Proceedings of ICTACEM 2014
International Conference on Theoretical, Applied, Computational and Experimental Mechanics
December 29-31, 2014, IIT Kharagpur, India
ICTACEM-2014 (No. 335)

An experimental study on droplet combustion of different fuels and biofuel blends in open atmosphere

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ABSTRACT

The current trend in aviation field is the use of alternative fuels (biofuels) or their blends with aviation kerosene, because of the fluctuations and increase in fuel price and also for reducing HC and CO emissions. Fuel is supplied into the combustion chamber in the form of fine droplets. Droplet combustion experiments give deeper understanding about the burning behaviour, efficiency and other properties of fuels. The present study focuses on the blending of petrol (gasoline), diesel and kerosene with biofuels like ethanol, and butanol. Base fuels blended with 5%, 10% and 20% by volume of ethanol and butanol is used in this study. The experimental result shows that butanol and ethanol blending improved the burning characteristics of base fuels. Diesel and kerosene have shown improvement in burn rate, whereas the burn rate of petrol (gasoline) is reduced by blending. We also observed micro explosions during droplet burning, and their intensity increasing with blending ratios. These micro explosions are due to the volatility difference between the base fuel and the blend and they improve the burn rate of diesel and kerosene. The results also showed improvement in droplet temperature distribution with blending.

Keywords: Droplet Combustion, Blending, Biofuels, Burn rate

1. INTRODUCTION

Due to depletion of fossil fuels and their impact on the environment, especially green-house-gas (GHG) emission, renewable energy sources are getting significant attention. The present energy system is not sustainable because of equity issues along with environmental, economic, and geopolitical concerns [1]. Liquid biofuels are important because they are derived from renewable feedstocks and may replace petroleum fuels (or at least reduces the dependency on them) in the future.

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The generally used biofuels are ethanol derived from sugar, starch or non-food sources such as switch grass, and butanol. Butanol can be produced from a variety of biomass and it has higher energy content, volatility of gasoline, non-corrosive nature, and knock resistance [2]. Hansen et.al [3] found that 10% or less ethanol blending makes no significant difference in the performance of diesel engines. While studying the synergistic droplet combustion of ethanol blended diesel and bio-diesel, Botero et.al. [4] observed micro explosions which are stronger for biodiesel-ethanol mixture. Blending also reduced gasification time and soot formation. Abdel-Rahman et.al [5] observed that ethanol-gasoline blending improved the SI engine performance, power and compression ratio. This effect is predominant for 10% and more ethanol blend. Hsieh et.al [6] studied the effect of ethanol-gasoline blends on the performance and pollutant emission of SI engines and found that ethanol blending increased the octane number and vapour pressure of the fuel. They also observed an increase in torque and fuel consumption. A dramatic reduction in CO and HC and increase in CO_2 indicated improved combustion. He et.al [7] also observed similar results in their study on EFI engine emission characteristics with ethanol blends. Considering SI engine performance and CO emission levels, Bayraktar [8] experimentally recommended a 7.5% ethanol blending against a theoretically predicted 16.5%. Hasan’s [9] study showed that 20% ethanol blending with gasoline gives best engine performance parameters such as increase in brake power, torque, volumetric and brake thermal efficiencies and combustion efficiency.

Several extensive studies have been performed on the use of biofuels in SI and CI engines. However, the interests in the use of biofuels in gas turbine engines are recent. McNamara [10] showed that a gas turbine engine could be run with pure ethanol. Hemighaus et al. [11] studied the viability of different alternative fuels, such as ethanol, methanol, and fatty acid methyl esters for gas turbine use. Biodiesel droplet has a longer ignition delay and it also has a higher flame temperature, burn rate and shorter burn out time than the diesel fuel droplet [12]. The biofuels blending matched the sooting propensity and soot standoff ratios of Jet-A fuel better, but also it cannot show certain features of the Jet-A fuel such as Flame standoff ratios and burning rates [13]. The burning rate of both oxygenated and hydrocarbon fuels are similar [14] and some result shows that the methanol fuel flame is lying near the stoichiometric mixture fractions [15].

Droplet burning will give a detailed understanding of combustion phenomena of the fuels. The primary goal of this study is to understand the effect of ethanol and butanol blending on the burning behaviour of fuel droplets.

