EFFECTS OF NANOPARTICLE ADDITION ON RADIATIVE HEAT FLUX IN A LAB SCALE FURNACE

K. Waheed*, S. W. Baek and I. Javed,
E-mail: khalid.waheed.sh@gmail.com
Division of Aerospace Engineering, School of Mechanical, Aerospace and Systems Engineering,
Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-Gu,
Daejeon 305-701, Republic of Korea.

Abstract
In order to improve the thermal efficiencies of industrial furnaces, high radiative heat fluxes are required in their combustion chambers. Radiative heat flux plays major role in controlling heat transfer from flame to the furnace wall. The radiative heat flux generated from gaseous fuel combustion is lower than that obtained from liquid and solid fuels combustion. High contribution to radiative heat flux from these fuels is because of the soot particles generation in case of liquid fuel combustion and the formation of fly ash or coal particles in solid fuel combustion. Such solid particles are usually absent or present in low concentrations in gaseous fuel fired furnaces which resulting in low contribution to radiative heat flux. Therefore, adding solid particles to gaseous fuel combustion can improve the contribution of radiative heat flux to total heat flux. This research is focused to investigate the effect of solid particles addition to gaseous fuel combustion. Noncombustible (alumina, Al2O3) nanoparticles were added in form of water suspension at varying concentration to gaseous fuel combustion. Improved radiative heat flux fractions were observed by introducing such nanoparticles suspensions in a lab-scale furnace.

Introduction
Replacement of high carbon fossil fuel with low carbon gaseous fuel is important in order to limit the pollution emissions especially COx, NOx and SOx. High carbon liquid and solid fuels contain fuel bound nitrogen and sulphur as impurities. These impurities result in pollution generation to some significant levels. A representative pollution emission from various types of fossil fuels is provided in table 1.

Table 1: Fossil fuel emission levels (pounds/billion BTU of energy input) [1].

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Natural Gas</th>
<th>Oil</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>117,000</td>
<td>164,000</td>
<td>208,000</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>40</td>
<td>22</td>
<td>208</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>92</td>
<td>448</td>
<td>457</td>
</tr>
<tr>
<td>Sulphur dioxide</td>
<td>1</td>
<td>1122</td>
<td>2591</td>
</tr>
<tr>
<td>Particulates</td>
<td>7</td>
<td>84</td>
<td>2744</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.00</td>
<td>0.007</td>
<td>0.016</td>
</tr>
<tr>
<td>Total</td>
<td>117,140</td>
<td>165,687.004</td>
<td>214,000.016</td>
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</table>

Pollution emission from fossil fuel is now recognized as global problem causing a lot of environmental issues especially the release of air toxics and greenhouse gases (GHGs). Studies by Intergovernmental Panel on Climate Change (IPCC) [2] shows that approximately three-
fourths of the increase in atmospheric CO$_2$ is produced by firing fossil fuels in stationary and non-stationary sources. This release of CO$_2$ to atmosphere resulted in substantial increase of GHG levels causing global warming. Although methane and chlorofluorocarbons (CFC’s) have much higher global warming potential as per mass of gases but the large quantities of CO$_2$ in atmosphere is contributing about 60 percent of global warming effect [2] [3]. The three options of reducing total CO$_2$ emission into the atmosphere are: (1) reducing energy intensity; (2) reducing carbon intensity, i.e., use of carbon-free fuel; and (3) enhancing the sequestration of CO$_2$ [4]. Efficient utilization of energy delivers the objective of first option. Carbon intensity may be reduced by switching to low carbon gaseous fuels or introducing renewable energy and renewable energy sources like bio-fuels. The third option involves post combustion capturing of CO$_2$ and sequestration.

