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The shock wave curvature close to the shock tube wall

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THE SHOCK front curvature, especially of that part close to the shock tube wall is investigated by a sensitive thin film technique. In a working range 0.01 Torr $< p_1 <$ 0.1 Torr ahead of the shock front the curvature becomes quite substantial and surprisingly follows the theoretical curvature up to less than one mean free path distance from the wall.

Przeprowadzono badania krzywizny frontu fali uderzeniowej w rurze uderzeniowej stosując nową technikę pomiarową gęstości. W zakresie stosowanych w tym eksperymencie ciśnień przed frontem fali uderzeniowej — krzywizna staje się istotna.

Проведены исследования кривизны фронта ударной волны в ударной трубе, применяя новую технику измерения плотности. В интервале применяемых в этом эксперименте давлений перед фронтом ударной волны, кривизна становится существенной.

IT IS well-known that the flow deviates from the ideal one in a shock tube at low initial pressures: the lower the initial pressure has been set, the more it the flow deviates. The reason for this behaviour is the boundary layer growing behind the shock wave (see Fig. 1 and 2). Since the gas is hot between the shock wave and the contact surface the boundary layer acts as a sink in this region. The flow has a radial component towards the wall. It is on account of this component that the shock wave has to be bulged in its running direction.

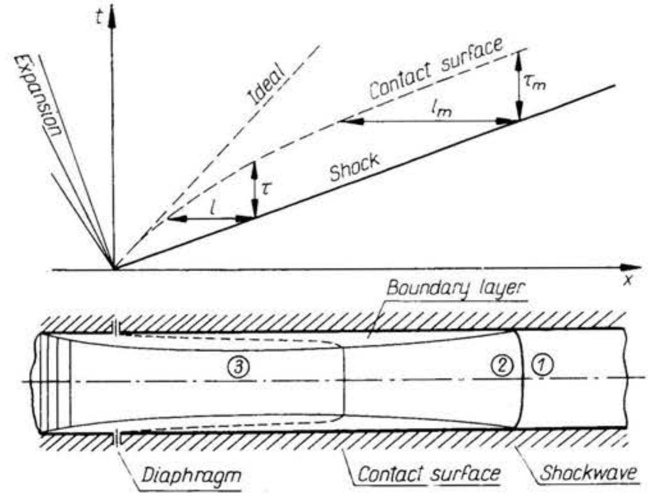

FIG. 1. $x-t$ diagram and regions in the shock tube.

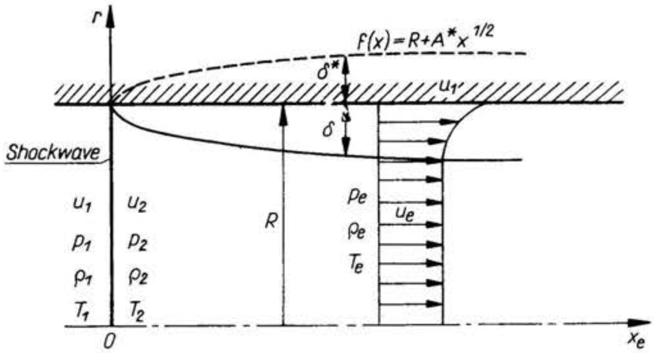

FIG. 2. Boundary layer development behind the shock wave (shock fixed coordinates).

The induced disturbances are small and the whole problem can be treated with the potential theory. At the low initial pressures considered here the boundary layer is laminar in the region between the shock wave and the contact surface. The influence of the boundary layer is simulated by a continuous sink distribution at the wall with a sink strength proportional to the displacement thickness δ^*. Further assumptions are: thin boundary layer $\delta/R \ll 1$, small inclination of the shock wave $\operatorname{tg}\alpha = \frac{dx}{dr} \ll 1$ (Fig. 3), small change of the inclination angle $R\frac{d\alpha}{dr} \approx R\frac{d^2x}{dr^2} \ll 1$, axial velocity u_2 approximately equal to $c = \sqrt{u_2^2+v^2}$. We shall see that the theory gives good results even far outside the limits set by the assumptions. As seen on Fig. 4 the theoretical curve, calculated after DE BOER [3], agrees well with the experimental results, even for the points within one mean free path distance from the wall. Looking on the curve for $p_1 = 10\ \mu$, the shock front curvature is by far not small and the inclination is substantial. Further, the good

