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Experimental study of natural gas temperature effects on the flame luminosity and NO emission

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ABSTRACT

The flame radiation enhancement in gas-fired furnaces significantly improves the thermal efficiency without significantly affecting the NO_x emissions . In this paper, the effects of inlet natural gas preheating on the flame luminosity, overall boiler efficiency, and NO emission in a 120 kW boiler have been investigated experimentally. Flame radiation is measured by use of laboratory pyranometer with photovoltaic sensor. A Testo350XL gas analyzer is also used for measuring the temperature and combustion species. The fuel is preheated from the room temperature to 350°C. The experimental measurements show that the preheating of natural gas up to about 240°C has no considerable effect on the flame luminosity. The results show that increasing the inlet gas temperature from 240°C, abruptly increases the flame luminosity. This luminosity increase enhances the boiler efficiency and also causes significant reduction in flame temperature and NO emission. The results show that increasing the inlet gas temperature from 240°C to 300°C increases the flame luminous radiation by 60% and boiler efficiency by 20%; while the maximum flame temperature and the boiler NO emission show a 10% and 8% decrease respectively.

Keywords: Inlet fuel temperature, radiation effect, soot formation, flame luminosity.

1. INTRODUCTION

Due to the great environmental pollution of liquid fuels, many of industrial furnaces are replaced by their gas fueled alternatives. This substitution leads to a significant reduction in luminous radiation and consequently causes an overall reduction in furnace efficiency [1]. The luminous radiation is related to the carbon number (C to H ratio) of the fuel molecule and it is weak for low carbon number fuels, especially natural gas. Many investigations were conducted worldwide to improve the radiation of natural gas

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flames [1–10]. Flame radiation in furnaces is due to gaseous and particulate contributions [1, 3]. From the standpoint of radiation heat transfer, although thermal radiative gases of CO_2 and H_2O are the two important species, but the role of particulates, specially soot, in luminous flames radiation is much more important [1, 3]. The formation and presence of soot in adequate quantities is a desirable phenomenon within combustion furnaces because soot radiation improves the thermal efficiency of these devices. The presence of less than 0.05 ppm of soot in flame increases radiation rate by more than 30% [9]. On the other hand, the release of fine soot particles into the exhaust gases leads to environmental pollution which has became an increasing concern. Thus, effective control of soot formation and oxidation processes in combustion is highly desirable [2].

Various methods for increasing the soot content in the natural gas flames such as injecting liquid fuel [1], using electric fields [11], and preheating the gaseous fuel [7, 12] have been studied by many researchers. Also, an increase in the flame soot content has been observed in the studies concerning applying high temperature air in combustion furnaces (HiTAC). Highly preheated air combustion significantly increases flame luminosity which results in flame temperature and NO emission decrease [8]. Atreya et al. [10] used HiTAC with oxygen enriched air for metal processing and obtained high flame temperature and thus thermal NO. To reduce the flame temperature and thermal NO, they needed intense flame radiation by increasing soot content of flame. They suggested that the required soot can be achieved using slightly rich combustion or alternatively adding some pulverized coal dust to the reaction zone [10].

Since highly preheating the combustion air needs an enormous amount of energy, preheating the gas fuel due to its simplicity and low energy consumption seems an effective method that has attracted the researchers' attention [7, 12], but still needs more investigations. The fuel preheating increases the carbon content in hydrocarbon flames by increasing the fuel pyrolysis rate, according to the following reactions[13, 14]:

$$CH_4 \rightarrow C_S + 2H_2, \qquad \Delta H^0_{298} = -74.9 \text{ kJ/mol} \qquad \text{Reaction (1)}$$

$$2CH_4 \xrightarrow{\nearrow H_2} C_2H_6 \xrightarrow{\nearrow H_2} C_2H_4 \xrightarrow{\nearrow H_2} C_2H_2 \xrightarrow{\nearrow H_2} C_2 \qquad \text{Reaction (2)}$$

The primary aim of the present work is to increase soot content of flame by preheating of fuel (natural gas). The inlet fuel temperature required to reach the desired flame radiation and luminosity is measured experimentally in a 120 kW boiler. The effects of the natural gas temperature on the luminous radiation, efficiency enhancement, and NO emission have also been investigated.

