Hot-Film Anemometer Measurements in a Starting Turbulent Jet

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Introduction

IT has become common practice when modeling diesel engine combustion to assume that a two-phase fuel spray can be treated as a homogeneous, quasisteady turbulent gas jet.[1,2] The physical description used to support this assumption proposes that the atomization process is rapid when the liquid-jet velocity is sufficiently high. Since finely dispersed droplets will decelerate rapidly, the velocity of the droplets will quickly become accommodated to the velocity of the air entrained by the jet. Thus, at a short distance from the jet orifice the fuel spray will behave as a classical quasisteady free-air jet that is carrying with it continually evaporating fuel droplets.

Considering how often this simple model is used, it is surprising that quantitative verification has not been even partially established. It is admittedly difficult to confirm an analogy between two-phase sprays and homogeneous gas jets; however, the assumption of treating a suddenly started transient jet as a quasisteady free jet is amenable to verification. The experiment briefly described in this Note addresses this question, in addition to providing some measurements on the tip penetration rate of suddenly started turbulent air jets. Further details can be found in Ref. 3.

The Experiment

Because the ultimate application of the techniques developed for this air jet study is the investigation of fuel-injected internal-combustion engines, the experiment was designed with this goal in mind. A small electric motor was used to simulate the engine. The motor drove a digital shaft encoder at a speed of 10 rps. The binary-coded decimal output word of the encoder gave the absolute angular position of the motor shaft with a resolution of 0.1 deg. A computer interfaced to the encoder was programmed to control a solenoid valve, which produced an intermittent air jet once each revolution of the motor. The "on-time" of the jet was varied, typical values being 4-100 ms. Synchronous with the turn-on and turn-off times of the jet, the computer digitized and recorded the signal from a constant temperature hot-film anemometer probe located on the centerline of the jet.

The ambient temperature jet was formed using dried house air supplied from a constant pressure plenum. Outflow from the plenum went directly to a solenoid-activated fuel injector through a restriction-free line. Two injector orifice designs were used, as illustrated in Fig. 1. Nozzle A was the baseline configuration of the injector. The modified nozzle B was used to create a larger effective orifice diameter. Because the configurations were complex, it was not possible to characterize the jet behavior using the physical dimensions of each orifice. Instead, the steady-state jet for each test condition was studied first. The mean axial velocities measured along the centerline were fit to the analytic solution of Warren,[4] providing an empirical determination of the effective nozzle radius r_j. The velocity measured at the exit plane of the injector u_j was used to complete the characterization of the jet conditions.

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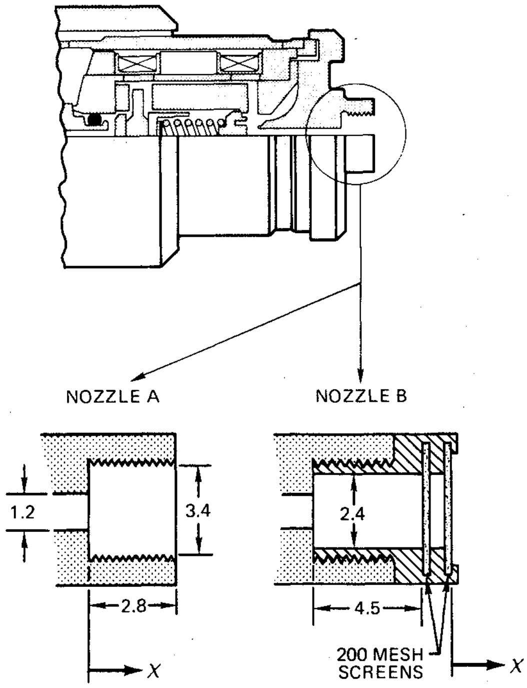

Fig. 1 Solenoid-actuated valve and nozzle configurations used in the experiment (*x* is the location of the origin of the axial coordinate; all dimensions in millimeters).

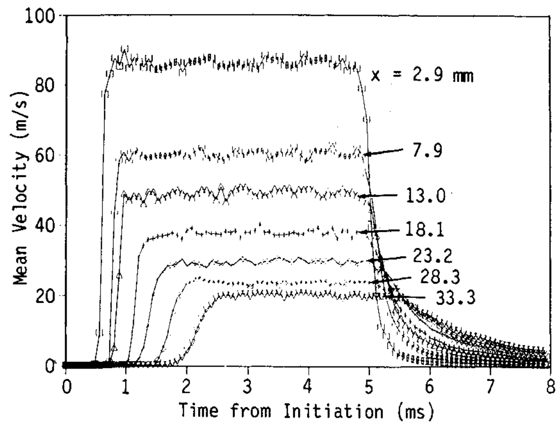

Fig. 2 Ensemble-averaged measurements of starting-jet centerline mean velocities, using nozzle A (the jet was on for 4 ms).

The transient jet velocity measurements were made by positioning the hot-film probe at various locations along the axis of the injector. The nonlinearized anemometer bridge output was digitized by the computer at specified times triggered by the shaft encoder. At 10 rps with 0.1 deg resolution, the maximum achievable data rate was 36 kHz, which was used when making measurements near the jet origin. At locations far from the orifice, where less time resolution was required, the data rate was reduced. The digitized anemometer signal was converted to velocity by the computer using a fourth-order polynomial fit to a calibration curve. The velocity measurements at each crank-angle position were ensemble-averaged for 100-500 cycles of the jet, yielding the mean velocity and its standard deviation.

