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Heat Transfer Effects on Aerodynamics and Implications for Wind-Tunnel Tests

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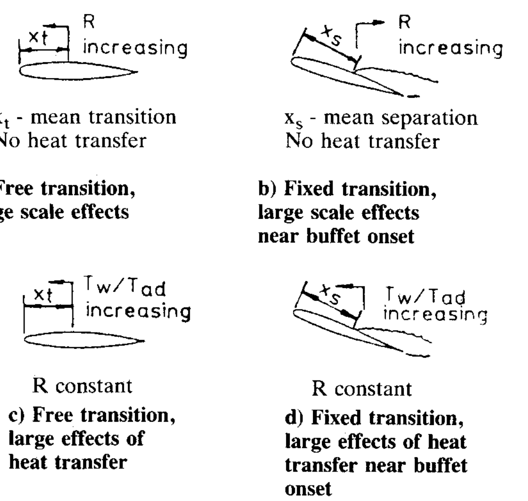
This review summarizes the large effects of heat transfer on steady aerodynamics. Cooling the surface delays flow separation and thus is roughly equivalent to an increase in Reynolds number. Conversely, heating promotes flow separation and is roughly equivalent to a decrease in Reynolds number. Cooling can also increase the extent of laminar boundary layers. These characteristics might be exploited to identify conditions for which large-scale effects occur. The review has found no discussion of the effects of heat transfer on unsteady aerodynamics. From the steady effects, some tentative suggestions are inferred about the probable influence of heat transfer on buffet excitation measurements in wind tunnels.

Nomenclature

C_f, C_F = local and average skin-friction coefficient
C_L, C_D = lift and drag coefficients
C_p = pressure coefficient
c = chord
f = frequency, Hz
ℓ = bubble length
M = freestream Mach number
M_e = local external Mach number
M_1 = shock upstream Mach number
$\sqrt{nF(n)}$ = local rms pressure fluctuations
$\tilde{p}$ = total rms pressure fluctuations
q = freestream kinetic pressure
R = unit Reynolds number
r = recovery factor, Eq. (2)
T_{ad} = adiabatic wall recovery temperature
T_e = local external static temperature
T_t = total temperature, K
T_w = wall temperature, K
U = freestream velocity
U_e = local external velocity
u = local velocity in boundary layer
x = streamwise coordinate
y = distance from surface
α = incidence
δ, δ^* = thickness and displacement thickness of boundary layer
λ = effective Reynolds-number ratio
μ_w = molecular viscosity at wall

Introduction

THE author has compiled a comprehensive review of scale effects due to variations in Reynolds number in time-dependent aerodynamics.[1] Two observations may be inferred from the limited experiments available. The first observation (Fig. 1a) is that if boundary-layer transition is free, scale effects appear relatively large and difficult to predict. The second observation (Fig. 1b) is that if transition is fixed so that all shear layers are turbulent, large scale effects are confined to the region close to the onset of flow separation—or buffet onset. If in experiments the variations in Reynolds number are combined with variations in heat transfer, spurious scale effects may be associated with these observations, as explained below.



a) Free transition, large scale effects

b) Fixed transition, large scale effects near buffet onset

c) Free transition, large effects of heat transfer

d) Fixed transition, large effects of heat transfer near buffet onset

Fig. 1 Heat transfer as a possible source of spurious scale effects.

Transition Reynolds numbers are very sensitive to heat transfer variations at constant Reynolds number,[2] transition Reynolds numbers decreasing as walls are heated (Fig. 1c). Thus, variations in heat transfer would give spurious scale effects due to the movement of transition. Again flow separation is also sensitive to heat transfer,[3,4] separation being enhanced as walls are heated (Fig. 1d). Thus, variations in heat transfer also would cause spurious scale effects due to the movement of separation. Hence, ideally, within any investigation of scale effects (experimental or theoretical) the sensitivity of these effects to variations in heat transfer should be considered.

This ideal situation has rarely been achieved. There are a few steady aerodynamic investigations to be reviewed in which heat transfer rates are varied systematically at constant Reynolds number. There are *no* corresponding buffet investigations known to the author. However, the observed sensitivity of steady force measurements raises a further issue. Can heating or cooling a model simulate a change in Reynolds number? The limited steady measurements suggest that, although a quantitative simulation is impossible, flows sensitive to variations in Reynolds number may be identified.

These matters may be somewhat academic. However, the large effects of heat transfer on flow separation can influence

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the accurate measurement of drag in conventional wind tunnels; they can influence steady[4] measurements in cryogenic tunnels and the landing performance of lifting re-entry vehicles.[3] Heat transfer effects on separated flows would also be expected to influence unsteady measurements.

Effects of Heat Transfer on Shear-Layer Development

The general effect of heat transfer with respect to the development of attached boundary layers is fairly well-understood and the discussion is based on that provided by Van Driest[5] for a laminar boundary layer developing on a smooth flat plate. (Similar results apply for turbulent boundary layers.) The effect of heat transfer on separated shear layers is still uncertain, and so the discussion here is tentative, based on heuristic arguments that need to be compared with experiments. These ideas are then discussed in the context of time-dependent aerodynamic phenomena and scale effects.

