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Experimental Study of Natural Gas Fuel Temperature Influence on Radiation Enhancement and Emission

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ABSTRACT

The enhancement of the flame radiation in gas fueled burners not only improves the thermal efficiency, but also can suppress the rate of NO emission due to reducing the flame temperature. In this experimental investigation, the effect of inlet gas temperature on the flame radiation intensity and the rate of NO formation are studied. To serve this aim, with increasing the temperature of inlet methane to the burner up to 310^{o}C, the variations of CO and NO level in exhaust gases and also the exhaust gas temperature are recorded by gas analyzer device. In each case, the flame radiation intensity was also measured by a photovoltaic module. The results revealed that by increasing the inlet gas temperature up to 250^{o}C, the NO concentration and the exhaust gases temperature are raising. But when the inlet gas temperature exceeds from 250^{o}C and reaches to 310^{o}C, the flame luminosity gradually increases which results in 70 percent growth in flame radiation and 10 percent drop in exhaust gas temperature. The results of the preheating of inlet air also show the same behavior.

Keywords: Flame luminosity, Radiation enhancement, NO emission, Fuel temperature, Radiation Measurement

INTRODUCTION

As a result of great environmental pollution of liquid fuels, many of industrial boilers and furnaces are replaced by their gas fueled alternatives. Substitution of liquid fuel burners with gaseous fuel burners leads to a significant reduction in radiative heat transfer rate and consequently causes an overall decrease of furnace temperature. Thermal radiation in gaseous media could be an important mode of heat transfer in high temperature chambers [1]. Thermal radiation significantly affects the structure and extinction characteristics of a methane-air flame due to the radiative cooling mechanism and also affects the NO formation due to the dependency of thermal NO kinetics to the temperature [1]. Radiation heat transfer in furnaces is due to gaseous and particulate contributions. From the standpoint of radiative heat transfer, radiative gases of CO_2 and H_2O are the two most important gaseous species which are produced from gas and liquid fuels combustion [2]. But the roles of particulates on liquid flame radiation are much more important than natural gas flames. It is known that liquid flames are much more luminous than natural gas flames due to presence of particulate contributors. Soot is one of the most important particulate contributors to radiation heat transfer in practical systems [2]. 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 prior to a programmed burnout. Although many studies have been carried out on the influence of soot particles on the flame radiation, but improving thermal radiation by using particulate production in gaseous flames has received much less attention. On the other hand, the release of fine soot particles into the exhaust gases leads to environmental pollution which has become an increasing concern. Thus, effective control of soot formation processes in combustion is highly desirable [3]. The presence of even small amounts of soot in the high temperature reaction zone significantly increases the flame emissivity [4,5,6,7]. The amount of produced soot in natural gas flames is too little. The one methods of soot production (Carbon Black) in hydrocarbon flames is fuel pyrolysis (Thermal Decomposition). Natural gas pyrolysis reaction is mildly endothermic and its rate is seen to increase strongly with increasing heat of combustion [8]. Since flame radiation is playing an important role in combustion process, many investigations toward improving flame radiation of gas fuel burners are conducted worldwide. An effective method for improving thermal radiation in natural gas flames is using highly preheated combustion air which recently many experimental and numerical investigations are carried out concerning this method [9]. Applying high temperature air in combustion furnace, reduce significantly NO emission, which disagreements with common expectation [10]. The results give evidence to assume that soot formation plays a key role for the radiative heat loss and also affects NO emissions [11].

Improving thermal radiation of gaseous flames by using highly preheated fuel is another method of radiation enhancement in gas burners which has not received proper attention. In this paper, the effects of fuel temperature in natural gas furnaces on thermal radiation and NO emissions are investigated.

