Hypersonic, Turbulent Skin-Friction and Heat-Transfer Measurements on a Sharp Cone

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Turbulent skin-friction coefficients directly measured on an axisymmetric 5° half-angle sharp cone by two floating-element skin-friction balances at a freestream Mach number of 7.90 are presented. Heat-transfer distributions are obtained simultaneously. These results yield directly the Reynolds analogy factor. On the basis of measured skin-friction coefficients, which covered a range of wall-to-stagnation temperature ratios (Tw/To) of 0.24 to 0.41 and Reynolds numbers at the location of the skin-friction balance of 1.45×10^7 to 2.17×10^7, we conclude that the method of Van Driest and that of Clark and Creel predict the measurements within about 10%. The methods of Spalding and Chi and of Sommer and Short underpredict the data by about 30% and 20%, respectively. Except for the relatively low-Reynolds-number case, the directly measured sharp-cone Reynolds analogy factor is between 1.01 and 1.07, which is in good agreement with the recent flat-plate measurements of Keener and Polek. Finally, results indicate that the Stanton number is essentially constant for Tw/To between 0.20 and 0.36, whereas it decreases by about 10% at $Tw/To = 0.11$.

I. Introduction

RECENTLY, there has been considerable interest in studying hypersonic, turbulent, boundary-layer flows at low-wall temperatures. This is undoubtedly because of their significance in the optimal design of re-entry vehicles useful for defense and space applications. From an engineer's point of view, the desired goal of such a study is to establish the usefulness of a predictive scheme which is both simple and accurate. In this respect, we might mention the rather extensive study of Spalding and Chi,[1] who compared 20 methods with a large number of directly and indirectly measured flat-plate skin-friction data. Subsequently, heat-transfer data on cones and heat-transfer and skin-friction data on flat plates and nozzle walls have been used by various investigators to evaluate different theories.[2–13] Conclusions from these studies may be summarized as follows.

1) The methods of Van Driest[14] and Coles[15] predict skin friction within about 10% of experimental flat-plate and tunnel-wall data for the wall-to-recovery temperature ratio $Tw/Taw > 0.3$.[8,10,11]

2) For $Tw/Taw \sim 0.15$, results obtained from the method of Spalding and Chi[1] agree reasonably well with the skin-friction measurements obtained in a shock tunnel.[4]

3) Evaluation of theories for heat-transfer predictions depends critically on the accepted value of the Reynolds analogy factor. However, a recent survey conducted by Cary[16] indicates a definite need for more systematic studies on the subject.

4) The effect of wall temperature on measured heat-transfer rate is still not yet settled. For example, results of Cary[17] indicate little influence for $0.2 \leqq Tw/To \leqq 0.7$, whereas Drougge[18] and Wilson[7] both suggest a rather large decrease in the Stanton number for $Tw/To \gtrsim 0.2$.

It is therefore clear that there is still a need for simultaneously measured turbulent skin-friction and heat-transfer data especially at low-wall temperatures. Furthermore, directly measured skin-friction coefficients on pointed axisymmetric bodies, which are of great technical interest, appear to be quite limited. The purpose of this paper is to present turbulent skin-friction coefficients directly measured on an axisymmetric 5° half-angle sharp cone by two floating-element skin-friction balances designed and constructed at the Naval Ordnance Laboratory (NOL). In addition, heat-transfer measurements are obtained simultaneously. These results yield the Reynolds analogy factor which will be compared with the flat-plate data of other investigators. Furthermore, the effect of wall temperature on the Stanton number will be presented. Finally, comparisons with the predictive schemes of Spalding and Chi,[1] Van Driest,[14] Sommer and Short,[19] and Clark and Creel[20] will also be made.

II. Apparatus and Test

The experimental investigation was conducted in the NOL Hypersonic Tunnel at a freestream Mach number of 7.90 in air. A sharp, sting-supported, 5° half-angle cone was used for the test. This combination of freestream Mach number and cone half-angle yielded a local Mach number of 7.15 at the edge of the boundary layer. The model was made of Armco 17-4 PH stainless steel and was equipped with four pressure taps, two skin-friction balances and 40 thermocouples. A sketch of the cone, together with some pertinent dimensions, is shown in Fig. 1.