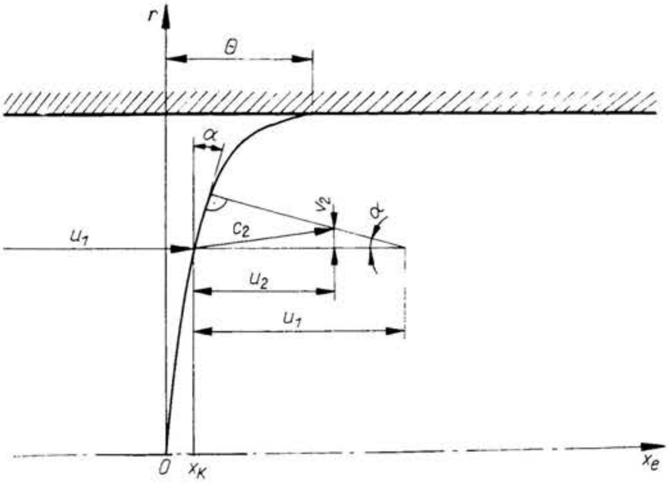

FIG. 3. Velocities at the curved shock wave.

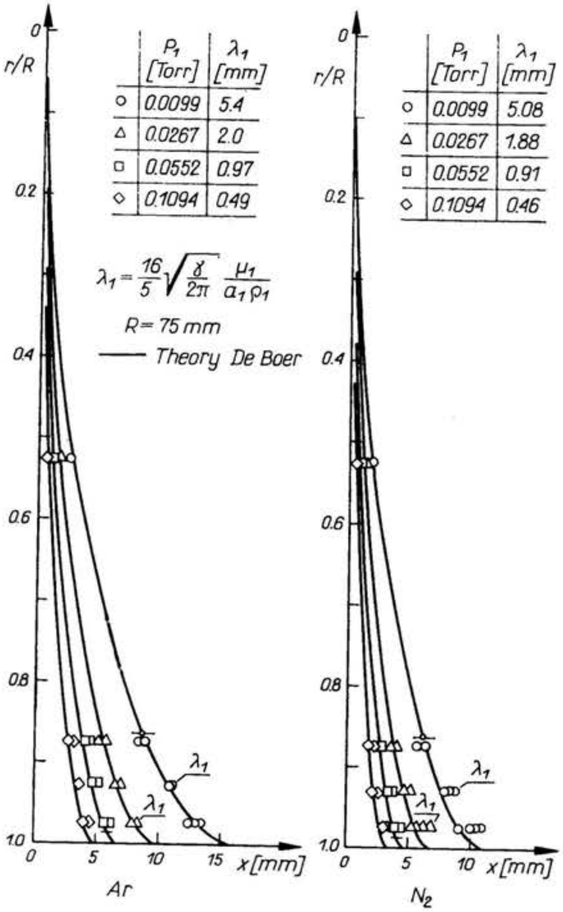

FIG. 4. Comparison of the theory of DeBoer and our experimental results.

agreement is surprising because for $p_1 = 10\ \mu$ and a shock tube diameter of 150 mm the separation distance between the shock wave and the contact surface is of the order of the shock wave thickness. The shock wave is not infinitely thin, the hot region is almost non-existent and the boundary layer is relatively thick.

Since, theoretically, the radial velocity v becomes infinite at the leading edge of the boundary layer, the shock wave ends tangential at the wall. This is physically impossible. The wall angle of the shock wave will definitely be closer to 90 degrees than to zero degrees. So there should be an inflection point in the curvature very close to the wall. However, our experimental results are not sensitive enough to show this. The experimental technique used does not allow to do measurements in this narrow region very close to the wall.

Now about the results of others. The experimental results of LEŚKIEWICZ, PACZYŃSKA and WALENTA [5] can be arranged to fit the theory of DeBoer (Fig. 5). They too did not measure close enough to the wall to give a definite answer about the wall angle of the shock front. FISZDON, WALENTA and WORTMAN [4] have estimated the wall angle, using

