INVESTIGATIONS ON THERMAL RADIATIVE CHARACTERISTICS IN A LAB SCALE FURNACE: EFFECT OF ADDITION OF NANOPARTICLES TO LPG COMBUSTION

Khalid Waheed1,2, Seung Wook Baek1, Irfan Javed1,2, Yupiter Kristiyanto1
1Korea Advance Institute of Science and Technology (KAIST)
KAIST 291 Daehak-ro (373-1 Guseong-dong), Yuseong-gu, Daejeon 305-701, South Korea
2Pakistan Institute of Engineering and Applied Sciences (PIEAS)
P.O. Nilore, Islamabad, Pakistan
Khalid.waheed.sh@gmail.com, swbaek@kaist.ac.kr, ijkasuri@gmail.com

ABSTRACT
Use of nanoparticles in thermal applications have attained large interest in recent years because of their improved heat transfer characteristics. Effect of nanoparticle addition on radiative heat transfer characteristics from gaseous fuel combustion has been studied in this research. Radiative heat fluxes (RHF) are considered to play a very important role in improving the thermal efficiency of furnaces by controlling heat transfer from the flames to the furnace wall. Among many contributors, presence of particles (soot and fly ash) contributes to larger percentage of radiative heat flux. However, in gaseous fuels combustion these kinds of particles are usually not generated or produced in low concentrations resulting in lower contribution of radiative heat transfer. Current research work is focused to investigate the effect of addition of combustible carbon black particle and noncombustible metal oxide nanoparticles on radiative heat transfer capabilities of LPG combustion. For this purpose, a furnace was designed with a vertical downward-propagating flame configuration to avoid any sedimentation of solid particles in the furnace. Diffusion flame was generated by providing separate supplies of fuel and oxidant. Noncombustible and combustible nanoparticles suspended in water in dilute concentrations were introduced to combustion chamber through a capillary placed at the center of fuel pipe. Concentration of nanoparticles in water suspensions was varied from 0.1 wt. % to 0.50 wt. % to avoid choking of feeding capillary. Temperature data inside furnace was obtained and significantly lower peak temperatures were observed. Heat flux data was recorded at the furnace wall and heat fluxes was significantly influenced by varying nanoparticle nanoparticles concentration. An overall increase in RHF was observed with maximum increase of 28% obtained with highest concentration of noncombustible nanoparticles. Higher contribution of RHF led to substantial increase in total heat flux.

INTRODUCTION
Nanofluids or engineered NPs laden fluids, gathered a great attention of researchers in recent years. Initially, they were solely employed as heat transfer fluids, but recently, due to discovery of enhanced characteristics of NPs, the nanofluids also found a broad range of applications in several areas of life, as discussed in several review papers [1-6]. Nanofluids are primarily useful in enhancement in heat transfer, higher critical heat flux and improvement in mass transfer [7]. Although the basic mechanism, explaining the unique properties of nanofluids has several limitations and uncertainties [3], their practical applications are unrestricted and widely popular. The current paper attempts to discuss for the first time, the effect of alumina nanofluids on radiative heat flux in LPG combustion. In any combustion process of fossil fuels, radiative heat transfer plays an important role in the efficient conversion of chemical to thermal energy, leading to the maximum possible extraction of heat out of a process. Contribution of radiative heat transfer to the total heat transfer can vary from 20-35% in diesel engines [8] to 95% in coal fired furnaces [9, 10], and thus cannot be neglected. A large volume of research articles [11, 12] and reference books [13-16] are available for explanation of radiative heat transfer in combustion phenomena in various application ranging from small engine to mammoth industrial furnaces. However, most of the references provide a detailed discussion only on the heat transfer process itself, with minimal or no comments on how to control such transfers effectively depending upon the end application. Many systems, such as, power plant furnaces, cracking furnaces, steel production and reheating furnaces require a high contribution of radiative heat to yield higher thermal efficiencies.

