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START UP RESEARCH EFFORT IN FLUID MECHANICS

Research Project No.1:

ADVANCED METHODS FOR ACOUSTIC AND THRUST BENEFITS FOR AIRCRAFT ENGINE NOZZLE

PERFORMANCE REPORT-97

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ADVANCED METHODS FOR ACOUSTIC AND THRUST BENEFITS FOR AIRCRAFT ENGINE NOZZLE

SUMMARY

In accordance with the project plan for the report period in the proposal titled above, HU and FML teams investigated two sets of concepts for reduction of noise and improvement in efficiency for jet exhaust nozzles of aircraft engines and screws for mixers, fans, propellers and boats. The main achievements in the report period are: **a)** Publication of the paper [7] in the AIAA Journal, which described our concepts and some results. **b)** The Award #RE-136 in the Civil Research and Development Foundation (CRDF) competition. This 2 year grant for Hampton University (HU) and Central AeroHydrodynamic Institute (TsAGI, Moscow, Russia) supports the research implementation under the current NASA FAR grant. **c)** Selection for funding by NASA HQ review panel of the Partnership Awards Concept Paper "Mixing, Noise and Thrust Benefits Using Corrugated designs" prepared by M.M. Gilinsky and J.M. Seiner. This two year grant also will support our current FAR grant. **d)** Publication of a Möbius Strip concept in NASA Technical Briefs, June, 1996, and a great interest of many industrial companies in this invention. Successful experimental results with the Möbius shaped screw for mixers, which save more than 30% of the electric power by comparison with the standard screws. Creation of the scientific-popular video-film which can be used for commercial and educational purposes. **e)** Organization work, joint meetings and discussions of the NASA LaRC JNL Team and HU professors and administration for the solution of actual problems and effective work of the Fluid Mechanics Laboratory at Hampton University.

In this report the main designs are enumerated. It also contains for both concept sets: the statment of the problem for each design, some results, publications, inventions, patents, our vision for continuation of this research, and present and expected problems in the future.

Advanced Methods for Acoustic and Thrust Benefits for Aircraft Engine Nozzle

Prepared by the
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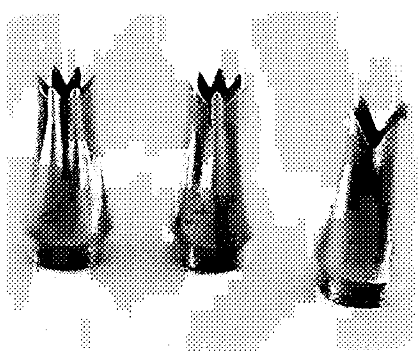

Fig.1

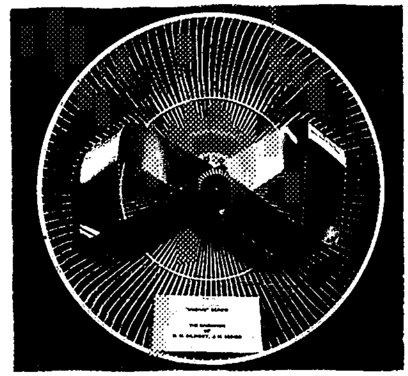

Fig.2

I. INTRODUCTION

In June of 1996 a new Fluid Mechanics Laboratory (FML) was established at Hampton University under the direction of Dr. Samuel G. White Jr., Dean of the School of Engineering and Technology (E&T). The start of this laboratory was made possible by a NASA HQ grant NAG 1-1835. The goal of the FML program is to attract promising minority students into the field of Fluid Mechanics with an emphasis on Aeroacoustics. The program offers training in this area through courses of instruction at Hampton University and research opportunities at both Hampton University and the NASA Langley Research Center.

The FML's principal research scientist is Dr. Mikhail M. Gilinsky, who has over 25 years experience in the field of Computational Fluid Mechanics while at Moscow State University in Russia, the Courant Institute at New York University, and as a senior National Research Council (NRC) Fellow at the NASA LaRC. While serving as an NRC Fellow, he pursued research in computational and experimental Aeroacoustics with Dr. John M. Seiner. Dr. Seiner is Leader of the Jet Noise Team (JNT). The JNT conducts jet noise aeroacoustics research in NASA focused programs such as the Advanced Subsonic Technology (AST) and the High Speed Research (HSR). The team operates and maintains the JNL, a modern laboratory equipped with a wind tunnel and aero-propulsion model with balance to access exhaust nozzle noise suppression concepts. The laboratory also contains smaller jet facilities that are ideal for generic studies and the training of students.

