Aerodynamics of the reentry capsule EXPERT at full modeling viscous effect conditions

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CONTENTS

Introduction

1. Hypersonic wind tunnels AT-303 and T-313. Parameters of the flow in the test section and about the reliability of the measurement systems.

2. Aerodynamic characteristics of the EXPERT reentry capsule in the range of $M_\infty = 4,10,12,14,18$.

Conclusions
INTRODUCTION

1. Since 2002 till now, experimental studies of the EXPERT reentry capsule have been performed in ITAM wind tunnels. These studies have been performed in consecutive ISTC projects No. 2109, 3151, and currently ongoing project No. 3550.

2. To get more reliable results the program consist developments and improvements of some elements of the wind tunnel and tests for validation of flow quality and accuracy of the measurement system of the AT-303 wind tunnel.

3. Three models of the reentry capsule EXPERT scaled 1:8 was designed and manufactured at ITAM. A large series of balance tests was performed at Mach number M=4 in the blowdown supersonic wind tunnel T-313, and at Mach numbers 10, 12, 14, and 18, angles of attack $\alpha=0^\circ, 3^\circ, \text{ and } 6^\circ$, and natural Reynolds numbers in the hypersonic adiabatic compression wind tunnel AT-303.

4. It should be noted that at first time AT-303 was equipped by conical nozzles, which form a nonuniform flow along the test section.
5. At present to get more accurate results in frame of the ISTC № 3550 at ITAM was designed and manufactured manyregims contoured nozzles generating a significantly more uniform flow at the nozzle exit.

6. From the viewpoint of testing advanced hypersonic vehicles the following requirements are realized in our facilities:
   • maximum close simulation of flight conditions;
   • wide range of flow parameters: Mach number (M), Reynolds number (Re), stagnation pressure (P0), stagnation temperature (T0), etc.;
   • high quality of the flow in the test section;
   • high accuracy and credibility of the measurement results.
Blowdown  Supersonic wind tunnel T-313

In terms of its parameters, quality of the flow, and characteristics of the completely automated measurement system, it is a top-level wind tunnel where research is performed within various Russian and international space-related projects.

\[ M = 1.75-7; \quad Re_1 = (2/80)10^6, \quad \alpha = -4\div20^\circ \]

Test Section 0.6 x 0.6 m.
Hypersonic wind tunnel AT-303
Sketch of hypersonic wind tunnel AT-303

<table>
<thead>
<tr>
<th>Technical parameters</th>
<th>First turn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter $D$, mm</td>
<td>300 - 600</td>
</tr>
<tr>
<td>Settling chamber volume, dm$^3$</td>
<td>6</td>
</tr>
<tr>
<td>Stagnation pressure $P_0$, KPa</td>
<td>3000</td>
</tr>
<tr>
<td>Stagnation temperature $T_0$, K</td>
<td>2000</td>
</tr>
<tr>
<td>Mach number $M$</td>
<td>7 - 20</td>
</tr>
<tr>
<td>Reynolds number $Re_0$</td>
<td>$10^8 - 10^9$</td>
</tr>
<tr>
<td>Run duration $t$, s</td>
<td>0.04 - 0.5</td>
</tr>
<tr>
<td>Test gases</td>
<td>Air, nitrogen</td>
</tr>
</tbody>
</table>
Requirements to simulation

Simulation of hypersonic flying vehicle in wind tunnels imposes high requirements to the purity of the gas-flow and the running time for Reynolds numbers from $3 \cdot 10^6$ to $10^8$ within the Mach number range from 8 to 20.

- full reproduction of natural Mach and Reynolds numbers;
- full correspondence of the chemical composition of the gas ahead of the flying vehicle and its model;
- constant flow parameters in the wind tunnel during the entire time of model testing
The integral estimate of nonuniformity in the flow core in the model location zone varies from 1% to 2%.

\[ M_\infty = 16.0 \]

\[ M_\infty = 18.0 \]
Flow visualization

The Schlieren pictures of the hypersonic airflow around the HB-2 model for various angles of attack in AT-303. Good quality of the Schlieren pictures illustrating density gradient on shock waves and expansion fan is worth noting.

