CQUNIVERSITY RESEARCH

RESEARCH WITH IMPACT

EFFECT OF ENCLOSED FLAME ON SPRAY CHARACTERISTICS AND EMISSIONS FROM PREHEATED BIO-OIL USING AN AIR-BLAST ATOMIZER

HEENA PANCHASARAA, AJAY AGRAWAL

Bibliographic citation

Panchasara, H., & Agrawal, A. (2017). Effect of Enclosed Flame on Spray Characteristics and Emissions from Preheated Bio-oil Using an Air-blast Atomizer. *Energy Procedia, 110*, 216–222. https://doi.org/10.1016/j.egypro.2017.03.130

Link to Published Version: https://doi.org/10.1016/j.egypro.2017.03.130

If you believe that this work infringes copyright, please provide details by email to acquire-staff@cqu.edu.au

aCQUIRe CQU repository

This is an open access article under Creative Commons license.

Downloaded on 02/08/2022

Please do not remove this page

aCQUIRe

CRICOS: 00219C

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 110 (2017) 216 – 222

Energy Procedia

1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

Effect of enclosed flame on spray characteristics and emissions from preheated bio-oil using an air-blast atomizer

Heena Panchasara[a,*], Ajay Agrawal[b]

[a]*Department of Mechanical Engineering, School of Engineering and Technology, CQ University, Melbourne, Victoria 3000, Australia*
[b]*Department of Mechanical Engineering, School of Mechanical Engineering, The University of Alabama, Tuscaloosa, AL 35401, USA*

Abstract

Global atmosphere pollution has become a serious problem for today. The emissions from the combustion of fossil fuels contribute a notable part to this pollution. Given a wide spread of different biofuels available for combustion applications, the present study concentrates on atomization spray characteristics of vegetable oils. In this study preheated vegetable oil (VO) is used to reduce the kinematic viscosity, and thus, improve atomization. A commercial air-blast atomizer operated at ambient conditions of temperature and pressure is used to atomize the VO. Flame spray characteristics are measured using a laser sheet visualization system and a Phase Doppler Particle Analyzer system. Experiments are conducted for unheated and preheated VO at 100 °C for a given ALR of 2.0 in enclosed flame conditions simulate realistic gas turbine conditions. VO is combusted in an atmospheric pressure burner with air blast atomizer and swirling combustion air around. The mean axial and RMS velocities, SMD and drop size distribution data are acquired. The measurements are taken for preheated VO at 100 °C and 150 °C respectively. The transverse profiles of mean axial velocity showed peaks at the center while they showed a decreasing trend at the outer edges of the spray. RMS axial velocity increases for flame spray compared to cold spray. Higher VO inlet temperatures led to smaller droplets and higher mean axial velocity for a given ALR. Results also suggest that insulated enclosure provide additional heat feedback from the flame to improve the overall spray characteristics, an effect that has been quantified in the present study.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.

Keywords: Bio-fuels; Laser diagnostics; Spray measurements; Atomization; PDPA.

* Corresponding author. Tel.: +61409960230.
E-mail address: h.panchasara@cqu.edu.au

1876-6102 © 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.
doi:10.1016/j.egypro.2017.03.130

1. Introduction

Global atmosphere pollution has become a serious problem for today. The emissions from the combustion of fossil fuels contribute a notable part to this pollution. Environmental care together with the limited stock and growing prices of fossil fuels has given alternative fuels the potential to supplant a significant portion of fuel for combustion applications such as gas turbine engines and IC engines. Given a wide spread of different biofuels available for combustion applications, the present study concentrates on atomization spray characteristics of vegetable oils. Vegetable oils have energy density, cetane number, heat of vaporization and stoichiometric air/fuel ratio comparable to diesel fuel. Different ttechniques have been employed so far to improve on the physical properties of bio-oils and thus opening the doors to clean combustion. The high kinematic viscosity has an adverse effect on the combustion of vegetable oils, posing problems in the associated fuel supply line and injector system, as discussed in chapters 2 and 3. Some well-known techniques to deal with high kinematic viscosity levels of neat vegetable oils include dilution, pyrolysis, micro-emulsion and trans-esterification. These techniques however, require additional energy input to improve the physical properties of the fuel. Preheating of the fuel is also one of the ways that reduces the kinematic viscosity to improve the atomization. Preheating is employed in the present study to investigate the spray characteristics in a non-evaporating spray as well as flame spray. The atomization and subsequent propagation of the fuel droplets, their vaporization and combustion are the most important processes concerning the formation of pollutants with the use of liquid fuels. For example in diesel engines, gas turbine engines, and oil burners, the combustion rate of fuel is controlled by effective vaporization of the fuel. The liquid fuel atomization rate has a strong influence on vaporization rates because the total surface area of the fuel is increased greatly by the atomization process. The fundamental mechanisms of atomization have been under extensive experimental and theoretical study for more than a century [1]. Still, one of the major thrusts in worldwide combustion research has been to gain insight into the physics of liquid fuel combustion in the primary zone of the combustor [2].

