Experimental and numerical study of supersonic flow over two blunted wedges

M A Kotov, L B Ruleva, S I Solodovnikov and S T Surzhikov
A. Ishlinsky Institute for Problems in Mechanics of the Russian academy of sciences, Vernadsky prospekt 101(1), Moscow, 119526, Russia
E-mail: ma_kotov@mail.ru, ruleva@ipmnet.ru

Abstract. Shock-wave experiments with aerodynamic primitives in the form of a half wedge/double wedge with blunt edges are performed. Experimental studies were conducted using models, which are located at the exit of the supersonic nozzle of the hypersonic aerodynamic shock tube (HAST). Schlieren fragments of shock-wave formation over wedges were experimentally obtained. Calculations of the shock wave interactions over models carried out with the use of the authors’ computer codes. The predicted results and their comparison with experiment showed a satisfactory agreement.

1. Introduction
Shock-wave interactions are characteristic feature of high-speed flows near the various elements of constructions of high-speed vehicles. The variety of arising shock-wave configurations makes the task of experimental and theoretical study very complex. However, the practical importance of the problem of the understanding of the mechanisms of shock-wave interaction between themselves and with surfaces of the vehicles puts this problem in a number of high priorities of experimental, theoretical and computational aerodynamics and physical mechanics.

In recent years experimental and computational studies [1–23] have allowed to classify the main problems, the study of which is of greatest interest and at the same time, the greatest difficulties. Among them:

- Calculation process of numerical evaluation of flow conditions in sections of high-speed ground test facilities and comparison with experimental data to understand the physics of hypersonic interactions in the facility sections [1–8] and hypervelocity flow interactions over sharp and blunt bodies with different incoming flow conditions [9–11];
- Ground test measurements for aerothermal and thermochemical effects on spherical capsule geometries with different gases for re-entry applications [12–15];
- Velocity/altitude simulation for scramjet engine testing at different flight conditions [4,16];
- The flow structure and heat exchange in the zone of interference between an inclined shock and the surface of a flat plate [17] and blunt bodies [18,19];
- Investigations of leading edge bluntness influence on flow in air-inlet model with rectangular cross-section [20,21];
- Transition between regular and Mach reflections of steady shock waves and its influence on flow characteristics [22,23].

In our previous works, the models of flat inlet sections were experimentally investigated with the use of the laboratorial hypersonic aerodynamic shock tube (HAST) [24-28]. Along with the
experimental research some shock-wave configurations were calculated using authors' computational codes [25, 27, 29 – 31].

The present work continues the series of conjugated experimental and computational research. Technical capabilities of the HAST installation, as well as a short overview of previously obtained results are shown below.

2. Review of experimental and numerical results, previously obtained on the HAST
Detailed description of the HAST is presented in [24 – 28]. Scheme of the HAST function is shown in figure 1. Photo of the 15-meter facility with the receiver section is presented in figure 2.

Figure 1. Scheme of the HAST facility. 1 – high-pressure section; 2 – low-pressure section; 3 – vacuum chamber; 4 – hypersonic nozzle; 5 – critical orifice; 6 – pressure gauge; 7 – high-speed valve device; 8 – diaphragm; 9, 10 – high-frequency dynamic pressure sensors; 11, 12, 14, 17 – sensors; 13 – observation windows.

Figure 2. Photo of the HAST.

When shock wave is initiated in a cylindrical channel it follows multiple shock reflections from the ends of the shock tube and portioned outflow through the crucial section of the supersonic nozzle onto the model at Mach numbers M = 6...7. The shock dynamic processes are registered and recorded by high-speed video camera and high-frequency dynamic pressure sensors.

Shock wave initiation parameters were as follows: pressure in the high pressure chamber was of 500 bar (air), pressure in the low pressure chamber was of 60 mbar; pressure in the vacuum chamber was of $10^{-3}$ mbar.
Figure 3 shows graphs of pressure registered by the sensors of pressure (the PCB sensors) at different distances from the exhaust nozzle. From the graph (figure 3) it follows that the initial shock velocity in shock tube is 757.7 m/s.

