AN EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN A SEPARATING TURBULENT BOUNDARY LAYER

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ABSTRACT

Heat transfer from a constant-temperature surface in the two-dimensional, steady free-stream, adverse-pressure-gradient separating turbulent boundary layer of Simpson et al. (1981a,b) was studied experimentally using a constant-current resistance thermometer and a fast response thin-layered surface heat flux gage. Upstream of the incipient detachment (ID) location (1% backflow), the Stanton number St obeys the attached flow correlation recommended by Moffat and Kays (1984). Downstream the St vs. enthalpy thickness Reynolds number that is valid for zero and mild adverse-pressure gradient flows breaks down. The time-mean heat transfer decreases rapidly downstream of ID with a broad minimum near the location of time-mean detachment (50% backflow), which is approximately 30% below attached-boundary-layer levels. Downstream of the location of time-mean detachment, heat transfer increases rapidly. The surface heat transfer under the backflow region was correlated to large near-wall velocity fluctuations and is approximately described by the correlation of Maciejewski and Moffat (1992). The rms of surface heat flux fluctuations attain a maximum value near the location of time-mean detachment. Skewness and flatness factors of surface heat flux fluctuations increase to large values downstream of detachment because of the intermittently large heat transfer due to large-scale turbulent structures.

INTRODUCTION

Boundary layer separation is often unavoidable in many engineering applications where convection heat transfer is of interest. As pointed out by Hacker and Eaton (1995) current CFD codes employing the turbulent Prandtl number fail in separated flows. Current turbulence models are only good in the region away from the wall and often over-predict surface heat transfer (Shishov et al, 1988; Launder, 1988). Over the last fifty years, a large amount of research on heat transfer in basic separated turbulent flows has been reported. Almost all previous heat transfer studies have been in cases where the separation point is fixed by a sharp corner such as flow over a backward facing step (Hacker and Eaton, 1995). No previous studies of heat transfer in flows separating from smooth surfaces have included surface heat transfer, the detailed temperature field and detailed fluid mechanics data.

The case studied in the current investigation is the mean two-dimensional, steady free-stream velocity, adverse-pressure-gradient-induced separated flow of Simpson, Chew, and Shivaprasad (1981 a, b), which was a computational test case for the 1980-81 AFOSR-Stanford Conferences on Complex Turbulent Flows. The streamwise free-stream velocity distribution is shown in Fig. 1. Simultaneous surface heat flux and temperature at various locations across the boundary layer were measured by Lewis and Simpson (1996) at several streamwise locations from far upstream of detachment to downstream of detachment. The correlation between surface heat flux and the turbulence structure was determined from the coherency between surface heat flux and temperature. The statistical and spectral characteristics of the surface heat flux and temperature field were compared to the turbulence structure data from previous studies. Due to space limitations, only the mean and rms surface heat transfer results are reported here.

SOME PREVIOUS WORK ON SEPARATING TURBULENT BOUNDARY LAYERS

Turbulent boundary layer separation due to an adverse pressure gradient is the entire process of "*departure* or *breakaway* or the breakdown of boundary-layer flow" and occurs over a significant streamwise distance (Simpson, 1989). The separated flow is very unsteady and the whole region surrounding separation is one of intermittently forward and reverse flow. Four streamwise locations along a separating TBL have been defined: *incipient detachment* (ID) occurs with instantaneous backflow 1% of the time (γ = fraction of time that the flow moves downstream; γ_{pu} is minimum value near wall = 0.99); *intermittent transitory detachment* (ITD) occurs with instantaneous backflow 20% of the time (γ_{pu} near wall = 0.80);

transitory detachment (TD) occurs with instantaneous backflow 50% of the time (γ_{pu} near wall = 0.50); and *detachment* (D) occurs where the time-averaged wall shearing stress is 0. Data suggest that TD and D occur at the same location (Simpson, 1981). The length of the region between ID, ITD, TD, and D points will depend on the geometry of the flow.

The boundary layer upstream of ID is similar to a "normal" attached turbulent boundary layer (Simpson, 1989). The mean flow obeys the "law-of-the-wall" and the "law-of-the-wake" as long as the maximum shearing stress is less than 1.5 times the wall shear stress. Since the wall shearing stress approaches 0 at detachment, it is a poor parameter to use in describing mean velocity profiles away from the near-wall region. When $-\rho uv > 1.5\tau_w$, the Perry & Schofield (1973) mean-velocity profile correlation for the outer flow, the law of the wall for the near-wall flow, and the Ludwieg-Tillman skin-friction equation apply upstream of ID and remain approximately valid upstream of ITD. The qualitative turbulence structure is not markedly different from a flat plate TBL except that the maximum turbulent fluctuations occur in the middle of the boundary layer.

