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Research Paper

Experimental study of the effect of a radiant tube on the temperature distribution in a horizontal heating furnace

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HIGHLIGHTS

- 1:1 scale experimental study of the temperature distribution by a radiant tube.
- Two burners are investigated for the heat transfer comparisons.
- The non-uniformity coefficient ε is adopted to quantify temperature deviation.

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ABSTRACT

This article reports the experimental study of the heat transfer characteristics in a horizontal heating furnace that is extensively used in the petroleum industry of China. To avoid furnace burnout caused by an uneven furnace wall temperature, a straight radiant tube is proposed to be installed in the furnace, which transfers heat to the furnace wall mainly via a radiation pattern. Seven groups of measure points were selected to record the temperature data; each group consisted of two testing points at the top wall and middle wall. Two burners were investigated to compare the temperature distribution along the horizontal furnace wall. A non-uniformity coefficient ε of the wall temperature was used to quantify the temperature deviation. The experimental results show that the radiant tube can significantly reduce the temperature deviation on the furnace wall. The furnace wall with the SR100 burner has a generally larger ε than that with the HQ05 burner without the radiant tube. The SR100 burner has a larger overall decrease in ε than the HQ05 burner after the radiant tube is installed.

1. Introduction

Horizontal heating furnaces are widely used in the petroleum industry of China. Because of direct contact with the combustion flame, the internal-wall temperature of the heating furnace is non-uniformly distributed. At a component that has a high heating load, the internal wall can easily be destroyed by combustion [1–6]. Although sufficient measures, such as material selection, have been considered, failures of the heating furnace cannot be thoroughly avoided and can cause major safety accidents, which are dangerous during the operation in the petroleum industry.

In the last decade, some numerical and experimental studies have been performed to inspect the heat and mass transfer behaviors of the heating furnace. Ahanj et al. [7] presented a new methodology to simulate a three-dimensional reheating furnace of steel billets with natural gas burners. The energy transport equation was modified to convert the transient movement. The effects of excess air and inlet air on the heater efficiency were also studied. Tsioumanis et al. [8] studied the combustion process in an industrial burner with a radiant tube. The effects of certain radiant-tube boiler design features were analyzed and the heat transfer processes in the burner were reported. Casal et al. [9] presented a new modelling methodology for a three-dimensional simulation of a reheating furnace with natural-gas burners. The results were consistent with the data obtained in an actual facility, which implies that the proposed methodology was adequate for the simulation of that system. Tu et al. [10] simulated the effects of the furnace chamber shape on the moderate combustion characteristics of natural gas. The results showed that the angle between the furnace roof and sidewalls significantly affected the combustion status. Saario et al. [11] simulated the reacting flow in a heavy fuel oil fired laboratory furnace. They found that the standard k-ε model did not satisfactorily predict the highly swirling flow field

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in the furnace. The RSM method was shown to improve the flow field prediction. Irfan and Chapman [12,13] analyzed the thermal stresses in radiant tubes. The analysis was verified using a finite-element model. The axial temperature gradients were not a source of thermal stresses as long as the temperature distribution was linear. However, spikes in the axial temperature gradient were sources of high thermal stresses. Hu et al. [14] simulated the flow combustion and radiative heat transfer in the furnace. The results showed that the design of the radiation outlet caused asymmetric flue gas temperatures, concentrations and velocity profiles. There were large recirculation zones near the reactor tubes, which made the temperature distribution in the middle of the furnace more uniform. Oliveira et al. [15] conducted a thermal simulation to investigate whether it was possible to reduce fuel consumption and CO_2 emission rates by controlling the combustion temperature. Yang et al. [16] investigated the temperature deviation in pulverized-coal boiler furnaces using simulation. They concluded that the nonlinear flow characteristics were key for the velocity and temperature deviations.