With this experimental facility was obtained schlieren photography of M = 4.5...7 airflows over the model 10° half wedge [24], in channels with honeycombs [26], for spherical and conical models [27].

With the improvement of the equipment and experimental research methods [24, 25], several calculations of gas-dynamic characteristics have been produced using the developed computational codes [24 – 28]. Comparison of the experimental and computed results showed their satisfactory agreement [24 – 28]. Some examples of such a comparison are shown in figures 4, 5.

The upper parts of figure 4 and figure 5 correspond to the experimental data and the lower correspond to the calculations. Most of shock structures such as the incident waves, shear layers and expansion fans on the upper part of the figure coincide with the numerical simulation results.
3. Experimental study of the double wedges configurations

The most detailed were investigated double wedges with sharp and blunt edges. For these two experimental configurations the CFD investigation was carried out with definition of gas-dynamic parameters which add information obtained in the experiments. At first we will analyze some experimental data and then the results of the experimental and corresponding CFD investigations will be considered. The double wedges were investigated for the three configurations of experimental models. These are described shortly below.

3.1. Double half wedge with blunt top and sharp bottom edge (configuration #1)

Experimental model is shown in figure 6. The distance between the front edges was changed. Initially, they were located in the same plane (see figure 7 from the left).

**Figure 6.** Configuration of the model #1: Blunt double wedge and sharp bottom wedge.

Then the bottom half wedge was moved to a distance at which the shock wave from the top wedge interacts with the front edge of the bottom model. In this case, the distance between edges is of 64 mm (figure 6, L parameter). Frames of high-speed video from these experiments are shown in figure 7.
goals of these experiments were obtaining the schlieren images of the shock wave configurations not only for validation the authors’ computational codes, but also for receiving of the additional (indirect) information concerning parameters of input gas flow. It was established that these experiments corresponded to the following gas dynamic parameters on the test models (which were used in the calculations): \( p_\infty = 9.977 \times 10^4 \) erg/cm\(^3\), \( V_\infty = 1.402 \times 10^5 \) cm/s, \( T_\infty = 100 \) K.

**Figure 7.** Schlieren image of M=7 air flow near the double wedge configuration #1.

3.2. Experiments with blunt bottom edge (configuration #2)
Experiments were carried out with models of blunt lower edge, as shown in figure 8.

**Figure 8.** Configuration of the model #2: Blunt double wedge and blunt bottom wedge.

As expected, the concentration of reflected shock waves in the experiment was stronger with blunt bottom edge case. This may be due to the formation of high-enthalpy boundary layer and its effect on the flow behavior between models (figure 9).

**Figure 9.** Schlieren image of M=7 air flow near the double wedge configuration with blunt edges #2 at different mutual location.

3.3. Experiments with two blunt wedges (configuration #3)
Two blunt half wedges with an angle 15° were tested at Mach number M=7. The radius of blunting a half wedge is of 2 mm, thickness of the upper half wedge is of 21 mm and lower one is of 11.5 mm,
the distance between the models is of 20 mm. The shift of the lower half model relative to the upper half model was in range of 89 mm. It is just due to the mutual position of the models the detached shock from the upper blunted wedge reaches the front edge of the lower blunted wedge, what is shown in schlieren figure 10. Last frames in figure 10 illustrate the flow instability which is observed in experiments.

![Figure 10](image)

**Figure 10.** Shadow video sequence of airflow process evolution over blunt half wedges.

4. Numerical simulation results

4.1. Numerical investigation of the experimental configuration #1

A numerical simulation code NERAT-2D [30, 31] was used for this study. Used computational grid contains six blocks of the nonhomogeneous structured grids, which are shown in figure 11. Blocks #1 and #4 of the computational grid correspond to flowfield of blunted edges, block #3 describes compression flow, and block #5 corresponds to internal flow between two edges. Calculations were performed for the initial conditions presented in part 3.1. In these calculations instead of a bottom blunt wedge we used the blunt plate, because below the blunted nose of the bottom element of the model the flow field is not the point of our present investigation.