Physical properties such as kinematic viscosity, surface tension and volatility are the key parameters that affect the process of fuel atomization and evaporation. The liquid kinematic viscosity affects not only the drop size distribution of the spray but also the fuel injector pressure drop. An increase in kinematic viscosity lowers the Reynolds number, hindering the development of any natural instabilities in the fuel jet or sheet, which help to further disintegrate the drops. These combined effects delay any further disintegration thus increasing the droplet sizes in the spray. Many alternative fuels are expected to have high kinematic viscosity which makes them difficult to atomize well and thus affecting the combustion efficiency.

A comprehensive study on turbulent diffusion flames using intrusive probing techniques was made by [3]. They suggested that the spray flame structure is similar to that of a gaseous diffusion flame in turbulent flow. The study conducted by [4], used a non-intrusive detection technique to measure the Sauter Mean diameter (SMD), drop velocity, and number density of air assisted spray and spray flames. A series of experimental and numerical studies of air assisted sprays and spray flames have been made by [5, 6]. Their observations concluded that the presence of fuel drops and reactions alters the structure of the gas-phase turbulence and that local clustering of drops exists for both non-reacting and reacting cases. A large portion of the experimental research in liquid fuel combustion is focused on pressure atomization mainly in the diesel engine applications. Relatively few studies have been reported on air blast atomization and their potential optimum strategies in alternative fuel combustion. Moreover, very little attention has been given to the evaporation characteristics of the air blast atomized sprays of alternative fuels. Detailed studies on the characteristics of spray flames are necessary to mitigate environment problems and enhance the performance and efficiency of liquid bio fuel combustion systems.

The present work seeks to experimentally investigate the spray characteristics of the fuel droplets in a non-evaporating as well as flame spray conditions using the Phase Doppler Particle Analyzer. An air blast atomizer is selected for the present investigation to generate the spray. The objective of the present work is to investigate the effects of combustion on enclosed spray flames of bio-oil for which little experimental data are available. Experiments are conducted using an insulated enclosure as well as VO heated at 100 °C and 150 °C. The mean axial and RMS velocities, SMD and drop size distribution data are acquired. The primary focus is placed on liquid fuel spray characteristics, and their effects on emissions. It can be envisioned that smaller droplets in the spray would lead to premixed combustion and hence lower emissions. The inferences from this study would aid in designing future liquid fuel combustors. Hereafter the details of the experimental set-up, results and discussion, and conclusions are presented in this study.

2. Experimental Setup and Procedure

Figure 1a shows the experimental setup with inlets for primary combustion air, atomizing air, and liquid fuel. The primary air entered the combustion system through a plenum filled with marbles to breakdown the large vortical structures. The primary air passes through a swirler into the mixing section, where gaseous fuel is supplied during the startup. Then, the primary air (or reactants) enters the combustor through a swirler with six vanes positioned at 28 ºC to the horizontal to produce swirl number of about 1.5. The bulk axial inlet velocity of the primary air varies from 1.9 to 2.1 m/s, which results in Reynolds number between 5960 and 6750.The combustor is 46 cm long pentagonal enclosure, shown schematically in Fig. 1b. The enclosure is made with two sides of quartz glass and remaining three sides of steel plates. The enclosure is insulated with four layers of Alumina blanket to minimize the heat loss to the surroundings. A small window of insulation, 10.2 cm by 10.2 cm, on the two quartz glass plates was removed for optical access. The primary airflow rate was measured by a laminar flow element with reported calibration error of ±5 liters per minute (lpm). The fuel temperature at the injector inlet was measured by a K-type thermocouple.

