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Pattern Formation in Diffusion Flames Embedded in von Kármán Swirling Flows

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1 Introduction

Pattern formation is observed in nature in many so-called excitable systems that can support wave propagation [1]. It is well-known in the filed of combustion that premixed flames can exhibit patterns through differential diffusion mechanism between heat and mass (see, e.g. [3], [6]). However, in the case of diffusion flames where fuel and oxidizer are separated initially there have been only a few observations of pattern formation. It is generally perceived that since diffusion flames do not possess an inherent propagation speed they are static and do not form patterns. But in diffusion flames close to their extinction local quenching can occur and produce flame edges which can propagate along stoichiometric surfaces. Recently, we reported experimental observations of rotating spiral flame edges during near-limit combustion of a downward-facing polymethylmethacrylate disk spinning in quiescent air [4]. These spiral flames, though short-lived, exhibited many similarities to patterns commonly found in quiescent excitable media including compound tip meandering motion. Flame disks that grow or shrink with time depending on the rotational speed and in-depth heat loss history of the fuel disk have also been reported [5]. One of the limitations of studying flame patterns with solid fuels is that steady-state conditions cannot be achieved in air at normal atmospheric pressure for experimentally reasonable fuel thickness.

As a means to reproduce the flame patterns observed earlier with solid fuels, but under steady-state conditions, we have designed and built a rotating, porous-disk burner through which gaseous fuels can be injected and burned as diffusion

*This work was supported by the NASA Microgravity Combustion Science Program

flames. The rotating porous disk generates a flow of air toward the disk by a viscous pumping action, generating what is called the von Kármán boundary layer which is of constant thickness over the entire burner disk. In this note we present a map of the various dynamic flame patterns observed during the combustion of methane in air as a function of fuel flow rate and the burner rotational speed.

2 Experiments

Figure 1 shows a schematic illustration of the experimental setup. Experiments are carried out using a rotating, porous-disk burner. The burner assembly consisted of a sintered, porous, bronze disk of diameter 7.8 inches and thickness 1/2 inch, mounted on a perforated water-cooled copper back-plate and a cup-shaped plenum chamber. A guard ring of width 1 inch is attached flush to the burner surface to minimize the edge effects due to sudden changes in flow velocities along the burner edge. The fuel gas and the cooling water are supplied through concentric copper tubes located along the axis of this assembly. These supply tubes are connected to external feed tubes through O-ring seals so that the entire burner assembly can be rotated around its axis. A stepper motor controlled by a lap-top computer drives the burner. During an experiment the burner is placed horizontally with the exposed porous surface facing downward and then spun at a desired rotational speed with the cooling water supply turned on. Fuel gas is fed to the burner from a compressed-gas bottle through a programmable mass-flow controller at a specified flow rate and ignited in air at atmospheric pressure by a propane torch. The entire experimental setup is enclosed in a large plexiglass box to prevent draft. All the flames observed in this study were blue and clearly visible to the naked eye. However, commercially available color CCD cameras are not sensitive enough to capture the flame emission in this wavelength. Therefore in this study we use a, gated, intensified-array camera. The flame images are video-taped using a 45° mirror placed directly below the burner (see, Fig. 1) at approximately 8 inches away to minimize flow disturbances.

3 Experimental Observations

The experimental results reported here are for methane fuel burning in air at atmospheric pressure. The rotational speed of the fuel disk Ω, was varied from 0 to 20 revolutions per second (rps), and the fuel flow rate S from 0.5 to 5 standard liters per minute (slpm). Experiments are started with a stationary burner and then the burner rotational speed is slowly incremented in steps of 0.2 rps until

