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Regular reflection of the plane shock wave from an inclined wall

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THE PURPOSE of the present work was to investigate the structure of the plane shock wave, reflecting regularly from an inclined wall, in close vicinity of the point of reflection. The experiments were performed in a shock tube at low initial pressures (about 0.04 mm Hg) using electron beam attenuation technique together with thin film heat transfer gauges. The reflection of the primary shock wave from an inclined end wall of the tube was studied. The main results indicate that, within the accuracy of the experiment, at the distances from the wall less than 30 mean free paths in the gas behind the incident shock and outside the region of overlapping of the incident and reflected shocks both shocks are plane and the shock thicknesses and the density ratios across the shocks are constant.

Celem niniejszej pracy było zbadanie struktury płaskiej fali uderzeniowej, odbijającej się w sposób regularny od skośnej ścianki, w bezpośrednim sąsiedztwie punktu odbicia. Pomiary były wykonywane w rurze uderzeniowej przy niskim ciśnieniu początkowym (około 0,04 Tr) przy pomocy wiązki elektronów oraz czujników temperaturowych. Uzyskane wyniki wskazują, że w odległościach od odbijającej ścianki nie przekraczających 30 dróg swobodnych cząsteczek gazu w obszarze za padającą falą uderzeniową, a poza obszarem "nakładania się" fali padającej i odbitej, obie fale są płaskie, a poza tym ich grubości i stosunki gęstości po obu ich stronach są stałe.

Целью настоящей работы являлось исследование структуры плоской ударной волны отражающейся регулярным образом от косой стенки в непосредственной окрестности точки отражения. Измерения были проведены в ударной трубе при низком начальном давлении (около 0,04 торр) с помощью пучка электронов и температурных датчиков. Полученные результаты показывают, что на расстояниях от отражающей стенки не превышающих 30 длин свободного пробега молекул газа в области за падающей ударной волной и вне области „наложения" падающей и отраженной волн обе волны плоски и кроме этого их толщины и отношения плотностей по обоих их сторонах постоянны.

Notation

M_s	Shock Mach number,
U	velocity of the incident shock,
x	distance measured along the reflecting plate,
y	distance from the reflecting plate,
α_M	Mach angle,
ε	shock wave thickness (Fig. 4),
λ	mean free path,
ω	angle between the shock wave plane and reflecting wall,
ϱ	density,
ϱ_2'	density in front of the reflected shock,
τ	time.

Subscripts

1	conditions in front of the incident shock,
2	conditions behind the incident shock,
5	conditions behind the reflected shock,
B	value measured with the electron beam,
M_s	value calculated on the basis of the measured shock Mach number.

1. Introduction

The purpose of the present work was to investigate the flow of gas in close vicinity of the point of regular reflection of an oblique shock wave at a plane wall. It was a continuation of the former work on the structure of the shock wave moving along a plane wall in close vicinity of that wall [1].

The main objective was to find the shapes of both incident and reflected shocks as well as the dependence of the parameters of these shocks on the distance from the wall. The problem seemed interesting since its solution could give some information on the applicability of the assumption, widely used in hydrodynamics, of a continuous medium and no-slip condition at the wall.

Theoretically, three configurations of the shock waves were possible (Fig. 1). The first one would have occured if the no slip condition at the wall was applid. Then both the incident and reflected shocks would have been inclined to the wall at the Mach angle. The second one (which on the basis of the former work seemed the most probable) would have occured if very little viscous effects were present. Finally, the third configuration seemed possible as a bridge to the case of the Mach type reflection of the shock wave.

