A Survey of Heat Transfer in Compressible Separated and Reattached Flows

W. Merzkirch
Universität Essen, Essen, Federal Republic of Germany
and
R. H. Page and L. S. Fletcher
Texas A&M University, College Station, Texas

Nomenclature

c_p = specific heat
c = speed of sound
C = Crocco number (u/u_{max})
D = length scale parameter
h = convective heat-transfer coefficient
h_b = base heat-transfer coefficient
H = base or step height
k = conductivity
ℓ = characteristic near-wake length
L = cavity length
M = Mach number (u/c)
Nu = Nusselt number (hx/k)
n = exponent for Reynolds number correlation
Pr = Prandtl number $(c_p\mu/k)$
Re = Reynolds number $(\rho ux/\mu)$
S = characteristic cavity size
$\tilde{S}$ = Lamb's correlation parameter
St = Stanton number $(h/\rho uc_p)$
T = temperature
T_0 = stagnation temperature
u = velocity
x = distance
δ_1 = boundary-layer thickness before separation
δ_2 = free shear layer thickness
θ = angle on a hemispherical base
μ = viscosity
ρ = density
σ = similarity parameters for turbulent mixing
σ_i = incompressible similarity parameter

Introduction

A GENERAL review of this subject was provided over a decade ago.[1] Much research, both experimental and theoretical, has been conducted in this area of convective heat transfer in compressive flows. It is now well understood that flow separation and flow reattachment, with the accompanying zones of recirculation, have a major impact on the heat transfer that occurs between a separated flow and a wall. It is realized that the paths for convective heat transfer become quite complicated when separation is present. Yet one observes a multiplicity of vehicle and structural designs about which the external flows often separate. Also, there are a great number of internal flow configurations that often involve separation and its influence on heat transfer.

Because of the broad technical areas in which heat transfer in separated and reattached flows occurs, numerous investiga-

---

Wolfgang Merzkirch is Professor of Fluid Mechanics at Essen University. He studied physics at the University of Freiburg from which he received his Dr.Rer.Nat. in 1963. He has been a Visiting Research Scientist with NASA at the Ames Research Center. From 1971 to 1984 he was a leader for the experimental gas dynamics program at the Ruhr University-Bochum. Professor Merzkirch is a Visiting Professor and member of the Graduate Faculty of Texas A&M University and journal editor for *Experiments in Fluid*. His primary field of specialization has been flow visualization, an area in which he has widely published.

Robert H. Page is the Forsyth Professor of Mechanical Engineering at Texas A&M University. He received his B.S.M.E. from Ohio University, his M.S. and Ph.D. degrees from the University of Illinois, the latter in 1955. He has had previous positions with Esso Research and Engineering Company, University of Illinois, Stevens Institute of Technology, and Rutgers University. Professor Page's primary field of specialization has been compressible flow separation analysis and its design application. He is an Honorary Professor of Ruhr University-Bochum (West Germany), a Fellow of several professional societies, and an Associate Fellow of AIAA.

Leroy S. Fletcher is Professor of Mechanical Engineering, Associate Dean of the College of Engineering at Texas A&M University and Associate Director of the Texas Engineering Experiment Station. He received his Ph.D. degree from Arizona State University in 1968. He was a Research Scientist at NASA-Ames Research Center for six years, and has held full-time academic positions at Rutgers University and the University of Virginia. His major areas of specialization are heat transfer and fluid mechanics. Professor Fletcher has published several books and numerous papers and reports. He is a Fellow of the American Institute of Aeronautics and Astronautics, the American Association for the Advancement of Science, the American Astronautical Society, the American Society for Engineering Education, the Institution of Mechanical Engineers, and the American Society of Mechanical Engineers.

Received May 23, 1986; revision received April 28, 1987.

tions have been undertaken. It is impractical in this review to recognize all the contributions of the past decade. The authors have selected what they believe to be key references; the reader with a specific interest will find additional references therein. In some cases, incompressible investigations have been included because they help to clarify the phenomena. It must be emphasized that this review is focused on heat transfer and not on pressure in separated flows, a subject covered by other literature.

In addition to the topics covered in the earlier review, the authors have noted a growing interest in the study of combustion in separation flow regions and in the study of separated regions that are driven by a steady flow yet are themselves oscillatory. Accordingly, this review includes brief consideration of these special situations.

Basic Parameters for Convective Heat Transfer

The majority of the investigations of heat transfer in supersonic and hypersonic separated or base flow are conducted in order to define the thermal protection requirements for the specific flight vehicles. The heat-transfer characteristics of separated flow are much more complex than those of an attached flow and they are difficult to analyze because of the necessary coupling between the secondary, vortical flow and the external freestream. The greater portion of the investigations are experiments that have been performed with various body shapes and flow conditions, in free-flight or ground tests and with different measurement techniques. Determining the heat transfer in the separated flow regime or to the base in the form of a Nusselt (or Stanton) number is a general aim of many investigations. Since the value of this number depends on a set of parameters (the total number of which is not known), it becomes a serious problem to correlate the experimental values so that results from different tests can be compared and results of a more general physical nature can be derived. The appropriate definition of the reference conditions for forming nondimensional quantities appears to be more art than science.