With the association of the NASA Langley Jet Noise Laboratory and Team, the Hampton University's Fluid Mechanics Laboratory can develop many minority professionals in the field of Fluid Mechanics and Aeroacoustics. It is well known that reduction of aircraft engine noise is a significant driver to the success of the NASA AST and HSR programs in their attempt to meet new stringent international environmental regulations on noise for commercial aircraft. The research at the Hampton University's FML also supports reduction schemes associated with the emission of engine pollution for commercial aircraft and concepts for reduction of observables for military aircraft. These research endeavors satisfy the goals of the NASA Strategic Enterprise in Aeronautics concerning the development of environmentally acceptable aircraft. It is in this precise area, where the U.S. aircraft industry, academia, and Government are in most need of trained professionals, which is a high priority of the Minority University Research and Education (MUREP) goals.

As a first step to meeting these goals, a research and training program for minority students is being offered by Hampton University's FML in cooperation with the NASA Langley Jet Noise Laboratory to jointly study promising jet, fan, and propeller noise reduction concepts. Joint efforts in this area have already been established with the Central AeroHydrodynamics Institute (TsAGI, Moscow) in Russia under a 2 year Civil Research and Development Foundation (CRDF) grant. Under this grant it is possible to bring to Hampton University world class research scientists to teach and provide instruction to students. The NASA Langley Jet Noise Team also provides instruction to students and the opportunity to work with US Aerospace professionals at Boeing, McDonnell Douglas, GE Aircraft Engines, and Pratt&Whitney Aircraft.

Hampton University (HU) represents a unique opportunity to successfully offer this research and training opportunity for the development of minority professionals. As one of the oldest Historically Black Colleges and Universities (HBCU), it has provided over one hundred years of dedicated service to higher education. In this decade HU is configured as a major research institute with close ties and proximity to the NASA Langley Research Center. HU offers M.S. and Ph.D degrees in Physics, and M.S. degrees in Computer Sciences and Mathematics. These programs are important to the present research offer, since fluid mechanics and aeroacoustics research requires significant training in these areas.

In accordance with the project plan in the proposal HU and FML teams investigated two sets of concepts for reduction of noise and improvement in efficiency for jet exhaust nozzles and screws for mixers, fans, and boats. Below we will enumerate the main designs of both sets, the statement of the problem for each design, some results, publications, inventions, patents, our vision for continuation of this research, and present and expected problems in the future.

II. PROMISING EXHAUST NOZZLE CONCEPTS

2.1 A Bluebell Nozzle. Several examples of the Bluebell nozzle concept are shown in Figures 1 and 3. A Bluebell nozzle involves the use of chevrons to enhance the nozzle exit perimeter to increase the area for mixing and internal corrugations to generate counter-rotating axial vorticity to enhance mixing of high speed primary flow with low speed secondary flow. It is very important that the corrugation depth increases downstream smoothly. This forms swirling flow at predefined locations and a boundary layer flow that can be controlled by geometric nozzle parameter variation. These features lead to jet noise reduction. The nozzle's corrugated interior surface also leads to an increase in nozzle projected area for thrust augmentation. The experimental tests of several Bluebell nozzle designs were conducted in the small Anechoic Jet Noise Facility (SAJF) at the NASA LaRC. These tests have shown noise reduction relative to a convergent-divergent round nozzle with design exhaust Mach number $M_e = 1.5$. The best design provides an acoustic benefit near 4dB with about 1% thrust augmentation. In Fig. 3 is shown schematically the flow through a Bluebell nozzle and downstream into an exhaust jet. The benefits are caused by increasing nozzle lip line edge that enhances longitudinal waves **3**, and corrugations generate counter-rotating axial vorticities **2** at the internal nozzle surface **1**.

The research with this main design in the considered period was: **a)** To improve the theoretical and numerical simulation approach in accordance with the desires and critical remarks of two reviewers of the paper [7], which was presented before to the AIAA Journal by J.M. Seiner and M.M. Gilinsky. In particular, a more correct boundary layer approximation was applied for thrust calculation. This led to better agreement with the numerical simulation results based on full Navier-Stokes Equations(NSE). **b)** Reviews, meeting, discussions, preparation of the necessary documents for the Patent Application "Bluebell Nozzle for improving the mixing of exhaust Jets with Ambient Air". This work has conducted with the NASA patent workers of the NASA Technology Application Group (TAG).