Except for soot particles generated as a result of combustion, most of the two phase thermal radiations result from micron sized particles of coal and ash. By contrast, in gaseous fuel combustion, where micron sized coal and ash particles are absent and soot generated is also in small fraction, the radiative heat transfer contribution becomes significantly lower. The concentrations of particulate matter can be increased by seeding some nanoparticles to gaseous fuel flames. The effect of addition of nanoparticles to gaseous flame can profoundly increase the RHF contributions by increasing particulate matter within the furnace. However, to the best of our knowledge, no experimental research work has been performed so far to understand the effects of NPs on radiative heat transfer (transport of thermal radiation) in a combustion system. The use of NPs in combustion system is not so straight forward. Addition of nanofluids/nanoparticles in combustion process may result in a highly complex scenario of radiative heat transfer mechanism. To this end, temperature difference between hot combustion gases and nanoparticles may exist, along with changing absorption and scattering properties of hot combustion environment. In addition, there are considerable limitations on their practical applications in industrial furnaces.

The three major drawbacks in this regard are cost feasibility, deposition of particulate matter on heat transfer surfaces and particulate emission. The use of NPs would not be much costly if we are able to understand how they affect the radiative properties. The deposition of NPs can pose significant impact on the working life and efficiency of convective heat transfer zone by forming a virtual cover on it. Before using NPs in furnaces it is important to analyze the efficiency of whole system, especially the possible decline in convection section efficiency.
and how to improve the combustion chamber efficiency. Another prime concern regarding the use of nanoparticle is the generation of additional aerosol, which may deteriorate the environment considerably. To this end, many researchers are working toward the removal of nanoparticles from gaseous stream and several reviews articles [17, 18] are available on this issue. Therefore, the study of NPs in combustion system for a thorough understanding of their role in radiative heat transfer mechanism would be important both from the industrial and academic standpoint. In this regard, the current research would provide a useful foundation for future work.

Due to continuous depletion of fossil fuels, hydrogen becomes a promising candidate as the alternate energy source. As early as in 1929, Suzuki pioneered in studying hydrogen as an alternative fuel for industrial furnaces, which was published in 1982 [19]. Following this, a number of researchers started studying the usage of hydrogen as an alternative fuel to the fossil fuel [20-23]. However, in order to employ hydrogen as a furnace fuel, extensive studies are needed to improve its heat transfer characteristics. Most of the industrial furnaces are designed for luminous flame, whereas, hydrogen has a non-luminous flame or considerably weak visible radiations [24]. The luminous flame of hydrocarbon gives a higher radiative heat transfer in comparison to hydrogen. In furnaces, fired with coal or liquid fuel, particles, such as, soot and ash, with varied sizes (from nano to micron) are generated as a result of combustion. Flame luminosities are strongly affected by the concentration of solid particles in furnaces—a high flame luminosity leads to a higher RHF [25, 26]. Butler et al. [10] showed that the presence of coal particles in a furnace contributes to the radiative heat transfer. Soot formation in industrial furnaces is an important factor in controlling radiative heat transfer. Research shows that the radiative heat transfer increases with the level of soot [25,26]. Ahluwalia et al. [27] showed that increased concentrations of soot and fly ash contribute to the RHF in coal-fired furnaces. In this regard, experimental investigation to understand the effect of nano sized particle addition to gaseous fuels on radiative heat transfer characteristics would be interesting.

The effects of particle addition on radiative heat transfer in the combustion of low-carbon gaseous fuels was first studied by Steward and Guruz [28]. They introduced micron-sized aluminum and magnesium oxides to a 50% propane / 50% propene flame, and concluded that the radiative heat transfer decreased with increasing particle concentration. Baek et al. [29] added micron-sized combustible carbon and noncombustible aluminum oxide particles to a hydrogen flame and reported a decrease in the RHF with the increase of non-combustible particles. However, none of these reports indicated an increase in the RHF, and to the best of our knowledge, there are no other studies claiming to enhance the RHF by introducing particles to the combustion of gaseous fuels. It is worth noting that previous studies seeded relatively high concentrations of micron-sized particles that resulted in heat blockage, thereby reducing the radiative contribution to the total heat flux. In the current work, nanoparticles in relatively lower concentrations have been used instead of micron-sized particles, and the process of feeding particles into the combustion chamber was different. In all the prior approaches the particles were gas-fed with the oxidant stream, while reducing the residence time of the particles in hot flame regions. By contrast, the current approach introduced NPs as a liquid suspension into the fuel stream to give the particles a longer time to heat up in flame region.