Implementing idea of reducing carbon intensity is inexpensive as compared to the carbon capture and sequestration. The process of carbon capture and sequestration increases the cost of electricity production by 80 percent and 30 percent decrease in generating capacity [5]. The associated problem of utilizing low carbon gaseous fuel is their lower thermal efficiency. Thermal efficiencies can be enhanced by either increasing furnace temperatures or efficient harvesting of energy generated by combustion process. Energy generated from combustion process is harvested either by means of convective heat transfer or radiative heat transfer from high temperature combustion gases while conduction is negligible in high temperature environment. Low carbon gaseous fuel exhibits lower contribution of radiative heat flux (RHF) where 30 to 45 percent of heat is transferred by the mode of radiative heat transfer [6] as compared to ~95 percent in case of coal combustion [7] [8]. Reference [8] also showed that the presence of coal particle in the furnace contributed to radiative heat transfer. These results show that solid particles doping can potentially enhance the contribution of radiative heat transfer in low carbon gaseous fuel flame. Another study [9] points to fact that radiative heat transfer increases with increase of soot concentrations.

The effect of particle addition on radiative heat transfer in a furnace fired with low carbon gaseous fuels was first studied by Steward and Guruz [10]. They introduce micron size aluminum and magnesium oxides to 50 percent propane and propene flame and observed that radiative heat transfer decreases with the increase in particle concentrations. Baek et al. [11] studied the effects of micron-sized combustible (carbon) and noncombustible (aluminum oxide) particles addition to hydrogen flame. They found a decrease and increase in RHF with the addition of noncombustible and combustible particles, respectively. To best of our knowledge, there is no other study about observing RHF by adding particles in to the combustion of gaseous fuel. It is worth mentioning that all previous researchers were seeding micron-sized particles with high concentrations that may result in reduced radiative heat transfer. This research work is different from their studies in many ways. Firstly, nanoparticles are used instead of micron size particles as studied in previous researches. Secondly, mechanism of particle feeding to the combustion chamber is different i.e. liquid suspension is adding in this study unlike gas phase injection of particles as in previous studies. Lastly, the liquid suspension in this research is directly supplied to the center of flame which is different from previous studies where particles were supplied with main oxidant supply. Considering these differences with previous studies this research work is planned to identify the effect on radiative heat transfer with the addition of noncombustible (alumina) nanoparticles to the combustion of low carbon gaseous fuel.
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 1 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 1.6 mm outer diameter (OD) and 0.254 mm ID is installed at the center of fuel pipe which provides nanosuspensions. A separate oxidant supply at a constant pressure of 0.15 MPa is provided in this capillary. This oxidant is used for the atomization of liquid containing suspended nanoparticles. 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.

Measurements of RHF become a vital part of this study as the experiment was designed to measure the effect of different combustion conditions on radiative heat transfer. For this purpose a calibrated Vatell’s transducers; model TG-1000-1 for total heat flux (THF) and Model TG-9000-9 for RHF, were used. The basic principle of these transducers was proposed by Gardon [12]. The working principle of this type of heat flux sensor is simple in the fact that it measure electromotive force (emf) that is being generated because of the temperature difference between

![Figure 1](image_url)

**Figure 1** Experimental Setup (1) Furnace, (2) Burner, (3) Mass flow controller, (4) Dry air storage tank, (5) Air dryer, (6) Air compressor, (7) LPG cylinder, (8) Peristaltic pump, (9) Liquid suspension, (10) High pressure air cylinder, (11) Thermocouple, (12) Heat flux sensor, (13) Data acquisition system.
surfaces of the sensor to the middle part of sensor. Temperature inside furnace is measured with fine-wire Pt/ and Pt 87% and Rh 13% thermocouples coated with silica. Each wire passes through a dual bore ceramic tube (0.4 cm diameter) that is inserted through probe ports at the furnace wall. Thermocouple has an unavoidable error due to the radiative heat loss from thermocouple bead. Therefore, measured temperature is here calibrated using thermocouples with three different sizes of bead (0.3 mm ~ 0.5 mm) as studied by Baek et al [11].

Liquid suspensions were fed to the combustion chamber using a low flow rate peristaltic pump. Peristaltic pump, model BT 100-2J was obtained by Langer Instruments which can regulate liquid flow rate from 0.0002 to 380 ml/min. Only low concentrations of alumina particles were introduced to avoid blocking of feeding capillary. Commercially available 50 nm alumina particles suspended in water with concentration of 20% (by wt.) were obtained from Sigma Aldrich. This primary suspension is further diluted with deionized water (18.3 μΩ) and homogenized by ultra-sonication in order to obtain the desired concentrations of nanoparticles suspensions.