Attached Boundary Layers

Figure 2 (reproduced from Ref. 5) shows a schematic drawing of an attached laminar boundary layer in a compressible fluid. Before considering how heat transfer alters the details of Fig. 2, it is helpful to recall some important relations influencing the heat transfer. For air, the external static temperature is given by isentropic relationship:

$$T_e = \frac{T_t}{(1 + 0.2M_e^2)} \tag{1}$$

The adiabatic wall recovery temperature T_{ad} is important because this is the wall temperature at which no heat transfer occurs between the freestream and the wall. This temperature is usually calculated from the total temperature by the relation

$$\frac{T_{ad}}{T_t} = \frac{(1 + 0.2rM_e^2)}{(1 + 0.2M_e^2)} \tag{2}$$

The recovery factor is about $r = 0.82$ for a laminar boundary layer or about $r = 0.89$ for a turbulent boundary layer. For a fully insulated wall, there can be no heat transfer, so that $T_w/T_{ad} = 1.0$ and the static temperature will fall monotonically from T_{ad} to T_e as the distance y from the wall increases, as sketched in Fig. 2 for a laminar velocity profile.

When the wall is heated, so that $T_w/T_{ad} > 1$, the static temperature again falls smoothly from T_w to T_e as y increases. The increase in temperature throughout the boundary layer decreases the density, and hence the boundary-layer displacement thickness δ^* and overall thickness δ both increase. (The increase in δ is evident in Fig. 2.)

In addition to the increase in thickness, the boundary-layer velocity profile is altered. The effect of heating is to make the velocity profile u/U_e less "full" (Fig. 3), i.e., more appropriate to a boundary layer at a lower Reynolds number or closer to separation at the same Reynolds number. Even if this change in velocity profile is ignored, with heating the value of y/δ is smaller for a fixed value of y, and hence u/U_e is smaller giving a smaller velocity gradient at the wall. This is reduced further by the change in shape of the velocity profile. The smaller velocity gradient at the wall occurs in conjunction with a small increase in molecular viscosity μ_w because a fair approximation is

$$\mu_w \,\alpha (T_w)^{0.75} \tag{3}$$

Thus, the combined effect of the decrease in velocity gradient and the small increase in viscosity at the wall is a small decrease in the local skin-friction coefficient c_f due to wall heating. This trend is the same for both laminar and turbulent boundary layers.

When the wall is cooled so that $T_w/T_{ad} < 1$, the temperature first increases as y increases (due to viscous dissipation) and then falls monotonically to T_e (Fig. 2). The increase in density decreases the boundary-layer thicknesses δ^* and δ, and makes the velocity profile more "full" (Fig. 3), i.e., more appropriate to a boundary layer at a higher Reynolds number or further from separation at the same Reynolds number. There is an increase velocity gradient at the wall (due to the combined effects of the change in velocity profile and the decreased thickness), which together with a small decrease in μ_w gives an increase in the local skin-friction coefficient due to wall cooling.

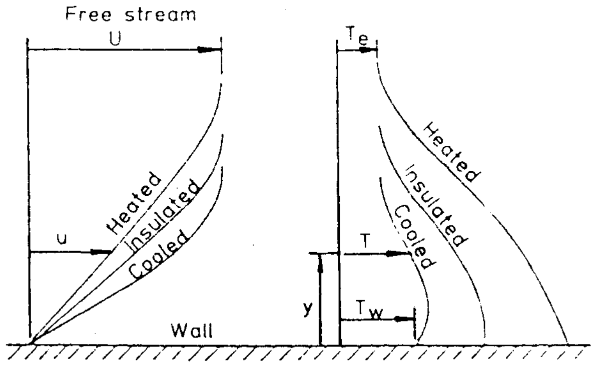
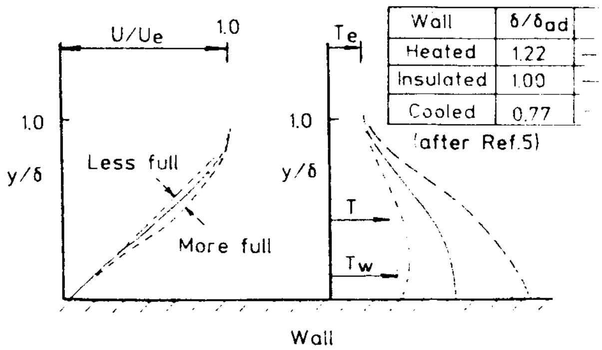


Fig. 2 Schematic of boundary layer in a compressible viscous fluid.



a) Velocity **b) Temperature**

Fig. 3 Velocity and temperature profiles for an attached boundary layer with heat transfer.

