Applied Thermal Engineering 125 (2017) 232–239

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental analysis of the addition and substitution of sub-bituminous pulverized coal in a natural gas premixed flame

Julián Obando, Camilo Lezcano, Andrés Amell *

Grupo de Ciencia y Tecnología del Gas y Uso Racional de la Energía, Universidad de Antioquia, calle 67 No. 53 108 (block 19), Medellín, Colombia

HIGHLIGHTS

- Pulverized coal addition to natural gas increases the radiation intensity.
- The natural gas flame front was lengthened by the addition of pulverized coal.
- Turbulence intensity had no significant effect on the radiation intensity.

ARTICLE INFO

Article history:
Received 4 March 2017
Revised 26 May 2017
Accepted 1 July 2017
Available online 3 July 2017

Keywords:
Turbulence intensity
Hybrid combustion
Natural gas
Coal
Radiation intensity

ABSTRACT

This paper presents the experimental results of the addition (increasing thermal power) and substitution (constant thermal power) of a sub-bituminous pulverized coal in a natural gas flame in a laboratory-scale premixed burner. The analyzed variables include radiation intensity, temperature profile, and flame shape. It was found that with the addition of 15% and 30% coal (energy based) into the natural gas flame, the radiation intensity was increased by 37% and 65%, respectively. However, with the substitution of 15% and 30% coal for methane (energy based), the radiation intensity was reduced by 10% and 61%, respectively. Additionally, regarding the flame temperature, it was observed that 30% coal addition increased temperature by approximately 5%, while 30% coal substitution led to a reduction in flame temperature of 35%. Regarding flame shape, it was found that increased turbulence shortened the flame, while both the addition and substitution of coal into a methane flame lengthened the reaction zone.

1. Introduction

There is a growing concern over the preservation of the environment from the adverse effects of atmospheric pollution coming from the combustion of fossil fuels. These adverse effects include global warming, acid rain, photo-chemical smog, and human respiratory illnesses [1–3]. On the other hand, thermal energy is very relevant in industrial processes, taking place in diverse situations such as: productivity, quality of products, occupational health, and pollutant emissions [4]. Therefore, the development of cleaner and more efficient combustion systems is an important contributor to the reduction of the above mentioned environmental problems. As such, research into fossil fuel combustion is still of great interest to the scientific community, in order to decrease its adverse effects while allowing for its continued use.

In general, industry has a high demand for natural gas because it is considered a relatively clean fossil fuel [5]. However, natural gas flames have a low emissivity, which causes these kinds of flames to have a low radiation intensity [6]. Therefore it would be valuable to find a means to increase the radiation intensity of natural gas flames, as it could improve their efficiency and increase the rate of heat transfer.

Furthermore, due to uncertainty in the price and availability of fossil fuels [7,8], it could be beneficial to develop combustion systems that allow for the reliable and efficient combination of various fuels with different characteristics. The adverse environmental effects of the more contaminating fossil fuels, such as coal, could diminish when combustion takes place simultaneously with a relatively clean fuel, such as natural gas, if efficiency is found to increase. Therefore, it is important to study the combustion behavior of mixtures of fuels with different characteristics, e.g. natural gas with pulverized coal. This is useful in the design of combustion devices that burn both fuels simultaneously in a stable, efficient, and safe manner.

Regarding previous studies on the behavior of mixtures of natural gas with pulverized coal, Pourhoseini and Moghiman [9] carried out measurements in a laboratory scale cylindrical furnace,

* Corresponding author.
E-mail address: andres.amell@udea.edu.co (A. Amell).

http://dx.doi.org/10.1016/j.applthermaleng.2017.07.003
1359-4311/

which had a length of 1000 mm and a maximum thermal power of 116 kW. They used a type-S thermocouple to measure the temperature and a calibrated thermopile to measure the radiation. The measurements were done at four axial distances from the burner. Additionally, they measured the flame luminosity with a photovoltaic cell. The distribution of soot particles was observed in a qualitative manner by means of a digital camera with an infrared optical filter located in front of it. They concluded that the addition of pulverized anthracite into a natural gas flame significantly increases the radiation and the reaction zone volume. They attribute this result to the emissivity of the pulverized coal and the release of volatiles from the coal. Furthermore, found that if the addition of anthracite is small, the change in the flame temperature is insignificant.

Liu et al. [10] studied the flame propagation of a pulverized coal suspension (with variable concentration from 37.5 g/m^3 to 320 g/m^3) in a mixture of methane and air with an equivalence ratio of 0.2 (outside the flammability limits). The suspension was burnt in a vertical chamber with a height of 500 mm and a square cross section with a side length of 80 mm. Ignition of the suspension was initiated at the bottom part of the chamber by means of a spark. A sub-bituminous coal was used with an average particle size of 54 μm. The study was carried out by means of a high speed camera and a Schlieren optical system. It is highlighted that when the mixture was just methane and air, combustion did not take place. Additionally, when the mixture was just air and pulverized coal (320 g/m^3), without any methane, combustion did not take place. This result is important as it gives some insight into the combustion behavior of mixtures of pulverized coal, air, and methane. Furthermore, this confirms that the ignitability of a mixture of methane and pulverized coal is superior to that of either component alone.