EXPERIMENTAL SETUP, PROCEDURE AND MATERIALS

To understand the effect of particle addition on flame’s heat transfer characteristics, a furnace was designed with vertically downward flame configuration. Such configuration helps to reduce the particulate deposition in the combustion chamber. A series of experiments were performed in this lab scale furnace, starting from pure gaseous fuel combustion and ending with the addition of noncombustible nanoparticles suspensions in it.

Figure 1a explains the schematics of experimental setup which shows a vertical combustor to maintain axial symmetry as far as possible with an inside diameter of 0.4 m and height of 1.0 m. Burner is located at the top of combustor and fired downward in order to avoid the sedimentation of solid particles fired with flame. Burner is designed to produce diffusion flame by maintaining separate supplies for fuel and oxidant. Fuel and oxidant are supplied through mass flow controllers which enable to maintain precise flow rates to the furnace with two concentric pipes. The inner pipe of 17 mm inner diameter (ID) supplies fuel whereas the outer pipe of 38 mm ID provides oxidant. A stainless-steel capillary with external diameter 1.6 mm and internal diameter of 0.508 mm was placed at the center of the fuel pipe. A separate oxidant supply was provided with a constant pressure of 1.0 bar. Oxidant supply to the capillary was provided to ensure atomization of the liquids containing the suspended nanoparticles. Figure 1b shows the cross-sectional view of burner and provides the location of feeding capillary. A total of 9 measuring ports were provided on each side of the furnace to measure the temperature and heat flux data. Each port is at an interval of 0.1 m where first port is located at 0.1 m away from burner tip. Diffusion flames are influenced by the mixing process of fuel and oxidant. Swirling flow was generated with the help of a radial type guide vane swirler with eight guide vanes. Liquid suspensions were fed into the combustion chamber using a low-flow-rate peristaltic pump (Langer Instruments, BT 100 2J), which was able to regulate the liquid flow rate in the range of 0.0002–380 ml/min. Low concentrations of alumina particles were introduced to avoid blocking the feed capillary. Measurements of the total heat flux were carried out using a calibrated Vatell TG-9000-9 transducer. The radiative heat flux was measured using a Vatell TG-9000-9 transducer. The principle of this measurement technique is described by Gardon [31]. For long-duration measurements, the sensor was cooled by circulating room-temperature water. The sensor was able to measure heat fluxes in the range 0 - 20 W/cm² using a bezel angle of 120°. The temperature inside the furnace was measured using a fine-wire Pt and Pt–Rh (87% Pt, 13% Rh) silica-coated thermocouples. Each wire passed through a 0.4-cm-diameter dual-bore ceramic tube that was inserted through probe ports in the furnace wall. Visible/near infrared (Vis-NIR) radiation from the furnace was analyzed and its spectra were recorded using an Ocean optics USB2000+ spectrometer in the wavelength range of 350-1026 nm.
Experiments were performed with liquefied petroleum gas (LPG) as main fuel because of its easy availability and safe operation. A total flow rate of LPG was fixed at 7.0 l/min. LPG cylinder was used to supply main fuel which contains ~95 percent propane. Fuel is then passed through the mass flow controller recently calibrated to maintain precise amount of main fuel flowing into combustion chamber. Main oxidant, in this case is atmospheric air, was supplied by separate air compression unit which compresses the air to high pressure, stored in compressed air tanks. Regulators were used to regulate air pressure at constant pressure before entering to mass flow controllers for air. Air flow rate of 250 l/min was maintained by mass flow controllers. High pressure air cylinder was used for the supply of air to atomization capillary which ensures the atomization of liquid suspensions in the combustor.

Deionized (DI) water was used to suspend the aluminum oxide (alumina, Al2O3) nanoparticles with mean diameter of 50 nm (obtained from Sigma Aldrich in 20 wt. % suspension in water) and carbon nanoparticles with mean diameter 50 nm (obtained from Sigma Aldrich in powder form) which are acted as missing fly ash and soot particles in low carbon gaseous fuel combustion. Water suspensions were fed to combustion chamber using a low flow rate peristaltic pump. Nanoparticle suspensions with concentrations (0.1 and 0.5 %) were tested in this series of experiments.

RESULT AND DISCUSSION
Experiments were carefully designed to study the effects of addition of liquid suspension on radiative heat transfer from gaseous fuel combustion. The effect of various liquid suspensions on RHF can be differentiated by setting some baseline. First, experiment was performed with pure LPG to set some baseline for comparison of temperature and heat fluxes for various additives to LPG flame. Detached flame was observed during the experiment because of air jet coming from the capillary for atomization of liquid.

