THE NATURE OF THE ANOMALOUS FLOW IN THE DUST STREAM OF HYPERSONIC WIND TUNNELS AROUND BLUNT BODIES

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A hypothesis explaining the nature of the deformation of detached compression shocks observed in testing blunt models in the dust stream of hypersonic wind tunnels is proposed and given a foundation.

The case of anomalous flow around blunt models, manifested by the origination of a kind of "liquid cone" ahead of the detached shock, which is similar to the case of flow around bodies with a needle, can be observed (Fig. 1) in tests on blunt models in a dusty hypersonic stream. Similar distortions of the detached shocks are remarked in [1, 2], but, in the former case, they arose because of periodic generation of a vortex in the hemispherical recess on the frontal surface of the body, and in the latter case, because of upstream blowing. In the case given, the cause of the arising distortions was the dustiness of the stream. An analysis made of a dusty gas flow [3] and a number of additional investigations permit the clarification of the nature of this phenomenon.

In the supersonic flow around a blunt body in front of which is another body of small size (a thin filament ahead of a cylinder, say (Fig. 2)), the flow picture depends substantially on the mutual location of the bodies. When the filament is a short distance from the cylinder, so that the filament lies between the shock and the cylinder, its influence on the flow is insignificant (Fig. 2a). As the filament is moved ahead of the shock, the shock interacts with the aerodynamic wake of the filament (more precisely, with the subsonic part of the wake). The gas propagated from the high pressure domain behind the shock along the neck of the wake, causing the streamlines to be driven back into the external stream. Ahead of the cylinder there arises a wedgelike separation zone with reverse currents near the plane of flow symmetry (Fig. 2b). The apex of the "liquid wedge" coincides with the filament but, as it recedes from the cylinder, a time approaches when the apex of the "liquid wedge" separates from the filament. The flow picture changes abruptly: the separation zone diminishes in size, and a normal compression shock originates ahead of it (Fig. 2c).

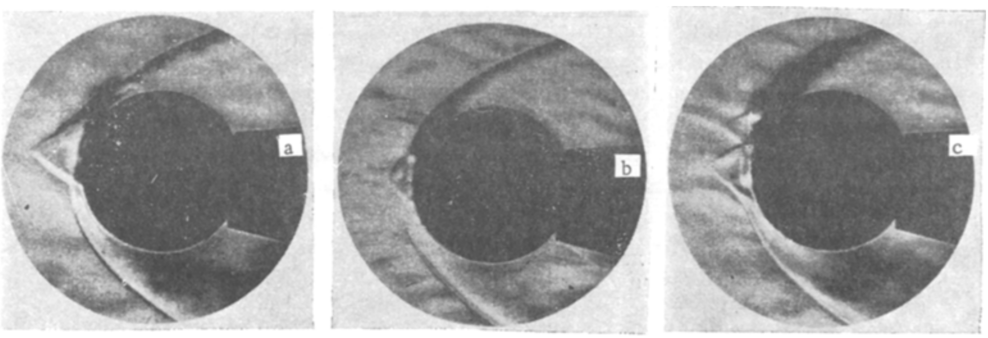

Fig. 1. Various cases of the deformation of a detached compression shock (M = 10-15).

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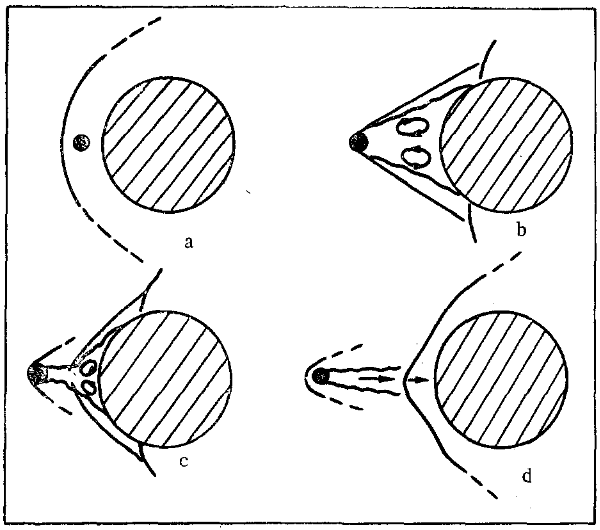

Fig. 2. Diagram of the supersonic flow around a cylinder when a filament is placed ahead of it (a–d for $M > 1$).

