EXPERIMENTAL CAPSULE AFTERBODY FLOW INVESTIGATION

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ABSTRACT

The wake behind an Apollo shaped capsule is investigated in the framework of the ‘afterbody heating’ topic in the RTO WG043 working group. Measurements are performed by means of stereo particle image velocimetry and used for CFD validation purposes. The model geometry is a scaled version of the AS-202 and they are tested at Mach 2 at 0° and 25° angle of attack. For the 0° model, the wake was completely separated while for the 25° model the wake was partially separated and reattaches half way the model. Overall the PIV data return a quantitative three dimensional description of the velocity field around the capsule.

Key words: Supersonic flow, Afterbody flow, Particle image velocimetry.

1. INTRODUCTION

Uncertainties in afterbody heating predictions can be related for given re-entry flight conditions to both the thermochemistry between the vehicle surface material and the fluid, as well as to the actual flow field established around the vehicle. In the comparative assessment of the heat transfer prediction performance of different CFD models against free flight test data, the absence of reliable information on the flow field structure can form an important source of uncertainty which can be up to 200%. Moreover, the effects of flow transition to turbulence and of large scale flow unsteadiness require to be ascertained before proceeding with CFD computations, based on the laminar flow regime or the inclusions of turbulence modeling.

In this view a ‘afterbody heating’ topic was conceived within working group RTO WG043. This paper gives preliminary experimental velocimetry and schlieren results for the flow around an Apollo-like capsule that was tested at Mach 2. In order to build a high quality experimental data base for CFD comparison stereo particle image velocimetry was used.

2. EXPERIMENTAL APPARATUS

2.1. Flow facility and wind tunnel model

The flow facility used in the experiments is the TST27 transonic/supersonic blowdown wind tunnel, see figure 1. It has a $27 \times 28cm^2$ test section and features two flexible nozzle walls in order to continuously vary the Mach number between 0.5 and 4.2. The total pressure in the settling chamber can be varied from 2 bar at Mach 0.5 to 20 bar at Mach 4.2, this results in a unit Reynolds range from $25 \times 10^6$ to $150 \times 10^6$. The maximum run-time of the facility is 300 s. In the current experiments, the wind tunnel was operated at Mach 2 with a total pressure of 2.7 bar and a total temperature of 288 K.

The capsule geometry used for the definition of the wind tunnel model is a scaled version of the AS-202 outer mold line as defined in Wright et al. [1]. The model has a diameter of 50 mm and is fabricated out of Makrolon, it is side-mounted on a stainless steel sting. Two models are used for 0 and 25 degrees angle of attack, see figure 2.

2.2. Particle image velocimetry

The PIV measurements are performed using a high rep rate illumination and imaging system. A Quantronix Darwin Duo Nd-YLF double pulse laser was used as light
source at a repetition rate of $500 \text{Hz}$. The laser was rated at $20 \text{ mJ per pulse}$ with a duration of $200 \text{ ns}$. The pulse time separation was set to $\Delta t = 5 \mu \text{s}$ which resulted in a particle displacement of approximately $2.5 \text{ mm}$ between two illuminations. The light was formed into a sheet and introduced into the wind tunnel by means of a retractable probe as shown in figure 3.

The particle images were recorded by means of two PCO FastCAM cameras which are equipped with a $1024 \times 1024$ pixel CMOS sensor. A Nikkor lens with a focal length of $60 \text{ mm}$ was used at an $f# = 2.8$, furthermore the particle images were slightly defocussed in order to prevent peak locking. For each model two fields of view were considered; the wake region and the ‘far’ wake region, see figure 4, each field of view was set to $8 \times 8 \text{ cm}^2$. The measurement planes were offset in the $z$ - direction (symmetry plane) and the following planes were measured: $z = [0, 4, 7, 10, 13, 16, 19, 22, 25, 28, 31, 34] \text{ mm}$. For each plane 500 recordings were used to obtain the velocity data.

PIV measurements were done using a stereo setup which enabled to measure all three velocity components in the plane [2]. The PIV image interrogation window size was set to $32 \times 32$ pixels with an overlap factor of $75\%$. This corresponds to a measured vector pitch of $0.7 \text{ mm}$.