2. EXPERIMENTAL SETUP

Hundreds of components in hydrocarbon fuels make the theoretical analysis complicated. Experimental studies are widely used for obtaining the evaporation rate and burning characteristics of such fuels and their blends. An open atmospheric test facility as shown in Fig-1 was used for the droplet combustion. Droplets with a volume of 5 microliter were generated using an Eppendorf Multipette M4. Quartz fiber of about 0.1 to 0.3 mm diameter was used to hold the droplet since it has a minimum thermal conductivity and intrusion. The droplets were ignited using a 26 gauge kanthal wire, which was heated up by using a Variac. A digital camera of 25 fps and 1 MP was used for image capturing and the images were analyzed using the image processing application in Matlab. Petrol, diesel and kerosene were selected as the base fuels and the biofuels, butanol and ethanol, were used for blending. Based on the literature, blending ratios of 5%, 10% and 20% were chosen for our study. All the samples prepared had a volume of 5 millilitres and all the experiments were conducted in the quiescent atmosphere at standard atmospheric conditions.

The burning rate was calculated using the well-known D^2 –law,

$$\left(\frac{D}{D_0}\right)^2 = 1 - K\left(\frac{t}{D_0^{\,2}}\right) \tag{1}$$

where D-diameter of the droplet in mm, D_0-initial diameter of the droplet in mm, K-burn rate/evaporation rate, t- time in seconds. The droplet is kept on a horizontally placed quartz fiber and the droplet diameters were calculated from images using the relation (2) [16],

$$D = (D_h^{\,2} D_v)^{\frac{1}{3}} \tag{2}$$

where D_h -horizontal diameter of the droplet, D_v -vertical diameter of the droplet.

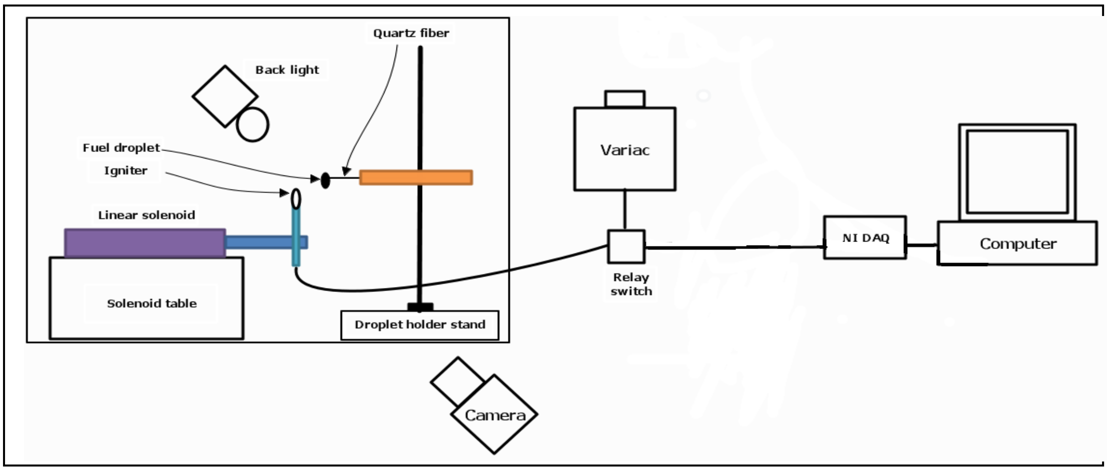

Figure 1: Experimental set up.

A 0.3 mm bit thermocouple was used for the droplet temperature measurement. For the flame study and droplet temperature measurement, we have used a 4 microliter volume droplet since it was not possible to hold the 5 microliter droplet on to the thermocouple bit. The colour images of droplet burning sequence give the details of micro explosions.

3. RESULTS AND DISSCUSSION

3.1. Evaporation of Single Component Fuel Droplet

A single component evaporation study has been carried out on ethanol and butanol before proceeding to the detailed study of the multi-component droplet burning. The evaporation study was performed in a quiescent atmosphere with 303 K and 1 atm pressure with a volume of 5 microliter, same as the volume used in the multi component study. From Fig-2, we can see that ethanol has a higher evaporation rate than butanol. Also, ethanol evaporation was numerically analyzed by a simplified rapid mixing model [17].

Evidently, ethanol blended fuels could have a higher evaporation rate than the butanol blended ones. Numerically calculated evaporation rate for ethanol is in good agreement with the experimental results, as shown in Fig-3.

