論 文

Investigation of Transonic Test Section with Perforated Walls*

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Abstract

This report presents experimental data on test section with perforated walls used in transonic wind tunnels. Effects of Reynolds number, diameter of holes on the perforated walls, blockage due to model, opening ratio of the perforated walls and length of the test section on mass-flow removal through the walls necessary to obtain transonic Mach numbers in the test section were investigated at comparatively high Reynolds numbers by blowing down compressed air through a model tunnel with a 5×4 cm test section. The results indicate that perforated walls of opening ratio larger than 30 percent increases mass-flow removal greatly and the longer is the test section the more the required suction increases, while the first three elements do not have any appreciable effects over the range of the present experiment. The experiment also shows that pressure and temperature in the plenum chamber are nearly equal to the test section pressure and the reservoir temperature, respectively.

1. Introduction

A plan of building a transonic wind tunnel of moderate size capable of furnishing aerodynamical data useable in practical airplane design is now in progress at newly organized National Aeronautical Establishment in Japan. This project appears, in a sense, to be an engineering adventure because we have had no experience of this type of wind tunnel and also because the driving power of the tunnel is expected to be more than ten times as big as the biggest one we had in the past. Although there exist a number of large scale transonic wind tunnels in America and in European countries, some of which are now in operation and others under construction, their quantitative data have rarely been opened presumably because of international disturbances.

In such circumstances it is urgently requested to have our own data necessary for design and construction of the tunnel. The present study was planned and conducted in cooperation with

and under partial financial support of N. A. E. for the purpose of obtaining aerodynamical data on transonic test section having perforated walls.

In the present study, experiments on transonic test-section with perforated walls have been carried on at comparatively high Reynolds numbers primarily to get quantitative data on the relation of mass-flow removal to the attainable Mach number and on Reynolds number effect on it. Effects of opening ratio, diameter of holes perforated in the wall, length of the test-section and blockage due to a model have also been investigated.

2. Experimental Arrangement

Inasmuch as the primary object of the present study was to obtain quantitative data applicable to the design of a large scale transonic wind tunnel, it was most desirable to conduct experiment at high Reynolds numbers, if possible, comparable to that of the actual tunnel now in program at N. A. E. This fundamental requirement could be almost satisfied by use of the high-pressure air-source at Institute of Science and Technology, University of Tokyo. It is com-

* Received, June 8th, 1956.

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posed of the following parts in the order: an air-compressor (50 hp., max. pressure; 200 atm.), ten bottles of high-pressure air-storage (volume; 0.4 m^3 each, max. pressure; 200 atm.), a regulating valve and a settling chamber (volume; 1.29 m^3 , max. pressure; 30 atm.). The air-source is usually used for a blow-down supersonic wind tunnel. In the present study, a model wind tunnel illustrated in Fig. 1 was installed at the exit of the settling chamber and air was blown down through it to the atmosphere. The pressure in the settling chamber was raised up to 21 atm. in the experiment, and accordingly, the highest Reynolds number of the model tunnel attained was roughly comparable to that of one-atmospheric tunnel with a $0.8 \times 1.0 \text{ m}$ test section.

Fig. 1. Top and side views of the model tunnel.

The model tunnel had an entrance cone, a test section and a short divergent channel in the main passage and an plenum chamber enclosing the test section. The test section was 20 cm long and had a $4 \times 5 \text{ cm}$ rectangular cross-section. Its broader sides consisted of perforated walls and narrower ones of solid walls. Descriptions of the perforated walls used in the experiment are shown in Table 1. The holes on the wall were perforated in zig-zags and distributed uniformly.

Table 1. Description of the perforated walls used in the experiment.

WALL NO.	THICKNESS (mm)	DIAMETER OF A HOLE (mm)	OPENING RATIO (%)
1	1	1	20
2	2	2	20
3	2	2	30
4	2	2	40

The test section was completely enclosed by a cylindrical plenum chamber as shown in Fig. 1.

