Impacts of Synchronous Combustion of Small Amounts of Coal Particles with Natural Gas on Enhancing Radiative Characteristic and NO_x Flame Pollutant Emission

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Radiation is the most important regime of heat transfer of a flame which is directly affected by temperature and emissivity coefficient of the flame. Natural gas has a nonluminous flame, although, the flame temperature is high, but, the emissivity coefficient of the flame is small. In this paper the impacts of synchronous combustion of small amounts of anthracite coal particles with natural gas on the detailed emissivity coefficient of the flame, radiative species and pollutant emissions were investigated experimentally and numerically. A sprint CFD code was used in numerical solution and the pollutants were measured by a Testo 350XL gas analyzer. The results showed that a small amount of coal particles injected into the hot flame of natural gas increases the volume distribution and radiation view factor of high-emissive intermediate solid soot particles in the flame which enhances the total flame emissivity coefficient. Also, coal particle injection leads to a decrease in the upstream flame temperature and an increase in the downstream region creating a more uniform temperature distribution and decreases the concentration of thermal NO pollutant of the natural gas flame. Furthermore, the role of solid soot particles on the total emissivity coefficient is remarkable, while an increase in CO_2 and H_2O concentrations has an insignificant effect on the flame emissivity coefficient.
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Key words: radiation, coal particles, natural gas, temperature, emissivity coefficient, pollutant

1. Introduction

Currently, the energy crisis and extreme air contamination are two of the most concerning issues in the world leading many researchers toward finding more reliable, durable and environmentally friendly energy resources [1, 2].

As heavy fossil fuels have undesirable environmental effects, widespread usage of natural gas as an alternative fuel in combustion systems has been increased [3]. Due to the high-temperature flames in industrial natural gas burners, radiation heat transfer is one of the most important methods of heat transfer. A significant part of heat generated during the combustion process has to be transferred by radiation [4]. Therefore, studying the radiation heat transfer characteristics of a natural gas flame and finding practical and environmental friendly methods to improve these characteristics is crucial.

According to the Stefan Boltzmann law, radiation heat transfer of a substance is affected by two parameters, temperature and emissivity coefficient. Hence, by assuming flames as a high-temperature body, the rate of heat transfer from the flame depends on the temperature and emissivity coefficient of flame products. Carbon dioxide (CO_2) and water vapor are the predominate products of natural gas complete combustion. These contents, therefore, are the main elements in radiation heat transfer of natural gas flames. These gaseous products, however, have weak radiation bands in the dominantly infrared region [5, 6].

Liquid and solid fossil fuel, apart from CO_2 and water vapor also produce a notable amount of solid soot particles. These particles have appropriate radiation properties and enhance the rate of radiation heat transfer as well as thermal efficiency [7].

Saji and colleagues [8] explored the effect of production and oxidization of soot particles in radiation heat transfer of an ethylene diffusion flame. The choice of ethylene as the target fuel is due to the fact that unsaturated hydrocarbons such as ethylene, acetylene and benzene have a substantial effect on soot formation. Their results demonstrated that in comparison with a methane-air flame, an ethylene-air flame is larger in size, and more luminous. Furthermore, considering the high radiation heat transfer of the soot particles, the maximum temperature of the flame diminished to 150° centigrade. Additionally, the position of maximum concentration of soot particles and maximum radiation were rather coincident.

Guo and colleagues [9] numerically studied the impact of adding hydrogen to a diffusion ethylene-air flame. They concluded that the injection of hydrogen into the flame reduces the rate of soot formation.

Paul and Paul [10] investigated the radiation characteristics of a nondiffusion propane-air flame in a 3-dimensional combustion chamber. As the study indicated, radiation heat transfer from the luminous flames, as a black body, is affected by temperature and absorption coefficient. Besides, the absorption coefficient depends on the temperature and concentration of CO_2, water vapor and soot particles. It is worth mentioning that soot has the highest influence on the absorption coefficient of the flame. They also showed that in the area in which soot particles are denser, the rate of heat transfer is higher.

Furthermore, Khatami and Levendis [11] compared different models of radiation from soot particle heat transfer and found that it is sensible to consider soot particles as a grey body.

A couple of methods have been introduced for the purpose of increasing the amount of soot particles in natural gas flames. Preheating fuel, known as HTF (high-temperature fuel), and preheating the combustion air, known as HTAC (high-temperature air combustion), are two of these methods. Lim and colleagues [12] preheated the air entering the combustion chamber from 300 to

560 K. They discovered that the concentration of hydrogen atoms in the combustion chamber steeply increased. This was because of the enhancement of the thermal decomposition rate and consequently the segregation of hydrogen from the methane and soot formation.

