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3D printing technologies for creating models and nozzles in an aerodynamic shock tunnel experiment

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Abstract. The features of 3D printing method for rapid prototyping and manufacturing of models for a pulsed high-speed gas-dynamic experiment are considered. Modern additive technologies allow the production of models. The basic properties of the materials and the advantages of 3D printing methods are described. The structure and properties of the obtained models can be unattainable using traditional manufacturing techniques. The design of the wind tunnel nozzle block is considered, which provides for the production of profiled contours using 3D printing. The advantages and disadvantages of use of such units on the shock tube are considered.

1. Introduction

The study of heat transfer between high-speed flows of weakly ionized gas and the solid surface of an aircraft is an urgent task related with the solution of the problem of vehicles entering the atmosphere of the Earth and other planets. An important scientific direction is the search and development of effective methods for controlling high-enthalpy gas flows near the surface of high-speed aircraft. For example, it seems promising to study the possibility of using gas discharges of various types and configurations with the goal of global and local modification of the aerodynamic characteristics of aircraft [1-4]. To successfully solve these problems, it is necessary to be able to experimentally study heat fluxes to the surface of a body located in a supersonic and hypersonic gas stream with a significant degree of ionization in a wide range of enthalpies. An important task for the development of scientific ideas about heat transfer processes during high-speed motion is to obtain reliable experimental data using pulsed aerodynamic installations and to compare these data obtained at various installations with similar flow parameters. A relatively simple device for creating high-enthalpy gas flows is a shock tube, coupled with a supersonic nozzle. As a rule in order to create a flow in the nozzle located behind the end wall of the shock tube the shock wave is reflected from the end flange and the flow characteristics in the nozzle are determined by the gas parameters (temperature and pressure) in the region near the shock tube end wall [5]. An important technical step in these studies is the development and manufacture of three-dimensional models of various shapes for the implementation of their flow around a supersonic stream. The shape of the models in such experiments can vary from simple geometric shapes and their combinations, such as a “cone-cylinder” [6], hemisphere [7], wedge and half-wedge [8], to complex structures, for example models of descent vehicles and space aircrafts with external and internal complex structural elements for installing inserts of various materials, sensors and actuators.



2. Model manufacturing technologies

The choice of material for the manufacture of the model is an important issue from different points of view:

1. Since the model is surrounded by a high enthalpy gas stream, it is subjected to intense mechanical and thermal stresses;
2. In the case when the incident flow has a sufficiently large degree of ionization (thermal, or specially created using an auxiliary electric discharge), the conductive properties of the material also become significant;
3. Models for a gas-dynamic experiment can have a complex structure, including fittings for mounting sensors and inserts, as well as internal channels of various shapes.

For such cases, materials are required from which it is possible to qualitatively manufacture such products. From the experimental point of view, the models are divided into those made of a dielectric (and electrostatic charging of their surface in a hypersonic flow is possible) and models of electrically conductive materials (to which it is possible to transfer the required electric potential).

Currently, all used model-making technologies can be divided into three broad categories:

- Additive technology (3D printing) [9-13], in which during the manufacturing process the material is added to the workpiece or base to obtain a finished model;
- Traditional, usually subtractive technology, where material is removed from the workpiece (by turning, milling, drilling and other methods);
- Combined, in which at different stages of manufacturing requires the use of different technologies and methods (for example, casting, molding or machining of printed models).

In application for a gas-dynamic experiment, the technologies used require the following capabilities:

1. Production of models with the required geometric, mechanical and electrophysical parameters;
2. Low manufacturing cost;
3. Quick processing of models if necessary;
4. Production of models in a given, usually short time.

Traditional technologies, as a rule, do not allow even a simple model (for example, a cylinder) to be made in one operation. For example, after turning, drilling of mounting holes, milling of surfaces and threading may be required to place the model in the experimental chamber. The installation of various sensors on the model surface, for example, piezoelectric pressure sensors or heat flux sensors, as a rule, requires complex internal channels in the model. In this case, the manufacture by traditional methods may not be possible or require the implementation of many different operations, which significantly increases the time of the study.