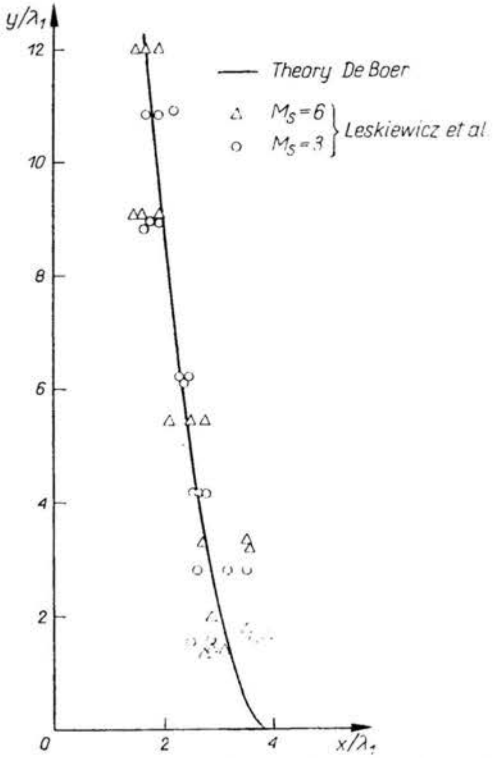

FIG. 5. Comparison of the theory of DeBoer and the experimental results of Leśkiewicz, Paczyńska and Walenta.

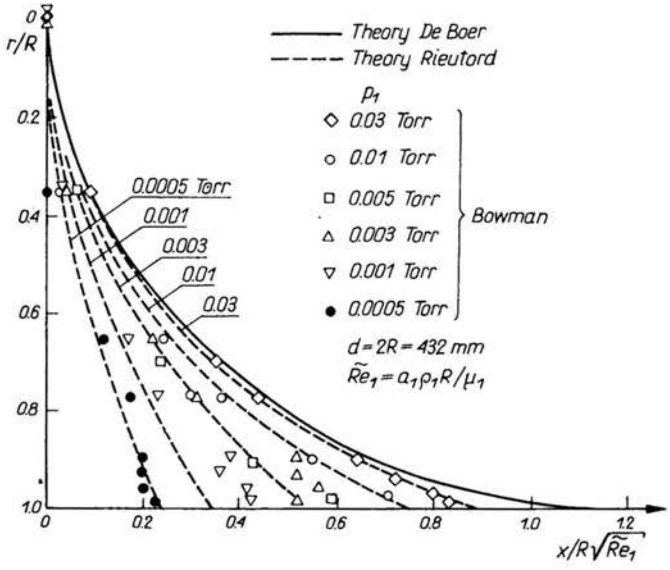

FIG. 6. Comparison of the theoretical results of DeBoer and of Rieutord with the experimental results of Bowman.

an order of magnitude approach to the leading edge problem of the boundary layer. Their result is that a continuum theory approach can give the right answer. To my mind, their measurements were not close enough to the wall to be conclusive. The calculated wall angle may be the right one but the experimental results don't show this definitely.

The experimental results of **BOWMAN** [1] show an increasing deviation from the theory of DeBoer with decreasing initial pressure (Fig. 6). It is possible to attribute this to the slip at the wall, as Bowman has done. He introduced the slip concept and obtained good agreement with his former experimental results [2].

Another way to alter the influence of the boundary layer, especially at the leading edge, is to assume linear growth of the boundary layer for a distance of the order of the shock thickness. This has been done by **RIEUTORD** [7]. The result of this modification is seen in Fig. 6. The agreement with Bowman's experimental results is very good. But our experimental results don't agree with Bowman's.

Comparable conditions are given in two experiments if the separation distance, measured in tube diameters, is the same. The separation distance, measured in shock tube diameters d, is proportional to $p_1 d$. Bowman conducted his experiments in a 17″ shock tube, ours were done in a 150 mm or 6″ shock tube. Therefore our results for $p_1 = 10\ \mu$ should be close to Bowman's results for $p_1 \approx 3\ \mu$. That is not the case, our results agree with DeBoer's theory, Bowman's do not. Down to $p_1 = 10\ \mu$ our results don't show the trend Bowman's results, in agreement with the theory of Rieuford, show (see Fig. 7). I don't as yet know what the reason for this discrepancy is. In general, I am surprised about the good agreement of our results with the pure continuum theory of DeBoer. At $p_1 = 10\ \mu$ (in our 150 mm tube) the separation distance is less than the shock thickness. Our experiments were performed at $L/d = 56.3$ and $L/d = 76$ (L — distance from diaphragm).