These concepts for a flat boundary layer in a zero pressure gradient can be applied to wings or bodies with finite thickness and pressure gradients. The important condition for boundary-layer separation is reached in the limit when

$$C_f \rightarrow 0 \tag{4}$$

Hence, wall cooling will delay separation (by increasing C_f), whereas wall heating will provoke separation (by decreasing C_f). This result is observed in steady experiments,[3,4] and is very important for experiments involving incipient separation, particularly for the measurement of buffet onset.

The total drag of wings or bodies depend upon the sum of the skin-friction drag and the form drag. Although the skin-friction drag is increased a little by cooling, the greatly reduced boundary-layer thickness reduces the form drag. The combined result of the increase in skin friction and the decrease in form drag is usually a net reduction of overall drag. This trend is observed in steady experiments,[3,4] but is not of great importance with respect to unsteady experiments. Since even for attached flow the temperature effects on skin friction and form drag are of opposite sign and different character, it is unlikely that any simple similitude could be established between the effects of heat transfer and variations in Reynolds number.

The wall temperature ratio also has an important influence on the transition from laminar to turbulent flow on the boundary layers on flat plates or cones. Liepmann and Fila showed experimentally[6] that "transition in the boundary layers of a gas flow is hastened by increased surface temperature because inflection-point profiles develop." They also observed that for liquids the situation is reversed. "Increasing surface temperature should delay transition in a liquid because here the viscosity decreases with increasing temperature, delaying the development of inflection point profiles."

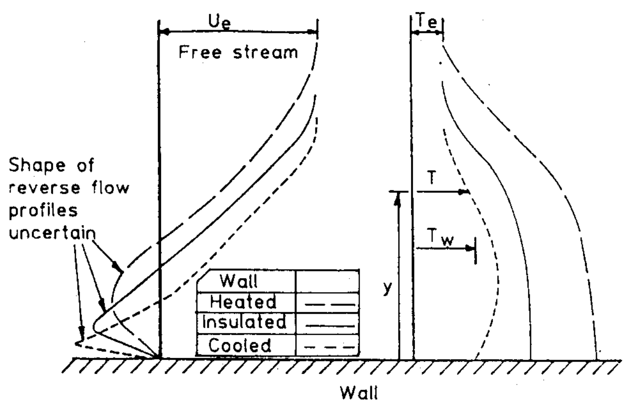
Separated Shear Layers

Figure 4 is conjectural and suggests how a separated shear layer in a compressible fluid might be influenced by heat transfer. (Some early theoretical studies of this problem for a laminar boundary layer are given in Ref. 7).

The velocity profile has two important regions. Close to the wall there is a narrow region of reversed flow (often with maximum speeds in the range of $0.3U_e$–$0.5U_e$), whereas further away from the wall there is a wider region of flow in the stream direction. The outer region always comprises the largest part of the shear layer. The mean velocity profile in this region may be described by a wake function similar in character to that for an attached boundary layer close to separation. Hence, it is reasonable to infer that in this large region the turbulence structure is also similar in character to that for an attached boundary layer, so that the temperature distributions should be comparable.

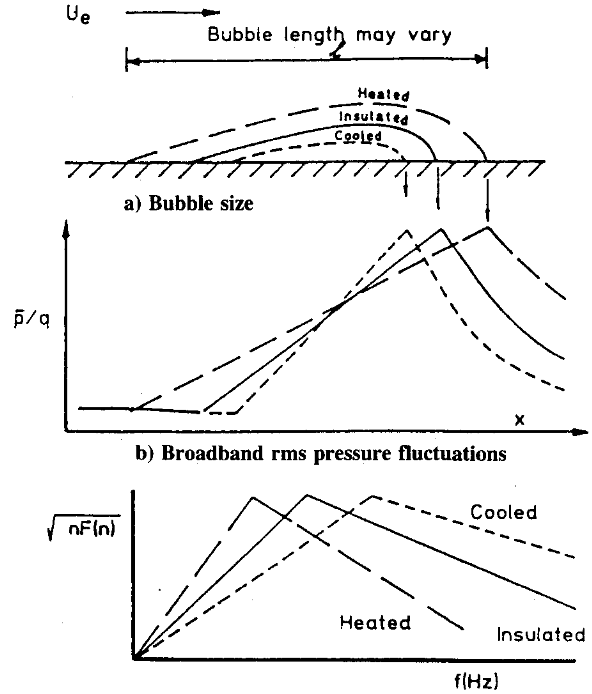
It may be inferred from the attached boundary layer upstream of separation that the point $U = 0$ will move away from the wall as the separation is promoted by heating. Conversely, this point will move towards the wall as the separation is reduced by cooling. Within the reverse flow region, the influence of heat transfer is uncertain and very complex. In this thin region, the velocity gradients change signs rapidly and mixing rates are very large. Hence, it is plausible to suggest, as a rough approximation, that in this region the static temperatures are close to those for an attached boundary layer of the same thickness. Subject to this assumption, the maximum reverse flow velocity would increase due to cooling and decrease due to heating.

