Skin-Friction Reduction by a Micro-Blowing Technique

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Nomenclature

A	= area of test plate
C_f	= total skin-friction coefficient, (skin-friction force)/($\frac{1}{2}\rho_\infty u_\infty^2 A$)
C_{fw0}	= total skin-friction coefficient of porous plate with no blowing
C_{f0}	= total skin-friction coefficient of nonporous solid flat plate
D	= diameter of blowing holes, mm
F	= blowing fraction, $(\rho_b v_b)/(\rho_\infty u_\infty)$
Re/m	= Reynolds number per meter
T	= thickness of plate, mm
u_∞	= freestream velocity
v_b	= average blowing air velocity
ρ_b	= blowing air density
ρ_∞	= freestream density
$2F/C_{fw0}$	= blowing parameter

Introduction

ONE of the most challenging areas of research in aerodynamics is the reduction of skin friction, especially for turbulent flow. Many techniques and methods have been tried[1,2]; however, none has significantly reduced skin friction in the flight environment. For the past 20 years, attention has been focused on surface suction to delay transition so that a large area of the laminar flow region can provide skin-friction reduction.[1] There are many problems associated with this technique: laminar flow is very unstable and tries to transit into turbulent flow, even when a very small foreign object is present. Also, laminar flow is susceptible to separation. As a result, this technique is still in the research stage. Another method to reduce skin friction is to place riblets on the surface,[1] but this method limits drag reduction to under 8%.

Another way of reducing skin friction is surface mass injection (or blowing). This method has been ignored because many researchers believe that, because the flow is susceptible to flow separation, the penalty associated with blowing is very large. Despite this shortcoming, in the 1970s many experiments were conducted on a flat plate with no pressure gradient. Thus it became well established that blowing a porous plate significantly reduced its skin friction in comparison to that of the same porous plate without blowing. However, the skin friction of unblown porous plates was found to be very high in comparison with that of a nonporous solid flat plate.[3] Reducing the skin friction of such porous plates by blowing is impractical because a very large amount of blowing air (which blows away the boundary layer) is required to reduce the skin friction below that of a solid flat plate.

The results of an innovative skin-friction reduction technique, called the Micro-Blowing Technique (MBT, patent pending), are presented. This is a unique concept in which an extremely small amount of air is blown vertically at the surface through very small holes with a high aspect ratio. The microblowing reduces the surface roughness and the gradient of the flow velocity profile on the surface, thereby reducing skin friction. A phase-I, proof-of-concept experiment, conducted in the Advanced Nozzle and Engine Components Test Facility[4] at the NASA Lewis Research Center, proved that this technique can reduce skin friction by as much as 60% for a wide range of simulated flight conditions. Details of the experiment can be found in Ref. 5.

Received March 18, 1997; revision received Sept. 12, 1997; accepted for publication Nov. 17, 1997.

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Skins Tested

The most important factor in achieving success with the MBT is the skin. One proposed MBT skin consists of two layers, as depicted in Fig. 1. For this investigation, the inner layer was always a 30-μm, high-density polyethylene plate that was 9.14 mm thick. The gap between the inner layer and the outer layer was about 0.8 mm. (This same test is conducted later without the inner layer.) Seven outer layers (each 12.36 × 25.06 cm) were tested (see Table 1 for the specifications of the plates). The NASA PN2 and PN3 skins were laser drilled; the shape of the holes was irregular. It is believed that a streamline on the surface should pass over the holes as often as possible to get the benefit of vertical blowing air. The GAC series plates (designed for acoustic testing) were provided by Northrop Grumman Corporation.

Results and Discussion

The total skin-friction coefficients of a nonporous solid flat plate, C_{f0}, were measured first. The skin-friction coefficients C_f were measured at different Reynolds numbers per meter for different outer-layer porous test plates. The skin-friction ratios for porous plates without blowing (unblown skin-friction ratio) are shown in Fig. 2. Only three porous plates, NASA PN2, NASA PN3, and GAC1897, had skin-friction ratios lower than 1.2, i.e., just 20%

Table 1 Specifications of test plates

Plate name	Shape of hole cross section (side view)	Hole size D, mm	Skin thickness T, mm	Porosity, %	Aspect ratio T/D
NASA PN2	Straight	0.165	1.02	23	6.2
NASA PN3	Straight	0.254	1.02	23	4
GAC2004	Conical	0.381	0.787	21	2.1
GAC2003	Conical	0.152	0.305	21	2
GAC2005	Conical	0.076	0.152	23	2
GAC2002	Conical	0.229	0.394	31	1.7
GAC1897	Hourglass	0.060	0.305	50[a]	5.1

[a]Fifty percent is based on surface in contact with flow and 4% is based on small neck area of hourglass.