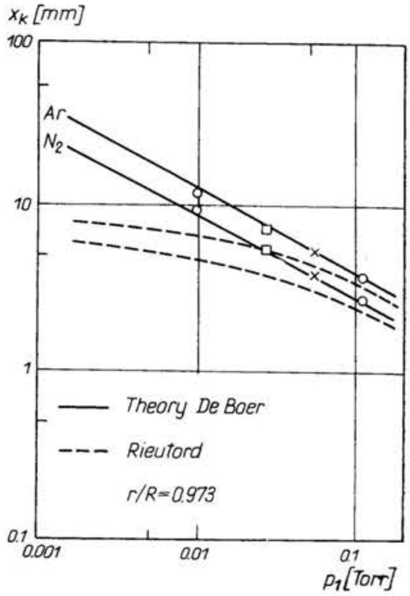

FIG. 7. Comparison of the theoretical results of DeBoer and of Rieutord with our experimental results at $r/R = 0.973$.

Now we shall have a look at the interaction region between the shock wave and the boundary layer beginning (Fig. 8). It is a very small region of approximately 12 upstream mean free paths, λ_1, in flow direction and 5 upstream mean free paths in radial direction. To my knowledge only one theoretical paper, published in 1962 by M. SICHEL [8], exists about this problem. Sichel treated the problem for very weak shock waves using continuum concepts. Experimental results appear not to exist.

Despite the small size of the interaction region we came on this problem in connection with two experiments: the measurement of the shock curvature, including the touch down angle at the wall and the regular reflection of a shock wave at an inclined wall (see Fig. 9).

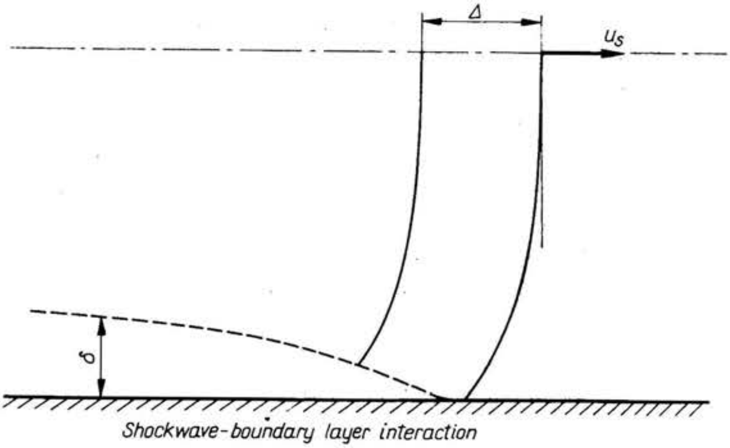

FIG. 8. The shock wave boundary layer interaction region.

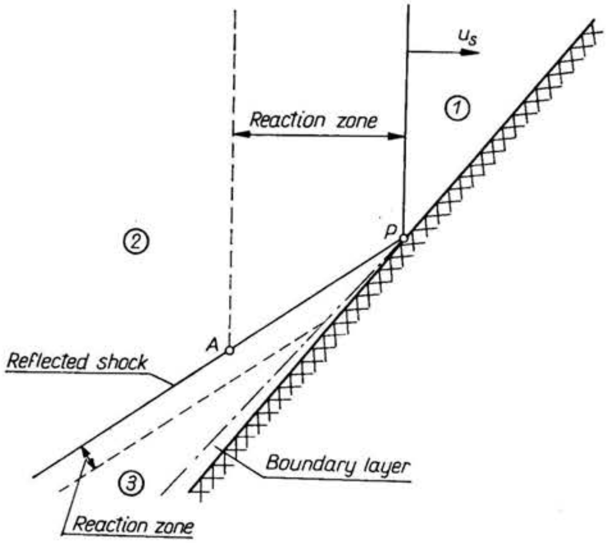

FIG. 9. Reflection of a strong shock with reaction zones (vibration, dissociation) at an inclined wall.

In the curvature experiments the wall angle is uncertain and for the regular reflection the reflected shock, moving into the reaction zone of the incoming shock, should be curved. Experiments, conducted by OERTEL jr. [6], show a straight reflected wave despite the reaction zones ahead and behind the reflected shock and the boundary layer behind the reflected shock. Nothing is known about the interaction region.

To investigate these interaction regions is of fundamental interest. Not very much is known about flow fields close to a solid wall in the slip flow and transition region. We hope to be able to perform density measurements in such a region with a laser differential interferometer. It is not quite clear yet if it will be possible to get good results. The reduction of the raw data is very complex. Good theoretical results should be obtainable with the direct simulation Monte Carlo method of BIRD [9]. Here, too, it is not easy to tackle the problem because of its two-dimensional character. This, however, doesn't present such a general difficulty as the computer time problem does.

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