It is interesting to speculate how these local changes might influence the development of a two-dimensional separation bubble of length ℓ, which is followed by reattachment under an adverse pressure gradient (Fig. 5). Heating should move separation upstream and might thus lengthen the bubble, whereas cooling might delay separation and reduce the length of the bubble (Fig. 5a). The review has revealed no relevant experiments, and hence Fig. 5a is drawn with widely varying bubble lengths. Apart from possible variations in bubble length and thickness, heating should not influence either the character of the turbulence or the associated pressure fluctuations. Hence, the model described in Ref. 8 (based on bubbles without heat transfer) should be applicable. An increased bubble



a) Velocity b) Temperature

Fig. 4 Hypothetical velocity and temperature profiles for a separated shear layer with heat transfer.



a) Bubble size

b) Broadband rms pressure fluctuations

c) Spectra of excitation at reattachment points

Fig. 5 Hypothetical influence of heat transfer on a two-dimensional bubble.

length due to heating would provide an increase in the overall excitation or buffet, even if the rms levels $\bar{p}/q$ are unchanged (Fig. 5b), having the same maximum close to the reattachment point for the three bubble sizes.

In addition, if the turbulence is unaffected by heating, the peak excitation should move to a somewhat lower frequency f (as shown in Fig. 5c), because according to Ref. 8

$$\frac{f\ell}{U_e} = \text{const} = 0.6 \text{ to } 0.8 \tag{5}$$

However Eq. (5) represents a relationship[8] between conditions at reattachment (where the pressure fluctuations are largest) and separation (where the pressure fluctuations are smaller). Hence, Eq. (5) may need to be modified to include the mean reverse flow velocity as well as the freestream velocity. This may offset the changes in frequency associated with possible changes in bubble length given by Eq. (5).

Possible Implications with Respect to the Simulation of Scale Effects

It is evident from this brief description that heat transfer has important effects on aerodynamic performance, which are complex and difficult to quantify. The limited steady measurements available are reviewed here. For unsteady aerodynamics, scale effects are significant only close to buffet onset.[1] The question arises as to whether scale effects on flow separation can be simulated by variations in heat transfer? The answer depends on the character of scale effects.

Elsenaar distinguishes between direct and indirect scale effects[9] (Fig. 6). The direct scale effects occur because of variations in the boundary-layer development (such as local skin friction and displacement thickness), which leave the mean pressure distribution virtually unaltered. In particular, the circulation—and hence the lift—is constant. Thus, direct scale effects are normally fairly small and may be predictable for attached boundary layers. In marked contrast, indirect scale effects are often large and occur because variations in boundary-layer development (often movements in transition or separation position) may alter the mean pressure distri-

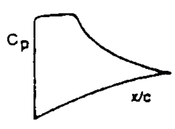
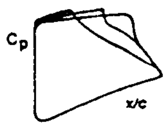
SCALE EFFECT	DIRECT	INDIRECT
On pressure distributions	 Constant	 Variable
On circulation	Almost constant	Variable
On magnitude of changes	Small and predictable	Large and often unpredictable
Simulation by varying heat transfer	Probably impossible (drag sum of skin friction + form drag)	May be possible

Fig. 6 Nature of direct and indirect scale effects due to variations in Reynolds number.

bution. Thus, indirect scale effects change the circulation about a wing. It will now be suggested how this distinction between direct and indirect scale effects might be identified by variations in heat transfer (Fig. 7) at constant Reynolds number.

Suppose the subsonic flow on a model is attached with turbulent boundary layers at the highest Reynolds number available in the tests (Fig. 7a). Scale effects due to a further increase towards the full-scale Reynolds number (which is not available) should then be confined to direct effects that should be small. This might be confirmed by cooling the model at the test Reynolds number, and establishing that the lift increases slowly and the drag decreases slowly, consistent with small, direct scale effects. In addition, it might also be possible to predict by theoretical calculations the effects of variations in Reynolds number without heat transfer and the effects of variations in heat transfer at constant Reynolds number. If this were possible, the same theory could then be used with confidence to predict the lift and drag at full-scale Reynolds numbers in the absence of heat transfer, perhaps using the pressure distributions or forces measured on the cooled model in preference to those on the model at adiabatic conditions.

Suppose that the flow on the model has just separated at the test Reynolds number—the buffet onset condition (Fig. 7b). A further increase to full-scale Reynolds number (not available) should produce both direct and indirect scale effects. The indirect scale effects would be due to a reduction in the area of separation and would be large and extremely difficult to predict. This might be confirmed by cooling the model. Initially, there should be large effects as the separation is reduced to some limiting value, appropriate to the geometry and test Reynolds number. This assumed limiting value, achieved by cooling, might be comparable with the limiting value achieved by increasing Reynolds number. If so, there shold be no further indirect effects. The small direct effects due to heat transfer might be predictable using the pressure distributions or forces measured on the cooled model. The same pressure distributions might be used to predict the direct scale effects due to a variation in Reynolds number in the absence of heat transfer.