Separation begins only intermittently at a given streamwise location i.e., flow reversal at that location occurs only a fraction of the time. At progressively farther downstream locations, the fraction of time that the flow moves downstream is progressively less. A spanwise line of detachment does not move up and downstream as a unit. Small three-dimensional elements of flow move upstream for a distance and are later carried downstream. Large eddies grow rapidly and agglomerate with one another. These large-scale structures supply turbulence energy to the near-wall detaching flow. The velocity fluctuations in the backflow regions are greater than or at least comparable to the mean backflow velocities. Intermittent backflow occurs as far away from the wall as the maximum shearing-stress location $y/\delta > 0.5$. Due to the large-scale unsteadiness, mean flow streamlines do not represent pathlines for elements of fluid. Fluid is supplied locally rather than from far downstream as mean flow streamlines suggest (Simpson, 1989).

Outer region mean velocity profiles of the detaching and detached flow are shown in Fig. 2. The near-wall region downstream of separation lacks many characteristics normally associated with turbulent boundary layers. Profiles of turbulence intensity do not have a peak close to the wall. Profiles of mean velocity do not have a log region related to the friction velocity. Simpson (1983) has proposed a similarity relation for the mean streamwise velocity profiles in the backflow region that scale on the maximum mean backflow velocity U_N and the distance from the wall N (Fig. 3). The Reynolds shearing stress remains small and turbulent bursts are relatively infrequent. There is little production or convection of turbulence kinetic energy. Turbulence energy dissipated here is supplied by diffusion from the separated shear layer above rather than by production due to the mean velocity gradient (Simpson, 1989). Mixing-length and eddy viscosity models fail because the Reynolds shearing stress is related to the turbulence structure and not the local mean velocity.

The values of u are as large as U in the near-wall region while the v fluctuations are small. Peak energy in u spectra occurs at very low frequencies, suggesting large scales on the order of the shear layer thickness (Simpson et al., 1981b). These observations suggest that the velocity fluctuations in the near-wall region are produced by large-scale vortices which do not produce Reynolds stress in the near-wall region.

EQUIPMENT AND FLOW CONDITIONS

The low turbulence level wind tunnel, the equipment for the flow measurements, and the flowfield, as documented by Lewis and Simpson (1996), are the same as used and described by Simpson et al. (1981a,b). Fig. 1 shows the free-stream velocity distribution outside of the boundary layer, with the x coordinate originating from the test section entrance. For these heat transfer measurements, Lewis et al. (1994) and Lewis and Simpson (1996, 1998) give more details on the aluminum floor heat transfer surface, the thermocouples, the heat flux gages (50kHz response) and their calibration, and the data reduction techniques. Flow temperatures inside the thermal boundary layer was measured using a cold wire or hot-wire anemometer operating in the constant-current mode. Sufficiently high data sampling rates and record lengths were used to obtain ergodic results.

Free-stream temperature (25 ± 1 °C), heated aluminum floor temperature (45 ± 0.5 °C), and the dynamic pressure monitored by a pitot-static probe at the throat were held constant to prevent wandering of the time-mean detachment location over time. Tunnel speed was adjusted to keep the reference dynamic pressure constant.

RESULTS AND DISCUSSION

First, to validate this experimental apparatus, the surface heat flux was measured with the Model HFM-3 Heat Flux Microsensor (Vatell Corp.) along a zero-pressure-gradient flow in this wind tunnel. The Stanton number at x_{TC} = 222.6cm was St = 1.837×10^{-3}. The Stanton number measured at this location with the Schmidt-Boelter gauge was 1.84×10^{-3}. The Stanton number distribution calculated using the thermal energy integral equation of Kays and Crawford (1980) agreed with the data within 1% rms. The good agreement shows that the measured heat transfer along the surface obeys the zero-pressure-gradient constant temperature flat plate heat transfer relations.

