On Some Research Activities in Combustion at Jadavpur University

Amitava Datta
Department of Power Engineering
Jadavpur University, Salt Lake Campus, Kolkata 700098

Overview :

A group of faculty members of the Department of Power Engineering and the Department of Mechanical Engineering of Jadavpur University are now actively working together in basic combustion related research and activities along with their students and associates. The present interest of the group and their work in the recent past include flame diagnostics and computation, droplet and spray combustion, atomization and spray formation, modeling and measurements of soot and soot precursors in flames, flame synthesis, combustion control, and thermodynamic analysis of combustion.

An experimental facility available at the Department of Power Engineering is being used for the diagnostic of species in flames using gas chromatography. The formation of the intermediate molecules and radicals in a flame depends on the kinetics of reaction as well as transport rates and determines the final emission products from the flame. In an intrusive technique the sample is collected from different points of the flame iso-kinetically and analyzed using gas chromatography. The facility is developed under an ongoing project from All India Council for Technical Education.

A new experimental facility is coming up in the Department of Mechanical Engineering under the Special Assistance Programme (SAP) of the UGC for the studies and research on combustion control and combustion instabilities.

Indigenous numerical models have been developed for several aspects of combustion by different researchers of the group for the study of jet flame, droplet and spray flames. Soot and NO formation in flames have been modeled. The effect of gravity and burner geometry on jet flame structure and the flame irreversibilities have been studied.

The droplet combustion has been modeled based on spherico-symmetric assumption in quiescent atmosphere as well as in convective ambience. A unit cell model for the combustion of multiple droplets in sprays is developed and the multi-droplet effects in dense and dilute sprays on the evaporation and combustion processes have been studied. Multi-component effect of droplet combustion is also under study. The spray combustion process, e.g. in gas turbine application, is modeled based on stochastic separated flow approach considering Eulerian continuous phase and Lagrangian discrete phase analysis.

Studies on atomizer hydrodynamics and spray formation are the other fields of interest for the group. Work has been done on the flow prediction through pressure swirl atomizer. A model on spray size and velocity distribution has been developed based on the Maximum Entropy Principle. Work is also in progress on the liquid sheet break-up and the resulting formation of spray in which a numerical model for spray formation will be developed that would predict the spray characteristics in terms of the initial sheet parameters, flow condition and the properties of the liquid and the ambient.

One of the current interests among the members of the group is in the field of nano-particle synthesis from combustion of hydrocarbon fuels. Some preliminary work in this direction has already been started in which flame synthesis of metal encapsulated carbon nanofibres (CNF)/carbon nanotubes (CNT) in a laminar flame will be studied. The growth and nature of CNF/CNT produced will be characterized with the location of the substrate within the flame.

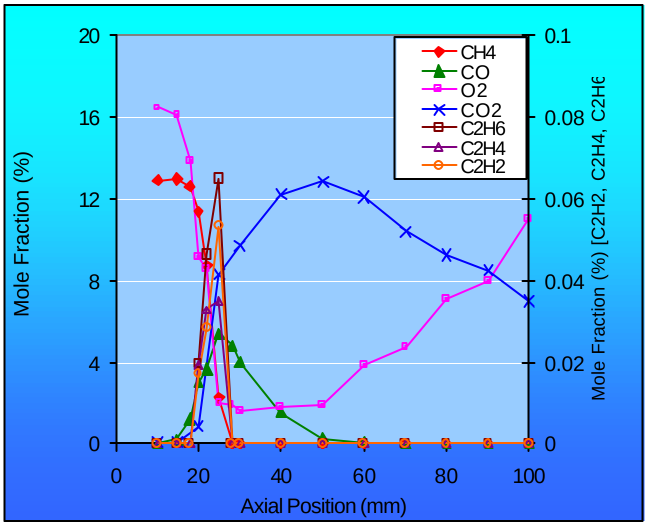
The members of the group also have experience of working on different laser based diagnostics of combustion, e.g. laser extinction measurement of soot volume fraction, coherent anti-Stokes Raman spectroscopy for temperature and species measurements and rainbow Schlieren deflectometry for the measurement of temperature as parts of their international exposure.