3. Features of 3D printing for a pulsed gas-dynamic experiment

Of all the manufacturing technologies, three-dimensional printing is especially distinguished, which allows the technological production of a finished model from polymer and polymer-composite materials in a minimum number of operations. Among the methods of three-dimensional printing, it is worth noting:

1. Fused deposition, or fused deposition modeling (FDM), in which the model is formed layer by layer when applying a molten polymer or polymer-composite thermoplastic material using an extruder moving relative to the model using a precision numerically controlled drive;
2. Stereolithography (SLA), in which the model is obtained using selective layer-by-layer curing of a photocurable polymer or polymer-composite material.

Both technologies under consideration allow the production of models in one step (with possible simple refinement) in a short time. In this case, the material model is built on the basis of a computer, which allows one to calculate the mechanical, thermal and electrical properties, as well as freely modify it to meet emerging needs.

In a pulsed gas-dynamic experiment, the models related with high pulsed thermal and mechanical loads, the free-stream temperature can reach thousands of K for times of the order of units of

milliseconds, which both makes demands on the thermomechanical properties of the material used and allows the use of polymers with a relatively low softening temperature. Thus, it is possible to produce both practically monolithic models (Figure 1a), and porous ones with various internal structures, pores, gradient or step filling (Figure 1b), and even light porous skeleton structures (Figure 1c).

Suitability criteria are:

1. The amount of shrinkage when printing, which determines the possibility of using the material with a 3D printer without a working chamber with a stabilized temperature, ease of printing, as well as the possibility of distortion of the size of the model when the material hardens;
2. The maximum operating temperature of the material in the solid state;
3. Static tensile strength, determining the possibility of using models in an aerodynamic experiment with high mechanical loads.

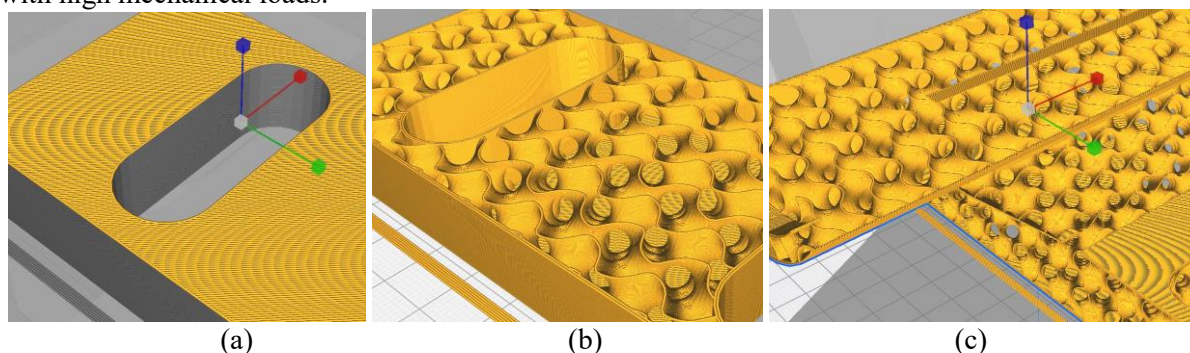


Figure 1. An example of an almost monolithic internal model filling in CAD (a), a porous internal structure with gyroidal filling, which is characterized by high strength (b) and a wallless frame gyroid structure (c).

The main properties of the monitored polymeric materials for three-dimensional printing are presented in table 1.

Table 1. The main properties of the materials for 3D printing.

