A Study of Laminar Hypersonic Cavity Flows

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An experimental investigation of the distributions of pressure, recovery factor, and heat-transfer coefficient on 20° cones incorporating annular cavities was carried out in helium at $M_\infty = 11$. The effects of Reynolds number, cavity length-depth ratio, and reattachment region geometry were studied. Attention was confined to the laminar, "open" cavity flow regime. The results showed that the pressure was virtually constant on the cavity floor for a cavity length-depth ratio less than seven. A definite pressure gradient appeared at higher length-depth ratios. The recovery factor was virtually constant within the cavity and downstream and was very close to the laminar attached-flow value. The distribution of heat-transfer coefficient showed a pronounced minimum on the cavity floor, falling to about 10 to 20% of the attached-flow value. The heat-transfer coefficient passed through a maximum in the reattachment region, then went asymptotically to a value lower than the attached-flow value. The integrated heat-transfer rate in the separated flow region was in excellent agreement with Chapman's laminar mixing layer theory, being about 55% of the attached-flow value. However, this significant reduction in heat transfer was almost nullified by the increased heat-transfer rates close to reattachment.

Nomenclature

A = model surface area
C_p = specific heat at constant pressure
D = maximum depth of cavity, measured in direction normal to slant side of cone
H = comparison parameter defined by Eq. (1)
h = local heat-transfer coefficient defined by modified Newtonian law, $q = h(T_w - T_{aw})$
k = coefficient of thermal conductivity
L = length of cavity, measured along slant side of basic cone
L_1 = length of model surface between nose and separation shoulder, measured along slant side of cone
$\tilde{L}$ = swept or wetted length of cavity, $\tilde{L} = L + (\pi - 2)D$ in present instance
M = Mach number
Pr = Prandtl number, $C_p\mu/k$
p = pressure
q = local heat transfer per unit area per unit time
R = reattachment shoulder point
R_1 = cavity floor point at beginning of reattachment corner radius
Re = Reynolds number, with fluid properties evaluated at the edge of the boundary layer or shear layer
r = local recovery factor, defined by $r = (T_{aw} - T_e)/(T_0 - T_e)$
S = separation shoulder point
S_1 = cavity floor point at end of separation corner radius
St = Stanton number, $h/\rho_e C_p u_e$
T = absolute temperature
u = velocity component in x direction
x = distance coordinate measured from nose along slant side of cone
$\bar{x}$ = distance upstream or downstream measured from the reattachment point along slant side of basic cone
$\tilde{x}$ = distance along surface of cavity measured from the reattachment shoulder point
δ_S = boundary-layer thickness at separation point
ϵ = height of the reattachment shoulder above the surface of the basic cone, measured normal to the cone surface
μ = coefficient of viscosity
ρ = mass density

Subscripts

aw = adiabatic wall conditions
cone = conditions on basic 20° cone
e = values at edge of boundary layer or shear layer
w = model wall conditions
∞ = freestream conditions ahead of all shock waves

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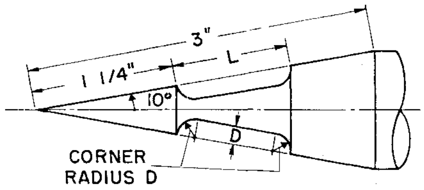
Introduction

THE present work is an experimental investigation of a particular form of hypersonic separated flow. An attempt has been made to construct and study as clean a configuration as possible, with flow complications reduced to a minimum. This approach was chosen in an effort to learn more about the basic nature of a separated flow and also to provide a foundation for an investigation of more complex forms of flow separation.

In practical terms, the design of the experiments was influenced by the work of Chapman and his co-workers, who demonstrated[1] that the stability of the laminar separated layer increases greatly with increasing supersonic Mach number. Chapman also showed in a theoretical analysis[2] that the over-all heat-transfer rate in a region of laminar separated flow was little more than half that which would occur with a corresponding attached laminar boundary layer. As a result, regions of laminar separated flow seemed to offer a means of reducing heat-transfer rates in critical areas on hypersonic flight vehicles. Experimental investigations[3,4] added support to this suggestion.

The present tests were therefore run at a sufficiently high Mach number to obtain regions of pure laminar separated flow; the laminar regime being attractive not only because of its simplicity, but also because of its possible practical utility as a means of alleviating kinetic heating problems.

A cavity flow was chosen for the investigation because this type of flow retains the defining features of a separated flow without the complication of free separation and reattachment points. The cavities were mounted on the surface of a sharp-nosed cone in order to obtain a thin and well-defined boundary layer at separation and also to provide a normalizing configuration on which the surface pressure was constant. All cavity flows were "open," i.e., the dividing streamline bridged the cavity from separation to reattachment and did not reattach on the cavity floor. Measurements were confined to



CONFIGURATIONS TESTED		
L (INCHES)	D (INCHES)	L/D
5/16	1/8	2·5
5/16	3/32	3·33
5/8	1/8	5·0
5/8	3/32	6·67
5/8	1/16	10·0
1 1/4	1/8	10·0
1 1/4	3/32	13·33
1 1/4	1/16	20·0

Fig. 1 External geometry of models.

the laminar regime, and the Mach number at the edge of the shear layer was always hypersonic.

