Experimental Investigation of Wake and Envelope Flames around an Octane-Wet Porous Sphere

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Abstract

Two-phase reactive flows with fuel of iso-octane and with oxidizer of air are experimentally investigated. Velocity field and OH concentration field are measured respectively with PIV and LIF techniques. Some interesting combustion phenomena have been revealed from the experiments, including triple flame structure and vortex structures in wake flame as well as stagnation flow and combustion in envelope flame. The present work provides some important insight to better understand the dynamic interactions between convection and chemical reaction in the complicated two-phase reactive flows.

Introduction

For two-phase reactive flows, even nowadays only a limited amount of experimental data is available for detailed analysis of dynamic interactions between flow, evaporation and chemical reaction processes, although some research was done previously [1, 2].

Most practical liquid fuels are composed of higher hydrocarbons. Not only the detailed chemistries involved for such fuels are complex and the same time incomplete, but also some kinetic data are based only on estimation or approximation. Simple chemistries still have to play quite important role in such numerical simulation. Apart from the chemistry, the two-phase transport models have not been fully developed, either. All these factors make the numerical simulation of two-phase combustion full of uncertainties. Under such circumstances, it seems to be necessary to have some reliable experimental data which can be used to validate the models used in numerical simulation of two-phase phenomena, at least partly. On the other hand, modern laser technology has developed quite fast recently. Many measurement devices using laser technique with their corresponding hardware and software become more and more stable and some of them are commercially available.

As a contribution to bridge the gap in the numerical simulation of two-phase combustion and to provide reliable experimental data, in the current work the velocity fields and the OH concentration fields for the two-phase reactive flows of iso-octane and air have been investigated with PIV and LIF techniques, which are considered to be particularly suitable to provide detailed and reliable information about combustion processes.

Experiments

The experimental setup consists of a porous sphere of 20 mm in diameter, in which octane is continuously provided from inside, and of a nozzle-like device to provide air flow at Reynolds number of less than 2000 range. Octane is supplied to the porous sphere such that the flow rate of octane matches its evaporation rate on the surface of the sphere, so that the combustion process is fully controlled by the evaporation process of the liquid fuel. Furthermore, the surface of the sphere is kept to wet-bulb condition whenever possible. Figure 1 shows the schematic setup for velocity measurement of wake flames with a PIV equipment. A similar but modified setup is used to accommodate LIF measurements of OH concentration fields in wake flames and, alternatively, envelope flames.

Results and Analyses

In the current paper, wake and envelope flames are the main focuses of the investigation though there is another interesting flame phenomenon in between, that is, the “sit-on” flame which sits on the sphere’s

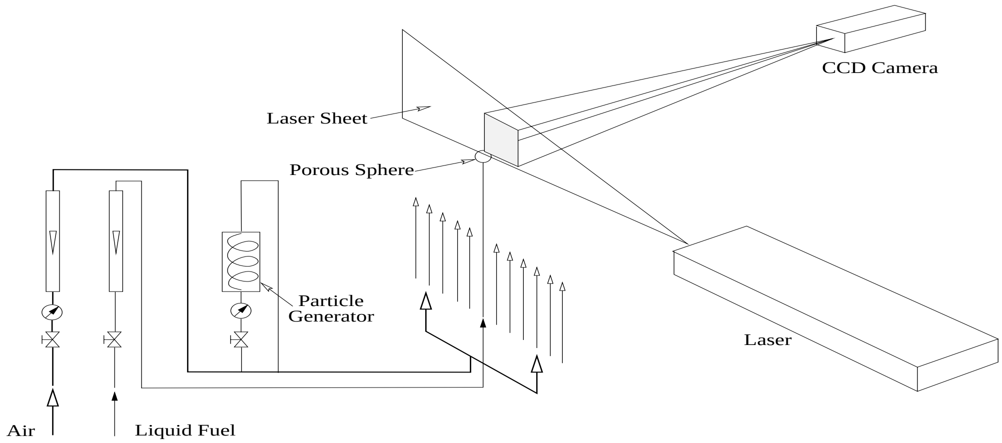

Figure 1: Experimental setup of a two-phase reactive flow around a porous sphere.