Its size was purposely made excessively large in order to get completely stagnant condition of air inside the chamber. There were twenty four holes in the end parts of the chamber each of which was attached with either a blind plate or a orifice. When air is blown through the main passage, a part of the total mass-flow is taken off through the perforated walls and discharged from the orifice or orifices to the outside atmosphere provided the pressure at the test section is higher than the atmospheric one. The discharged mass-flow was regulated by changing the number of the orifices open to the atmosphere. Special care was taken to make these orifices all in identical size and shape.

In each run of the tests, the pressure in the settling chamber was kept constant at a predetermined value by regulating the valve and pressure along the test section were measured at nine pressure holes on one of the solid walls. At the same time pressures and temperatures in the settling chamber and the plenum chamber were measured. The removed mass-flow from the main passage was calculated from number of orifices on the plenum chamber open to the atmosphere by use of orifice constant determined in the preliminary experiment as described in the subsequent section. Ordinary Burdon-tube-pressure-gages and copper-constantan thermocouples were used for pressure and temperature measurements, respectively.

3. Experimental Results and Discussion

Before starting the principal experiment, it was needed to make accurate calibration of discharged mass-flow through the orifice. In case the pressure ratio of the outside atmosphere to the plenum chamber is below the critical value (0.528 for air), as was the case of the present experiment, the air flows out through the orifice on average at the critical velocity corresponding to the condition in the plenum chamber. In such a situation, the discharged mass-flow m_0 through the orifice is written as

$$m_0 = k a \rho_p a_p \left(\frac{\pi}{4} \right) d_0^2, \quad (1)$$

where ρ_p and a_p are density and velocity of sound of the stagnant air in the plenum chamber, d_0

the diameter of the orifice ($=5.5$ mm), α a numerical constant equal to 0.578 for air and k is the orifice constant in which are included effects of Reynolds number and non-uniformity of discharge velocity across the orifice. Since ρ_p and a_p are calculable from temperature and pressure in the plenum chamber measured in the experiment, m_0 can be computed from Eq. (1) provided the value of k is determined.

In order to determine the orifice constant k , a circular pipe, 150 cm long and 5.29 cm in diameter, was attached outside one of the orifices and the discharged mass-flow m_0 under various pressures above critical in the plenum chamber was determined by measuring total head and temperature distributions at the exit of the pipe. k was calculated by use of Eq. (1). The orifice constant

Fig. 2. The orifice constant k versus the orifice Reynolds number Re_o .

thus obtained is plotted in Fig. 2 in correlation to the orifice Reynolds number, $Re_o (=a_p^* d_o / \nu^*)$: a_p^* is the critical velocity and ν^* is the kinematic viscosity of the air at the critical state). The two vertical lines in Fig. 2 show range of Reynolds number covered in the experiment described below.

The circles in Fig. 3 are experimental results of the model tunnel with No. 1 perforated walls and at the settling chamber pressure P_s equal to 6 atm. showing the correlation of the mass-flow removal and the test-section Mach number M . Here, Δm is equal to m_0 in Eq. (1) multiplied by number of the orifices and m is a calculated total mass-flow through the entrance of the test section. In subsonic Mach numbers, m was computed as $\rho_E V_E A_E$ where ρ_E and V_E are, respectively, density and velocity calculated from the pressure at the first pressure hole in the test section by use of the isentropic relation and A_E is the cross-sectional area of the test section. In supersonic Mach numbers, ρ_E and V_E were always replaced by density and velocity, respectively, at

the critical state. m is always larger than the actual total mass-flow because of the effect of viscosity. The difference, however, would be a few percent in this experiment.

Fig. 3. Mass flow removal required versus Mach number for No. 1 walls and comparison with other data.

It is found in Fig. 3 that, in case the orifices are all closed or $\Delta m/m=0$, the tunnel is in the choking condition at the test section Mach number 0.81. In a solid-wall wind tunnel without a model, the choking Mach number is usually above 0.90. The lowering of the choking Mach number in the present experiment was caused by roughness of the walls due to perforation and also by the extremely long test section (the ratio of the length to the height is 4).

The greater becomes the mass-flow removal by increasing the number of the orifices, the higher test section Mach number can be attained. Quantitatively speaking, sonic velocity at the test section is obtained by 3 percent mass-flow removal and Mach number 1.3 by 7 percent suction. It must be noted here that the experimental curve becomes almost horizontal at Mach number 1. Its significance is that, in designing a transonic wind tunnel of this type, special care must be paid in order to regulate the suction very finely over the Mach number range from 0.95 to 1.05 where a small change of suction produces a large variation of Mach number on the one hand, while on the other, effect of Mach number on aerodynamical characteristics of a body is incomparably large.