In a similar way, Rubtsov et al. [11] studied the ignition of pulverized coal suspensions in methane-air mixtures. They performed their study in a quartz cylinder externally heated to a temperature of 685 °C. The cylinder had a diameter of 36 mm and a length of 250 mm. They analyzed the combustion of three different coals with 38%, 17%, and 8% volatiles, all of them with an average particle size less than 90 μm. Additionally, the pulverized coal concentration was 786 g/m^3. In their study they used a high speed camera in order to observe the ignition process, and used a spectrometer in order to measure the emission spectra. They showed that ignition is accelerated when coal particles are added to the methane-air mixture at temperatures between 650 °C and 750 °C.

Elfeky et al. [12] used a specially designed burner to study the co-combustion of bituminous pulverized coal and methane. In their burner, the pulverized coal was axially injected with air from a central nozzle, while a natural gas premixed multi-flame was injected and burned transversely to the coal jet. They found that coal combustion limits were extended and that there was a reduction in NO_x emissions because a reduction zone was formed between the multiple natural gas flames.

Tenappan and Gollahalli [13] studied the propagation velocity of a turbulent natural gas-air premixed flame, adding three different types of pulverized coal with an average particle size of 45 μm. Their study was carried out in a long pipe of length 3680 mm and inside diameter of 52.5 mm, where the flame was stabilized by means of a V-gutter. A hot wire anemometer was used to measure the radial velocity profile in the blower outlet. Two photodiodes located at different axial positions were used to measure the deflagration velocity. Although the method used to measure the deflagration velocity is not fully trustable, they found that as the Reynolds number increases, there is an increase in the deflagration velocity as well. Additionally, they evaluated the deflagration velocity dependence on coal concentration over the range of 10–80 g/m^3, finding that it was greater when coal concentration was lower, but in all cases the velocity was greater than in the base case of no coal. Furthermore, they found that the deflagration velocity increased when the volatile content of the coal was higher.

The aim of this paper is to report on the change in radiation intensity with the addition and substitution of pulverized coal in a natural gas premixed flame, as most authors have studied the effect of the addition of coal without taking into account the increase in power of the flame. The study was carried out in a laboratory scale burner and the parameters studied include flame shape, radiation intensity, temperature profile, and turbulence intensity.

2. Experimental setup

The measurements were performed using a laboratory scale premixed burner where a mixture of natural gas and air was burned. The main details of the system used are shown in Fig. 1. Combustion air was supplied by means of a blower, where the air passed through an ejector. This was done in order to create a low pressure zone where the pulverized coal could be added to the air flow. The pulverized coal was fed by means of a high-precision variable-speed screw feeder. The coal is entrained due to the low pressure zone created by the ejector. Natural gas was also added through a side port in the ejector, the natural gas flow being measured by means of a rotameter. The mixture of natural gas, air, and pulverized coal was then carried to the burner head, where combustion took place. The air flow was kept constant at 11.3 S m^3/h for all experimental conditions.

Before reaching the burner head, the gas-particle mixture was passed through a perforated plate, as shown in Fig. 2, in order to increase the turbulence intensity at the burner outlet. In order to vary the turbulence intensity at the burner, three ducts with different lengths were interchanged between the perforated plate and the burner outlet. At the outlet, a premixed flame was generated and stabilized by means of multiple natural gas pilot flames which surrounded the premixed flame. In addition, a stream of cooling water flowed through a pipe in the burner head, also shown in Fig. 2.

A hot wire anemometer was used to measure the turbulence intensity after the perforated plate. The hot wire probe was a Dantec 55P11 connected to hold model 55H21 in module Dantec MiniCTA 54T42 for signal conditioning. The probe of the anemometer was located at the burner discharge, but the measurement was performed without any coal or natural gas, just air, i.e. without combustion taking place, like has been performed by Kobayashi et al. [14], Kobayashi et al. [15], Tamadonfar and Gülder [16], and Rockwell and Rangwala [17]. Turbulence measurements were made with three ducts that were interchanged after the perforated plate, which had lengths of 61 mm, 87 mm, and 140 mm. The average velocity, Reynolds Number, and turbulence intensities are presented in Table 1.

In total, six different mixtures were analyzed. Three correspond to a fixed total thermal power of 10 kW, based on low heating value (LHV), where different degrees of pulverized coal substitution for methane gas were used. The percentages of substitution evaluated were: 0%, 15%, and 30% coal, on an energy basis. The equivalence ratio was held nearly constant, varying from 0.90 to 0.88 for 0% and 30% coal, respectively, signifying a 2.2% change in the equivalence ratio over the sample range. The coal substitution mixtures are denoted as CS1, CS2, and CS3, respectively, as can be seen in Table 2.

For the remaining three mixtures evaluated, the total thermal power was not kept constant; instead, the natural gas thermal power, based on LHV, was held fixed at 10 kW with the equivalence ratio based on just the natural gas kept constant at 0.9, and