2. EXPERIMENTAL APPARATUS

The effects of inlet natural gas temperature on combustion parameters, including exhaust temperature, NO emission, and flame radiation were studied experimentally in a 120 kW fire tube water heater (boiler) shown in figure 1, which is described in the European Standard EN 676 [15]. The diameter and the maximum length of the

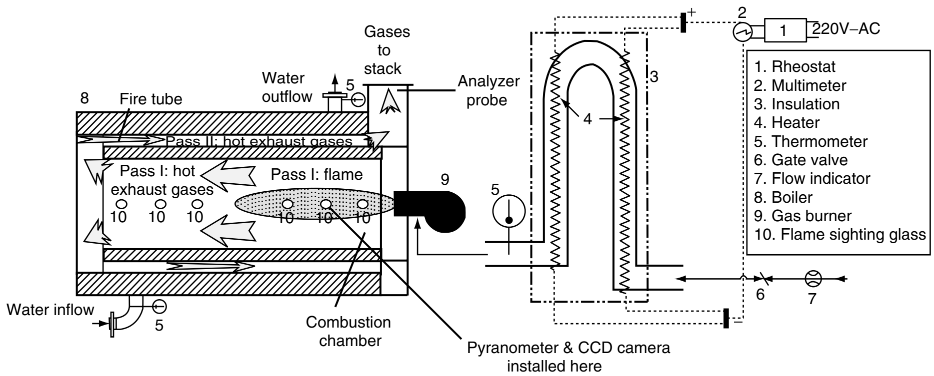

Figure 1: Schematic illustration of experimental apparatus and fire tube water heater (boiler).

combustion chamber were 400 and 1200 mm, respectively. The main network volumetric composition of natural gas was 85% CH_4, 12% C_2H_6, and 3% C_3H_8 and other gases (such as N_2, CO_2, O_2, etc.).

In the first step, natural gas entered the burner automatic valve and then the U shaped pipe. There was a 2 kW electric heating element for each branch of the U-pipe. The U-pipe was well insulated in order to reduce heat losses and provide conditions for increasing gas temperature from room temperature to 400°C. In the fire tube water heater, all the surfaces in contact with hot gases were cooled by water. Four groups of fire tubes had been placed around the combustion chamber and flame was formed in the center. Gas inlet temperature was controlled by variable power electrical heaters. The flame was generated with a forced air blown burner of 60–120 kW firing rate range in which the fuel issued from a 10 mm inner diameter horizontal tube and the air from the annular region between the fuel tube and a 100 mm diameter concentric tube. A fixed straight blade radial swirler with 90 mm outlet diameter was placed at the outlet plane of the burner (inlet plane of the furnace). Seven circular slots had been cut into side of the boiler cladding so that thermocouple probes could be inserted into the center of the cylindrical furnace of boiler. The axial distance of the slots from the inlet port of furnace were 100, 200, 300, 400, 600, 800, and 1200 mm. A calibrated ceramic-sheathed type S-thermocouple with the resistance temperature up to 2000 K was used for measuring the gas temperature at different points on the central axis of the furnace. The described system measured temperatures within a tolerance of 1 K. Flue gas temperature and species concentrations were measured using Testo350XL gas analyzer.

The air and gas mass flow rates were kept constant in all the experiments using control valves. The inlet air temperature was fixed to the value of 20°C in all the experiments. In the current work the experiments were carried out with the natural gas mass flow rate of 5.6 kg/hr with 13.9% excess air and the boiler water flow rate of 0.4 litr/s. The water inflow temperature was set to 25°C, also the water exit temperature was in the range of 65 to 85°C. The soot emission (in the exhaust gases) was measured using the filter paper technique within a tolerance of 5e-8 soot volume fraction (AVL LIST GMBH 2001).