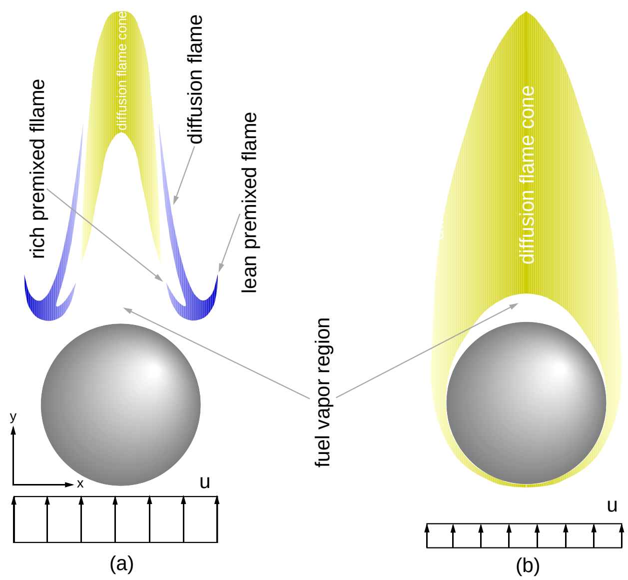

Figure 2: Schematic of a wake (a) and an envelope (b) flame structure in two-phase reactive flows.

surface, as indicated. For the wake flame, a triple-flame like structure has been observed and investigated in detail. For the envelope flame, the attention in the experiment is focused on the vicinity of the lower stagnation point. In fact, the triple flame structure appears already when the flame extinguishes at the lower stagnation point and sits on the sphere's surface caused by relatively lower velocity of incoming air.

In the case of wake flames, liquid fuel evaporating from the sphere's surface and oxidizer carried by the incoming flow at a Reynolds number of about 1900 generate a mixing layer in the wake of the sphere. A stable triple flame structure is formed around the lower edge of the wake flame, see Fig. 2 (a). This premixed mixing layer is generated shortly after in an obvious evaporation- and diffusion-dominated process. The formation of this mixing layer which is essential to the triple flame structure reflects the effect of the interaction between the convection, evaporation and chemical reaction in this two-phase reactive flow. The fuel-rich premixed branch inside and the fuel-lean premixed branch outside are rather small but the diffusion branch in between extends quite far to the downstream and connects to the diffusion flame core in the middle of the flame cone. At the lower part of flame cone, no combustion appears inside (directly above the sphere) because very dense fuel vapor and little oxygen exist there.

Shown in Fig. 3 is a part of the typical velocity field for a wake flame obtained with the PIV technique. The flow field shows some unique features. At above the sphere and away from sphere's