2.2 A Chisel Nozzle. It can be more effective than the Bluebell nozzle. In Fig.4 is the external design 1 of the Telescope-Chisel nozzle. A gas flowing along a nozzle wall produces a larger thrust if corrugation convexities are contracted toward the nozzle exit. Thus a cross section contour is described by a periodic piecewise continuous function with alternation of cavities and convexities. A cavity depth (or a convexity height) increases along the nozzle centerline from zero at the throat to the maximum value at the exit. A cavity (convexity) width also linearly increases (decreases) downstream from zero (maximum) at the throat to the maximum (zero) at the nozzle exit. For such a configuration, two expanded flows near the nozzle wall flow into two neighbouring cavities to meet each other at some angle α. The flows then mutually penetrate and more effectively mix. A flow impulse on the lateral area of the convexities increases the resulting nozzle thrust. A Chisel nozzle can be more efficient with smooth corrugations, like a Bluebell nozzle. The example is shown in Fig.5.

The smoothed Chisel nozzle was tested only numerically using Kriko-Godunov marching scheme (KGMS) based on Euler inviscid approximation. Design of this model for experimental tests in TsAGI's anechoic chamber is based on the CRAFT and CFL3D codes for NSE approximation. In present time this research is in process.

2.3 A Telescope Nozzle. This nozzle is shown in Fig.4 as one of several modifications. A divergent flow can act on a plate or airfoil inserted into a flow so that a resulting force is directed against the flow. Inserting one supersonic conical nozzle inside another or downstream into an exhaust jet so that the pressure integral on the low side of its surface is more than on the upper side produces increased thrust. The analytical theory was developed and numerical simulations [6,8], in particular, have shown that a Telescope nozzle can increase thrust $\sim$ 10-20% over the optimal single nozzle. Both are defined for the same flow rate, nozzle length or height. The working efficiency of a Telescope nozzle grows as Mach number increases.

Several modifications of the Telescope nozzle are designed and under numerical tests using our **JNT/CFD complex** including KGMS, CRAFT and CFL3D codes. The invention disclosure " Telescope Nozzle for a Thrust Benefit of Rocket & Aircraft Engine" was submitted to NASA in 1996, but is not yet approved. After numerical tests, the optimal design will be determined, and then designed, drawn and submitted to TsAGI (Russia, Moscow) in the 3rd quarter 1997, where it will be fabricated and tested in the TsAGI's anechoic chamber in accordance with the CRDF's grant schedule in 1998.

2.4 Corrugated Separate Flow Co-Annular Nozzle (CSFCAN). The general purpose of this invention **CSFCAN** design ([3])is to reduce jet noise through additional enhanced mixing with ambient air and to increase thrust by comparison with the usual separate flow co-annular nozzle with smoothed walls which are subject of the known Inverted Velocity Profile (IVP) and Normal Velocity Profile (NVP) concepts. This purpose is achieved by the special design of the corrugated lip line edges for both co-annular designs (external and internal parts of the nozzle), by corrugated cross sections of these parts and of the centerbody (plug). Corrugated shape of the design walls and centerbody (plug) provide introduction of counter-rotating vorticities along cavities of the nozzle walls and centerbody (plug). Two expanded flows near the wall flow into two neighbouring cavities which meet each other at some angle. Then the flows mutually penetrate and effectively mix. A flow impulse on the lateral area of the convexities increases the resulting nozzle thrust due to increase in nozzle wall lateral area.

The **CSFCAN** design was fabricated at NASA LaRC and will be tested in April-May 1997 in the large scale wind tunnel by the NASA JNL Team. In this time the comparison of the experimental and numerical simulation results will be fulfilled. Numerical simulations are conducted using our **JNT/CFD complex**. The preliminary results will be presented and discussed at the 3rd AIAA/CEAS Aeroacoustics Conference in Atlanta, May 12-14, 1997.