Using the heat flux measurements for the Simpson et al. flow, Figure 4 shows the streamwise variation of the Stanton number, defined as:

$$St = \overline{q_0''}/\rho C_p (T_w - T_\infty) U_\infty \qquad (1)$$

with C_p and ρ evaluated at the film temperature, $(T_w + T_\infty)/2$. The solid line in Fig. 4 shows the St calculated using the streamwise velocity variation (Fig. 1) and the 2-D flat plate correlation (Kays and Crawford, 1980),

$$St = 0.0125\, Pr^{-0.5} Re_{\Delta_2}^{-0.25} \qquad (2)$$

which is also valid for mild adverse pressure gradients (Moffat and Kays, 1984), in the 2-D thermal energy integral equation

$$St = \frac{1}{U_\infty}\frac{d(\Delta_2 U_\infty)}{dx}. \qquad (3)$$

The integral started at the beginning of the heated section. The measured St starts to decrease slightly below the calculated values downstream of x = 285 cm and falls rapidly downstream of *incipient detachment* (x = 311.5 cm) The mean heat transfer attains a broad minimum near detachment (x = 345.4 cm) and increases rapidly in the mean backflow region. Figure 4 also shows the streamwise variation of heat flux fluctuations, St_{rms} defined:

$$St_{rms} = (q_0'')'/\rho C_p (T_w - T_\infty) U_\infty . \quad (4)$$

The rms Stanton number increases toward detachment and remains about constant in the separated region. The rms value of h attains a maximum value near the location of time-mean detachment and decreases slightly downstream of detachment.

Figure 5 shows the streamwise variation of the skewness and flatness factors of surface heat flux fluctuations. The heat flux skewness $S_q = (q_0'')^3/((q_0'')')^3$ and flatness $F_q = (q_0'')^4/((q_0'')')^4$ factors increase monotonically from near Gaussian values upstream ($S_q = 0$, $F_q = 3$) to relatively large values in the backflow region. The large skewness and flatness values are the result of large-scale unsteadiness in the backflow region that produce intermittently high heat transfer rates.

The measured mean temperature ($\Theta = (T_w - T)/(T_w - T_\infty)$) (Lewis and Simpson, 1996) and interpolated velocity profiles from Simpson et al. (1981a) were integrated to calculate the enthalpy thickness Δ_2 at each station:

$$\Delta_2 \equiv \int_0^\infty \frac{U}{U_\infty}(1 - \Theta)\, dy \quad (5)$$

The Δ_2 increases approaching separation, although there is some scatter in Δ_2 in the region between ID and TD so the streamwise derivative of Δ_2 is uncertain in this region.

Figure 6 shows the measured-heat-flux Stanton number upstream of detachment as a function of the enthalpy thickness Reynolds number and the above 2-D flat plate correlation, which is valid in the region upstream of incipient detachment. Note the good agreement within experimental uncertainties upstream of incipient detachment, but expected poor agreement downstream.

The streamwise variation of enthalpy thickness was used to check the surface heat flux measurements. Using equation (3) the streamwise x derivative of $U_\infty \Delta_2$ was estimated from a quadratic curve fit to the data. The data point at x = 332.4 cm was omitted from the curve fit. Stanton numbers computed this way are compared with the measured Stanton numbers in Fig. 4. Agreement is within 5% for all of the measured Stanton numbers.

Integral parameters were calculated in the backflow region by treating each velocity and temperature profile in the near-wall region from the wall out to the location of maximum backflow velocity, N, as a boundary layer profile. The backflow enthalpy thickness was defined by:

$$\Delta_{2_N} \equiv \int_0^N \frac{U}{U_N}\left(1 - \frac{\Theta}{\Theta_N}\right) dy. \quad (6)$$

where U_N and Θ_N are the values of U and Θ at y = N. Backflow velocity profiles at x = 407 cm and x = 440 cm were obtained from the backflow velocity profiles measured at x = 397 cm and x = 434 cm (Simpson et al., 1981) by assuming that the backflow similarity law (Simpson, 1983) remains valid. Values of N and U_N at x = 407 cm and 440 cm were obtained from a curve fit to the streamwise variation of N and U_N in Simpson et al. (1981). Values of Δ_{2N} are presented in Table 1.