This review is concerned predominantly with flow separation in supersonic and hypersonic flow. The basic geometric configurations, shown in Fig. 1, are the cavity, backstep, and base of a body. In the two former cases, and if the base forms an abrupt edge with the forward portion of the body

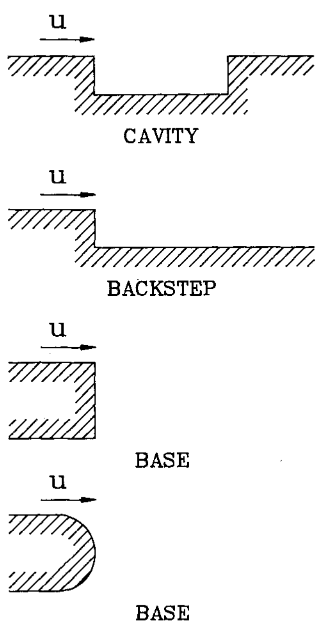


Fig. 1 Basic shapes.

contour, the position of separation is known a priori. The position of reattachment, and the shape and size of the separated region, are not known a priori and depend on the specific flow situation. Particular points of interest are the influence of a number of parameters on the heat transfer to the wall in the separated region (e.g., Reynolds number, Mach number, angle of attack) and the correlation of the heating characteristics with these parameters. Results, both theoretical and experimental, are considered here that were not included in an earlier review of the same subject.[1] Separated flows caused by the impingement of a shock onto a wall boundary layer are not examined here.

Characteristic Length Scales

The primary mechanisms for energy transport into the separated flow regime are dissipation and diffusion through the free shear layer. The transport processes are dependent on profiles of velocity and enthalpy at the origin of the free shear layer, according to Lamb.[2] These profiles, in turn, are related to corresponding distributions in the attached flow upstream of the separation. The boundary-layer thickness before separation δ_1 is, therefore, a characteristic length that may be used in defining a Reynolds number. Equivalent to this characteristic length are the thickness of the free shear layer δ_2 or a characteristic near wake length[3] ℓ. However, the problem has at least one or, as in the case of the cavity, two additional length parameters: base height or step height H and cavity length L. Laminar and turbulent local heat-transfer data have been correlated with the length scale parameter[2] $D=\delta_1/(\delta_1+H)$. For steps and cavities with varying height, this parameter varies between 1 (flat plate) and 0 (infinitely high-step or vanishing boundary-layer thickness). For turbulent heat transfer in cavities, Lamb[4] proposes a novel length scale: $S=LH/(L+H)$ (characteristic cavity size). These two parameters, D and S, are used by Lamb together with additional combinations of δ_1, δ_2, or L.

Ota et al.[5-7] extensively studied the heat transfer in the separated regions of the leading surfaces of blunt flat plates and blunt circular cylinders. Here, the characteristic length scale must be related to the body cross section.

Reynolds Number

A characteristic length scale is needed to define an appropriate Reynolds number. As pointed out by Inoue and Page,[8] the heat transfer to the base is influenced by two resistive elements in the separated region: heating between the recirculating region and the base wall and heating across the mixing layer in the wake. These two flow elements, recirculating flow and free shear layer, are strongly dependent on the Reynolds number, so heat transfer to the wall in the separated region must also depend on Reynolds number, as does the base pressure. The aim of many experimental investigations is to explore the relationship between heat transfer in the form of a Nusselt or Stanton number and a Reynolds number. Generally, such a relationship is more complicated than in the case of low-speed flow,[9] since flow and temperature field may depend on a number of additional parameters, e.g., Mach number, Prandtl number, real-gas effects, and ablation products.

Some authors present the heat-transfer data or respective correlations as functions of the thickness of the free shear layer δ_2 or of the thickness of the separating boundary layer δ_1. Since the ratio δ_1/δ_2 depends on the base pressure or on the expansion ratio, it again becomes evident that the heat transfer is a function of base pressure or Reynolds number.[8] A change in Reynolds number may affect base heat transfer in different ways. The thickness of the free shear layer decreases with increasing Reynolds number, thus resulting in a higher temperature gradient across the free shear layer and a higher heat-transfer rate for a given fluid. At the same time, the base pressure decreases, which may lead to a reduction of the convective heat transfer. The existence of such counteracting effects and the variety of parameters of influence explain the number of different approaches in correlating the data in relation to the Reynolds number.

Correlations generally are given in the form of the Nusselt or Stanton number as a function of Re^n. The Stanton number is an inverse function of Re ($n<0$), while $n>0$ holds when the heat transfer is expressed by the Nusselt number (see Bulmer[10,11]). This difference in the sign of n is due to the fact that the Nusselt number is the product of the Stanton, Prandtl, and Reynold numbers. In some cases, the correlation formula describes the average heat transfer to the base wall or to the wall of a cavity; in other cases, Nu or St are presented as local quantities. The value of n depends on whether the flow is laminar or turbulent (see Nestler and Brant[12]).

