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PREMIXED TURBULENT FLAME PROPAGATION IN MICROGRAVITY

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Objective and Relevance of the Study

To reduce pollutant formation there is, at present, an increased interest in employing premixed fuel/air mixture in combustion devices. It is well known that greater control over local temperature can be achieved with premixed flames and with lean premixed mixtures, significant reduction of pollutant such as NOx can be achieved. However, an issue that is still unresolved is the predictability of the flame propagation speed in turbulent premixed mixtures, especially in lean mixtures. Although substantial progress has been made in recent years, there is still no direct verification that flame speeds in turbulent premixed flows are highly predictable in complex flow fields found in realistic combustors.

One of the problems associated with experimental verification is the difficulty in obtaining access to all scales of motion in typical high Reynolds number flows, since, such flows contain scales of motion that range from the size of the device to the smallest Kolmogorov scale. If L denotes the integral length scale, η the Kolmogorov scale, then the range of scales increase with Reynolds number $(Re_L = u'L/\nu)$ by the relation $L/\eta = (Re_L)^{3/4}$. Here, u' is the turbulence intensity and ν is the kinematic viscosity. In addition, high Reynolds number flows typically involve high velocities, large scales, high pressure or low temperature (in gases) or a combination of all four. High pressure in reacting systems is undesirable in the laboratory, especially in premixed systems while low temperature is excluded in flames by their very nature. Since, in laboratory devices, the large scales are fixed by the size of the device, a possible approach to access the micro scales in a turbulent flow field is to reduce the flow velocity. This would increase the microscale (e.g., the Kolmogorov scale) to observable size while still retaining Reynolds numbers of realistic turbulence. However, in this case, the large scale turbulent stresses responsible for momentum transport become overwhelmed by buoyancy stresses (at 1g). Since this phenomena is not present in real devices, experiments in a microgravity environment is required to allow the reduction of gravitational effects while still maintaining reasonable operating pressure, combustion temperature and observable scales at all sizes.

The overall objectives of this study is to characterize the behavior of turbulent premixed flames at reasonable high Reynolds number, Re_L. Of particular interest here is the thin flame limit where the laminar flame thickness, $\delta_F = \alpha/S_L$ is much smaller than the Kolmogorov scale, L_K. Here, S_L is the laminar flame speed and α is the thermal diffusivity. Thin flames occur in many practical combustion devices and will be numerically studied using a recently developed new formulation (that is described briefly below).

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To achieve the requirements noted above, a Couette Flow configuration will be used. A Couette flow is a flow between two parallel plates moving in opposite directions at a fixed velocity U and is a classical textbook flow. This flow presents some interesting tests for computation, while being fundamentally simple. Past studies (e.g., Reichardt, 1956) have shown that in cold flows, for a Reynolds number ($Re = UH/\nu$, where H is the distance between the two plates) larger than 1800 the flow becomes turbulent. Thus, the Reynolds number needed to attain sustained turbulent flow is not too large, the mean flow speed is quite low, and therefore, only a limited range of scales needs to be resolved.

Research Approach

The present study is a combined experimental and numerical approach. The experimental effort will be ground based and the use of the NASA Lewis 2.2 sec drop tower is envisioned in the third or fourth year of this research. In the following, the experimental and numerical approaches are briefly discussed.

Experimental Approach

The experimental device currently under construction is designed to be consistent with the dimensions of the frame used in drop tower experiments. Thus, compared to some of the earlier experimental devices (e.g., Reichardt, 1956; Aydin and Leutheusser, 1987; Tillmark and Alfredsson, 1992), the current configuration is relatively smaller. To resolve all the measurement issues in this new facility, the first phase of the experiments focuses on cold flow, to be followed later by reacting flows. Therefore, the device under construction is designed only for cold flow. Figure 1 shows a schematic of the experimental setup. The Couette flow channel is made of infinite-belt type, where both walls move at the same speed, but in opposite directions. The belt is made of Mylar, which is a transparent plastic, so as to allow optical access to the channel for diagnostics. The belt is 0.1 mm thick and 305 mm wide and is supported and driven by two solid Aluminum cylinders, 76 mm in diameter. A DC motor is used to drive one of the cylinder while the other cylinder has adjustments available to adjust the tension of the belt. In order to minimize the flutter of the belt, it is supported by 10 mm thick glass plates on either side. The belt speed is determined using a proximity switch that measures the rpm of the driving shaft. To study a range of Reynolds numbers, both the belt speed and the belt spacing can be varied. A maximum belt speed of 2 m/s is possible with the current configuration and the belt spacing H which is controlled by two steel guide rollers on each side and 25 mm in diameter, can be varied from 10 mm to a maximum of 76 mm. Thus, a range of Reynolds number upto a maximum of around 10,000 can be achieved in the present facility which has a test section 381 mm long where measurements can be made.