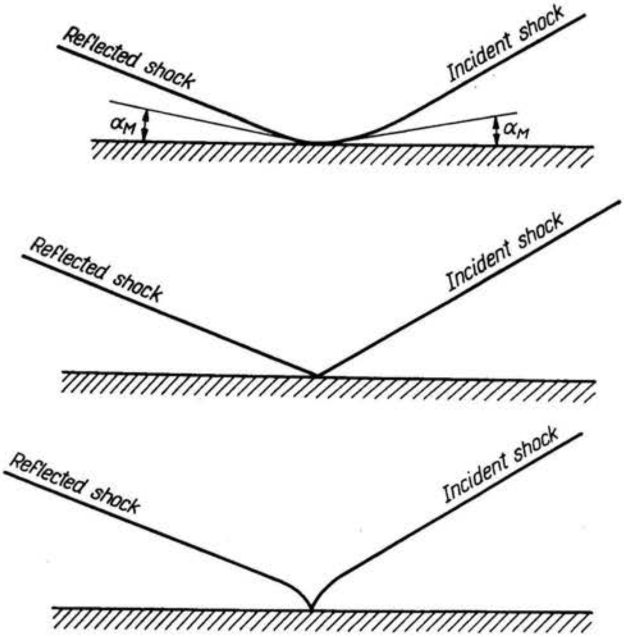


FIG. 1.

2. Experiment

The experiments were performed in a shock tube with a cylindrical cross-section 120 mm in diameter and about 10 m long. Reflection of the shock wave from the plate placed inside the tube at its end was studied.

The measurements of gas density inside the incident and reflected shocks were made with the standard electron beam attenuation technique [2, 3, 4, 5, 6]. The electron beam was perpendicular to the tube axis and parallel the reflecting plate (Fig. 2). The reflecting plate could be placed at an arbitrary angle to the tube axis and its distance from the beam could be varied. From a series of runs taken at various distances between the beam and the plate with a thin-film heat transfer gauge at a fixed position with respect to the plate, it was possible to obtain the structure of the flow in the region investigated. A typical oscilloscope trace obtained in this way is shown in Fig. 3.

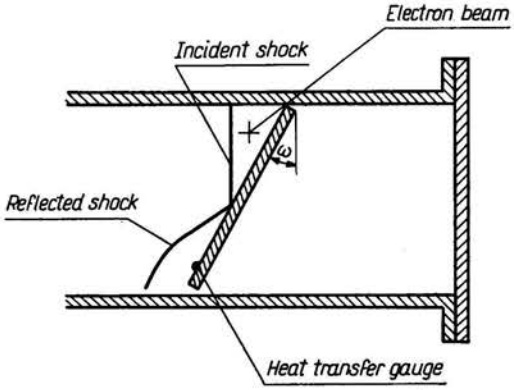


FIG. 2.

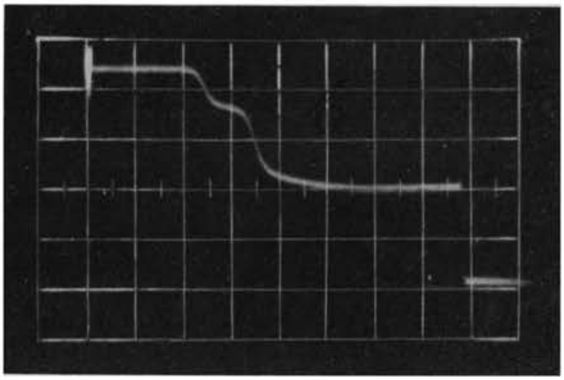


FIG. 3.

The experiments were performed in nitrogen and argon gases at initial pressures about 0.04 and 0.045 Tr, respectively, and initial temperatures about 295 K. The mean free path under these conditions was about 1.2 mm, which was large enough to produce the reflection region sufficient for measurements and at the same time small enough with respect to the tube diameter to produce the shock wave sufficiently plane.

The Mach numbers of the incident shocks were kept close to 3.25. It was sufficiently low not to produce any real gas effects like dissociation or ionization and at the same time sufficiently high not to introduce any difficulties connected with detecting weak shock waves.

The value of the angle between the plane of the shock wave and the reflecting plate was chosen equal to 30° (Fig. 2). This value was sufficiently high, so that the problem could no longer be considered one-dimensional and viscous effects should have been noticeable. On the other hand it was low enough so that Mach-type reflection was excluded and besides this, behind the reflected shock a supersonic flow occured and a finite region of flow, undisturbed by the edge of the reflecting plate, could be found.