The investigation consisted of measurements of the local distributions of pressure, recovery factor, and heat-transfer coefficient. Measurements were made within the cavities and also downstream of reattachment. The reattachment region was investigated in some detail because of the importance of the flow in this region in defining the over-all properties of the cavity flow.

Experimental Method

All experiments were conducted in the 3-in. helium hypersonic wind tunnel of the Gas Dynamics Laboratory at Princeton University. This tunnel is fully described in Ref. 5.

All tests were made with a stagnation temperature of room temperature. Most of the tests were made in a contoured nozzle that gave a freestream Mach number of 11. With this nozzle, tests were normally run at 3 stagnation pressure levels, 400, 700, and 1000 psia. A few tests were made in another contoured nozzle at a freestream Mach number of 20. All models tested were based on a 20° total-angle cone, and the significant Mach and Reynolds numbers are the cone-surface values. Table 1 gives the freestream Mach number, the Mach number on the cone surface, and the Reynolds number per inch based on conditions at the edge of the cone boundary layer, calculated from the tunnel calibration tests and from the inviscid-flow tables of Ref. 6.

Heat-transfer measurements were made using various versions of the transient technique. Sudden exposure of the initially isothermal models to the flow was achieved by quickly withdrawing a lucite plug from the nozzle throat. High-speed schlieren motion pictures showed that the final configuration of shock waves and shear layers could be established in about $1\frac{1}{2}$ msec.

Most heat-transfer measurements were made using thin-walled nickel models instrumented with thermocouples. Conduction rates along the skin were found to be important, and it was felt to be necessary to check the results obtained from conventional thin-wall data reduction methods by using the full heat-transfer equation for an element of the model skin. This is the "conduction method" of data reduction referred to in the figures. Full details of the data reduction and interpretation may be found in Ref. 7.

Table 1

p_0, psia	M_∞	M_{cone} (20° cone)	Re_e/in.
400	11.0	6.46	5.9×10^5
700	11.3	6.54	9.73×10^5
1000	11.6	6.61	13.38×10^5

As a check on the absence of initial transient disturbances in the cavity flows, measurements were made of the heat-transfer rate at a station on the cavity floor of one model using a modification of the insulated mass technique described by Westkaemper.[8] In this method, a measuring element of low heat capacity is mounted in an insulating support on a basic model of very high heat capacity. By using an external source of heat transfer (in our case, infrared heating lamps outside the tunnel) to reverse the action of the convective stream, the temperature of the measuring element can be made to cross the temperature-time history of the basic model, first under the action of the stream and the external heat-transfer source and then under the action of the stream alone. At the latter crossing point, the model surface will be virtually isothermal if the basic model is made of an excellent conductor, and transient heat-transfer measurements can be made a considerable time after the model has been first exposed to the flow.

To provide supplementary information in situations where the thin-wall technique was not practical, some measurements were made using the transient calorimeter method. This technique was used in particular to obtain the average heat-transfer rate in the immediate vicinity of the reattachment shoulder on two cavity configurations. The measuring element used in these cases was an insulated copper ring mounted in the reattachment region.

Most recovery factor measurements were made using the thin-wall heat-transfer models, steady-state conditions being reached within the 8-min maximum running time of the helium tunnel. A check on the absence of significant conduction errors was made by building several Plexiglas recovery factor models instrumented with surface thermocouples.

The external geometry of the models tested is given in Fig. 1. All models were axisymmetric and were tested at zero angle of attack. Each model had a nose diameter of 0.005 in. The models were aligned with the stream while the tunnel was running, using four pressure taps spaced 90° apart at a single axial station. Pressure models were built for all configurations listed in the table of Fig. 1. However, for the heat-transfer and recovery factor tests, the $\frac{1}{16}$-in.-deep cavity models were omitted.

A conventional single pass schlieren system was used to take plate and motion picture photographs of the flow patterns. The movie camera was run at up to 8000 frames/sec in studying the steadiness of the cavity flows.

Experimental Results

Measurements were made of the distributions of pressure, recovery factor, and heat-transfer coefficient on simple 20° cone models for normalization and comparison purposes, and these data will be presented first. The spot checks made on both cone and cavity models at a freestream Mach number of 20 yielded normalized results that were virtually identical to the Mach 11 tests. As a result, only data at $M_\infty = 11$ have been presented in the figures that follow. For the heat-transfer tests, the model wall temperature was varied somewhat around room temperature (the stagnation temperature of the tunnel), and heat transfer was always from model to stream.