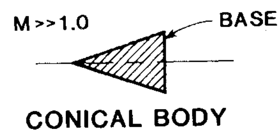
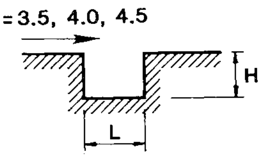
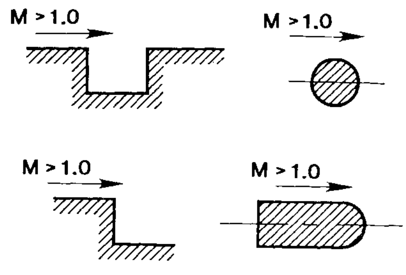
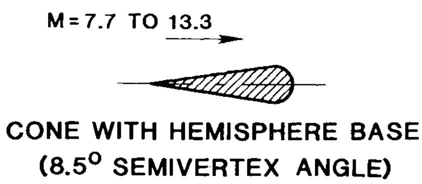
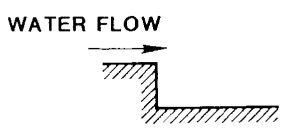
In the case of laminar flow, Lamb[2] finds that the exponent n is the same as for the incompressible flat-plate solution; this applies to cavity, backstep, and cylinder in supersonic flow. With the length parameter $D=\delta_1/(\delta_1+H)$ and with the definition of an "equivalent" Stanton number, it is possible to convert all experimental points so that they fall on the curve of the flat-plate solution, $St=2.07/Re(\delta_1)$ for $P_r=0.72$. Turbulent heat transfer in cavities and for base and backstep geometries are correlated by Lamb[2] with the same length parameter D. In a different approach, which applies to cavities only,[4] a novel parameter $\tilde{S}$ is used for the correlation

$$\tilde{S}=(L/\delta_1)\cdot(S/L)\cdot(\sigma_i/\sigma)$$

where $S=(LH)/(L+H)$ is the characteristic cavity size, L the cavity length, $\sigma/\sigma_i=1+0.056\cdot\exp(3.4C^2)$ the turbulent free shear layer growth parameter, and C the Crocco number.

It remains questionable whether the data for such different configurations as cavity, step and base and for a wide range of Mach numbers can fall onto one universal correlation curve. The flow field in the separated region that governs the convective heat transfer might be quite different in individual cases. On the other hand, along a wavy wall, where one would expect close similarity to the flat-plate conditions, Brandon et al.[13] find significant differences in local heat transfer between the surface areas with separated and attached flows. The height of the structures causing local separation is much smaller than the boundary-layer thickness of the main flow and, consequently, correlation of the heating data is very complex, with the main flow being itself a shear flow. A two-dimensional step configuration in a shear flow (i.e., the case of the step height being small compared to the thickness of the separating boundary layer) has

Table 1 Reynolds number correlations

Bulmer[10,11] $\dfrac{Nu_{\text{base}}/Pr_{\text{base}}}{Nu_{\text{cone}}/Pr_{\text{cone}}}=35.5\left(\dfrac{Re_{\text{base}}}{Re_{\text{cone}}}\right)^{2.2}$ Note: Subscript "base" refers to evaluations at conditions where the approach flow has isentropically expanded to the base pressure. The characteristic length is the local radius on the base. Subscript "cone" refers to conditions immediately before the base. The characteristic length is the length of attached flow on the cone.	Turbulent flow Local for ($10^6<Re_{\text{base}}<10^7$)	
Gortyshov et al.[17] $St=0.48Re_L^{-0.4}(H/L)^{-0.2}$ Note:Stanton and Reynolds number properties and velocity are evaluated at freestream condition. The Stanton number refers to the average heat transfer in the cavity.	Turbulent flow Average for ($2.5\times10^5<Re_{\text{approach}}<3.5\times10^6$)	
Lamb[2] $St_{\text{eq}}\simeq2.07\cdot Re_{\delta_1}^{-1}$ Note: St_{eq} is Lamb's correlation. Reynolds number properties and velocity are evaluated upstream of separation at freestream conditions. The St_{eq} is related to heat transfer on the leeward surface. The Mach number range is 2.2–6.9. The characteristic length in the Reynolds number is the boundary-layer thickness at separation.	Laminar Flow Average	
Kim[23] $St\sim Re^{-0.3}$ Note: Stanton and Reynolds number properties and velocity are evaluated at freestream approach conditions. The Stanton number refers to the average heat transfer in the separated region on the base. The Reynolds number length is the surface distance up to the maximum body diameter station.	Turbulent Flow Local for ($3\times10^6<Re_\infty/\text{ft}<1.5\times10^7$)	
Orlov et al[16] $Nu_{\text{backstep}}\sim Re^n$ Note: The length in Nu and Re is the step height. Nusselt number and Reynolds number properties and velocity are evaluated at freestream conditions in the approach flow. The heat transfer coefficient refers to local values on the downstream wall prior to flow reattachment and immediately downstream of reattachment.	Turbulent flow (incompressible) ($0.56<n<0.70$)	

been analyzed theoretically by Inger.[14] Jakubowski and Lewis[15] performed experiments for the same geometric and flow conditions in an arc-heated wind tunnel at Mach number near 4. Heating rates upstream and downstream of the step were measured and it was noted that an increase in step height caused a sharp drop in the initial heat transfer.

