Effect of wall shear on the propagation of a weak spark-generated shock wave in argon

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Photo-acoustic deflection (PAD) measurements are presented for a weak spark-generated shock wave propagating in argon at 40 Torr in a cylindrical tube. Measurements indicate that for a given shock strength, there is a maximum distance of travel beyond which the shock front is nonplanar, consistent with the predictions of numerical calculations reported recently [S. M. Aithal and V. V. Subramaniam, Phys. Fluids 12, 924 (2000)]. The initially planar shock wave exhibits curvature at downstream locations in the shock tube in the absence of any imposed temperature gradients. Since the PAD signal is a line-of-sight measurement, it is sensitive to the axial gradient of density at all radial locations, and shock curvature manifests itself as a split and spread PAD signal. In contrast, a planar shock registers a sharp, delta-function-like PAD signal. The curvature of weak shocks observed in the present experiments is due to viscous action alone, as the wall shear retards the near-wall portions of the front relative to its near-axis portions. The PAD signal associated with shock curvature due to wall shear alone is found to closely resemble that due to externally imposed radial temperature gradients such as in a glow discharge plasma. © 2001 American Institute of Physics. [DOI: 10.1063/1.1378033]

Experiments in the former Soviet Union1–4 and, more recently, in the United States5–11 have documented certain characteristics of shock waves propagating through a weakly ionized (n_e/n ≈ 10^{-8}–10^{-6}) plasma in a shock tube. These include an increase in shock propagation velocity within the plasma and an apparent broadening of the shock front as recorded by photo-acoustic deflection (PAD) measurements. Recent work5–12 has attributed the former effect to heating of the gas by the glow discharge and the latter to the presence of radial temperature gradients within the glow region. Radial temperature gradients can indeed produce different velocities for the shock front on the tube axis and the region near the wall. It has been suggested that this results in curvature of the shock front and explains the apparent broadening and splitting observed in photoacoustic deflection signals. Recently, numerical calculation of the characteristics of spark-generated shock waves has shown that wall shear can also produce curvature of the shock front in the absence of any radial thermal gradients, depending on the shock strength and available length of the tube. In this Brief Communication, we present experimental measurements verifying the predictions of Ref. 12 for a weak spark-generated shock wave propagating in argon at 40 Torr and 300 K, under the action of viscous effects alone and in the absence of radial thermal gradients.

The experimental apparatus comprises a pyrex glass tube (1 m long and 5 cm in diameter), with a Kolb tube for generating the shock at one end (see Refs. 5–8 for further details). As shown in Fig. 1, the shock is produced by a high-voltage spark discharge (lasting on the order of microseconds) in argon gas at a pressure of 40 Torr. This rapid energy addition into the gas results in a sudden rise in gas temperature and pressure, and produces compression waves that steepen to form shock waves traveling in opposite directions. The shock tube has three flanges labeled 1–3 in Fig. 1, starting from closest to the Kolb tube, and shock characteristics are explored at various axial locations downstream from the first flange (position 1) using photoacoustic deflection.5–8 Typically, spark discharge voltages in excess of about 3 kV are required to reliably produce shock waves which then are capable of traveling the entire length of the tube. The numerical results of Ref. 12 show that the maximum distance traveled by such a shock before succumbing to the effects of wall shear depends on the amount of energy initially imparted to the gas by the spark discharge. Unfortunately, it is extremely difficult to control the energy loaded into the gas by the spark in a repeatable manner simply by adjusting the spark duration or supply voltage. Consequently, another means to observe the effects of wall shear on weak shock waves is used in the present work. When the spark is discharged in the gas, two shock waves are produced, one traveling to the right along the shock tube and one traveling to the left, as described in Ref. 12. The leftward moving shock reflects off the short end of the tube and follows the primary shock that travels to the right. This secondary, reflected shock, is weaker (M=1.009) than the primary shock wave (M=1.025) and lags approximately 265 μs behind. The secondary shock wave is further weakened by passing it through a constriction with an axially centered orifice, 6 mm in diameter, located at position 1 (see Fig. 1). The primary shock wave also passes through this orifice. After the primary shock wave emerges as a curved front and then steepen...
ens into a planar shock, it remains planar for the remainder of the tube. The secondary shock also emerges as a curved front that then straightens into a planar shock front propagating along the shock tube (see Fig. 2). However, this secondary shock wave is much weaker than the primary and does not sustain itself as a planar front beyond a certain location along the tube. It was shown in Ref. 12 that a shock of given strength will succumb to viscous effects after traveling a certain length along the tube. A weaker shock will therefore exhibit effects of curvature for shorter lengths of travel compared to stronger shocks, despite the fact that wall shear increases with shock strength. Since the shock tube used in the present experiments is 1 m long, the distance of travel over which shock curvature due to viscous effects can be studied is limited. For this reason, the characteristics of the weaker secondary shock are examined in this work in order to study its formation and propagation in the presence of viscous effects alone.

