Role of Flow Visualization in the Development of UNICORN

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Abstract: This paper describes how visualizations have been used in the development and evaluation of a reacting-flow-simulation model known as UNICORN (UNsteady Ignition and COMbustion with ReactionNs). UNICORN, which solves full Navier-Stokes equations, has evolved over a 6-year period and is perhaps one of the most thoroughly evaluated codes of its kind. It evolved hand-in-hand with experiments that have been conducted to test its ability to predict ignition, extinction, and the dynamic characteristics of diffusion and premixed flames of hydrogen, methane, and propane fuels and that are stabilized in different ways. This paper also describes how UNICORN has been used, in conjunction with experiments, to provide new insights into combusting flows. Also, predictions of unobserved phenomena that were later confirmed by experiments are described. This paper demonstrates that the judicious use of a well-validated simulation in conjunction with laser based diagnostics is an effective way of understanding complex combustible flows.

Keywords: vortices, visualization, flames, combustion, laser diagnostics, turbulence.

1. Introduction

Studies of jet diffusion flames are important in understanding combustion phenomena, developing theories of combusting processes, and developing and evaluating design codes for practical combustion systems. Because of this, jet flames have been actively investigated since the classic works of Hottel et al. (1949). Considerable data on statistical quantities such as time-averaged and root mean squared (rms) values of velocity, temperature, and species concentrations have been obtained with single point measurement techniques. These data have formed the bases for understanding many of the processes occurring in jet diffusion flames. However, such understanding has limited applications for engineering problems because of the time-averaged description of the underlying unsteady combustion processes. In many cases, the mean and fluctuating quantities can mask the physics and chemistry that are germane to understanding the fundamental processes that give rise to the statistical results. This is particularly true for laminar and near-transitional jet flames in which the large-scale, low-frequency (0-40 Hz), organized, and absolutely unstable buoyancy-induced vortices on the air side of the flame and medium-frequency (100-1000 Hz), Kelvin-Helmholtz-type vortex structures on the fuel side of the flame dominate the flame characteristics. For example, high-speed visualizations of a buoyant jet diffusion flame have revealed that the flame surface is actually wrinkled as a result of the interaction of vortices, while time-averaged visualizations indicate a smooth surface. To gain insight into these low- and medium-frequency dynamic processes, it is helpful—and, perhaps, essential—to think in terms of the time-dependent characteristics of jet flames.

Several numerical investigations made in the past for dynamic jet flames using conserved-scalor approach, global-chemistry and detailed chemistry models have revealed important aspects of combustion such as effect of
heat-release rate (Ellzey et al., 1989; Yamashita et al., 1990), role of buoyancy (Davis et al., 1991; Katta and Roquemore, 1993; Patnaik and Kailasananth, 1994), enhancement of soot formation (Kaplan et al., 1996), and Lewis-number effects (Katta et al., 1994a; Takagi and Xu, 1994; Takagi et al., 1996). However, most of these studies, involving finite-rate chemistry, are limited to hydrogen fuel as the kinetic models for this fuel are relatively simple. Because of the complex nature of the reaction mechanisms, flame calculations for hydrocarbon fuels are restricted to either steady-state problems or chemically lazy flames in which chemistry is not important. Simulation of dynamic hydrocarbon flames with sufficiently accurate models for physical and chemical processes is required for understanding ignition, blow-out, instabilities, and emissions.

The authors have been developing a time-accurate CFDC (computational Fluid Dynamics with Chemistry) code (Katta et al., 1994a, 1994b, 1994c) known as UNICORN (UNsteady Ignition and COMbustion with ReactioNs) for the past six years. UNICORN is continuing to be developed as a research tool to better understand the dynamic characteristics of flames and as a future design tool for combustion systems. From its conception, the development of UNICORN has been strongly coupled with experiments that are designed: to evaluate the chemistry and transport models used in the code and to challenge its ability to predict complex dynamic characteristics of combusting flows. Because of the strong coupling with experiments, UNICORN is perhaps one of the most thoroughly evaluated Navier-Stokes based codes that have been developed. Visualizations have been used extensively in the development of UNICORN and in providing insights into the different combusting flows that have been studied. A simple view of the approach used to develop UNICORN is illustrated by the flame visualization in Fig. 1. The idea was to start the development of UNICORN by trying to predict the steady and dynamic characteristics of simple laminar like flames such as illustrated in Fig. 1(a), and then progress in a methodical way to the more complex flames illustrated in Figs. 1(b) and 1(c). This approach has proven to be extremely useful in systematically identifying and correcting deficiencies in the models used in UNICORN. It has also been demonstrated the power of using computations and experiments in concert to better understand both diffusion and premixed combustion flows. Indeed, UNICORN has evolved to the point where it has correctly predicted unknown combustion phenomena that were later confirmed experimentally. This paper illustrates the role of visualizations in the development of UNICORN and describes some of the insights into combustion processes that have resulted from the combined use of experimental and computational visualization methods.

![Fig. 1. Vertically mounted jet diffusion flame for different jet velocity conditions: (a) low-speed, laminar flame; (b) medium-speed, transitional flame; (c) high-speed, turbulent flame.](image)