A 2D Phase Doppler Particle Analyzer (PDPA) was used to measure drop diameter and velocity simultaneously. PDPA is a point sampling device based on the light scattering interferometry principle. The laser beams from the transmitter probe intersect to form a sample measurement volume. The laser beam from a 2-W water-cooled argon-ion laser is separated into a pair of 514.5 nm green beams and a pair of 488 nm blue beams using a beam separator assembly. One beam of each pair is shifted by a 40 MHz Bragg cell. Facilitated by the pentagonal combustor design, the PDPA receiver is set at a constant angle of 144 degrees from the transmitter to collect the refracted light intensities from the spray. The detected signal is acquired by a data acquisition system, and analyzed using the TSI Flow Sizer software to obtain mean and RMS velocities, SMD, and drop velocity and 6 diameter distributions. Measurements are obtained by moving the PDPA system using a three way traversing system, while the combustor is kept stationary. PDPA system was traversed to acquire radial profiles at axial planes between from z = 5 mm and 40 mm in 5 mm intervals. Data rates of up to 30-40 kHz were obtained near the center of the spray, but they decreased to nearly zero as the detection volume approached the outer edge of the spray. Experiments were conducted for fixed VO flow rate of 12 mlpm. Atomizing airflow rate was kept constant at 25 lpm, which corresponds to air to liquid ratio (ALR) by mass of 2.5. The primary airflow rate was 125 lpm and the total airflow rate was constant at 150 lpm, which resulted in equivalence ratio of 0.79, also verified from oxygen and carbon dioxide concentration measurements in combustion products. Experiment was started with methane-air combustion before the liquid fuel was gradually introduced. Steady state was reached after two hours of continuous operation on liquid fuel, when the outer surface temperature of insulation was about 130 °C.

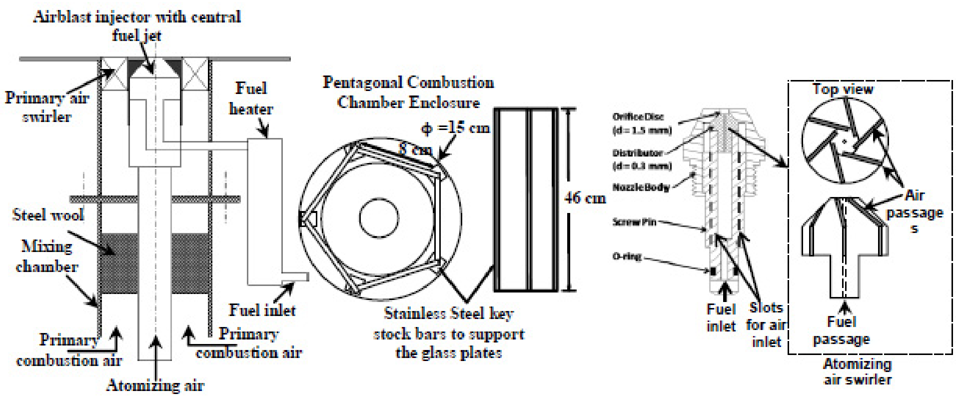


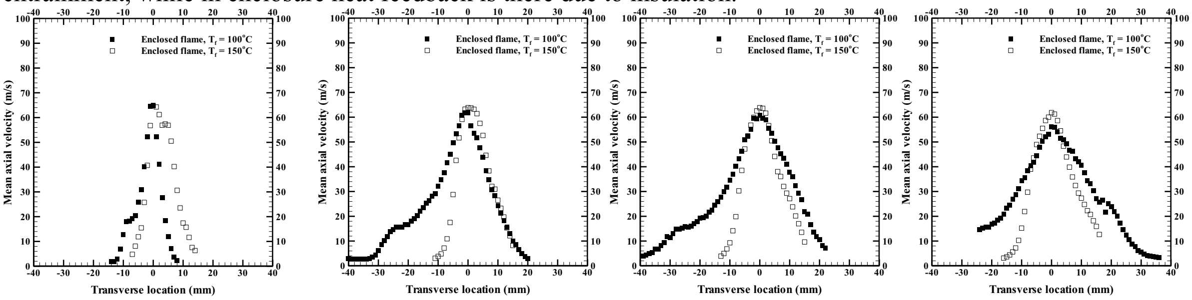
Fig. 1. (a) Experimental Set-up; (b) Pentagonal Combustor; (c) Fuel Injector.