Apart from that, one series of runs in argon gas was taken for the plate perpendicular to the tube axis. This was done to check the validity of the results obtained, since this problem had already been investigated by other authors [6, 7].

The accuracy of the experiments was estimated to be $\pm 17\%$ for the density ratio across the incident shock, $\pm 21\%$ across the reflected shock and $\pm 12{,}5\%$ for shock thickness. The estimated accuracy of the simple measurement of the shock position ranged from 5 to 8 mean free paths in the gas behind the incident shock.

3. Results

The results of the experiments are summarized in the following figures:

In Figs. 5a, 5b the measured shapes of the incident and reflected shock waves are presented. The points correspond to the positions of the "shock wave head" defined in Fig. 4. (Note two definitions valid outside and inside the region of overlapping of the shocks). It is evident that within experimental accuracy both shocks are plane.

The angle between the wall and the reflected shock is smaller than calculated for an ideal gas, which is in qualitative agreement with calculations of the reflection from a perpendicular wall, taking into account the heat transfer to the wall [7]. In Fig. 5c a similar picture is shown for the case of the reflection from a perpendicular wall (the distance along the plate replaced by the time coordinate). This picture is also in qualitative agreement

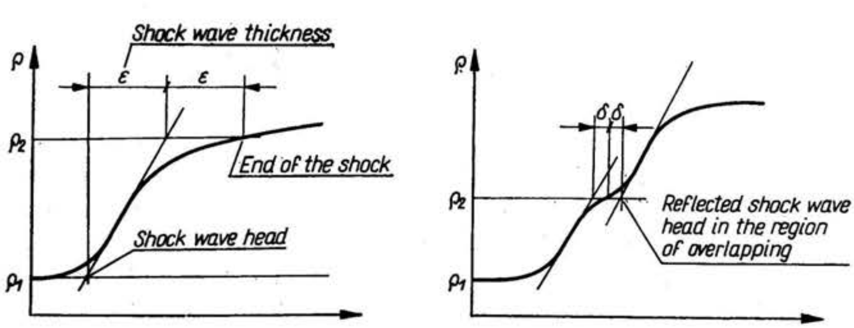


FIG. 4.

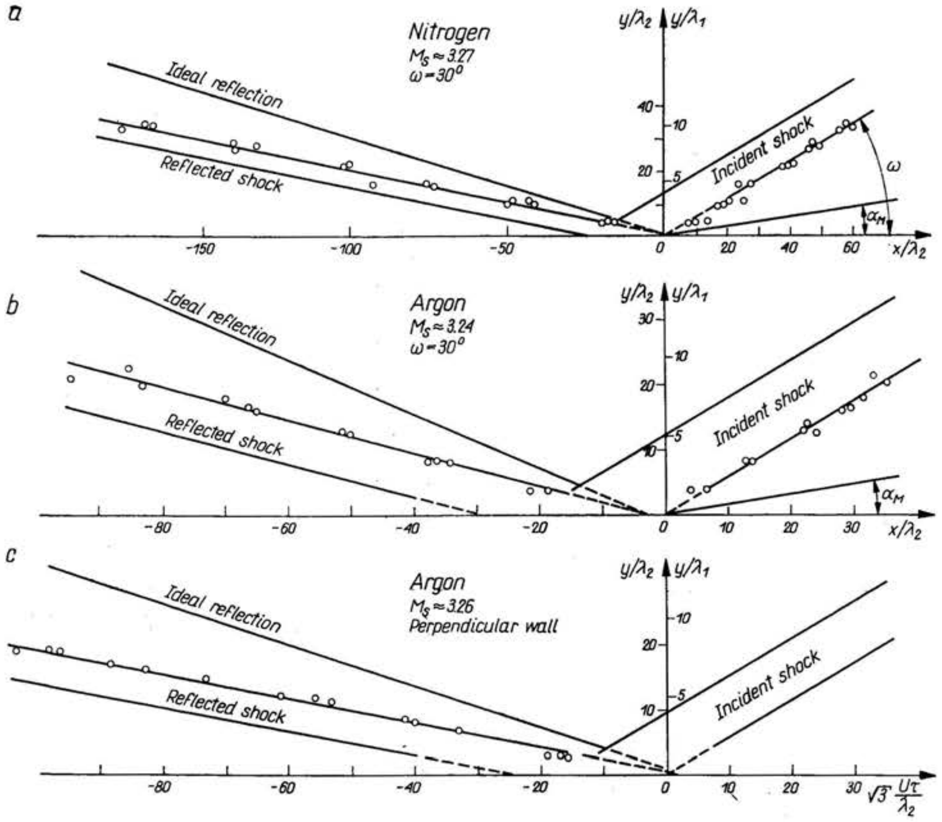


FIG. 5.