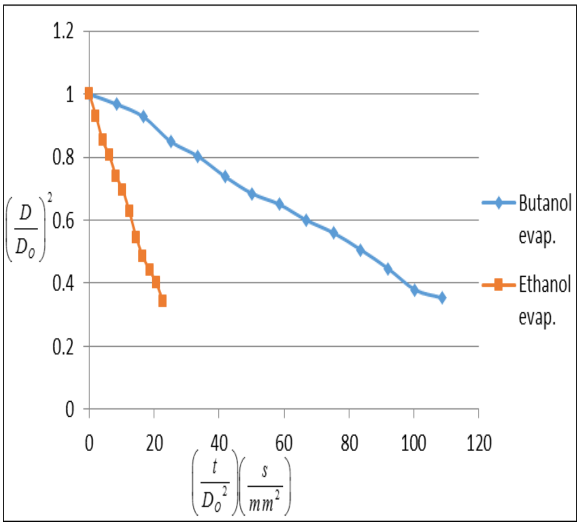

Figure 2: Ethanol and butanol evaporation curve (experiment)

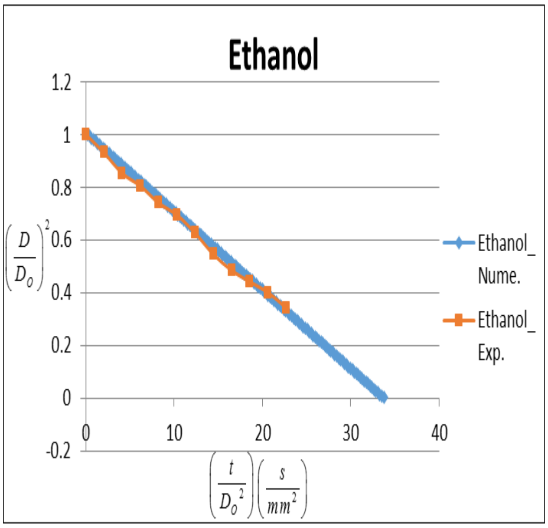

Figure 3: Ethanol evaporation curve (experiment and numerical comparison)

3.2. Evaporation and Burning of Multi-component Fuel Droplet

Case-1. Diesel and its blends

For ethanol blending, a maximum burn rate is observed with 20% blending (Fig-4 and Fig-6). For butanol blending, it corresponds to 10% blending (Fig-5 and Fig-7). Maximum increment in burn rate is around 45% for ethanol blending and 36% for butanol blending. Micro explosions and boiling were observed during the experiments. This is due to the rapid heating of volatile content in the mixture leading to an increase in internal pressure in the droplet [18]. The intensity of micro explosions increased with the blending ratios for both butanol and ethanol leading to the increased burn rate of diesel blends. From the burning sequences, (Fig-10), it is evident that micro explosions are stronger and continuous for higher blending ratios. For same blending rations, micro explosion intensities are higher for ethanol blending compared to that of butanol blending. Hence ethanol blends exhibit a higher burn rate compared to that of butanol blends. The droplet temperature distributions for all the blends are shown in Fig-8 and Fig-9. For diesel-ethanol and diesel-butanol blends, the maximum droplet temperature obtained decreases with increase in blending ratio.