3. Results and Discussion

Experiments were done to study the effect of enclosure on flame spray characteristics and combustion emissions. The enclosure was insulated to provide thermal feedback to the VO flame and maintain a stable VO flame during all experimental conditions. It required about 2 hours to preheat the enclosure with a stable VO flame before the methane flow rate was reduced to about 3.8 SLPM which corresponds to φ = 0.89. This mode of operation resulted in no condensation of the droplets on the glass window of the enclosure. Practically in the continuous combustion operations of gas turbine applications the enclosed flames are used, and hence the present work also incorporates insulated enclosure effect on the spray characteristics and emissions.

3.1. Transverse Profiles of Mean and RMS Axial Velocity

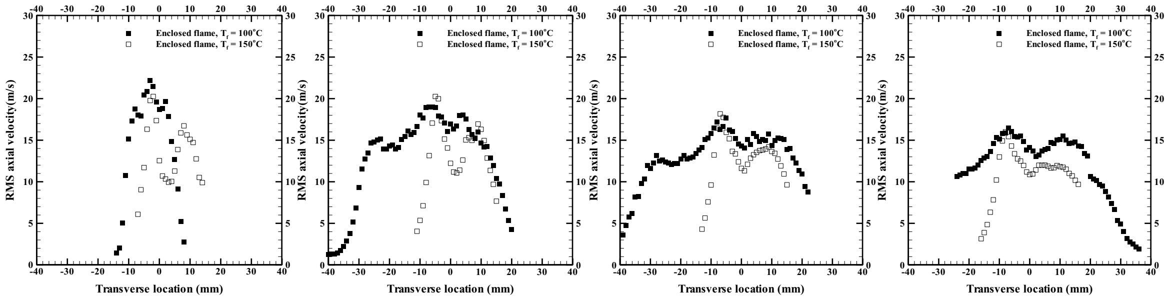
Figure 2 shows the mean axial velocity profiles for enclosed flames of VO preheated to 100 °C and 150 °C. As seen in figure 6 (a), at Y = 5 mm, mean axial velocity shows a peak at the center and gradual decrease towards the edge of the spray. The peak mean axial velocity for both cases is nearly the same. For both cases, the axial velocity peaks at 70 m/s, and both the profiles almost overlap each other, with slight difference towards the edge of the spray. At Y = 10 mm and 15 mm the profiles are again observed to be overlapping, although at higher fuel inlet temperature the spread of the spray is observed to be narrower as compared to VO at 100 °C. The transverse spray for VO at 100 °C is extended widely from -40 mm to 30 mm while for VO at 150 °C, the spread narrows down to a -15 mm 20 mm for Y = 5, 10 ,and 15 mm axially. Farther downstream, the peak axial velocity decreased down to 60 m/s for VO at 150 °C and 50 m/s for VO at 100 °C. Unlike velocities, a significant difference is observed in the droplet sizes as shown in the SMD profiles for the enclosed flame. In enclosure, the co-flow swirling air is the combustion air for the flame without any ambient entrainment. In open flame there is no heat feedback but there is a lot of ambient entrainment, while in enclosure heat feedback is there due to insulation.



