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High-Speed Flow Visualization of Fluid Instabilities¹

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The fluid instability resulting from the impulsive acceleration a thin, heavy gas layer embedded in a lighter gas is characterized through high-speed flow visualization. The shock-accelerated event occurs over the course of 1 *ms*. A laser sheet illuminates a plane of the gas layer and its evolution is recorded by a camera observing high-angle scattered light. Two sets of diagnostics were evaluated. These derived their time resolution either from gating the camera or pulsing the illumination source. The arbitrary inter-exposure timing associated with the gated camera was found to be significantly advantageous over the fixed intervals of the pulsed laser. The intensified, gated camera also placed more manageable requirements on the light source and provided sufficient data to measure the instability growth rates. However, the pulsed laser arrangement produced superior spatial resolution primarily due to the lack of an intensifier.

Previous work has been done utilizing the same gas shock tube facility. Jacobs *et al.*^{1,2} traced the flow of the heavy gas layer through the addition of a fluorescent tracer gas (biacetyl) which was illuminated by a pulsed dye laser tuned to the tracer. Utilizing an intensified camera, this arrangement produced a single image per event, and discovered three distinct nonlinear growth patterns. Budzinski *et al.*³ used the preferential Rayleigh scattering from the heavy gas layer as the diagnostic, with two dye lasers providing greater than 200 *mJ* per illumination pulse to produce two images per event. This study correlated the observed flow patterns to the initial layer state at the instant of shock impact. The primary goal of the current study was to produce greater than two images of the development of the gas curtain for each event so that the growth rates of the instability can be estimated.

Experimental Details

A thin curtain of SF_6 embedded in air was shock accelerated within a horizontal shock tube with internal dimensions of 75 *mm* square. This approximately 4 *m* tube is shown in Figure 1. The facility and procedures are similar to the work of Jacobs *et al.*¹. The impulsive acceleration of the curtain came from the impact of Mach 1.2 shock generated by breaking a diaphragm separating a driver section (pressurized to a gauge pressure of 137 *kPa*) from the driven section (at ambient pressure) with a solenoid actuated cutter. Due to the large jitter associated with the diaphragm bursting process, the timing for each event came from three flush-mounted pressure transducers. Two of these provided measurements of the speed and "quality" of the shock front while the transducer closest to the test section provides the electronic trigger input to the diagnostics.

The generation of the embedded SF_6 curtain in the test section is depicted in Figure 2. An initially varicose spatial perturbation is imposed on the layer by the nozzle through which it flows into the section from the top. An exhaust slot at the bottom of the section attached to a suction system removes the curtain material as well as air entrained by the curtain. The flow rates were small and the curtain remained laminar (though temporally varying in shape) throughout the vertical extent of the test section. The motion of the curtain gas ($\mathcal{O}(10\text{cm/s})$) is small compared to the shock piston velocity ($\mathcal{O}(100\text{m/s})$) or the instability growth rates ($\mathcal{O}(10\text{m/s})$).

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Figure 1: Experimental Facility

The curtain was composed of SF_6 (with a density approximately five times that of air) mixed with a small quantity of particulates (smoke). The smoke is generated through the use of a modified theatrical fog generator, and is composed of droplets of water and glycol. Pressurized SF_6 carrying "fog fluid" (American DJ Co., Euro Fog Fluid) moves through the heating chamber of an American DJ Co., Fog Hog theatrical fog generator. The resulting smoke enters a heat exchanger which condenses any remaining vapor, and ensures that the mixture entering the test section will be cool and incondensable.

The gas curtain is illuminated by a horizontal laser light sheet. The camera collects the scattered light from the curtain at approximately a 90° angle. The enhanced Rayleigh scattering from the smoke particles allows multiple images to be obtained for each event using available light sources. Due to the layer's thickness and its mean motion downstream at the piston velocity of the shock, it was possible to lay multiple exposures on a single CCD camera array during the course of a single event. Two techniques were applied to obtain time resolution of the resulting exposures.

In the first method, an intensified, gated CCD camera (Hadland Photonics SVR) was used in conjunction with a CW laser (Lexel Model 94). Each exposure was $2 \mu s$ in duration, which with the laser's output of $\approx 1 W$, gives excellent image quality at $2 \mu J$ of optical energy. The camera uses two back-to-back Gen-1 intensifiers and provides the full CCD resolution of 1134×437 pixels. The results are 8-bit images. Arbitrary gating times can be set, with the only limitation that there be no overlap of the exposures on the CCD (which is determined by thickness of the layer and the mean downstream velocity).