Figure 2 shows both the primary shock and the secondary shock from the same experiment at a location of 57.5 cm from position 1. It can be seen from their sharp delta-function-like PAD signal shown in Fig. 2 that both are planar. Note that the secondary shock is significantly weaker (i.e., has a lower amplitude) than the primary shock and is 8.56 cm (265 μs) behind the location of the primary shock. The location of the secondary shock (and, hence, its arrival time), relative to the primary shock at a given downstream location, is repeatable. The separation between the two shock waves is observed to increase as they travel down the length of the shock tube. The secondary shock lags the primary shock by ~265 μs downstream of position 1, but lags by as much as 280 μs towards the end of the shock tube. Figures 3(a)–3(c) show PAD signal data for the secondary shock wave at various axial locations downstream from the orifice (position 1). In Fig. 3(a), it can be seen from the split and spread PAD signal that the secondary shock is curved immediately downstream of the orifice. It then steepens into a planar shock front [note the delta-function-like appearance in Fig. 3(b)], and is subsequently nonplanar, as can be seen from the split and spread PAD signal 63 cm downstream from position 1, shown in Fig. 3(c). Figure 4 shows details of the PAD signal of both the primary and secondary shock from the same experiment at a location of 63 cm downstream of the orifice. Figures 3 and 4 clearly show that the secondary shock is nonplanar immediately after it emerges from the orifice, straightens out, and that it becomes nonplanar again further downstream due to the action of wall shear.

The PAD signal is generated as the shock traverses the path of the transverse laser beam. The streamwise density gradient across the passing shock front causes the laser beam to be deflected onto the detector, resulting in the generation of a sharp peak. The amplitude of this peak is proportional to the magnitude of the density gradient. Thus, we may write

\[ I_{\text{PAD}} \propto \int_{-R}^{R} \frac{\partial \rho}{\partial x} dr. \]  

For a perfectly planar front \( \frac{\partial \rho}{\partial x} \) is constant versus \( r \), the radial coordinate. In this case, a split or spread PAD signal is indicative of curvature of the front itself since the signal samples various radial locations along the line of sight. On the other hand, if \( \frac{\partial \rho}{\partial x} \) exhibits nonmonotonic variation with \( x \), this can contribute to splitting and spreading of the
PAD signal as well. The numerical calculations reported in Ref. 12 show that both effects are present, but that nonplanarity of the front has a greater influence on PAD signal structure. Furthermore, nonmonotonic variation of the density with \( x \) would result in multiple PAD signal peaks that are on the order of 30 \( \mu s \) apart, with the troughs approaching zero signal. In contrast, PAD signals in the present experiments exhibit split peaks that are on the order of 10 \( \mu s \) or less apart and troughs with nonzero amplitude [see Figs. 3(c) and 4]. We can therefore be reasonably certain that the observed splitting and spreading of the PAD signals is indeed due to nonplanarity of the shock front.