Distribution of gasdynamic functions for the case where the shock wave reflected from the upper edge of the model is incident on a blunt edge are shown in figures 12, 13.

Comparison of experimental and numerical data is shown in figure 13, where obtained numerical solution of shock-wave interaction for $L = 64$ mm combined with a schlieren photos for configuration of blunt double half wedge and blunt lower edge. Combined analysis of presented experimental and numerical data allows mark some significant peculiarities of the flow. Among those are:

- region of high pressure above blunt leading edge (see block 1 in figure 12);
- region of elevated pressure on bottom surface (see block 3 in figure 12);
- regions of elevated pressure on the bottom and top surfaces of the entrance region (see block 5 in figure 12);
regions of braking of gas flow in all places along the surface with elevated pressure (see blocks 1, 3, 4, 5 in figure 13);

- in the point of interaction of shock wave with boundary layer (see block 5, top surface, figure 13) the separated flow is observed;

- waves rarefaction beyond the turn of the top surface are visible in experimental data (see figure 10);

- regions of elevated pressure are observed at intersections of shock waves and shock wave with boundary layer (figures 10, 12).

Noticeable, that elevated pressure accompanied by the increasing of temperature.

Figure 11. Six blocks of the grid for numerical simulation configuration #1.

Figure 12. Pressure (left) and temperature for $M=7$, $T=100$ K.

Figure 13. Longitudinal velocity and comparison of experimental and computational Schlieren images $M=7$; $T=100$ K.

So, these data demonstrate good agreement. Note that for precise control of parameters in reference points of given configuration, it is necessary to have experimental sensor readings.
4.2. Numerical investigation of the experimental configuration #3

As before, the NERAT-2D [30, 31] was used for these calculations. Used computational grid contains six blocks of the nonhomogeneous structured grids, which are shown in figure 14. Blocks #1 and #4 are introduced for numerical simulation of flowfield above blunt edges, block #3 describes compression flow near bottom surface of the upper wedge, and block #5 corresponds to internal flow between the two wedges. Calculations were performed for the initial conditions presented in part 3.1. One can see that the difference from the previous calculation case consists in absent of turn of bottom surface for upper wedge. Four configurations of mutual location of upper and low wedges are investigated in the present numerical study, correspondingly:

- \( D_1 = X_{R2} - X_{R1} = 8.3 \) cm,
- \( D_2 = 7.9 \) cm,
- \( D_3 = 7.4 \) cm,
- \( D_4 = 6.1 \) cm,

where coordinates of \( X_{R1} \) and \( X_{R2} \) are shown in figure 14.

![Figure 14. Six blocks of the grid for numerical simulation configuration #2.](image)

The numerical simulation show gradual change of the location of falling shock wave relative to the nose of the bottom wedge at decreasing of distance \( D \). Distribution of temperature for these four configurations are shown in figure 15 (correspondingly, figures 15,a,b,c,d). In the first case (\( D = D_1 \)) the shock wave is falling on bottom surface of the nose of the bottom wedge. In the second case the shock wave is falling to the crucial point (\( D = D_2 \)), while in the third case the shock wave is falling to the top part of the nose (\( D = D_3 \)). In the last case (figure 15,d) the shock wave is falling to the top surface of the bottom wedge inside channel. Distributions of pressure along surfaces 'b-c-d-e' and 'f-g' for these four configurations are shown in figure 16.

Note that the configuration #2 (figure 15,b) coincides with the experimentally investigated case (see figure 10 (the upper left frame)).

So, the numerical simulation allow perform not only prediction of the possible shock wave configurations for different mutual locations of elements of tested models, but also to perform detailed comparison observed and numerical fields for the same initial conditions. Numerical data presented in figures 16 allow give prognostic decisions for further experimental study with the use of pressure transducers.

Finally we present numerical simulation results obtained for the second configuration of the wedge location (\( D_2 = 7.9 \) cm), but for another initial conditions, estimated by numerical calculations of flowfield in conical nozzle, namely \( p_{\infty} = 112.2 \) erg/cm\(^3\), \( V_{\infty} = 1.242 \times 10^5 \) cm/s, \( T_{\infty} = 50 \) K (figure 17).