№	Name	Density, kg/m ³	Printing method	Maximum operating temperature, °C	Relative shrink when printing	Static tensile strength, MPa
1	ABS	1.01-1.27	FDM	61.9 - 76.9	Significant	13.0-65.0
2	PLA	1.24	FDM	50.0-60.0	Low	13.6-38.1
3	Polycarbonate	1.18-1.20	FDM	145.0	Significant	30.0-75.0
4	PETG	1.27	FDM	51.0-73.0	Low	28.3-58.6
5	Polypropylene.	0.9	FDM	100.0	High	40.0
6	Polyamide (Nylon)	1.06-1.14	FDM	60.0-100.0	Significant	32.0-70.0

Of polymeric materials for printing prototypes in the manufacture of models by other methods, the most suitable are:

- PETG, due to the simplicity of printing, the possibility of using the material with almost any FDM 3D printer and the transparency of the material in unpainted form;
- PLA, due to the simplicity of printing and the possibility of using the material with almost any FDM 3D printer.

The most suitable substance for producing models in order to obtain flow pictures in an aerodynamic experiment from materials for printing by the method of layer-by-layer deposition are:

- ABS, due to the relatively high strength, relatively high operating temperature and relative ease of printing, although it is recommended to use a thermal camera when printing;
- PETG, due to its ease of printing and relatively high strength and operating temperature.

The range of materials for printing by stereolithography is quite wide, and for most materials suitable for printing on semi-professional printers the manufacturer does not provide thermal properties in the material documentation. To print models for prototyping and to obtain flow pictures in an aerodynamic experiment one should select photopolymer material according to its mechanical properties from the material documentation.

4. Axisymmetric nozzle block

In almost all wind tunnels for flow acceleration a geometric action is used known as the Laval nozzle. To accelerate from zero speed to the speed of sound, a converging channel is used. Further acceleration from the speed of sound to supersonic and hypersonic speeds occurs in an expanding channel. For the acceleration of the gas flow, the cross section shape of the channel does not play a big role. Therefore, the nozzle cross section is usually selected from technological considerations in the form of a simple circle or rectangle [14]. Changing the area in length can also be arbitrary. However, when choosing the law of changing the area along the length of the nozzle, a number of conditions must be taken into account. The most important of them is the need to obtain a uniform distribution of gas-dynamic parameters in the outlet section of the nozzle, which can be reached by using special profiling methods [14-20].

The manufacture of nozzle contours from metal, especially profiled contours, is a rather complicated and time-consuming process. Firstly, for the manufacture of such a part, even in an assembly version, a metal billet is needed and its characteristic dimensions in length, width and height must exceed the length of the nozzle and the dimensions of its outlet section, respectively. Moreover, this excess should not only be the value of the thin-walled geometry at the exit of the nozzle, but also exceed it by at least a few millimeters to ensure the corresponding tolerances and limits of the machine tool which is used for processing workpiece. Secondly, the ratio of the volume of consumable metal (i.e. material that is unsuitable for further use) to the volume of an all-metal manufactured part can significantly exceed 1. It is the reason for the high material and labor costs of producing such a nozzle. Thirdly, the preparation of such a nozzle contour can be carried out only by a highly qualified staff of turners and millers due to the work complexity. Given the typical characteristic centimeter sizes of nozzles of aerodynamic setup, high-precision compliance with all sizes of the geometric structure of the contour (in particular, profiled) up to tenths of a millimeters is necessary. Otherwise, locking, flow stalling, vortex flows, etc. can occur, which leads to local strength and temperature loads in the contour. As a result, the manufactured nozzle will function in off-design mode or will not work at all.

When using three-dimensional printing methods, the plastic consumption of the printer will be almost equivalent to the volume of the printed part. Small losses of material occur during heating in the printer nozzles directly during printing, but they are incomparably small. It allows one to pre-calculate the required amount of plastic for the manufacture of a model or a series of parts. Also, if it is necessary to place registration sensors or optical observation windows of various geometries inside the nozzle, the manufacture of the necessary holes becomes much simpler than in case of metal processing. In fact, the placement parameters of such elements are set at the stage of designing the model in CAD (Figure 2a), after which the geometry is sent for printing.

