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AUGMENTATION OF HEAT TRANSFER BY SUBSONIC DIFFUSION AT A NEARLY SEPARATED STATE

by Donald R. Boldman

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

Measurements of mean velocity, turbulence intensity, and wall heat transfer were obtained in a 13° total angle of divergence conical diffuser coupled to a constant diameter recovery section. The results indicated that the boundary layer was in a nearly separated state. Turbulence intensity levels approaching 0.4 were observed in the latter stages of diffusion. The convective heat transfer was always equal to or higher than corresponding values for fully developed pipe flow at the same Reynolds number. The augmentation in heat transfer was greatest during the latter stages of diffusion where the Stanton number was nearly three times the pipe flow value.

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SUMMARY

Measurements of mean velocity, turbulence intensity, and wall heat transfer were obtained in a 13° total angle of divergence conical diffuser coupled to a constant diameter recovery section. The results indicated that the boundary layer was in a nearly separated state. Turbulence intensity levels approaching 0.4 were observed in the latter stages of diffusion. The convective heat transfer was always equal to or higher than corresponding values for fully developed pipe flow at the same Reynolds number. The augmentation in heat transfer was greatest during the latter stages of diffusion where the Stanton number was nearly three times the pipe flow value.

INTRODUCTION

Acceleration of the flow in a smooth wall conical nozzle produces an attentuation of the local heat transfer relative to the value for fully developed pipe flow at the same Reynolds number (ref. 1). Qualitatively extrapolating these results to the case of a decelerating flow, one might expect a corresponding augmentation of the local heat transfer or Stanton number. The present note describes the results of an experiment in which heated air was supplied to a water-cooled conical diffuser in order to determine the feasibility of augmenting the local heat transfer by subsonic diffusion.

Measurements of mean velocity profiles in subsonic conical diffusers have been reported by other investigators (e.g., ref. 2); however, to the author's knowledge, turbulence and heat-transfer information in this type of flow system is not extensive. In this study, velocity and turbulence intensity profiles as well as the wall heat transfer were measured to provide insight concerning the mechanism for convective heat-transfer enhancement.

SYMBOLS

C_f	skin friction coefficient
C_p	specific heat at constant pressure
D	diameter
Pr	Prandtl number
q	measured heat-transfer rate
R	radius
Re	Reynolds number based on local diameter
St	Stanton number
T	temperature
U	time-mean velocity
u'	rms value of fluctuating component of velocity in mean flow direction
V	mass-averaged velocity
x	distance along wall from diffuser entrance
y	distance normal to wall
ρ	density

Subscripts:

c	centerline value
fd	fully developed pipe flow
m	mean value
o	entrance condition
w	wall condition
0	stagnation condition

APPARATUS

The apparatus for this study consisted of a 13° total angle of divergence water-cooled conical diffuser coupled to a constant diameter pipe recovery section as shown in figure 1. The internal walls of the diffuser and tail pipe were machined to a surface finish of 81.2 microcentimeters rms. Air entered the diffuser through a bellmouth and a 7.62-centimeter-diameter pipe section. Flow control was attained by means of a 3.81-centimeter-diameter nozzle located downstream of the tail pipe. Heat-transfer and wall temperature measurements were obtained with 0.317-centimeter-diameter plug-type heat flux meters similar to those described in reference 3. These measurements were obtained at seventeen axial stations in the diffuser and at five stations in the tail pipe.

Boundary layer mean velocity and turbulence intensity profiles were measured at three stations in the diffuser and at two stations in the tail pipe as shown in figure 1. These measurements were obtained with a constant temperature hot-wire anemometer using 0.0005-centimeter-diameter tungsten hot wires.

RESULTS

All tests were conducted at a total pressure of 207 newtons per square centimeter. The nominal total temperature in the heat-transfer tests was 539 K. The hot-wire measurements were obtained at a nominal total temperature of 311 K. These stagnation conditions provided a nominal inlet velocity of 68 meters per second with the heated air and 51 meters per second with room temperature air. Although the stagnation temperatures were different for the heat-transfer and boundary layer measurements, the latter results are expected to be representative of the conditions with heat transfer.