Stanton number and enthalpy thickness Reynolds number for the backflow were defined:

$$St_N \equiv \frac{\overline{q_0''}}{\rho C_p U_N (T_w - T_N)}, \quad Re_{\Delta_N} \equiv \frac{U_N \Delta_{2_N}}{\nu} \quad (7)$$

and are presented in Table 1. The enthalpy thickness Reynolds numbers ranged from 10 at the location just downstream of separation to 160 at the most downstream location. Figure 7 shows St_N versus $Re_{\Delta N}$ for the measurement locations in the backflow region. Also shown are the turbulent relation for St as a function of Re_Δ, Eq. (2) and the laminar relation (Kays and Crawford, 1980):

$$St = 0.2204 Pr^{-4/3} Re_{\Delta_2}^{-1} . \quad (8)$$

Except for the first location, $St_N \sim Re_{\Delta N}^{-1/4}$ as for the above turbulent relation, eqn. (2), but the proportionality factor is approximately 4 times larger than the constant in Eq. (2).

For two-dimensional boundary layer flows, Maciejewski and Moffat (1992) relate the local heat flux to the streamwise component of the turbulent normal stress through the use of a Stanton number based on u'_{max} as

$$St' \equiv h/(\rho C_p u'_{max}) \quad (9)$$

where u'_{max} is the maximum value of u' found in the boundary layer or freestream at the location where h is measured. Note that St' is not to be confused with St_{rms} which is the nondimensional rms heat flux fluctuations. The St' correlation is of limited practical value since it requires a detailed knowledge of the turbulence structure which is usually not available.

Maciejewski and Moffat (1992) suggest a functional form of the relation between St' and turbulence intensity $Tu = u'_{max}/U_{ref}$ for air (Pr=0.71) as

$$St' = 0.0184 + 0.0092 \exp -[(Tu - .11)/0.055]^2 \quad (10)$$

This form has a peak value at a turbulence level of 11%. For turbulence intensities above 0.20, $St' \approx 0.0184$. Maciejewski and Moffat applied this correlation to heat flux experiments for various complex flow situations from the literature and found Eq. (10) to be valid to within 15% at (20:1) odds, independent of flow geometry or Reynolds number. For large turbulence intensities such as in the backflow, Eqn. (10) yields St' = 0.0184. Values of St' for the backflow region were computed from the data using:

$$St_N' = \frac{\overline{q_0''}}{\rho C_p (T_w - T_N) u'_N} \quad (11)$$

and range from 0.020 to 0.025. Values of "free-stream" turbulence for each backflow velocity profile, $Tu_N = u_N/U_N$, were taken as the turbulence intensity at the location of maximum backflow velocity given in Table 1. Values of $St_N = St'/(Tu_N) = 0.0184/(Tu_N)$ were calculated for the backflow and are compared with the measured values of St_N in Fig. 7. The calculated values are 10% to 25% lower than the measured values, but agree qualitatively with the St_N distribution. This agreement supports the idea that the backflow region is similar to a turbulent boundary layer with high free-stream turbulence.

CONCLUSIONS

Heat transfer in the two-dimensional, steady free-stream, adverse-pressure-gradient separating turbulent boundary layer of Simpson et al. (1981a,b) was studied experimentally using a constant-current resistance thermometer and a fast response thin-layered heat flux gage. Measurements were performed at streamwise locations from far upstream of the location of time-mean detachment to downstream of detachment. At each location time-resolved surface heat flux was measured simultaneously with temperature over a range of locations across the boundary layer.

Upstream of incipient detachment, the St obeys the correlation (eqn..2) recommended by Moffat and Kays (1984) within experimental uncertainties. The time-mean heat transfer decreases rapidly downstream of the location of *incipient detachment* and attains a broad minimum near the location of time-mean detachment, which is approximately 30% below attached-boundary-layer levels. The relation between enthalpy thickness Reynolds number and Stanton number that is valid for zero and mild adverse-pressure gradient flows breaks down downstream of the location of incipient detachment. Downstream of the location of time-mean detachment, heat transfer increases rapidly. The surface heat transfer under the backflow region was correlated to large near-wall velocity fluctuations and is approximately described by the correlation of Maciejewski and Moffat (1992). The rms of surface heat flux fluctuations attain a maximum value near the location of time-mean detachment. Skewness and flatness factors of surface heat flux fluctuations increase to large values downstream of detachment because of the intermittently large heat transfer due to large-scale structures.