Kim and colleagues [13] experimentally studied the impact of preheated air on LPG combustion. They announced that increasing the temperature of the preheated air enhances the soot formation and makes the flame far more luminous.

In other research, Atreya [14] claimed that a consequence of the increase in temperature of combustion air is a reduction in NO_x emission and an improvement in the radiation heat transfer of the flame.

Yang and Blasiak [15] numerically investigated the effect of preheating the fuel and high-temperature preheating of the combustion air on temperature and pollutant emissions of a propane-air flame. They concluded that increasing the fuel temperature decrease the maximum temperature of the flame and NO_x formation.

The injection of solid carbon into the flame is another interesting method to enhance the soot concentration in nonluminous flames. Baek and colleagues [16] injected solid coal to a hydrogen flame to investigate its effect on temperature and radiation heat transfer. They recognized that solid coal particles raise the radiation heat transfer of the flame to the walls. Besides, the more soot particles injected, the better the radiation heat transfer that occurs.

Pourhoseini and Moghiman [17] injected anthracite coal particles into a natural gas diffusion flame. They surveyed the effect of coal particle injection on temperature and radiation heat transfer of the flame. They concluded that the anthracite coal particle injection makes the flame more luminous and the radiation heat transfer higher.

There are notable resources of coal in the world. Also, as mentioned above, the injection of coal particles into a clean natural gas nonluminous flame is an applicable and feasible method to enhance its radiation heat transfer. Nevertheless from a theoretical point of view, the radiative characteristics of the flame (particularly emissivity coefficient) and the share of soot and gaseous products of combustion in the emissivity coefficient of the flame, which are not possible to experimentally determine, have not been adequately analyzed. Furthermore, the effect of synchronous combustion of solid coal particles with natural gas on emission pollutants, especially NO_x pollutant, has not been considered. Therefore, in this study mathematical modeling along with experimental measurements were used to investigate the impacts of synchronous combustion of small amounts of coal particles with natural gas on the detailed radiative characteristics of the flame (such as flame temperature, radiative species concentration, total and gas emissivity coefficient of the flame) and pollutant emissions.

2. Mathematical Modeling

To simulate the problem (Fig. 1), a sprint CFD code being an early version of Fluent [18] was employed. The volume flow rates of air and natural gas were 0.750 m^3/min and 3.804 m^3/h, respectively. The gas conservation equations were solved by applying a control volume approach.

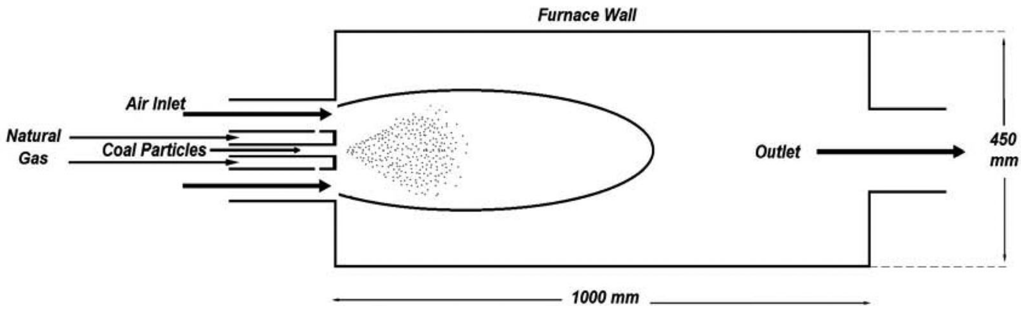


Fig. 1. Computational domain and furnace geometry.

Using the power law scheme, the convective terms were discretized. The flow field pressure was solved by implementing the SIMPLE algorithm. In the end, the convergence criterion was defined in such a way that the maximum value of the normalized residuals of the equations would be less than 1×10^{-3}.

Turbulent fluctuations play a significant role in combustion phenomenon. Applying the k-ε model, these fluctuations, which are called Reynolds stresses, were simulated [19]. The aforesaid model is considered one of the most appropriate and common ones in combustion modeling. Besides, for regions located near the walls, a conventional wall function approach was used. Coal particles were injected at a mass flow rate of 0.81 kg/h using surface type injection. Combustion and radiative characteristics of the particles are exceedingly affected by the particles diameter [20]. Owing to the aforementioned fact, there is a need for taking into account the particles diameter distribution; hence, the Rosin–Rammler distribution was used. The dispersion of particles due to turbulence in the gas phase was predicted by applying the stochastic tracking model. The stochastic tracking model consists of the effect of instantaneous turbulent velocity fluctuations on the particles trajectories. The Eddy-Dissipation Concept (EDC) of Magnussen and Hjertager [21] was implemented in order to consider the turbulence effects on the reaction rate and a two-step process was used for modeling the combustion.