5. Conclusion

Shock-wave experiments with wedge models with blunt edges have been performed. Experimental studies were conducted using models, which are located at the exit of the supersonic nozzle of the hypersonic aerodynamic shock tube (HAST).

Schlieren fragments of shock-wave interaction for different mutual location of two wedges were experimentally obtained at Mach number \( M = 7 \).
Calculations of the shock wave interactions have been carried out with the use of the authors' computer codes. Numerical data and their comparison with experiment showed a satisfactory agreement.

Figure 15. Temperature fields for four experimental configurations of mutual location of top and bottom elements of the model tested for $M=7$, $T=100$ K.

Figure 16. Distributions of pressure along top surface (points b-c-d-e from figure 14) and along bottom surface (points f-g-h) for four experimental configurations of mutual location of top and bottom elements of the model tested for $M=7$, $T=100$ K.
Figure 17. Mach number, longitudinal velocity ($V_\infty u/V_\infty$), density (Ro=\rho/\rho_\infty), and temperature (in K) M=7.5, $p_\infty=112.2$ erg/cm$^3$, $V_\infty=1.242\times10^5$ cm/s, $T=50$ K.

Acknowledgments
This study was supported by RFBR grant No. 16-01-00379 and by the Program of Basic Researches of the Russian Academy of Sciences.

References
[1] MacLean M, Candler G and Holden M 2005 Numerical Evaluation of Flow Conditions in the LENS Reflected Shock-Tunnel Facilities Proc. 43rd AIAA Aerospace Sciences Meeting AIAA 2005–0903
[2] Hornung H G 2010 Ground Testing for Hypersonic flow, Capabilities and Limitations CALIFORNIA INST OF TECH PASADENA GRADUATE AEROSPACE LABS
[3] Cummings R M, McLaughlin T E and Barlow D N 2011 Supersonic Research Facilities and Opportunities at the United States Air Force Academy Proc. 17th International Conference on Engineering Education TU.A.SA 11.309
[4] Northam G B, Andrews E, Guy W, Pellett G L, Drummond P, Cutler A D and Rock K An Overview of Hypersonic Propulsion Research at NASA Langley Research Center
[5] Schneider S P 2008 Development of Hypersonic Quiet Tunnels Journal of Spacecraft and Rockets 45 4
[6] Hadassah N 2010 Analysis and design of quiet hypersonic wind tunnels PhD dissertation Rutgers The State University of New Jersey
[7] Antón P S, Gritton E C, Mesic R, Steinberg P and Johnson D J 2004 Wind Tunnel and Propulsion Test Facilities: An Assessment of NASA’s Capabilities to Serve National Needs. RAND NATIONAL DEFENSE RESEARCH INST SANTA MONICA CA
[8] MacLean M, Wadhams T, Holden M, Candler G and Nompelis I. 2009 Integration of CFD and Experiments in the CUBRC LENS Shock Tunnel Facilities to Understand the Physics of Hypersonic and Hypervelocity Flows Proc. 4th Symposium on Integrating CFD and Experiments in Aerodynamics, von Karman Institute, Belgium
[9] MacLean M, Wadhams T, Holden M and Hollis B 2005 Investigation of blunt bodies with CO2 test gas including catalytic effects Proc. 38th AIAA Thermophysics Conference AIAA 2005-4693

[10] MacLean M, Dufrene A, Wadhams T and Holden M 2010 Numerical and Experimental Characterization of High Enthalpy Flow in an Expansion Tunnel Facility Proc. 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition AIAA 2010-1562

[11] Hornung H G 2010 Selected Achievements and Discoveries Made in High-Enthalpy Flow Facilities CALIFORNIA INST OF TECH PASADENA GRADUATE AEROSPACE LABS

[12] MacLean M and Holden M 2006 Catalytic effects on heat transfer measurements for aerothermal studies with CO2 Proc. 44th AIAA Aerospace Sciences Meeting and Exhibit AIAA 2006-0182