The intensity of flame luminosity radiation was detected by a pyranometer which had a photovoltaic sensor with spectral range of 300 to 1100 nm that corresponds to flame luminosity spectral range [16]. The output signal of pyranometer, which had been in the range of 0 to 3 Volts DC, was calibrated to be proportional to a measured range of 0 to 1400 W/m^2. For each inlet fuel temperature, the flame image was captured in order to compare the flame luminosity. The Image of flame was recorded by a CCD camera with constant exposure time of 1/200 second. To ensure that the measurements had been performed in the steady state conditions of the boiler, measurements were repeated in 15 minute intervals until the measured parameters, especially of inlet gas and outlet water temperatures, reached a steady value within a 5% tolerance. Each data point was obtained from the average of three runs performed on different samples at the same inlet fuel temperature. The repeatability of the data was regularly checked during each experimental session. The axial and outlet temperatures of the furnace were repeatable within ± 30°C and ± 5°C, respectively. The uncertainty associated with the NO measurements was dominated by uncertainly of the temperature measurements. On average, all of the temperatures for gaseous species in Celsius scale could be reproduced to within 10% of the mean value. The values of uncertainty related to CO mass fraction and outlet water temperature are 5 and 4% respectively. Also the uncertainty of radiation measurement was estimated about 5–15%.

3. RESULTS AND DISCUSSION

In this paper, the effects of preheating the inlet gas fuel on the flame luminosity and also on pollutant formation were experimentally investigated. The schematic of the boiler and the inlet gas preheating setup have been illustrated in figure 1.

In figure 2 the photos of the flame with different inlet gas temperatures ranging from 26 to 310°C are depicted. It can be seen that for fuel gas temperatures higher than 240°C, the flame luminosity increases abruptly and the flame radiation enhancement is expectable. At 300°C, the flame luminosity sharply increases, therefore the exposure time is decreased from 1/200 to 1/250 second in order to keep the flame visible. This means that if the same exposure time was used, like in others, then the photo of the flame would be even brighter. To evaluate the increase of flame luminosity as a function of inlet fuel temperature, a dimensionless radiation coefficient is defined as follows:

$$\Gamma = \frac{\dot{E}_T - \dot{E}_0}{\dot{E}_0} \qquad (1)$$

In this equation, $\dot{E}_0$ and $\dot{E}_T$ are the radiation intensities (W/m^2) at non-preheated and preheated gas temperatures measured by pyranometer, respectively.

The variations of dimensionless radiation coefficient (Γ) as a function of inlet gas temperature is illustrated in figure 2. It can be seen that the preheating of natural gas up

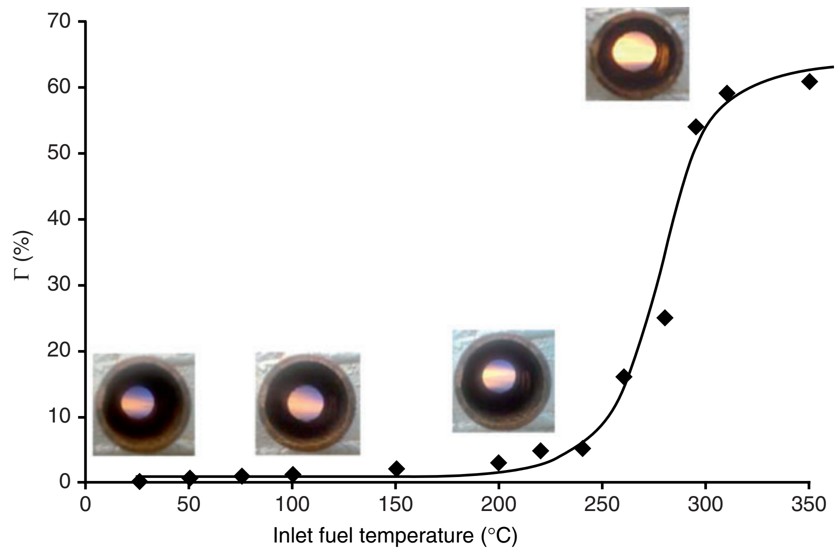

Figure 2: Flame luminosity photos and dimensionless radiation coefficient as a function of inlet fuel temperature.