The entire Couette flow set-up is enclosed in a glass box whose dimensions are 889 mm x 737 m x 356 mm, and 10 mm thick. Thus, optical access is possible from the side and top directions and the dimensions of the box are designed to be larger than that of the belt assembly, in order to provide a stagnation chamber at both ends (and, in which the rotating cylinders reside) larger than the size of the test section. A similar arrangement was used in an earlier study (Tillmark and Alfredsson, 1992) where it was shown that this approach reduces reflection from the rotating cylinders and thus, a sustained Couette flow can be achieved for a relatively long time.

For reacting flows (to be studied later) we are primarily interested in fuel-air gas mixtures such as hydrogen-air/oxygen and methane-air. Therefore, to mimic such mixtures in the present cold flow facility, non-reactive gas mixtures such as air and Helium-air/oxygen will be studied.

The mean and fluctuating velocities and the Reynolds stresses will be measured in this facility. In addition, two-point spatial correlations will be obtained for a variety of Reynolds number. The Reynolds number will be varied by changing both the belt speed and the belt spacing to characterize the turbulence in this facility. The velocity measurements in the Couette channel will be made using laser Doppler Velocimeter (LDV). A 5 watt two-component Argon-ion TSI LDV system operating at 488 nm and 514.5 nm wavelengths will be used. At the beam crossing, there is an elliptical probe volume of diameter 0.07 mm and length 0.5 mm with the fringe spaced at 1.8 microns. Therefore, it is estimated that a spatial resolution of the order of 1 mm can be attained. The entire Couette flow assembly will be mounted on a three axis translation table to enable measurements over a three dimensional grid of points.

For the reacting case (to be studied later), an issue of significant interest is the structure and propagation speed of the flame front. However, this issue cannot be addressed in the cold flow facility. Another interesting phenomena of considerable interest is the turbulent diffusion of a passive specie in the present configuration since there is no data available. Therefore, we plan to take advantage of the cold flow facility to address this phenomenon by using planar laser-induced fluorescence (PLIF). Acetone has been found to be a suitable tracer for concentration measurements using PLIF in gaseous flows (Loxano et al., 1992). Acetone absorbs over a broad band of wavelengths (225-320 nm) with a maximum between 270 and 280 nm. The fluorescence emission is broadband in the blue (350-550 nm) with peaks at 445 nm and 480 nm. Acetone is nontoxic and is economical and therefore, is an ideal choice for seeding in this case. A tunable Lambda Physik excimer laser will be used as the light source for this study. Planar images of the diffusion front will be acquired using a Kodak Ektapro 1012 intensified, digital, high speed video system. The camera has a resolution of 239 x 192 pixels, and a framing rate of 1000 Hz while acquiring full images; however, a framing rate as high as 12,000 Hz can be obtained by reducing the frame size proportionately.

The images obtained in this study will be used to provide qualitative information about turbulent diffusion of a passive scalar in the Couette flow environment.

Computational Approach

Computational modeling of the experimental facility will be carried out in parallel to the experimental study. In fact, computational results for the reacting flow case will be obtained prior to the construction of the hot flow facility to address issues regarding the measurement requirements. Since the flow of interest is unsteady, time-accurate simulations are required. Some preliminary direct numerical simulations (DNS) of cold flows are underway; however, for reacting flows DNS is impractical and therefore, methodology based on large-eddy simulations (LES) is being developed. In LES, all scales larger than the grid resolution are resolved in a space- and time-accurate manner while the small scales are modeled by subgrid models. For the momentum transport, it is well known that the small scales typically provide a dissipative mechanism for the energy transferred from the large scale motion and thus, subgrid models based on eddy-viscosity concepts have been successfully used in the past. With recent development of dynamic subgrid models (models whose coefficients adjust to the flow as a part of the solution) for the subgrid kinetic energy (Kim and Menon, 1995), the LES approach is capable of handling the momentum and large-scale energy transport reasonably well. However, for reacting flows, this approach is not possible because (i) combustion occurs at the small scales (that are not resolved), (ii) the nonlinear production/destruction terms due to finite-rate kinetics are difficult, if not impossible to model, and, (iii) inclusion of full kinetics prohibitively increases the computational cost of the simulations.