Orlov et al.[16] measured local heat-transfer coefficients behind a two-dimensional back step in water with turbulent flow. Orlov's and other correlations are given in Table 1.

According to Nestler and Brant,[12] the main source for base heating at very high Mach numbers ($M \sim 50$) is the impingement of a nonuniform, jet-like reverse flow onto the base wall, because the flow velocities in the recirculating region are not small under these circumstances. Then, the convective heating to the base occurs through a base boundary layer and the heating rate is determined by means of analyzing a stagnation-point heating distribution. Sample calculations again result in relationships of the form $St \sim Re^n$, with the values of n being similar to those which had been derived under different assumptions. Gortyshov et al.[17] report on the formation of different flow types in a cavity exposed to a supersonic exterior flow. The type of flow depends on the ratio H/L and essentially determines the heating mechanism to the cavity floor. In shallow cavities ($H/L < 0.09$), the primary separated flow attaches to the floor, whereas one observes different vortex configurations in the cavity at larger values of H/L.

Since the absolute value of heat-transfer sensitivity depends on whether the flow is laminar or turbulent, Bulmer[18] could conclude from a sudden change in the base heat transfer that a transition had occurred.

Unfortunately, there appears to be no single equation or relationship that adequately describes the separated flow heat transfer as a function of Reynolds number. Table 1 includes five of the correlations that have been supported by experimental data. Note that in these relationships, the Nusselt number varies with Reynolds number from a power of 0.56 (Orlov[16]—incompressible) to a power of 2.2 (Bulmer[17]—hypersonic). The variation of the turbulent Stanton number is not as extreme. Reported correlations show it varying with a Reynolds number to the negative 0.3 and 0.4 power. For the laminar case, Lamb's correlation for the Stanton number is recommended.

The authors would like to present a specific recommendation or correlation for determining turbulent heat transfer in compressible separated and reattached flows. However, the current status of this area is that much more research needs to be done before we reach that level of sophistication.

Mach Number

The reported investigations were performed over a wide range of Mach numbers. If the state of the flow immediately before separation is chosen as a reference condition for the respective quantities in the separated region, the Mach number is automatically included in the modeling or correlation. The range of this local Mach number is much smaller than the range covered for the freestream Mach number. Bulmer[10,11] correlates data taken at successive positions during free flight when the Mach number decreases with time. A typical hypersonic Mach number effect is the reported description of the base heat-transfer mechanism by means of the impingement of a reversed jet flow.[12]

From the component analysis of Inoue and Page,[8] it can be seen that the wall temperature at the location before separation significantly influences the value of base heat transfer. It follows that the stagnation conditions are more predominant than the value of the Mach number. Lamb[2] has taken account of this effect by means of the factor $(T_0/T)^{0.3}$ in his correlations of laminar data, where T is the temperature at separation and T_0 the stagnation temperature. The Crocco number, which is also related to the temperature ratio T_0/T, is part of Lamb's correlation analysis for turbulent cavity flow.[4]

At high Mach numbers and high stagnation temperatures, real-gas effects might become significant. Balakrishnan and Chu,[19] whose theory is based on Inoue and Page's component analysis, present results of base heating for planetary entry probes with hemispherical afterbodies entering the Jupiter atmosphere. Turbulent base heating values are given as functions of attached boundary-layer thickness for frozen and equilibrium flows. The frozen flow calculations predict lower base heating than the equilibrium model. This result is of interest for the simulation of these flow conditions in a test facility where the flow might be frozen. Further, predictions of this theory are that maximum heating occurs in a warm Jovian atmosphere according to the applied frozen-flow model. The equilibrium model, on the other hand, predicts that maximum heating will occur in a cool atmosphere. Bulmer[20] attributes the observed differences in the heat-transfer level of data taken in ground tests and in free flight, to real-gas effects, without specifying the mechanism. Yamamota[21] carried out a numerical simulation for laminar flow over a capsule at a Mach number of 7.0 that showed high heating rates on the windward cylinder surfaces due to strong recompression.

Body Geometry, Local Heat Transfer, and Angle of Attack

Again, if one chooses the reference conditions in the boundary-layer flow immediately before separation, it becomes possible to compare the average heat-transfer values for bodies having different shapes. This is quite evident in the correlations made by Lamb.[2] The local heat-transfer values strongly depend on the shape of the base, afterbody, or cavity. By correlating measurements of different authors, Bulmer[22] derives a relation for the local heat transfer, expressed by the Nusselt number, as a function of the radial position on the flat base of slender cones. A systematic investigation of the local heat transfer on the hemispherical base of a sharp-nosed cone has been performed by Kim[23] for a range of Mach numbers between 8 and 13. Kim points out that because of the gradual flow expansion along the hemispherical base, the heat transfer over the base is far from uniform, as it is often assumed to be for stepwise configurations. From his measurements, Kim found a relationship between the base heat-transfer coefficient h_b and the angle θ along the base, which could be expressed in the form $h_b \sim \Theta^{-1.75}$ for turbulent flow. It appears that for the local heat transfer varying over such a wide range, the correlation is no longer adequate with near-wake bulk properties. Igarashi[24] studied the heat transfer behind a circular cylinder with the wake modified and observed large variations.