The pressure on the basic cone model was found to be constant with axial distance from the nose when allowance was taken of the slight Mach number gradient in the test section. This indicated that the chosen nose diameter was indeed small enough for the effects of nose bluntness to be neglected.

The cone recovery factor results are given in the upper-half of Fig. 2 as local recovery factor against Reynolds number at the edge of the boundary layer. On this figure, the theoretical recovery factor in laminar flow[9] is given, together with the well-known approximation to the turbulent recovery factor, $r = (Pr)^{1/3}$. It is seen that the experimental re-

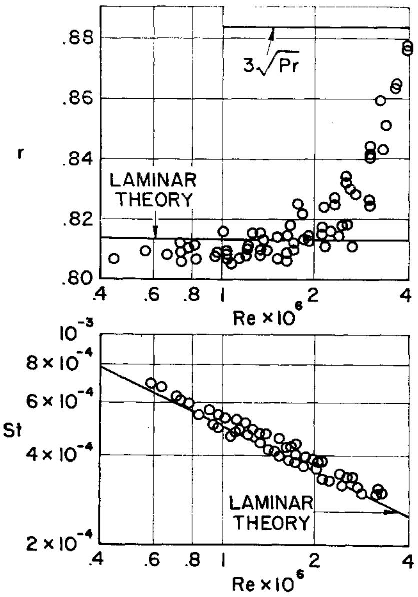


Fig. 2 Cone recovery factor and heat transfer.

sults agree quite well with the laminar theory up to a Reynolds number of about two million. At higher Reynolds numbers, the measured recovery factor increases and approaches the turbulent value at about $Re = 4 \times 10^6$. Natural transition apparently occurs on the basic cone at about $Re = 2 \times 10^6$, and some confirmation of this result was obtained from schlieren photographs.

The cone heat-transfer data are given in the lower-half of Fig. 2, where the local heat-transfer coefficient has been presented in terms of the Stanton number. The theoretical dependence in laminar flow from Ref. 9 is also given on the figure, and it is seen that good agreement is obtained between theory and experiment. However, the heat-transfer data do not show transition. This is largely due to the fact that a constant value of the (laminar) recovery factor was used throughout to obtain the heat-transfer coefficient from the measured heat-transfer rate rather than the true experimental variation, and this will tend to obscure the rise in the heat-transfer coefficient in the early stages of transition. Only the laminar regime was of interest in the present study.

Transition was also found to occur on the cavity models within the working range of the tunnel. The Reynolds number at which transition appeared was determined from schlieren photographs and from measurements of the local recovery factor, as was done for the pure cone, and also by measuring the pressure in the cavity reattachment corrner. (This latter method is described by Larson and Keating in Ref. 10.) It was concluded that natural transition occurred on the cavity models at a reattachment Reynolds number (based on the length from nose to reattachment shoulder) of two million. To within the present order of accuracy, therefore, the laminar cavity flows were as stable as the corresponding attached laminar boundary layer, in agreement with the trend of Chapman's data[1] for high supersonic Mach numbers. It should be remembered, however, that in the present investigation the ratio of the model wall temperature to the laminar adiabatic wall temperature was always greater than or equal to unity. No information was obtained for the "cold-wall" case.

Since the present investigation was concerned with the laminar regime only, the experimental range of reattachment Reynolds number was restricted to values below about two million. Laminar data could be obtained for the $\frac{5}{16}$-in.-long cavities at all 3 test levels of stagnation pressure; the $\frac{5}{8}$-in.-long cavities were laminar at stagnation pressures of 400 and 700 psia, and the $1\frac{1}{4}$-in.-long cavities were laminar only for $p_0 = 400$ psia.

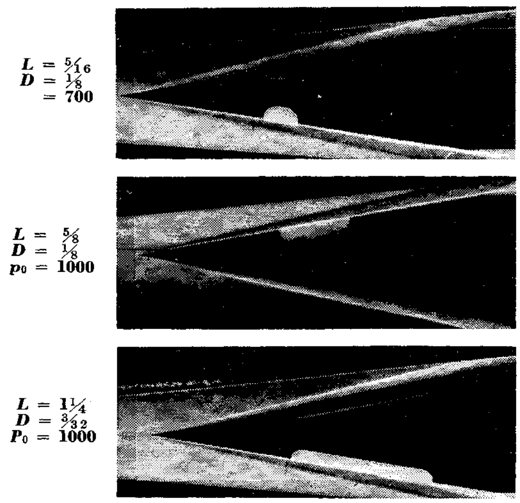


Fig. 3. Typical schlieren photographs.

Sample schlieren photographs of the flow over various cavity models are given in Fig. 3. These photographs show clearly that the cavity flows were "open." Dummy model studies at various values of cavity length-depth ratio showed that the change from open to closed flow took place between $L/D = 20$ and $L/D = 40$. As a result, only cavities with $L/D \leq 20$ were studied in the present investigation.

