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Effect of pulverized anthracite coal particles injection on thermal and radiative characteristics of natural gas flame: An experimental study

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HIGHLIGHTS

- Anthracite coal injection into natural gas flame considerably enhances its poor radiation.
- Anthracite particles increases the flame reaction zone and luminosity.
- The small amount of injection has an insignificant effect on flame temperature.
- The main role of small amount of injection is to improve the flame emissivity coefficient.

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ABSTRACT

Natural gas is increasingly used as a clean fuel. In many industrial combustion systems, such as industrial furnaces and boilers, a large portion of heat is transferred by radiation. The use of natural gas in such industrial systems leads to a decrease in radiative heat transfer. The addition of solid reactant particles into flame is widely proposed in the literature as a method to enhance radiation from non-luminous flames, with a preponderance of research on hydrogen flame. The present study explores how the injection of pulverized anthracite coal particles into natural gas diffusion flame, as a non-luminous one, affects the thermal and radiative properties of natural gas. A novelty of our research method is the exploitation of yellow chemiluminescence of soot particles together with infrared photography to locate radiative particles and discover their qualitative distribution. The IR filter used in our technique was tested with Thermo Nicolet Avatar 370 FTIR Spectrometer for its spectral transmittance to be determined. The results indicate that the injection of coal particles into natural gas flame leads to a rise in the soot content of flame. Having the advantage of high absorptivity and emissivity coefficients in the near IR region, the soot particles in turn increase the flame luminosity and, more importantly, its emissivity coefficient. Also, the heat released from the combustion of particles increases the average temperature of flame about 29 °C. These raise the radiative heat transfer and thermal efficiency of flame as much as 43% and 21%, respectively. It is noteworthy that the average temperature difference and emissivity coefficient, respectively, account for 17% and 83% of the enhancement of the average radiation flux.

1. Introduction

Natural gas is a major source of energy generation in combustion equipment and burns more cleanly than other fossil fuels [1]. Although natural gas is the cleanest fossil fuel, radiation heat transfer from its flame is significantly less than that of liquid and solid fuels. In combustion devices, however, radiation is a major contributor to the total heat transfer [2].

Flames are categorized as luminous or non-luminous. The luminosity of flame depends on the amount of solid particles held suspended in it. For hydrocarbon fossil fuels, the solid matter existing in the flame is soot (solid carbon). When heated, it produces a brilliant yellow or luminous flame. The rate of soot formation in flame is proportional to the carbon number (C/H) in fuel chemical structure. Thus, heavy liquid and solid hydrocarbons have luminous flames, whereas light hydrocarbon fuels such as natural gas have non-luminous flames [3].

In non-luminous flames, CO_2 and H_2O are the main products of complete combustion and the principal sources of radiation heat transfer. However, they have a weak radiation band in infrared wavelengths [3,4].

Luminous flames also contain soot particles that serve as highly emissive gray bodies in the flame and enhance the radiation heat transfer in comparison with non-luminous flames [5,6].

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The following materials intensify the sooting tendency in the fuels containing them in the specified order: naphthalenes > benzenes > acetylenes > olefins > paraffins [7].

The type of flame (premixed or diffusion) and the mixing process, as well, are important parameters in soot formation. Besides, the optical properties of soot, in addition to the quantity of its particles in flame, strongly influence flame radiation [8].

For practical purposes, it is desirable to increase the concentration of the intermediate soot without change in the final soot emission level. This, consequently, enhances radiation heat transfer [9].

High-temperature preheating of combustion air is a common method of increasing soot concentration through thermal decomposition of fuel [10,11]. Fuel preheating is another way of increasing soot concentration in non-luminous flames [12]. Wolanin [13] demonstrated that, to generate soot, the optimum temperature for fuel preheating should be approximately 1150–1180 °C.

In such a high temperature, some of the fuel molecules are broken up and converted to solid carbon. Both of these methods enhance the radiation of flame, but in practice they are expensive and problematic: they need special thermal devices such as electric furnaces for high-temperature preheating. Furthermore, in order to generate soot particles from natural gas, the high-temperature preheating process must be done extremely fast, which is enormously difficult.

Considering the above problems, there has been a growing tendency to study how the injection of various solid particles, on micro and nano scales, into flame affects the mechanism of radiative heat transfer. Steward and Guruz [14], for instance, examined the effect of injection of magnesium oxide (MgO) and aluminum oxide (Al_2O_3) particles on radiation from methane–air flame. Their study showed that these non-reactive particles do not have appreciable effect on radiation heat transfer from flame.

Solid soot particles have a key role in enhancing the radiation heat transfer of liquid and solid heavy hydrocarbons. Therefore, it has been of prime importance to research the processes of formation and production of soot particles and the radiation models of them in different flames, far more than the other solid particles.