A cooling box was used to control the surface temperature of the model. Liquid nitrogen, liquid CO_2, and compressed air (heated or unheated) were employed in the investigation to

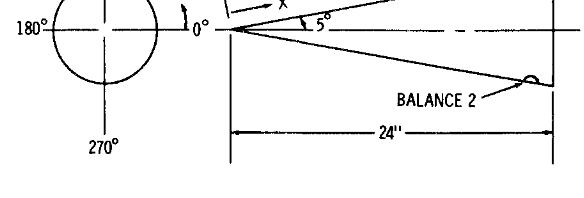

Fig. 1 Schematic of the model.

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Table 1 Test conditions and skin-friction data

Run no.	Po psi	To °R	Re/L 10^6/ft	Tw/To	$10^3 C_f$
18	2189	1440	11.07	0.197	...
19	2188	1437	11.10	0.322	1.15
20	2183	1467	10.74	0.194	...
21	2186	1469	10.73	0.351	1.21
23	2185	1495	10.44	0.351	...
24	2196	1471	10.76	0.362	...
26	1470	1442	7.42	0.340	...
27	1470	1443	7.42	0.409	1.17
29	1481	1450	7.41	0.366	...
30	2188	1462	10.82	0.108	...
31	2191	1461	10.85	0.242	1.26

obtain a rather wide range of wall-to-stagnation temperature ratios. The test conditions are summarized in Table 1. Details of the apparatus and the test can be found in Ref. 21.

III. Data Reduction

Heat Transfer

The recorded temperature history of the model wall was used in the transient-thin-wall technique to obtain the heat-transfer data. Calculation indicates that errors due to normal conduction through the thin skin of the model are negligible. At each thermocouple location, a least-squares second-degree polynomial fit to 16 successive temperature readings was employed to calculate $\partial Tw/\partial t$. A history of measured heat-transfer coefficient h_m was obtained from the relation

$$h_m = \frac{\rho_m C_{pm} \delta_m}{(Taw - Tw)} \frac{\partial Tw}{\partial t} \tag{1}$$

The values of the density ρ_m, the specific heat C_{pm}, and the skin thickness δ_m, of the model used in the data reduction are contained in Ref. 21. The Thomas-Fitzsimmons initial-lateral-conduction-correction method[22] was then applied to the data block of h_m to yield a heat-transfer coefficient at time zero, the time at which aerodynamic heating began. Ten such data blocks, consecutive in time, and the corresponding heat-transfer coefficients at time zero $h_a(o)$ were generated. When the variation in $h_a(o)$ from several consecutive data blocks was small, their average was selected to be the proper value. The method was checked with two low-supply-pressure runs and good agreement with the laminar boundary-layer theory was obtained. The heat-transfer data are listed in Table 2. The estimated probable error is about $\pm 5\%$.

Skin Friction

A simulator was used to install the two skin-friction balances for bench-top calibrations. Pictures showing the setup, the model, and the balances, and typical calibration results can be found in Ref. 21. Based on a least-squares linear fit, the balance proved to be linear within about 0.3%. An average of the repeated calibrations conducted between runs on site were used in the final data reduction. For every run, two tare readings were recorded, one before and one after the test. The result would be discarded if the difference between the two tare readings proved to be large. The skin-friction results are also listed in Table 1. The estimated probable error is about $\pm 5\%$. More details of the data analysis can be found in Ref. 21.

IV. Predictive Methods

For a laminar flow, the well-known Blasius solution with Mangler transformation and the reference-temperature method of Rubesin and Johnson[23] can be used to give the skin-friction coefficient C_f. The heat-transfer result can then be obtained by

Table 2 Heat-transfer data

Run 18

$10^{-6} Re_x$	$10^4 S_t$
1.8	5.5
2.8	4.1
3.7	3.6
4.6	4.1
8.3	7.2
9.2	7.4
12.0	7.4
12.9	6.8
14.8	6.8
15.7	6.8
16.6	6.5
18.5	6.5
20.3	6.1
20.3	6.2

Run 19

$10^{-6} Re_x$	$10^4 S_t$
1.8	4.9
2.8	4.2
3.7	3.7
4.6	4.4
5.5	4.2
6.5	4.5
7.4	7.8
8.3	6.6
9.2	7.8
12.0	7.5
12.9	7.0
12.9	7.1
13.8	7.3
14.8	6.5
14.8	6.8
15.7	6.9
16.6	6.7
16.6	6.9
17.5	6.2
18.6	6.0
20.4	6.1

