# Reflected Shock Wave Bifurcation in Tubes with Different Roughness

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## 1 Introduction

The interaction of a reflected shock wave with a boundary layer results in the distortion of the shape of a reflected shock wave in the shock tube. Under certain conditions, such interaction can lead to the formation of an oblique shock wave AB (Fig. 1), a rear shock BC, as well as to the flow separation in the wall region. Such a structure can be recorded during measurements as shown at the bottom of Fig.1. This phenomenon is called of reflected shock wave bifurcation. As a result of bifurcation, below the triple point the wall region gas starts moving with the front of the reflected shock wave. The gas between points A and B passes then through the two shock waves. Such a difference in the gas heating way, the creation of vortices due to bifurcation [1, 2], and the pressure difference in the bifurcation region led to the emergence of the opinion that bifurcation can affect chemical kinetics measurements to be made in shock tubs [3, 4].

The relationship between the bifurcation dynamics and the boundary layer type may give some ideas how to reduce the bifurcation influence on the flow or how to improve aerodynamics [5, 6]. The main objective is to change a boundary layer Reynolds number [7]. One of the simplest methods to control the boundary layer is to use the shock tube surface roughness [8].

The most fundamental works on reflected shock wave bifurcation are devoted to research in rectangular shock tubes and only few of them performed in cylindrical ones [9, 10]. Nevertheless, most of the experimental studies of chemical reactions are made in cylindrical shock tubes. The present work analyzes the bifurcation development in argon and air with time and distance in the cylindrical shock tube where measurements were also conducted for two different types of the shock tube surface roughness at three different locations from the endwall in an effort to learn the stabilizing influence of the surface roughness on the flow.

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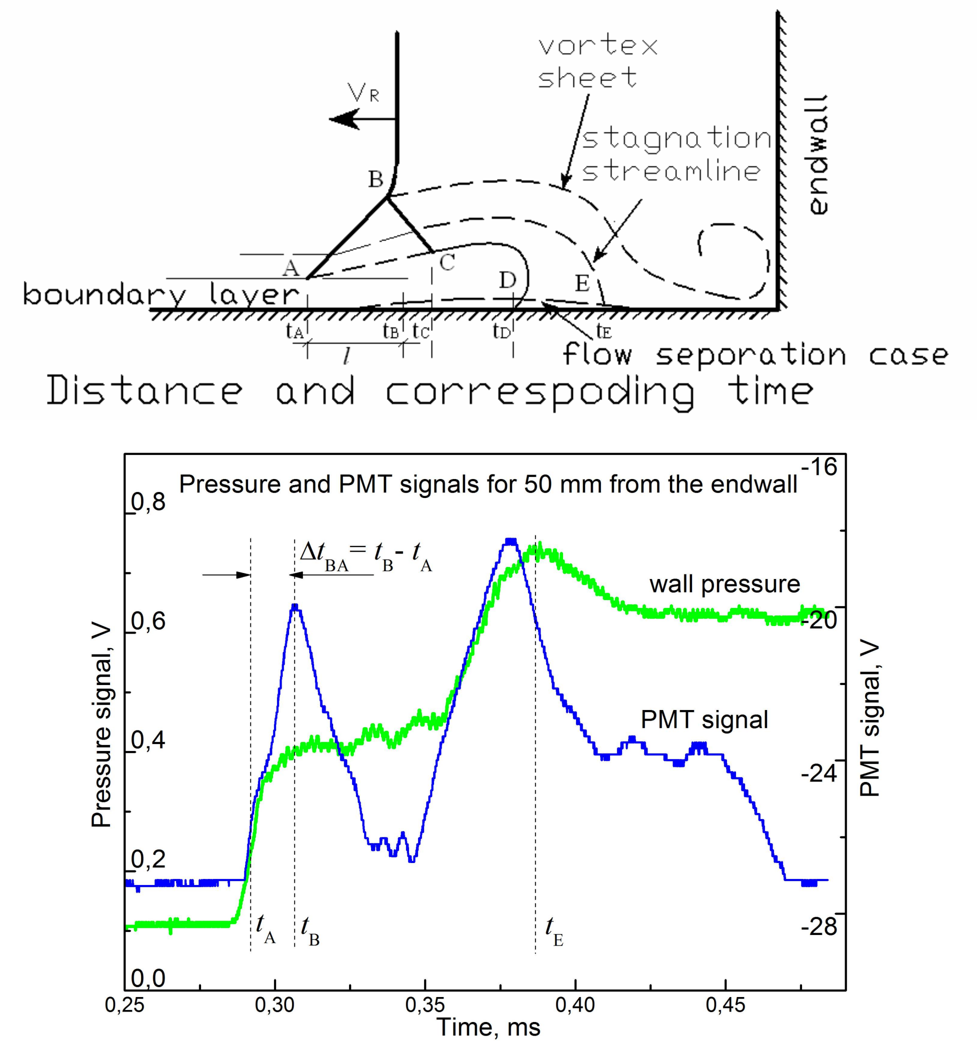



