Experimental Investigations of the Flow through Slotted Wall in Transonic Wind Tunnel*

LIU GUANGYUAN, LIU DAWEI, GUO QIUTING
China Aerodynamics Research and Development Center, Mianyang, 621000, China
Corresponding author: liugyu@mail.ustc.edu.cn

Abstract. Experimental study of the flow through slotted wall was conducted in 0.6m transonic and supersonic wind tunnel. Transverse flow properties, such as flow angle, pressure, velocity components were measured using travelling probe, and distributions of Mach number, total pressure recovery were acquired for both empty tunnel and airfoil model cases. Shear layer thickness was calculated based on test results. Results showed that, transverse velocity from shear layer through slot into plenum chamber is approximately linear, and wall shear layer thickness was up to 3 to 4 times slot widths on slot center plane, and homogeneous boundary conditions were inaccurate.

1. Introduction
The slotted walls utilized in transonic wind tunnels not only reduce the blockage interference and wave reflection, but also induce the cross flow along the normal direction in wall vicinity\cite{1}. This cross flow is one of the most factors influencing the calibration and operation of the facility, and relates to wall interference to a great extent\cite{2}. It is one of the key problems in the field of transonic wind tunnel testing. Experimental study on flow crossing the slotted wall began in the 1970s. Researchers measured flow directions for various model conditions experimentally and evaluate the total pressure losses through the wall to analyze the cross flow characteristics. The test conducted by Chen\cite{3} confirmed the feasibility of applying the homogeneous boundary condition of the slotted wall. Berndt\cite{4} measured the pressure differences across the slotted wall, the flow angle distribution and the energy loss through the slotted wall with empty tunnel and airfoil model installed cases. Results proved that flow angle gradient contributions introduced by testing model must be considered in equations of wall boundary condition. Everhart\cite{5} measured the flow characteristics in the centerline of the slot. The results show that the viscous losses in the slotted wall is the main contribution of the cross flow characteristics. The total pressure from the inlet of the slot is reduced to the static pressure in the chamber. Everhart\cite{6} experimentally studied the non-linear relationship between the pressure differences and flow angle gradients based on viscous flow analysis. Results show that the viscous contribution term must be added to classical linear homogeneous boundary condition.

In this paper, the travelling probe is used to measure the distributions of the flow angles and pressure distributions in the wall vicinity for both normal and longitudinal directions of the slotted wall. The influences of the airfoil model on the cross flow and shear layer development are examined. Results can be used for the design of the slotted wall geometries and interference corrections.

2. Experimental Equipment

\* Supported by National Natural Science Foundation of China (11802328)
2.1 Wind tunnel

Cross flow measurement experiment was carried out in 0.6 m transonic and supersonic wind tunnel belongs to CARDC. The test section is 0.6m wide, 0.6m high, and about 2.0m long, with solid vertical walls and slotted horizontal walls. Each wall has six slots with a width of 15 mm. Slot geometries are shown in Table 1.

| Table 1. Slot geometries in 0.6m wind tunnel |
|---------------------------------------------|
| Slot distance | Acceleration region | Test model region | Support region |
| 120mm | 120mm | 120mm |
| Slot width | 0~15mm | 15mm | 17mm |
| Permeability | 5.22% | 12.50% | 10.63% |
| Wall thickness | 8mm | 8mm | 8mm |
| Slot number | 6 | 6 | 6 |

In order to change longitudinal pressure distribution along the slotted wall, NASA SC(2)-0714 supercritical airfoil is installed in test section as disturbance model, which is 14% in thickness and 3.5% blockage for 0 angle of attack.

2.2 Travelling Probe

Figure.1 and Figure.2 demonstrate schematic diagrams of the traveling probe and installation in the test section, respectively. During the test, with traveling probe installed on the upper wall, measurements for both normal and longitudinal directions were performed, and the range is 120.0 mm and 1000.0 mm, respectively. The positioning accuracy is less than 0.10 mm. The seven-hole probe was used to measure the total pressure, static pressure, and flow angles. The probe was a PS5 type seven-hole probe manufactured by AeroProbe Co., Ltd, with conical tips, a total length of 152.0mm and a head diameter of 3.18mm.