Qualitative explanation of the increase in heat transfer for a separated flow region of a yawed blunted core was provided by Nomura.[25] For inclined, noncircular cylindrical body configurations, Bertin et al.[3] found that the average base heat transfer is a linear function of the angle of attack. Freestream Mach numbers covered the range $5 < M < 15$. A similar relationship follows from the experimental results of Zappa and Reinecke,[26] who investigated 60 and 70 deg half-angle cones at a Mach number $M = 11.5$.

The heat transfer occurring with turbulent separated flow across almost circular cavities was studied by Bales and Korst.[27] The characteristically low heat-transfer rates behind an axisymmetric bluff body were measured by Charalumbous.[28] The backward-facing step in subsonic flow has been the subject of a large number of investigations, all of which show the same general trends of low heat-transfer rates immediately behind the step. Chen and Tsou,[29] Gooray et al.,[30] Seki et al.,[31,32] Sparrow et al.,[33] and Tsou[34] all represent recent works in this area. Finite-element simulation was shown by Lamb and Polansky.[35] Calculations of the axisymmetric backward-facing step were demonstrated by Chieny and Launder.[36]

Location of Maximum Heat Transfer

Models of heat transfer at separation and reattachment were developed by Gerhart et al.[37] Traditionally, it was assumed that peak heating occurs at the point of attachment (Reynolds analogy between heat transfer and skin friction). This assumption applied to the reattaching shear layer downstream of a step or on the downstream side of a cavity, as well as to the reversed jet-like flow impinging on the base of a body in hypersonic flight. However, from a number of experimental studies in which local heating rates were investigated, it became evident that the attachment point or line is not necessarily a location of maximum heat transfer and that the predicted heating rate in the reattachment region is higher than the measured values. This tendency has also been observed in studies where a free shear layer is formed due to the impingement of a shock onto the body surface (e.g., Nestler[38] and Matthews and Ginoux[39]) or where such a layer develops upon the intersection of two shock waves (e.g., Rudy and Burch[40] and Keyes[41]) and later attaches to the body surface.

Reynolds analogy primarily applies to two-dimensional flow on a flat plate. In the semiempirical analysis of Gerhart,[42] which is based on the application of integral boundary-layer equations, an indication is given that the analogy fails close to the attachment line. Werle et al.[43] describe a first step for extending the two-dimensional boundary-layer/inviscid flow interaction model to the three-dimensional case. As an important result of these investigations, it appears that an effect of a crossflow near reattachment is to shift the peak heating downstream from the reattachment line.

Significant progress in solving the peak heating problem is made in the analysis of Inger,[44] who theoretically establishes the existence of instabilities (lateral vortices) near the reattachment of a nominally two-dimensional laminar and turbulent flow over a step configuration. The calculated heat-transfer variations in spanwise direction are not in phase with respective shear stress disturbances, from which one concludes that the Reynolds analogy here is not applicable. Inger's flow model, from which heat-transfer variations up to 40% are predicted, is in close agreement with respective flow visualization experiments.

The low-speed subsonic results of Vogel and Eaton[45] also illustrate the failure of the Reynolds analogy when dealing with local values of skin friction. Other subsonic experimental data (e.g., Kang et al.,[46] MacGregor,[47] and Suzuki et al.[48]) show that the peak heat transfer occurs upstream of reattachment. Local values of heat transfer in a circular sudden expansion have also been reported.[49]

Combustion in Separated Regions

Combustion chambers in such units as aircraft gas turbines and ramjets have utilized the recirculation phenomena of a separated flow as a flameholding mechanism. The earliest studies of combustion of air-fuel mixtures in a flowing stream recognized the role of the separation regions of cylinders or V-gutters for flameholding. The recirculation region provides for an upstream flow of the hot products of combustion. This flow serves to ignite the oncoming flow that crosses into the separation zone. The combustion literature provides much insight into the flameholding characteristics of various geometries,[50] as well as modeling techniques.[51]

During the past decade, considerable interest has focused on combustion in the bluff base of projectiles.[52] Experimental and theoretical studies were focused on carrying out combustion in the separated zone as an approach to reducing the base drag of projectiles, missiles, and high-speed aircraft. This extensive interest provided much information about the effects of heat transfer,[53] but little information concerning the magnitude of heat transfer during combustion.