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 use 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. An air flow rate of 240 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) which are acted as missing fly ash in low carbon gaseous fuel combustion. Water suspensions were fed to combustion chamber using a low flow rate peristaltic pump. Alumina suspensions with various different concentrations (0.1, 0.35, 0.5 and 0.91%) were tested in this series of experiments.

Result and Discussion

LPG Combustion

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 standards for comparison of temperature and heat fluxes for various additives to LPG flame. Detached flame was observed during the experiment because of a separate air jet coming from the capillary for atomization of liquid.

Figure 2a shows the axial temperature profile whereas figure 2b displays the temperature contours for pure LPG combustion case. 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. Radial temperature was taken along radial direction at an interval of 0.05 m, started from center of furnace (0.00 m) to the wall of furnace (0.20 m away from the center line). Observed radial temperature profiles from port 1 to 5 indicate significant temperature
variation in radial direction. This high variation in temperature indicates the presence of flame in that region. Lifted flame cause a dip in temperature at radial position of 0.05 m on measuring port 1. Temperature gradient reduces significantly as hot gases exit the flame region and it is confirmed by radial temperature profiles recorded along measuring port 6 to 9. Low radial temperature gradient shows steady hot combustion gases flowing through combustor.

Figure 2 LPG combustion temperatures; (a) axial temperature profile, (b) temperature contours

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.

Figure 3 Heat flux profile of LPG
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 [13]. A low flow rate (2 ml/min) of water was selected to avoid any significant change in temperature profiles.

A comparison of the axial temperature profile between the case of water addition (LPG+W) and pure LPG combustion is given in Figure 4a. The temperature contours for LPG+W case are shown in Figure 4b. Addition of water to LPG combustion altered the flame structure significantly and it was started after 0.2 m in contrast to pure LPG combustion where flame was initiated after 0.1 m. Also, a substantial reduction in peak temperature was observed with addition of such small amount of water to LPG flame. Maximum temperature of 1092 °C was recorded at axial location 0.3 m away from burner indicating delayed formation of flame. High temperatures in region away from the burner were observed because of the fact that high concentration of unburned LPG was present in that region. By comparing figures 2b and 4b, it is evident that high temperature region in LPG combustion existed near burner and is stretched in axial direction while lower temperatures existed within flame region and flame region is started away from burner in case of water addition. Another interesting fact with lower peak temperature is that pollution emission may have been restricted as explained by Zeldovich [14].

![Figure 4](image.png)

Figure 4 Temperatures with water addition (a) axial temperature profile (b) temperature contours

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 5. 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 observed. 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. Higher contribution of water vapors in CHF restricted the decrease in THF. A comparison of RHF between the case of LPG+W and pure LPG combustion is also plotted in Figure 5. RHF 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.

**Effect of Alumina Nanoparticles Addition on LPG Combustion**
Alumina 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 (0.1, 0.35, 0.5 and 0.91%) of alumina nanoparticles were introduced into flame. Here and below, the mass percent values are used.

**Effect of Nanoparticles Concentration on Temperature**
A comparison of axial temperature profiles of 0.1, 0.35, 0.5 and 0.91% alumina suspensions with LPG and with LPG+W is shown in figure 6a, b, c and d, respectively. The temperature contours with the addition of above mentioned alumina suspensions are presented in figure 7a, b, c and d, 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 is 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 0.1% 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 that of case with LPG combustion in regions away from burner. Temperature contours for the case of 0.1% alumina are shown in figure 7a. Increase in area confined between isotherm lines of 903 to 993 °C shows that combustion process is more uniform in furnace.