(a) (b) (c) (d)

Fig 2.Transverse profiles of mean axial velocity for enclosed flame at axial location of (a) Y = 5 mm, (b) Y = 10 mm, (c) Y = 15 mm and (d) Y = 20 mm

Figure 3 shows the RMS axial velocity profiles for enclosed flame. For VO at 100 °C at Y = 5 mm, the peak RMS axial velocity is 22 m/s while for VO at 150 °C the peak RMS axial velocity is 20 m/s. For VO at 100 °C, the profiles show a local minima at the jet center line while double peaks at flame locations i.e. X = -30 mm to 15 mm, and Y = 10 mm to 35 mm. The magnitude of the RMS axial velocity range from about 2 m/s to 22 m/s for Y = 5 mm to Y = 35 mm. Comparatively for VO at 150 °C, the RMS axial velocity profiles looks more symmetrical with local minima dip in the centerline as well as double peaks on the flame locations. This result is attributed to the fact that the jet center is subjected to the small turbulent fluctuations with lower RMS values compared to that at the edge of the spray. Near the injector exit i.e. at Y = 5 mm to 15 mm, the peak RMS axial velocity for both the cases overlaps with no significant difference in the velocity values. At locations farther downstream, the peak RMS axial velocities for 150ºC are higher at X = 20 mm, indicating higher velocity fluctuations compared to VO at 100 °C.

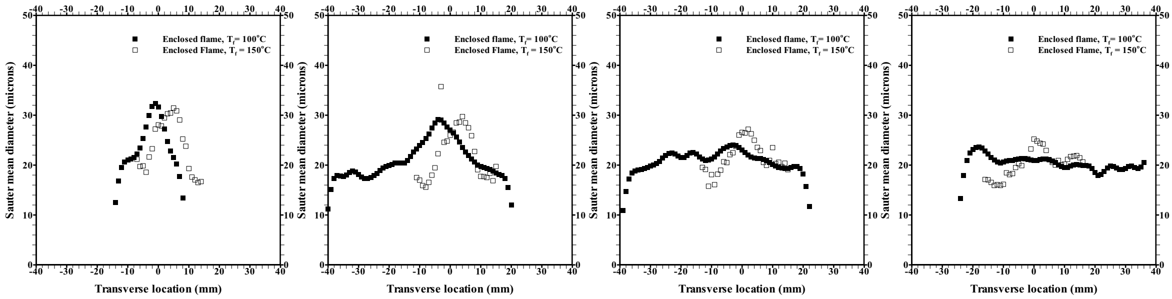


(a) (b) (c) (d)

Fig 3.Transverse profiles of RMS axial velocity for enclosed flame at axial location of (a) Y = 5 mm, (b) Y = 10 mm, (c) Y = 15 mm and (d) Y = 20 mm

3.2. Transverse Profiles of Mean and RMS Axial Velocity

Fig. 4 shows the transverse profiles of SMD for enclosed VO flame at 100 °C and 150 °C. Fig. 9 (a) shows the SMD profile at Y = 5 mm. The profiles show peak SMD value at the center of the spray. The maximum SMD for VO at 100 °C is 34µm, while for VO at 150 °C is 32 µm. At Y = 15 mm and 20 mm, the range of SMD values decreases. The profiles no longer show a well-defined central peak as compared to near the injector exit. SMD values range from 10 µm to 25 µm for VO at 100 °C while for VO at 150 °C the SMD ranges from 18 µm to 28 µm. Farther downstream, at Y = 25 mm to 35 mm, the larger droplets are observed to have moved towards the periphery of the spray causing higher SMDs at the outer edge of the spray as seen in figurer 10 (e and f).The profiles show a central depression as compared to central peak observed in the near injector locations (Y = 5 and 10 mm). For VO at 100 °C, the SMD ranges from 16 µm to 25 µm, which is larger compared to 18 µm to 22 µm for VO at 150 °C. For VO at 150 °C, the transverse distribution of SMD is narrower compared to VO at 100 °C. This result is attributed to the higher fuel inlet temperature and improved vaporization of the droplets thus reducing the SMD at downstream locations in the flame.