The curve A in Fig. 3 is the one computed from the simple one-dimensional isentropic flow theory. The difference between the curve A and the experimental one is caused by the existence

of the boundary layer. It was not cleared in this experiment why the experimental result showed smaller slope than the theoretical curve in the supersonic region. The other curves *B* to *D* and *E* to *G* in Fig. 3 are experimental and theoretical ones taken from the data obtained at AEDC⁽¹⁾ and Cornell Aeronautical Laboratory⁽²⁾ in America, respectively. Since, in the former, exact values of the opening ratio is not known, and in the latter, the Mach number scale is not given, detailed comparison of the present experiment with them is impossible.

Fig. 4 shows pressure distributions along the test section at subsonic, nearly sonic and supersonic Mach numbers obtained in the tests shown in Fig. 3. Uniformity of the pressure is not good except for the narrow region near the center. In representing the present experimental results, the test section Mach number M was defined as that corresponding to the averaged value of the pressures at No. 4 and No. 5 pressure-holes. It is found that an entrance length

Fig. 4. Pressure distribution along the test section with No. 1 walls.

at least one and half of the tunnel height is needed before the flow reaches nearly uniform condition. Proper distribution of the holes on the perforated walls other than the uniform one must be considered to make the entrance length shorter. In the downstream part of the test section there always appeared a tendency of pressure drop. This was due to the effect of the rapid expansion in the downstream part of the test section. The experimental results correlating the ratio of the plenum chamber pressure P_p to the settling chamber pressure P_0 with M is shown in Fig. 5, in which the solid line is the theoretical curve obtained as P_p is equal to the test section pressure P corresponding to M . Fig. 6

Fig. 5. Plenum chamber pressure versus test section Mach number for No. 1 walls.

also shows the ratio of the plenum chamber temperature T_p to that in the settling chamber T_0 . Since a stagnant condition is attained in the plenum chamber, the temperature ratio is nearly unity independent of M as the theory shows.

Fig. 6. Plenum chamber temperature versus test section Mach number.

The solid line in Fig. 6 is the calculated temperature of the flow in the test section.

The effect of Reynolds number on the mass-flow removal necessary to obtain transonic Mach numbers is shown in Fig. 7, in which are plotted

Fig. 7. Mass flow removal versus test section Mach number at various values of settling chamber pressure.

experimental results obtained at various values of P_0 from 6 to 21 atm. Against our expectation the experiment showed very small Reynolds number effect on suction over the range covered by the present experiment.

The results mentioned above were obtained by use of No. 1 walls. Next problem was to check

the effect of the hole diameter in perforated walls on the suction. Since the range of lateral influence of holes must be proportional to the hole diameter, a small hole diameter is preferable in a transonic wind tunnel in view of uniformity of the flow. In the present experiment, however, the scale of the model tunnel is so small that it was obliged to adopt large hole diameters, 1 mm. and 2 mm., relative to the tunnel height because of the difficulty in manufacturing. The results are shown in Fig. 8 which indicate indiscernible change of the suction due to the variation of the hole diameter.

Fig. 8. The effect of hole diameter on mass flow removal.

On the contrary, the effect of opening ratio (area ratio of all holes to the wall) on the suction was found to be very large as shown in Fig. 9. Fig. 10, which is a cross-plotting of Fig. 9, indi-

Fig. 9. The effect of opening ratio on mass flow removal with opening ratio as parameter.

cates rapid increase of suction between 30 to 40 opening ratio. This is thought to be caused by thickening of the boundary layer due to the increase of free boundary. Hence, it seems prohibitive in view of suction-power economy to make use of perforated walls of more than 30 percent opening ratio.

Fig. 10. The effect of opening ratio on mass flow removal with M as parameter.