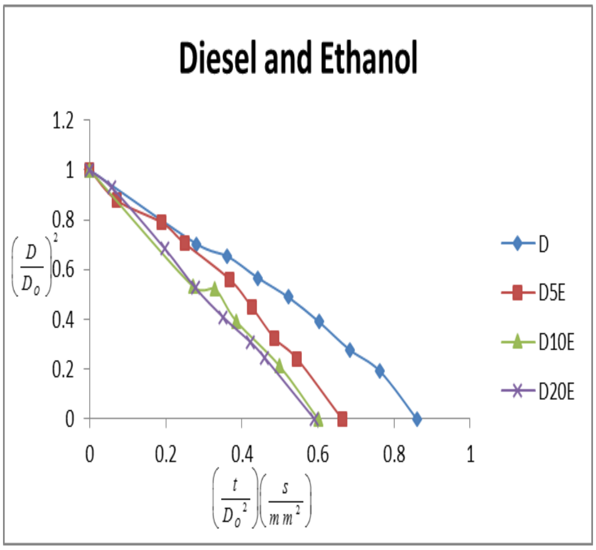

Figure 4: Evaporation or Burn rate curve

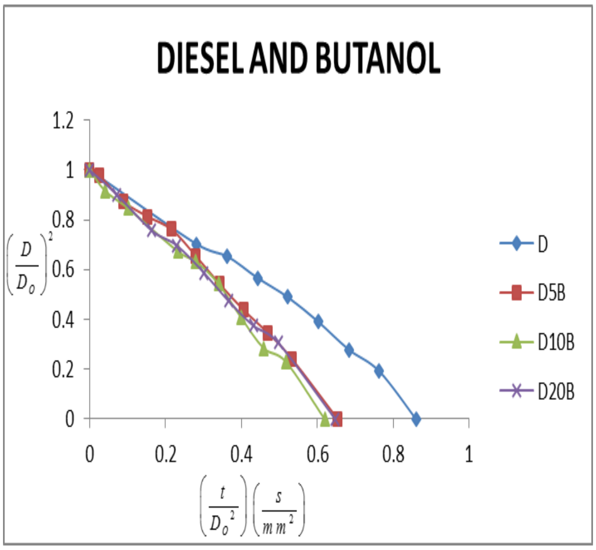

Figure 5: Evaporation or Burn rate curve

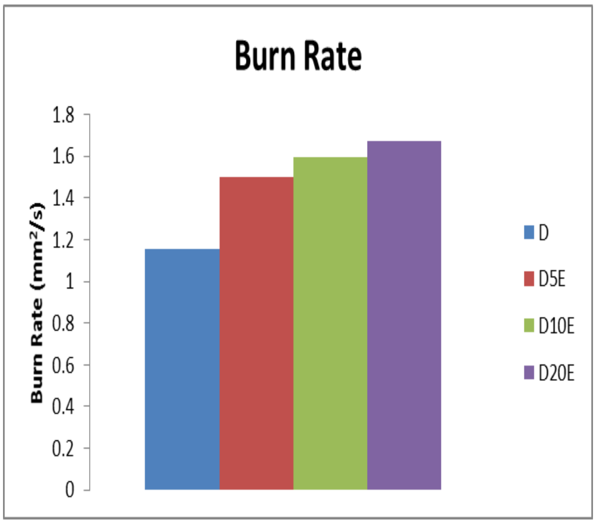

Figure 6: Evaporation or Burn rate (diesel and ethanol blending)

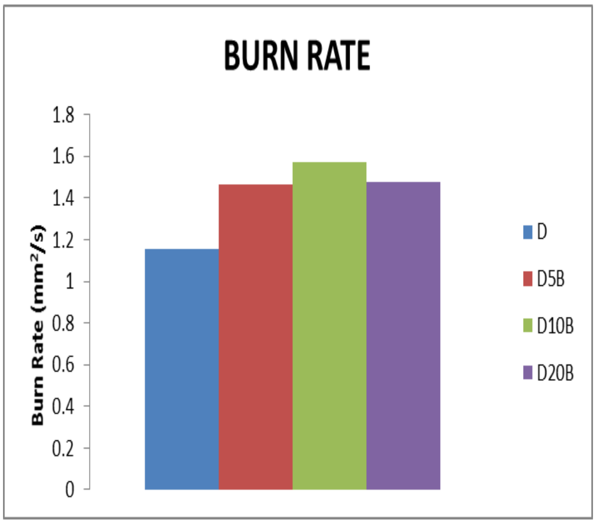

Figure 7: Evaporation or Burn rate (diesel and butanol blending)