As long as soot particles have an important role in the radiative characteristics of flames, applying a suitable soot formation model is essential. Therefore, various sorts of models were tested and the Khan and Greeves [22] model was selected. This model predicts the rate of soot formation based on a simple empirical rate. Combustion of soot particles, also, is governed by the Magnussen combustion rate. Consequently, the net rate of soot generation (R_{soot}) is calculated by the following equation:

$$R_{soot} = R_{soot,form} - R_{soot,comb}, \tag{1}$$

where $R_{soot,form}$ and $R_{soot,comb}$ are the rates of soot formation and combustion, respectively.

The rate of soot formation $R_{soot,form}$ is calculated by the following equation:

$$R_{soot,form} = C_S P_{fuel} \varphi^r e^{\frac{-E}{RT}}, \tag{2}$$

where C_s is the soot formation constant, ϕ is the equivalence ratio, $r = 3$ is equivalence ratio exponent and $\frac{E}{RT}$ is the activation temperature.

Also, soot combustion rate ($R_{soot,comb}$) is the minimum of the following two rate expressions:

$$R_{soot,comb} = \min\left(R_1, R_2\right). \tag{3}$$

In the above equation, R_1 and R_2 are determined from the following equations:

$$R_1 = A\rho Y_{soot}\frac{\varepsilon}{k}, \tag{4}$$

$$R_2 = A\rho(\frac{Y_{oxid}}{\nu_{soot}})(\frac{Y_{soot}\nu_{soot}}{Y_{soot}\nu_{soot} + Y_{fuel}\nu_{fuel}})\frac{\varepsilon}{k}, \tag{5}$$

where Y_{oxid}, Y_{soot}, and Y_{fuel} are the mass fractions of oxidizer, soot and fuel, respectively. Furthermore, ν_{soot} and ν_{fuel} are the mass stoichiometry for soot and fuel combustion.

It is worth mentioning that the Khan and Greeves model is an empirically based one and the constant parameters in the model have been validated for a wide range of hydrocarbon fuels such as natural gas and anthracite.

The following model, for discrete ordinates (DO) radiation, solves the radiative transfer equation [23]. In this model, the radiative transfer equation is

$$\nabla.I\left(\vec{r}, \vec{s}\right) + \left(a + \sigma_s\right) I\left(\vec{r}, \vec{s}\right) = a\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r}, \vec{s}')\varphi(\vec{s} . \vec{s}')d\Omega', \tag{6}$$

where I is the radiation intensity which depends on position $\vec{r}$ and direction $\vec{s}$ and α is the absorption coefficient of CO_2 and H_2O gray gases joined by solid soot particles. Moreover, according to Mie theory, the scattering coefficient σ_s is negligible.

The CO_2, H_2O, and soot particles are the most prominent substances in the radiation heat transfer of a flame. As a result, it is vitally important to determine their radiative properties separately. The Weighted-Sum-of-Gray-Gases Model (WSGGM) has been utilized to calculate the emissivity coefficient of H_2O and CO_2. In the model, the emissivity coefficient of gases species is affected by temperature, their concentration, and the overall pressure as well as path length. Additionally, in order to account for the soot particles' emissivity, the following equation is introduced [24, 25]:

$$a_{soot} = b_1\rho_m\left[1 + b_T\left(T - 2000\right)\right], \tag{7}$$

where ρ_m is soot density in kg/m^3, $b_1 = 1232.4\frac{m^2}{kg}$, and $b_T = 4.8 \times 10^{-4}K^{-1}$.

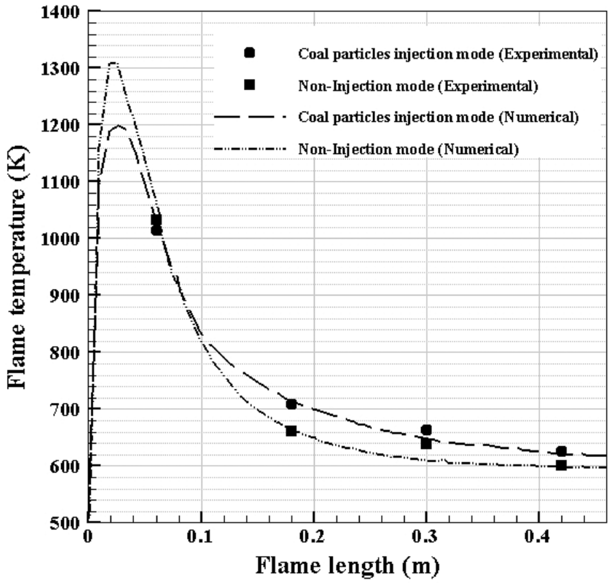


Fig. 2. Temperature distribution along the furnace centerline for injection and noninjection modes (Experiment from Ref. 17).