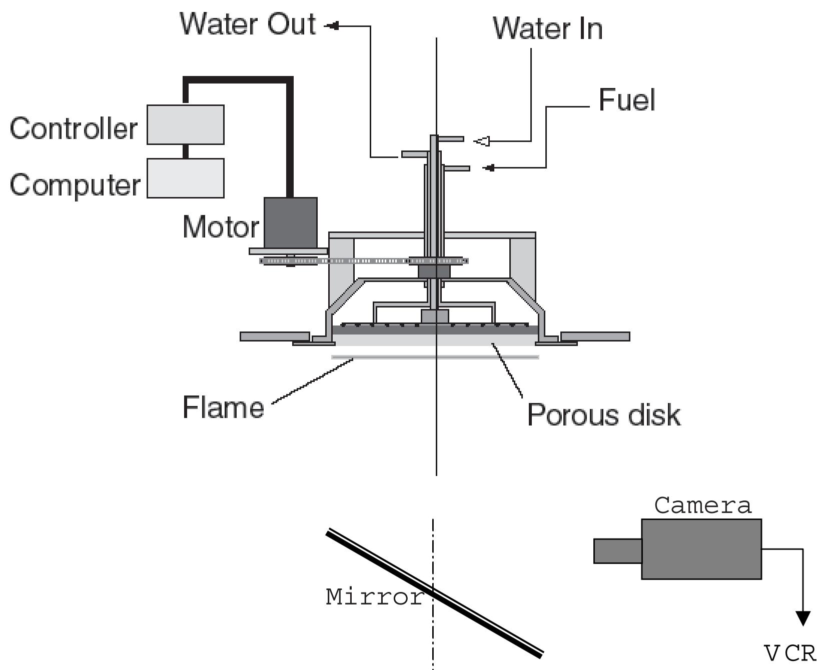

Figure 1: Schematic illustration of the experiment

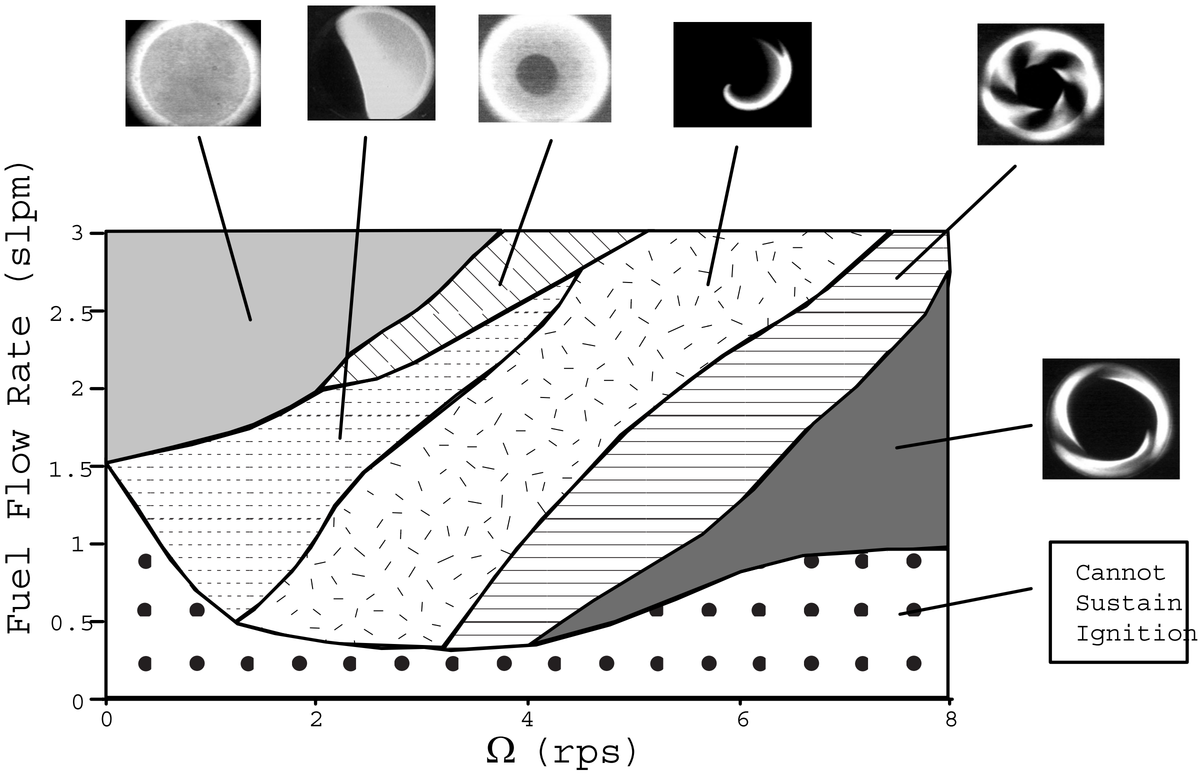

Figure 2: A map of flame patterns in S-Ω coordinates for methane burning in air.

the flame is completely blown off from the burner surface. This step is repeated for different fuel injection rates S. At each value of S and Ω, the experiment is run for several minutes to stabilize the burner thermally before video images are obtained.