A significant drawback in the applicability of additive technologies for tasks of this kind lies in the local-time problems of the process of directly three-dimensional printing, such as the amount of shrinkage and distortion of the model size both during printing and during hardening of the material [21-26]. When choosing ink for the manufacture of parts for an aerodynamic experiment with high-level mechanical loads, it is important to remember the parameters of the working temperature of the material in the solid state and its static strength. Thus, the quality indicators of the manufactured models depend both on the used polymer material and on the conditions for the manufacture of the model, so the choice of a 3D printer and material is an important criterion. However, local irregularities, inhomogeneities and roughness that arose during the creation of the model can be removed by polishing and abrasive surface treatment.

It must be remembered that, due to their density, fragility and roughness, the printed plastic elements cannot be used for fixing directly to the installation, since it will not be possible to provide the necessary degree of sealing and vacuumization in the working sections of facility. In other words, due to limitations on the materials used in 3D printing, it is not yet possible to consider the completely plastic construction of the nozzle block. However, its accommodating and fastening elements can be made of metal. A similar structure is proposed in this paper.

4.1. Scheme

The construction consists of three main elements (Figures 2b,c). Flange 1 is located between the driven tube and the test section. It secures the nozzle block on the inner wall of the test chamber with six through holes for studs and nuts with M18 thread. The nozzle 2 is inserted into the flange 1 in such a way that its inlet section is located in the end wall of the driven tube, and the outlet in the test section. On the outside of the element there is a protrusion 5 mm high over the entire external cross-section of the part. It serves to accommodate the flange 3, which is put on the output section of the nozzle 2. On the flanges 1 and 3 there are six threaded holes for the M4 studs, which are used to fix the entire nozzle block.

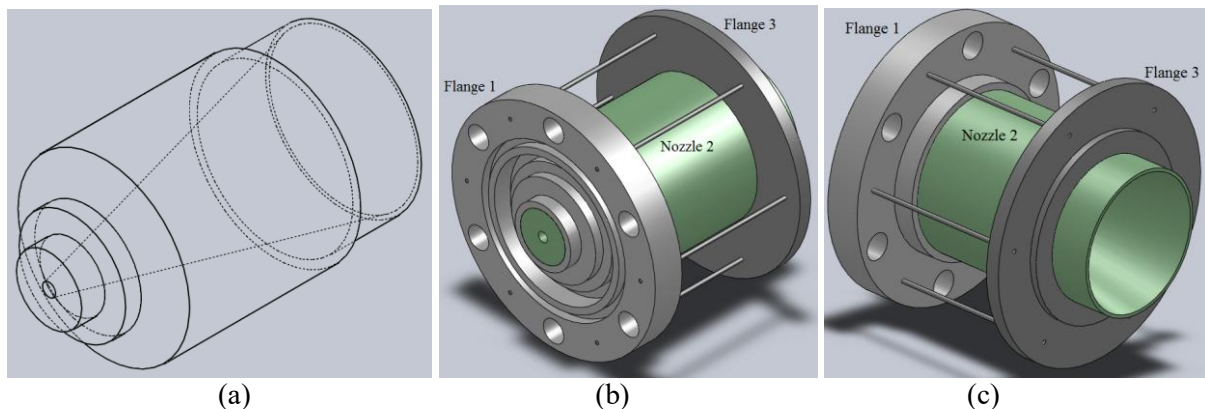


Figure 2. 26 ° conical nozzle contour (a) and different orientations of the nozzle block construction (b-c) in SolidWorks CAD.

