The Mach Reflection of a Detonation Based on Soot Track Measurements

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This paper presents a series of soot tracks formed by gaseous detonation waves diffracting around wedges with different wedge angles. These cellular structure patterns describe the Mach-reflection processes of a detonation and reveal some unique characteristics. They can be used to analyze the relationship between the trajectory angle of the triple point, wedge angle, and initial pressure in Mach reflection. Compared to the Mach-reflected one-dimensional shock wave in nonreactive air, all these unique characteristics for a Mach-reflected detonation should be attributed to the transverse-wave structure of the detonation front; meanwhile, the precursor shock wave and transverse wave influence the Mach-reflected detonation, respectively. The experimental results support the recently published numerical simulation of this complex phenomenon.

INTRODUCTION

The reflection of an oblique gaseous detonation has become increasingly important in the last decade due to its application in supersonic propulsion and the also because the cellular structure is universal. Quite a number of papers presented at the 1999 International Symposium on Computational Fluid Dynamics (CFD) held in Bremen, Germany deal with this subject. It is now shown that detonation cells are likely to occur in many types of detonations, ranging from frequently encountered chemical systems to thermonuclear supernovae. Consequently, the chemical and physical parameters required for a numerical simulation of a supernova blast are better known than those in any but the most idealized terrestrial problems.

In an academic sense, the reflection of detonation has not been studied extensively compared with the reflection of shock waves. Gvozdeva et al. [1] and Edwards et al. [2] have shown that there exists Mach reflection as well as regular reflection for detonation. In the 1990s, the problem was revived by the work of Meltzer et al. [3] and the Mach-stem overdriven detonation wave was studied in detail. Yu [4] and Akbar [5] performed a systematic investigation of the interaction between a gaseous detonation and a wedge. Zhang et al. [6] conducted large-scale experiments for the Mach reflection of detonation waves in an acetylene-air mixture. Recently, Ohyagi et al. [7] carried out a numerical simulation of the reflection processes of a detonation wave on a wedge. Their numerical simulation shows that where Mach reflection occurs, the cell sizes in Mach stem are smaller than those in the incident wave and are distorted. Their results also show that the trajectory of the triple point is not a straight line but deflects during the interaction process between the transverse waves and the wedge surface. Miltiadis et al. [8] also performed a numerical study of wedge-induced detonation. They studied the influence of the top corner of a wedge on the structure of the reaction zone for long and short wedges, respectively. Jones et al. [9] demonstrated numerically that the transverse-wave structure of the detonation front is critical to the reignition process in area expansions. Laser shadowgraphy and numerical simulation were the main methods adopted in these studies. Within this chain of investigation, the present article provides some new experimental results based on soot-track measurement. Soot track is a conventional measurement in gaseous

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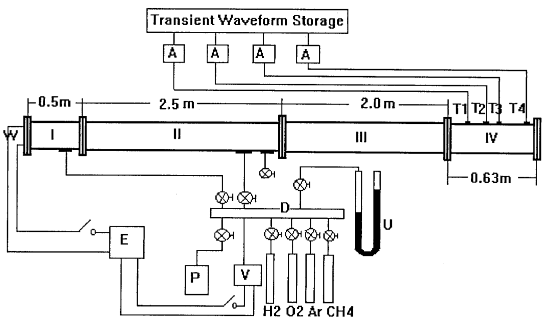

Fig. 1. Experimental facilities.

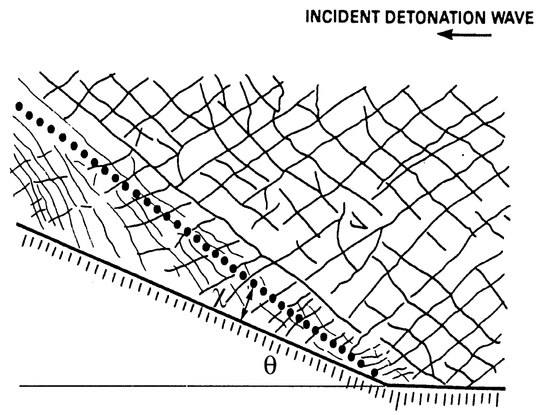

Fig. 3. Scheme of a Mach-reflected detonation on a wedge, θ wedge angle; χ trajectory angle; ●●● trajectory of triple point.

detonation studies. Combined with other measurements, it is here used to analyze the interaction between a gaseous detonation and a wedge. The experimental study reveals some unique characteristics of a Mach-reflected detonation and agrees with the numerical simulation of Ohyagi et al. [7]. The present results may also be used to understand the critical effect of the transverse-wave structure of the detonation front in area contraction, and to infer the respective effect of the precursor shock wave and the transverse wave in Mach reflection of detonation.