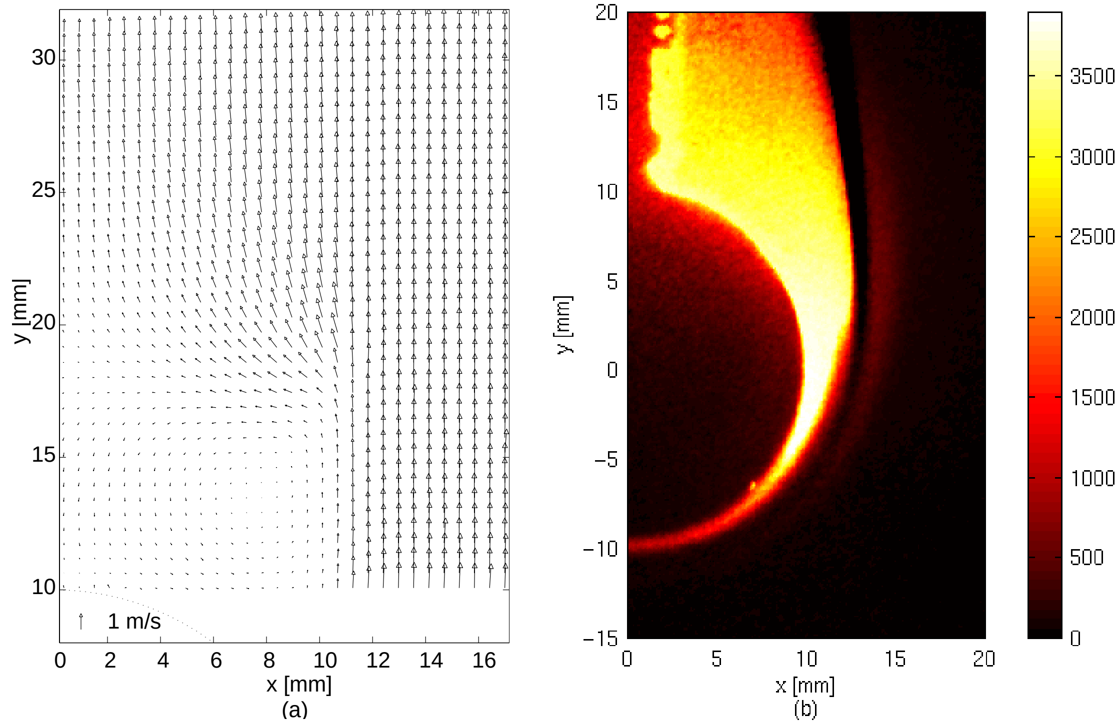

Figure 3: Flow field (a) in the region of triple flame with combustion rate of 0.0348 L/h and Reynolds number of 1900 and fluorescence intensity (b) of OH in an envelope flame with combustion rate of 0.09 L/h and Reynolds number of 355 for iso-octane flames. Reynolds numbers are based on sphere's diameter and incoming air flow; a Ø20 mm porous sphere is located at origin and dotted line indicates sphere's surface.

vertical axis, there is a stable and distinct vortex which induces also a downward flow in a direction of sphere's vertical axis. The triple flame sits, in fact, itself on the vortex. Above the vortex, convection and thermal expansion make the flow converging into the middle and the main flow direction is however upward. Consequently, a back-to-back counter flow is formed there. Though gravity greatly affects the flow and combustion behavior in the current case, an analogy does exist between such wake flame and flame's "blow-away" phenomenon in droplet combustion.

On the other hand, an envelope flame is formed if the incoming flow is at a relatively low Reynolds number, see Fig. 2 (b). The flow pattern close to the stagnation point is quite similar to that in a Tsuji burner. Figure 3 (b) shows fluorescence intensity of OH (detected by LIF device) of a typical envelope flame. The higher OH concentration shows roughly the reaction zone in the flame. At the lower part the sphere there is a very thin layer of reaction zone; flame becomes thicker and thicker when it goes up.

Such a thin combustion zone close to the lower stagnation point exists mainly because the flame is strongly stretched there. Furthermore, the region near the stagnation point is also the starting point for the flame extinction when higher velocity is provided. With the increasing incoming air velocity, the thickness of the reaction zone there becomes thiner and thiner until the flame starts to extinguish. Then the flame will transit into a "sit-on" flame and triple flame structure begins to merge on the sphere's surface. In many practical situations, such a triple flame structure may also appear above a relatively fuel-wet surface.

With even higher velocity, the flame's lower edge moves up on the sphere's surface, finally it is lifted and wake flame with triple flame structure is formed in the wake of the sphere.

Final Remarks

The present investigation with PIV and LIF technique improves the basic understanding of the combustion phenomena close to the fuel-wet surface, especially the newly observed triple flame structure and its surrounding flow phenomena.

The experimental data of velocity filed and the relative concentration fields of OH obtained can help to develop and validate the models of transports and reaction in numerical simulations.

Furthermore, the present experiments have important implications to droplet combustion with respect to flame propagation, spread and extinction, even though in the cases considered here gravity plays an important role and the Reynolds number is relatively high.

Acknowledgments

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