LPG Combustion
Figure 2a shows the axial temperature profile whereas figure 2b displays the THF and RHF along furnace length. Maximum temperature was observed at 0.2 m downstream of burner tip indicating flame formation started away from burner tip. Temperature decreases as the reactants move downstream with a maximum temperature of 1241 °C recorded at measurement port 2. THF and RHF were measured at wall along axial directions. Figure 3 shows the THF and RHF for the case of pure LPG combustion. Maximum THF (86.03 kW/m²) was observed at port 4 where the flame has its maximum width. Decrease in THF was following the trend of axial center line temperature profile. High turbulence in near burner region causes high mass flux of hot gases to move towards furnace wall, which gives rise to the contribution of convective heat flux (CHF). Since THF is summation of convective and radiative heat flux, along with increased contribution of CHF, higher temperatures in flame region led to augmented contribution of RHF as well. The overall radiative heat flux fraction (RHFF) which is the ratio of RHF to THF remained around 0.57.

Flame intensity form visible near infra (Vis-NIR) radiations were observed using ocean optics spectrometer USB 2000+ recorded against first 5 measuring ports. Figure 3a shows the Vis-NIR radiations spectrum of LPG combustion. Maximum counts of Vis-NIR radiations were observed along port 2 where the maximum temperature was recorded and radiation counts decreased following the axial temperature profile. Because of spectrometer precincts, OH* radical radiations at 281 nm, 306 nm and 343 nm were not observed. There are two distinctive parts of Vis-NIR spectrum, below and above 600 nm. In the first part peak at 430 nm, corresponds to CH*, and numerous peaks at 465, 472, 511, 514, 516, 555, and 562 nm were observed corresponding to the emissions of C2 radical (swan bands) [30] with an additional peak at 588-589 nm, which is conceivable that it is a CO or COH band [31]. Above 600 nm, high intensity of Vis-NIR radiations was detected with continuous spectrum similar to black body emissions. These Vis-NIR radiations were considered to be emitted from the heated furnace wall. However in this region, some characteristic peaks were there as well, viz. at 766 and 769 nm, which may correspond to numerous vibrational levels and the superimposed rotational energy levels of
whole molecules [31]. A peak at 930 nm was observed at all five ports, which was possibly due to the insulation material on the other side of the furnace. The radiations intensity in W/m².Sr was calculated from the obtained spectrum at the first five ports and was plotted along with the centerline temperature in Fig. 3b. It is noteworthy that this intensity is only from Vis-NIR radiations so it does not include the contribution of H₂O and CO₂ infrared bands. Intensity of the radiations coming out of the furnace appeared to follow the trend of axial temperature profile since the intensity was higher at higher temperature regions and the value decreased with a decrease in temperature.

![Figure 2 LPG combustion; (a) axial temperature profile, (b) heat flux profile](image)

**Effect of Water Addition**

The effects of water addition (LPG+W combustion) on temperatures and heat fluxes are important to determine because it is used as a base fluid to suspend nanoparticles. Water is also a participating specie which actively takes part in radiative heat transfer by absorbing, scattering and emission of thermal radiation [26]. A low flow rate (2 ml/min) of water was selected to avoid any significant change in radiative characteristics in the furnace.

A comparison of the axial temperature profile between the case of water addition (LPG+W) and pure LPG combustion is given in Figure 4a. Addition of water to LPG combustion significantly caused a temperature drop in near burner region. A maximum temperature of 1092 °C was recorded at port 3 where the maximum temperature without water addition was observed at port 2. High temperatures in region away from the burner were observed. Another interesting fact with lower peak temperature is that pollution emission may have been restricted as explained by Zeldovich [32]. The effects of water addition on heat fluxes are identified by comparing them with those obtained for pure LPG combustion and the results are shown in Figure 4b. No significant change in THF was observed in near burner region even with lower temperatures. But after the flame region, a slight decrease in THF was observed. Maximum THF (86 kW/m²) was recorded at port 4 where maximum flame width was perceived. Addition of water to LPG combustion augmented the concentration of water vapors in the furnace and led to higher contribution of convective heat flux as compared to the case with LPG combustion as it condenses on heat flux sensor surface. RHF on the other hand, has strong dependence on temperature and with such a lower peak temperature it decreased considerably. The overall lower radiative heat flux fraction of 0.55 was obtained in contrast to the case with LPG where RHFF was 0.57.