The heat-transfer complications that occur when solid particles are carried with gas flow has been treated by Maeda et al.[54]

Nonsteady Separated Regions

High-speed flow over cavities always leads to flow separation and reattachment. The flow separates from the leeward edge of the cavity and reattaches near the trailing edge. There has always been a considerable interest in the drag of cavities and the resonant phenomena that may occur in cavities under certain conditions. Precise method for predicting the occurrence of pressure oscillations within the cavity (resonance) have not been developed, although it has been possible to predict the frequency of the pressure oscillations.[55] Recently, control of the oscillations has been explored.[56] It is well understood that the heat-transfer rate within resonant cavities is strongly affected by the self-induced pressure oscillations. Local Stanton numbers and recovery factors have been obtained for subsonic and transonic flow over a resonating cavity.[57]

Conclusions

A striking feature of the current situation in the field of separated and reattached flows is that few attempts have been made to compare or cross-check the available experimental data. Reasons for this lack of comparative data checking include the great number of independent parameters whose values rarely coincide in the experiments of different investigators and the fact that most of the data are presented in a form which does not allow for deducing those quantities necessary for the purpose of a direct comparison. A possible guideline for performing the necessary cross-checking is the theory of Inoue and Page,[8] although this analysis applies to the two-dimensional case only. An alternate method is to correlate the measured data with certain combinations of nondimensional quantities. Again, the great number of dependent parameters makes it questionable whether the traditional correlation procedure will result in a deeper insight into the heat-transfer mechanism in separated flow regimes. It might be helpful if the various investigators could define a limited number of parameters whose influence on the heat-transfer mechanism should be explored in detail and if the correlation procedure could be performed in conjunction with an evaluation of Inoue and Page's theory.

Inger's analysis[44] probably is the key to explaining the observed discrepancy between experimental and theoretical results for peak heating. At the same time, it becomes evident how complex it is to correctly analyze the three-dimensional flow and heat-transfer field near separation and reattachment. Recognizing the complexity of the situation, one might conclude that the large quantity of experimental data still is much too limited for developing in an empirical way a correct physical model for the heat-transfer mechanism in high-speed separated flows.

References

[1]Fletcher, L. S., Briggs, D. G., and Page, R. H., "Heat Transfer in Separated and Reattached Flows: An Annotated Review," *Israel Journal of Technology*, Vol. 12, 1974, pp. 236-261.

[2]Lamb, J. P., "Convective Heat Transfer Correlations for Planar, Supersonic, Separated Flows," *Transactions of ASME Journal of Heat Transfer*, Vol. 102, May 1980, pp. 351-356.

[3]Bertin, J. J., Lamb, J. P., Zickler, J. L., and Goodrich, W. D., "Heat Transfer Measurements for Cylindrical Configurations in Hypersonic Streams," *Journal of Spacecraft and Rockets*, Vol. 10, 1973, pp. 217-218.

[4]Lamb, J. P., "Correlation of Convective Heat Transfer for Open Cavities in Supersonic Flow," *AIAA Progress in Astronautics and Aeronautics: Aerothermodynamics and Planetary Entry*, edited by A. L. Crosbie, Vol. 77, AIAA, New York, 1981, pp. 36-50.

[5]Ota, T. and Kon, N., "Heat Transfer in the Separated and Reattached Flow Over Blunt Flat Plates—Effects of Nose Shape," *International Journal of Heat and Mass Transfer*, Vol. 22, Feb. 1979, pp. 197-206.

[6]Ota, T., Kon, N., Hatakeyama, S., and Sato, S., "Measurements of Turbulent Shear Stress and Heat Flux in an Axisymmetric Separated and Reattached Flow over a Longitudinal Blunt Circular Cylinder," *Journal of the JSME*, Vol. 23, No. 184, Oct. 1980, pp. 1639-1645.

[7]Ota, T. and Kon, N., "Turbulent Transfer of Momentum and Heat in a Separated and Reattached Flow over a Blunt Flat Plate," *Transactions of ASME Journal of Heat Transfer*, Vol. 102, Nov. 1980, pp. 749-754.

[8]Inoue, Y. and Page, R. H., "Aerothermodynamic Base Heating," *AIAA Progress in Astronautics and Aeronautics: Aerodynamic Heating and Thermal Protection Systems*, edited by L. S. Fletcher, Vol. 59, AIAA, New York, 1978, pp. 49-65.

[9]Aung, W., "Interferometric Investigation of Separated Forced Convection in Laminar Flow Past Cavities," *Proceedings of Joint ASME-AICHE National Heat Transfer Conference*, ASME 83-HT-81, New York, 1983.

[10]Bulmer, B. M., "Flight Test Correlation Technique for Turbulent Base Heat Transfer with Low Ablation," *Journal of Spacecraft and Rockets*, Vol. 10, March 1973, pp. 222-224.

[11]Bulmer, B. M., "Re-Entry Vehicle Base Pressure and Heat-Transfer Measurements at $M = 18$," *Journal of Spacecraft and Rockets*, Vol. 13, 1975, pp. 522-524.

[12]Nestler, D. E. and Brant, D. M., "Development of an Afterbody Radiative and Convective Heating Code for Outer Planet Probes," AIAA Paper 78-862, 1978.

[13]Brandon, H. J., Masek, R. V., and Dunavant, J. C., "Aerodynamic Heating to Corrugation Stiffened Structures in Thick Turbulent Boundary Layers," *AIAA Journal*, Vol. 13, Nov. 1975, pp. 1460-1466.

[14]Inger, G. R., "Supersonic Laminar Base Pressure, Heat Transfer, and Upstream Influence Correlation for Small Steps," *AIAA Journal*, Vol. 12, Aug. 1974, pp. 1157-1158.

[15]Jakubowski, A. K. and Lewis, C. H., "Experimental Study of Supersonic Laminar Base Flow With and Without Suction," *AIAA Journal*, Vol. 11, 1973, pp. 1670-1677.

