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Experimental study of burning of methanol fed porous spheres in grid generated turbulent field

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ABSTRACT

Experimental investigation of the effect of flow turbulence on the steady state burning of methanol is reported. A vertical air tunnel has been mounted with a grid at its exit plane in order to generate turbulence in the free jet stream. The flow field has been characterized using a hot-wire anemometer. Mean and fluctuating flow velocities and integral scale have been measured at an axial location of around 2 times its exit diameter (*D*). Three types of grids have been used. Classical porous sphere experiments have been carried out to analyze the steady-state burning rate of methanol over the surface of an inert sphere having constant diameter. Experiments have been done at atmospheric pressure under ambient temperature and normal gravity conditions. A porous sphere is positioned at an axial location of 2*D*, where the approaching flow has been characterized in detail. Results show that the burning rate as well as the flame stability are greatly influenced by the free stream turbulence. The ratio of turbulent time scales and the chemical time scales for grid mounted cases have been estimated from the integral scale, root mean square velocity fluctuation, flame stand-off distance and the vapor blowing velocity. Empirical expression relating the normalized burning rates to diffusion scale based Damköhlar number has been presented. A correlation for Sherwood number as a function of Reynolds number and turbulent intensity has also been proposed.

1. Introduction

An important process to be carried out before using a liquid fuel in an engine or burner is to characterize its vaporization and burning behavior. This forms an important step especially when new/alternative fuels are to be used. Such tests have to be carried out in different environmental conditions such as at different pressures, temperatures and convective conditions, including the turbulent regimes. Vaporization and burning studies under steady state conditions can impart thorough knowledge of the fuel characteristics under different environmental conditions. Based on this background, in the present study, porous sphere burning experiments have been carried out in a turbulent flow field at atmospheric pressure condition and normal gravity. Porous sphere experiment reveals the steady burning characteristics of liquid fuels under different convective conditions considering different sphere sizes. Experimentalists have come up with numerous techniques such as porous sphere technique [1], freely falling droplet [2], suspended droplets [3], and free falling chamber [4] to analyze the vaporization and combustion of isolated liquid fuel particles. An extensive review on this subject has been reported by Williams [5]. The general approach in these studies were to use larger particle sizes and lower convective air velocities as opposed to a spray environment, where, particle/droplet sizes are quite small and they travel at higher velocities. The general practice has been to keep the Reynolds number, calculated based on particle diameter and air velocity, almost the same in isolated particle experiments and in engines. Literature reporting burning of isolated liquid fuel particles in a turbulent flow field is scarce.

Using grids, perforated plates and jet actuators are some of the methods used to generate quantifiable turbulence in a flow field [6]. Grid generated turbulence has been an important area of research for several decades [7–9]. Despite the strong inhomogenous character very close to the grid, at a distance 40 or 50 times grid size, the turbulent flow became almost homogeneous and isotropic. Further, introduction of a contraction downstream of the grid improved the degree of isotropy. An extensive review of the flow through screens and wire gauzes has been reported by Laws and Livesey [10]. Mohamed and Laure [11] studied the sensitivity of decay exponent, decay co-efficient and virtual origin in the decay power law for grids with bi-planar square and circular cross sections as a function of parameters such as Reynolds number, solidity, rod cross section and surface roughness. It was found that

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the decay exponent and virtual origin were independent of these parameters, however, the decay co-efficient was highly dependent on these parameters. The skewness $S(u) = \left(\overline{u'^3}/\overline{u'^2}\right)^{1.5}$ was experimentally determined along the longitudinal axis along the flow. Skewness tends to zero when the turbulence in the flow is isotropic.

A study, similar to the configuration employed in the present one, was reported by Lehman et al. [12]. They investigated the modification in the characteristics of a circular jet by placing two types of grids, namely, annular and disc grid, at the nozzle exit plane. They quantified the flow using a single wire hot wire anemometer. They found that the presence of annular mesh reduced the shear layer width as well as the turbulent intensity of the flow upstream. There was also evidence of the formation of organized structures in the jet mixing layer. In contrast, such variations were weakly present in the jet with disk grid. Their jet exit Reynolds number was around 3.4×10^5. Stephans et al. [13] carried out a similar study for an axisymmetric shear flow behind a honey comb structure. They employed the honey comb structure as a passive flow control device at the exit plane of a circular jet nozzle for the same Reynolds number of that of Lehman et al. [12], and observed similar results. Recently, Senthil et al. [14] studied the effects of grids on the evolution of turbulence in round jets. They found that the transition to an equilibrium turbulence is much quicker when grids were employed in the jet stream.

Steady state evaporation and burning of liquid fuel droplets using the porous sphere technique in a free and forced convective oxidizer environment have been addressed by several authors [1,15–17]. Recently, Balakrishnan et al. [18], Raghavan et al. [19] and Parag and Raghavan [20] used porous sphere technique to evaluate the steady state burning rates of alcohols and their blends in a laminar forced convective flow of air. Porous sphere technique has revealed several important features of heterogeneous combustion of liquid fuels in terms of steady mass burning rate and flame stability aspects under different ambient and convective conditions. This has facilitated development of correlations for spray droplet burning. However, as opposed to suspended or moving droplet experiments, transient evaporation process and liquid phase behavior cannot be studied using this technique.