4.2. Flange 1

The main task of flange 1 is to serve as the basis for the entire construction. It is both the basic element, to which all the others are fixed, and acts as a connecting link and provides a transition from the end wall of the driven tube to the inlet of the test chamber. Figure 3 shows a model of flange 1. The cylindrical surface 1 (Figure 3, yellow) serves to fix the end-wall nut with the hole in the nozzle contour. To do this, on the surface 1 is a notch thread with an appropriate step. If during the design of flange 1 there is a need for a deeper placement of the end wall (for example, to reduce the incident shock wave propagation or to set the fixed distance between the recording element cross section and the end wall, desired for investigation), the length of surface 1 can be increased. However, when carrying out these operations, it is necessary to remember the nozzle contours planned for implementation and the reduction in the ratio of their cross sections and the internal cross-section of the driven tube depending on the immersion depth of the end wall. When the value of this ratio is close to 1, it will not be possible to produce a nozzle 2 due to geometric constraints.

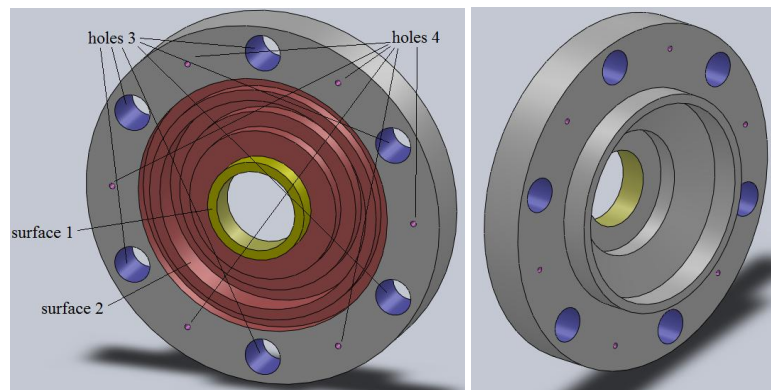


Figure 3. Designed flange 1 model.

The geometric characteristics of surfaces 2 (Figure 3, red) coincide with the characteristic dimensions of the output constructive element of the driven tube and are used to connect the sections and place sealing materials and gaskets. Six through holes 3 (Figure 3, blue) are used to fix the nozzle block from the inner wall of the test section using threaded studs M18 and nuts. Depending on the mounting characteristics, the outer diameters of the surfaces, the number of holes and their sizes on the flange 1 may vary during design for a particular experimental facility. Several threaded holes are made (Figure 3, pink) for connection to flange 3 by using studs.

4.3. Nozzle 2

Unlike flanges 1 and 3, which are made of metal, the “nozzle 2” part is created using additive technologies of three-dimensional polymer printing. The part model is designed in CAD, at this stage the path of the nozzle contour and its profiling parameters are set. Figure 4 shows the designed three-dimensional model of the conical section nozzle. Surfaces 3 (Figure 4, yellow) are designed to be fixed in flange 1. For reliability of placement it can be modeled with a small tolerance of 0.1-0.5 mm reduction along the perimeter of sections or sanded after printing. The membrane, which provides the separation of the driven tube and the test section, is located on surface 4 (Figure 4, red) and is pressed by the end-wall nut (Figure 2b), which is put on the flange 1. A protrusion is made at a certain distance from the inlet section of the nozzle (surface 5, highlighted blue in Figure 4) designed to accommodate flange 3.

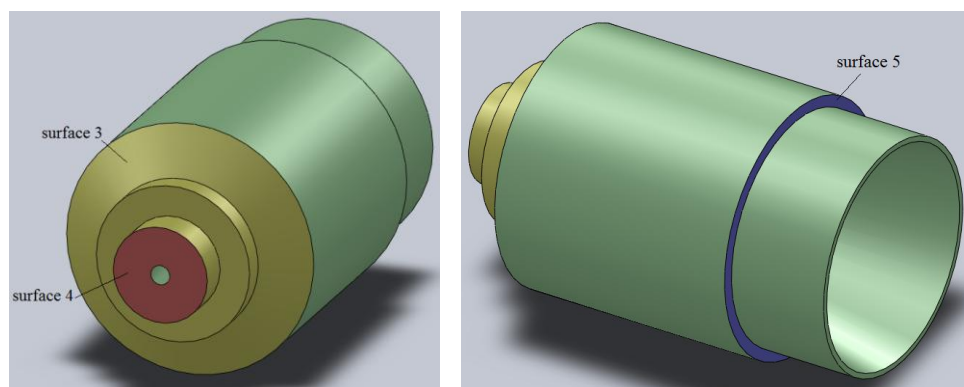


Figure 4. Nozzle 2 model in SolidWorks CAD.