2.5 A Nozzle with Screwdriver centerbody (plug). The idea of a corrugated surface provides acoustic benefits through use of a centerbody (plug) shape. The proposed surfaces belong to a family of shapes formed by rectilinear intervals joining corresponding points of two different closed curves in space. A screwdriver body uses a circle as an initial curve and one or several crossing rectilinear intervals as an end curve. These intervals are symmetrically located relative to a body's axis of symmetry. We propose to use a crucial screwdriver shaped centerbody. A 4-petal screwdriver centerbody is shown in Fig.6. Here a convergent nozzle contains a cylindrical centerbody and downstream, after a throat, it transfers to a screwdriver centerbody. There are several geometric parameters, which define the centerbody: number of petals, petal size and centerbody length. The axisymmetric centerbody with conical or optimal contour in a meridional plane can be taken as a baseline centerbody for comparison and for definition of screwdriver centerbody efficiency. However, numerical simulation based on the KGMS code has shown that the primary proposed axisymmetric Screwdriver centerbody shape with the rectilinear longitudinal intervals is not optimal, because downstream of the nozzle throat weak shock waves arise. Therefore, other smoothed longitudinal curvilinear intervals were applied. The optimal centerbody shape (with the maximal thrust) was determined by the numerical tests using KGMS and CRAFT code. Then it was designed, drawn and drafts are in the process of submission to TsAGI. This design will be fabricated in the first place and will be tested in the TsAGI's anechoic chamber in the 1st quarter 1998. In Fig.16 this design is shown in different views. The submitted drafts contain additional information.

We can obtain the same result in the case of a 2D nozzle through the application of linear or curvilinear surfaces. Such a nozzle is a 2D analogue of an axisymmetric Screwdriver centerbody, and one modification is shown in Fig.7. This design we are planning to test theoretically in the second year of the grant period.

2.6 Corrugated and permeable small scale nozzles in domestic appliance. In addition to the previous ideas, which we propose to simulate basically for application to the aviation industry, some small scale nozzle designs were tested at smaller expence. In particular, these tests can be conducted in the future by students outside NASA LaRC and large gas-holders with high pressure are not necessary for the experimental tests. Such domestic appliances are applied in industrial spraying, pablic waste management systems, automotive fuel delivery systems, industrial mining etc. One such appliance was tested in NASA by M.M. Gilinsky and F.D. Backley. Primarily, this equipment was intended for anti-corrosion paint spraying in the car industry. On the base of this standard spraying nozzle design several new additional options were investigated. These options change the acoustic characteristics of the equipment. A Bluebell nozzle, moving external cylindric tube as well as impermeable and permeable with different angles channals were examined. Preliminary results are very interesting and promising and require analysis and continuation. The experiments, theory and approximate numerical approach are very convenient for teaching HU's students initial knowledge in Fluid Mechanics, Gas Dynamics and Acoustics.

III. MOBIUS STRIP CONCEPT

3.1 Möbius Strip modifications The new concept for improving the working efficiency of propellers and screws was proposed in the invention disclosure of Prof. Mikhail M. Gilinsky and Dr. John M. Seiner [2], 1993. NASA Technical Briefings has published the note [4], 1996, which presents the short description of this invention. The concept is based on the Möbius strip-one-side surfaces. There are several embodiments of such shapes. Each of them can be optimal for different application in different surrounding media. In short in this and the next section we will describe the idea of the invention and first positive experimental results. For details one can see the invention description [2] and the note [4].

The main goal of the invention [2] is to reduce rotated element drag and, simultaneously, to increase the area for capture of the still medium without increasing the power needed for rotation. Such surface can be the Möbius strip which is one-sided surface. The Möbius strip has been proposed as the basis for optimally shaped airplane and boat propellers, fans, helicopter rotors, mixing screws, coffee grinders, and concrete mixers. The ambient medium can be air, water, concrete, coffee beans etc. Conventional (non-Möbius) devices of this type consist mostly of two-sided blades, which are not optimal.

A Möbius strip is made by giving a half twist to a strip of elastic material, then joining the ends to obtain a smooth surface (see Fig.8). This design is one-side in the sense that in principle, one can trace out a continuous line along the strip from any point on its surface to any other point on the surface, without leaving (for example, through a border) or penetrating the surface. The one-sided, smooth shape of a Möbius strip provides a large capture area while generating the least possible turbulence in three-dimensional flow, and thus maximized working efficiency. Several possible modifications are shown in Fig.2, 9-12. Möbius screws in FIg. 9-12 are based on the super-elliptic contour in a meridional plane.