Figure 1. Bifurcation structure. Top: bifurcation structure, were AB – oblique shock wave; BC – rear leg; A – flow separation point; B – triple point. Bottom: corresponding pressure at the surface and photomultiplier signals in case of light passage through the measurement cross-section.

## 2 Experimental facility and measurements

Measurements were performed in a 76 mm inner dia., helium-driven shock tube at the deflection of a plane-parallel beam propagating at a small angle to the reflected shock wave plane at 50 mm, 150 mm and 250 mm from the endwall. Light propagated through the quartz optical windows mounted at the level of the corresponding cross-sections of the shock tube. The width of a light beam was reduced to 0.55 mm via a vertical slot. Considering the width and the slope of the light beam, the method resolution was 0.8 mm. Since the optical system did not allow simultaneous measurement on more than two bases, it was moved to the third base to make measurement there. Thereafter, experiments were repeated under the same conditions. Pressures were measured by PCB Piezotronics pressure sensors mounted flush with the surface of shock tube at a distance of 50 mm, 150 mm, 250 mm from its endwall, and at it. The arrangement of pressure sensors, their notation, as well as the path of light beams are seen in Fig. 2. In experiment the plane-parallel light beam was obtained with a schlieren system IAB-451. The light beams which had passed through the test volume were recorded using photomultipliers PMT-119 identified as PMT-1 and PMT-2 in Fig. 1. Typical records of pressure and PMT signals are presented in Fig. 1.