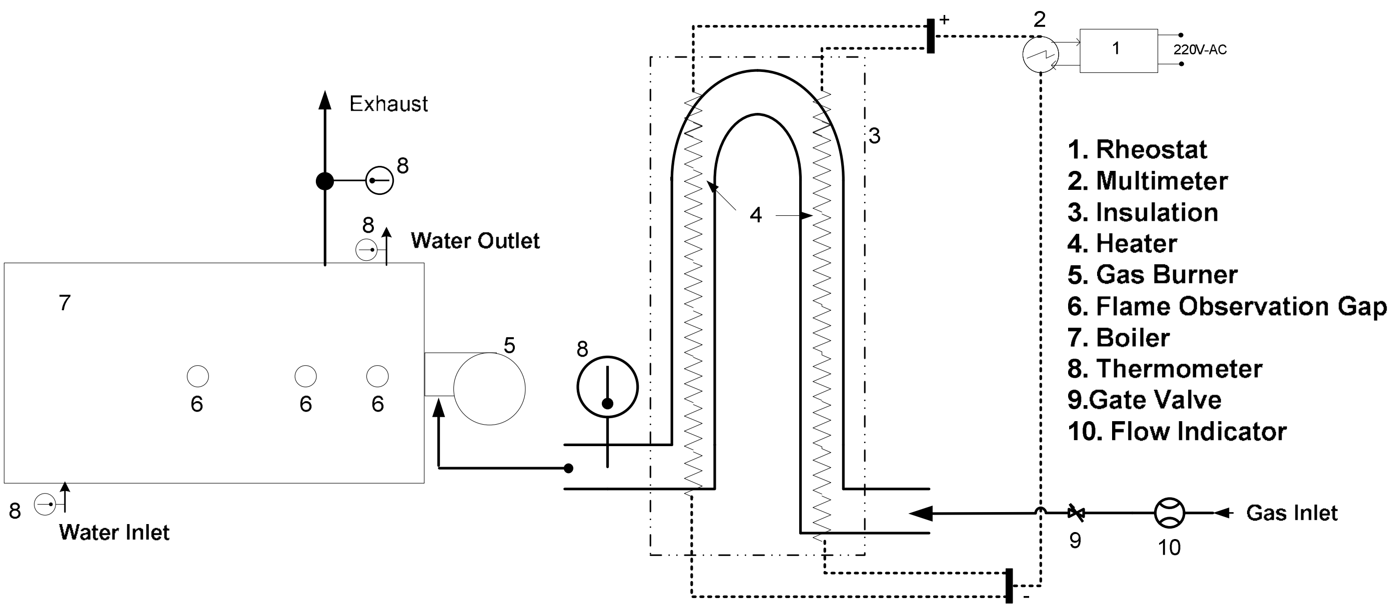

Figure 1: Schematic Illustration of Testing Apparatus

EXPERIMENTAL APPARATUS

The design objective was to develop a test setup for evaluating the effect of inlet gas temperature on several combustion parameters including exhaust temperature, NO formation and flame radiation. A schematic illustration of the setup is presented in Figure 1. Setup is constituted of a fire tube water heater, a burner, measurement devices and some other devices for heating and controlling the natural gas temperature and flow rate. At the first step gas passes through the burner's automatic valve and then it enters into a U shaped pipe. For each branch of the U shaped pipe there are 2 electric heating elements; One inside the tube and the other one out of the tube but attached to its surface. These parts are well insulated to reduce heat losses and providing conditions for increasing gas temperature as high as possible; In order to control the gas temperature a dimmer switch is placed before heating elements. The temperature of gas flows is recorded via a K-type thermometer and enters into the gas burner. The gas burner has a capacity ranges between 30,000 to 100,000 kcal/hr which is adjustable by controlling gas flow rate. In the fire tube water heater (Fig. 2), all the surfaces in contact with hot gases were cooled by water. Four groups of fire tubes were placed around the combustion chamber Flame formed in the center of the combustion chamber. Two passes of the flue gases were in the combustion chamber. The first pass was the flame itself and the second one which was named as hot exhaust gases was around the flame and, the flue gases flowed back to the front of the combustion chamber in the fire tube. After the second pass in the fire tubes, the flue gas left the fire tube water heater into the stack.