To circumvent these problems, a LES modeling approach has been developed that removes all these limitations. For premixed combustion, in the thin flame limit (appropriate for the present study), a model equation for the propagating flame front can be used in which the local flame speed u_F explicitly appears. If the local flame speed is known, a progress variable G can be defined that is governed by the equation (Kerstein et al., 1988; Menon and Jou, 1991): $\partial G/\partial t + \vec{u} \bullet \nabla G = -u_F|\nabla G|$, where $\vec{u}$ is the fluid velocity. This equation describes the convection of the flame by the local fluid velocity and the flame propagation into the unburnt mixture through a Huygens type mechanism, $u_F|\nabla G|$. Here, by definition, $G = 1$ corresponds to the premixed fuel, $G = 0$ corresponds to the fully burnt state, and the flame is located at prescribed $G = G_o$ level surface, where $0 < G_o < 1$. For laminar flows, the local speed u_F is the laminar flame speed S_L which contains all the information on the chemical kinetics and molecular dissipative mechanism. Thus, this approach avoids the cost of simulating multiple species conservation equations since all the kinetics information is implicit in the specification of the laminar flame speed. However, for turbulent flows, the flame speed u_F is the local turbulent flame speed u_T which is known to be a function of the local turbulence intensity u' and S_L. Various models (e.g., Yakhot, 1989) have been proposed; however, the exact relation is a matter of considerable uncertainty. In conventional LES, implementation of the turbulent flame speed model such as the one proposed by Yakhot (1989) requires explicit knowledge of the subgrid turbulence kinetic energy. This approach has been successfully employed in past studies by using a one-equation model for the subgrid kinetic energy to close both the subgrid stresses in the momentum equation and to obtain a local estimate of the turbulent flame speed.

However, the conventional approach is subject to the same limitations as subgrid closures for other molecular properties and furthermore, the determination of a general functional relationship between the turbulent and laminar flame speed which is valid for all types of fuels and flow conditions appears to be difficult. Therefore, in this study, a new formulation (described in more details in Menon et al., 1993, 1994) will be employed that no longer requires a specification of the turbulent flame speed and in fact, allows a direct estimation of the local turbulent flame speed. Thus, this approach can be used to examine models developed in the past. The basic approach is to carry out the combustion process within the subgrid scales while the large-scale features (as resolved by the LES equations) are computed as in conventional LES. The key feature of the new approach is the separate treatment of the three primary physical processes within the small scales: (i) local laminar flame propagation of the thin flamelets, (ii) turbulent wrinkling of the flame front due to the local small-scale turbulence, and, (iii) thermal expansion due to heat release. To maintain and resolve the distinction between all relevant small scales, the evolution of the scalar field is simulated in one (linear) spatial dimension which represents a characteristic statistical state of the scalar field within each LES cell. This linear dimension can be considered as a time varying space curve aligned with the local subgrid scalar gradient (e.g., Kerstein, 1990; Menon et al., 1994).

The large-scale LES computed processes are coupled to the subgrid combustion processes by two mechanisms. The first mechanism which involves the transport of the subgrid scalar field across the LES cell boundaries as prescribed by the large-scale resolved velocity field is implemented by convective transport mechanism. The second mechanism which involves the transfer of the effect of subgrid processes (heat release and thermal expansion) onto the large-scale momentum and energy transport is implemented by obtaining the cell-averaged properties (from the subgrid scalar field) and then utilizing this information to update the LES resolved density and temperature fields. Detailed description of this methodology is given elsewhere and omitted here for brevity (Menon et al., 1994).