The studies on the effects of turbulence on transient droplet vaporization have been carried out by several authors in the past [21–26]. Ohta et al. [27] investigated evaporation and combustion of droplets in a three-dimensional, nearly isotropic turbulent flow environment, however, with almost zero mean flow velocity. Such an environment was established by placing a suspended droplet inside a multifold woven wire cage surrounded by four rotating vanes. The burning rates were obtained from the droplet regression rates captured through a motor driven camera. The flame shapes, unlike those in a forced convective environment, were highly wrinkled and almost spherically-symmetric. There was no considerable change in the flame shapes and transition from enveloped to wake was absent. Further, the burning rates were reported to increase proportionately with the eddy diffusivity.

Klyachko [28] developed a theory for estimating the flame blow off velocity for benzene droplet using both falling droplet (with droplet diameter ranging from 0.2 mm to 1 mm) and suspended droplet techniques (droplet diameter in the range of 1 mm at an ambient temperature of 1100 K). A comparison between the blow off velocity and the turbulent fluctuation velocity is made through the developed correlation and the analytical model relating the turbulent fluctuation. The experimental data of Tichomirov [29], Mizutani et al. [30] and Myers et al. [31] were used to compare the sustainability of the flames under similar turbulent environment. It was concluded that the burning rate of a droplet in a turbulent flow field has been promoted through high temperature, high pressure and smaller droplet size.

Recently, Senthil et al. [32] conducted experiments on burning of suspended n-heptane droplets in a grid induced turbulent field. It was found that the increase in turbulent intensity beyond certain critical values resulted in a reduction of mass burning rates, similar to Ohta et al. [27]. The experiments, however, unlike those of Ohta et al. [27], were performed with non-zero mean velocities.

As per the above literature survey, it is clear that numerous papers on evaporation studies in turbulent flow fields are available. However, basic fuel characterization studies on measuring steady state mass burning rates of alternative fuels in general, methanol in particular [33–36], and especially in turbulent flow fields, are highly scarce. Methanol can be obtained from coal gases and biomasses. It is a simple fuel with known kinetics mechanism and the flame is non-luminous also. This forms the motivation of this study. This work is a fuel characterization study, where the effect of grid generated turbulence on heterogeneous combustion of methanol fed porous sphere is studied thoroughly. The results can be useful to understand the effects of turbulence on burning rate and lift-off stability and the correlations proposed here can be used in specifying spray droplet burning rate in applications having low to moderate pressures.

2. Experimental setup

A porous sphere experimental setup (Fig. 1) consists of a vertical stainless steel tube/tunnel with an internal diameter (D) of 48.5 mm and a height 265 mm. A flow straightener and three steel wire woven meshes having solidity ratio less than 0.5 have been arranged one above the other to facilitate laminar flow of the air. Three different grids have been individually employed at the exit of the tube, in order to generate turbulence in the jet flow exiting the tunnel. All the grids have been fabricated using sheet metal of 1 mm thickness, and square holes of equal size cut in the interior (Fig. 2) using laser cutting technology. Provisions have been made such that the grids can be mounted to the exit plane of the vertical tunnel. The grid dimensions are reported in Table 1. The solidity ratio ($\sigma = 1 - (M^2/(M + W)^2)$ of all the grids have been kept constant as 0.75.

A medical grade infusion pump (Concept SP-50M, accuracy of flow rate: ±3%) has been employed to inject the fuel into the porous sphere. This pump can accommodate a 50 ml glass syringe and can inject a liquid fuel at a minimum rate of 0.1 ml/h. The syringe tip has been connected to a water cooled hypodermic needle of 0.6 mm diameter and 100 mm length, to which a porous sphere can be mounted. Fine radial holes have been drilled at the tip of the needle to distribute the fuel into the porous sphere quite uniformly.

Porous spheres are alundum spheres prepared in-house using Al_2O_3, silica gel and water. The preparation methodology is well described in Balakrishnan et al. [18]. The porous spheres are baked in an oven at a specified temperature of 800–1000 °C for 5–6 h. Then they are worked to spheres having exact diameters in the size range of 10 mm to 12 mm, using a fine grade emery sheet. A porous sphere is then gently fitted into the tip of the needle ensuring a tight fit that avoids any leakage of the fuel through the outer surface of the inserted needle. The needle tip penetrates up to the center of the sphere. A water cooling jacket, made of copper tubes is made to surround the exposed needle length such that it is cooled by feeding water with a help of small submersible aquarium pump. This process avoids vapor formation within the needed as a result of flame heating, which can prevent continuous supply of liquid fuel flow into the sphere.