If the subsonic flow on the model is separated at the leading edge at the test Reynolds number and the wake "closes" well downstream (Fig. 7c), a further increase to full-scale Reynolds number (not available) should produce only small, direct scale effects. This might be confirmed by cooling the model. If so,

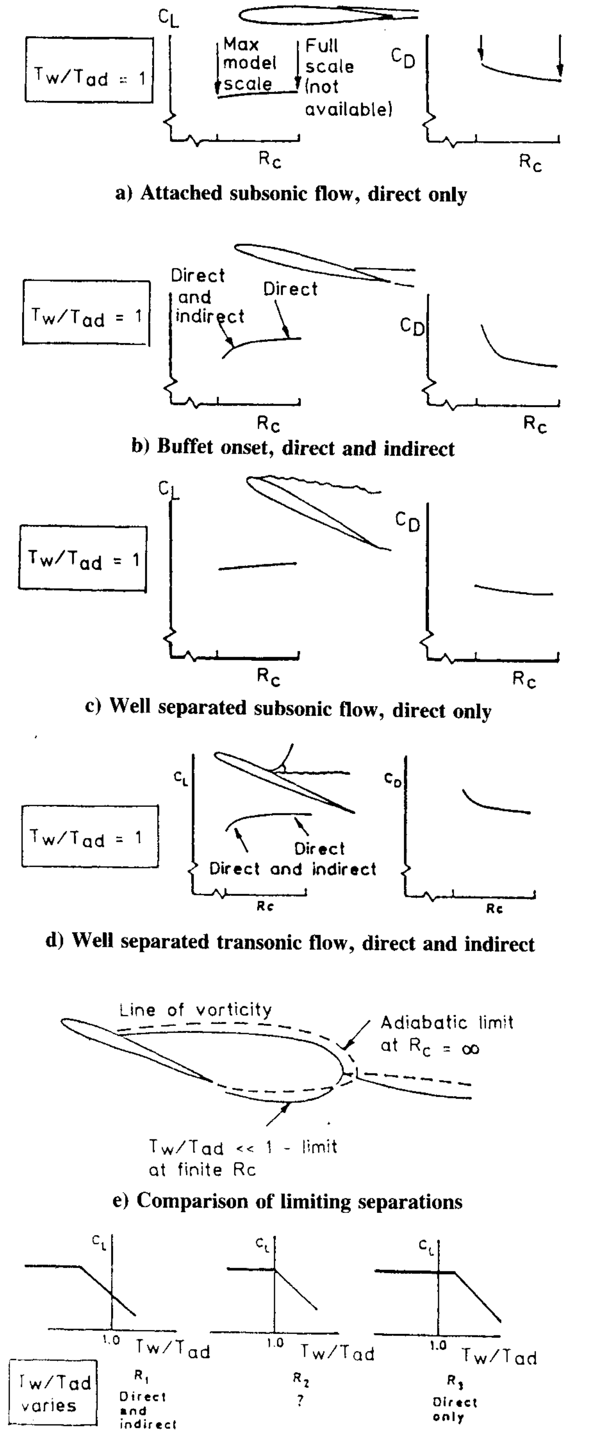


Fig. 7 Identification of type of scale effects due to hypothetical variation in Reynolds number.

there would be only small effects on the lift and drag and virtually no effect on the pressure distribution. There may be no changes in the bubble length and hence no change in the buffet excitation according to Fig. 4.

Next, suppose that at transonic speeds there is a large shock-induced separation at the test Reynolds number (Fig. 7d). Here an increase to full-scale Reynolds number would generally produce a small, indirect scale effect. This might be confirmed by cooling the model. If so, initially there would be an increase in lift, then an almost constant lift should be achieved, with no further change in the pressure distribution. This condition might be used to predict the direct scale effects due to a variation in Reynolds number in the absence of heat transfer. Direct and indirect scale effects might also occur with attached flows at transonic speeds, due to the complexity of the shock/boundary-layer interaction (cf. Fig. 7 of Ref. 4).

Thus, for each of the four test conditions there is the possibility of being able to identify the type of scale effect by cooling the model, even if the precise magnitude of these effects cannot be determined. Figure 7 has been drawn to suggest that there are no indirect scale effects with fully attached (Fig. 7a) and fully separated subsonic flows (Fig. 7c). According to Ref. 1, unsteady experiments in these regions should therefore be subjected to negligible scale effects. In contrast, there will be indirect scale effects close to buffet onset (Fig. 7b) and in this region significant scale effects must be expected, even in unsteady aerodynamics. Reference 1 offers no evidence for scale effects with well-separated flows at transonic speeds (cf. Fig. 7d).

Perhaps there is a limiting separation position (and lift) achieved by wall cooling at finite Reynolds number that could be the same as that achieved by increasing Reynolds number. Consider the concept of the limiting inviscid separation. This is the separation obtained in the limit of an infinite Reynolds number (Fig. 7e). For a given Mach number, angle of incidence, and geometry the inviscid separation may be idealized by a fixed separation and by an infinitely thin line of vorticity, e.g., as in the Kirchoff model of flow separation. If a limiting separation is obtained at a finite Reynolds number with a highly cooled boundary layer (which has a velocity profile before separation appropriate to a higher Reynolds number), this separation may not be greatly different, because after separation the major part of the velocity profile (the wake region) may be similar to that for an adiabatic boundary layer. (Note that with adiabatic boundary layers, changes in the wake profile with Reynolds number are normally small compared to the very large changes due to adverse pressure gradients. Hence, the effects of heat transfer may be small compared to the very large changes due to adverse pressure gradients.) The wake region exerts the decisive influence on closure conditions downstream of the wing, and together with the separation position, the overall lift.