3.2 Möbius shaped screws for mixers. All industrial companies, who are interested in the invention [2], agree to participate in funding of research, development and joint marketing. However, these companies require preliminary experimental and numerical simulation proofs, that it can be effective and adapted to the company's product. As yet, we have only been able to conduct cheap and simple tests. Several Möbius shaped screws for the middle class of the kitchen mixers have made and tested. Some of them are shown in Fig.13. These pairs are mounted in the mixer, which was established on the top of vessels filled with water and small plastic particles on the bottom (Fig.14,15). The rotation speed of the screws increased smoothly by the voltage regulator, and power expenditure was measured by the Digital Wattmeter. These are shown on the right and left of the vessel respectively in Figures 14 and 15. When rotation speed mounted to a definite value, the particles acquire a motion, go up and involve in vortex motion with water, and mixing process arises. The power value corresponding to this mixing start characterizes efficiency of the mixer. The tests have shown that the mixer with the Möbius shaped screw pair (right in Fig.13) is most efficient, and saves more than 30% of the electric power by comparison with the standard (left in Fig.13). The video film about these tests can be used with the scientific-popular goals, for teaching, and with commercial goals. In particular, the discovered effect can be applied in the manufacture of liquid semiconductors.

The current strategy and necessary documents were worked out in the regular working meetings of the LaRC JNT and Technology Application Group (TAG) with HU's researchers and administration. The memorandum of agreement for commercialization of the invention between NASA LaRC-Hampton University-Company was written and concerted. The agreement includes the invention development, applications, marketing, joint patents etc.

Möbius concepts was the subject for creation of the scientific-popular video-film which can be used for the commercial and educational purposes. Besides the JNL Team, several scientists from different NASA LaRC subdivisions participated in its criation: F. D. Backley (Advanced Machining Development Section), R.R. Baize, R.L. Yang, S.F. Beam and others.

The NASA patent "Blade of a Rotary Machine Having Improved Efficiency" is in the provision file, and in two months will be filed completely.

Note, that this work was only a start for the future benefit of NASA and HU. At the present time there are not any sources to conduct analogical preliminary experimental research for cooling, boat, fans, and other applications, which require essential more expenses.

IV. CONCLUSION

The current research is focused on the development of a Bluebell nozzle and Möbius strip concepts through numerical and experimental simulations. The Bluebell nozzle concept, for which a patent application has been filed through NASA, can be utilized as a noise reduction concept for separate flow co-annular nozzle in the NASA AST program. In this aspect students can be involved in tests at the NASA JNL. Already Boeing, GE Aircraft Engines and Pratt&Whitney Aircraft have expressed interest in the development of this concept for subsonic commercial engine technology pending a successful outcome of testing and analysis. The application of the research to the future supersonic US aircraft engine design is also very promising on the basis of the preliminary positive results of the experimental and numerical simulations.

The main achievements in the report period are: **a)** Publication of the paper [7] in the AIAA Journal, which is described our concepts and some results. **b)** The Award #RE-136 in the Civil Research and Development Foundation (CRDF) competition. This 2 year grant for Hampton University (HU) and Central AeroHydrodynamic Institute (TsAGI, Moscow, Russia) supports the research implementation under the current NASA FAR grant. **c)** Selection for funding by NASA HQ review panel of the Partnership Awards Concept Paper "Mixing, Noise and Thrust Benefits Using Corrugated designs" prepared by M.M. Gilinsky and J.M. Seiner. This two year grant also will support our current FAR grant. **d)** Publication of a Möbius Strip concept in NASA Technical Briefs, June, 1996, and the great interest of many industrial companies in this invention. Successful experimental results with the Möbius shaped screw for mixers, which save more than 30% of the electric power by comparison with the standard screws. Creation of the scientific-popular video-film which can be used with the commercial and educational purposes. **e)** Organization work, joint meetings and discussions of the NASA LaRC JNL Team and HU professors and administration for the solution of actual problems and effective work of the Fluid Mechanics Laboratory at Hampton University.