In experimental studies, Cha et al. [17] investigated the effect of a non-uniform boundary–velocity gradient along the rim of a circular-nozzle burner. They found that the flames in the U-bend tubes had larger velocities than the case with straight tubes. Lou et al. [18] experimentally tested the temperature distribution and radiative properties in an oil-fired tunnel furnace using radiation analysis. The results showed that the temperature was higher in the center and lower near the refractory wall surface and decreased along the length of the tunnel furnace. Liu et al. [19] experimentally investigated the performance of a W-shaped regenerative radiant-tube burner. They found that the tube wall temperature was symmetrically distributed along the length of the tube, with an M-shaped profile and good temperature uniformity. Scribano et al. [20] studied a self-recuperative radiant-tube burner to find the best operating conditions in terms of the optimal equivalence ratio, thermal power and lower pollutant emissions, which resulted in the development of a new burner configuration. Abu-Qudais [21] conducted a test using a cylindrical water-cooled furnace to compare different fuels based on the combustion efficiency, heat transfer to the water jacket and gaseous and particulate emissions in a wide range of air-to-fuel (A/F) ratios at different energy input levels. Pan et al. [22] experimentally studied a cold-state model with a 1:10 scale for a regenerative heating annular furnace to measure the interior velocity distribution.

Temperature control of heating furnaces is another key issue. Shi et al. [23] designed a self-adapting PID controller to regulate the temperature of heating furnaces. Dou et al. [24] found that traditional PID control could not effectively overcome the effects of the interference, load change and parameter change of the system and other factors. They improved the controller with a variable slope, which significantly enhanced the robustness of the system. Feng et al. [25] designed a new device that was able to remove most of the sand before it flowed into the heating furnace, which improved the safety and reliability of the heating furnace.

The above literature review shows that there are few reported studies regarding the horizontal heating furnace (Fig. 1) in the petroleum industry. According to an investigation of horizontal-heating-furnace failure in the Daqing petroleum industry of China, the horizontal furnace wall is often burned because of serious uneven heating (Fig. 2), which introduces safety issue and severely affects the daily production of crude oil. Accordingly, a radiant tube is proposed to be added to the furnace to reduce the temperature deviation on the internal wall by changing the heat transfer mode to the surrounding furnace wall to dominant radiation heat transfer. Prior to the tentative application, detailed experimental investigations of the heat transfer characteristics must be performed in a 1:1 scale of the horizontal heating furnace in Daqing petroleum industry. This article reports this experimental work and provides valuable suggestions for industrial application. The two most common burners (SR100 (passive) and HQ05 (active)) were used to compare the temperature distributions along the horizontal furnace wall before and after the installation of a radiant tube.

Fig. 1. Horizontal heating furnace in the Daqing petroleum industry of China.

2. Experimental description

2.1. Brief of the experimental system

The heating furnace in the experiment was composed of boiler steel. The length was 8000 mm, the inner diameter was 800 mm, and the wall thickness was 4 mm. A schematic diagram of the testing system is shown in Fig. 3. Natural gas was first prepared, and the main component was methane, with a concentration of 94%. The calorific value of the gas was 36.27–40.24 MJ/N m^3; the gas pressure was 0.174 MPa. The internal wall temperature of the heating furnace was measured using K-type thermocouples with an inherent accuracy of ±2.5 °C. Seven groups of measuring points were selected along the horizontal direction; each group consisted of two testing points at the top wall and middle wall. A picture of the site testing system is presented in Fig. 4(a). The testing point arrangement on the heating furnace wall is schematically shown in Fig. 5.

The temperature was recorded using the data acquisition unit TM-902C, which has an inherent accuracy of ±0.5%. The exhaust gas components NO/NO_2 and CO/CO_2 were recorded using two gas analyzers, CLD822S and ULTRAMAT23, respectively. Their accuracy was ±1 ppm. The flow rate of the cooling water in the furnace water jacket was measured using an ultrasonic flowmeter, FSC S10C1. The temperature of the inlet and outlet water was measured using Pt100, which has an accuracy of ±0.1%FS. The detailed testing apparatus is summarized in Table 1.

Two different burners (Fig. 6) were installed at the left entrance of the horizontal heating furnace. The passive-type burner SR100 introduces natural gas into the heating furnace via the chimney effect. The SR100 burner has three channels: one for natural gas and the other two for air flow. The kinetic energy induced by high-speed natural gas produces a pressure difference, which brings air into the burner. The air volume can be adjusted using the guide wind plate. The active-type burner HQ05 uses a powerful fan to blow natural gas into the combustion chamber. Air is accelerated through the air channel before it reaches a circular disc, which is full of small holes for flame stability. The premixed gas passes through a swirling blade before it enters the burning chamber. The blade is used to generate a swirling flow to increase the combustion efficiency. Table 2 shows the detailed specifications of these two burners.