![Figure 3 Radiative characteristics of LPG combustion; (a) Vis-NIR Spectrum, (b) Radiation Intensity](image)
Figure 4 Effect of water addition on LPG combustion; (a) axial temperature profile (b) heat flux profile

Figure 5a shows Vis-NIR radiations spectrum of LPG+W. Similar to that of LPG, Vis-NIR radiations counts are maximum at port 2, with significantly lower values compared to that of LPG, and it decreased following the temperature profile. The only difference between LPG and LPG+W, besides the lesser counts of spectrum with LPG+W, is low intensity for 430 nm, 516 nm and 589 nm, and also the peak corresponding to 766 and 769 nm was not observed. The Vis-NIR radiations spectrums obtained from ports 3 to 5 were similar to that of the LPG. The radiation intensities were plotted along with the centerline axial temperature in Figure 5b. Similar to the LPG combustion, the intensity of radiation coming out of the furnace in LPG+W also seemed to follow the trend of centerline axial temperature profile.

Figure 5 Effect of water addition on radiative characteristics of LPG combustion; (a) Vis-NIR Spectrum, (b) Radiation Intensity

EFFECT OF NANOPARTICLES ADDITION ON LPG COMBUSTION

Nanoparticles were seeded to LPG combustion in form of suspensions and the flow rate of these suspensions was kept same to the flow rate of water i.e. 2 ml/min. In order to avoid the blockage of feeding capillary, low concentrations (0.10, and 0.50%) of noncombustible (alumina, Al₂O₃) and combustible (Carbon, C) nanoparticles were introduced into flame. Here and below, the mass percent values are used. A comparative analysis of the centerline axial temperature profiles, heat fluxes (THF and RHF), Vis-NIR radiations spectrums and intensities for the different concentrations of combustible and noncombustible nanoparticles to the pure LPG and LPG+W cases is presented in the subsequent sub-sections, respectively.

Effect of Noncombustible Alumina Nanoparticles addition
Temperature
A comparison of axial temperature profiles for 0.10, and 0.50% alumina suspensions with LPG and with LPG+W is shown in figure 6a, and b respectively. Similar to the case of LPG+W, feeding of relatively dilute (0.1%) suspension of alumina to LPG combustion also resulted in delayed flame formation and flame instigated at 0.2 m away from burner tip. Considerable lower peak temperature was recorded with addition of 0.1% alumina suspension as compared to the case of pure LPG combustion. Peak temperature was also lower than the case of water addition. Maximum temperature of 1048 °C was recorded at 0.3 m away from burner. Comparison of axial temperature profile for 0.10% alumina suspension with pure LPG and with LPG+W combustion is given in Figure 6a. Delayed initiation of flame may have led to even distribution of LPG in furnace resulting in uniform temperatures higher than LPG combustion in regions away from burner.

Figure 6 Effect of noncombustible alumina nanoparticle concentration on axial temperatures (a) 0.10%, and (b) 0.50%.

Heat Flux
A comparison of THF and RHF with the addition of 0.10 and 0.50% alumina nanoparticles suspensions to LPG combustion with corresponding fluxes obtained in LPG and LPG+W combustion is shown in figure 7a and b, respectively. Addition of 0.10% alumina suspension to LPG combustion caused a slight decrease in THF in near burner region similar to that of LPG combustion. Early formation of flame give rise to the temperatures in near burner region which became higher than LPG+W case but lower than temperatures observed with pure LPG combustion due to presence of water. A comparison of axial temperature profile between 0.5% alumina suspension addition, LPG and LPG+W is shown in figure 6b. Maximum temperature of 1165 °C was recorded at axial position of 0.2 m away from burner indicating existence of flame. Overall higher temperatures were recorded in region away from the burner. Considering these temperature profile it is evident that an increase in particle concentration led to surprisingly higher peak temperatures. Though no extra source of energy was supplied yet the addition of inert alumina particles tends to increase the peak temperature which is opposite to the general understanding, the detailed explanation of this is provided in subsequent subsection.
increase in THF was due to considerable higher contribution of RHF because of higher temperatures and high concentration of nanoparticles present in the furnace. Maximum THF was recorded (~93 kW/m²) at port 4 similar to previous cases. Higher values of THF were observed along furnace length as compared to LPG. It is evident from this comparison that THF is significantly higher than that of LPG in near burner regions and in regions away from burner. High concentration of heated nanoparticles results in noteworthy increase in RHF. Maximum enhancement of ~28% in RHF was recorded along port 2. In comparison to the LPG+W combustion case, where no substantial change in temperatures was observed in region away from burner, lower values of THF and RHF in case of LPG+W combustion indicates that increase in THF and RHF is solely because of addition of nanoparticles to the LPG combustion, while raising the value of RHFF to 0.62.