Thermodynamic analysis of the combustion systems has been carried out in spray and jet combustion to identify the contribution of various transports and chemical processes on the generation of entropy and loss of exergy in combustion. The fundamental information obtained here may be applied in the practical applications to find the exergy loss in different combustors and furnaces.

Species Diagnostics in Flame

Figure1. Experimental Set up for the species measurements in flames

Figure 1 shows the test set up for the species diagnostics in a flame using gas chromatography. A quartz micro-probe having 250 ?m diameter orifice at the tip and fitted to a sampling chamber is used for the collection of the sample. The chamber has to be purged and evacuated for the collection of the sample from the flame. The burner is placed on a traversing stage by which the relative position of the flame and the probe can be adjusted. The sampled gas is analyzed in a gas chromatograph using suitable columns and detectors. Studies have been conducted with partially premixed flames. Figure 2 shows the image of a partially premixed methane/air flame from a co-flow burner with a fuel-air mixture having equivalence ratio of 1.5 issuing through the central port and air through the annular port. A double flame structure consisting of an inner rich premixed and an outer non-premixed flame is observed. Samples have been collected from different locations along the flame centerline as well as at different radial locations to analyze the species. The distribution of CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2 and O_2, measured along the flame centerline is given in figure 2. The results can be used for the description of the kinetics of different intermediate reactions and pollutant formation. The concentration of acetylene (C_2H_2) and ethylene (C_2H_4) give indications about the soot formation propensity of the flame.



Gravity Effect on Laminar Diffusion Flame Structure

A numerical study on the effect of gravity on the structure and entropy generation of laminar confined diffusion flame has been made. The wider flame at reduced gravity is predicted and the effect of Froude number on the flame width has been studied. Figure 3 shows the flame contour, velocity distribution and temperature distribution in the flame at normal gravity and zero gravity.

Figure 3. The structure of confined laminar diffusion flame at normal gravity (left) and at zero gravity (right).

Modeling of Drop size distribution in spray using Maximum Entropy Principle

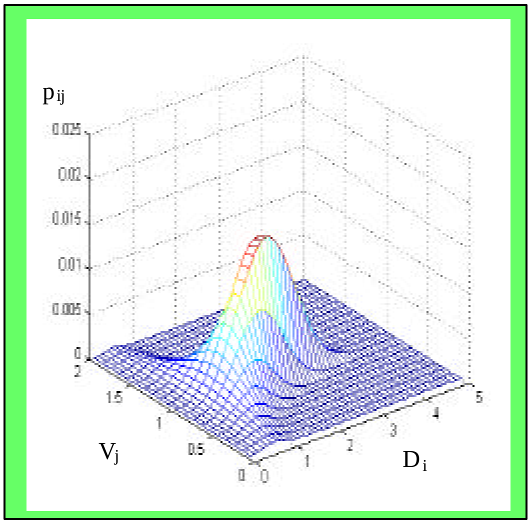


Figure 4. Size and Velocity distribution of drops from a pressure swirl atomizer predicted using the maximum entropy principle

A model based on maximum entropy principle has been developed for the prediction of droplet size and velocity distributions in a spray from a pressure swirl atomizer. The constraint equations have been formulated using the performance parameters of the spray, so that the effects of atomizer geometry and spray characteristics can be included on the drop size distribution. Figure 4 shows a combined size and velocity distribution of droplets in a spray predicted by the model. The model has been used to predict the drop size distributions at different injection pressure, ambient pressure, liquid type and also for different atomizer geometries. The model output is also used to predict the efficiency of atomization for the different cases.

Modeling of Soot Formation in Flame

The Soot formation in jet flame has been modeled using a semi-empirical approach to predict the soot volume fraction and number density across the flame. The contributions of soot nucleation, surface growth, coagulation and oxidation have been considered in the model. The model is calibrated against the experimental data from the literature. The adjacent figure 5 shows the soot volume fraction in a non-premixed methane jet flame predicted by the model. The flame front surface in the figure depicts the zone of heat release. The maximum soot concentration is found to be inside the flame surface and the soot is oxidized above the flame zone.