The final step is to determine the emissivity coefficient of the mixture by integrating that of three aforementioned portions, H_2O, CO_2, and soot as follows [26]:

$$a = a_{CO_2,H_2O} + a_{soot}. \tag{8}$$

Since coal particles act as a gray body in the flame, their emissivity ($a_{particles}$) should be considered. Coal particles emissivity depends on the particles imaged surface per their unit volume ($\frac{A}{V}$). Consequently, their emissivity ($\varepsilon_{particles}$) is estimated by the following equation:

$$a_{particles} = \lim_{V\to 0} \sum_{n=1}^{N} \varepsilon_{particles} \times \frac{A}{V}. \tag{9}$$

Finally, the overall emissivity of the flame is represented as follows:

$$a = a_{CO_2,H_2O} + a_{soot} + a_{particles}. \tag{10}$$

3. Results and Discussion

Figure 2 indicates the axial flame temperature distribution with the injection of anthracite coal particles and without any injection. It is obvious that the numerical results present an acceptable prediction of experimental data [17]. One of the most remarkable characteristics of diffusion flames is the peak in the axial flame temperature profile. Note that, where the fuel and air mixing rate is the highest, temperature reaches its maximum level. The combustion process of gaseous fuels is shorter than that of both liquids and solids. Hence, in comparison with liquid and solid flames, the

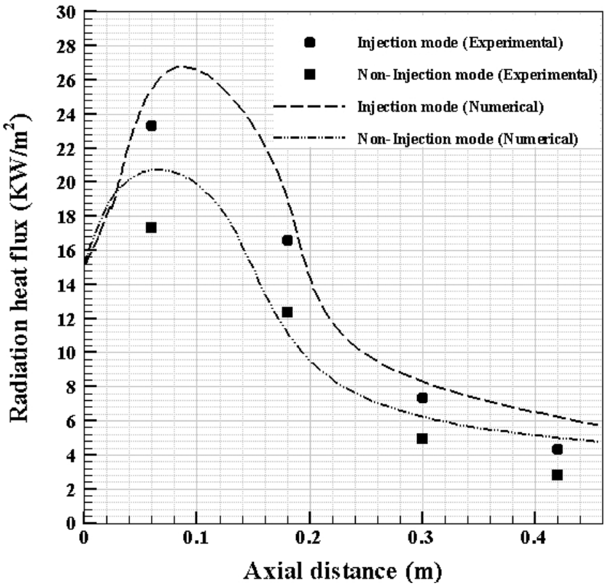


Fig. 3. Axial radiation heat flux along the furnace centerline for injection and noninjection modes (Experiment from Ref. 17).

peak temperature in gaseous fuel flames is closer upstream. Consequently, by synchronizing the combustion of natural gas and coal particles, temperature distribution is expected to become more uniformed due to the combination of the natural gas diffusion flame with a peak temperature closer to the upstream and solid coal particles with a peak temperature further from the flame upstream.

Also, it can be seen that coal particles injection reduces the peak temperature of the flame in the upstream region and augments the temperature in the downstream region. It can be concluded that the reduction in the temperatures of the upstream region is because of the coal particles' heat absorption to accomplish thermal decomposition. As the procedure is endothermic, the peak temperature is reduced. Subsequently, the combustion of species produced by thermal decomposition of the coal particles increases the downstream temperature. These two consequences, thus, make the temperature distribution more uniform. Also, based on the heating values and flow rates of coal injection and natural gas, the ratio of coal heat input (power) is 0.2 KW/KW of natural gas, and therefore, as we expect, the difference of mean flame temperature in the injection and noninjection modes is small.

Figure 3 indicates the rate of radiation heat transfer from the flame for injection and noninjection modes. It can be seen that the numerical results present an acceptable prediction of experimental data [17]. As the results reveal, in the injection mode, the enhancement in radiation heat transfer is obvious in comparison with the noninjection case. Besides, from upstream to downstream, the rate of radiation heat transfer is decreased in both the aforesaid cases. Radiation heat transfer is directly affected by the temperature and emissivity coefficient. Besides, according to Fig. 2, the injection of small quantities of coal particles does not have a noticeable effect on mean flame temperature. Consequently, the most significant factor to enhance the radiation would be the improvement of the flame emissivity coefficient.