with the previous ones — the velocities of both shocks are constant. The velocity of the reflected shock is as before smaller than for an ideal gas.

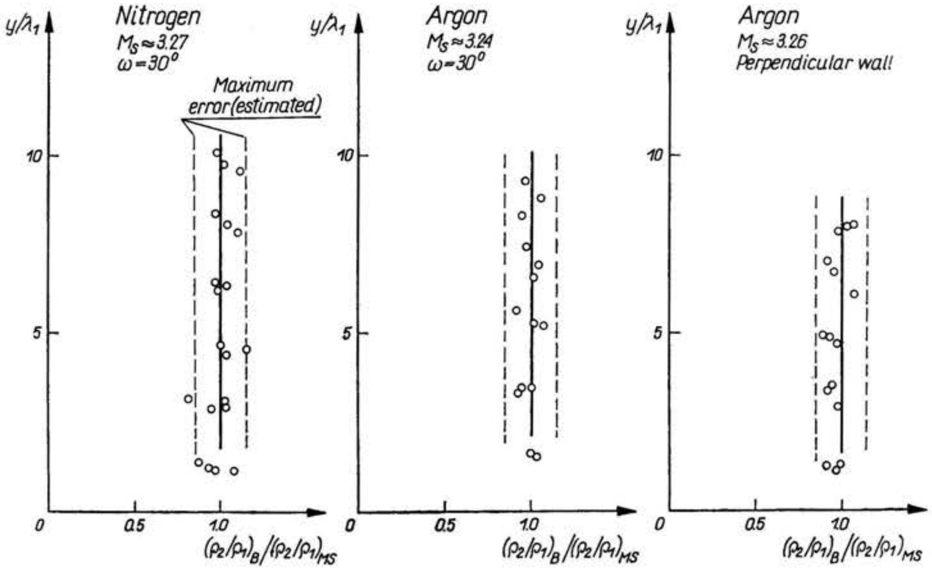
In Fig. 6 the density ratios across the incident shocks in all three cases considered are shown. These ratios are independent of the distance from the wall.

In Fig. 7 similar diagrams of the density jumps across the reflected shocks are shown. They are also independent of the distance from the wall, with the exception of the jump measured in argon at closest distance from the wall. This point is probably inside the thermal layer at the wall and the density is increased by its influence.

In Fig. 8 the thicknesses of the incident shocks are shown. They are independent of the distance from the wall.

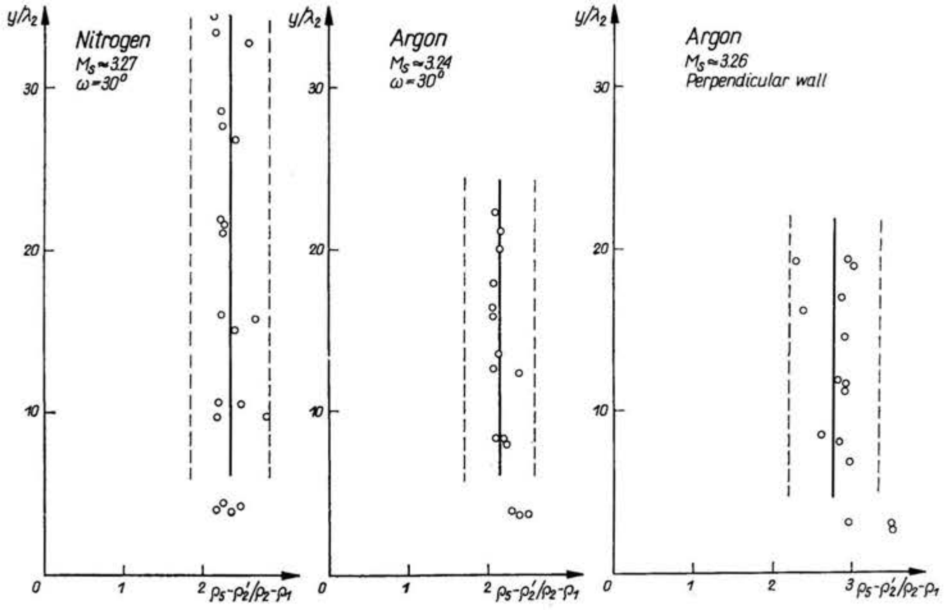
In Fig. 9 analogous pictures for the reflected shocks are shown. These pictures indicate no definite dependence of the reflected shock thickness on the distance from the wall. It can be stated safely that in the region considered the thicknesses of the reflected shocks change by no more than 15 per cent.