The key feature of this approach is that since the flamelets are allowed to propagate using the local laminar flame speed while simultaneously undergoing wrinkling due to local turbulence, no closure of the production/destruction term is required and furthermore, locally within each LES cell, the local flame speed is S_L (which is well known given the fuel-air mixture) is used. In addition, the local subgrid processes within each LES cell can be used to estimate the effective local (turbulent) flame speed. Thus, given the turbulence intensity (from the experimental data) and the laminar flame speed (known for a given fuel-air mixture), it will be possible to determine the turbulent flame speed from the simulation. Furthermore, new information on the local geometrical structure of the flame front (e.g., the local flame curvature) can be determined from the simulation data.

Progress to Date

This project started in June1994 and since then, the design of the cold flow test facility has been completed and the construction of the facility is well underway. The schematic of this facility is shown in Figure 1. The facility is expected to completed by the end of April 1995. The data acquisition and the LDV systems have been set up and it is expected that preliminary results will become available by July 1995.

The numerical methodology is currently under validation studies. For this purpose, both DNS and LES are being carried out for a configuration for which data is available from other studies (e.g., Kristoffen et al., 1993; Aydin and Leutheusser, 1987). Preliminary cold flow results for the mean velocity profile, obtained using a constant-coefficient and a dynamic subgrid model for the subgrid kinetic energy is shown in Figure 2, along with earlier experimental and numerical data. The results show that the present scheme (which is based on a second-order time-accurate and fourth-order spatially accurate finite volume MacCormack scheme) is capable of resolving mean motion. Further validation of the LES methodology will be carried out before studying the flow field similar to the current experimental setup. The subgrid combustion model is currently being validated (under a ONR sponsored project) and is expected to be available soon.

Future Work Plan

The current work plan envisions detailed validation of the cold flow facility within the next few months by obtaining detailed turbulence data for a range of Reynolds numbers. Subsequently, the study of diffusion of a passive scalar will be investigated using acetone seeding. The turbulence data will be used to initialize the LES code and numerical simulations will be carried out for cold flows. Once the baseline LES code is validated for the present test configuration, the LES model will be extended to study thin flame combustion using both the conventional approach (using the turbulence flame speed model) and the new subgrid combustion approach. Preliminary numerical simulations should provide information on the behavior of the propagating flame front. Note that, for the reacting flow experiments it is going to be quite difficult to characterize the flame front shape. Therefore, given the turbulence intensity data from the experiments, it is hoped that the LES data will be able to characterize the turbulent flame front shape.

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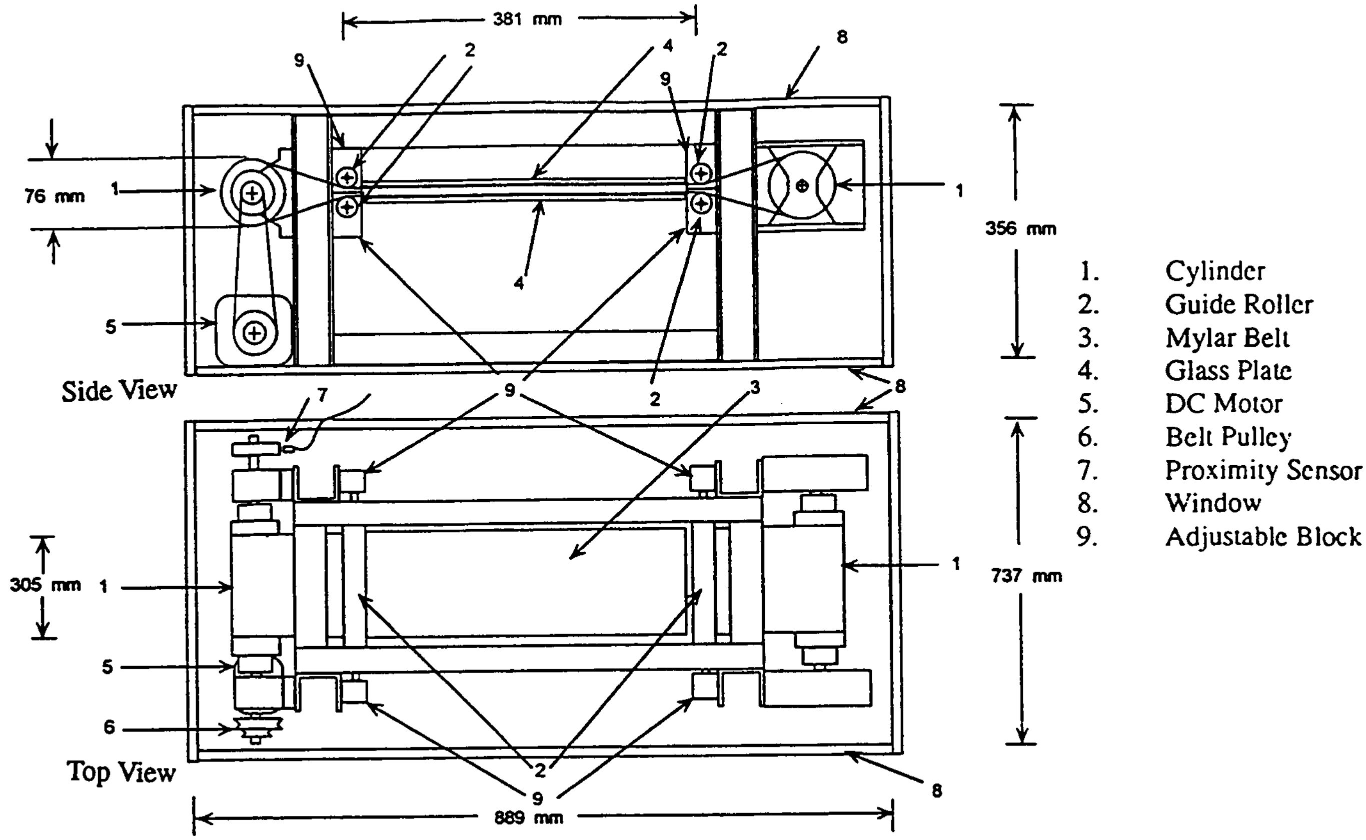