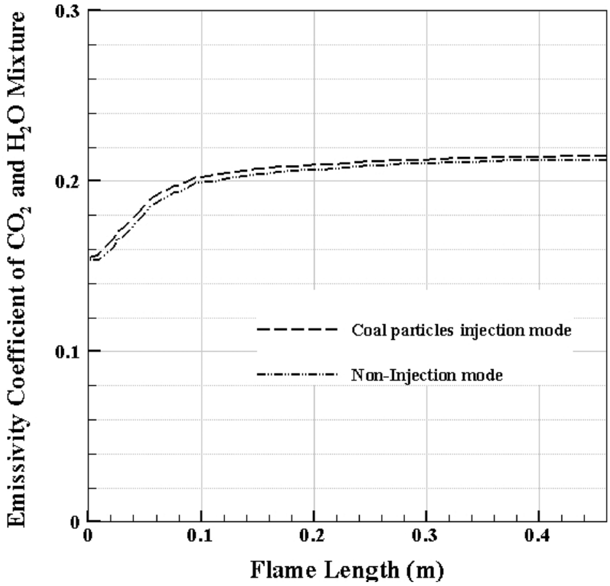
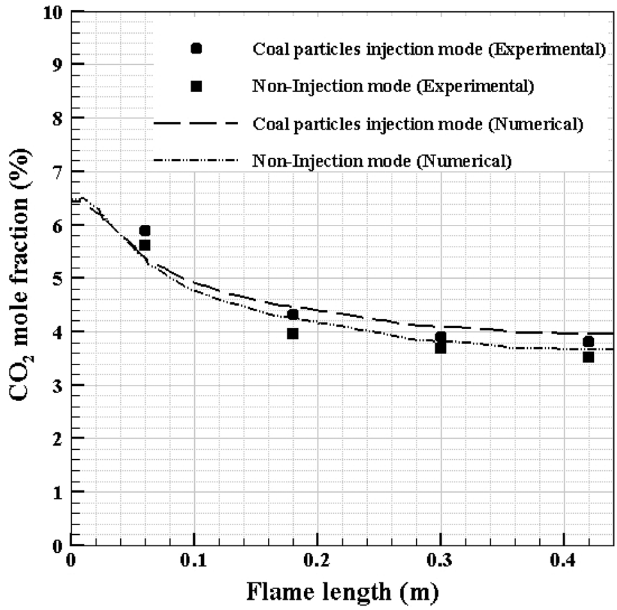


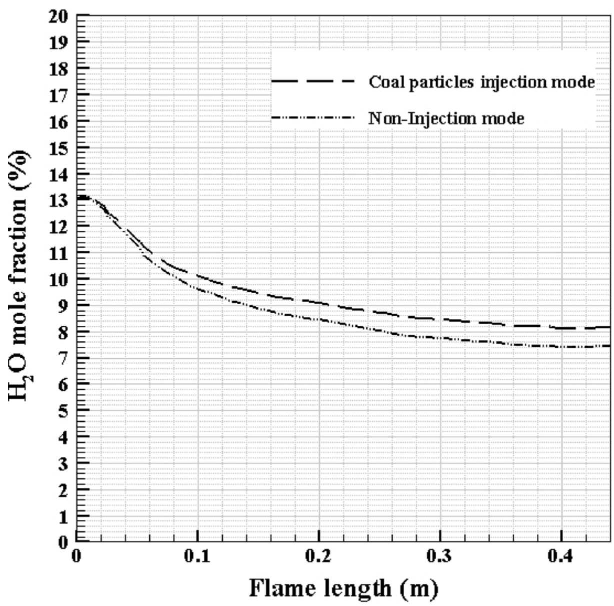
Fig. 4. Emissivity coefficient of the CO_2 and H_2O gas mixture along the furnace centerline for injection and noninjection modes.

The CO_2 and H_2O, as the main gaseous products of combustion and solid soot particles, are the most important radiative elements of the flame. Figure 4 shows the emissivity coefficient of CO_2 and H_2O in the flame for coal particles injection mode and noninjection mode. It can be realized that the emissivity coefficient of the CO_2 and H_2O gas mixture are almost the same for both injection and noninjection modes.

Based on Hottel's model for radiation from gray emissive and absorptive gases, the emissivity coefficients of the gaseous mixture depends on the elements concentration, temperature, partial and total pressures and mean path length of the rays. For the two modes of injection, the furnace geometry and its operating conditions were the same. Therefore, the mean path length of rays, which is a geometric characteristic of radiation and the total pressure of furnace, would stay the same in both the aforementioned cases. Moreover, based on the results from Fig. 2, the temperature difference between noninjection and injection modes was negligible. Consequently, the only factor that could affect the emissivity coefficient of the flame is the CO_2 and H_2O gas concentrations. Therefore, along with the numerical result, a Testo 350 XL gas analyzer was used to measure the concentration of CO_2. In Figs. (5a) and (5b), the axial concentration of CO_2 and H_2O was determined and shown for noninjection and injection modes, respectively. When coal particles, as a hydrocarbon fuel, are injected into the natural gas flame, they are finally combusted and converted to CO, CO_2, and H_2O. Therefore, the total concentration of the aforesaid gases is increased. However, since the mass flow rate of coal injection is small, an increase in concentrations is not remarkable in comparison with the noninjection mode. Consequently, it can be concluded that for a small rate of solid coal particles injection, CO_2 and H_2O gases do not affect the rate of radiation heat transfer from the flame due to the small amount of their increase and their relatively low-emissivity coefficient.