EXPERIMENTAL METHODS

Experiments were performed in a 5.7-m-long detonation shock tube with $40 \times 40\text{-mm}^2$ cross-section. The shock tube consisted of four sections with different lengths: the 0.5-m long driving section I and the 5.13-m driven sections II–IV, including a 0.63-m test section IV, as shown in Fig. 1. A diaphragm was inserted between sections I and II, when experiments were performed at low initial pressure. In order to get high-quality cellular patterns, the stoichiometric oxyhydrogen mixture diluted with argon filled the high-pressure driving section and also the low-pressure driven section.

All wedges have identical heights (35 mm) and widths (39 mm) but different lengths, ranging from 35 mm (45°-wedge) to 198.5 mm (10°-wedge) according to respective wedge angle. So there is an identical gap for all wedges for detonation waves to flow through. The wedge was mounted on the sidewall in the test section about 4.65 m downstream from the diaphragm, as shown in Fig. 2. The smoked glass was placed at the bottom of the channel to record the cellular structure pattern when Mach reflection occurred. Piezoelectric pressure transducers were mounted along the top wall to record the pressure history and measure the detonation velocity, the first of which was at ~4.65 m downstream from the diaphragm. In order to be as close as possible to the surface of the wedge, the transducers T_2 and T_3 deviated from the central axis 7.5 mm to ensure that at least one transducer from T_2 and T_3 could

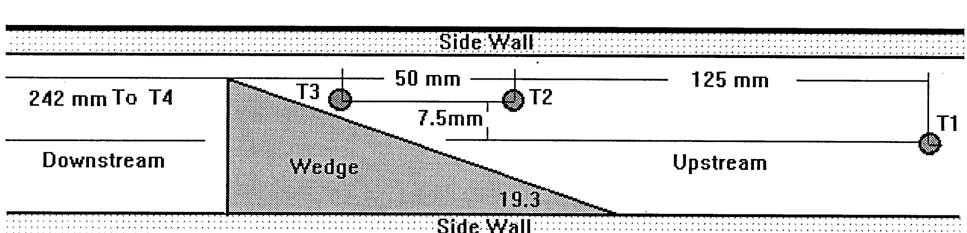

Fig. 2. Scheme of wedge mounting and the distribution of transducers T_1–T_3.

TABLE 1

The Experimental Data of Detonation Pressure (Wedge Angle 19.3°, $2H_2 + O_2 + Ar$)

P_0 (kPa)	P_{theo} (kPa)	P_1 (kPa)	P_2 (kPa)	P_3 (kPa)	P_2/P_1	P_3/P_1	P_3/P_0	P_2/P_0	P_1/P_0	Err (%)
17.33	317.9	334.1	339.6	401.5	1.02	1.20	23.17	19.60	19.28	5.1
20.00	368.6	380.7	391.0	463.5	1.03	1.22	23.18	19.55	19.04	3.3
26.67	496.8	498.7	491.5	625.1	0.99	1.25	23.44	18.43	18.70	0.4
33.33	625.9	612.5	614.4	762.0	1.00	1.24	22.86	18.43	18.38	2.1
40.00	755.9	772.5	760.8	932.0	0.99	1.21	23.30	19.02	19.31	2.2
46.67	886.6	896.7	898.4	1073.3	1.00	1.20	23.00	19.25	19.22	1.2
53.33	1018.0	1013.5	1027.9	1257.8	1.01	1.24	23.58	19.27	19.00	0.4

P_0, Initial pressure; P_1, pressure measured at T_1; Err, the error of P_1/P_0 (theoretical to experimental value); P_{theo}, theoretical pressure of incident detonation; P_2, pressure measured at T_2; P_3, pressure measured at T_3.

measure accurately the pressure in the Mach-stem region, as shown in Fig. 2.

Stoichiometric hydrogen-oxygen mixtures diluted with 25% argon ($2H_2 + O_2 + Ar$) were used in the present experiments. Two groups of experiment were carried out:

1. To show the relationship between trajectory angle χ and wedge angle θ (Fig. 3), one test series was performed under identical initial pressure 16.0 kPa for different wedges. Eight different wedge angles—10, 15, 19.3, 26.6, 30, 35, 40, and 45°, respectively—were employed in these tests. Figures 4 to 9 show some typical soot tracks of cellular structure patterns in this case.
2. To show the relationship between trajectory angle and pressure in the Mach-stem region as well as initial pressure, a second test series was performed. A 19.3°-wedge was mounted in the test section. Different initial pressures ranging from 16.0 to 40.0 kPa, respectively, were adopted. Figures 5, 10, and 11 show the typical cellular structure pattern in this case.