V. REFERENCES

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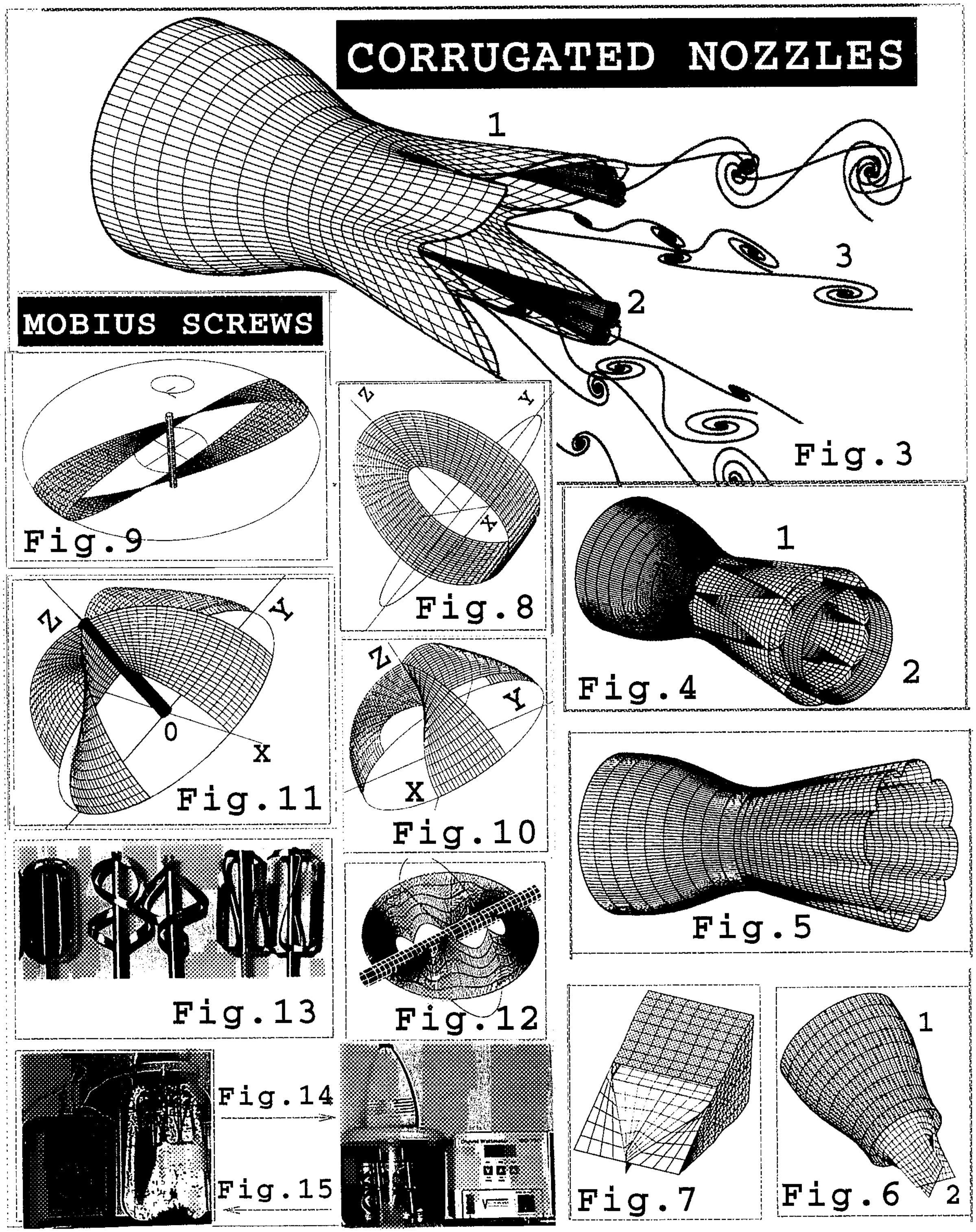

<u>CORRUGATED NOZZLES:</u> **Fig.3 A Bluebell nozzle; 1-design, 2-axial vorticities, 3-longitudinal vorticities. Fig.4 The 8-petal Telescope-Chisel nozzle; 1-external design, 2-internal design. Fig.5 The smoothed 8-petal Chisel nozzle. Fig.6 The axisymmetric 4-petal Screwdriver centerbody (plug); 1-nozzle, 2-centerbody. Fig7. The 2D Screwdriver nozzle (or plug).**

<u>MOBIUS SCREWS:</u> **Fig.8 A Möbius strip. Fig.9 The propeller. Fig.10 The 3-petal boat screw. Fig.11 The 4-petal boat screw. Fig.12 The corrugated mixer screw. Fig.13 The tested mixer screws. Fig.14 The small vessel with particles, mixer with tested screw pair, and wattmeter. Fig.15 The big vessel with particles, mixer with tested screw pair, and voltage regulator.**