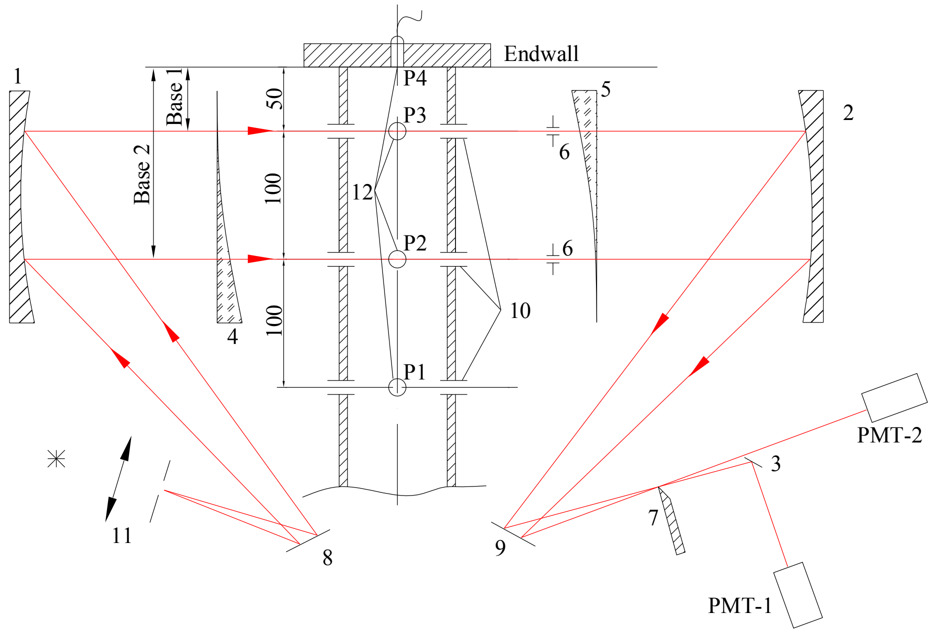



Figure 2. Optical scheme, the scheme of light beams propagations, and the arrangement of pressure sensors: 1, 2, 3 – mirrors; 4, 5 – menisci; 6 – vertical slot 0.55 mm in width; 7 – knife edge; 8, 9 – rotary elements of the setup; 10 – optical windows; 11 – vertical slot and the lighting system of IAB-451; 12 – pressure sensors.

Experiments were conducted for a smooth surface of a measurement section with Ra = 0.18±0.04 μm and for a rough surface with Ra = 60±5 μm. In both cases, Ra was measured along the shock tube.

We measured the time difference between the points of flow separation ($t_A$) and normal reflected shock wave propagation ($t_B$) through the measurement cross-section, that is, $\Delta t_{BA}$. The corresponding notations are shown in Fig. 1. The length of the oblique shock wave projection onto the shock tube inner surface $l$ was calculated as the product $\Delta t_{BA} V_R$ where $V_R$ is the reflected shock wave velocity.

Studies were performed in the following conditions: for argon $T_5$ = 670 – 2900 K, $P_5$ = 0.365 – 1.652 MPa, $\rho_5 = 2.79\pm0.14$ kg/m$^3$, $\gamma_2 = \gamma_5 = 1.667$, M = 1.56 – 3.50; for air $T_5$ = 480 – 1740 K, $P_5$ = 0.395 – 1.419 MPa, $\rho_5 = 2.80\pm0.13$ kg/m$^3$, $\gamma_2$ = 1.334 – 1.394, $\gamma_5$ = 1.303 – 1.386, M = 1.50 – 3.60.

## 3 Results and discussion

Studies of bifurcation in argon have first been performed with the intent to test the method used here, but since argon often serves as a bath gas, this procedure is also of great interest for bifurcation research. There are several models that predict different values of bifurcation lower and upper limits existence. However it is still an open question which model can be adopted for interpretation of experimental results [9]. According to Mark's theoretical calculations [5], the bifurcation structure in argon can exist within the range M = 1.57 – 2.8. When shooting the bifurcation above a flat surface with the use of the schlieren method, the bifurcation existence limits in pure argon could not be detected. The method we used allows us to analyze more carefully the phenomena occurring near the shock wave front due to its high sensitivity and the possibility of quantitative estimation of changes in the front structure near the surface as the distance from the endwall is increased.

For a smooth surface at a distance of 50 mm, $l$ does not grow, but as the distance is increased from the endwall, $l$ values grow (Fig.3). This may indicate a transition to the interaction with a turbulent boundary layer developing at a certain distance from the endwall. When the boundary layer development is enhanced by the presence of roughness, $l$ grows even at a distance of 50 mm. It is also interesting to note that for a rough surface at a distance of 150 mm and 250 mm, the dependence of *l* on the Mach number almost coincide.