(a)



(b)

Fig. 5. (A) CO_2 concentration along the furnace centerline for injection and noninjection modes, (B) H_2O concentration along the furnace centerline for two modes of injection.

Pyrolysis is the thermochemical decomposition of organic materials such as fossil fuels at elevated temperatures in conditions of low oxygen. Therefore, when the anthracite coal particles are injected into the core of a high-temperature natural gas flame, as long as the natural gas molecules have formerly been burnt, the coal particles face a low-oxygen condition and they are mostly

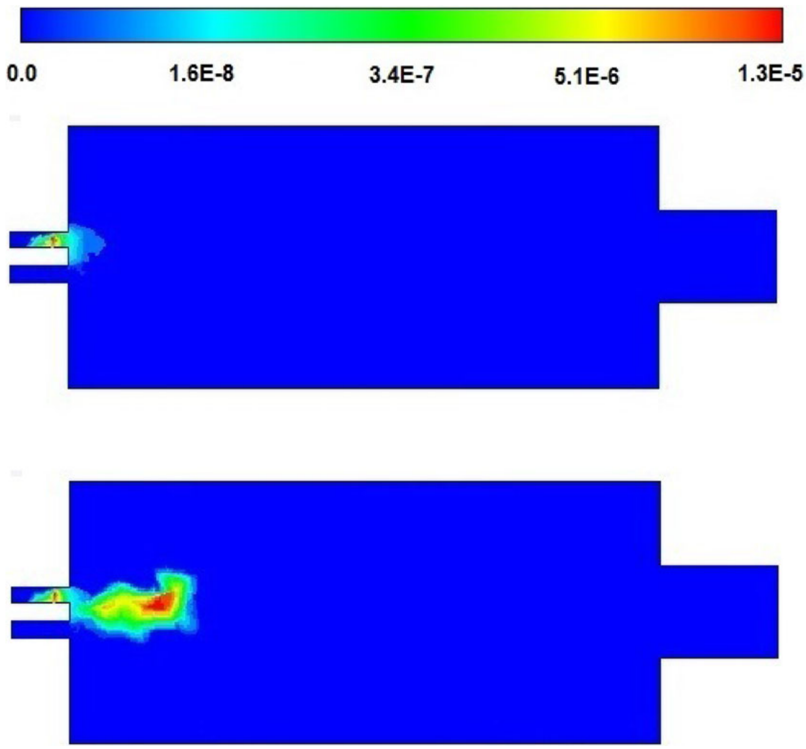


Fig. 6. Soot particles distribution within the furnace for noninjection (top) and injection (bottom) modes. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com/journal/htj.]

pyrolized to solid carbon. As a result, the concentration of solid soot particles in the flame zone is expected to increase.

Figure 6 indicates the soot particles distribution within the furnace for noninjection (top) and injection (bottom) modes. It can be declared that the amount of soot generated in a natural gas flame is negligible. Also, since the volume of the natural gas flame in noninjection mode is small (as it was mentioned earlier in Fig. 2), the maximum concentration of soot particles is formed primarily in the flame region where the temperature is high; therefore, the view factor of the soot particles (the proportion of the radiation which leaves solid soot surface and strikes the wall of the furnace) would be decreased. In spite of the foregoing statement, when coal particles are injected into the natural gas flame (Fig. 6, bottom), the soot particles concentration in the flame zone increased and they spread across a larger area within the furnace. This leads to an augmentation in view factor of the soot particles for transferring radiation to the furnace wall. It should be noted that, later on, the soot particles, which were formed in the flame upstream region, are burnt; as a result, the concentration of soot particles in the exhaust of the furnace stays the same as the noninjection mode and yet in standard level.