Radiative Characteristics

Radiative characteristics of LPG combustion fed with alumina nanosuspensions were studied by obtaining Vis-NIR radiation spectrum and radiation intensity for different concentrations. The Vis-NIR radiation spectra and radiation intensity with addition of 0.10 and 0.50% alumina suspensions are shown in Figure 8a, b, c and d respectively. The Vis-NIR radiation spectrum for 0.10% in figure 8a shows similar behavior as of LPG and LPG+W combustion cases with maximum counts of Vis-NIR radiations observed at port 2 which monotonically decreased at port 3, 4 and 5, following the temperature profile. Although the intensity counts of peaks at 430 nm and 516 nm were same as that obtained with LPG+W but the peak at 589 nm has a much higher intensity. The higher intensity of 589 nm peak may have been obtained due to some chemical activity at the surface of alumina nanoparticles generating higher concentrations of CO in the flame region. Also the peaks at 766 and 769 nm reappeared similar to the LPG combustion case which were absent for LPG+W. Radiation intensity in (W/m².Sr) was calculated from the obtained Vis-NIR spectrum and plotted with axial temperature profile obtained for 0.10% alumina suspension. A comparison of centerline temperature line and radiation intensity for 0.10% alumina with LPG and LPG+W combustions is shown in figure 8b. The maximum radiation intensity was observed at port 2 and the maximum temperature was observed at port 3 similar to that obtained when pure water was used. The radiation intensity seems to follow the trend of axial temperatures in regions away from burner. However for the case of 0.10% alumina the peak temperature was significantly lower yet the radiation intensity obtained was similar to LPG+W case.

The Vis-NIR spectrum of LPG combustion with the addition of 0.50% alumina suspension is shown in figure 8c. Similar to the case with LPG, the addition of 0.50% alumina suspension yielded the peaks at 430 nm and 516 nm with comparable counts. The intensities of 589 nm peak was even higher with an additional shoulder peak of 586 nm which may correspond to CH* radical [30] was not appeared in 0.10% alumina. Similar to the cases discussed previously, the maximum Vis-NIR radiations counts were achieved at port 2 with lowered radiation counts at port 3, 4 and 5 following the temperature profile. The peaks at 766 and 769 nm had larger intensities than those for pure LPG. A comparison of centerline temperature curve and radiation intensity for 0.50% alumina with LPG and LPG+W combustion cases is shown in figure 8d. An increase in the nanoparticle concentration increases the radiation intensity which is higher than that for the pure LPG combustion even at a lower temperature. The higher radiation intensity also resulted in an overall higher temperature across the furnace. Although the radiative heat flux obtained at the surface of furnace included all range of thermal radiations, especially H₂O and CO₂ IR bands, the current study was restricted only in the Vis-NIR range to gain insight into the mechanism of RHF contribution increase with an increase in alumina NP concentration. Unlike the radiations from soot particles which generate continuum spectrum across a thermal radiation range depending upon their temperature, the addition of alumina nanoparticles generated some unique bands of thermal radiations, of which intensities increased with an increase in the particle concentration. It is also well established that the heated surface of solid particles emit thermal radiation similar to the black body emission depending upon its emissivity and temperatures of surface. Addition of nanoparticles in combustion provided such solid surface and led to a
higher emissivity from the gas/solid mixture. This higher emissivity of the gas/solid mixture can be visualized by comparing the radiation counts above 600 nm from different cases. The higher emissivity associated with nanoparticle addition, along with some significant bands of thermal radiation, increases the overall contribution of thermal radiation. Therefore, it can be concluded that the observed increase in RHF was due to the addition of solid alumina nanoparticle and the RHF value increased with an increase in the nanoparticle concentration within the furnace. This can be explained that at a higher NP concentration with a large RHF value, higher temperature could be easily attained due to early flame formation while overcoming of any water quenching of the flame. The increase of peak temperatures with NP concentration cannot be explained adequately by considering the inert nanoparticles which are non-participants in the combustion process; instead, aluminum solid surface of alumina nanoparticles can attach fairly large amount OH radical [33]. Hydroxyl radical plays an important role in sustaining combustion, and higher concentrations of OH radical can lead to increased temperature [34].