The geometry, surface finish, and operating conditions of the present study were selected largely on the basis of the design criteria in reference 4. The objective was to obtain a nearly separated diffusing flow which would provide appreciable turbulence enhancement and convective heat transfer. Actually, such a flow is difficult to achieve and maintain since diffusing flows have a tendency to separate locally and nonuniformly around the circumference of the diffuser, particularly if the flow is in a state of imminent separation (refs. 2 and 5). The absence of a separated profile at a given location in the diffuser does not necessarily imply the absence of separation at other positions on the circumference (ref. 2). Therefore, caution must be exercised in interpreting and generalizing the results for a given diffuser configuration.

The boundary layer velocity profiles are presented in figure 2. The boundary layer at the diffuser entrance ($x/D_o = 0$) is relatively thin, $\delta \simeq 0.2\ R$; however, as the flow diffuses, the boundary layer rapidly fills the channel. Profiles at $x/D_o = 3.24$ and 5.93 in the diffuser as well as the profiles at $x/D_o = 10.16$ in the tail pipe indicate that the flow is in a state of imminent separation (ref. 2). Further development in the tail pipe results in a readjustment to a nearly uniform profile across the duct.

The radial distributions of turbulence intensity u'/U_c at the five stations are shown in figure 3. The profile at the diffuser entrance indicates a free stream intensity of about 1.0 percent and a maximum value of nearly 8.0 percent. Upon diffusing, the flow experiences a pronounced increase in intensity with peak values of u'/U_c approaching 40 percent ($x/D_o = 10.16$). The maximum in the intensity distribution moves toward the centerline as the flow diffuses. Near the exit of the tail pipe, where the flow is apparently attempting to reestablish some form of equilibrium, the maximum value of u'/U_c occurs near the wall. The observed trend of increasing turbulence intensity with decreasing axial velocity has also been observed by Spangenberg, et al. (ref. 6) in a two-dimensional diffusing flow. In reference 6 values of u'/U in excess of 0.5 were obtained in a region very near the wall. In the present conical diffuser, similar values of u'/U were obtained in the near wall region at $x/D_o = 3.24$. However, in the latter stages of diffusion (e.g., at $x/D_o = 5.93$ and 10.16), the high levels of intensity ($u'/U > 0.4$) were not only present in the wall region but also near the duct centerline. This can be noted by dividing the intensity u'/U_c in figure 3 by the corresponding value of velocity ratio in figure 2.

The large values of turbulence intensity suggest an enhancement of the convective heat transfer provided the boundary layer does not separate. The experimental heat transfer can be presented in terms of the Stanton number St where

$$St = \frac{q}{\rho V C_p (T_m - T_w)} \tag{1}$$

The mean temperature T_m was approximated from a one-seventh power law as

$$T_m = 0.833\,(T_0 - T_w) + T_w \tag{2}$$

where $T_0 \simeq T_c$.

The reference value for the heat transfer is based on the Martinelli (ref. 7) expression for fully developed flow with a uniform heat flux which can be expressed as

$$St_{fd} = \frac{\sqrt{C_f/2}}{0.833\left[5Pr + 5\ \ln(5Pr + 1) + 2.5\ \ln \dfrac{Re\sqrt{C_f/2}}{60}\right]} \tag{3}$$

The friction coefficient C_f in this expression was assumed to be given by

$$C_f = 0.046\ Re^{-0.2} \tag{4}$$

The ratio St/St_{fd} is presented as a function of length x/D_o in figure 4. Since the diffuser entrance was preceded by a short pipe (see fig. 1), the heat-transfer ratio at the entrance was approximately unity. However, in progressing downstream, the Stanton number ratio increases and appears to maximize near the diffuser exit (x/D_o = 7.23). A maximum value of St/St_{fd} of about 3.25 was obtained. Subsequent relaxation of the flow in the tail pipe results in a reduction in St/St_{fd}; however, at the exit station (x/D_o = 15.91) the Stanton number is still over two times the value for pipe flow (eq. (3)).