SONIC NOZZLE WITH THE SCREWDRIVER CENTERBODY AS A UNIT

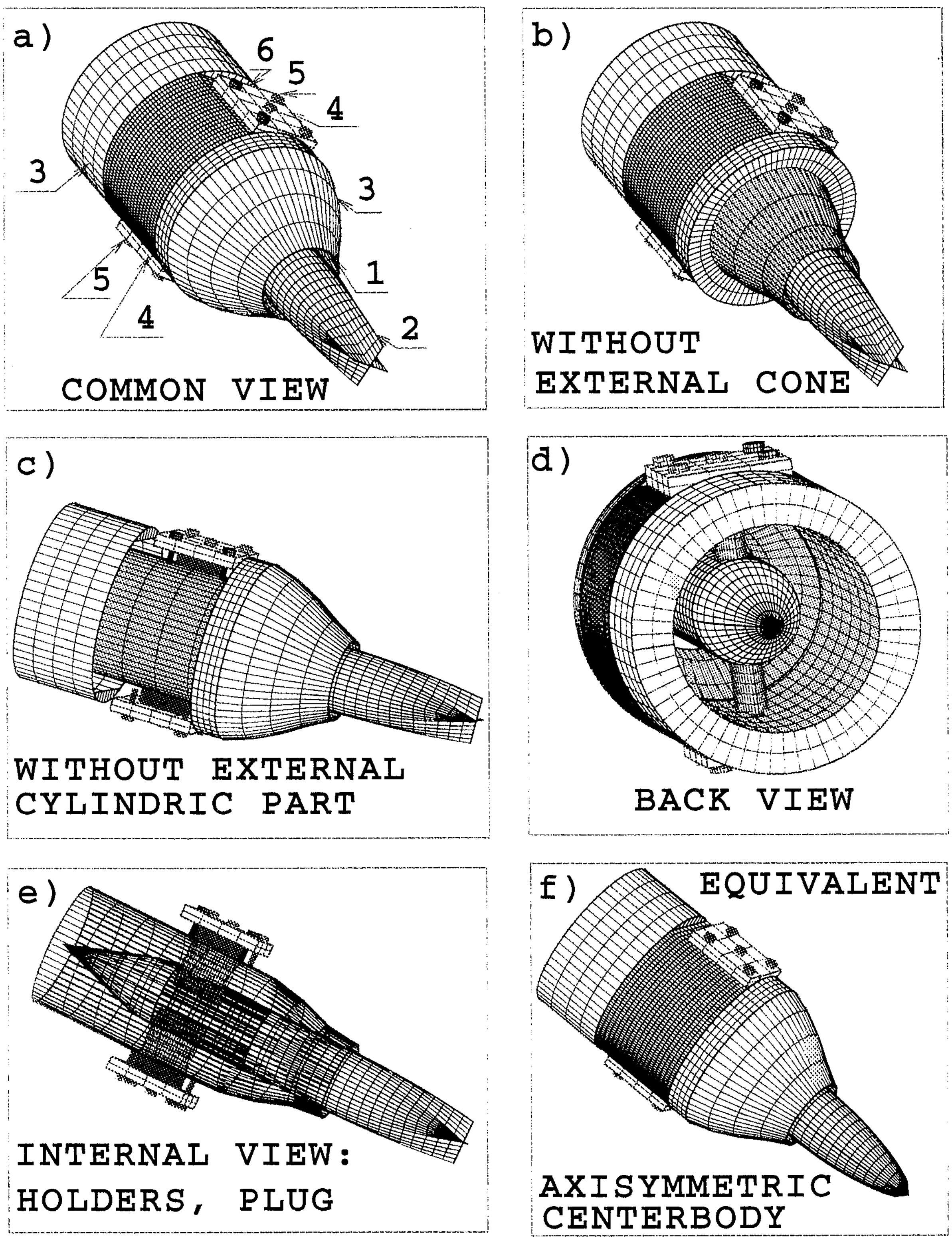

Fig.16 A sonic nozzle with the Screwdriver Centerbody as a unit. The model for the experimental tests.

a) common wiew: 1-sonic nozzle throat, 2-screwdriver centerbody, 3-external nozzle surface, 4-plate to keep the holders, 5-bolts to keep the plate and to compress the holders, 6-plane ground for the plate;

b) view without the external cone; c) lateral view without the external cylindric part; d) back view; e) internal view without some shades; f) axisymmetric centerbody with the equal cross section areas as well as the screwdriver centerbody.