Figure 8 Effect of noncombustible nanoparticle addition on radiative characteristics of LPG combustion; (a) Vis-NIR Spectrum 0.10% alumina, (b) Radiation Intensity 0.10% alumina, (c) Vis-NIR Spectrum 0.50% alumina, (d) Radiation Intensity 0.50% alumina.

Effect of Combustible Carbon Nanoparticles addition

Temperature

A comparison of axial temperature profiles for 0.10, and 0.50% carbon suspensions with LPG and with LPG+W is shown in figure 9a, and b respectively. Different to the cases of LPG+W and 0.10% Alumina suspension, feeding of relatively dilute (0.10%) suspension of carbon to LPG combustion, flame instigated earlier as that obtained with LPG combustion. The peak temperature was also similar to the LPG with only a slight decrease in peak temperature. Peak temperature for 0.10% carbon suspension was recorded at port 2 with a temperature reading of 1220 °C slightly lower than obtained for LPG. A comparison of axial temperature profile for 0.10% carbon suspension with pure LPG and with LPG+W combustion is given in Figure 9a. Overall high temperatures were recorded across the furnace length.

A comparison of axial temperature profile of 0.50% carbon suspension with that obtained for LPG and LPG+W is shown in figure 9b. Similar to the LPG and 0.10% carbon suspension peak temperature was recorded along port 2. However with higher concentration of carbon nanoparticle a slight decrease in peak temperature was observed. The peak temperature of 1189 °C was recorded which is lower as compared to 1251 and 1220 °C of LPG and 0.10% carbon suspension. However overall higher temperatures were recorded in region away from the burner in comparison to that obtained for LPG.
Heat Flux

A comparison of THF and RHF with the addition of 0.10 and 0.50% carbon nanoparticles suspensions to LPG and LPG+W combustion is shown in figure 10a and b, respectively. Addition of 0.10% carbon suspension to LPG combustion caused a significant increase in THF as compared to LPG and LPG+W combustion in near burner regions as shown in figure 10a. Addition of carbon nanoparticles resulted in higher contribution in RHF which led to higher total heat flux along with extra energy generated by carbon combustion. Maximum THF (95 kW/m²) was recorded at port 4 similar to the case with LPG and LPG+W. Away from burner, where complete particle burn out is expected, with only hot combustion gases RHF was similar as that of LPG. Maximum increase in RHF was observed at port 2 where ~16% increase in RHF was observed. Although significant increase in absolute value of RHF was observed in near burner regions but RHFF was actually decreased. RHFF is the ratio of RHF to the THF, and higher THF resulted in lower value of RHFF. Average RHFF of 0.53 was observed, which was lower than that obtained with LPG.

Higher concentration of carbon nanoparticles shows similar behavior with even higher THF as compared to that obtained for 0.10% carbon suspension. A comparison of THF and RHF with 0.50% nanoparticles loading rate to that of LPG and LPG+W is shown in Figure 10b. Among all studied cases, maximum increase in THF was recorded by introducing 0.50% carbon suspension. Maximum THF was recorded (~97 kW/m²) at port 3. The higher concentration of carbon nanoparticles also contributed to even higher RHF as compared to 0.10% carbon suspension. A maximum increase of 26% in RHF was recorded along port 2. Presence of higher concentration of particles ensured higher RHF even with lower peak temperature as compared to LPG and 0.10% carbon suspension. Similar to the case of 0.10% carbon suspension the RHF is higher in near burner regions which ultimately became similar to that obtained for LPG further downstream. This result led to the conclusion that presence of particles plays a vital role in improving radiative heat transfer in furnace. However because of much higher THF, RHFF still remains lower than that obtained with LPG. An average value of RHFF was maintained at 0.56 which is higher than 0.10% carbon suspension but lower than LPG.
Radiative Characteristics