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Table 1 Backflow velocity and temperature profile parameters.

x (cm)	N (cm)	U_N (m/s)	Tu_N	Θ_N	$Re_{\Delta N}$	Δ_{2N} (mm)	St_N	St_N'
352.4	0.50	0.45	2.77	0.64	10.3	0.407	0.0606	0.0219
364.5	1.00	1.11	1.10	0.70	32.9	0.524	0.0223	0.0203
407.0	1.96	1.72	0.85	0.81	65.9	0.683	0.0211	0.0248
440.1	2.64	1.90	0.76	0.89	164	1.528	0.0187	0.0246

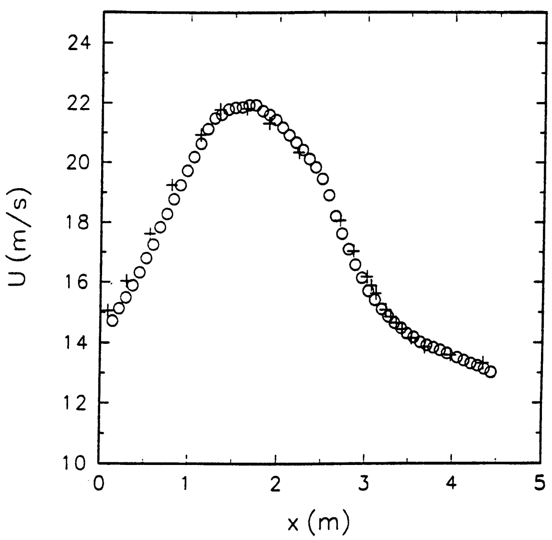

Fig. 1 Streamwise velocity variation in the potential core of the test section: O current data; + Simpson et al. (1981a).

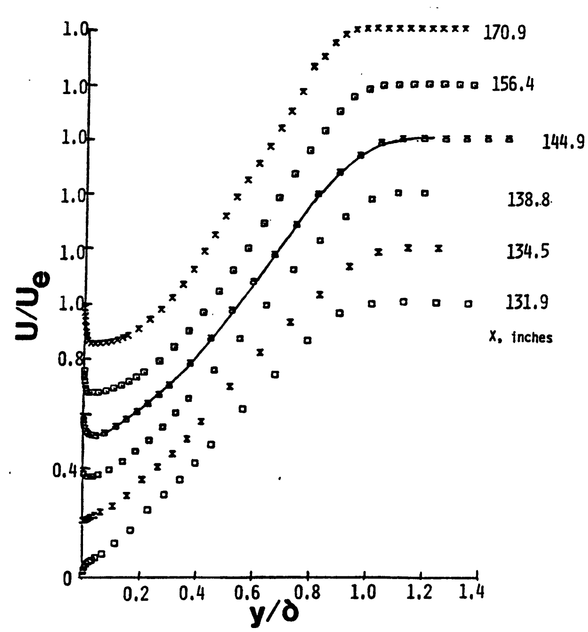

Fig. 2. Detaching flow mean velocity profiles of Simpson et al. (1981a) for $Re_\theta = 16300$. Solid line denotes $Re_\theta = 47000$ data of Hastings and Moreton (1982) at same mean velocity profile shape factor. From Simpson (1985).

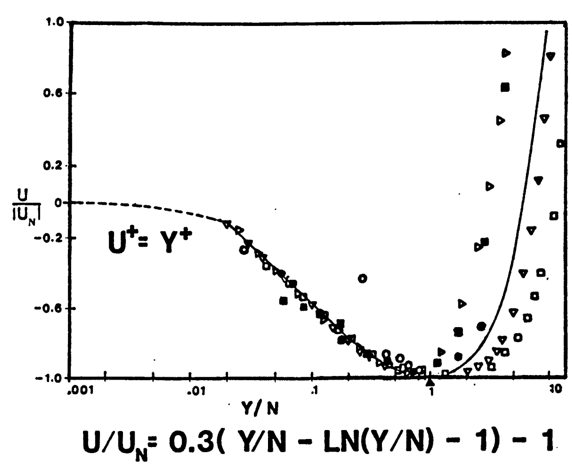

Fig. 3. Normalized mean backflow profiles of data from various experiments. From Simpson (1983).