Obviously the question—that a limiting separation with cooling at a finite Reynolds number is nearly the same as that with an adiabatic boundary layer at infinite Reynolds number—needs to be investigated, preferably both by special experiments and by calculations. If the limiting separations sketched in Fig. 7e were identical, the lift would be identical and the indirect scale effects would be represented correctly at the low Reynolds number with the cooled wall. However, it is unlikely that the *direct* scale effects would be represented correctly.

In conclusion, Fig. 7f illustrates how the variation of particular measurements (say lift coefficient) with wall temperature ratio might be used to identify the type of scale effects at three increasing unit Reynolds numbers. For the lowest Reynolds number R_1, the large variation with T_w/T_{ad} at $T_w/T_{ad} = 1.0$ suggests direct and indirect scale effects: hence extrapolation to full scale would be difficult or impossible. For the intermediate unit Reynolds number R_2, the discontinuity at $T_w/T_{ad} = 1.0$ suggests that indirect scale effects have only just been eliminated: hence extrapolation to full scale might just be possible from this limiting (minimum test Reynolds number). For the highest unit Reynolds number R_3, the insensitivity of the measurements to T_w/T_{ad} at $T_w/T_{ad} = 1.0$ suggests that indirect scale effects are negligible: hence extrapolation to full scale should be possible.

We have seen that large aerodynamic effects occur due to wall cooling. Hence, a careful choice must be made of a lower limit for the wall temperature ratio T_w/T_{ad}. In a conventional transonic wind tunnel ($T_t = T_{ad}$ about 300 K), the air is normally dried to a frost point of about $-50°C$ (223 K). Thus, to avoid ice forming on the model, $T_w = 223$ K would be a practical lower limit, giving a ratio of

$$T_w/T_{ad} = 0.75 \tag{6}$$

The cooling requirements implied by Eq. (6) are large but not totally impractible. This surface temperature would correspond to a ratio of $T_w/T_{ad} = 0.83$ at low speeds. The boiling point of liquid nitrogen is only 67 K at ambient conditions, and so precooling a model, to say 230 K, for tests in an intermittent tunnel should be comparatively easy.

The mechanical properties of the model material also influence the choice of wall temperature, because low temperatures, while generally increasing the ultimate tensile strength, also give greater brittleness (represented by lower values for an Izod impact test). A nickel-steel alloy widely used for wind-tunnel models (EN25) suffers little change in mechanical properties from 293–223 K, but below 223 K its properties deteriorate rapidly. Hence, $T_w = 223$ K ($-50°C$) is probably the practical lower limit for most existing steel models. An important property of aluminum and its alloys is that they do not lose their ductility or shock resistance however low the temperature. Hence, for aluminum models the need to avoid frost on the model ($T_w = 223$ K) involves no restriction.

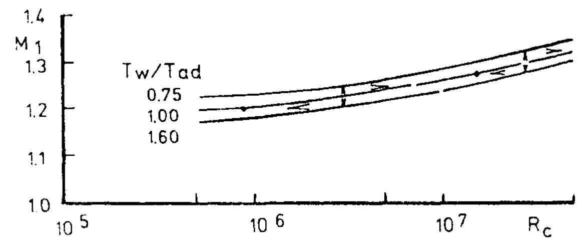
Effects of Heat Transfer on Aerodynamic Measurements

It is shown elsewhere[10] that for transition, skin friction, and separation,[10-20] the effects of modest heat transfer at constant Reynolds number are relatively large compared to vast variations in Reynolds number without heat transfer. Here space restrictions only allow the classification outlined in Fig. 7 to be illustrated by pressure measurements on an aerofoil at subsonic and transonic speeds.

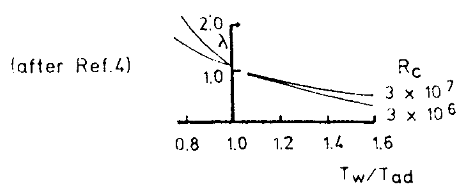
Pressure Measurements on an Aerofoil at Subsonic and Transonic Speeds in a Cryogenic Wind Tunnel

Reference 4 describes a theoretical and experimental investigation of the effects of heat transfer on a two-dimensional aft-loaded aerofoil section. The main objective was to establish how closely model wall temperature must be controlled in a cryogenic wind tunnel. The investigation confirmed the earlier predictions of Green et al.[21] that the model temperature should be within 1% of the adiabatic wall temperature, and also illustrates the sensitivity of transonic flows to heat transfer. Reference 4 is now used to illustrate how variations in heat transfer may be used to identify regions in which indirect scale effects occur, and possibly even to simulate these scale effects.