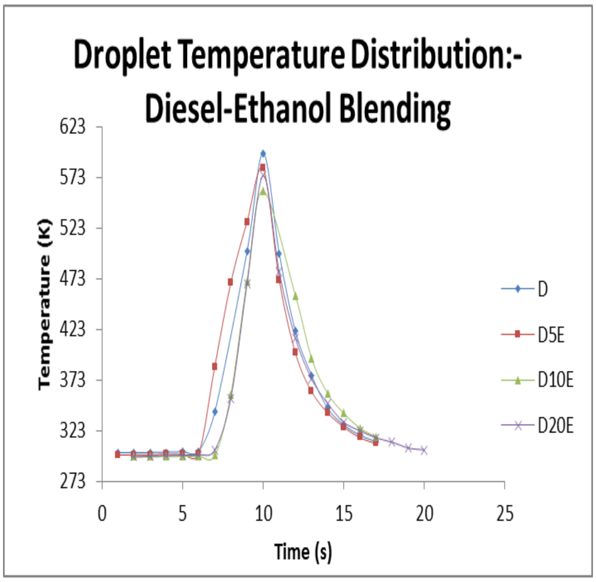

Figure 8: Droplet temperature distribution

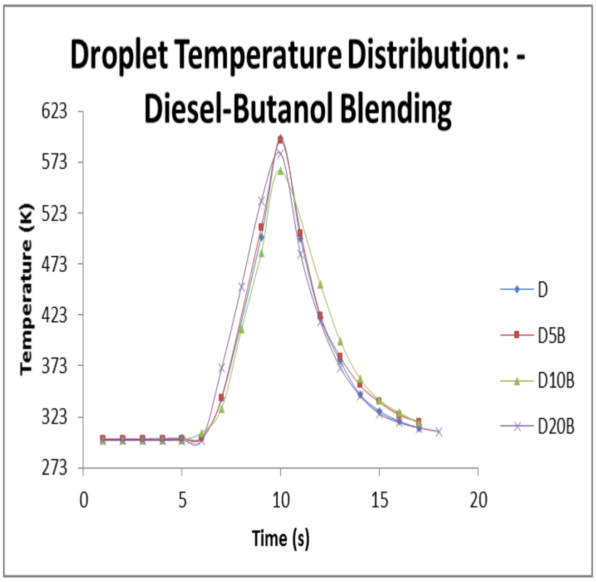

Figure 9: Droplet temperature distribution

Diesel

D5B (5% butanol blend)

D5E (5% ethanol blend)

D10B (10% butanol blend)

D10E (10% butanol blend)

D20B (20% butanol blend)

D20E (20% ethanol blend)

Figure 10: Droplet burning sequences of diesel and its blends

Case-2. Petrol and its blends

The burn rate of petrol decreases with both ethanol and butanol blending. Burn rate decreases with an increase in the blend ratio for both ethanol and butanol (Fig-11 to Fig-14). The maximum reduction in burn rate is 29.6% for butanol blending and 17.325% for ethanol blending. Fumes and soot during burning were reduced by blending. Micro explosion intensities were smaller compared to diesel and kerosene.

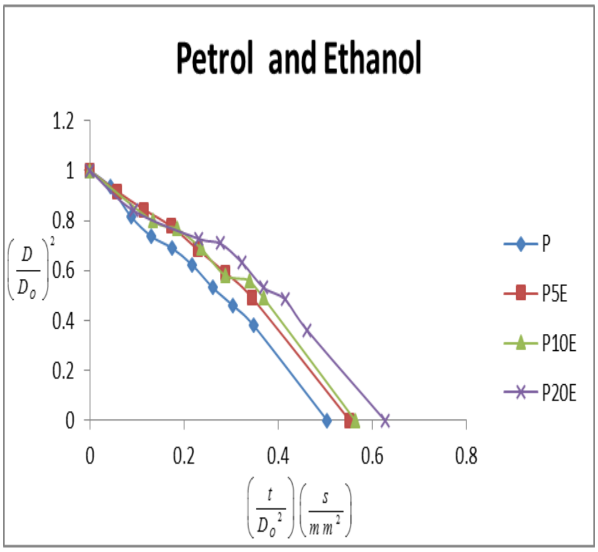

Figure 11: Evaporation or Burn rate curve

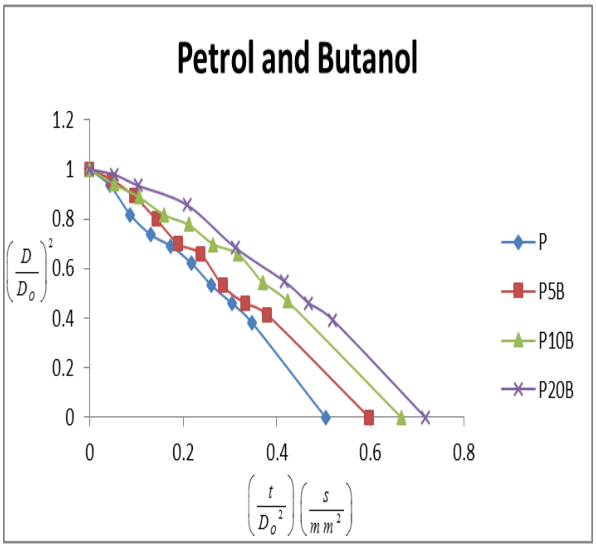

Figure 12: Evaporation or Burn rate curve

As in the case of diesel and kerosene blends, the droplet temperature distribution is steep and maximum temperature is lower for petrol blends (Fig-15 and Fig-16). Micro explosion intensity increases significantly with blending ratios for ethanol blending (Fig-17).