Table 1 shows the pressure distribution for a 19.3° wedge for different initial pressures.

RESULTS

Figure 4 shows the characteristic lozenged pattern of incident Chapman-Jouguet (CJ) detonation in a tube with smooth inner walls without wedge for the Stoichiometric $2H_2 + O_2 +$ Ar-gas mixture.

Figures 5 to 9 show the cellular structure patterns for the same mixture and different wedge angles under identical initial pressures. In every pattern there is a sharp dividing line emerging near the wedge apex and extending downstream. On both sides of this line, the size, shape, and number of cells are obviously distinct. When the wedge angle is less than 30° (Fig. 5–7), the cells below the line are smaller than those above the line and are distorted in shape. This dividing line is the boundary between the undisturbed incident CJ detonation region and the region disturbed by the wedge. From these patterns, it is appropriate to say that the reflection on the wedge occurs in Mach-

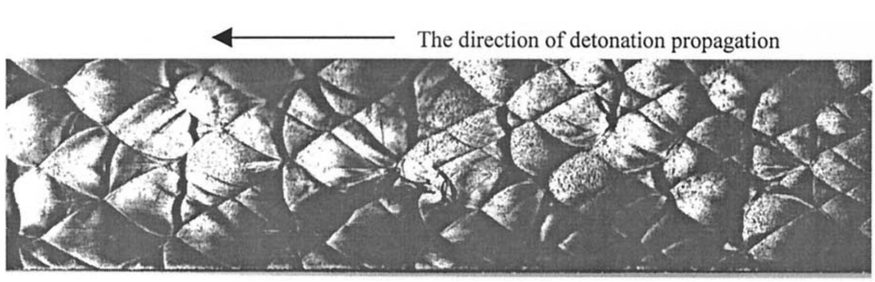

Fig. 4. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation without wedge.

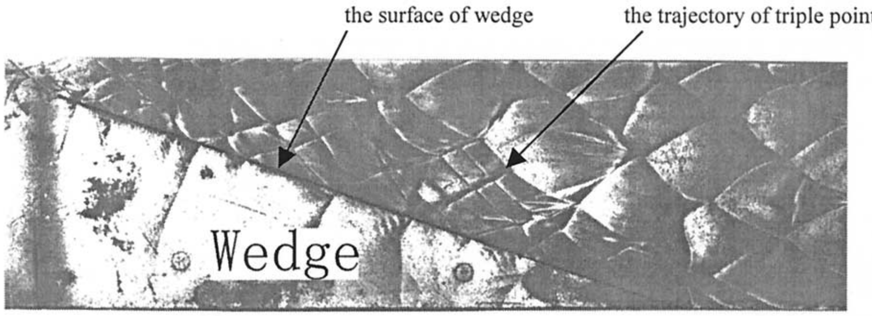

Fig. 5. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation diffracting a wedge with $\theta = 19.3°$. Note the trajectory of triple point near the apex of the wedge.

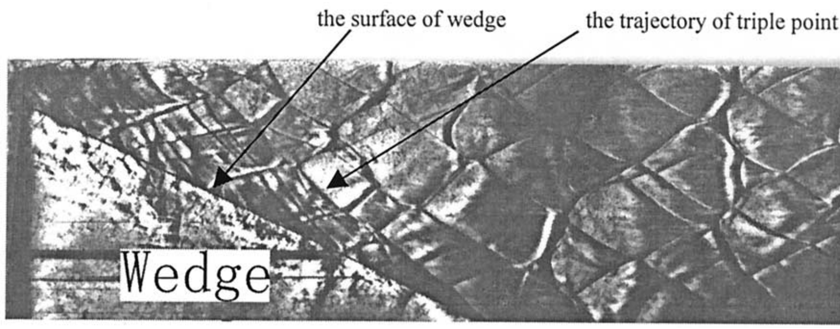

Fig. 6. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation diffracting a wedge with $\theta = 26.7°$.