The results presented here show an unexpectedly high value of the density jump across the reflected shock (Fig. 7). The reason for this is most probably the flow nonuniformity between the incident shock and contact surface, which is characteristic for low-density shock tubes [8]. According to the control measurements made with a stagnation point



y/λ_1
Nitrogen
$M_S \approx 3.27$
$\omega = 30^0$
Maximum error(estimated)
10
5
0
0.5
1.0
$(\rho_2/\rho_1)_B/(\rho_2/\rho_1)_{MS}$
y/λ_1
Argon
$M_S \approx 3.24$
$\omega = 30^0$
10
5
0
0.5
1.0
$(\rho_2/\rho_1)_B/(\rho_2/\rho_1)_{MS}$
y/λ_1
Argon
$M_S \approx 3.26$
Perpendicular wall
10
5
0
0.5
1.0
$(\rho_2/\rho_1)_B/(\rho_2/\rho_1)_{MS}$

FIG. 6.



y/λ_2
Nitrogen
$M_S \approx 3.27$
$\omega = 30^0$
30
20
10
0
1
2
$\rho_S - \rho_2'/\rho_2 - \rho_1$
y/λ_2
Argon
$M_S \approx 3.24$
$\omega = 30^0$
30
20
10
0
1
2
$\rho_S - \rho_2'/\rho_2 - \rho_1$
y/λ_2
Argon
$M_S \approx 3.26$
Perpendicular wall
30
20
10
0
1
2
3
$\rho_S - \rho_2'/\rho_2 - \rho_1$

FIG. 7.