![Figure 1](image1.jpg)  **Figure.1** Schematic of the travelling device

![Figure 2](image2.jpg)  **Figure.2** Installation of the travelling probe

2.3 Error analysis
The resolution and stability of the seven-hole probe determined the accuracy and reliability of the experimental results. In the test, DTC Initium was used to continuously record the pressure of each point of the measuring probe with sampling rate of 100 Hz. And the average of 20 points was believed to be the steady-state pressure of the step. Aerodynamic quantities such as angles, velocity, Mach number, were calculated using probe’s calibration map and pressure data acquired from probe as shown in Figure 3. To accurately reduce data at different Mach number and Reynolds number, the seven-hole probe uses all available calibration files. Each calibration file corresponds to a different velocity [7], and the probe calibration map used in the test ranged from 5 m/s to \( M = 2.0 \).

The test results accuracy was examined using probe travelling along normal direction. Measured results are shown in Figure 4, which showed a good repeatability. The difference between the flow angles in normal positions of the two measurements is less than 0.4°, the difference of the total pressure recovery is less than 0.001, and the Mach number difference is smaller than 0.005. Based on the above results, it can be considered that the seven-hole probe can accurately measure the flow characteristics in slotted wall vicinity.

![Figure 3 Probe data reduction method](image)

**Figure 3** Probe data reduction method

![Figure 4 Data repeatability of travelling probe method (M=0.40)](image)

**Figure 4** Data repeatability of travelling probe method (\( M = 0.40 \))

### 3 Experimental Results

#### 3.1 Flow angle distributions

Figure 5 and Figure 6 shows the typical experimental results of the flow angle distributions in longitudinal and normal directions of the slotted wall, respectively. The test locations are one time slot width in side of plenum chamber and 1 chord length upstream and 0.5 chord length downstream. Results indicated that:

- In the case of empty tunnel (marked with square symbol), outflow to plenum chamber dominates the cross flow;
- With model installed, flow from plenum chamber into test section enhances, especially for positive incidence.
- Model blockage slightly strengthens outflow in region upstream of model leading edge. Flow in the wall region over aft body and wake have opposite effects.
- Positive incidence enhances the inflow to test section in model downstream region, which is consistent with previous results. Flow angle is nearly linear across the slot regardless of cross flow directions.
3.2 Shear layer for empty wind tunnel

Velocity distributions, as well as total pressure recoveries in the shear layer were measured at four longitudinal locations during the experiment. Figure 7 shows the results of the empty wind tunnel condition. As can be seen from the distribution of the total pressure recoveries that as the Mach number increases, the viscous loss of the cross flow increases gradually: When \(M=0.40\), the total pressure of stable flow on the side of plenum chamber is 0.88 times of the total pressure on test section entrance, 0.77 times of the total pressure for \(M=0.60\), and 0.65 times of the total pressure for \(M=0.80\). At the same time, the viscous loss gradually increases along the flow direction, from \(x/c=-1.00\) to \(x/c=0.80\), the shear layer on the slotted wall surface is gradually thickened, and the length of the mixing zone on the chamber side is gradually extended.

Table 2. Shear layer thickness for empty tunnel

| \(x/c\)   | \(\delta/d\) | \(\delta*/d\) |
|---------|-------------|-------------|
| \(M=0.40\) | 3.324       | /           | 0.402       | /           | 0.466       | /           |
| \(M=0.60\) | 2.710       | 2.965       | 3.116       | 0.367       | 0.427       | 0.463       | 0.468       |

The velocity profile inside the shear layer indicate that the slotted wall shear layer extends from the test section side by 2 times the slot width to the chamber side, and the depth of the mixing zone on the side of the chamber gradually increases along the flow direction. At position of \(x/c=-1.00\), the mixing zone depth extends 2 times the slot width on the side of the chamber, and at position of \(x/c=0.80\), the mixing zone depth is close 4 times the slot width.

