Combustion Research Facility News

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Collaborative experiments expand model-validation library

The Turbulent Diffusion Flame (TDF) laboratory forms one of the cornerstones for an international collaboration to develop an internet-accessible library of experimental results on turbulent nonpremixed flames for validation of combustion models. The library begins with simple hydrogen jet flames and progresses to more complicated geometries and fuels.

Several recent experiments in the TDF lab and at collaborating universities have significantly expanded this library. Rob Barlow, Greg Fiechtner and Cam Carter (ISSI, Dayton, OH), and Tom Prast obtained detailed multiscalar data (T, major species, OH and NO) in turbulent $CO/H_2/N_2$ jet flames. Velocity measurements for the same flame conditions were carried out by Matthias Flury at ETH Zurich, Switzerland. Jonathan Frank (PSI, Andover, MA) joined Rob for an extensive series of experiments on piloted methane/air flames. Velocity measurements on these flames are in progress at the Technical University of Darmstadt, Germany, under the direction of Egon Hassel. Pieter Nooren (Technical University of Delft, Netherlands) visited the TDF lab last year to add multiscalar measurements to the data set on the Delft piloted natural gas flames (Figure 1).

Figure 1. The Delft piloted natural gas flame during experiments in the TDF lab.

Multiscalar data from the TDF lab also provide fundamental insights on combustion processes, such as scalar transport and unsteady strain. Figure 2 compares measurements in a turbulent $CO/H_2/N_2$ flame with results from two types of laminar flame calculations provided by J.-Y. Chen (UC Berkeley). The turbulent data are better represented by the laminar calculation that specifies equal diffusivities, indicating that turbulent transport dominates over molecular diffusion in determining major species concentrations. Differential molecular diffusion has been shown to be important at lower Reynolds numbers and at locations closer to the nozzle. Therefore, models that account for the varying roles of molecular diffusion and turbulent transport may be necessary for a complete description of laboratory-scale flames.

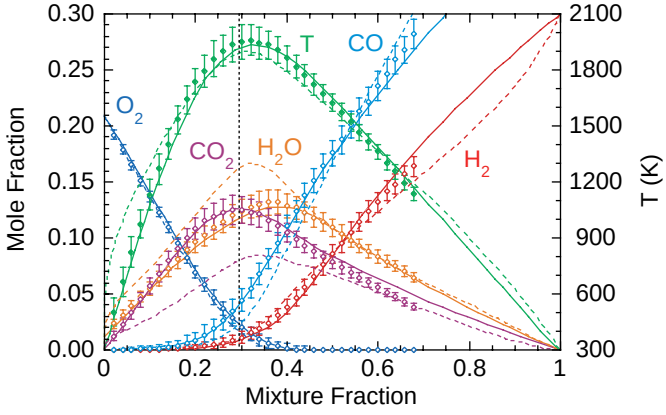


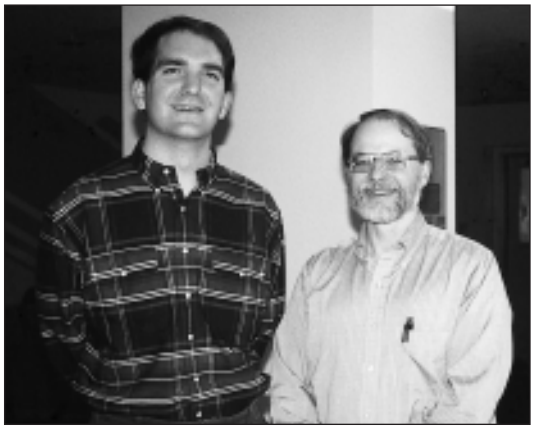
Figure 2. Measured conditional means of temperature and major species in a turbulent jet flame of $CO/H_2/N_2$ at Reynolds number 16,000 are compared with strained laminar flame calculations. Symbols represent conditional means and error bars show conditional rms fluctuations of measurements taken 30 nozzle diameters from the jet exit. The dashed curves show results of a laminar opposed-flow flame calculation at a strain rate of a=100 s^{-1} and with full molecular transport (differential diffusion) included. The solid curves show results of a laminar flame calculation at the same strain rate but with all diffusivities set equal to the thermal diffusivity.