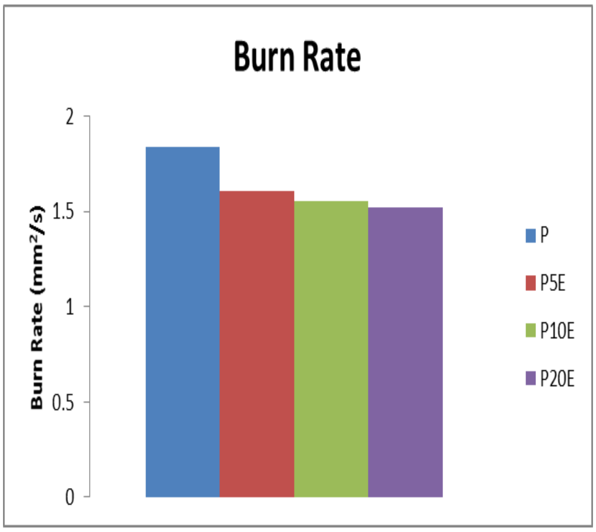

Figure 13: Burn rate (ethanol blending)

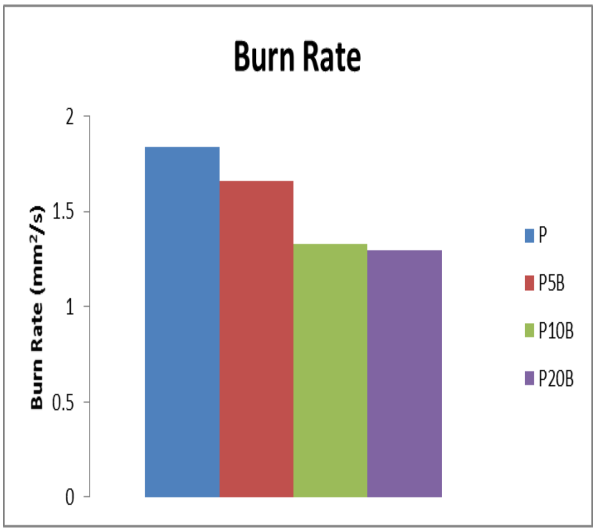

Figure 14: Burn rate (butanol blending)

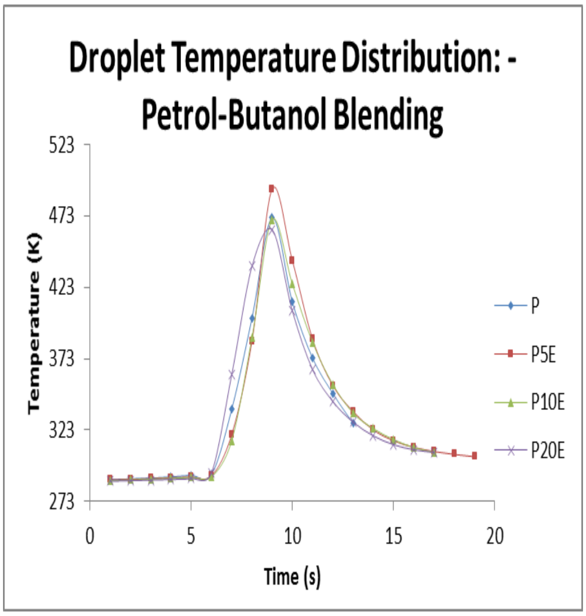

Figure 15: Droplet temperature distribution

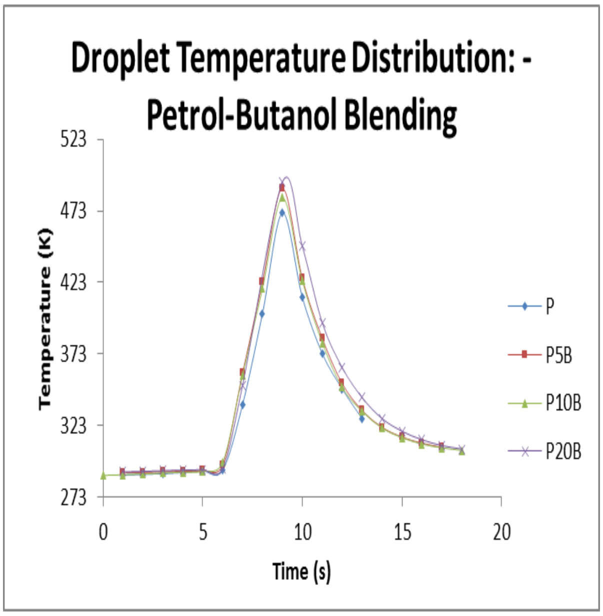

Figure 16: Droplet temperature distribution

Petrol (gasoline)

P20B (20% butanol blend)

P20E (20% ethanol blend)

Figure 17: Droplet burning sequences of petrol (gasoline) and its blends

Case-3. Kerosene and its blends

Both ethanol and butanol blending improved the burn rate (Fig-18 and Fig-20). The burn rate improvement is found higher for the 10% blending and an improvement of burn rate by 18.3% for butanol and 4.45% for butanol additions (Fig-19 and Fig-21).