Similar trend was observed with the addition of 0.35% alumina suspension to LPG combustion with a maximum temperature of 1076 °C was observed along axial location at 0.3 m away from burner. In comparison to case with 0.1% alumina suspension (a), slight increase in temperatures was observed because alumina nanoparticles may have provided some catalyst surface for water gas shift reaction, oxidizing CO with water. As a result of this oxidation, heat released and hydrogen may be produced which ultimately converted back to water and releasing
more heat [15]. Similar to the previous case (0.1% suspension), peak temperature was considerably lower as compared to LPG combustion but high combustion rate gave similar temperatures as that of LPG+W case. Temperature profiles in axial direction show slightly higher temperatures as compared to LPG but no difference was observed in comparison to the LPG+W case.

Figure 6 Axial temperature profiles with the addition of alumina nanoparticles suspensions of various concentrations (a) 0.1%, (b) 0.35%, (c) 0.5%, and (d) 0.91%.

Figure 7 Temperature contours with the addition of alumina nanoparticles suspensions of various concentrations (a) 0.1%, (b) 0.35%, (c) 0.5% and (d) 0.91%.
Relatively higher concentration (0.5%) of nanoparticles may have caused reduced velocity of air jet coming out of the atomization capillary. Reduced velocity ensue early ignition of LPG and flame initiated 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 6c. 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. Temperature contours with 0.5% alumina suspension is shown in figure 7c. In contrast to the early formation of flame, area between the isotherm lines of 903 to 993 °C is also higher as compared to that of LPG combustion indicating that alumina nanoparticles have been acting as catalyst for water gas shift reaction generating hydrogen and producing heat which resulted in higher temperatures [15].

A comparison of the axial temperature profiles between 0.91% alumina suspension with LPG and LPG+W combustion is shown in figure 6d. Introducing 0.91% nanoparticles suspension to LPG led to slightly higher axial temperature profile as compared to the case with 0.5% nanoparticle addition to LPG combustion. But, in near burner region, the axial temperatures are still lower than the temperatures of pure LPG. Flame started earlier as it was observed previously (in 0.5% suspension). Maximum temperature of 1181 °C was recorded at axial position of 0.2 m away from burner indicating existence of flame. Overall higher temperature in axial direction (from 0.3 m to 0.9 m) was observed because of the fact explained earlier. Temperature contours with the addition of 0.91% alumina suspension is shown in figure 7d. Extension in flame length was observed with addition of 0.91% alumina suspension to LPG combustion and higher temperature region is also stretched in both radial and axial direction.

**Effect of Nanoparticles Concentration on Heat Fluxes**

A comparison of THF and RHFF with the addition of 0.1, 0.35, 0.5 and 0.91% alumina nanoparticles suspensions to LPG combustion with corresponding fluxes obtained in LPG and LPG+W combustion is shown in figure 8a, b, c and d, respectively.

Addition of 0.1% alumina suspension to LPG combustion caused a slight decrease in THF in near burner region as compared to LPG and LPG+W combustion. But after the flame region, a slight increase in total heat flux was observed. Maximum THF (83 kW/m²) was recorded at port 4 where maximum flame width was observed. As discussed in previous section, flame was formed away from the burner that led to lower temperatures in region near burner, which led to lower heat flux. Strong dependence of RHF on temperature caused a significant decrease in RHF in that region (near the burner). Maximum decrease in RHF was observed at port 1 where ~15% decrease in radiative flux was observed. Higher temperatures in region away from the burner established higher THF with higher contributions of RHF. Heated surface of nanoparticles also contributed to higher RHF. It is well known that heated solid particles emit thermal radiation to all direction and emit a continuous radiation spectrum unlike water and CO₂ gases which radiate certain band of radiations [13]. This continuous band of radiation augmented radiative heat flux in region away from burner. Increased contribution of RHF led to slightly higher RHFF as compared to the case of LPG+W, while approaching to RHFF of LPG. Average RHFF was maintained at 0.56, higher than the case with water but still lower than that of the case with LPG combustion. A comparison of THF and RHFF for the case with 0.1% alumina suspension feeding to that obtained from LPG combustion is shown in Figure 8a.
The effect of 0.35% alumina suspension addition on heat flux is plotted in comparison to pure LPG and LPG+W combustion as shown in Figure 8b. Addition of 0.35% alumina suspension to LPG combustion ensued a slight decrease in total heat flux in flame region but marginally higher than the one obtained with 0.1% alumina suspension. Although the temperature is more or less same as that of the case for 0.1%, but higher THF was observed in comparison to that of 0.1%. The same trend was observed with lower value of THF in near burner region and became higher in region away from burner in comparison to LPG combustion. Maximum THF (83.5 kW/m²) was also observed at port 4 where maximum flame width was observed. Even with low temperatures in near burner region, THF is not significantly decreased. The presence of high concentration of nanoparticles is observed to lift up RHF. Maximum decrease in RHF was observed at port 1 where ~15% decrease in radiative flux was observed. Higher temperatures in region away from the burner resulted in higher THF with increased contributions of RHF. High concentration of nanoparticles contributed to higher RHF as discussed above. Higher contribution of RHF was recorded with average value of RHFF 0.59 which is higher as compared to the case of 0.1% and LPG.