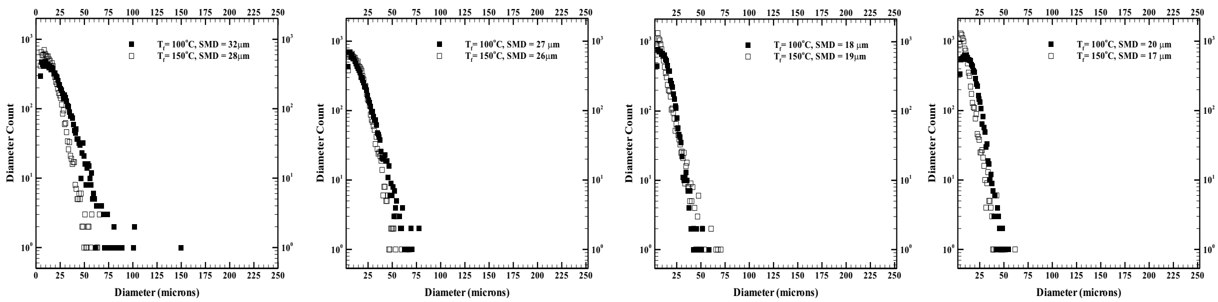


(a) (b) (c) (d)

Fig 4. Transverse profiles of SMD for enclosed flame at axial location of (a) Y = 5 mm, (b) Y = 10 mm, (c) Y = 15 mm and (d) Y = 20 mm.

3.3. Droplet Diameter Distribution Profiles

Figure 5 shows the droplet size distribution profiles for enclosed VO flame at 100 °C and 150 °C respectively. At Y = 5 mm, X = 0 mm, the largest diameter for VO 100 °C is 150 µm while that for VO at 150 °C is 60 µm. For VO at 150 °C, a narrow distribution profile is observed with greater number of smaller droplets. 90 % of the droplet sizes are in the range of < 50 µm. The presence of few large drops highly influences the SMD in case of lower fuel inlet temperature, i.e. VO at 100 °C. The SMD for VO at 150 °C is 28 µm while for VO at 100 °C is 32 µm. The lower fuel inlet temperature i.e. VO at 100 °C, has more large droplets compared to that for VO at 150 °C. The SMD for VO at 100 °C is 27 µm and for VO at 150 °C is 25 µm. Largest diameter for VO at 150 °C is of about 60 µm and for VO at 100 °C is of about 80 µm respectively.



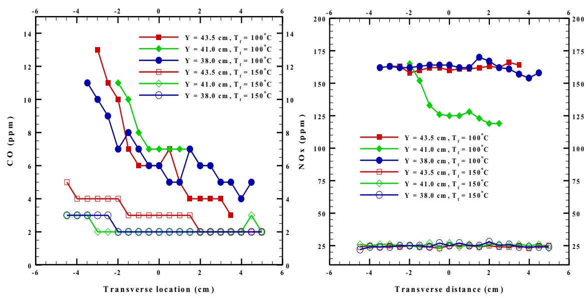
(a) (b) (c) (d)

Fig 5. Droplet Distribution Profile for Enclose Flame (a) Y = 5 mm, X = 0 mm, (b) Y = 10 mm, X = 0 mm, (c) Y = 30 mm, X = 0 mm and (d) Y = 35 mm, X = 0 mm

The respective SMDs for both the cases are 20 µm and 18 µm which are influenced by the presence of few large droplets in the case of VO at 150 °C. At Y = 35 mm, X = 0 mm, the largest diameter for VO at 150 °C is 60 µm whereas for VO 100 °C is 55 µm. The respective SMDs for both the cases are 16 µm and 20 µm, which is attributed to the fact of larger percentage of smaller droplets for higher fuel inlet temperature i.e. VO at 150 °C compared to that of lower fuel inlet temperatures. As the axial distance increases the droplet distribution is observed to be narrower and also more number of smaller droplets is observed for both the cases. Comparatively the higher fuel inlet temperature shows improved atomization with higher percentage of smaller drops compared to that of lower fuel inlet temperature.