SUMMARY OF RESULTS

Measurements of mean velocity, turbulence intensity, and wall heat transfer were obtained in a 13^o total angle of divergence conical diffuser coupled to a constant diameter recovery section. Tests were performed with air at nominal total temperatures of 311 and 539 K and at a nominal total pressure of 207 newtons per square centimeter. The unit Reynolds number and inlet velocity at the cold flow conditions were nominally 63.2 per meter and 51 meters per second, respectively. The mean velocity profiles in the diffuser were characteristic of a boundary layer in a nearly separated state. Corresponding turbulence intensity measurements revealed that the location of the maximum value of intensity (normalized by the local centerline velocity) moves from a position near the wall toward the centerline as the flow diffuses downstream. Very high values of intensity were observed in the latter stages of diffusion with u'/U_c approaching 0.4. Augmentation of the convective heat transfer relative to the value for fully developed pipe flow at the same Reynolds number was observed. The Stanton number was nearly three times the value for pipe flow in the latter stages of diffusion.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 13, 1972,
501-24.

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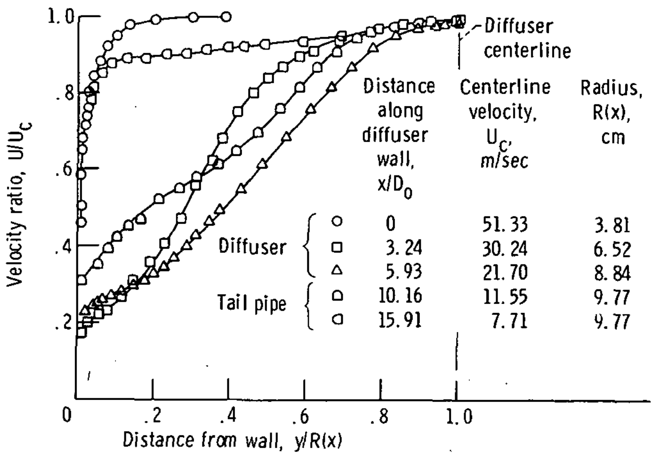

Figure 2. - Hot-wire measurements of mean velocity profiles in diffuser and tailpipe sections. Reynolds number, Re ≈ 63.2 per meter; entrance diameter, D_0 = 7.62 centimeters.

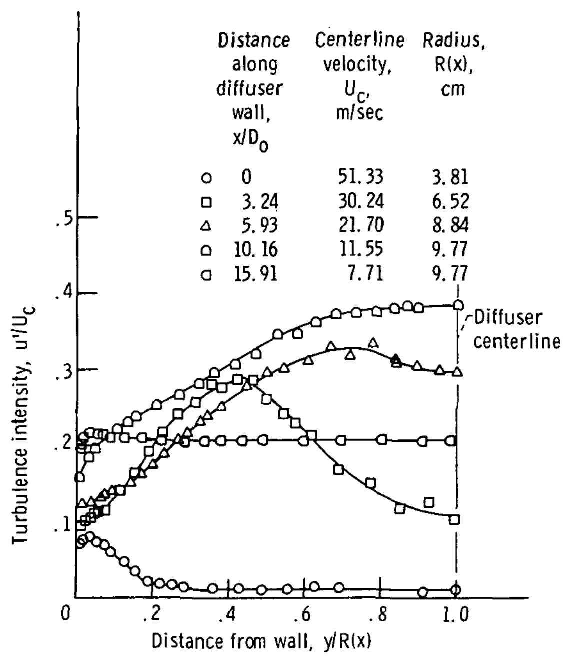

Figure 3. - Turbulence intensity measurements in diffuser and tailpipe sections. Reynolds number, Re ≈ 63.2 per meter; entrance diameter, D_0 = 7.62 centimeters.