An unintensified and thermoelectrically cooled camera (Photometrics) was used in the second technique; deriving temporal resolution from a pulsed laser (Positive Light Merlin Nd:YLF). This method guarantees the camera the use its entire resolution and dynamic range of 512×512 pixels of 10-bit data. In this arrangement the primary limitation is in the temporal resolution due to the fixed pulse repetition rate of the laser. For the data shown, the laser was producing $15 W$ equivalent CW at $5 kHz$, which gives excellent images quality at $3 mJ$ of optical energy.

Figure 2: Schematic of Test Section

Results

The primary difficulty in moving toward several images per event was that the illumination power requirements were unattainable using Rayleigh scattering solely from the SF_6 . The present study increases the light-scattering efficiency of the heavy gas layer by seeding the flow with smoke. Such a method depends on the particulate accurately tracing an impulsively-accelerated flow. Estimates indicate that these small particles follow the acceleration of the Mach 1.2 shock with excellent fidelity, and the smoke-traced flowfield possesses similar features to both previous experimental observations as well as theoretical models. Also, the fine detail of the structures in the images strongly suggests that the smoke accurately tracks with the flow.

Figures 3, 4 and 5 show the results obtained using the gated, intensified camera/CW laser diagnostics arrangement. In the images, the shock induced mean motion of the gas curtain moves it from left to right. The leftmost exposure in each case shows the gas curtain immediately prior to shock impact. Each of the images shows one of the three primary late-time flow topologies. An in-depth physical analysis of these results can be found elsewhere⁴. For these diagnostics, the peak pixel values in the earlier exposures (prior to the flowfield becoming diffuse due to either turbulent mixing or large interfacial stretching) reside near 50% of the maximum (saturation) values of the 8-bit dynamic range. Some events have peak values nearing saturation. However, the laser sheet was not expanded to cover the entire test section. Instead only the central 3-4 periods were illuminated to provide sufficient lighting. Note, though, that the light energies used to produce these images are five orders of magnitude smaller than those used in previous work producing lower signal-to-noise³.

The arbitrary inter-exposure timing shown in these figures allows 8 dynamic images as well as an initial image just prior to shock arrival. The temporal spacing of the dynamic images (not including the spacings between the initial conditions and the first dynamic) are 60, 80, 80, 120, 120, 120, 120 μs .

Figure 3: Gated Camera, Downstream Mushrooms

Figure 4: Gated Camera, Sinuous

Figures 6 and 7 show results for the pulsed laser/open camera diagnostics. The fundamental differences between these data and the previous data sets are numerous. First, the entire extent of the test section was able to be illuminated while producing acceptable images without the use of an image intensifier. However, the illumination source used was producing 15 times the average power of that used with the gated, intensified camera and 1500 times the effective pulse energy. Also, the spatial resolution and the dynamic range of these latter data exceed that of the former. This is due in large part to former data's reliance on an image intensifier and its limitations on resolution and dynamic range. However, the intensifier also enables the arbitrary inter-exposure gating times of the previous method.

By far the most significant limitation of this second diagnostic method is in the temporal resolution. Here we get only 3-4 dynamic images per event. The free-running laser also does not allow the specification of the first dynamic exposure relative to the initial conditions and often overlap of the exposures occur. The limited number of dynamic exposures does not ensure the accurate estimation of the instability growth rate for each event. We are not aware of laser systems having higher pulse repetition rates and adequate pulse energies.

Figure 5: Gated Camera, Upstream Mushrooms

Conclusions

The limits imposed upon the images by the use of the image intensifier (i.e. resolution and dynamic range constraints) have not shown themselves to be obstacles in the physical interpretation of the results⁴. Therefore, the images using the gated, intensified CCD camera are very much more useful due to the arbitrary inter-exposure timing that it affords and the resulting greater number of dynamic images per event. more advanced intensified cameras that are available that use multiple intensified CCDs can practically eliminate any imposed minimum inter-exposure spacing. Such cameras will allow essentially any arbitrary time resolution to be obtained.

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Figure 6: Pulsed Laser, Upstream and Downstream Mushrooms

Figure 7: Pulsed Laser, Upstream Mushrooms