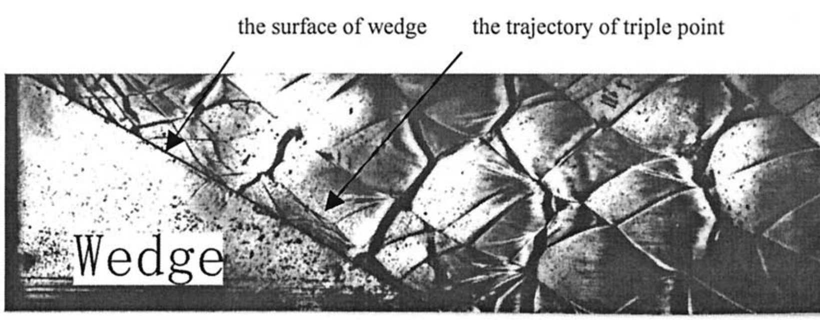

Fig. 7. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation diffracting a wedge with $\theta = 30.0°$.

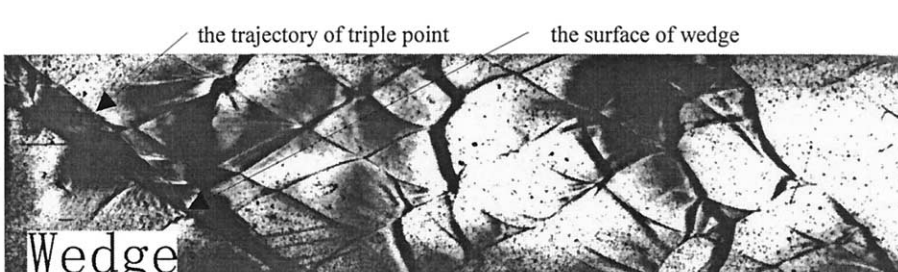

Fig. 8. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation diffracting a wedge with $\theta = 35.0°$.

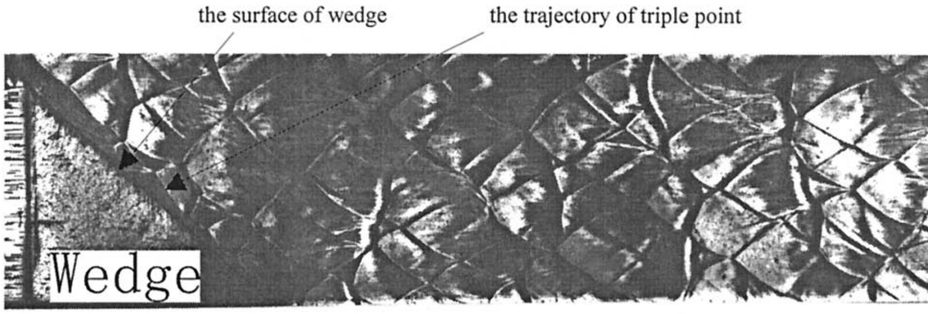

Fig. 9. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation diffracting a wedge with $\theta = 40.0°$.

reflection mode and that the dividing line denotes a triple-point trajectory. When the wedge angle is larger than 30° (Fig. 8–9), the spatial scale in Mach-stem region is so small that no sharp cellular structure can be seen from the soot track. However, the trajectory of triple point is still quite sharp. The relation between the triple-point trajectory angle and the wedge angle for both detonation and shock wave is shown in Fig. 13. From these data it is possible to estimate the critical angle at which the transition from regular to Mach reflection occurs. According to our experiment, the critical angle for stoichiometric oxyhydrogen mixture diluted with 25% argon is in the range 50° to 53°. This result is very close to the data cited in Nettleton [10].

Figures 5, 10, and 11 show the cellular structure patterns for one wedge (19.3°) under different initial pressures. In Fig. 11, the triple-point trajectory is rather hard to identify because the initial pressure becomes high and all cells become small. One notices that a sharp triple-point trajectory was obtained only when the initial pressure is lower than 26.7 kPa. The relation between the trajectory angles of triple point and initial pressures is shown in Fig. 14. One can see that the trajectory angle is not sensitive to the initial pressure.

The two test series mentioned above indicate that triple-point trajectory angle χ for detonation waves is dominantly dependent on wedge angle θ and is not sensitive to the initial pressure P_0. This behavior is similar to that of a Mach-reflected shock wave in an inert gas. For a shock wave, the triple-point trajectory angle is a function of the incident Mach number and the wedge angle only. However, initial pressure slightly affects the incident Mach number.

For cases with small wedge angles (10 and 15°), the Mach stem is very weak and the trajectories are not easy to distinguish; their cellular structure patterns are not presented here.