Run 20

$10^{-6} Re_x$	$10^4 S_t$
1.8	4.6
2.7	3.9
4.5	4.5
5.4	5.3
9.0	7.7
11.6	7.5
13.4	6.8
14.3	6.9
15.2	6.9
16.1	6.8
17.9	6.8
19.7	6.4

Run 21

$10^{-6} Re_x$	$10^4 S_t$
1.8	4.9
2.7	4.0
3.6	3.8
4.5	4.4
7.2	6.8
8.1	7.4
9.0	7.5
11.6	7.6
12.5	7.2
13.4	7.4
14.3	7.0
14.3	7.3
15.2	7.1
16.1	7.0
17.9	6.9
19.7	6.0
19.7	6.2

Run 23

$10^{-6} Re_x$	$10^4 S_t$
1.7	5.8
2.6	4.1
3.5	4.1
4.4	4.1
5.2	5.3
6.1	5.8
7.0	7.5
7.8	8.0
8.7	9.4
11.3	7.7
12.2	7.2
13.1	6.9
13.9	7.1
14.8	6.9
15.7	6.7
17.4	6.7
19.2	6.6
19.2	6.3

Run 24

$10^{-6} Re_x$	$10^4 S_t$
1.8	5.6
2.7	4.2
3.6	3.8
4.5	4.2
5.4	4.9
7.2	8.1
8.1	7.9
9.0	7.9
11.7	7.6
13.5	6.8
14.3	6.8
14.3	6.7
15.2	7.0
16.1	6.7
17.9	6.6
19.7	6.0
19.7	6.5

Run 26

$10^{-6} Re_x$	$10^4 S_t$
1.2	6.9
1.9	4.9
2.5	4.2
3.1	4.6
4.9	4.6
7.4	6.2
8.0	8.7
8.6	8.2
9.3	8.1
9.9	8.1
9.9	8.4
10.5	8.0
11.1	7.0
11.1	7.7
11.7	6.8
12.3	7.2
13.6	6.5
13.6	6.8

Run 27

$10^{-6} Re_x$	$10^4 S_t$
1.2	5.7
1.9	5.2
2.5	4.3
3.1	4.7
3.7	4.5
4.9	5.0
8.0	9.1
8.6	8.5
9.3	8.3
9.9	8.5
9.9	8.3
10.5	7.8
11.1	8.1
11.1	7.5
11.7	7.3
12.3	7.4
13.6	6.9
13.6	6.9

Run 29

$10^{-6} Re_x$	$10^4 S_t$
1.2	6.4
1.8	5.8
2.5	4.2
3.7	4.6
4.3	4.3
4.9	5.3
8.0	8.6
9.2	8.0
9.9	7.9
10.5	7.4
11.1	7.4
11.1	7.5
12.3	7.0
13.5	6.6

Run 30

$10^{-6} Re_x$	$10^4 S_t$
2.7	3.6
3.6	3.2
4.5	3.7
5.4	4.9
6.3	6.1
7.2	7.1
8.1	6.3
9.0	6.8
11.7	6.4
13.5	5.9
14.4	6.0
14.4	6.1
15.3	6.1
16.2	5.9
18.0	6.0
19.8	5.7
19.8	5.8

Run 31

$10^{-6} Re_x$	$10^4 S_t$
2.7	4.2
3.6	3.8
4.5	4.3
7.2	7.9
8.1	7.5
11.8	7.6
12.7	7.1
13.6	7.0
14.5	7.1
14.5	6.8
16.3	7.0
16.3	6.6
18.1	6.7