Solid soot particles have by far better radiative characteristics than gaseous product of combustion such as CO_2 and H_2O. Therefore, an increased particle content in the high-temperature zone

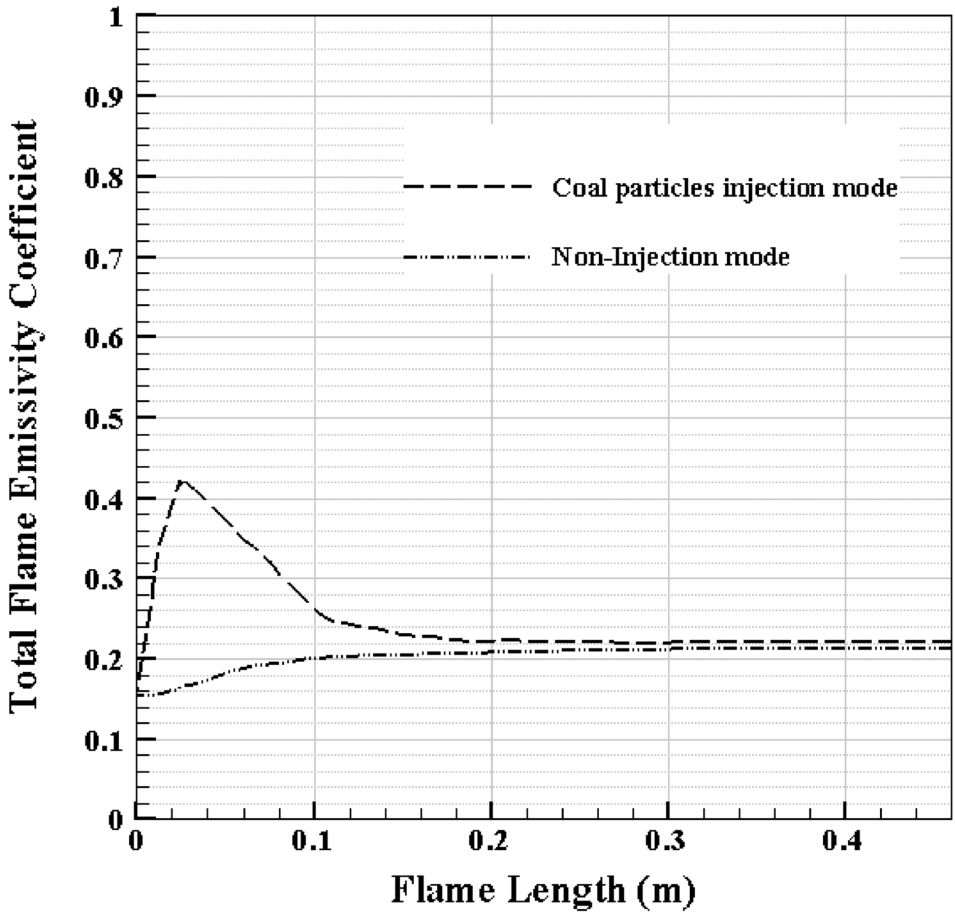


Fig. 7. Total emissivity coefficient of flame considering the radiation of soot particles for injection and noninjection modes.

of the flame can enhance its radiative properties. Figure 7 shows the total emissivity coefficient of flame considering the radiation of soot particles for injection and noninjection modes. It can be obviously seen that coal particles injection enhances the emissivity coefficient of flame in upstream region or high-temperature zone of flame. As was mentioned in Fig. 6, in this region, due to pyrolysis of the solid coal particles the concentration of intermediate solid soot particles increases. Conduction and convection heat transfer from hot gases to soot particles increases their temperature and makes them luminous and brighten. Consequently, these particles act as high-emissive gray bodies and enhance the total emissivity coefficient of the flame and its thermal radiation.

One of the disturbing drawbacks of heavy fossil fuels, such as coal, is high amounts of CO and NO emissions during the combustion process. Therefore, in natural gas–coal synchronous combustion, it is necessary to keep these emissions at the standard level.

Figure 8 displays the CO concentration across the furnace axis. When coal particles are injected into the natural gas flame, the CO concentration increased compared to the noninjection mode.

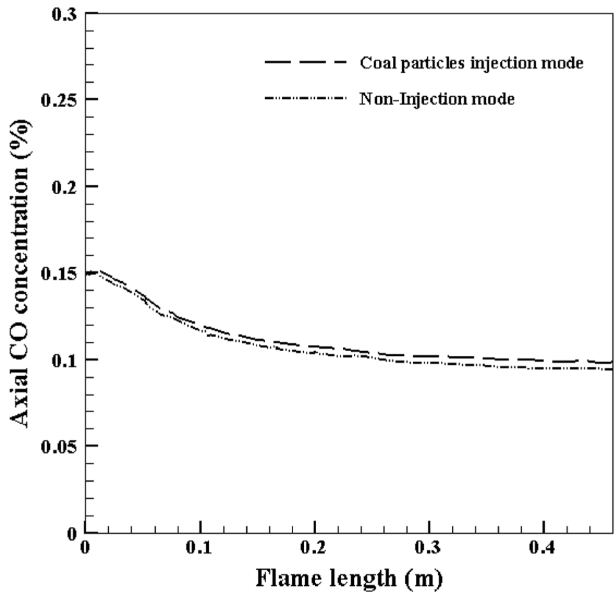


Fig. 8. CO concentration across the furnace axis for injection and noninjection modes.