to 200°C has no considerable effect on the flame luminosity. This is in accordance with results of Zhukov et al. [17]. The abrupt increases of flame luminosity and Γ occur simultaneously for fuel temperatures above 240°C. This can be due to increase in the soot content of the flame as a result of higher thermal decomposition of natural gas. The oxidation of these extra soot particles produces a luminous flame. The results of Guo and Smallwood [18] show that the drop in NO emission can be due to the formation of soot. The results of Mandal et al. [19] show that with a small increase in inlet air temperature (300°K to 400°K) the peak of soot volume fraction of air-natural gas combustion increases to more than five times its value.

Figure 3 shows the variations of relative efficiency of boiler which is defined by:

$$\eta = \frac{\dot{\eta}_T - \dot{\eta}_0}{\dot{\eta}_0} \tag{2}$$

where $\dot{\eta}_0$ and $\dot{\eta}_T$ are the overall efficiencies at non-preheated and preheated fuel temperatures, respectively. The boiler overall efficiency is defined as the ratio of the net heat transfer to the water to the sum of the heat supplied by the fuel (based on its flow rate) and the heat added to the natural gas by the heaters.

It can be seen in figure 3 that for temperatures above 240°C the ascending trend of the efficiency (and water exit temperature) is drastic, which implies higher heat transfer efficiency. The reason lies within the fact that under highly preheated fuel temperature conditions, the flame luminous radiation suddenly increases as depicted in figure 2.

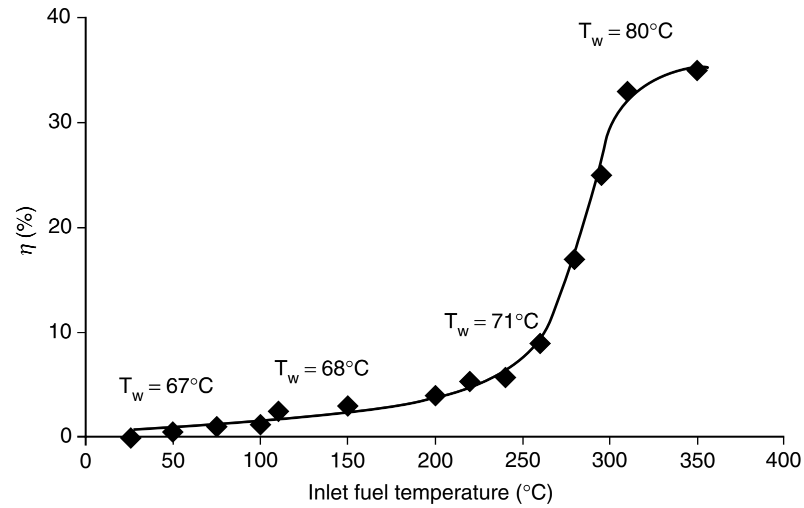

Figure 3: Variations of boiler efficiency and water exit temperature (T_w) as a function of inlet fuel temperature.

As the results illustrate, increasing fuel temperature above 240°C, remarkably increases radiation heat transfer and boiler efficiency. In addition, higher radiation of flame resulting in reduction of maximum flame temperature greatly reduces the NO emission. In figure 4, it can be seen that NO concentration and temperature of exhaust gases increase for inlet fuel temperatures up to 240°C, but decrease suddenly for fuel temperatures above 240°C. Regarding the intensive dependence of thermal NO formation on flame temperature, the decrease of NO concentration is a result of reduced flame temperature caused by flame radiation enhancement. This reduction in flame temperature is also predictable from exhaust temperature reduction. Yang and Blasiak's [7] studies also verify the NO emission reduction caused by the inlet gas preheating. According to their results when the temperature of the inlet fuel (propane) increases from 200°C (473K) to 300°C (573K), the emission of thermal NO significantly decreases from 180 ppm to 120 ppm.