Figure 8 shows how the upstream Mach number M_1, predicted for conditions of incipient separation, varies as a function of heat transfer and Reynolds number for a turbulent boundary layer. Figure 8a shows that, for a fixed Reynolds number, wall cooling allows a higher value of M_1 to be achieved



a) Influence of temperature ratio and Reynolds number



b) Influence of temperature ratio on effective Reynolds number for two Reynolds numbers

Fig. 8 Conditions for incipient shock induced separation.

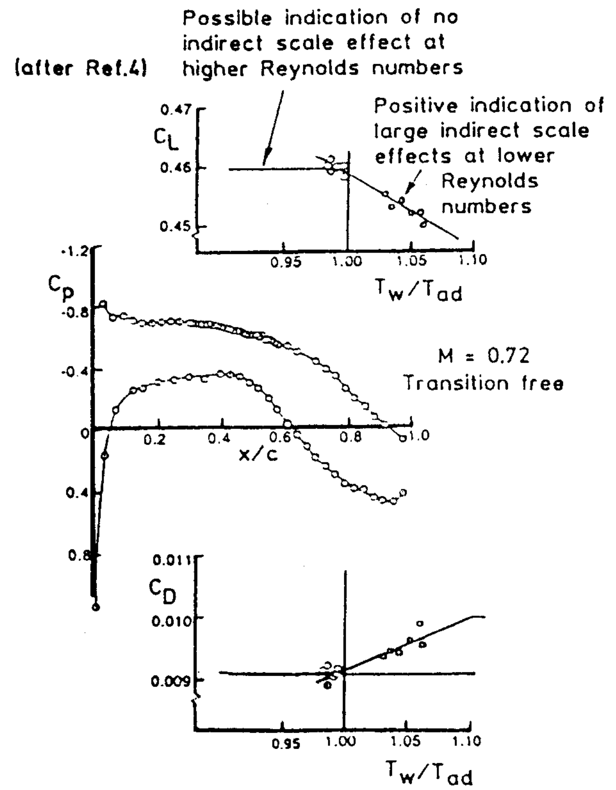


Fig. 9 Wind-tunnel measured effect of nonadiabatic wall.

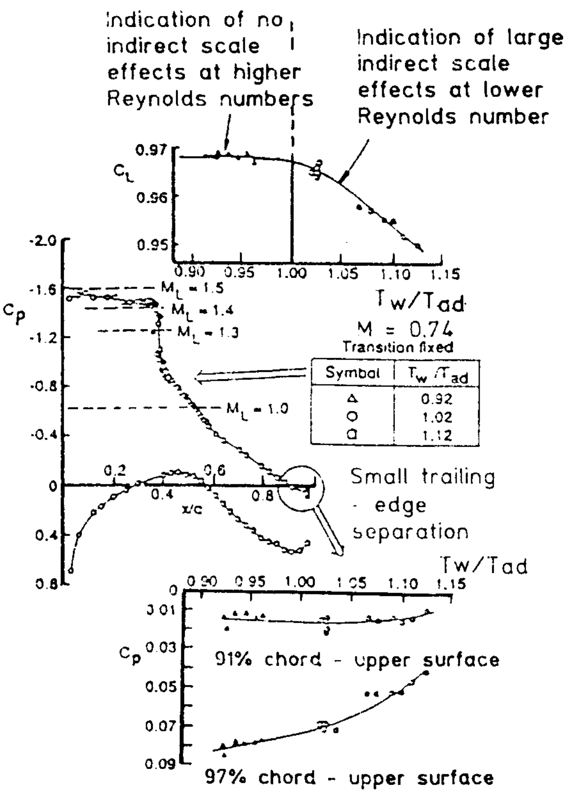


Fig. 10 Wind-tunnel measured effect of nonadiabatic wall on airfoil buffet onset (after Ref. 4).

before flow separation. In contrast, wall heating lowers the value of M_1 achieved. By following the adiabatic curve, it is easy to see how much the Reynolds number would have to be increased to achieve the higher value of M_1 appropriate to the cooled wall or decreased to achieve the lower value of M_1 appropriate to the heated wall. Thus, for a fixed Reynolds number an effective Reynolds-number factor may be derived as a function of the wall temperature ratio. Figure 8b shows that for a wall cooled to $T_w/T_{ad} = 0.75$, λ would be about 2.5 for $Rc = 3 \times 10^6$ although only about 1.7 for $Rc = 3 \times 10^7$. Both figures represent useful increases in effective Reynolds number.