Experimental Results

A typical set of results for the ensemble-averaged velocity histories measured at several axial locations for a jet that was suddenly turned on for a duration of 4 ms is given in Fig. 2. At each location the mean velocity rises smoothly to a steady-state plateau, with both the rate of rise and the plateau level decreasing with distance from the nozzle exit. The transient

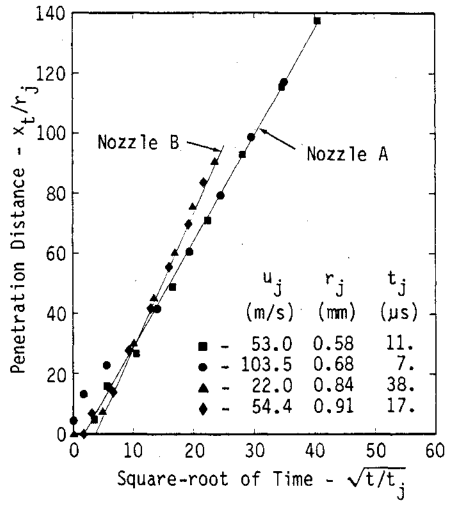

Fig. 3 Measurements of the tip penetration distance as a function of the square root of elapsed time from initiation of the jet.

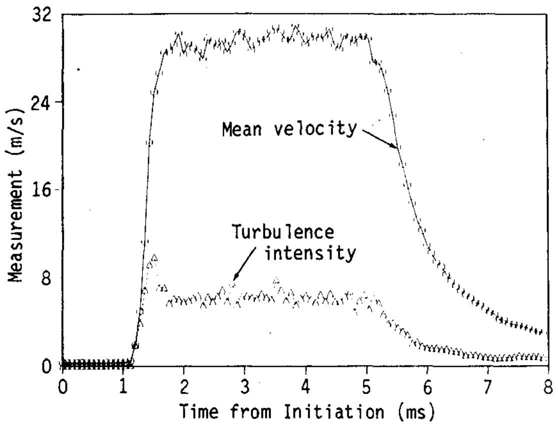

Fig. 4 Comparison of mean velocity and turbulence intensity measurements for a suddenly started jet, made at $x = 23.2$ mm with nozzle A.

jet plateau velocities for the four sets of test conditions studied were compared with the measured results for the steady-state jet centerline velocity. It was found that the transient and steady-state values were generally in agreement to within 5%. The very fast rate of rise to the plateau levels supports the quasisteady assumption of the analytical models mentioned earlier.

Following the procedure introduced by Abramovich and Salon,[5] who made hot-film measurements in starting laminar jets, the arrival time of the jet tip at a specific point in space, termed the penetration distance x_t, has been defined as the instant when the average jet velocity reaches 70% of the final plateau value. The results for this measurement are shown in Fig. 3, plotted as a function of the square root of elapsed time from initiation of the jet. The linear behavior of the results is consistent with the consensus model for spray penetration reported in a literature survey conducted by Hay and Jones.[2] The parameter used to nondimensionalize the abscissa of Fig. 3 was the ratio r_j/u_j, which defines a time constant t_j that appears to uniquely characterize the behavior and similarity of suddenly started turbulent jets. The difference in slope for the two nozzle configurations is believed to be due to differences in turbulence levels. Steady-state jet measurements of the turbulence intensity made along the centerline showed that nozzle A produced a jet of typical behavior, with an asymptotic relative turbulence level of about 25%. In contrast, the screens located in the orifice of nozzle B produced an uncharacteristically high turbulence level that reached 35% at $x/r_j = 100$, without showing an indication of approaching an asymptotic value. Increased entrainment from the greater turbulence caused the transient jets produced with this nozzle to penetrate at a slower rate.

The ensemble-averaging procedure used to determine the mean velocity is also applicable to evaluation of the turbulence intensity. The difficulty encountered with using this or any other averaging procedure, however, is that to do so implies a statistically repeatable mean velocity field. Much like the intermittent boundary regions of steady-state free-shear flows, the leading surface of a transient jet represents the interface between essentially nonturbulent ambient fluid and a fully turbulent flow. Variations in the arrival time of the jet tip at the measurement location bias both the mean velocity and the turbulence. The error in the former appears as a decrease in the rate of rise of the mean velocity to the plateau level, whereas the error in turbulence occurs in its absolute amplitude. Turbulence measurements made at a representative axial position in a suddenly started jet are compared in Fig. 4 with the mean velocity measured at the same location. The arrival of the front of the jet is marked by a momentary peak in the indicated turbulence, due to cycle-by-cycle variations in the arrival time of the leading surface. In general, the more abrupt the discontinuity or velocity gradient in the flow at the jet front, the greater the cyclic variation contribution to the measured turbulence intensity level. In order to account for this effect, conditional sampling procedures must be used.

Conclusions

Hot-film anemometer measurements show that the centerline mean velocity and turbulence intensity of suddenly started jets quickly reaches the steady-state jet value. This result serves to justify the often used hypothesis that transient jets can be treated as being quasisteady. Measurements of the location of the tip of the jet show that the tip penetration varies as the square root of time, and that the ratio of orifice radius to initial jet velocity defines a time constant that characterizes the behavior and similarity of the tip penetration of suddenly started jets.

Acknowledgments

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