By using four piezoelectric pressure transducers, the pressure histories of detonation waves were recorded and velocity of detonation was measured. Table 1 shows the experimental data

Fig. 10. Cellular pattern produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 20$ kPa, $M_{cj} = 5.15$) detonation diffracting a wedge with $\theta = 19.3°$.

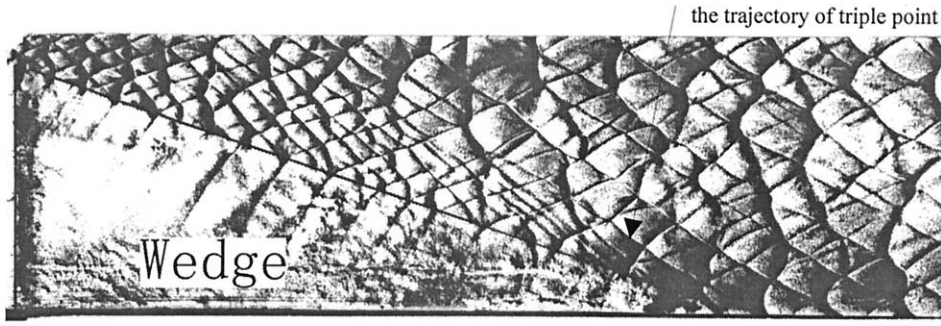

Fig. 11. Cellular structure produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 24$ kPa, $M_{cj} = 5.17$) detonation diffracting a wedge with $\theta = 19.3°$.

of pressure, where P_0 denotes initial pressure, P_1 is pressure of incident detonation, P_2 is pressure measured at T_2, P_3 is pressure measured at T_3 (pressure in Mach stem), and P_{theo} is theoretical pressure of incident detonation. From the table one finds that the ratio of the pressure in the Mach-stem region on the wedge and the pressure of the incident detonation (P_3/P_1) is not sensitive to initial pressure P_0. This behavior is similar to that of Mach-reflected shock waves in nonreactive air.

DISCUSSION AND INTERPRETATION

Two phenomena feature unique aspects of Mach-reflected detonations compared with Mach-reflected inert shock waves: 1) initiation stage of triple-point trajectory in Mach-reflected detonations; and 2) the triple-point trajectory of Mach-reflected detonation is not a straight line.

Initiation Stage of Triple-Point Trajectory in Mach-Reflected Detonations

Figures 5 and 12 show the different initiation stages of trajectory near the apex of the wedge in Mach-reflected detonation waves with the same composition and initial pressure for the same wedge angle. The trajectory angles in these two cases are 13.1° and 12.7°, respectively. This difference was not observed in previous studies using laser shadowgraphy. It is suggested that this might be due to the interaction between transverse and reflected waves produced at the inclined wedge surface. Below the trajectory, the transverse waves impinge constantly with the slope of the wedge, resulting in the shorter and shorter spatial scale. On the other hand, the transverse waves also impinge on the reflected wave produced at the slope of the wedge and form new cells. Of course, it should be noted that detonations in Mach-stem region

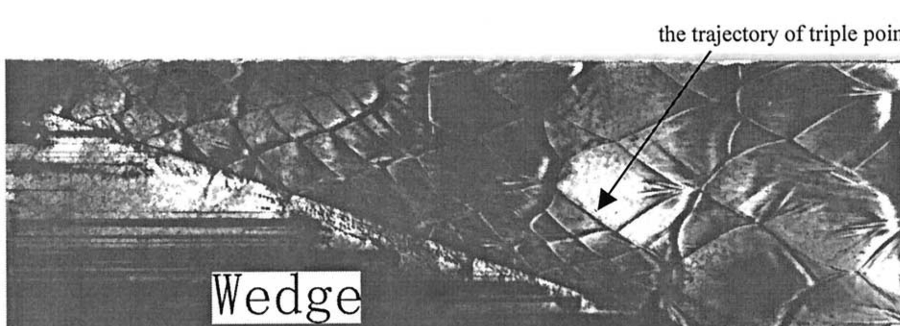

Fig. 12. Cellular structure produced by $2H_2 + O_2 + Ar$ ($\gamma = 1.45$, $P_0 = 16$ kPa, $M_{cj} = 5.12$) detonation diffracting a wedge with $\theta = 19.3°$. Note the trajectory of triple point near the apex of the wedge.