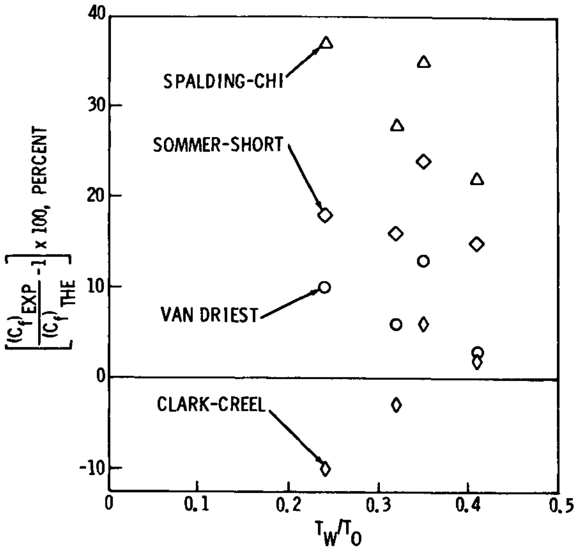

Fig. 2 Comparison of skin-friction data with theories.

using the well-known formula of the Reynolds analogy factor for a laminar flow

$$2S_t/C_f = Pr^{-2/3} \tag{2}$$

The Prandtl number is taken as constant, $Pr = 0.725$.

In the interest of simplicity, the turbulent-flow methods of Spalding and Chi,[1] Van Driest,[14] Sommer and Short[19] and Clark and Creel[20] are considered. The incompressible formula of Kármán and Schoenherr relating $\overline{C_f}$ to $\overline{Re_\theta}$ (Ref. 10) is used for predicting the compressible skin-friction coefficient from each of these methods. Since only surface properties were measured, the Reynolds number based on the momentum thickness Re_θ is calculated from the momentum integral equation for a cone

$$C_f/2 = dRe_\theta/dRe_{x'} + Re_\theta/Re_{x'} \tag{3}$$

where x' is the distance measured along the cone surface from the virtual origin of turbulent flow. The experimental results of Richards[3] suggest that the virtual origin may be determined by matching the momentum thickness θ from a turbulent-flow theory to that of the laminar theory at the midpoint of the transition zone. Calculations indicate that differences in the predicted skin-friction coefficient between this procedure and that where θ is matched at the end of the transition (as was suggested by Wallace[4]) are about 4% for Re_x (Reynolds number based on the distance along surface from the cone tip) $\sim 15 \times 10^6$, and only about 2% for $Re_x \sim 22 \times 10^6$. Finally, Kármán's formula for the Reynolds analogy factor, as modified by Bertram and Neal,[2] is used to provide the heat-transfer predictions. Present data (shown in Sec. IV) suggest $Re_x = 6 \times 10^6$ at the midpoint of transition. More details can be found in Ref. 24.

V. Results and Discussion

The comparison between the skin-friction measurements and the predictive schemes is illustrated in Fig. 2. Present data cover a range of Tw/To of 0.24–0.41 and Reynolds number (Re_x) at the location of the skin-friction balance of 1.45×10^7 to 2.17×10^7. Results indicate that the method of Van Driest and that of Clark and Creel predict the measurements within about 10%, whereas the other two predictive schemes underpredict the data considerably more. These observations are in general agreement with the conclusions of other investigators whose results were obtained on flat plates or nozzle walls.[10,11,20]

Heat-transfer distributions along the cone surface for various wall-to-stagnation temperature ratios are tabulated in Table 2. Some selected results are depicted in Figs. 3a–c. The data exhibit the familiar picture of a laminar, then transitional, and finally