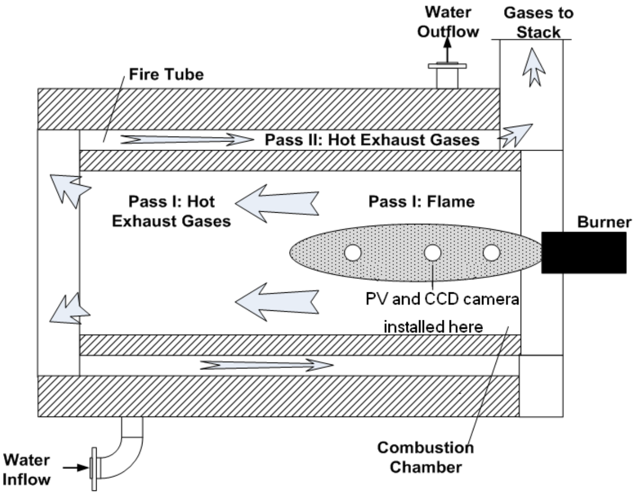

Figure 2: Schematic Diagram of 2 Pass Fire Tube Water Heater

TESTING PROCEDURE

As it was stated in the previous section, for increasing gas temperature, 4 heating elements are used which their overall capacity is controlled via a dimmer switch. First the experiment was conducted for the normal condition without fuel preheating and all of combustion products such as O_2, CO, CO_2, NO_2, NO, H_2, excess air and combustion products temperature were measured by gas analyzer type *TESTO 350XL*. At the beginning of the test with no gas preheating, the air damper is adjusted to meet the lowest CO concentration (about 40 PPM in exhaust gases). Also the excess air with 28°C was maintaining at the level of 5% in all the tests. For the next step, heaters were turned on and by controlling their capacity similar tests were conducted for temperatures from 100 to 500 degree Celsius. In addition to all these data, flame heat radiations were measured for all of above temperatures by a photovoltaic (PV) module which is fitted in flow observation gap (see fig. 2).It was observed during the tests that the utilized PV doesn't produce power when it is exposed to the flame of non-preheated gas. According to this fact, we can assure that the PV is highly sensitive to visible wavelength spectrum and the effect of other wavelengths on PV output power might be neglected. For each inlet gas temperature, the voltage and current of photovoltaic module were measured. Besides, to evaluate the change of the flame color for various fuel temperatures, the flame image was captured for comparing the yellowness of the flame.

For making sure of repeatability of the experiments, the tests were carried out in three sequential days and in test, the data were recorded 5 times repeatedly.

RESULTS AND DISCUSSION

In this paper, for the purpose of radiation heat transfer enhancement in gaseous fuel burners, the effect of preheating of the inlet gas fuel on the flame radiation intensity and also on pollutant formation is experimentally investigated. For preheating of the intake methane a 4kW electrical heater is employed and its implementation is illustrated in Figure 1.

In Figure 3 the images of the flame with different inlet gas temperatures ranging from 26-310°C is depicted. As it is evident, by increasing the fuel gas temperature from 240 to 310°C the flame brightness is increasing and the yellowish color of the flame dominates abruptly. According to this result, we can predict that the flame radiation rate is boosted.

In order to compare variations of flame radiation intensity for different fuel temperatures, a photovoltaic module is utilized which is connected to a 1.2kω resistance. In order to look at the increase of flame radiative heat transfer as a function of inlet fuel temperature, a dimensionless coefficient is presented as below:

$$\overline{q}_{rad} = (\dot{Q}_{rad} - \dot{Q}_0) / \dot{Q}_0 \qquad (1)$$

In this relation, $\dot{Q}_{rad}$ is the IR radiation flux which is recorded by the photovoltaic module for different inlet fuel temperatures and, $\dot{Q}_0$ is the recorded radiation flux for the condition that gas fuel enters the burner at room temperature.