Schlieren pictures of the flow around HB-2 model at M=10.
  a) $\alpha=4^\circ$; b) $\alpha=8^\circ$; c) $\alpha=12^\circ$. 
Comparison of drag and lift coefficients at $M=16$

Thus, the results of force-measurement tests performed in AT-303 confirm the reliability of the measurement unit and good quality of the flow.
CREDIBILITY OF THE RESULTS

Random error assessed through 11 repeatability test
The root-mean-square deviations at: M=10, Remin – α= 6°

\[ \sigma C_A = 0.0041 \] Confidence interval \( \pm 1.\sigma \)
\[ \sigma C_N = 0.0024 \] Student distribution with \( P=0.95 \)
\[ \sigma C_m = 0.0022 \]

Influence of model roll angle

\[ M = 14 - \text{Re}_{\text{max}} - \alpha = 0 - \gamma = 0/90° \]
\[ M = 18 - \text{Re}_{\text{min}} - \alpha = 0 - \gamma = 0/90° \]

The data obtained showed that the difference in aerodynamic coefficients for \( \gamma = 0 \) and 90° is within the root-mean-square error.

Measurement with \( \alpha \) more sensible strain gauge balance

\[ M = 10 - \text{Remin} - \alpha = 0/6° \] The difference \( C_A < \pm 2\sigma \).

To avoid possible random errors all tests duplicated
AERODYNAMIC CHARACTERISTICS OF THE EXPERT REENTRY CAPSULE

The general view of the model, its basic dimensions are shown here.

The geometric parameters and surface-coordinate points was supplied by ESA ESTEC.

The flow around this model is rather complicated and is accompanied by separated flows in the vicinity of the flaps with propagation of vortices in the gaps between the flaps.
EXPERT Tests in AT-303
Aerodynamic Coefficients Measurements

<table>
<thead>
<tr>
<th>M</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_n (mm)</td>
<td>300</td>
<td>544</td>
<td>300</td>
<td>590</td>
</tr>
<tr>
<td>Re</td>
<td>Re_min</td>
<td>Re_max</td>
<td>Re_min</td>
<td>Re_max</td>
</tr>
<tr>
<td>10.0</td>
<td>9.9</td>
<td>11.7</td>
<td>11.8</td>
<td>13.5</td>
</tr>
<tr>
<td>Re_{10^{-6}} (1/m)</td>
<td>5.8 - 7.4</td>
<td>31 - 36</td>
<td>2.1 - 2.3</td>
<td>11 - 13</td>
</tr>
</tbody>
</table>

Tests in T-313  \( h_{t.s.} = 0.6 \times 0.6 \) m
Where performed at M=4 and \( Re_{1} = 50.4 \times 10^6 \) 1/m
AERODYNAMIC COEFFICIENTS AT $M = 4$

Graph showing the variation of aerodynamic coefficients with angle of attack and Mach number. The graph includes data points for different angles of attack, with markers indicating the lift coefficient ($C_L$) and drag coefficient ($C_D$) for different Mach numbers and angles.

- $C_L$ and $C_D$ are plotted against angle of attack ($\alpha$, deg) and Mach number ($M$).
- The graph includes data for $\gamma = 0^\circ$ and $\gamma = 45^\circ$.

Additional images and diagrams:
- Front view of the model with a Pitot tube.
- Shock wave diagram with $M=4, \alpha=0^\circ$.
- Shock wave pattern with black representing initial roughness and white representing smooth surface.

Image of separation line and point 1 and 2 with corresponding markers.
This regime is of interest because the tests were performed in the nozzle with the effective exit diameter $D_n = 590$ mm.

The overall level of the drag force coefficient is within the range $C_A \sim 0.3 - 0.33$. As the Reynolds number increases, the value of $C_A$ decreases in the entire range of angles of attack $\alpha = 0 - 6^\circ$.

Boundary-layer tripping did not exert any noticeable effect on aerodynamic coefficients.
AERODYNAMIC COEFFICIENTS AT \( M = 14 \)

This regime was performed in the nozzle with the effective exit diameter \( D_n = 300 \text{ mm} \).

A decrease in \( Re \) leads to an increase in the drag force coefficient. With the Reynolds number decreasing in the range from \( Re_{\text{max}} \) to \( Re_{\text{min}} \), the value of \( C_A \) at zero incidence increases by \( \sim 35\% \).