[16]Orlov, V. V., Ovchinnikov, V. V., Mukhina, N. N., and Karsten, V. M., "Investigation of Turbulence and Heat Transfer in a Separating Flow Behind a Step," *Heat Transfer—Soviet Research*, Vol. 16, No. 2, March-April 1984, pp. 58-68.

[17]Gortyshov, Y. F., Varfolomeev, I. M., and Schchukin, V. K., "Study of Heat Transfer in Separated Zones Formed by Rectangular Cavities," *Soviet Aeronautics,* Vol. 25, No. 1, 1982, pp. 33-39 (English translation by Allerton Press, New York).

[18]Bulmer, B. M., "Detection of Flight Vehicle Transition from Base Measurements," *Journal of Spacecraft and Rockets*, Vol. 10, April 1973, pp. 280-281.

[19]Balakrishnam, A. and Chu, E., "Jupiter Entry Probe Afterbody Convective Heating," AIAA Paper 79-0040, Jan. 1979.

[20]Bulmer, B. M., "Heat Transfer Measurements in a Separated Laminar Base Flow," *Journal of Spacecraft and Rockets*, Vol. 14, Nov. 1977, pp. 701-702.

[21]Yamamota, Y., "Numerical Simulation of Hypersonic Viscous Fore- and Afterbody Flows over Capsule Type Vehicles at Angles of Attack," AIAA Paper 85-924, 1985.

[22]Bulmer, B. M., "Radial Base Heat-Transfer Gradients in Turbulent Flow," *Journal of Spacecraft and Rockets*, Vol. 11, Nov. 1974, pp. 798-800.

[23]Kim, B. S. C., "A Shock Tube Investigation of Heat Transfer in the Base Region of a Slender Cone-Hemisphere," AIAA Paper 78-846, May 1978.

[24]Igarashi, T., "Fluid Flow and Heat Transfer in the Separated Region of a Circular Cylinder with Wake Control," *Heat Transfer Japanese Research*, Vol. 11, No. 3, July-Sept. 1982, pp. 1-16.

[25]Nomura, S., "Similar Boundary-Layer Analysis for Lee-Surface Heating on Yawed Blunted Cone," *AIAA Journal*, Vol. 14, Nov. 1976, pp. 1509-1510.

[26]Zappa, O. L. and Reinecke, W. F., "An Experimental Investigation of Base Heating on Typical Mars Entry Body Shapes," *Journal of Spacecraft and Rockets*, Vol. 10, 1973, pp. 273-276.

[27]Bales, E. L. and Korst, H. H., "Heat Transfer Within and Across Nearly Circular Cavities," ASME Paper 74-WA/HT-62, 1974.

[28]Charalambous, C. S., "Convective Base Heat Transfer from an Axisymmetric Bluff Body in Subsonic Flow," M.S. Thesis, Mechanical Engineering Dept., Clemson University, Clemson, SC, Aug. 1985.

[29]Chen, S. J. and Tsou, F., "Computer-Based Data Acquisition of Heat Transfer in Short-Duration Flow over a Backward-Facing Step," ASME Paper 84-HT-47, 1984.

[30]Gooray, A. M., Walkins, C. B., and Aung, W., "Turbulent Heat-Transfer Computations for Rearward-Facing Steps and Sudden Pipe Expansions," *Transactions of ASME, Journal of Heat Transfer*, Vol. 107, 1985, pp. 70-76.

[31]Seki, N., Fukusako, S., and Hirata, T., "Turbulent Fluctuations and Heat Transfer for Separated Flow Associated with a Double Step at Entrance to an Enlarged Flat Duct," *Transactions of ASME, Journal of Heat Transfer*, Vol. 98, Nov. 1976, pp. 588-593.

[32]Seki, N., Fukusaki, S., and Hirata, T., "Laminar Heat Transfer Downstream of a Sudden Enlargement of a Duct," *JSME Bulletin*, Vol. 21, Feb. 1978, pp. 254-257.

[33]Sparrow, E. M., Samie, F., and Lau, S. C., "Heat Transfer from a Plate Elevated Above a Host Surface and Washed by a Separated Flow Induced by the Elevation Step," *Transactions of ASME, Journal of Heat Transfer*, Vol. 103, Aug. 1981, pp. 441-447.

[34]Tsou, F. K., "Computer-Based Data Acquisition of Heat Transfer in Short Duration Flows over Backward-Facing Steps," ASME Paper 84-HST-47, 1984.

[35]Lamb, J. P. and Polansky, G. F., "Finite Element Simulation of Incompressible Recirculating Flows with Heat Transfer," *Proceedings of the Symposium on Fluid Dynamics*, Dept. of Mechanical and Industrial Engineering, University of Illinois, Champange, April 1984, pp. 189-201.

[36]Chiney, C. C. and Launder, B. E., "On the Calculation of Turbulent Heat Transport Downstream from an Abrupt Pipe Expansion," *Numerical Heat Transfer*, Vol. 3, 1980, pp. 189-207.