Multiscalar measurements in a series of piloted methane/air jet flames, ranging in Reynolds number from 1,100 to 44,800, have revealed distinct trends in mass fractions of several species. Scalar transport and unsteadiness are believed to contribute, and accurate prediction of these measured trends will be an important test of turbulent combustion models.

The TDF Lab is described on the web at www.ca.sandia.gov/tdf/Lab.html. See also the note on the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames on page two, herein.

Alexander Grebenkov (left) and Anatoli Yakushan (right), both scientists from Belarus in the former Soviet Union, are collaborating with Larry Baxter (center) in developing technologies to remediate the contamination in Belarus, the Ukraine, and Russia from the Chernobyl power plant incident. Here they are discussing progress on construction of a pilot-scale facility. The commercial-scale facilities are foreseen to provide environmental remediation, address severe energy-supply problems in the region, and be profitable.

Chris Kennedy (seated) recently completed his postdoctoral assignment in the Reacting Flow Research Group, working with Jackie Chen (back, center), Roy Baty and Dan Aeschliman (neither shown) on a project concerning coherent structure in compressible jets. He also worked with Tarek Echekki (right), Hong Im (left), and Inge Gran (a Norwegian visitor, not shown) on numerical algorithms for DNS.



Robert Canaan (left), a post-doctoral fellow from the University of Texas, has spent the past year working with John Dec (right) and Eldon Porter (not shown) in the heavy-duty diesel engine combustion laboratory. Robert worked on several projects including measurements of liquid-phase fuel penetration (*CRF News* **20**:1), soot formation rates for fuel-water emulsions, and an investigation of NO formation during diesel combustion using PLIF imaging (*CRF News* **19**:5).

The Third International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames (TNF) will be held July 30 through August 1, 1998, in Boulder, CO, just before the Combustion Symposium. Information on this ongoing collaboration among experimentalists and modelers is available on the WorldWide Web at www.ca.sandia.gov/tdf/Workshop.html. The deadline for pre-registration is April 15. (See article on front page.)

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On January 20 and 21 the CRF hosted the most recent diesel combustion CRADA (cooperative research and development agreements) reviews. The reviews covered work with (1) Cummins, Caterpillar, and Detroit Diesel focusing on diesel combustion issues in the heavy-duty class of engines and (2) Chrysler, General Motors, and Ford concentrating on diesel engines intended for automobiles. Updates from research being conducted at the engine manufacturers as well as summaries of recent results from staff at Sandia, Los Alamos, the University of Wisconsin, and Wayne State University were presented.

The reviews are conducted jointly with the heavy-duty and light-duty engine manufacturers as a means of facilitating the interaction of Department of Energy-funded activities that have broad application. During the two-day meeting, the Diesel Collaboratory program was also reviewed (*CRF News* **19**:3). Sandia, Lawrence Berkeley, and Lawrence Livermore National Laboratories are involved in the collaboratory, in addition to the aforementioned CRADA participants in the heavy-duty class of engines.

Liquid-phase fuel penetration in diesel sprays investigated

Liquid-phase fuel penetration and evaporation are important factors in optimizing direct-injection diesel engine combustion processes, especially for the small-bore automotive diesels currently under development. Penetration of the liquid-phase fuel is needed to promote fuel-air mixing, but can lead to higher emissions if the liquid fuel impinges and collects on piston bowl walls. Liquid-phase fuel penetration in diesel sprays has recently been investigated by Dennis Siebers with support provided by DOE's Office of Heavy-Duty Vehicle Technologies and Office of Advanced Automotive Technologies. The research was conducted as part of Cooperative Research and Development Agreements with the automotive and diesel-engine industries.

The research examined the effects of a wide range of parameters on the maximum extent of liquid-phase fuel penetration in diesel sprays (i.e., the "liquid length") with the aim of identifying the processes controlling fuel vaporization and developing a scaling law that embodies this information.