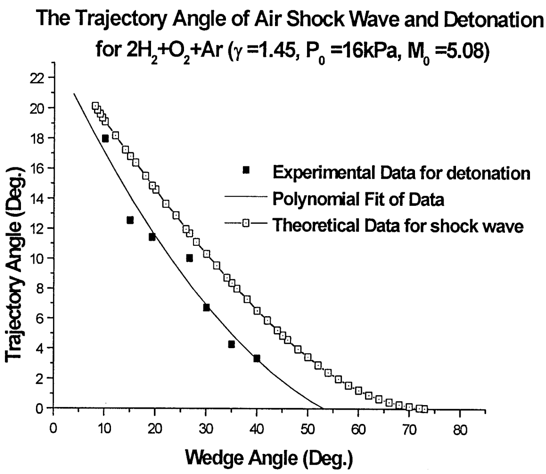

Fig. 13. The trajectory angle vs. wedge angle for air shock wave and detonation.

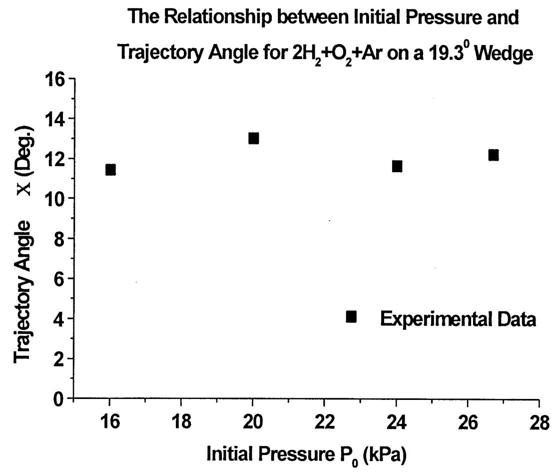

Fig. 14. The trajectory angle vs. initial pressure.

are overdriven detonation waves, so that the pressure and temperature in this region are higher than those in the CJ detonation wave front. These factors combined may affect the length scale based on the chemical reaction, such as the induction-zone length behind the wave front, and this could in turn modify the cell formation and cell size. Thus, it seems that there is an initiation stage [7] during which the cells in the Mach stem near the wedge apex are created. This process is stochastic, so Figs. 5 and 12 have basically identical trajectory angles but different initiating stages. For inert shock waves, the trajectory angle is only a function of the incident Mach number and the wedge angle. This is an essential difference between the Mach-reflected shock waves in nonreactive air and Mach-reflected detonation waves in combustible gas mixture. Experiments indicate that the initiation stage is not distinguishable for larger wedge angles.

The Triple-Point Trajectory of Mach-Reflected Detonation Is Not a Straight Line

Figures 5, 6, 10, and 12 show clearly that the trajectory of the triple point is not straight but irregular. One has to make a linear fit to the irregular line to measure the trajectory angle. From Figs. 7 to 9 the trajectories seem to turn into a straight line when the wedge angle is equal to or larger than 30°. This should also be attributed to the small spatial scale in the Mach-stem region, so that the irregularity of trajectory is not detectable. This is another difference between Mach-reflected shock waves in nonreactive air and detonations in combustible gas mixtures.

These unique characteristics of Mach-reflected detonations are consistent with the conclusions of Ohyagi et al. [7]. They also demonstrate that the transverse-wave structure of the detonation front is critical to the Mach-reflection process in area contraction as well as to the reignition process in area expansion [9].

SUMMARY AND CONCLUSIONS

From the experimental results reported in this article, one may derive the following conclusions:

1. Detonation waves in combustible gas mixtures and shock waves in nonreactive air have similar behaviors when they diffract over a wedge. The triple-point trajectory angle χ for detonation waves is also dominantly dependent on wedge angle θ and is not sensitive to the initial pressure P_0.
2. For Mach-reflected detonation, there is an initiation stage, during which the cells in the Mach-stem region near the wedge apex are created. So the triple-point trajectory could be "detached" from the wedge apex when the wedge angle is less than 30° in the present experiments.

3. For Mach-reflected detonations, the trajectory of the triple point is not a straight line. This should be attributed to the interaction between the transverse waves and the wedge surface. The distinguished cell size and distorted cell shape in the Mach-stem region are also attributed to transverse-wave interaction.
4. According to the ZND model of detonation, the detonation front includes precursor shock waves and transverse-wave structures. It is appropriate to say that in the Mach reflection of detonation, the precursor shock wave determines the relationship between the trajectory angle of triple point χ, wedge angle θ, and initial pressure P_0; however, the transverse-wave structure is mainly responsible for the different initiation stage and irregular trajectory of triple point.

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