[13] MacLean M and Holden M 2006 Numerical assessment of data in catalytic and transitional flows for Martian entry Proc. 9th AIAA/ASME Joint Thermophysics and Heat Transfer Conference AIAA 2006-2946

[14] MacLean M, Holden M, Wadhams T and Parker R 2007 A computational analysis of thermochemical studies in the lens facilities Proc. 45th AIAA Aerospace Sciences Meeting and Exhibit AIAA 2007-0121

[15] MacLean M, Mundy E, Wadhams T, Holden M and Parker R 2008 Analysis and Ground Test of Aerothermal Effects on Spherical Capsule Geometries Proc. 38th Fluid Dynamics Conference and Exhibit AIAA 2008-4273

[16] Holden M S 2005 Aerothermal and Propulsion Ground Testing That Can Be Conducted to Increase Chances for Successful Hypervelocity Flight Experiments CALSPAN UB RESEARCH CENTER BUFFALO NY

[17] Borovoi V Y, Egorov I V, Skuratov A S and Struminskaya I V 2005 Interaction between an inclined shock and boundary and high-entropy layers on a flat plate Fluid Dynamics 40 6

[18] Edney B E 1968 Effects of shock impingement on the heat transfer around blunt bodies AIAA Journal 6 1

[19] D'Ambrosio D 2003 Numerical prediction of laminar shock/shock interactions in hypersonic flow Journal of spacecraft and rockets 40 2

[20] Borovoi V Y, Egorov I V, Noev A Y, Skuratov A S and Struminskaya I V 2011 Two-dimensional interaction between an incident shock and a turbulent boundary layer in the presence of an entropy layer Fluid Dynamics 46 6

[21] Borovoy V Y, Mosharov V E, Radchenko V N, Skuratov A S and Struminskaya I V 2014 Leading edge bluntness effect on the flow in a model air-inlet Fluid Dynamics 49 4

[22] Ivanov M S, Klemenkov G P, Kudryavtsev A N, Nikiforov S B, Pavlov A A, Fomin V M and Hornung H G 1997 Experimental and numerical study of the transition between regular and Mach reflections of shock waves in steady flows Proc. 21st International Symposium on Shock Waves

[23] Ivanov M S, Vandromme D, Fomin V M, Kudryavtsev A N, Hadjadj A and Khotyanovsky D V 2001 Transition between regular and Mach reflection of shock waves: new numerical and experimental results Shock Waves 11 3

[24] Kotov M, Ruleva L, Solodovnikov S, Kryukov I and Surzhikov S 2014 Multiple Flow Regimes in a Single Hypersonic Shock Tube Experiment Proc. 30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference AIAA 2014-2657

[25] Kuzenov V V, Kotov M A 2014 Analysis of gas-dynamic processes and development of model of flows in hypersonic shock tube Herald of the Bauman Moscow State Technical University 1 94

[26] Kotov M A, Kryukov I A, Ruleva L B, Solodovnikov S I and Surzhikov S T 2015 Numerical and experimental investigation of the hypersonic flow structure in a complex flat duct Herald of the Bauman Moscow State Technical University 1 100
[27] Kotov M, Kryukov I, Ruleva L, Solodovnikov S and Surzhikov S 2015 Supersonic Air Flows around Some Geometrical Primitives Proc. 33rd AIAA Applied Aerodynamics Conference AIAA 2015-3012

[28] Kotov M, Kryukov I, Ruleva L and Solodovnikov S 2017 The Investigation of Shock-Wave Interaction with Aerodynamic Models Proc. 55th AIAA Aerospace Sciences Meeting AIAA 2017-0262

[29] Seleznev R and Surzhikov S 2015 Quasi-One-Dimensional and Two-Dimensional Numerical Simulation of Scramjet Combustors Proc. 51st AIAA/SAE/ASEE Joint Propulsion Conference AIAA 2015-4166

[30] Surzhikov S T and Shang J 2012 Coupled radiation-gasdynamic model for stardust earth entry simulation Journal of Spacecraft and Rockets 49 5

[31] Shang J S and Surzhikov S T 2012 Nonequilibrium radiative hypersonic flow simulation Progress in Aerospace Sciences 53