3.4. Effect of Enclosed Spray on Combustion Emissions

The emissions of CO and NOx were measured for three different axial locations in the flame. The radial profiles are plotted for axial locations at Y = 43.5 cm, 41.0 cm and 38.0 cm. Figure 6(a) shows the CO profile for VO at 100 °C and 150 °C at Y = 43.5 cm, 41.0 cm and 38.0 cm at the combustor exit plane. At 100 °C, the CO emissions are seen to be higher on negative transverse location of the flame as compared to positive transverse location as seen in the plot. The CO emissions for VO at150 °C range from 2 to 5 ppm while those of VO at 100 °C range from 4 to 12 ppm. The CO emissions show a minor decreasing trend in axial direction but mostly they are in similar range. The decrease in emissions for VO at 150 °C is about 8 ppm compared to VO at 100 °C, which is attributed to the smaller droplet diameter for flame with higher fuel inlet temperature. Figure 6(b) shows the NOx emissions profile at the aforementioned axial locations in the flame. A significant reduction in NOx emissions is observed for VO at 150 °C compared to VO at 100 °C. The NOx emissions for VO at 150 °C are constant at about 25 ppm, whereas for VO at 100 °C, the NOx emissions are significantly higher, in the range of 120 ppm to 160 ppm. Spray droplet characteristics cannot be directly compared to the emissions, since the emissions data were taken at the axial locations farther downstream near the combustor exit plane. Most of the droplets were consumed and vaporized in the flame and the PDPA system could not detect the droplets, because of the low data rate after Y = 40 mm. near the injector exit, the CO emissions could not be measured because it was not possible to quench the reactions consuming CO.



(a) (b)

Fig 6. Effect of fuel preheating on VO flame emissions (a) Transverse profiles of CO, and (b) Transverse profiles of NOx.

4. Conclusion

The effect of enclosed flame was seen on two different fuel inlet temperatures with higher fuel inlet temperature producing finer droplets lowering the SMD, increasing the mean and RMS axial velocity. The insulated enclosure helped to provide heat feedback which enabled the PDPA measurements avoiding any fuel condensation in the measurement area. The confinement of the flame due to enclosure reduced the radial spread compared to open flame conditions. There was no significant difference in the mean axial velocities and SMD values. Based on this study we conclude that the smaller drop size distribution results in lower emissions of CO and NOx. Larger droplets tend to burn in diffusion mode compared to finer drops that lead to premix mode of combustion. Larger droplets that are burning in diffusion mode results into higher local temperatures and higher flame temperatures result in increase in NOx and the more likely chances of fuel pyrolysis, fuel coking problems and fuel decomposition resulting in higher CO emissions. It can be seen from the present investigation, that the flame environment enhances the reduction of droplet size and smaller droplet size distribution, significantly altering the mixing and entrainment due to high flame temperature, as well as faster fuel vaporization as a secondary effect of high temperatures consuming larger droplets. A significant change is not observed in the SMD and axial velocity for open and enclosed flame because of the addition of large amount of methane to sustain a stable VO flame in open conditions which results, in significant heat feedback in the near field region of the flame spray, thus neutralizing the influence of the insulated enclosure, effect that is observed in other cases.

Acknowledgements

This work was supported in part by The University of Alabama and Alabama Institute for Center for Manufacturing Excellence.

References

[1] Liu, A.B., and Reitz, R.D., Mechanisms of Air-Assisted Liquid Atomization. Atomization and Sprays 1993; Vol. 3, p. 55-75.
[2] Kneer, R., Willmann, M., Zeitler, R.,Wittig,S., and Collin, K.H., Phase Doppler Particle Sizing Inside a Gas Turbine Combustor. International Journal of energetic Materials and Chemical Propulsion 1993; Vol. 3, p.301-312.
[3] Onuma Y., Ogasawara, M., Studies on the structure of a spray combustion flame. Symposium on Combustion 1975; Vol 15, p.453-465
[4] Chigier,N.A., McCreath, C.G., Combustion of Droplets in Sprays 1974; Vol.1, I 5-6, p.687-710
[5] McDonell, V. G. and Samuelsen, S., Gas and Drop Behavior in Reacting and Non-Reacting Airblast Atomizer Sprays. Journal of Propulsion and Power 1991; Vol. 7, p. 684-691.
[6] Faeth, G. M., Hsiang, L.P., and Wu, P.K., Structure and Break-up Properties of Spray. International Journal of Multiphase Flow 1995; Vol. 25, p. 99-127.
[7] Gañán-Calvo, A. M., Enhanced Liquid Atomization: From flow-Focusing to Flow Blurring. Applied Physics Letters 2005; Vol. 86, p. 2141-2143.
[8] Lasheras, J. C., and Hopfinger, E. J, Liquid jet instability and atomization in a coaxial gas stream. Annual Review Fluid Mechanics 2000; Vol. 32, p. 275-308.