The pressure distribution between separation and reattachment on the cavity models is typified by the curves of Fig. 4. This figure shows the normalized pressure within the cavities of models with $L/D = 5$, 10, and 20, at $p_0 = 400$ psia. For the deepest cavity, the pressure is constant on the cavity floor, with recompression confined to the last 10% of the cavity near reattachment. With increasing length-depth ratio, however, a pressure gradient appears on the cavity floor, and recompression takes place along the entire cavity length. This effect is shown more clearly in Fig. 5, in which the normalized pressure at each end of the cavity floor is plotted against cavity L/D for all models at $p_0 = 400$ psia. This figure shows that, for $L/D < 7$, the constant floor-pressure cavity flow is obtained, and, for higher values of L/D, a pressure gradient appears which becomes more pronounced as the length-depth ratio increases. It should be emphasized that all data are for open flow. (Closed cavity flow exhibits a distinctive "kink" in the pressure distribution.) A number of other investigators[11-13] working with transitional

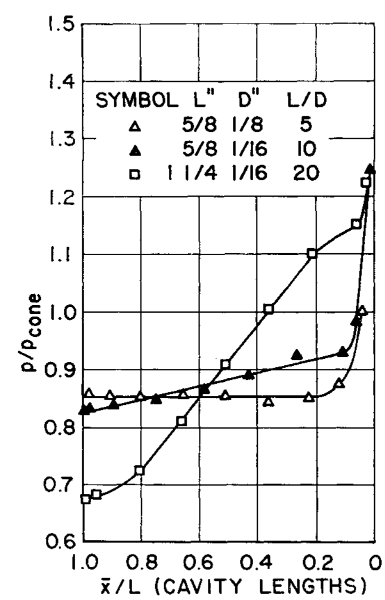


Fig. 4 Cavity pressure distributions, p_0 = 400 psia.

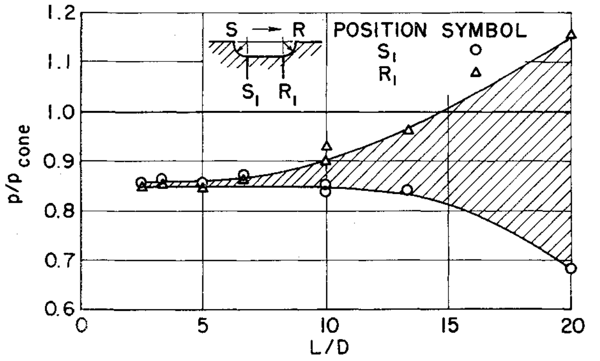


Fig. 5 Cavity floor pressures, p_0 = 400 psia.

cavity flows at supersonic Mach numbers have observed the change from constant floor pressure to flows with a pressure gradient as L/D increases. Johannesen[11] had laminar flow for his shortest cavities and suggested that the change was due to the appearance of transition within the cavity. This explanation is clearly incorrect, since all of the present data were obtained in purely laminar flow.

It is seen from Fig. 5 that the cavity floor pressure is somewhat lower than the cone pressure, indicating that the dividing streamline bends in toward the model axis at separation. Since a mass balance must be set up between mass reversed into the cavity at reattachment and mass drawn into the shear layer, the inward inclination of the dividing streamline may well be an attempt of the flow to compensate for the increasing cavity cross-sectional area with axial distance from the nose on the present conical geometry. However, this cannot be a complete explanation, because a similar effect has been observed in some two-dimensional flows.

The range of Reynolds number per inch investigated in the present study was not large, particularly because of the limitation introduced by the occurrence of transition. However, a small effect of unit Reynolds number was observed in the pressure results. This took the form of a small displacement of the pressure distribution curves in the cavities to higher values of p/p_{cone} with increasing stagnation pressure. This trend is the reverse of that observed in Ref. 13 for fully turbulent cavity flows.

The pressure distribution downstream of reattachment is typified by the p_0 = 400 psia results of Fig. 6. The abscissa in this figure is the distance downstream of reattachment measured in cavity lengths. On this figure, an inverse first-power decay curve is indicated for comparison purposes. It is seen that the high pressure at reattachment decays to the cone value about one cavity length downstream of the reattachment shoulder.

Typical recovery factor results are shown in Fig. 7, in which data from two $\frac{5}{8}$-in.-long cavities are presented. The

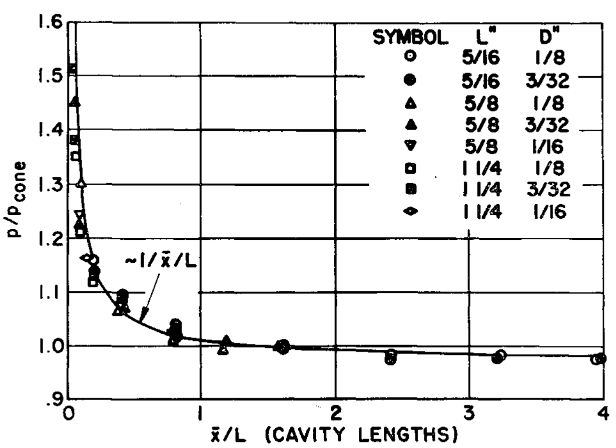


Fig. 6 Downstream pressure distribution, p_0 = 400 psia.