Based on the recorded images of the flame (figure 2) and the variations of the exhaust temperature and NO emission (figure 4), it is expected that for gas temperatures above 240°C the maximum flame temperature decreases as the inlet gas temperature increases. The increase of overall boiler efficiency and the flue gas temperature reduction when the fuel temperature exceeds 240°C reveal a remarkable enhancement in radiation heat transfer.

Temperature distribution on the axis of the furnace is depicted in figure 5 for three inlet fuel temperatures (100°C**,** 240°C and 310°C). It can be seen that for fuel preheating from 100°C to 240°C the flame temperature variation along the furnace axis does not change considerably. In contrast, by increasing the inlet fuel temperature from 240°C to 310°C, the maximum flame temperature along the furnace axis decreases by about 150°C due to the flame luminosity enhancement.

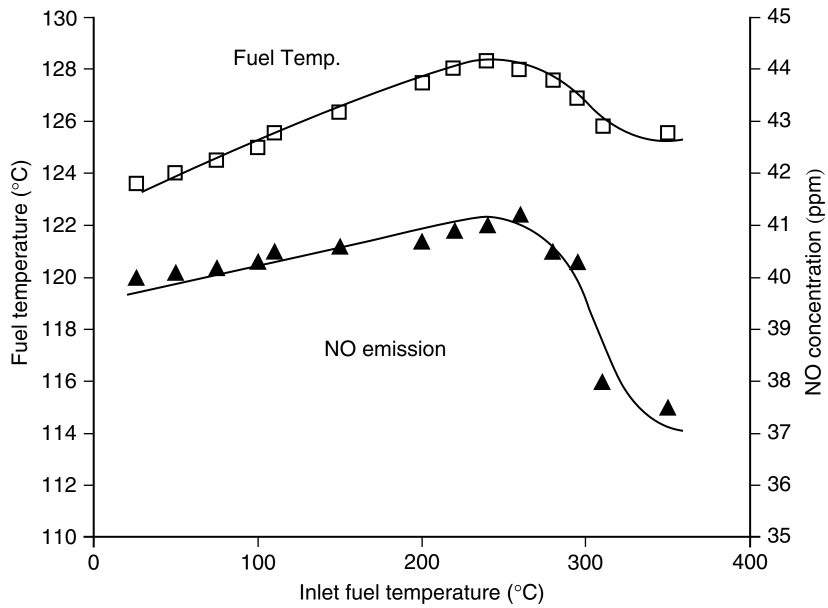

Figure 4: Variations of NO concentration and temperature in flue gas.