Parameters varied in the investigation included: the injection pressure, the orifice diameter and aspect ratio, the ambient gas temperature and density, and the fuel temperature and volatility. The ranges considered for the engine-related parameters included those in current and proposed diesel engine technologies.

The research was performed in the optically accessible diesel combustion simulation facility at the CRF using an electronically controlled, common-rail diesel fuel injector. Images of Mie scattered light from the liquid–phase fuel in diesel sprays were used to determine the liquid lengths.

Two significant trends observed in the data are shown in the figures: a linear dependence of liquid length on orifice diameter (Fig. 1) and an independence of liquid length on the injection pressure (Fig. 2). These two trends strongly suggest that vaporization in a diesel spray, like combustion after the initial premixed burn, is controlled by air entrainment (i.e., turbulent mixing). This conclusion was reached by considering the dependence of liquid length on orifice diameter and injection pressure expected in two limiting fuel vaporization cases: (a) control by air entrainment and (b) control by local interphase transport processes (e.g., heat and mass transfer at droplet surfaces). Only the former explains the trends in Figs. 1 and 2.

Other trends observed in the data included strong non-linear decreases in liquid length with increasing ambient gas density or temperature and an increase in liquid length with decreasing fuel volatility. The fuel volatility effects were the most significant at light load engine conditions. Comparison of liquid lengths for multi-component and single-component fuels also suggests that the liquid length of a multi-component fuel is controlled by its lower volatility fractions, or that a batch distillation-type vaporization process is occurring.

Analysis of the results is continuing and is providing new insight into the processes controlling fuel evaporation under diesel-spray conditions. A scaling law for the liquid length in a diesel spray is being developed that will aid the engine designer and provide a baseline for comparison with predictions of vaporization models in the multi-dimensional computational models being developed as engine design tools.

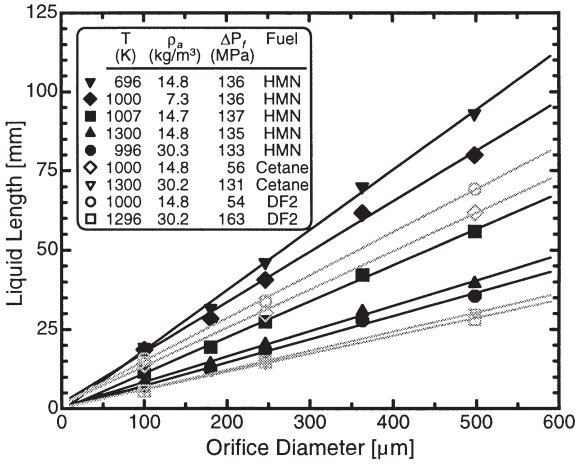

Figure 1. Liquid length versus orifice diameter for a wide range of conditions. The terms in the legend are the ambient gas temperature (T) and density (ρ_a), the orifice pressure drop (ΔP_f), and the fuel type (HMN is heptamethylnonane and DF2 is a commercial #2 diesel fuel). The lines in the figures are linear least squares fits to the data for each set of conditions given in the legend.

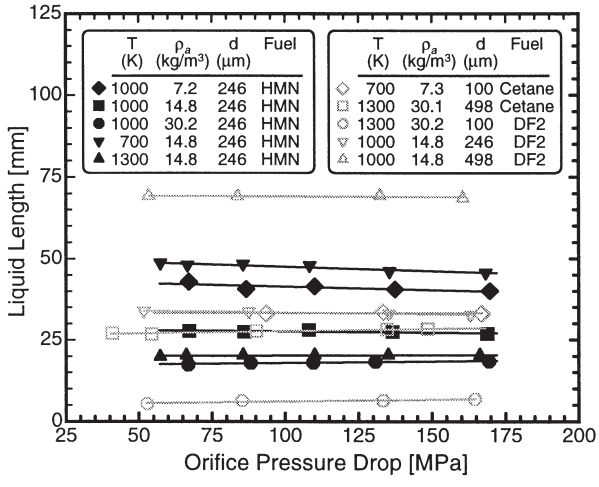

Figure 2. Liquid length versus the pressure drop across the injector orifice for a wide range of conditions. The term d in the legend is the orifice diameter. See Fig. 2 for definitions of the other terms.