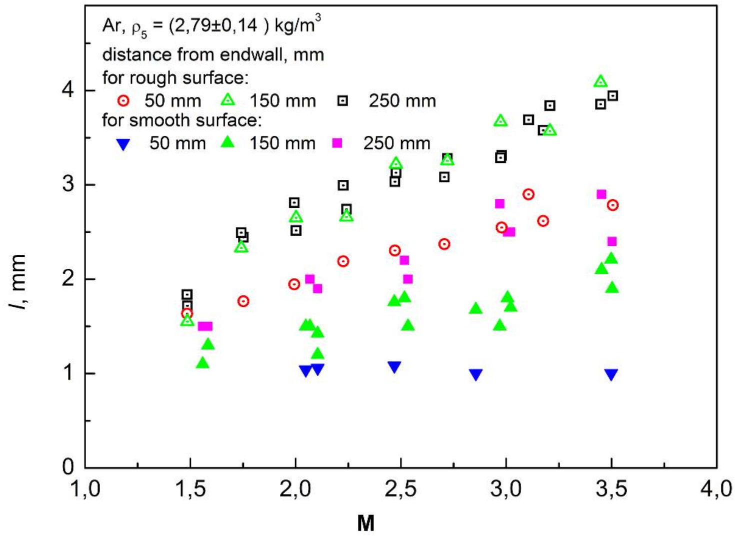



Figure 3. Length *l* vs. Mach number of an incident shock wave for argon.

At a transition to M > 3, the oscilloscope records show that photomultiplier signals significantly change their shape, which manifests itself in broadening the peak and may point to the changes in the reflected shock wave and boundary layer interaction either due to the bifurcation disappearance or due to the transition to a turbulent boundary layer. The reason for this can also be associated with a slight deviation of the shock wave front from the axial symmetry. The influence of only the shock wave front deviation from the axial symmetry is not confirmed by the pressure signals that do not reach a plateau immediately behind the front for M > 3. This is a manifestation of the differences in the flow region behind the normal shock wave and near the surface. These results indicate the presence of bifurcation or a slight front curvature at the surface. At a distance of 250 mm from the endwall for a smooth surface the length *l* is 3 mm at M = 3.5. However, for argon mixed with 8% of air, the disappearance of the front curvature is observed at M > 3.6 [3]. The authors marked the low sensitivity of the method and theoretical upper limit of bifurcation existence for an argon-air mixture at M = 3.27.

Since the bifurcation structure move with the reflected shock wave, we may assume that pressure changes with time near the pressure sensor are the same as those along the shock tube surface around the corresponding pressure sensor. The pressure distribution along the surface observed at a distance of 50 mm to the endwall for air plotted in Fig. 4. Pressure oscilloscope records are normalized to the endwall pressure $P_5$ to assess a pressure excess at the intersection point of the stagnation streamline and shock tube surface (point E, Fig.1) and to visualize the bifurcation development. In appropriate experiments, the local time of signal was multiplied by $V_R$ to find a distance behind the flow separation point A (Fig.1). For a rough surface at M > 3, it seems that in the region between points A and D the flow is re-attached and the pressure profile characteristic for the bifurcation structure is formed at lower Mach numbers.