Figure 2 shows a map of the observed flame patterns as a function of the fuel flow rate S and the disk rotation rate Ω. When the burner is stationary, a flat, blue diffusion flame covering the entire fuel disk is seen. However, to establish a steady flame, a fuel injection rate above a critical value is needed. As we slowly increase Ω, the flat diffusion flame becomes unstable and develops a relatively straight, quenched front that sweep across the burner. On occasion, the flame is extinguished completely in this mode and requires re-ignition. If the fuel flow rate is increased, this unsteady sweeping motion of the flame edge settles into a more periodic behavior of a pulsating flame hole. In this mode a small circular quenched region originates close to the burner center and expands outward toward the burner edge. At a certain hole radius the expansion stops and the edge propagates into the quenched region reestablishing the flame. The hole opening process is axisymmetric whereas that of hole closure is non-axisymmetric. For the range of parameters examined in this study the pulsation frequencies of the flame holes varied over a range of 1 to 4 Hz, the frequency increasing with Ω.

As the burner speed is further increased, the pulsating hole configuration transitions into a rotating single-armed spiral flame whose characteristics are similar to the spirals observed before with the solid fuels and described earlier [4]. The single-spiral flame rotates in the opposite direction to that of the burner, slowing down and eventually reaching a stationary state at a critical burner speed. The tip of the rotating spiral flames track a meandering petal-like formation while the tails execute a rigid-body-like rotation or a ratcheting motion (see, [4]).

The next mode shapes observed are the multi-armed spirals. Originating closer to the burner edge, the spiral arms extend toward the center of the disk, terminating at a finite radius. Spiral flames with two to seven arms were observed during the present experiments, with the number of arms increasing with Ω. Unlike the spiral flames, these flames rotate in the same direction as the burner with increasing velocities, as observed from the laboratory frame of reference. When the number of spiral arms reaches more than seven, the flame rotational speed becomes sufficiently high and the standard video framing rate of 30 frames per second cannot adequately resolve the flame shapes. It is also interesting to note here that the radius of the central, quenched core region increases with Ω. Eventually, the central core region expands almost to the edge of the burner with the arms of the spirals completely disappearing, leaving only a ring-shaped flame. The ringed patterns are certainly influenced by burner edge effects, and we can only speculate here that a larger diameter burner may produce different patterns. Further increase in burner speed completely blows the flame off the burner surface. A similar scenario develops when one travels vertically down at a sufficiently large rotation rate, as seen in Fig. 2. We have also noticed no hysteresis effects in the pattern formation process, i.e., the patterns occur at the same S-Ωvalues irrespective of the history of how that point was reached.

4 Discussions and Concluding Remarks

Though detailed theoretical explanations of the patterns observed here are not currently available, some initial attempts have been made in [4] - [5], primarily using the edge-flame idea originally proposed by Buckmaster [2]. In [4], assuming the leading edge of a flame spiral propagates with a constant speed relative to the swirling gas flow, the experimentally observed flame shapes were predicted well. A stability map showing regimes of flame-hole growth and shrinkage in a plane of the Damköhler number and the flame-hole radius was presented in [5]. Further attempts to understand these flame patterns and their dynamics are currently underway.

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13. ABSTRACT *(Maximum 200 words)*

Pattern formation is observed in nature in many so-called excitable systems that can support wave propagation. It is well-known in the field of combustion that premixed flames can exhibit patterns through differential diffusion mechanism between heat and mass. However, in the case of diffusion flames where fuel and oxidizer are separated initially there have been only a few observations of pattern formation. It is generally perceived that since diffusion flames do not possess an inherent propagation speed they are static and do not form patterns. But in diffusion flames close to their extinction local quenching can occur and produce flame edges which can propagate along stoichiometric surfaces. Recently, we reported experimental observations of rotating spiral flame edges during near-limit combustion of a downward-facing polymethylmethacrylate disk spinning in quiescent air. These spiral flames, though short-lived, exhibited many similarities to patterns commonly found in quiescent excitable media including compound tip meandering motion. Flame disks that grow or shrink with time depending on the rotational speed and in-depth heat loss history of the fuel disk have also been reported. One of the limitations of studying flame patterns with solid fuels is that steady-state conditions cannot be achieved in air at normal atmospheric pressure for experimentally reasonable fuel thickness. As a means to reproduce the flame patterns observed earlier with solid fuels, but under steady-state conditions, we have designed and built a rotating, porous-disk burner through which gaseous fuels can be injected and burned as diffusion flames. The rotating porous disk generates a flow of air toward the disk by a viscous pumping action, generating what is called the von Kármán boundary layer which is of constant thickness over the entire burner disk. In this note we present a map of the various dynamic flame patterns observed during the combustion of methane in air as a function of fuel flow rate and the burner rotational speed.

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