Laser-based sensor for steelmaking undergoes long-term tests

The final stages of developing a laser-based sensor for real-time control in the basic oxygen process of commercial steelmaking have been reached. Sandia's expertise in the development of optical diagnostics and combustion science are a natural fit with the needs of North American steelmakers for improved methods to monitor and control operations in the production and treatment of steel.

Sarah Allendorf, David Ottesen, Peter Ludowise, Alan Salmi, and James Ross are collaborating with Michel Bonin, Alan Alsing, and Soren Jensen (Insitec Measurement Systems), and Tim Miller, Dan Goldstein, and Alok Sharan (Bethlehem Steel) under a program jointly funded by DOE's Office of Industrial Technologies and a consortium of steel companies under the American Iron and Steel Institute. (Related projects to monitor the surface of the molten steel and contour of the refractory lining of the furnace are being led by Beth Fuchs and John Sakos.)

The team has built and is testing an optical sensor based on mid-infrared tunable diode lasers to measure in real-time the concentration and temperature of infrared-active gases emanating from a basic oxygen furnace (BOF). The BOF is the industry workhorse for the production of steel; a batch of approximately 350 tons of molten iron (containing 4% carbon) is converted to steel (nominally 0.05% carbon) by reaction with a stream of high-velocity oxygen in a period of 25 minutes. This batch process is currently controlled by a static materials and energy-balance model, and its efficiency and accuracy is limited by the lack of real-time monitoring capability.

> A promising result of recent tests is . . . a correlation with important processing variables such as final temperature and carbon content of the molten steel.

Primary gas-phase products of the basic oxygen process are CO and CO_2, and our laser beam is transmitted through the particle-laden gas (see figure) during the process of "oxygen blowing." A promising result of recent tests is that information from measured absorption line-shapes shows a correlation with important processing variables such as final temperature and carbon content of the molten steel.

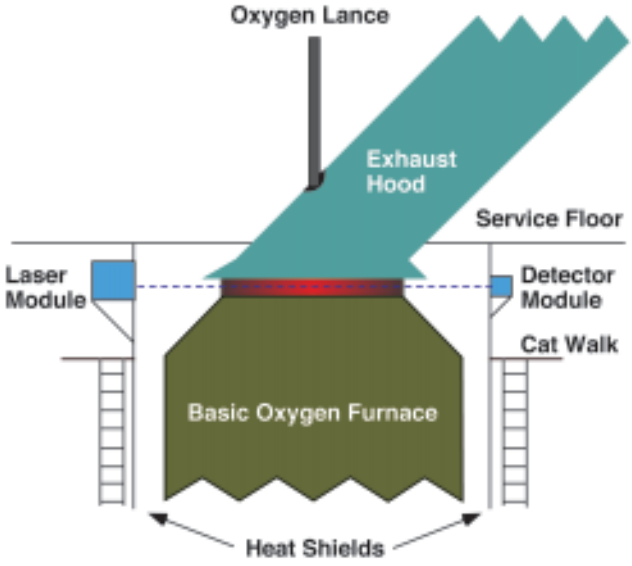

Diagram of the experimental arrangement.

In addition to developing the spectroscopic method for these real-time measurements, a major challenge in this project has been the creation of a rugged and reliable sensor package for continuous operation in the extremely harsh environment of a commercial steel mill. The work accomplished by the multi-organizational team has led to a successful prototype that was recently tested for a one-month period at Bethlehem Steel's BOF shop in Sparrows Point, MD.

A patent application for the laser-based sensor has been filed, and further long-term tests are planned for this spring at Bethlehem Steel to improve the sensitivity of the method for dynamic prediction of the final steel temperature and carbon content.

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