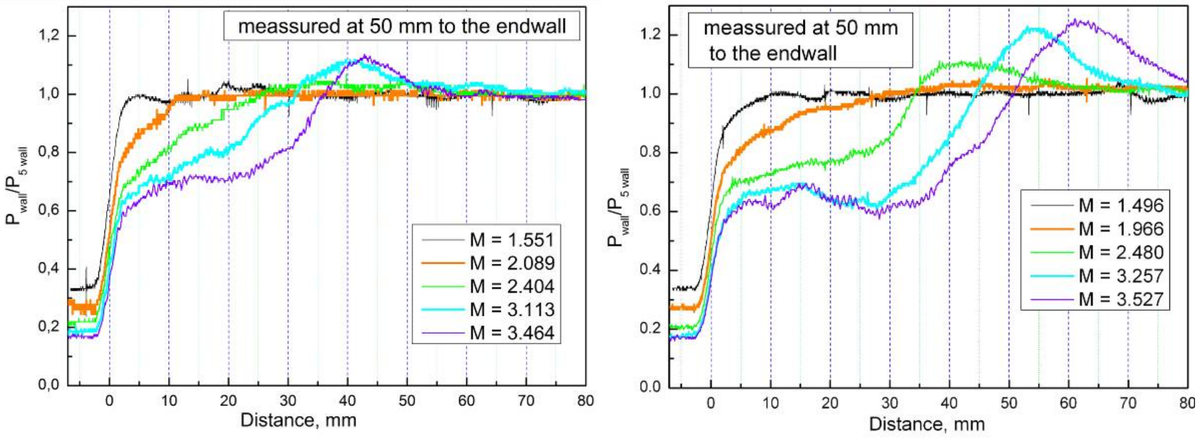
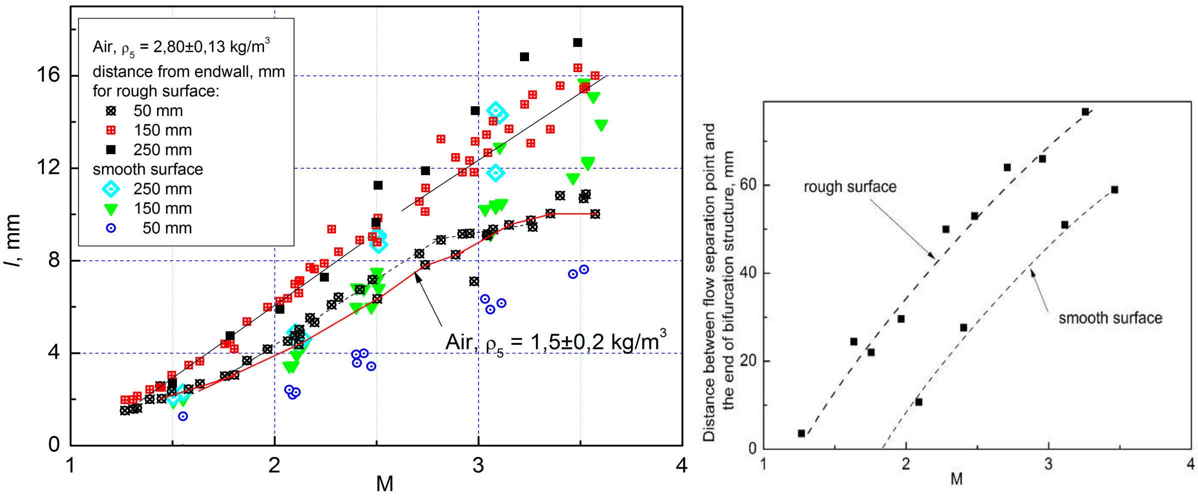



Figure 4. Surface pressure distribution measured at 50 mm to the endwall. Left: smooth surface. Right: rough surface.

For air, the $l$ value generally rises with Mach number and distance to the endwall (Fig. 5*a*). The $l$ growth remains close to the linear one for each distance to the endwall. The $l$ growth with distance for a rough surface is similar to the one outlined elsewhere in [8]. The increase in the data scatter with distance is probably caused by the wave front deviation from the axial symmetry. Fig.5*b* illustrates the distance between the point *A* and the end of wall pressure disturbance created by bifurcation. The approximation lines in Fig.5 stand for the Mach number, at which bifurcation starts growing. Mark's theory predicts the bifurcation existence for air over the range M = 1.33 – 6.45 [5]. From Fig.5*b* we may conclude that small roughness leads to the fact that the lower bifurcation existence limit becomes closer to its theoretical value. This probably means that the boundary layer gas at the rough surface has almost the same temperature as the wall. This has become the base of Mark's model. We also obtained the results for a density of 1.5 kg/m$^3$ for smooth and rough surface. The rough surface data are demonstrated in Fig.5*a*. As for the smooth surface, it makes no sense to present them here because they fairly agree with results for a density of 2.80 kg/m$^3$ and there is a strong data scatter in the smooth surface case.




*a* *b*

Figure 5. Bifurcation characteristic size vs. Mach number of an incident shock wave for air: *a*) $l$ vs. Mach number of an incident shock wave; *b*) distance between the flow separation point and the end of bifurcation structure at 50 mm to the endwall.

## 4 Conclusions

The values of $l$ (M) obtained for a rough surface show a smaller scatter for both air and argon in comparison with the smooth tube data. These results enable one to suggest that the rough surface can be used to stabilize the flow at the surface. Nevertheless the pressure pulsations will enhance at the wall with roughness. It is found that there exists an interesting correlation between the theoretical low limit of bifurcation existence according Mark's theory (1958) and the experimental results obtained for the rough surface.

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