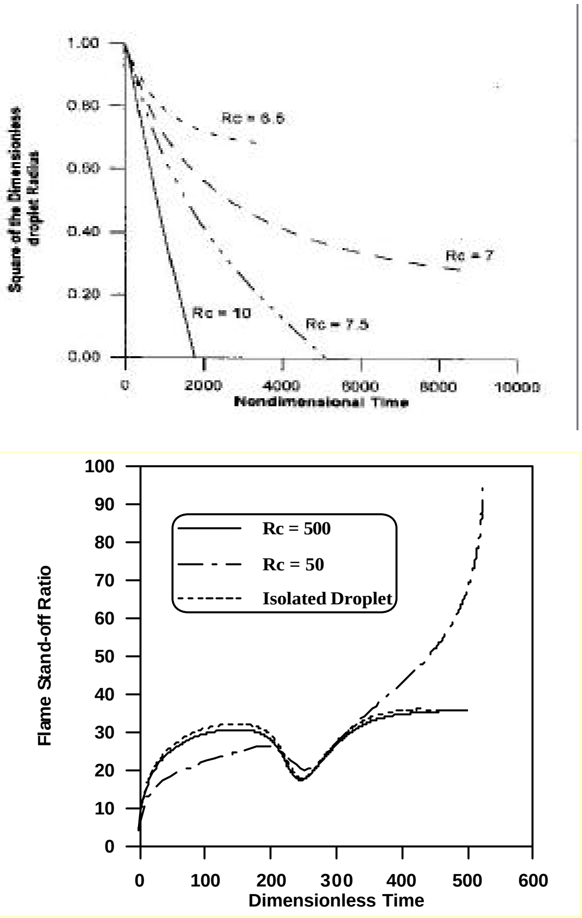


Figure 6. Spray Effects on Evaporating (above) and Burning (below) Droplets

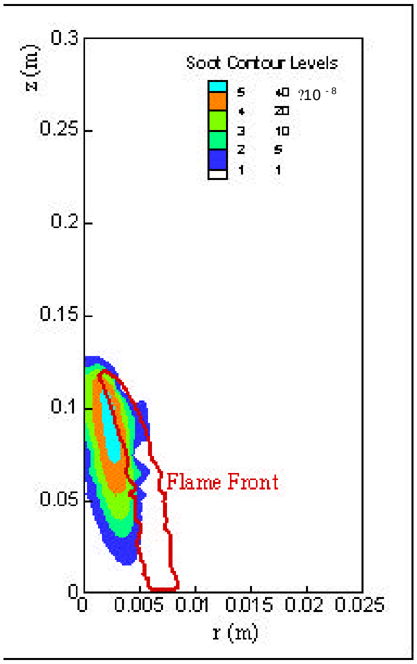


Figure 5. The flame front contour and the soot volume fraction distribution in a methane/air non-premixed, confined, laminar flame predicted from model

Modeling of Droplet Interference Effects

Models have been developed for combustion and evaporation of fuel droplets in a spray using spherical cell model. In this approach, the spray is considered to be divided into a number of cells, each cell containing a droplet. The interaction between different droplets is incorporated by applying suitable boundary conditions at the cell surface. The behavior of both evaporating and burning droplets in a spray is significantly different from that of isolated droplets, especially for dense and very dense sprays. Figure 6 shows that complete evaporation is not possible for droplets evaporating in a very dense spray, while for individually burning droplets in a dilute spray, the flame position significantly varies from that of isolated droplets.