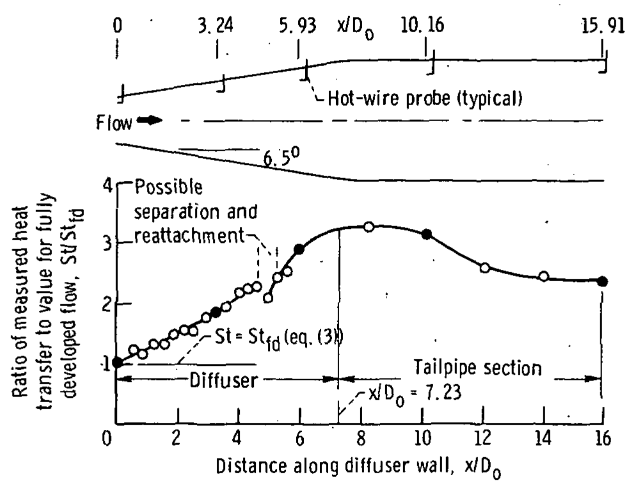

Figure 4. - Heat transfer in conical diffuser and tailpipe. Entrance diameter, $D_0 = 7.62$ centimeters. Solid symbols denote boundary layer survey locations.

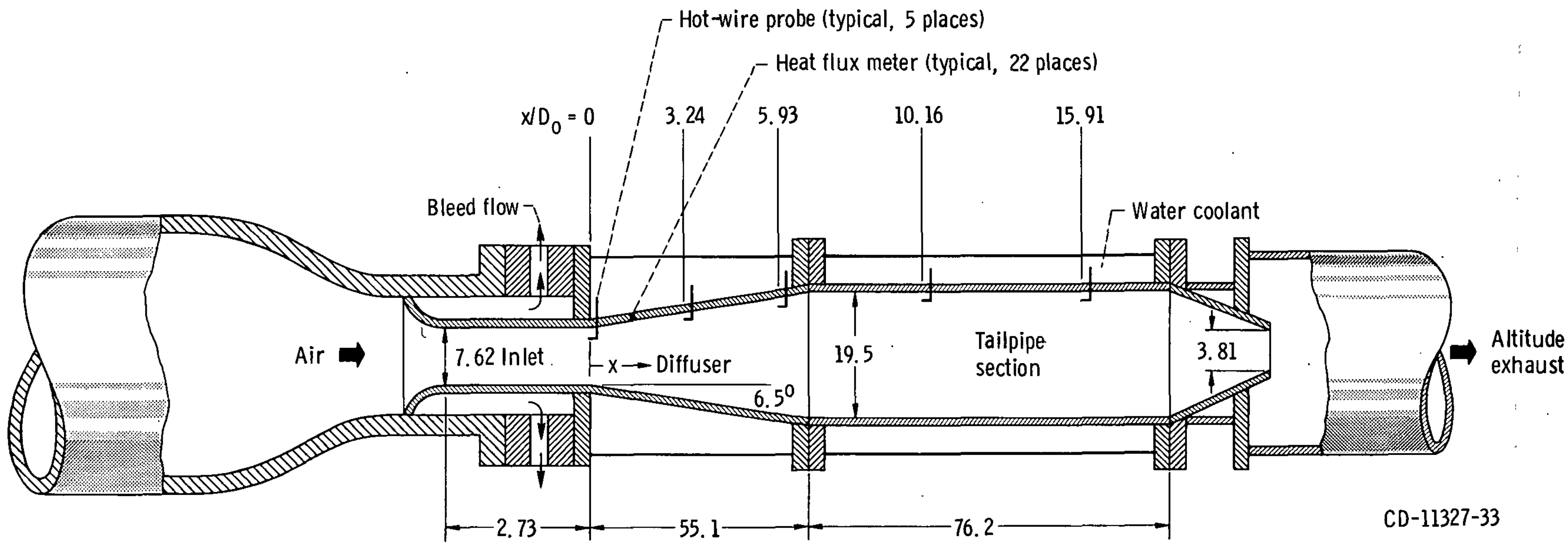

Figure 1. - Apparatus for study of diffusion augmented heat transfer. Entrance diameter, D_0 = 7.62 centimeters. All dimensions in centimeters.

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