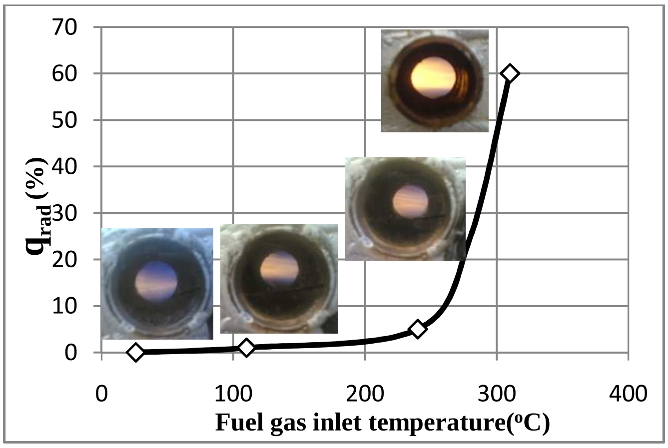

Figure 2: The Increase in Output Power of the Cell versus Fuel Temperature

For measuring the heat transfer efficiency, the output water temperature from the fire tube water heater for different fuel temperatures are recorded and shown in Figure 4, It can be observed that with increasing the gas fuel temperature, the outlet water temperature gradually increases. But when the fuel temperature goes beyond 240 to 310°C, the trend of outlet water temperature sharply increases which implies higher heat transfer efficiency. The reason lies within the fact that in this temperature the influence of flame radiation suddenly grows.

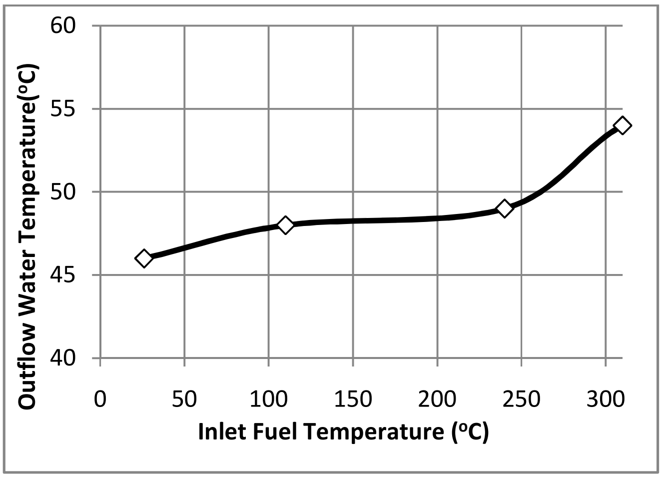

Figure 3: Outlet Water Temperature from the Water Heater for Different Fuel Temperatures

For the sake of clarification, since the flame temperature is not significantly changed by preheating gas, the radiation of gaseous component of combustion products (e.g. CO_2, H_2) is not considerably altered. In fact the increase of flame radiation occurs due to the addition of "black body" radiation from the soot particles (produced by preheating) that forms when hydrocarbons burn to the overall flame radiation [2].

As the results declare, by increasing fuel temperature, the radiation heat transfer efficiency promotes remarkably. On the other hand, the fuel temperature can greatly influence the combustion emissions. In Figure 4 the extra air percentage and CO2 and CO concentration is presented. It is observed that by increasing the fuel temperature, the CO concentration in the exhaust gas rises. Besides, the extra air percentage in exhaust increases as well.