Samanta et al. [15] carried out a numerical study to investigate how the injection of CO_2 in natural gas affects soot production and the radiation from its flame. They discovered that a rise in the mass fraction of CO_2 results in a fall in the rate of soot production and radiation. The diminution of the fuel calorific value and concentration of hydrocarbon radicals was identified as the cause of the above observed phenomenon.

Another numerical study was reported by Cheung et al. [16]. They explored the effect of soot production and distribution, beside the influence of soot particles radiation, on the total radiative properties of LPG diffusion flame. Their comparison of well-known soot models, including those of Khan-Greeves, Tesner and Moss-Brookes, revealed that the Moss-Brookes model best matches the experimental results. The significant contribution of soot radiation to the total radiation heat transfer was also attested. Acknowledging the importance of radiation in transferring heat from flame, Johansson et al. [17] appraised various models for the main radiative elements of luminous and non-luminous flames, i.e. carbon dioxide, steam and soot.

The recognition of soot significance in improving radiation lead Hunty and Lee [18] to use coal particles to produce soot. They found out that the injection of coal particles improves the radiative heat transfer from non-luminous hydrogen flame.

Similarly, Baek et al.'s [19] research assessed the influence of the injection of solid carbon and aluminum oxide particles on the hydrogen-air flame. They demonstrated that the injection of carbon particles improves the radiation rate of flame. On the other hand, the aluminum oxide diminishes the radiation of flame.

Evidently, relevant research in the literature mostly focuses on how the radiative heat transfer from hydrogen flame is enhanced by soot formation. The present paper, however, deals with how soot formation resulting from the injection of anthracite coal into natural gas flame affects its thermal and radiative properties. The reason behind our choosing natural gas is that its flame closely resembles that of hydrogen in appearance, specifically color, and in poor radiation from flame. Consequently, the research conducted on hydrogen flame can be set as an appropriate point of departure. Secondly, natural gas, as the cleanest fossil fuel, is used in a wider range of industrial applications than hydrogen. Besides, there are abundant resources of natural gas in the nature compared with hydrogen. Further, the largely available resources of anthracite coal, in addition to its 92–98% content of solid carbon (soot) make it a perfect choice for industrial applications.

2. Experimental set-up and procedure

The tests were carried out on a laboratory cylindrical furnace. It was 1000 mm long and 450 mm in diameter (Fig. 1). The furnace body was made of high temperature resistant steel and a natural gas burner with the maximum heat capacity of 100,000 kcal/h was installed on it. In order to measure temperature and radiation through the furnace, four holes were created on the furnace wall at the distances of 6, 18, 30, 42 cm from the burner entrance.

Also, a mannesmann helical tube was mounted on the inside wall of the furnace and cool water flowed through it to absorb heat from flame and measure thermal efficiency. The thermal efficiency (η_{th}), resulted from the 1st law of thermodynamics, is calculated through the following relation:

$$\eta_{th} = \frac{\dot{Q}_{absorb}}{\dot{Q}_{in}} \tag{1}$$

where $\dot{Q}_{absorb}$ is the heat energy absorbed by the water flowing in the helical tube and $\dot{Q}_{in}$ the total input energy of natural gas and coal particles, which is the product of the calorific value of the fuels by their flow rates. The calorific values of natural gas and anthracite coal are 8117 kcal/m^3 and 32.56 MJ/kg respectively.

$\dot{Q}_{absorb}$ is calculated by this equation:

$$\dot{Q}_{absorb} = \dot{m}c\Delta T \tag{2}$$

where $\dot{m} = 0.1$ kg/s is the mass flow rate of water, $C = 4.184$ J g^{-1} °C^{-1} is the specific heat capacity of water and ΔT the temperature difference for water between inlet and outlet of coil in steady-state mode.

The volume flow rate of air was measured by a TES-1340 Hot-Wire Anemometer and that of natural gas by a calibrated counter. The volume flow rates of air and natural gas were 0.750 m^3/min and 3.804 m^3/h, respectively.

Temperature was measured by an S-type thermocouple made of platinum and rhodium with the maximum operating temperature of 1500 °C and an accuracy of ±2.5 °C. Resistance to high temperature, having the advantage of great accuracy and reluctance to react with the species in flame make the S-type thermocouple an excellent choice for measuring temperature in combustion processes [20,21].

A calibrated thermopile was employed to measure the flame radiation. The apparatus included a number of thermocouples that were connected to each other in a series manner to strengthen the thermopile sensitivity. Thus, the thermopile can be used as a detector of radiative heat flux in the temperature range of 200–1500 °C [21,22].

The flame luminosity was measured by a photovoltaic cell which belongs to the family of photon detectors. A film of semiconductive selenium constitutes the outermost layer of the cell.