All changes in the normal force and pitching moment coefficients in the entire range of angles of attack are almost within the root-mean-square deviation \( \pm 2\sigma \).
AERODYNAMIC COEFFICIENTS AT $M = 18$

The model tip was located at the nozzle exit $D_n = 600$ mm.

As for all other values of the Mach number, an increase in the Reynolds number leads to a decrease in the drag force coefficient $C_A$. Variation of $Re$ within the range used in these experiments has only a weak effect on the values of $C_Z$ and $C_m$. This effect is within the root-mean-square deviation.

The experimental results were also processed with allowance for dynamic properties of the system «model+ balances supporting devices». The observed difference is within $\pm 2\sigma$. 

- $C_A$
- $C_Z$
- $C_m$
Slightly contradictory character is related to effect of flow conicity.
CONCLUSIONS

The agreed program of activities within the framework of the ISTC project No 2109, 3151 was completely fulfilled.

1. Some devices were developed, manufactured, and commissioned:
- System for the driver gas (P=35 MPa);
- Software necessary for processing experimental results and formation of the database was developed.

2. The Mach number distribution fields was tested in the test section at Mach numbers \( M = 10, 12, 14, 16, \text{ and } 18 \). The degree of nonuniformity of the Mach number fields in the core of the flow, expressed in root-mean-square deviations from the mean values, is less than 2% . This results obtained confirm that the nonuniformity of velocity and fields in the test section of AT-303 satisfies the modern requirements to the uniformity of flow parameters in hypersonic short-duration wind tunnels.

3. The aerodynamic of the AGARD reference model HB-2 were measured at Mach numbers \( M = 10, 12, \text{ and } 16 \) and compared with similar data obtained in wind tunnels of Germany, France, and USA. The comparison confirms the high quality of the flow and reliability of the measurement system of the hypersonic wind tunnel AT-303, which indicates that the measurement allows obtaining reliable and credible results.
4. Three models of the reentry capsule EXPERT scaled 1:8 was designed and manufactured. A large series of balance tests was performed at Mach numbers \( M = 10, 12, 14, \) and 18, angles of attack \( \alpha = 0^\circ, 3^\circ, \) and \( 6^\circ, \) and natural Reynolds numbers.

5. The flow around this model, even at zero incidences, is rather complicated and is accompanied by separated flows in the vicinity of the flaps with propagation of vortices in the gaps between the flaps. It can be assumed that flow reconstruction with some periodicity in time occurs under these conditions.

6. An analysis of these results and multiple repeated tests, including the results measured by different strain-gauge balances and also with boundary layer tripping, give grounds to argue that the measurement results are reliable and can be used for designing the natural vehicles.
Acknowledgement.

The work on the project was performed by a large team of ITAM and became possible due to support of collaborators of the ISTC project No2109, 3151 and 3550 J-M. Muylaert and Dr. Wilhelm Kordulla (ESA ESTEC), which is gratefully acknowledged.
A COMPARISON OF THE RESULTS MEASURED AT \( M = 10 \) \( \text{Re}_{\text{min}} \) and \( \text{Re}_{\text{max}} \).

In the entire range of angles of attack \( \alpha = 0-6^\circ \), the difference in the values of \( C_Z \) and \( C_m \) for \( \text{Re}_{\text{max}} \) and the lower level for \( \text{Re}_{\text{min}} \) does not exceed the root-mean-square deviation \( \pm 2\sigma \).

Therefore, for justified comparisons with numerical results, we use a correction for incoming flow conicity.
The regime considered and a possible relation of this phenomenon with flow separation from the flaps made it expedient to perform additional tests of the EXPERT model with boundary-layer tripping.

In contrast to the previously obtained data, only one level was obtained in both runs with the tripping device at the angle of attack $\alpha = 0$, namely, $C_A \sim 0.3$. For $\alpha = 6^\circ$, a similar picture was observed; in the other run, however, both levels were observed.