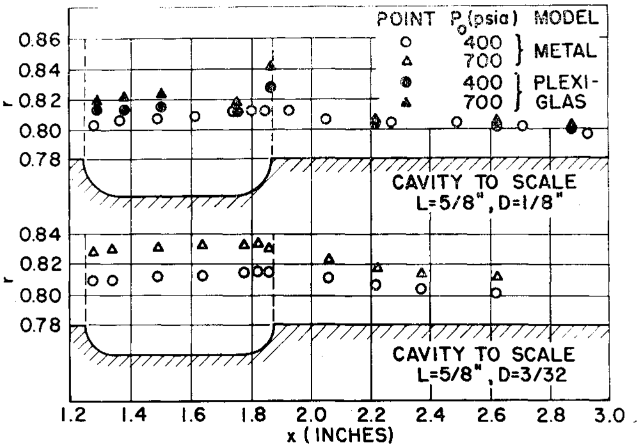


Fig. 7 Recovery factor on two models.

local recovery factor is virtually constant within the cavity and downstream, and this constant value is about the same as the laminar recovery factor on the basic cone. There is a slight increase in recovery factor level with increasing unit Reynolds number. The recovery factor right at the reattachment shoulder was measured for the $\frac{5}{8}$-in.-long, $\frac{1}{8}$-in.-deep cavity with a specially built Plexiglas model and was found to be of the order of 5% higher than elsewhere (see Fig. 7). There is some tendency in the literature to infer that the assumption of a Prandtl number of unity (and therefore a recovery factor of unity) will be better at a cavity reattachment point than elsewhere, since this is a stagnation point of the flow. The present results show that this inference is not justified. Chapman's theory[2] predicts that the average recovery factor in laminar cavity flow is essentially the same as that in an attached laminar boundary-layer flow, and the present experiments are in agreement with this theoretical result. The recovery factor distribution on every cavity model studied was found to exhibit the same general features as the results of Fig. 7.

The heat-transfer results are given in Fig. 8, and again only sample data are shown.† The distribution of heat-transfer coefficient shows virtually the same characteristics on each of the three cavities given, and this, in fact, was true of all the cavity geometries studied. Perhaps the most important feature of the heat-transfer distribution is the existence of an extreme minimum on the cavity floor, where the heat-transfer coefficient drops to about 10 to 20% of the attached flow value. The heat-transfer coefficient has a maximum in the vicinity of reattachment, where values several times higher than the cone value are obtained. In Fig. 8b, the average heat-transfer coefficient over the surfaces of a small element at the reattachment corner is noted, and it is almost three times the cone value. The reattachment heat-transfer peak is not noticeable in Fig. 8a, because, for the $\frac{5}{16}$-in.-long cavities, the shear layer was not thick enough at reattachment to allow instrumentation to be installed on the thin-wall model closely enough to the reattachment shoulder to pick up the highest values of the heat-transfer rate. However, measurements made on the $\frac{5}{16}$-in.-long, $\frac{1}{8}$-in.-deep cavity with a copper element mounted at the reattachment corner showed that the peak in heat transfer was present on this model as on the others.

The heat-transfer coefficient decays from the high reattachment values to the cone value about one cavity length downstream of reattachment, and, unless transition occurs, it

† The author would like to point out that the preliminary cavity flow heat-transfer data given in Ref. 16 are to be replaced by the present results. The preliminary measurements represent a "smeared" version of the present distributions and are much less accurate than the new measurements. The reason for these differences is discussed in detail in Ref. 7.

goes asymptotically to a final value lower than the cone value. This indicates that the presence of the shear layer thickens the boundary layer on the downstream surfaces relative to the boundary layer that would have occurred with the cavity absent.