[37]Gerhart, P. M. and Thimar, L. C., "A Model of Turbulent Momentum and Heat Transfer at Points of Separation and Reattachment," *Proceedings ot the Heat Transfer and Fluid Mechanics Institute*, Stafford University Press, pp. 122-134, June 1974.

[38]Nestler, D. E., "Engineering Analysis of Reattaching Shear Layer Heat Transfer," *AIAA Journal*, Vol. 11, 973, pp. 390-392.

[39]Matthews, R. D. and Ginoux, J. J., "Correlation of Peak Heating in the Reattachment Region of Separated Flows," *AIAA Journal*, Vol. 12, March 1974, pp. 397-399.

[40]Rudy, D. H. and Birch, S. F., "Mean Flow Development and Surface Heating for an Attaching Compressible Free Shear Layer," *Journal of Spacecraft and Rockets*, Vol. 11, May 1974, pp. 348-357.

[41]Keyes, J. W., "Correlation of Turbulent Shear Layer Attachment Peak Heating Near Mach 6," *AIAA Journal*, Vol. 15, Dec. 1977, pp. 1821-1823.

[42]Gerhart, P. M., "Heat Transfer Downstream of Attachment of a Turbulent Supersonic Shear Layer," *AIAA Journal*, Vol. 11, 1973, pp. 104-106.

[43]Werle, M. J., Vatsa, V. N., and Bertke, S. D., "Sweep Effects on Supersonic Separated Flow—A Numerical Study," *AIAA Journal*, Vol. 11, 1973, pp. 1763-1765.

[44]Inger, G. R., "Three-Dimensional Heat- and Mass-Transfer Effects Across High-Speed Reattaching Flows," *AIAA Journal*, Vol. 15, 1977, pp. 383-389.

[45]Vogel, J. C. and Eaton, J. K., "Combined Heat Transfer and Fluid Dynamic Measurements Downstream of a Backward-Facing Step," *Transactions of ASME, Journal of Heat Transfer*, Vol. 107, 1985, pp. 922-929.

[46]Kang, Y., Nishino, J., Suzuki, K., and Sato, T., "Application of Flow Surface-Temperature Visualization Techniques to a Study of Heat Transfer in Recirculating Flow Regions," *Flow Visualization II*, Hemisphere Publishing, Washington, DC, 1982, pp. 77-81.

[47]MacGregor, J. D. III, "An Experimental Study of Radial Jet Reattachment on a Flat Plate," M.S. Thesis, Mechanical Engineering Dept., Texas A&M University, College Station, May 1986.

[48]Suzuki, K., Ida, S., and Sato, T., "Turbulence Measurements Related to Heat Transfer in an Axisymmetric Confined Jet with Laser-Doppler Anemometer," *Proceedings of 4th Symposium in Turbulent Shear Flows*, Karlsruhe, FRG, Hemisphere Publishing, Washington, DC, Sept. 1983, pp. 18.1-18.6.

[49]Baughn, J. W., Hoffman, M. A., Takahashi, R. K., and Launder, B. E., "Local Heat Transfer Downstream of an Abrupt Expansion in a Circular Channel with Constant Wall Heat Flux," *Transactions of ASME, Journal of Heat Transfer*, Vol. 106, Nov. 1984, pp. 789-796.

[50]Ganji, A. R. and Sawyer, R. F., "Experimental Study of the Flow Field of a Two-Dimensional Pre-Mixed Turbulent Flame," *AIAA Journal*, Vol. 18, July 1980, pp. 817-824.

[51]Edelman, R. B., Marsha, P. T., and Schmotolocha, S. N., "Modeling Techniques for the Analysis of Ramjet Combustion Processes," *AIAA Journal*, Vol. 19, May 1981, pp. 601-609.

[52]Murthy, S. N. B., Osborn, J. R., Barrows, A. W., and Ward, J. R. (eds.) *AIAA Progress in Astonautics and Aeronautics: Aerodynamics of Base Combustion*, Vol. 40, MIT Press, Cambridge, MA, 1976.

[53]Hudgins, H. E. Jr., "Range Increase of Projectiles by Heat and/or Mass Addition to Base or External Flow," *AIAA Progress in Astronautics and Aeronautics: Aerodynamics of Base Combustion*, Vol. 40, edited by S. N. B. Murthy, J. R. Osborn, A. W. Barrows, and J. R. Ward, AIAA, New York, 1976, pp. 495–521.

[54]Maeda, M., Kiyota, K., and Mishita, K., "Heat Transfer to Gas Solids Two-Phase Flow in Separated, Reattached, and Redevelopment Regions," *Proceedings of 7th International Heat Transfer Conference*, Hemisphere Publishing, Washington, DC, 1982, pp. 249–254.

[55]Rossiter, J. E., "Wind Tunnel Experiments on the Flow Over Rectangular Cavities at Subsonic and Transonic Speeds," Royal Aeronautical Establishment, London, R&M 3438, AD 805489, 1966.

[56]Gharib, M., "Active Control of Cavity Shear Layer Oscillation," AIAA Paper 85-0528, 1985.

[57]White, R. A., "Some Results on the Heat Transfer within Resonant Cavities at Subsonic and Supersonic Mach Numbers," ASME Paper 71-FE-9, 1971.