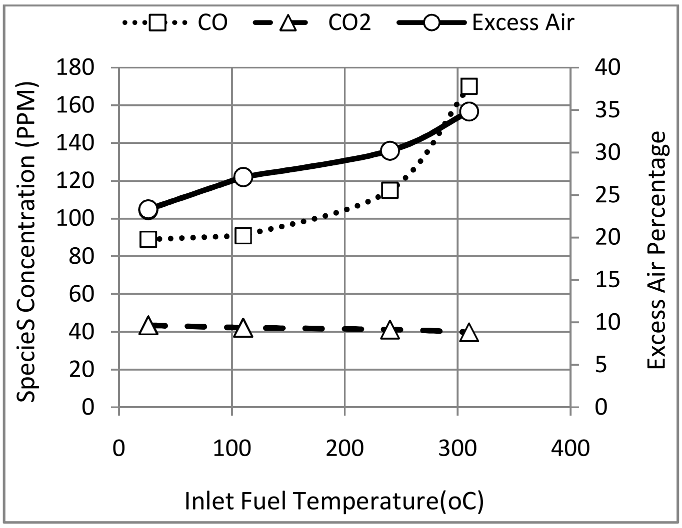

Figure 4: Variations Of ''Co'', ''Co$_2$'' And ''Excess Air'' Contained In the Exhaust Gas

Actually with increasing the fuel temperature, reaction rate of conversion of CO to CO_2 reduces and in spite of enough air for CO combustion, this chemical specie leaves the water heater unburned. The slight increase of excess air is caused by the additional pressure loss in gas pipe because of temperature increase.

NO is another important emission of the combustion which is considered as a great significance. In Figure 6, NO distribution in exhaust gases is displayed. As it can be seen, by increasing the fuel temperature to 240^{o}C, the level of NO increases accordingly. But by further increase of fuel temperature, the NO concentration suddenly reduces. Regarding the tight dependence of nitrogen oxides formation to flame temperature, the decrease of NO concentration from 240 to 310^{o}C can be resulted from reduced flame temperature followed by enhanced flame radiation and brightness. In Figure 6 also the exhaust gases temperature distribution is shown. With increasing the fuel temperature to 240oC, the exhaust temperature rises as well, but with greater increase in fuel temperature, the exhaust temperature drops significantly. As it was previously described, the reason is flame radiation improvement.

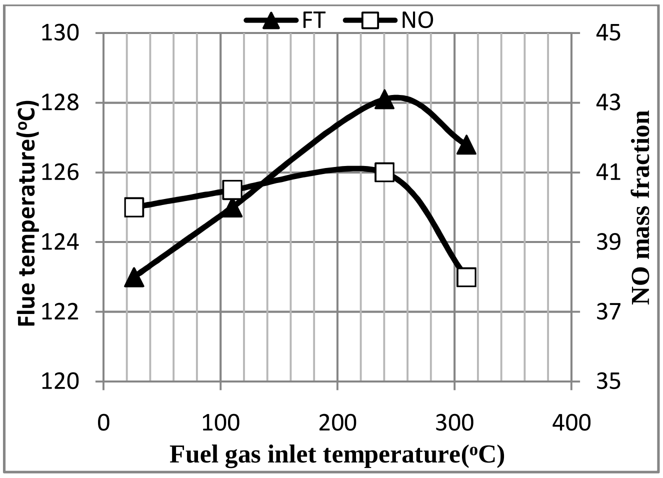

Figure 5: Variations of NO Mass Fraction and Temperature in Exhaust Flow

CONCLUSION:

The reduced allocation of radiation heat transfer in gaseous fuel flames in comparison with liquid fuel flames is considered as a big challenge in utilizing the gas fuel burners for industrial applications like metal melting furnaces. This experimental investigation aims to boost the radiation heat transfer portion of gas burners by increasing the fuel temperature and subsequently increasing the brightness and yellowish color of the flame. According to the results, some important conclusions are in brief:

1- With increasing the inlet gas fuel temperature from 240 to 310^{o}C, the yellowish color of the flame significantly increases.
2- The heat transfer efficiency from the flame to the furnace experiences a sharp growth in the mentioned temperature range of the fuel.
3- With increasing the fuel temperature, the CO formation rate increases too.

4- Increasing the fuel temperature to 240°C is associated with the increase of nitrogen oxides emission but with further increase of fuel temperature, NO formation suppresses because of the reduction of flame temperature.
5- The increase of outlet water temperature and the rapid reduction of combustion products temperature when the fuel temperature exceeds 240 °C show the enhanced heat transfer from the flame to the furnace.

In the end, all of the results imply the sudden change in flame structure while the fuel temperature alters from 240 to 310 °C.

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