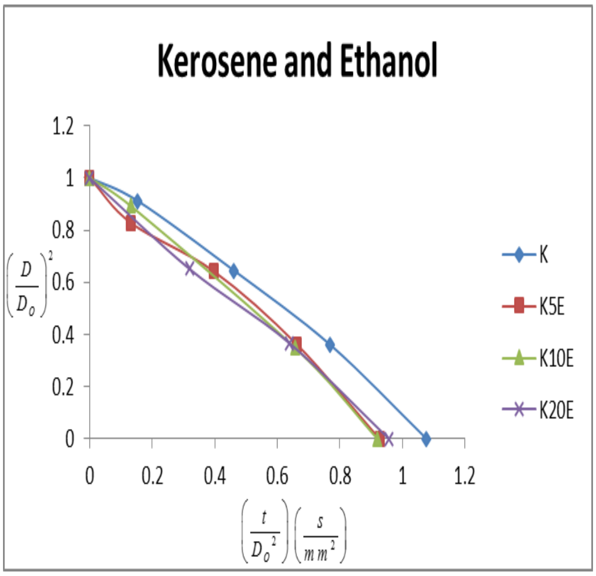

Figure 18: Evaporation or Burn rate curve

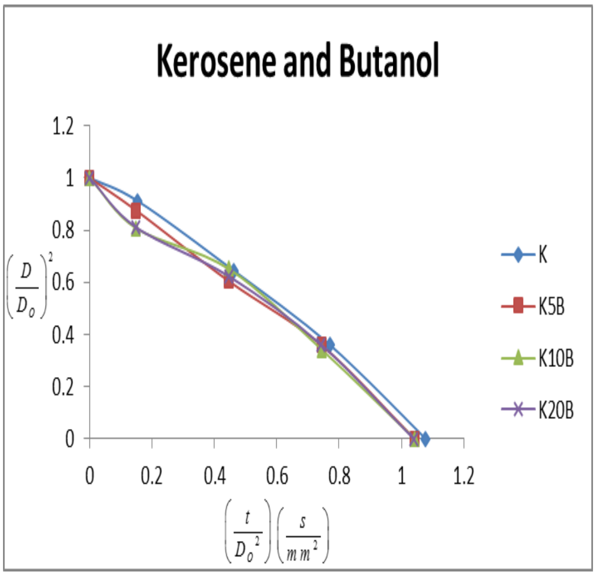

Figure 19: Evaporation or Burn rate curve

20% blending shows a reduction in the burn rate for both blends. The droplet temperature distribution for various blend ratios is shown in Fig-22 and Fig-23. The burning sequence (Fig-24) shows micro explosions, as in diesel blends, but with reduced intensity.

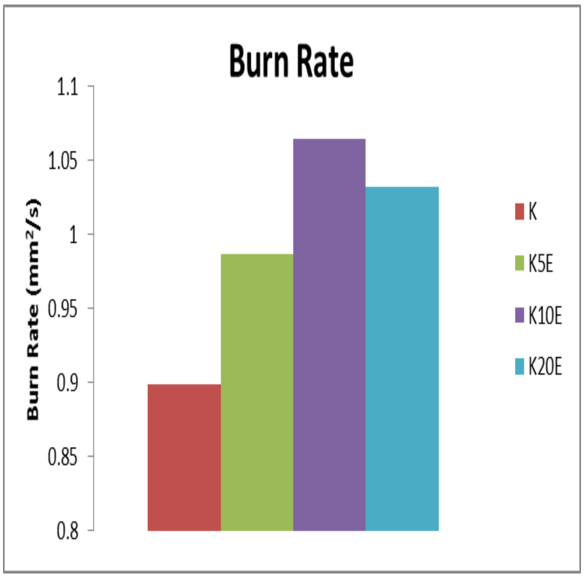

Figure 20: Burn rate (ethanol blending)