It has been observed experimentally that shock waves of moderate strength travel a greater distance before succumbing to wall shear, compared to weak (M~1) shocks. Their corresponding PAD signals remain sharply peaked compared to the weaker shocks, which exhibit split and spread PAD signals. There are two possible explanations for this observation. First, since wall shear is greater for the stronger shock, it is expected to be smeared near the wall. In this instance, the shock would remain largely planar until the near-wall regions where it would simply disappear, thereby resulting in a single sharp PAD signal. This is analogous to classical Fanno flow, where a supersonic flow can be reduced to subsonic speeds without shock formation, by the action of wall shear alone. The second possible reason involves sensitivity of the PAD measurement itself. Equation (1) shows the true nature of the PAD signal, which is comprised of contributions from streamwise density gradients at various radial locations. Consequently, the axial density gradients near the

**FIG. 3.** (a) PAD signal of the secondary shock wave at three axial locations (42, 48, and 50 cm downstream of position 1) showing the evolution of its planarity after it emerges from the orifice. Note the increasing amplitude of the signal vs axial location, indicative of steepening. Further, note the split and spread nature of the PAD signal, indicative of curvature of the front. (b) PAD signal of the secondary shock wave at three axial locations (52.5, 55, and 58 cm downstream of position 1) showing its planarity as it propagates down the tube. Note the relatively constant amplitude of the signal vs axial location, as well as its sharp delta-function-like appearance, indicative of its planarity. (c) PAD signal of the secondary shock wave at three axial locations (63, 67, and 70 cm downstream of position 1) showing the degeneration of its planarity as it succumbs to the effects of wall shear. Note the decreasing amplitude of the signal vs axial location as well as the split and spread nature of the PAD signal, indicative of curvature of the front and loss of planarity.

**FIG. 4.** PAD signal vs absolute arrival time, showing the primary and secondary shock waves from the same experiment at a location of 63 cm downstream of the orifice. Note that the primary shock (on the left) is still planar while the secondary shock (on the right) exhibits a split and spread structure, indicative of shock curvature. This figure should be compared to Fig. 2, where both shocks are planar upstream of the location presented in this figure.
presence of a glow discharge plasma in argon
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the PAD signal of a primary shock wave
of the observed split and spread PAD signals. Figure 5 shows
periments without a glow discharge, and with no externally
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; i.e., M = 1.0, the axial density gradients in the near-wall regions are comparable to
those near the centerline, and hence contribute significantly to the PAD signal. Thus, no effects on the PAD signal may be observed for a shock of moderate strength although its curvature may actually be greater than that of a weaker shock. In other words, while shock curvature due to wall shear may occur in shocks of all strength, it is more noticeable the weaker the shock strength, resulting in a split and spread PAD signal.

Radial temperature gradients that exist in a glow discharge have been shown to cause curvature of the shock front. However, curvature of the shock front has also been shown to occur in numerical calculations due to the presence of a retarding force such as wall shear. In the present experiments without a glow discharge, and with no externally imposed thermal gradients, wall shear can be the only cause of the observed split and spread PAD signals. Figure 5 shows the PAD signal of a primary shock wave (M ≈ 1.4) in the presence of a glow discharge plasma in argon (10 mA, 4.5 kV, 30 Torr). Also shown in Fig. 5 is the PAD signal of the secondary shock wave (M ≈ 1.009) previously displayed in Fig. 4 in the absence of a glow discharge. Note that the trailing peak is smaller in magnitude compared to the leading peak, consistent with the near wall portion of the shock having a shallower axial density gradient compared to the near axis portion of the shock. Although the two shock strengths in Fig. 5 are different, this figure serves to highlight the similarities between these PAD signals and shows that shock curvature can arise either from radial thermal gradients or due to wall shear alone. It is important to mention that the comparison in Fig. 5 could have been made for similar shock strengths. However, a much longer (several meters long) shock tube would have been required in order to observe the effects of wall shear alone on a M ≈ 1.4 shock wave. This work has experimentally verified the predictions of the numerical calculations reported in Ref. 12 regarding the influence of wall shear on the structure of weak propagating shock waves, and suggests that modification of shock structure by application of an external force is possible even in the absence of any thermal effects. Imaging of the shock front using laser-induced fluorescence would provide further valuable insight into the structure of the shock front itself.

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