In Fig. 9, all of the laminar heat-transfer data within the cavities have been presented as normalized heat-transfer coefficient against wetted length along the cavity measured in cavity lengths. An inverse first-power dependence has been presented for comparison purposes. In fact, close to the reattachment shoulder, the dependence is closer to an inverse half power (suggestive of a boundary-layer type of growth). The data of Fig. 9 show that the deeper cavities

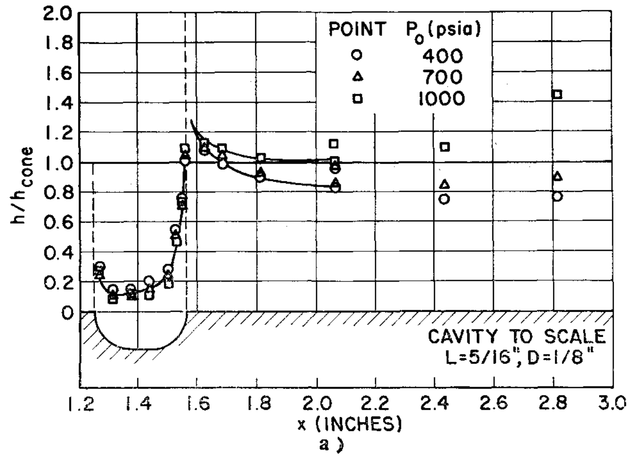


Fig. 8a Local heat-transfer coefficient, $L = \frac{5}{16}$ in., $D = \frac{1}{8}$ in.

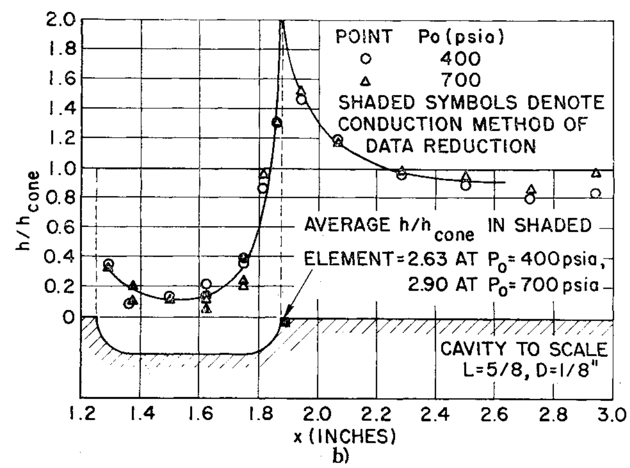


Fig. 8b Local heat-transfer coefficient, $L = \frac{5}{8}$ in., $D = \frac{1}{8}$ in.

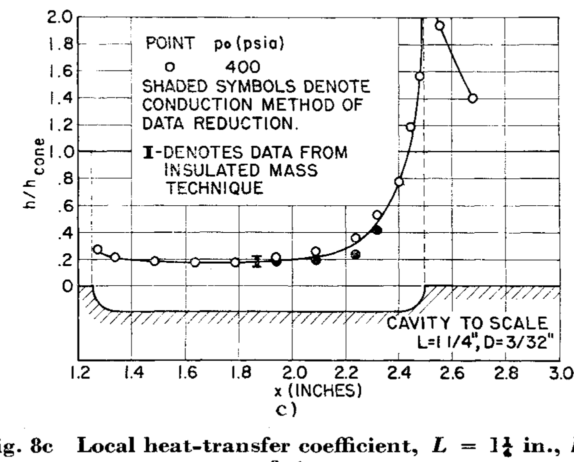


Fig. 8c Local heat-transfer coefficient, $L = 1\frac{1}{4}$ in., $D = \frac{3}{32}$ in.

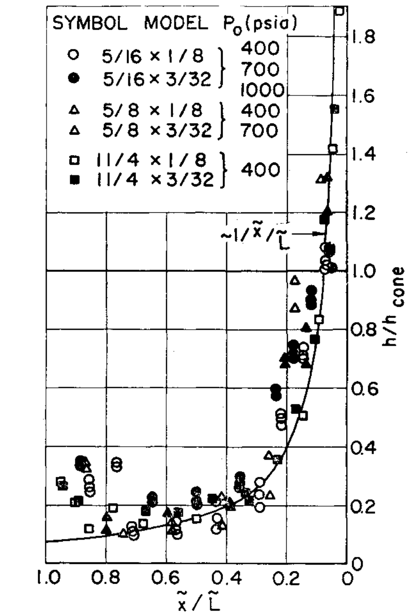


Fig. 9 Cavity heat-transfer coefficient, all tests.

have slightly lower values of floor heat-transfer coefficient, as one would expect from the thicker buffering core shielding the cavity walls from the external stream.

As mentioned previously, the average heat-transfer rate to a small element at the reattachment corners of the $\frac{5}{16}$- $\times$ $\frac{1}{8}$-in. and $\frac{5}{8}$- $\times$ $\frac{1}{8}$-in. models was measured. The values obtained were found to be about half as large as the values given by the theory of Chung and Viegas.[14] In addition, the theory indicates a value for the characteristic dimension of the reattachment region (the distance in which most of the pressure decay takes place) which is much smaller than that obtained in the present work. One possible reason for the discrepancy between the present experiments and the theory of Ref. 14 is that Chung and Viegas make the a priori assumption that the dividing streamline reattaches at a right angle to the cavity surface. On physical grounds, it seems difficult to justify this assumption.