As the filament recedes further from the cylinder, the "liquid wedge" degenerates, the flow becomes separationless, and only the curvature of the shock ahead of the cylinder indicates the presence of the filament (Fig. 2d).

The experiment described above was repeated with the sole difference that the filament was not withdrawn from, but rather brought closer to, the cylinder. The flow picture observed was the same but abrupt rearrangement of the stream occurred at other ranges, i.e., with a certain phase shift. Therefore the hysteresis characteristic for flows with separation zones took place.

The spectra of the flow around a blunt body obtained in a dusty stream disclose a considerable similarity to the flow diagrams presented in Fig. 2. Indeed, the flow pictures in Fig. 1a are similar to the cases presented in Fig. 2b, c, and those in Fig. 1b to the case presented in Fig. 2d. The diversity of the kinds of shock deformation is not limited thereby: there are double (Fig. 1c) and even triple "liquid cones."

On the basis of [3], the nature of the shock distortions observed can be described as follows. Because the particles lag behind the gas, an aerodynamic wake stretches out behind them. As the gas moves along the nozzle, the length of the wake increases, where the apex of the wake moves at the particle velocity and the tail at the gas velocity. At some time the tail of the wake reaches the model and causes distortion of the shock: first there originates a "nipple," which increases and stretches out into a cone as the particles approach. The total moment of momentum in the central jet of the wake current, which intersects the normal compression shock, is hence diminished and the time arrives when this current jet cannot penetrate into the high pressure region behind the shock. Rearrangement of the flow occurs with the formation of a dead zone ahead of the body (analogously to Fig. 2c). When the particle reaches the apex of the cone, this latter starts to vanish at the velocity of the particle motion (or at a somewhat lower velocity). It is possible that the observed shock distortions are the result of the combined effect of superposing wakes from several particles.

The following experimental facts may serve as additional proofs of the proposed hypothesis. Firstly, the distortions in the shape of the compression shock presented in Fig. 1 are noted only in scanning the stream using a spark source, and never in scanning with a mercury lamp, when the exposure is considerably greater, and also on adjacent frames when scanning at a frequency of 25–50 frames/sec. This means that the duration of the observed distortions (and also, according to the proposed hypothesis, the duration of the effect of the wake on the shock) is greater than the exposure in the former case and less than in the latter. Computations carried out according to the method in [3] verified that the expected duration of wake interaction with the shocks actually lies in the range indicated.

Secondly, the number of distortions observed is proportional to the average of the geometrically similar models and the dust particle density. This follows from the presented hypothesis since the quantity of particles interacting with the detached shock varies in proportion to the mentioned quantities as they change. It was remarked in comparative tests of models of diverse shapes that, other conditions being equal, the quantity of shock distortions is proportional to the area of the frontal surface of the body bounded by the sonic lines.

Other conditions being equal, the quantity of shock distortions in tests on models made of soft materials (tin, lead, aluminum, polyfluorethylene resin) was 1.5-2-fold less than in tests on models made of hard materials (tempered steel 45, fiberglass AG-4). The reason is the difference in the quantity of particles which escape after collision with models of different hardness and also capable of causing shock distortions according to the same scheme. It is difficult to establish the influence of the escaping particles exactly; it can be assumed approximately, in conformity with the observed discrepancy in the quantity of perturbations, that the escaping particles cause to 25-50% of the observed shock perturbations. The fact noted is important in itself because it indicates the possibility of improving the quality of the flow around blunt models only on account of the use of softer materials. The absolute value of the perturbations depends on the model size, the dustiness level, and the duration of the experiment.

The height of the "liquid cones" observed was quite diverse, but not more than one to two model diameters. Not once was the particle successfully fixed at the cone apex, which is explained both by the small size of the particles and by the significant displacement of the particle during the exposure. Distortions of the shock (attached in this case) were not observed in tests on pointed models.

It was remarked in experiments with an artificially increased dustiness level that the quantity of shock distortions first increases as the particle size increased at a constant dustiness level, and then diminished after reaching a maximum. The particle diameter at which the maximum is observed depends on the conditions of the experiment (the number M, the stagnation pressure, etc.).

LITERATURE CITED

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