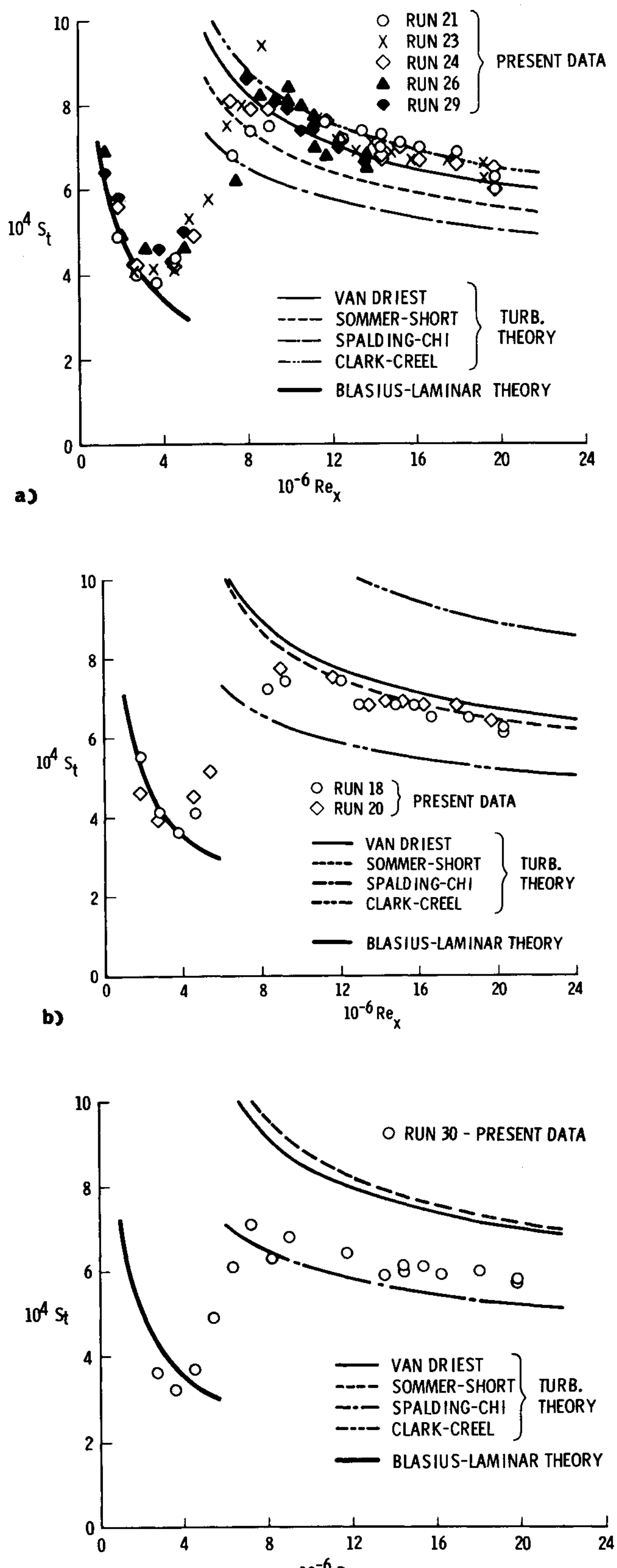

Fig. 3 Stanton number distribution: a) $Tw/To = 0.35$; b) $Tw/To = 0.20$; and c) $Tw/To = 0.11$.

turbulent flow. Except for the case of the lowest Tw/To ($=0.11$), the agreement between the laminar solution and the data is quite good. This again confirms the general reliability of the testing technique and the data-reduction method for heat-transfer measurements. On the other hand, the degree of agreement

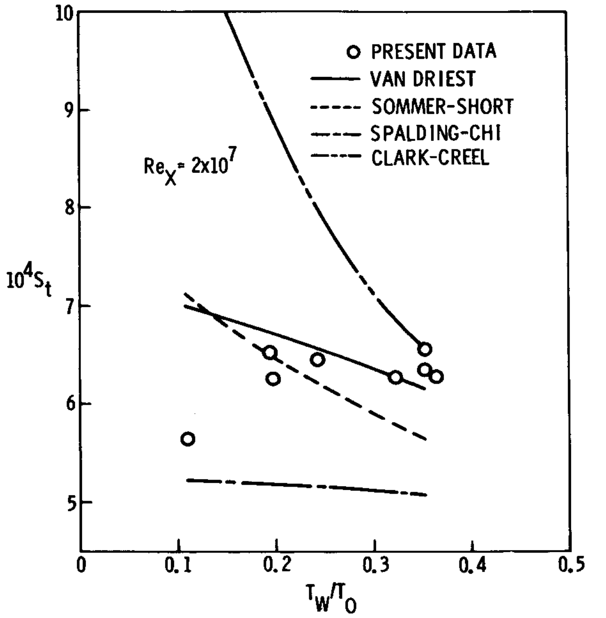

Fig. 4 Wall-temperature effect on the Stanton number.

between the turbulent data and the theories depends more strongly on Tw/To. This dependence is better seen in Fig. 4 for $Re_x = 2 \times 10^7$. Because of the scatter in the original data, a mean value for each run is used to construct the plot. In agreement with the results of Cary,[17] the presently measured Stanton number is essentially constant for Tw/To between 0.20 and 0.36. However, at $Tw/To = 0.11$, there appears a decrease in the Stanton number by about 10%. This is in the same trend as that reported by Drougge[18] and Wilson,[7] although the decrease measured here is smaller. More systematic studies are required before a definitive conclusion can be reached.