When modeling a part, it is important to take into account the characteristics of the 3D printer used and the useful geometric dimensions of its work area to avoid twist and warping of model during printing. If the ratio of the length of the nozzle to its width is greater than 1, one can design several connected parts that form a common contour. An example of such a simulation is presented in Figure 5. To connect the parts to each other, protrusions with similar dimensions are made (surfaces 6 and 7,

Figure 5, highlighted in pink). After printing, finished parts in these places are processed with plastic glue and fastened together.

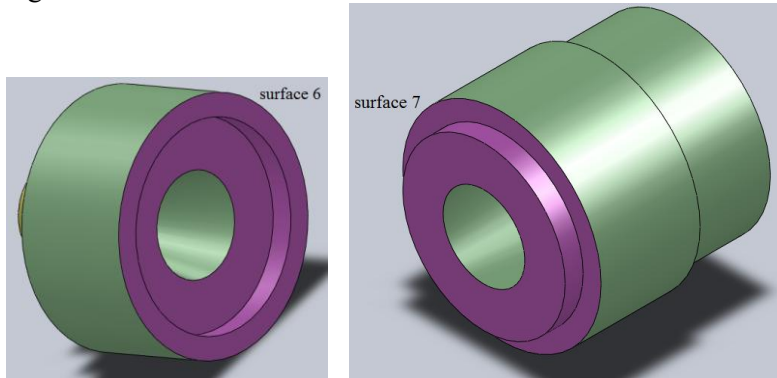


Figure 5. Two possible parts of Nozzle 2

4.4. Flange 3

This part is made of metal and is intended for fastening the entire nozzle block. It is located on the protrusion of the nozzle 2 and has holes, symmetrically located relative to the similar holes of the flange 1. Using the studs and nuts, the structural elements are fixed to each other (Figures 2b,c). Depending on the design parameters of the nozzle 2 and to increase its output section, the dimensions of the part can be changed by manufacturing a flange with a wider inner diameter.

5. Conclusion

Modern additive technologies allow the technological production of models suitable for use in a pulsed gas-dynamic experiment as well as their prototypes in a minimum time and a minimum number of stages on available equipment. The basic properties of the materials used and the advantages of three-dimensional printing methods were described, which allow creating models with rather complex geometric features due to the wide possibilities in their design. The structure and properties of the obtained models can be unattainable using traditional manufacturing techniques.

The designed construction of the axisymmetric nozzle block described in this work can be used in experimental aerodynamic facilities with a long working time, where the characteristic diameters of the nozzle exit section do not exceed several tens of cm, and the temperature parameters of the incoming flow do not exceed 60-100 °C. These values today are typical indicators of the useful print area of most 3D printers and the maximum operating temperature for most materials used in additive technologies and available on the market. This design can also be used in gas-dynamic setup of short duration and shock tubes, since the main heating occurs in the area in front of the metal end-wall nut of the nozzle 2 inlet section, and the period of high enthalpy loads directly on the nozzle contour is up to several tens of ms, which is relatively small for the limit values of the integral thermal load of materials. It can be noted that the presented logic of nozzle block design can be applied for the manufacture of parts and their use in facilities operating with flat rectangular nozzles.