It was another point to be checked in this experiment whether or not existence of a body in the test section had effect on suction in this type of transonic wind tunnel. To do this, a cone-cylinder (vertex angle; 17 deg., cylinder diameter: 8.3 mm) without yaw was inserted in the test section with No. 1 walls and mass-flow removal and pressure distribution were measured. The blockage ratio in this case was 2.7 percent. In Fig. 11 the pressure distributions in subsonic and supersonic cases are shown in solid lines, and for comparison, those without model and at nearly the identical Mach numbers in dotted lines. Effect of blockage in the subsonic case and that of the bow shock in the supersonic case are clearly seen

Fig. 11. Pressure distribution along the test section with model.

in this figure. As the test section Mach number M could not be defined by such wavy pressure distributions, it was determined, for convenience, from the plenum chamber pressure by making use of the experimental curve of P_p/P_0 versus M obtained in the vacant test section (Fig. 5). The mass-flow removal at Mach numbers thus defined is shown in Fig. 12. This experimental

Fig. 12. The effect of blockage on mass flow removal.

result indicates that existence of the model did hardly change the required suction at transonic Mach numbers.

All of the results mentioned already were obtained in the model tunnel with the 20 cm long test section. In the end of the experiment, effect of the length of the perforated walls on suction was examined by plugging the holes with paraffin in a portion of the perforated walls. The result is shown in Fig. 13. It is seen that the suction can be reduced appreciably by shortening the length of the perforated wall. This may be reasonably understood when effect of length of roughened

Fig. 13. The effect of length of perforated walls on mass flow removal.

surface on boundary layer growth is taken into accounts. Length of the test section in a transonic wind tunnel has to be determined from both sides of suction-power economy by shortening and of obtaining uniformity of flow by lengthening.

References

- 1) Goethert, B. H.: Flow Establishment and Wall Interference in Transonic Wind Tunnels, *Transonic Testing Techniques* (A Symposium). I. A. S. (1954).
- 2) Flax, A. H., Ross, I. G., Kelso, R. S., and Wilder, J. G.: Development and Operation of the C. A. L. Perforated-Throat Transonic Wind Tunnel, *Transonic Testing Techniques* (A Symposium). I. A. S. (1954).

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Surveys in Mechanics: ed. by G. K. Batchelor and R. M. Davies, pp. 475, Cambridge Univ. Press, 1956, 50 S. (2,750 円)

Cambridge の応用数学力学叢書中の 1 冊で、副題の示すとおり昨年 5 月 7 日に第 70 回の誕生日を迎えた Sir Geoffrey Ingram Taylor に捧げられた記念論文集である。この種の論文集によく見られる多くの人々による短篇集ではなく相当長い総合報告 10 編を集めたもので、その内容は塑性、転位の理論から流体力学、気象学の各方面にわたりそれぞれの分野での一流の学者が多く執筆している。しかもここに採り上げられた題目がほとんどすべて Taylor 自身によって開拓せられあるいは大きな発展をもたらされた問題に関するものであるのを見て、今更ながら彼の偉大な業績に感嘆せずにはいられない。次に各論文の筆者と表題とを挙げる。

R. V. Southwell: G. I. Taylor; A Biographical Note (6 p.)—R. Hill: The Mechanics of Quasi-

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Static Plastic Deformation in Metals (25 p.)—N. F. Mott: Dislocations in Crystalline Solids. (32 p.)—R. M. Davies: Stress Waves in Solids. (75 p.)—H. B. Squire: Rotating Fluids. (23 p.)—W. R. Lane and H. L. Green: The Mechanics of Drops and Bubbles. (54 p.)—F. Ursell: Wave Generation by Wind. (34 p.)—M. J. Lighthill: Viscosity Effects in Sound Waves of Finite Amplitude (102 p.)—G. K. Batchelor and A. A. Townsend: Turbulent Diffusion (48 p.)—T. H. Ellison: Atmospheric Turbulence. (31 p.)—K. S. M. Davidson: The Mechanics of Sailing Ships and Yachts. (45 p.)

以上の各論文はいずれも self-contained な解説を目指したもので基本的な概念の説明から始まり最近の発展までを概説してその題目の専門家でない読者にとっても近づき易く興味が深い。各篇にはいずれも多数の文献の目録が添えられている。なお別に Taylor 自身の論文集も刊行されるとのことである。

(阿 阪 三 郎)