Figure 9 shows a measured pressure distribution for an attached subcritical flow at $M_e = 0.72$ at $Rc = 7 \times 10^6$ with *free* transition. The large variations in C_L for $T_w/T_{ad} \geq 1.0$ suggest that even with this attached flow there would be large, indirect scale effects at lower Reynolds numbers, which would make extrapolation to full scale difficult or impossible. These effects are due to the variation of the transition position because the predicted drag variation with fixed transition is negligible (cf. Fig. 6 of Ref. 4). In contrast, the lines drawn by the authors of Ref. 4 suggest that for $T_w/T_{ad} \leq 0.95$, C_L would be constant and the variations in C_D would be small, because the transition position would have achieved the most extreme downstream position on both surfaces of the aerofoil. If this hypothesis is correct, the pressure distribution presented (which relates to $T_w/T_{ad} \leq 1.0$) should have no indirect scale effects and might be used to predict the aerofoil performance without heat transfer at higher Reynolds numbers. In other words, $Rc = 7 \times 10^6$ appears to be a minimum test Reynolds number for avoiding indirect scale effects; cf. unit Reynolds number R_2 in Fig. 7f.

Figure 10 shows an interesting set of measurements relating to buffet onset at $M = 0.74$ with fixed transition at an unspecified Reynolds number and angle of incidence. This condition is selected to give buffet onset with zero heat transfer. Reference 4 states that for $T_w/T_{ad} \leq 1.0$, the flow is attached. Here C_L is nearly constant, consistent with no indirect scale effects. Thus, this condition appears to be above the minimum test Reynolds number for avoiding indirect scale effects cf. unit Reynolds number R_3 in Fig. 7f. Hence, the pressure distribution measured for $T_w/T_{ad} = 0.92$ might be used to predict the indirect scale effects at higher Reynolds numbers with no heat transfer. In contrast, for $T_w/T_{ad} \geq 1.02$, the flow separates (shown by the forward movement of the shock in the pressure distribution and the change of pressure on the upper surface at $x/c = 0.97$ close to the trailing edge). Here C_L changes rapidly. According to the ideas suggested here, this region would represent an adiabatic condition at an ap-

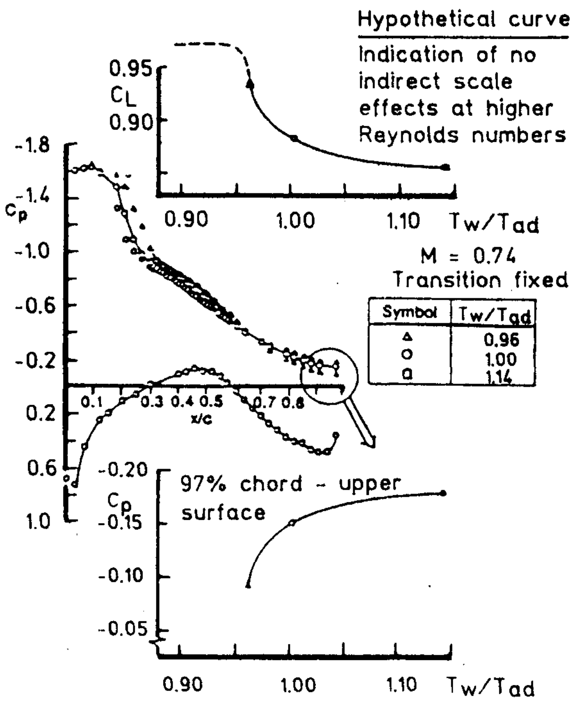


Fig. 11 Wind-tunnel measured effect of nonadiabatic wall on airfoil characteristics near maximum lift (after Ref. 4).

preciably lower range of Reynolds number. Here there would be large, indirect scale effects and extrapolation to full scale would be difficult.

Figure 11 shows another interesting set of measurements relating to maximum lift at $M = 0.74$ with fixed transition at an unspecified Reynolds number and angle of incidence. Here there is an extensive separation over the upper surface of the aerofoil, which is reduced significantly when $T_w/T_{ad} = 0.96$. For $T_w/T_{ad} = 1.14$, the shock is a little further upstream and the pressure of the upper surface at $x/c = 0.97$ is correspondingly lower. Further increases in wall temperature ratio (say to $T_w/T_{ad} = 1.20$) left C_L unchanged at a limit of about 0.85, suggesting that indirect scale effects would no longer be important at lower Reynolds numbers. However, this pressure distribution could not be used to extrapolate to full scale because the powerful indirect scale effects at intermediate temperature ratios would not be represented. However, if the wall had been cooled a little further (say to $T_w/T_{ad} = 0.92$ as achieved in Fig. 10), the C_L may again have been constant (at say about 0.96). If so, this would suggest that indirect scale effects would no longer be important at higher Reynolds number. This pressure distribution might then have been used to predict the direct scale effects at higher Reynolds numbers with no heat transfer. This would be a situation similar to that illustrated in Fig. 7d. The present adiabatic measurements correspond with conditions at the unit Reynolds number R_1 in Fig. 7f.

Conclusions

1) With regard to the simulation of viscous effects in steady flow, a comparatively small amount of model cooling is equivalent to a large increase in effective Reynolds number; thus cooling may be used to identify regions with large scale effects.

2) An important effect of model cooling on the prediction of buffet excitation is the delay of flow separation.

3) Cooling models in wind tunnels would make it easier to simulate laminar-flow aircraft. However, transition reversal due to surface roughness must be avoided.

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