Modeling of Flame Propagation in Channels

A thermo-diffusive model has been developed to investigate the interaction of non-unity Lewis number and heat loss for laminar premixed flames propagating in a channel. A coordinate system moving with the flame has been used to immobilize the flame within the computational

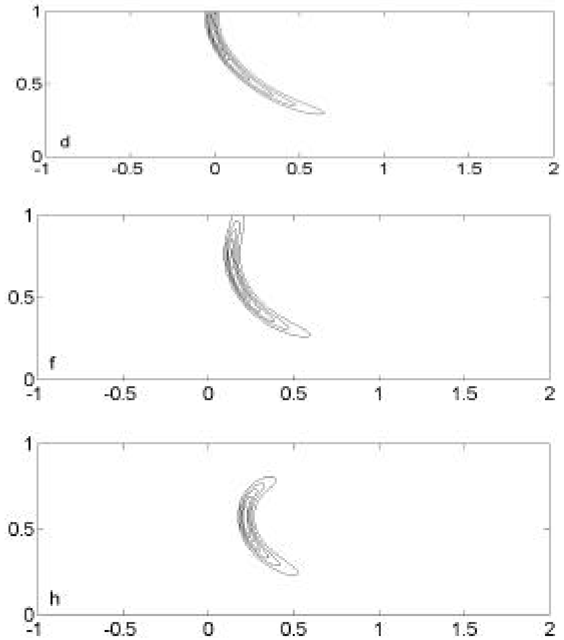


Figure 7. Effect of Biot Number on Flame Shape in a Channel for Le = 0.25 and various Biot numbers (Bi = 0.0, top; 0.5, middle; 1.0 for bottom)

domain. At Lewis numbers significantly below unity in presence of high heat loss, tip opening near the centerline and dead space near the wall are simultaneously observed, that gives rise to a "tulip"-shaped flame (Fig. 7). The heat loss has a stronger effect for fluid flows opposing the flame motion than for fluid flows aiding the flame motion. For Lewis numbers above unity, the dependence of reaction rate on Lewis number gets reversed as heat loss increases from zero to a finite value.

Control of NO_x Formation in Radiant Tube Burners

A model-based control structure for heat treating a 0.5% C steel slab in a batch furnace with low-NO_x radiant tube burner is designed and tested for performance to yield optimal parameter values. Combustion is considered in a highly preheated and product gas diluted mode. Controlled combustion with a proposed arrangement for preheating and diluting the air by recirculating the exhaust gas that can be retrofitted with an existing burner(cf. Fig.8) yields satisfactory performance and emission characteristics. Controlled preheated and diluted combustion yields uniform thermal heat flux inside the furnace and lower peak flame temperature with better potential for emission control. It is possible to obtain an optimal set of parameters for any such system to facilitate system optimization (cf. Fig.9).

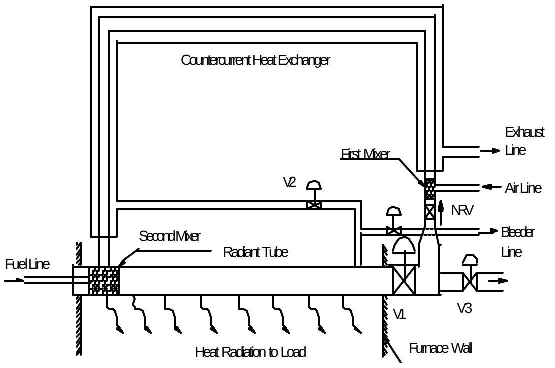


Figure8. Schematic of the conceived preheating and premixing arrangement

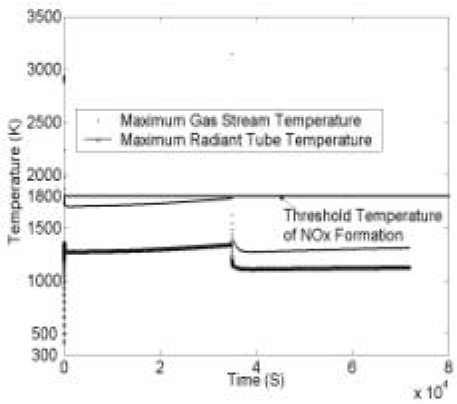


Figure 9. Maximum gas stream and radiant tube temperatures encountered during the entire heat treatment time of the load in controlled mode