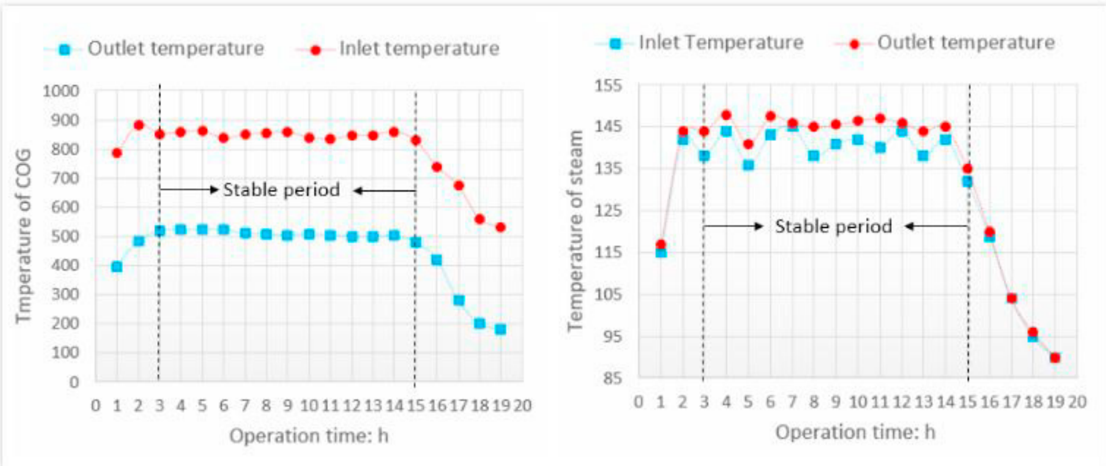


Fig. 3. Temperature variations of COG and steam

According to Eqs (1)(2)(3), the overall heat transfer coefficient in three periods is estimated as shown as Fig 4 and the flow rate of cold water is controlled at 0.3kg/s to 1kg/s. Among data of nine periods, only three of them are effective due to collection mistakes. The collected results demonstrated the positive relationships between mass flow rate of circulating water and overall heat transfer coefficient. On average, the minimum heat transfer rate (17.85W/(m^2K^{-1}) was captured as the mass flow rate of cold water was 0.kg/s. Average flow rate of COG is around 492.7Nm^3 /h, and each period generates 1424kg saturated steam. The maximum heat transfer rate (19.3 W/(m^2K^{-1}) was achieved when the mass flow rate of cold water was 1kg/s. In addition, average flow rate of COG is around 492.7Nm^3 /h, and each period generates 1424kg saturated steam. The specific heat of COG is 1.643kJ/(m^3*℃), and specific enthalpy of saturated water is 2133.8 kJ/kg. The average effectiveness of APHE for entire period is calculated at 69% in accordance with Eqs (1)(4)(5). The results can demonstrate that APHE is a promising solution with 69% effectiveness to recover sensible heat from COG for steam generation. Additionally, higher mass flow rate of working fluid is suggested to enhance overall heat transfer coefficient.

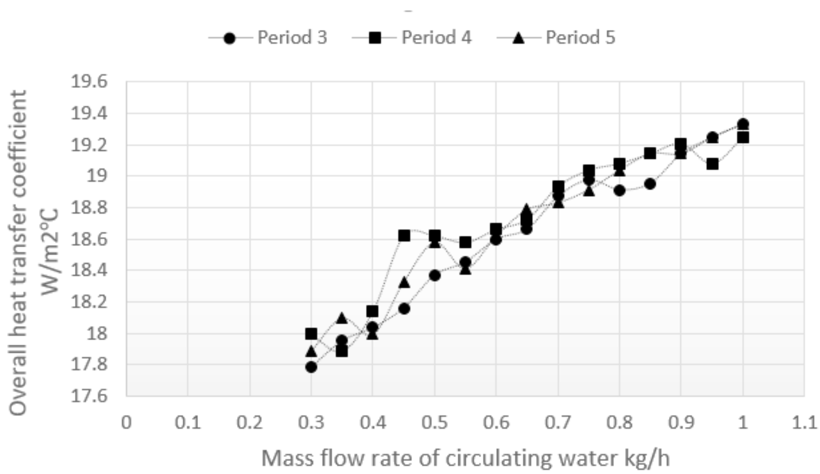


Fig. 4. Relationship between overall heat transfer coefficient and mass flow rate of cold water

5. Conclusion

Recovering sensible heat from COG becomes important to relieve energy shortage and environmental issues. This study implemented a pilot study in a coke oven plant to assess the thermal performance of APHE. According to analyzing data of nine periods, several conclusion were drawn as below:

- With increasing mass flow rate of working fluid, overall heat transfer coefficient of APHE will rise gradually as well.
- The average effectiveness of APHE for entire period is around 69%.

The results demonstrate APHE is a reliable choice to recover sensible heat from COG for steam generation. It is noted that coke-making process is divided into three sections which should be concerned for assessing thermal performance. In the future, authors seek to conduct in-depth analysis respect of role of some factors (e.g. volume flow rate of COG and type of working fluid) in impacting thermal performance of APHE.

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