A quantity that is of considerable interest in the study of separated flows is the ratio of the integrated heat-transfer rate in a separated flow to that in a corresponding attached flow. This ratio is the final product of Chapman's theory and is a measure of the advantage to be obtained (in terms of heat-transfer reduction) by separated flow. In order to integrate the local heat-transfer rate over the entire cavity length, it is necessary to know the heat-transfer rates in the reattachment region fairly accurately. For the present work, integration could be carried out only for the $\frac{5}{16}$- $\times$ $\frac{1}{8}$-in. and $\frac{5}{8}$- $\times$ $\frac{1}{8}$-in. cavities, because only for these two configurations were special models built which obtained the average heat-transfer rate right at the reattachment corner. Even for these cases, it was necessary to make assumptions about the variation of the local heat-transfer rate in the immediate vicinity of reattachment. However, the validity of these assumptions was checked by comparing extrapolations of the data trends from outside of the reattachment region, and it is believed that the assumptions are plausible.

In view of the fact that the recovery factor is virtually constant in the present cavity flows (see Fig. 7), integration was carried out using the heat-transfer coefficient rather than the heat-transfer rate. A comparison parameter H was defined as

$$H = \frac{\int_S^R \frac{h}{h_{\text{cone}}} h_{\text{cone}} \, dA_{\text{cavity}}}{\int_{L_1}^{L_1 + L} h_{\text{cone}} \frac{dA_{\text{cone}}}{dx} dx} \tag{1}$$

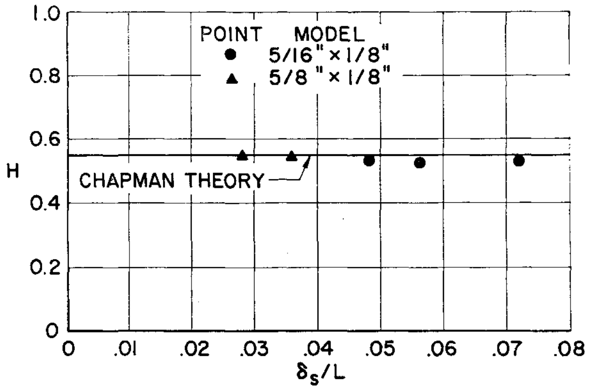


Fig. 10 Integrated heat-transfer comparison.

where h/h_{cone} is the normalized heat-transfer coefficient on the cavity model. The parameter H is comparable to Chapman's[2] parameter $q_w/(\bar{q}_w)_{bl}$.

H was calculated from the experimental data for the $\frac{5}{16}$- × $\frac{1}{8}$-in.-cavity model at p_0 = 400, 700, and 1000 psia and for the $\frac{5}{8}$- × $\frac{1}{8}$-in.-cavity model at p_0 = 400 and 700 psia. These five experimental points are shown in Fig. 10 as H against the ratio of the boundary-layer thickness at separation to the cavity length. Also shown in this figure is Chapman's theoretical prediction for a Prandtl number corresponding to helium. It is seen that there is excellent agreement between Chapman's theory and the present experimental results. However, it should be noted that the two cavity flows studied are particularly suitable for comparison with Chapman's theory. The boundary-layer thickness at separation is less than 10% of the cavity length in the cases investigated, and both cavity geometries have length-depth ratios less than 7 and are therefore in the constant floor-pressure regime.

The present experiments give further confirmation that a region of cavity flow can provide a sizable reduction in over-all heat-transfer rate. However, it is seen from the results of Fig. 8 that the heat-transfer rate is higher than the cone value for some distance downstream of reattachment. In assessing the total advantage of replacing an attached laminar boundary layer with a laminar cavity flow, it is necessary to take the downstream increase in heat transfer into account. In the present work, when integration was carried out over the cavity plus a number of cavity lengths downstream, it was found that the total reduction in heat-transfer rate was only 20% for the $\frac{5}{16}$- × $\frac{1}{8}$-in. model and 10% for the $\frac{5}{8}$- × $\frac{1}{8}$-in. model. In other words, most of the reduction in heat-transfer rate obtained in the separated flow region was effectively countered by the increased heat transfer downstream of reattachment. In fact, the main reason that any over-all reduction was obtained at all was that the asymptotic value of h/h_{cone} was less than unity.

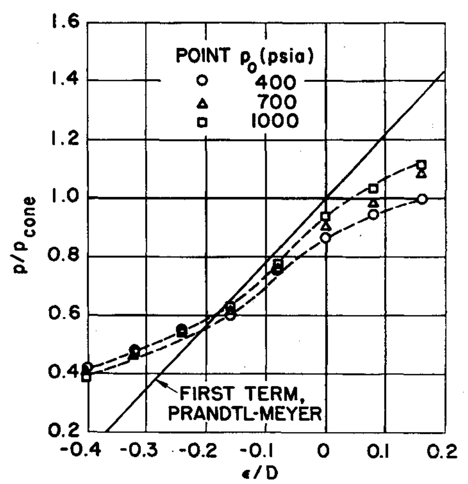


Fig. 11 Cavity floor pressure against reattachment shoulder height.