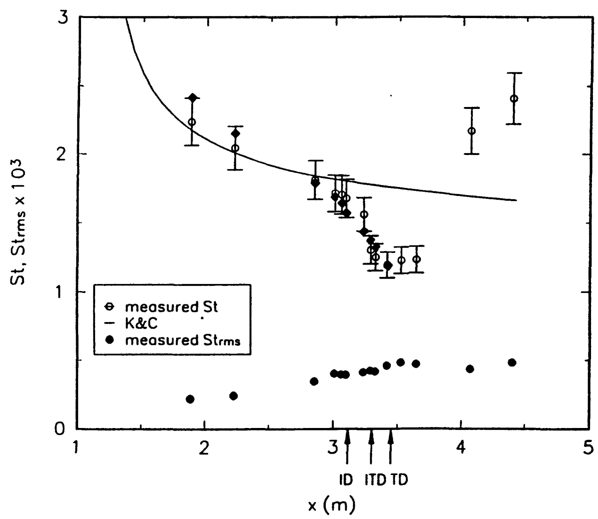

Fig. 4 Mean and rms Stanton numbers from measurements. Solid line is from the integral method of Kays and Crawford (1980). ♦ Stanton numbers calculated from thermal energy integral eqn. (3) and measured mean velocity and temperature profile data.

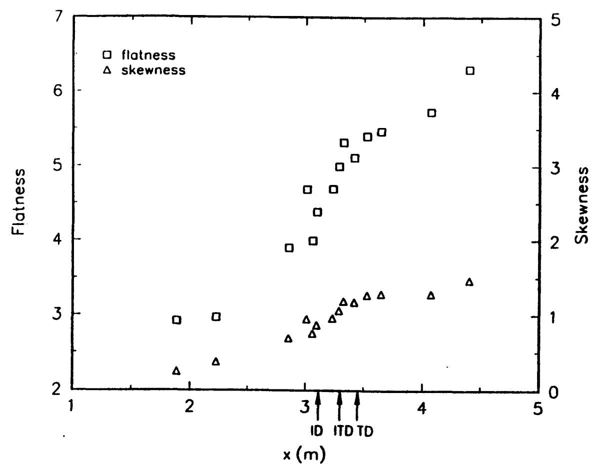

Fig. 5. Skewness and flatness factors of surface heat flux fluctuations. ID, location of incipient detachment; ITD, location of intermittent transitory detachment; TD, location of transitory detachment and detachment D.

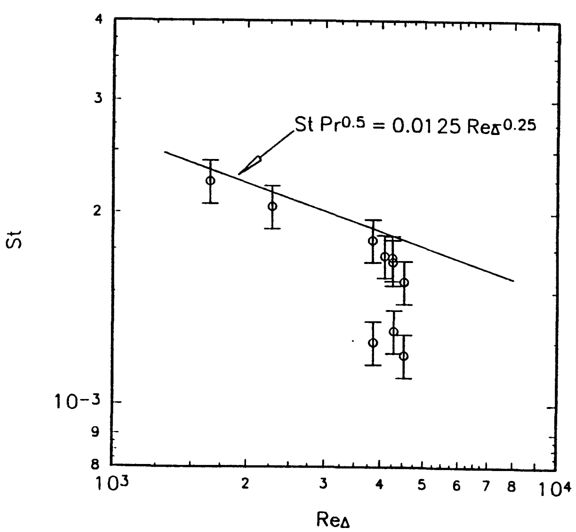

Fig. 6. Stanton number versus enthalpy thickness Reynolds number upstream of detachment. Solid line is correlation of Kays and Crawford (1980).

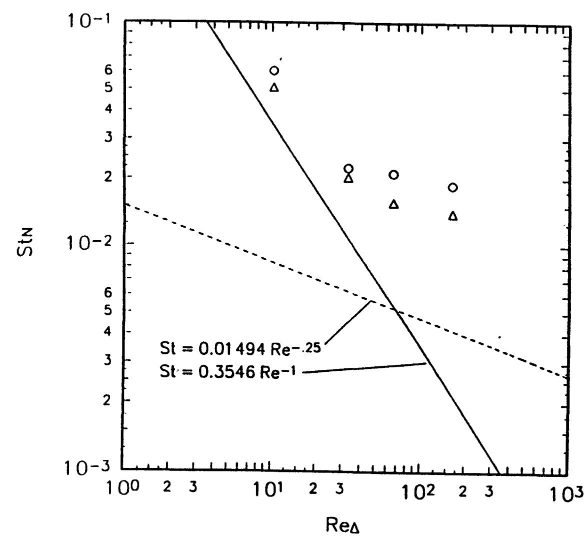

Fig. 7. Backflow Stanton number versus backflow enthalpy thickness Reynolds number downstream of detachment. Solid line is laminar correlation, eqn. (8). Dashed line is turbulent correlation, eqn. (2). ○ measured St_N; △ St_N from St' correlation of Maciejewski and Moffat (1992).