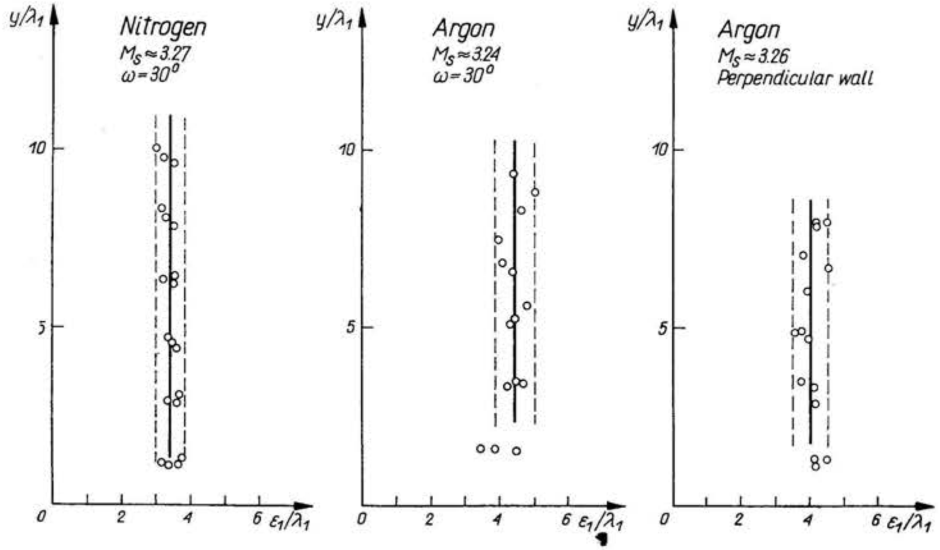

y/λ₁
Nitrogen
$M_S \approx 3.27$
$\omega = 30^0$
10
5
0
2
4
6
ε₁/λ₁
y/λ₁
Argon
$M_S \approx 3.24$
$\omega = 30^0$
10
5
0
2
4
6
ε₁/λ₁
y/λ₁
Argon
$M_S \approx 3.26$
Perpendicular wall
10
5
0
2
4
6
ε₁/λ₁

FIG. 8.

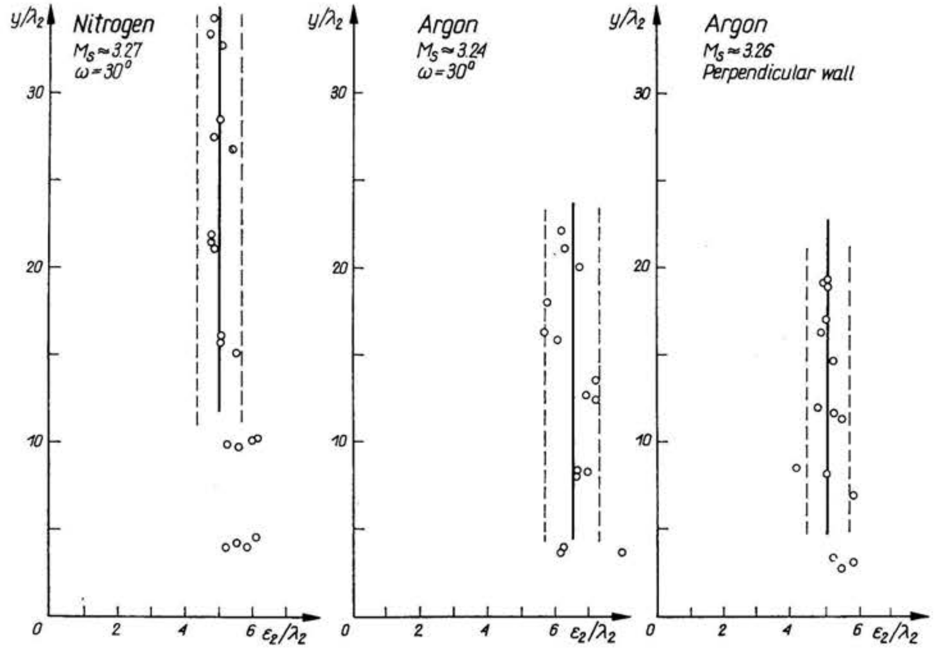

y/λ₂
Nitrogen
$M_S \approx 3.27$
$\omega = 30^0$
30
20
10
0
2
4
6
ε₂/λ₂
y/λ₂
Argon
$M_S \approx 3.24$
$\omega = 30^0$
30
20
10
0
2
4
6
ε₂/λ₂
y/λ₂
Argon
$M_S \approx 3.26$
Perpendicular wall
30
20
10
0
2
4
6
ε₂/λ₂

FIG. 9.

heat-transfer gauge, the distance between the shock wave and the contact surface is only about 2/3 of the shock tube diameter.

Some doubts concerning the overall accuracy of the experiments can be caused by the 10 per cent discrepancy between the incident shock thicknesses in argon for the inclined and perpendicular reflecting walls. This discrepancy can be attributed to the slight misalignment of the beam with the shock wave plane in the case of the inclined wall. This misalignment should have no effect upon the other measurements.

4. Conclusions

In conclusion it can be stated that viscous effects have little influence upon the picture of the reflection of the shock wave from an inclined wall, so the theoretical model describing the phenomenon should not be based on the no-slip condition at the wall. In the first approximation it may even be possible to neglect the viscous effects at the wall completely. In order to evaluate the influence of the other effects, mainly the heat transfer, the phenomenon must be calculated more precisely, taking into account the flow nonuniformities between the shock wave and contact surface.

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