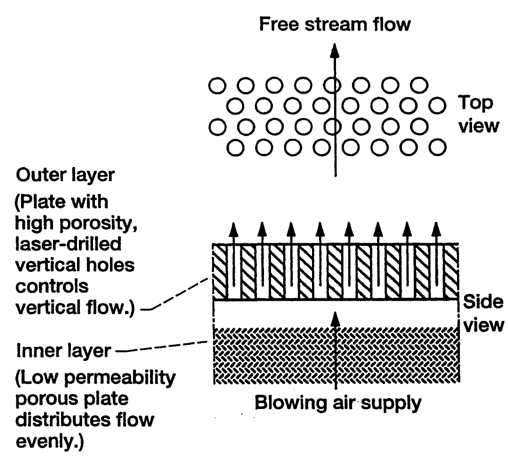

Fig. 1 MBT skin.

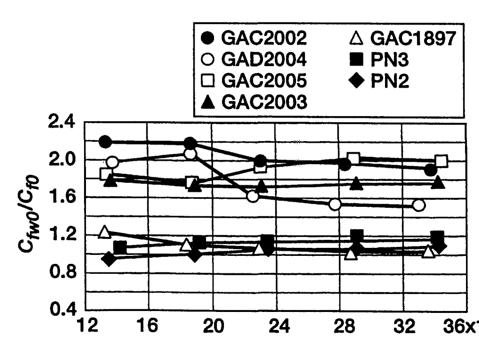

Fig. 2 Unblown skin-friction ratios.

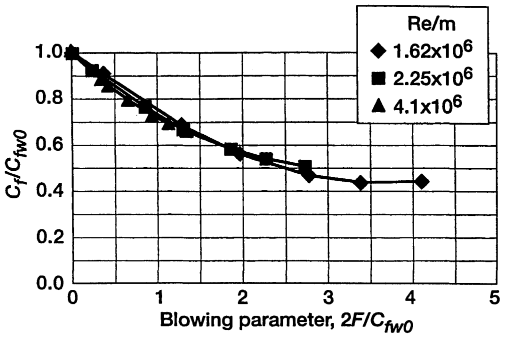

Fig. 3 Skin-friction ratio (based on C_{fw0}) of NASA PN2 as a function of blowing parameter.

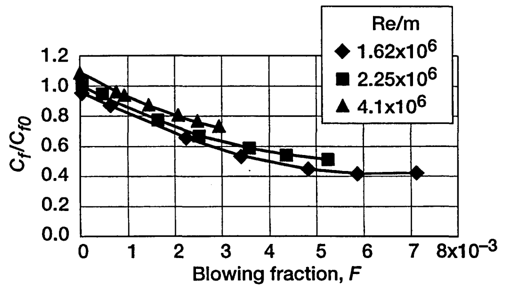

Fig. 4 Skin-friction ratio (based on C_{f0}) of NASA PN2 as a function of blowing fraction.

more than a solid flat-plate value. These plates were regarded as MBT skins. The unblown skin-friction ratios were so high for the other skins that reducing them to below a solid flat-plate value was not possible for practical application. Notice that the holes in the MBT skins have aspect ratios of 4 or higher (Table 1). These small, high-aspect-ratio holes not only are able to control the vertical blowing air during the microblowing but also are able to provide low skin friction without blowing. It also is believed that the slip flow on the surface of the MBT skin plays an important role in reducing the skin friction. The results of PN2 are presented herein.

In Fig. 3 the traditional parameters for injection are used to show the results for NASA PN2 porous plates. As expected, the data collapsed. However, because the collapsed data depend highly on the characteristics of the porous plate, no attempt has been made to compare them with the existing data. Because the skin-friction ratio C_{fw0}/C_{f0} is so different for various unblown porous plates (see Fig. 2), Fig. 3 provides only limited information about the effectiveness of a porous plate for blowing boundary-layer control. A more meaningful way to present the data for the NASA PN2 porous plates is shown in Fig. 4. Note that the reference skin-friction coefficient is that of a flat plate, C_{f0} instead of C_{fw0}.