The tripping device slightly increased the value of $C_A$ for $\alpha = 0$, but no effect of boundary-layer tripping was observed for $\alpha = 6^\circ$. 
Principal scheme of the test gas source

1 - High pressure barrels
2 - Hydraulic multiplier
3 - High-pressure section
4 - Settling chamber
5 - Control device
6 - Adiabatic compression system
7 - Electric storage heater
8 - Nozzle
The integral estimate of nonuniformity in the flow core in the model location zone varies from 1% to 3%.

\[ M_\infty = 10.0 \]

\[ M_\infty = 12.3 \]
The aerodynamic characteristics of the HB-2 reference model measured in AT-303 at \( M=12.6 \) (\( \text{Re}_L=2.85\times10^5 \)) and \( M=15.5 \) (\( \text{Re}_L=2.1\times10^6 \)) are compared with the similar data from ONERA [9] for Mach numbers \( M=10 \) (\( \text{Re}_L=2.1\times10^6 \)), \( M=14 \) (\( 3.3\times10^6 \)), and \( M=16.5 \) (\( \text{Re}_L=8\times10^5 \)), respectively, where the Reynolds number is based on the model length \( L \). Taking into account the differences in Mach and Reynolds numbers, the agreement of results obtained in different wind tunnels can be considered as satisfactory.

The dependence of \( C_{X0}(\alpha=0) \) on the Mach number shows the experimental data obtained in a wide range of Mach numbers in different wind tunnels. The red point is the measurement result in AT-303, which is also in good agreement with the data obtained in other wind tunnels.
A SPECIFIC FEATURES OF FLOW AROUND EXPERT MODEL AT M = 10, Re\text{min}

A rather long time interval $\Delta t \sim 150$-200 ms with almost constant flow parameters, including the Reynolds number, is observed.

Two rather long-time levels of the drag force coefficient are observed: the upper level with $C_A \sim 0.3$ and the lower level with $C_A \sim 0.2$.

Two levels of $C_A$ values is associated with certain reconstruction of the flow structure around the model. The flow around the model occurs with boundary-layer separation due to its interaction with shock waves arising on the flaps. A noticeable increase in the size of boundary-layer separation zones is observed.
Переход М = 4

Front view

Model with Pitot tube

\[ p/p_0 \]

\[ R_{e_{x0}} \]

point 1
point 2
black - initial roughness
white - smouthe surface

Graph showing the ratio \( p/p_0 \) against \( R_{e_{x0}} \) for different points (1 and 2) with markers indicating black for initial roughness and white for a smoother surface.
EXPERT Tests

Random error assessed through 11 repeatability tests
- $M = 10 - \text{Remin} - \alpha = 6^\circ$
- $\sigma C_A = 0.0041$
- $\sigma C_N = 0.0024$
- $\sigma C_m = 0.0022$
- Confidence interval $\pm 1.\sigma$
  *Student distribution with $P=0.95$*

Influence of model roll angle
- $M = 14 - \text{Re}_{\text{max}} - \alpha = 0 - \phi = 0/90^\circ$
- $M = 18 - \text{Re}_{\text{min}} - \alpha = 0 - \phi = 0/90^\circ$

Measurement with $\alpha$ more sensible strain gauge balance
- $M = 10 - \text{Remin} - \alpha = 0/6^\circ$

All tests duplicated

**ANALYSIS**

*Measurements results reliable:* through analysis multiple repeated tests; different strain gauge balances; transition tripping effect (flow regime)

*Possible contributors to be further studied:* flow complexity on the flaps (separation) and between the flaps (vortices propagation); flow conicity for the smaller nozzle; blockage of the flow core
The data for $M = 12$ and 18 were obtained in nozzles with $D_n = 544\text{mm and 600mm}$, respectively; the data for $M = 10$ and 14 were obtained in the nozzle with $D_n = 300\text{mm}$. Only for $M = 10$ and $Re_{\text{min}}$, both levels of drag, which were discussed above, are presented.

It is seen that the dependences $C_A(M)$ have a slightly contradictory character. For $D_n \approx 600\text{mm and M=12 and 18}$, the coefficient $C_A$ decreases with increasing $M$. At the same time, for $D_n \approx 300\text{mm}$, $M=10$ (lower level) and $M=14$, an increase in the values of $C_A$ with increasing Mach number is observed. We can assume that this is related to a greater effect of flow conicity and a significant degree of blockage of the flow core by the model. For better understanding of the reasons of this contradiction requires more detailed studies, including the measurement of pressure distributions on the model surface.