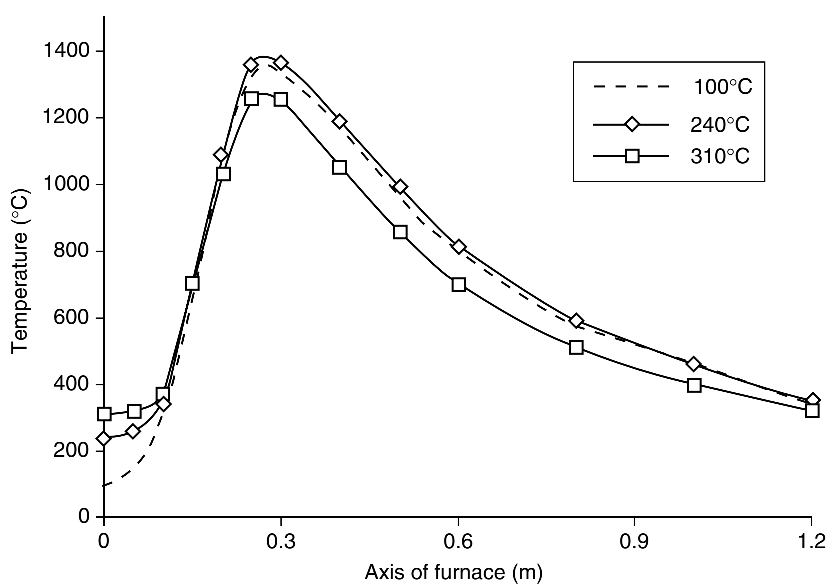

Figure 5: Comparison of the measured temperatures along the furnace central axis for three inlet fuel temperatures.

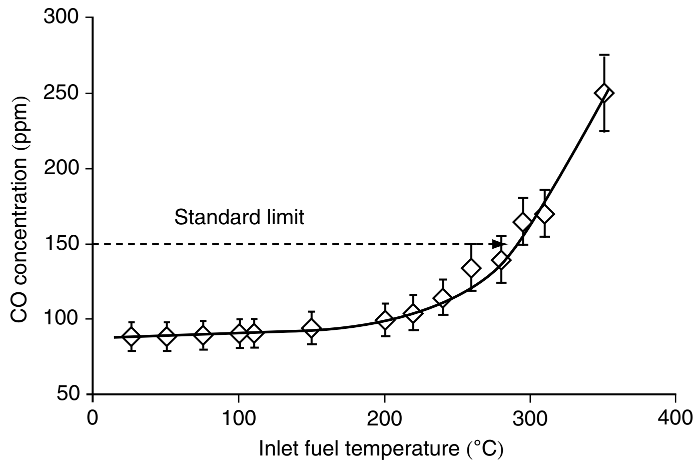

Figure 6: The effect of inlet fuel temperature on CO concentration.

In figure 6 the effect of inlet gas temperature on CO concentration is presented. It is observed that CO concentration in the exhaust gases rises by increasing inlet fuel temperature. The increase in CO concentration can be caused by the incomplete combustion of soot particles and CO itself due to lower flame temperatures. This increase in CO concentration for higher fuel temperatures has also been observed in high temperature air combustion (HiTAC) processes [8]. CO emission limit for forced draft burner for gaseous fuels in the European standard is CO ≤ 100 mg/kWh [15]. The CO emission was above the standard limit for fuel temperatures above 280°C, but it can be controlled by different methods of CO reduction of burner such as mixing improvement etc.

It was also observed that the mass fraction of soot in the exhaust gases was too low and did not show considerable change by preheating the fuel. It might be due to the fact that the produced soot in the high temperature reaction zone can be again oxidized before leaving the furnace.

4. CONCLUSION

Significant reduction in radiation heat transfer in gaseous flames in comparison with liquid fuel combustion is considered as a challenge in utilizing the natural gas burners for industrial applications such as metal melting furnaces. This experimental investigation aimed to enhance the radiation heat transfer in gas burners by increasing the gas fuel temperature. According to the results the most important conclusions are:

- Fuel preheating from room temperature to 240°C has no significant effect on flame luminosity and increasing the inlet gas fuel temperature over 240°C considerably increases the luminosity of the flame.
- The heat transfer efficiency experiences a sharp growth for fuel temperatures above 240°C.

- Increasing the fuel temperature up to 240°C increases the flame temperature and NO emission, while for fuel temperatures over 240°C NO formation decreases abruptly due to flame temperature reduction.
- This research reveals that by preheating the fuel gas between 240°C–300°C, it is possible to enhance the boiler efficiency considerably with NO and soot emissions below standard limits. The present method in comparison with high temperature air combustion (HiTAC) is a more economical approach because of less energy consumption.
- The ideal fuel temperature to operate the furnace would be 300°C because the boiler efficiency does not improve for above 300°C and CO concentration drastically increases for these temperatures.

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