Figure 4 indicates that, for PN2, even an extremely small amount of blowing air, i.e., $F < 0.0005$, reduced the skin friction below that of the solid flat plate and continued to reduce it effectively at a blowing fraction $F < 0.003$ with higher rate of skin-friction reduction. This small amount of blowing air is called the microblowing. The penalty for supplying blowing air in the MBT is probably very low because the blowing flow rate is so small. Figure 4 shows that up to 60% reduction ($C_f/C_{f0} = 0.4$) was achieved for this porous plate. A smaller reduction below the flat-plate value was shown at higher Reynolds numbers, as can be seen in Fig. 4 for the NASA PN2 porous plate.

Concluding Remarks

A proof-of-concept experiment (phase I) for the Micro-Blowing Technique (MBT) has been successfully completed. Preliminary results show that, with microblowing, up to 60% skin-friction reduction below a flat-plate value can be achieved over a wide range of flow conditions. Research indicates that the skin is the most important factor in achieving success with the MBT. This experiment identified three skins for use with the MBT, all having holes with aspect ratios larger than 4. One of the ways that the MBT reduces skin friction is by effectively reducing the roughness of the skin by means of very low blowing air. More experiments are required to determine the optimal MBT skin and to assess the penalty associated with this technique.

References

[1]Bushnell, D. M., and Hefner, J. N., *Viscous Drag Reduction in Boundary Layers*, Vol. 123, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1990.

[2]"Special Course on Skin Friction Drag Reduction," AGARD R-786, 1992.

[3]Wilkinson, S. P., "Influence of Wall Permeability on Turbulent Boundary-Layer Properties," AIAA Paper 83-0294, Jan. 1983.

[4]Beltran, L. R., Del Roso, R. L., and Del Rosario, R., "Advanced Nozzle and Engine Components Test Facility," NASA TM-103684, 1992.

[5]Hwang, D. P., "A Proof-of-Concept Experiment for Reducing Skin Friction by Using a Micro-Blowing Technique," AIAA Paper 97-0546, Jan. 1997.

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Hybrid Turbulence Model for Unsteady Boundary Layers

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Introduction

DURING the 1990s dynamic stall has remained an area of active research, primarily due to its occurrence in important applications such as high-angle-of-attack aerodynamics, rapidly maneuvering aircraft, helicopter rotors, wind turbines, and turbomachinery. The application of viscous–inviscid interaction methods[1] or Navier–Stokes solvers,[2] combined with turbulence models of varying complexity, to oscillating airfoils and wings has become prevalent in the last few years. A spectrum of models ranging from algebraic to two-equation models has been employed, and their results have been compared with airfoil integrated-load data ranging from attached flow through airfoil flutter (light stall) to massively separated flow (deep stall). By and large, the results are unsatisfactory, with attached and massively separated flow modeling attaining the best predictions, whereas light stall predictions are somewhat inferior.[3] For example, recent airfoil flutter investigations[2,4] revealed that a variety of turbulence models were unable to predict the pitching moment history, which is crucial for predicting rotor life.

There are many factors that influence the accuracy of current computational schemes. Carr and McCroskey[3] have identified turbulence modeling, grid dependencies, artificial viscosity, and the choice of numerical scheme as important areas that need to be addressed if computational efforts are to be directly useful. Ekaterinaris and Menter[2] have demonstrated the importance of transition modeling to capture the dynamic stall physical mechanisms. This study was undertaken to avoid the problem areas associated with both numerical artifacts, limiting boundary-layer assumptions, as well as physically ambiguous phenomena such as transition modeling, and unknown upstream influences. Here, the emphasis was placed on developing an unsteady turbulence model and then testing the model, per se, by comparing it to definitive experimental data. Consequently, this preliminary investigation considered a streamwise fully developed, large-amplitude pulsating turbulent pipe flow near separation rather than an unsteady boundary layer or a dynamic stall scenario, thus minimizing the aforementioned problems. The principal common denominators are that both flows are subjected to large, time-dependent streamwise pressure gradients and that both

Received Aug. 5, 1997; revision received Nov. 9, 1997; accepted for publication Nov. 21, 1997.

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