Coal particles as hydrocarbon fuel finally are burnt in the furnace and raise the total amount of CO and CO_2 in the flame. However, since the mass flow rate of injection is small, the increase in CO concentration is very small, lower than the standard level (150 ppm). It should be noted that when the amount of coal particles injected increases, CO and unburned hydrocarbons emissions increase at the exhaust of the furnace. Therefore, we used a Testo 350 XL gas analyzer to measure and control the emission of CO at the exhaust of the furnace. The mass flow rate of coal injection (0.81 kg/h), reported in this paper, is the maximum flow rate of coal particles injection while maintaining the emission of CO pollutant lower than the standard value. Under this condition, the CO emission at the exhaust of the furnace was 144 ppm.

Figure 9 illustrates the concentration of NO pollutant at the exhaust of the furnace in injection and noninjection modes measured by a Testo 350 XL gas analyzer. Surprisingly, NO in the injection mode is 5 ppm smaller than the noninjection case. Thermal NO formation, which is highly temperature dependent, is recognized as the most relevant source of natural gas combustion. Fuel NO is another source of NO formation during the combustion of solid and liquid fossil fuels such as coal particles, which have nitrogen content. Since the mass flow rate of injection is small and the maximum temperature of flame is decreased by injection, therefore, the portion of Fuel NO in total NO formation is small.

On the other hand, in the results from Fig. 2, it is evident that by synchronous combusting natural gas and coal particles, the heat absorbed by particles decreases the peak of the flame temperature in its upstream. Then, the combustion of the particles in the flame downstream increases the temperature of the flame in this zone. This results in a more uniformed temperature distribution. Since the thermal NO is highly temperature dependent, the elimination of peak temperature of flame by synchronous combustion of natural gas and small amount of coal particles can be used as an

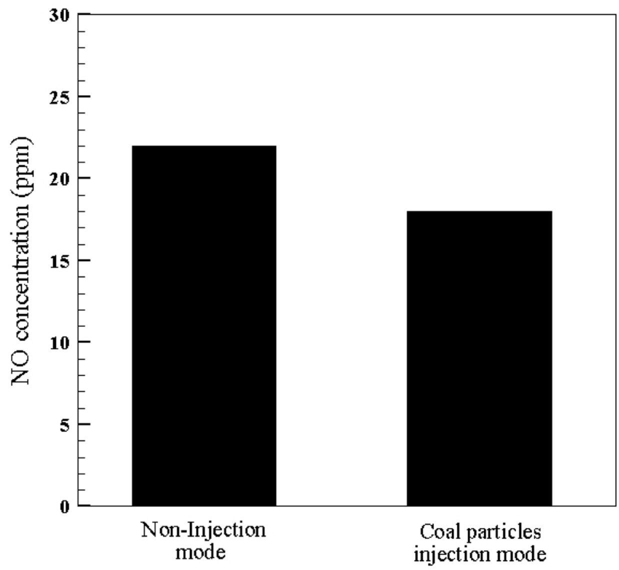


Fig. 9. NO pollutant emission in injection and noninjection modes.

applied means for reduction in thermal NO along with an enhancement in the radiation heat transfer rate in high-temperature industrial natural gas burners.

4. Conclusion

Despite the important role of radiation in heat transfer from the flame, there is some data on the radiative characteristics of the flame (particularly emissivity coefficient) and the share of soot and gaseous products of combustion in emissivity coefficient of flame. On the other hand, it is difficult to determine the above-mentioned data experimentally. The present work was an experimental and numerical study on impacts of the synchronous combustion of small amounts of coal particles with natural gas on the radiative species, emissivity coefficient and pollutant emissions of a natural gas flame. The main findings are as follows:

- The injection of a small amount of coal particles into the hot flame of natural gas creates a uniform temperature distribution along the furnace and decreases the formation of NO_X pollutant in the natural gas flame.
- Coal injection (in small amounts) into natural gas increases the volume distribution, concentration, and radiation view factor of high-emissive solid soot particles in the flame.
- The small amount of coal particles injection enhances the total emissivity coefficient of the low-radiative flame of natural gas.
- The role of solid soot particles on total emissivity coefficient is remarkable, while an increase in CO_2 and H_2O concentrations has an insignificant effect on the flame emissivity coefficient.

- The findings of the study reveal that synchronous combustion of small amounts of coal particles with natural gas can be used as a feasible solution to enhance the poor radiative characteristics of industrial natural gas flames.

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