Similar to the alumina suspension addition, radiative characteristics (Vis-NIR spectrum and radiation Intensity) of LPG combustion with carbon suspension addition is provided in this subsection. The Vis-NIR radiation spectra and radiation intensity with addition of 0.10 and 0.50% carbon suspensions are shown in Figure 11a, b, c and d respectively. The Vis-NIR radiation spectrum of 0.10% carbon suspension in figure 11a shows similar behavior as of LPG and LPG+W combustion cases with maximum counts of Vis-NIR radiations observed at port 2. However Vis-NIR radiation counts remained similar for port 3 and 4 which monotonically decreased for port 5 indicating large length of visible flame. Introduction of carbon nanoparticles also resulted in numerous radiation peak instead of two distinctive peaks at 430 nm and 516 nm observed for the LPG and alumina suspension. These numerous peak may have resulted as a result of swan band of C\textsubscript{2}. Similar to alumina case strong peak at 589 nm was obtained for the fact explained earlier. Carbon nanoparticles may have caused some higher concentration of CO and COH resulting in higher peak values of 589 nm. The peak at 766 and 769 nm was also significantly strong. Exact explanation of this strong peak at 766 and 769 is not reported in literature, but as explained earlier these peak may result as numerous vibrational levels and the superimposed rotational energy levels of whole molecules. However from the obtained data these peaks at 766 and 769 nm may have result from some carbon compounds. Along with these numerous peaks, introducing carbon nanoparticle to furnace had a significant effect on back ground radiation coming from opposite wall of furnace. Presence of carbon black particles in furnace may have increase the absorption coefficient of gas particle mixture. Higher absorption coefficient resulted in lower radiation intensity as shown in figure 11b. Even with higher temperature as compared to LPG+W intensity is merely reaching the Intensity level of LPG+W. Vis-NIR intensity level remained at certain level which increases as the carbon particles are consumed in region away from burner. Lower carbon contents in gas solid mixture resulted in lower background radiation as a result of higher temperature.

The Vis-NIR spectrum of LPG combustion with the addition of 0.50% carbon suspension is shown in figure 11c. Similar to the case with 0.10% carbon suspension, addition of 0.50% carbon suspension yielded in numerous radiation peak with the hint of peaks at 430 nm and 516 nm. The intensities of 589 nm peak was even higher as compared to the 0.10% carbon suspension. Similar to the cases discussed previously, the maximum Vis-NIR radiations counts were achieved at port 2 with lowered radiation counts at port 3, 4 and 5 following the temperature profile. The peaks at 766 and 769 nm had larger intensities among all cases studied. A comparison of centerline temperature curve and radiation intensity for 0.50% carbon suspension with LPG and LPG+W combustion cases is shown in figure 11d. An increase in the nanoparticle concentration increases the radiation intensity which is approaching to that obtained for the pure LPG combustion even at with a low temperature. However as discussed for the case of 0.10% carbon higher absorption resulted in lower radiation intensity is near burner region. The radiation intensity increases as the particles are consumed away from burner radiation intensity become higher than that of LPG due to higher temperatures.
Conclusions

An experimental study was conducted to investigate the effect of combustible and noncombustible nanoparticle addition on radiative heat flux for gaseous fuel combustion in a lab scale furnace. Combustible (carbon, C) nanoparticles and noncombustible aluminum oxide (alumina, Al₂O₃) nanoparticles were added in the form of water suspensions to gaseous fuel combustion with concentrations of 0.10% and 0.50% by weight in water. Temperature and heat flux data was recorded along with spectra of various different cases. Introduction of solid particles in furnace influence the temperatures and heat fluxes significantly. For non-combustible particle addition lower concentration yielded significant drop in temperature and heat fluxes which monotonically increase with the increase in particle concentration. Alumina nanoparticle also generated certain band of radiations at 589 nm as a result of some catalytic activity at the surface of alumina. The RHF contribution was significantly improved with higher concentration of nanoparticles all along the furnace length. This high contribution of RHF also resulted in higher THF. For the case of combustible carbon nanoparticles presence of particle ensured higher RHF in near burner regions but once the combustible particles were consumed the RHF became similar to that of LPG. This higher RHF in near burner region augmented with release of heat from combustion of carbon particle enhances the THF significantly. Maximum increase in THF was obtained with 0.50% carbon suspension.

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References