A preliminary measurement campaign was performed where the model was mounted from the back. The effect of the Mach and Reynolds number on transition of the shear layer emanating from the model shoulder was investigated by means of shadowgraphy. This is illustrated through a series of shadowgraph images, see figure 5. As the unit Reynolds number is increased from 29.6 to 53.8 for the Mach 2 free stream, shear layer transition moves upstream towards the capsule shoulder. Comparing the lowest unit Reynolds number cases for Mach 2 and 3, it is found that the shear layer transition is further downstream for the Mach 3 case although the unit Reynolds number is higher indicating that the shear layer is more stable for higher Mach numbers. However when the unit Reynolds number is increased for the Mach 3 free stream, shear layer transition again moves upstream.
4. RESULTS

For the final measurement campaign the models were used as they are shown in figure 2. Raw PIV recordings are shown in figure 6, in case of the 0° model there are no particles present in the wake making it impossible to perform a flow investigation by means of PIV in this region. In the shoulder region the flow undergoes large accelerations as it expands. Due to their inertia the tracer particles slip, see [3], which has two effects, it causes the particles to lag with respect to the surrounding flow and the particle streamlines are shifted with respect to the flow streamlines. The particle streamline is always shifted towards regions with lower accelerations. In case of the expanding flow over the shoulder it means that they are shifted outward, preventing particles to enter the wake.

![PIV recordings for the 0° and 25° models at Mach 2](image)

**Figure 6. PIV recordings for the 0° and 25° models at Mach 2**

4.1. Capsule at 0° angle of attack

In figure 7 on the bottom-right a schlieren visualization of the flow around the 0° capsule is shown. The bow shock is clearly visualized as well as the expansion over the model shoulder. As can be observed from the image, the flow overexpands and a lip shock is formed. Downstream of the shoulder the separated shear layer develops which does not reattach on the model. In the back of the image the bow shock reflection on the wind tunnel window is visible.

The stereo PIV (SPIV) results are given in the symmetry plane \( z = 0 \ mm \) and two horizontal cuts. The expansion from the low velocity region downstream of the bow shock over the model shoulder is clearly visualized. When the \( u, v \) and \( w \) velocity components at the front of the model are regarded with respect to \( z \), the three dimensionality of the flow is apparent; in the front the \( w \) component increases with \( z \) and the \( u \) component decreases. The \( v \) component of the velocity field including the ‘far’ wake region is shown in figure 8. Here the reflected bow shock coming from the wind tunnel wall is measured as well as a shock coming from the recompression in the capsule wake.

![SPIV results \( (v \ component) \) for the near and far wake FOV](image)

**Figure 8. SPIV results \( (v \ component) \) for the near and far wake FOV**

4.2. Capsule at 25° angle of attack

The PIV and schlieren results for the 25° model are given in figure 9. The overall flow structure looks similar to the 0° case however it can be observed that the shear only partially separates from the upper side of the capsule. At the model shoulder a small shock wave is present where separation occurs. Further downstream, approximately halfway the model, a stronger shock is formed where the shear layer reattaches. Downstream of the capsule a strong shock is present where the wake is recompressed. The shock emanating from the reattaching shear layer is also captured by the PIV measurements (the \( u \) component decreases and \( v \) component increases). Furthermore the velocity field gives a good overview of the three dimensional flow field directly behind the capsule.

The overview of the flow where the ‘far’ field is included is shown in figure 10. It clearly shows the three dimensional pattern of reattachment shock that emanates from the wake behind the capsule.

![SPIV results \( (v \ component) \) for the near and far wake FOV](image)

**Figure 10. SPIV results \( (v \ component) \) for the near and far wake FOV**
Figure 7. SPIV results and schlieren image of the $0^\circ$ model at Mach 2 and $P_t = 2.7$ bar

Figure 9. SPIV results and schlieren image of the $25^\circ$ model at Mach 2 and $P_t = 2.7$ bar
5. CONCLUSIONS

The three dimensional flow field around a capsule is investigated at Mach 2 for 0° and 25° angles of attack and the preliminary results are presented. The measurements are performed by means of stereo PIV, which enables all velocity components. Two $8 \times 8\, \text{cm}^2$ fields of view are considered (‘near’ and ‘far’ wake) and the planes are offset at 11 $z$ locations. The full three dimensional average velocity field is constructed by combining the measurement planes. Furthermore schlieren visualizations are performed as a complementary measurement technique. The results for the 0° capsule give a good overview of the three dimensional flow structure. The shear layer emanating for the capsule shoulder was found to be fully separated. Recompression of the wake occurs downstream of the capsule and the recompression shock is captured in the velocity field. For the 25° capsule, the shear layer was found to be only partially separated and shear layer reattachment occurs approximately halfway the capsule. This was found in both the schlieren visualization and the PIV results, however in case of the PIV results the three dimensional structure of the separation shock is captured.

REFERENCES