The level of the heat-transfer prediction depends on the particular Reynolds analogy factor employed. As shown in Fig. 4, if the modified Kármán's equation[2] is utilized, the method of Van Driest predicts the data reasonably well for $Tw/To > 0.2$. On the other hand, in agreement with Pearce,[9] at $Tw/To = 0.11$, only the method of Spalding and Chi gives a value that is within 10% of the measurement.

Finally, the present sharp-cone Reynolds analogy factor is depicted in Fig. 5. Also shown are the flat-plate results of Wallace,[4] Neal,[25] Keener and Polek,[26] Holden,[27] and that of

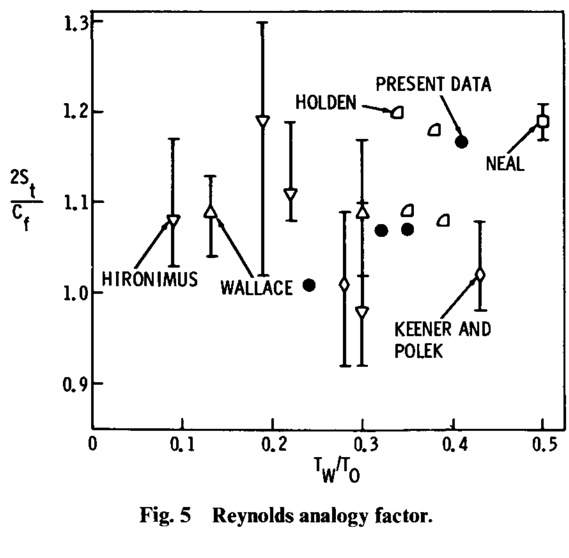

Fig. 5 Reynolds analogy factor.

Hironimus as rereduced and tabulated by Cary.[16] The symbol represents the average and the bar the variation at any given flow condition. The range of the Mach number included in Fig. 5 is from 6.6 to 8.1. For edge Mach number of 5.9 to 7.7, Keener and Polek[26] found no distinct effects of Mach number on the Reynolds analogy factor. Despite this fact, a considerable amount of scatter among all the data is still present in Fig. 5. Except for the relatively low-Reynolds-number case ($Re_x = 1.45 \times 10^7$ at $Tw/To = 0.41$), present sharp-cone data agree reasonably well with the flat-plate results of Keener and Polek which suggest a value close to the classical limit of unity. Note that the rate of decrease of the Stanton number for $Re_x > 8 \times 10^6$ as shown in Fig. 3a is distinctly faster for the lower-total-pressure runs (filled symbols). Whether this suggests a flow that is not yet fully turbulent is not clear. If all the data shown in Fig. 5 are considered, a Reynolds analogy factor, independent of Tw/To, and equal to 1.1, suggests itself. This value is quite close to the predictions given by the Kármán's equation. Obviously, more systematic investigations, especially at low Tw/To, are definitely required.

VI. Conclusions

In conclusion, simultaneous measurements of skin friction and heat transfer on an axisymmetric sharp cone have been successfully obtained at an edge Mach number of 7.15 and unit Reynolds number of 7.4×10^6 to 11×10^6 per ft. Following conclusions may be drawn: 1) for Tw/To between 0.24 and 0.41, both the method of Van Driest[14] and that of Clark and Creel[20] predict the skin-friction data within about 10%; 2) if the modified Kármán's equation for the Reynolds analogy factor is utilized, the scheme of Van Driest[14] gives reasonable predictions of heat transfer for $Tw/To > 0.2$, whereas only the method of Spalding and Chi[1] yields a value that is within 10% of the measurement at $Tw/To = 0.11$; 3) the wall-temperature effect on the Stanton number proves to be quite small for Tw/To above 0.2; 4) if only the data at $Re_x \cong 2.2 \times 10^7$ are considered, present measurements of the Reynolds analogy factor for the sharp cone are between 1.01 and 1.07 which agree very well with the flat-plate results of Keener and Polek[26]; and 5) the results of the present study and that of other investigators strongly suggest the need for more systematic investigations for $Tw/To \leqq 0.2$.

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