Figure 1. Schematic of the Couette Flow Experimental Set-up.

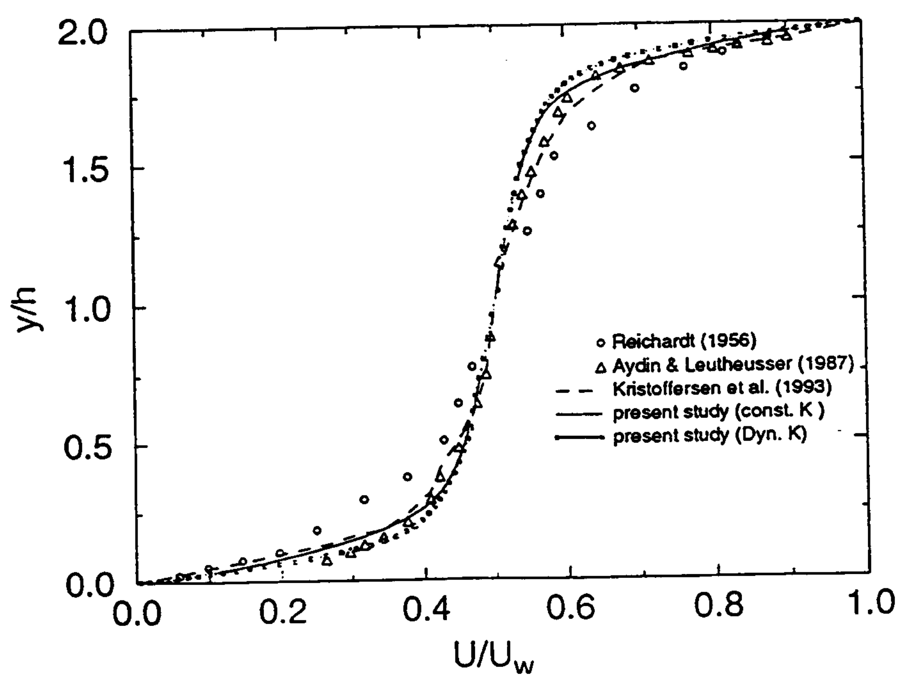

Figure 2. Turbulent mean velocity profile predicted by the present LES code using constant coefficient (Const. K) and dynamic model (Dyn. K) for the subgrid turbulent kinetic energy. Experimental data (Aydin and Leutheusser, 1987; Reichardt, 1956) and numerical study (Kristoffen et al., 1993) are also show for comparison. Test case for $H = 0.026m$ and $Re_H = 5200$ simulated using a grid resolution $48x64x32$.