![Figure 8](image)

**Figure 8** THF and RHFF profiles with the addition of alumina nanoparticles suspensions of various concentrations (a) 0.1%, (b) 0.35%, (c) 0.5% and (d) 0.91%.

A further increase in concentration of alumina nanoparticles caused a different behavior as compared to previously studied cases. A comparison of THF and RHFF with 0.5% nanoparticles loading rate to that of LPG and LPG+W is shown in Figure 8c. A significant increase in THF was recorded by increasing the suspension concentration to 0.5% of alumina. Early flame formation resulted in higher temperatures in region near burner as compared to the case with water feeding, although the peak gas temperature is still lower than that of the case with LPG. Lower peak temperatures have benefits for their lower pollution emission as explained earlier. Even with this lower peak temperature, THF has increased significantly. This increase in THF
was due to considerable higher contribution of RHF because of the high temperatures and high concentration of nanoparticles present in the furnace. Maximum THF was recorded (~93 kW/m²) at port 4 where maximum flame width was observed. 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.

With a further increase in nanoparticle concentration (0.91% alumina), the THF was profoundly increased in comparison to those obtained from the cases of LPG and LPG+W combustion as shown in Figure 8d. On the other hand, in comparison to 0.5% alumina suspension addition (figure 8c), only a slight increase in THF was recorded. Maximum THF was recorded along port 4 with a value of ~94.5 kW/m². RHF was significantly increased with increase of nanoparticle concentration with maximum enhancement of ~35.5% in RHF at port 3. As explained in previous case (with 0.5% alumina) early flame formation resulted in higher temperatures in near burner region as compared to the LPG+W combustion. Strong dependence of RHF on temperature led to enhanced contribution of RHF to THF with average value of RHFF rose to 0.65.

Conclusions
An experimental study was conducted to investigate the effect of noncombustible nanoparticle addition on radiative heat flux for gaseous fuel combustion in a lab scale furnace. Aluminum oxide (alumina, Al₂O₃) nanoparticles were added in the form of water suspensions to gaseous fuel combustion at varying concentration. Temperature and heat flux data was recorded and following results are concluded from this research work:

1- Lifted flame was observed because of high velocity jet of air coming from capillary used for atomization of liquid. Considerable lower peak temperature was observed with the addition of water and nanoparticle suspensions.

2- Increase in peak temperature was observed with increase in concentration of nanoparticle suspensions. Also, higher temperatures were observed with higher concentrations of nanoparticle suspensions throughout the furnace length.

3- For relatively dilute concentrations (0.1 and 0.35%), flame initiated after 0.2 m away from burner similar to the case with water addition. While with relatively dense concentrations (0.5 and 0.91%), flame initiated after 0.1 m away from burner similar to the case with LPG combustion.

4- Total heat flux was not reduced by addition of water however low contribution of radiative heat flux was recorded. Radiative heat flux contribution was increased by increasing alumina nanoparticles concentration.

5- Slightly low values of total heat flux were recorded in near burner region with dilute concentrations of nanoparticle suspension which became higher in regions away from burner.
Overall high total heat flux was recorded with relatively dense concentrations of alumina nanoparticles and a significant increase in radiative heat flux fraction was observed. High concentration of alumina nanoparticle suspension led to higher RHFF.

References