Table 2 shows the calculated thickness and displacement thickness of the shear layer for tunnel empty condition. Results indicated that the shear layer thickness increases along longitudinal direction from 2.7 to 3.3 times the slot width, and the displacement thickness is 0.3 to 0.5 times the slot width.
Table 3. Shear layer thickness with model installed

| x/c | M  | \(\delta/d\) | \(\delta^*/d\) |
|-----|----|--------------|---------------|
|     |    | TE | \(\alpha=0^\circ\) | \(\alpha=2^\circ\) | \(\alpha=-2^\circ\) | \(\alpha=4^\circ\) | TE | \(\alpha=0^\circ\) | \(\alpha=2^\circ\) | \(\alpha=-2^\circ\) | \(\alpha=4^\circ\) |
| 0.40 | 3.324 | 2.740 | 2.849 | 2.929 | / | 0.402 | 0.399 | 0.411 | 0.284 | / |
| -1.00 | 2.710 | 2.693 | 2.726 | 2.604 | / | 0.367 | 0.343 | 0.275 | 0.235 | / |
| 0.80 | 2.864 | 2.651 | 2.781 | 2.930 | / | 0.329 | 0.224 | 0.134 | 0.144 | / |
| 0.40 | / | 3.407 | 3.597 | 3.151 | 3.813 | / | 0.830 | 1.125 | 0.547 | 1.407 |
| 0.50 | 2.965 | 3.303 | 3.417 | 2.983 | 3.784 | 0.427 | 0.758 | 1.017 | 0.447 | 1.506 |
| 0.80 | 2.892 | 2.722 | 2.983 | 2.414 | / | 0.414 | 0.423 | 0.582 | 0.201 | / |

3.3 Shear layer with model installed

Figure 8 shows the calculated results after installing the model. The upper and lower graphs correspond to the measurement positions upstream and downstream of the model, respectively.

**Figure 8** Total pressure recovery in the shear layer with model installed

The positive pressure upstream causes outflow and thinning of the shear layer. As shown in previous longitudinal distribution of the flow angle, the cross flow is dominated by inflow, causing rapid thickening of the shear layer. Therefore, the shear layer along the wall not only modulates the cross flow, but also induces a displacement effect of the external inviscid flow.

The integral results of shear layer thickness is listed in Table 3. The shear layer thickness can be four times as great as the slot width, and displacement effect must be considered for the portion of shear layer with inflow near the wall.

Based on the above analysis, there is a strong shear flow on the grooved surface and the chamber side, the viscosity cannot be neglected, and the homogeneous boundary condition is not satisfied.

4 Conclusion

The distribution of flow characteristics in slotted wall vicinity was measured by the travelling probe. Based on the experimental results, the development of shear layer on slotted wall were obtained. The influence of Mach number and the test position on the shear layer thickness was analyzed.

The results show that in the test range, the flow angle of cross flow is linearly distributed along the normal direction of the wall, and the thickness of the shear layer is about 3 to 4 times the slot width. Viscosity has a serious effect on the flow in slotted wall vicinity and cannot be described by homogeneous boundary condition.
5 References
[1] D. M. Hiebert, F. W. Steinle. A Historical Perspective of Design Requirements for AEDC's Propulsion Wind Tunnel and Von Kármán Facilities: AIAA-2010-0138. Reston, VA: AIAA, 2010.
[2] N. Ulbrich, A. Boone. Determination of the Wall Boundary Condition of the NASA AMES 11ft Transonic Wind Tunnel. AIAA Paper 2001-1112.
[3] C. F. Chen, J. W. Mears. Experimental and Theoretical Study of Mean Boundary Conditions at Perforated and Longitudinally Slotted Wind Tunnel Walls. AEDC-TR-57-20, U.S. Air Force.
[4] S. B. Berndt, H. Sorensen. Flow Properties of Slotted Walls for Transonic Test Sections. Wind tunnel Design and Testing Techniques, AGARD-CP-174, pp. 17-1-17-10.
[5] J. L. Everhart. Theoretical and Experimental Studies of the Transonic Flow Field and Associated Boundary Conditions near a Longitudinally-Slotted Wind-Tunnel Wall. D.Sci. Diss., George Washington Univ.
[6] J. L. Everhart. Theoretical and Experimental Analysis of the Slotted-Wall Flow Field in a Transonic Wind Tunnel. SAE Tech. Paper Ser. 871757.
[7] E. S. Johansen, O. K. Rediniotis, G. Jones. The Compressible Calibration of Miniature Multi-Hole Probes. Journal Fluids Engineering, 2001, 123(1): 128-137.

Acknowledgments
Authors wishing to acknowledge the support of the National Nature Science Foundation of China (Grant No. 11802328 and No. 51327804).