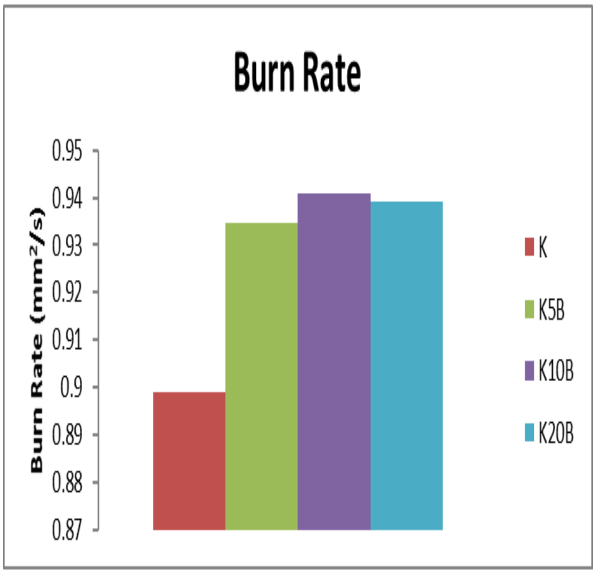

Figure 21: Burn rate (butanol blending)

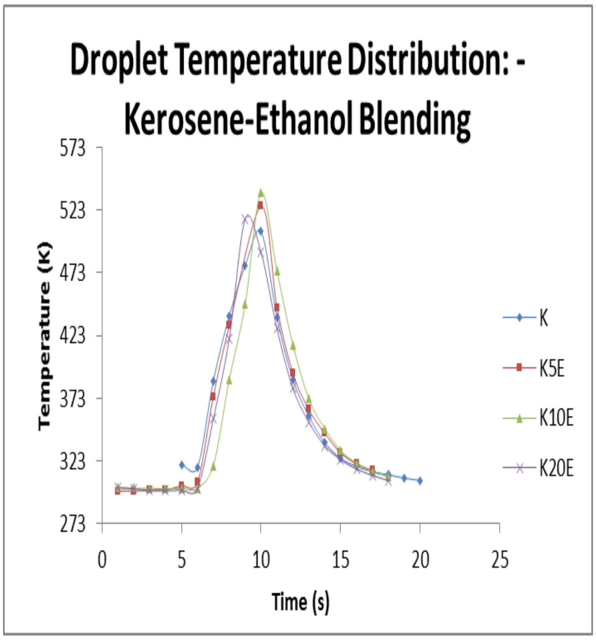

Figure 22: Droplet temperature distribution

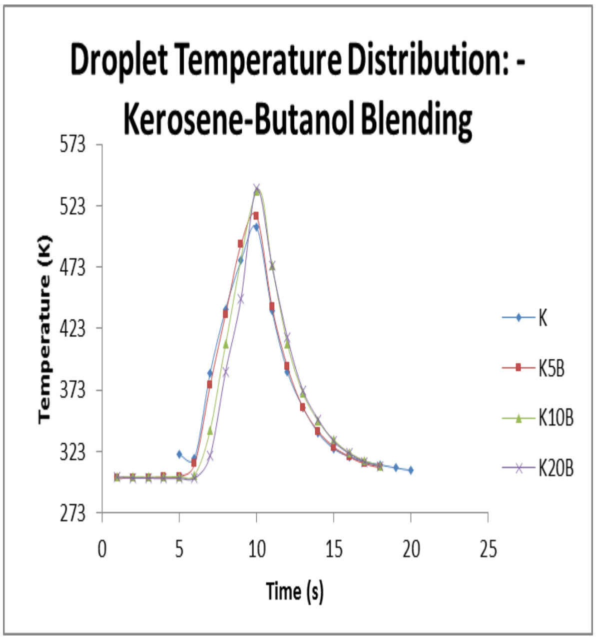

Figure 23: Droplet temperature distribution

Kerosene

K10B (10% butanol blend)

K10E (10% butanol blend)

Figure 24: Droplet burning sequences of kerosene and its blends

4. CONCLUSIONS

Both experimental and numerical analysis of single component evaporation is in good agreement. The burn rate of kerosene and diesel improved with ethanol and butanol blending. The ethanol blends show better burning characteristics compared to that of butanol blends. At higher blending ratios, the burn rates are higher which in turn reduces the burning time. In the case of petrol (gasoline) the burn rate gets reduced with both ethanol and butanol blending. This may be due to ethanol and butanol having a higher volatility than the petrol (gasoline). The droplet temperature distribution also shows an improvement with blending. The micro explosions are more intense in the case of ethanol blending leading to a higher burn rate compared to that of butanol blending. The micro explosions are stronger for diesel and kerosene blends compared to the petrol blends because of volatility difference.

ACKNOWLEDGMENTS

The authors would like to acknowledge their sincere thanks to the Department of Aerospace Engineering, IIT Kharagpur for providing facilities and support for the work.

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