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References

- [1] Adamovich I V 2010 *Encyclopedia of Aerospace Engineering* (John Wiley & Sons Ltd)
- [2] Lapushkina T A, Erofeev A V 2017 *Tech. Phys. Lett.* **43** (17)
- [3] Bobashev S V, Mende N P, Popov P A, and Sakharov V A 2010 *Tech. Phys.* **55** (12) 1760-5
- [4] Seleznev R K, Surzhikov S T and Shang J S 2019 *Prog. Aerosp. Sci.* **106** 43–70

- [5] Ya B Zel'dovich, Yu P Raizer 1966 *Physics of shock waves and high-temperature hydrodynamic phenomena* (Academic Press NY)
- [6] Kotov M A, Kryukov I A, Ruleva L B, Solodovnikov S I and Surzhikov S T 2015 Supersonic Air Flows Around Some Geometrical Primitives *AIAA paper* 2015–3012
- [7] M A Kotov et al 2017 *J. Phys.: Conf. Ser.* **815** 012025
- [8] Kotov M A, Kryukov I A, Ruleva L B and Solodovnikov S I 2017 The Investigation of Shock Wave Interaction with Aerodynamic Models *AIAA paper* 2017–0262
- [9] Daneshmand S, Aghanajafi C and Ahmadi N A 2010 *The effect of chromium coating in RP technology for aerofoil manufacturing 35 Part 5* (Indian Academy of Sciences) 569
- [10] Nannan G and Ming C L 2013 Additive manufacturing: technology, applications and research needs *Front. Mech. Eng.* **8** 215
- [11] K Olasek and P Wiklak 2014 *J. Phys.: Conf. Ser.* **530** 012009
- [12] T Lusiak, R Babel 2018 *J KONES* **25** 255
- [13] W Zhu 2019 Models for wind tunnel tests based on additive manufacturing technology, *Prog. Aerosp. Sci.* **110**
- [14] Aulchenko S M, Galkin V M, Zvegintsev V I, Shiplyuk A N 2010 Numerical design of multimodal axisymmetric hypersonic nozzles for wind tunnels *Journal of Applied Mechanics and Technical Physics* **51** (2)
- [15] V Ya Bezmenov, V Ya Borovoy, I V Struminskaya, L V Yakovleva 1999 Influence of disturbances generated by the nozzle boundary layer on the heat exchange on the cylindrical nose of a body in a hypersonic flow *Fluid Dynamics* **34** (1)
- [16] 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)
- [17] 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)
- [18] A N Kraiko, A S Telyakovskii, N I Tilyaeva 1994 Profiling the optimal contour of a supersonic nozzle in highly turned flow *Comput. Math. Math. Phys.* **34** (10)
- [19] S T Surzhikov 1995 Mathematical models of subsonic Laval nozzles of laser-plasma accelerators *High Temperature* **33** (3)
- [20] S T Surzhikov 1997 Radiation-gasdynamic model of a nozzle with a local heating *Mat. Model.* **9** (9)
- [21] Lapushkina T A, Erofeev A V, Ponyaev S A et al 2009 Supersonic flow of a nonequilibrium gas-discharge plasma around a body *Tech. Phys.* **54** 840–848
- [22] A M Springer 1998 *Application of Rapid Prototyping Methods to High-Speed Wind Tunnel Testing (MSFC Center Director's Discretionary Fund Final Report, Project No. 96–21)* (Marshall Space Flight Center, Alabama. NASA/TP—1998–208396)
- [23] Vasile D P A 2012 *Suitability of Rapid Prototype Modelling for Hypersonic Tunnel Testing* (Undergraduate Thesis, School of Engineering and Information Technology).
- [24] Chris Kennell, Andrew J Neely, Sean B O'Byrne and David Buttsworth 2015 Measurement of Vehicle Stability Coefficients in Hypersonic Wind Tunnels *AIAA paper* 2015-3690
- [25] M Moioli, C Reinbold, K Sørensen and C Breitsamter 2019 Investigation of Additively Manufactured Wind Tunnel Models with Integrated Pressure Taps for Vortex Flow Analysis *Aerospace* **6** (10)
- [26] P S Bychkov, V M Kozintsev, A V Manzhurov, A L Popov 2017 Determination of Residual Stresses in Products in Additive Production by the Layer-by-Layer Photopolymerization Method *Mechanics of Solids* **52**