We see, therefore, that the laminar cavity flow in its pure form does not offer a significant reduction in over-all heat-transfer rate. It does, however, offer a significant redistribution of local heat-transfer rate, and this might be useful in certain practical instances. The very low heat-transfer rate on the cavity floor might be used to shield a critical portion of the surface of a hypersonic flight vehicle, provided that the rest of the structure could be protected against the higher heat-transfer rates in the immediate vicinity of reattachment.

In an attempt to understand more clearly the reattachment process, a few pressure investigations were carried out in which the model geometry at reattachment was changed. Rounding the shoulder at reattachment was found to have virtually no effect on the pressure distribution. However, the effects of changing the height of the reattachment shoulder relative to the separation point were more interesting. In Fig. 11, the normalized pressure at the midpoint of the cavity floor on the $\frac{5}{8}$- × $\frac{1}{8}$-in.-cavity model is plotted against the ratio of the reattachment shoulder height to the cavity depth. The pressure that would be given by a simple Prandtl Meyer expansion, or slight compression, is also indicated. It is seen that the cavity floor pressure is less than the Prandtl Meyer pressure until a value of ϵ/D of -0.2. Further lowering of the reattachment shoulder results in higher floor pressures. During the experiments, it was observed that when ϵ/D was about -0.2, a slight ambiguity existed in the pressure distribution near reattachment. The model used had two pressure taps 180° apart at each measuring station, and, for this particular value of ϵ/D, the pressure was not always the same at each tap. In fact, the readings would change arbitrarily throughout the run between a number of steady positions.

The unsteadiness is apparently involved in the adaptation of the cavity type of flow to the flow over a rearward-facing step. As the reattachment shoulder height is dropped, a point will be reached at which reattachment can no longer occur at the shoulder and will occur downstream. The cavity is then completely immersed in a rearward-facing-step flow, as the pressure distribution over the model demonstrates. In Fig. 12, the pressure distribution on the $\frac{5}{8}$- × $\frac{1}{8}$-in.-cavity model is given for $\epsilon/D = -0.4$. The characteristic peak in pressure at the reattachment point has been replaced by the monatonic rise in pressure typical of a step flow.

In the present work, it was found to be most difficult to obtain information on the steadiness of the cavity flows. Simple calculations indicated that, if any oscillatory unsteadiness existed, the frequencies involved might be as high as half a megacycle. The limitations of conventional instrumentation make detection or analysis of frequencies of this order virtually impossible. However, some information was obtained from very high-speed movie photographs and randomly spaced 1-μsec spark schlierens. It was possible to determine that the cavity flow was quite unsteady as soon as transition occurred between separation and reattachment. (The unsteadiness took the form of fluctuation in the position of the transition point, wave radiation from the rear of the cavity, belling of the shear layer, and variation in the appearance of the weak shockwave as the flow reattached.) The spark schlierens also showed unsteadiness in some spike flows that were investigated. In the case of the laminar cavity flows, the maximum fluctuation of the shear layer which could be detected was less than 4% of the cavity depth, and the maximum bow shockwave fluctuation was about half this value. No fluctuations in pressure level were ever observed on the manometers in studying the laminar cavity flows. The heat-transfer and recovery factor experiments made in the laminar regime were always repeatable to a high-order of accuracy.

It was concluded from the foregoing that the laminar cavity flows were steady within the limits of the detection techniques. No evidence of mass shedding of the type observed by Charwat et al.[13] was ever detected in the present experiments. It is comforting to note that other investigators[10, 15] have found that the possibility of cavity resonance seems to decrease with increasing Mach number. Larson and Keating[10] found that the presence of resonance in their laminar cavity flows was hardly noticeable at a Mach number of four.

Concluding Remarks

The following conclusions and comments can be made from the preceding results.

1) It is possible to obtain a regime of open laminar cavity flow, characterized by well-defined and stable properties, at hypersonic Mach numbers and normal continuum-flow Reynolds numbers. The flow regime studied in the present investigation appears to be suitable as a basis for studies of more complex forms of separated flow.

2) Although the information obtained on cavity flow transition in the present study was limited, it appears that the laminar cavity flow is at least as stable as an attached laminar boundary layer at hypersonic Mach numbers.

3) The region of influence of significant flow disturbance due to the presence of a cavity extends about one cavity length downstream of reattachment. In addition, the asymptotic level of the heat-transfer coefficient is somewhat lower than the attached flow distribution when a cavity is present.

4) In laminar, open cavity flow, two forms of pressure distribution are possible. For a cavity length-depth ratio less than 7, the floor pressure is constant over the first 90% of the cavity length, with recompression confined to the last 10% of the cavity near reattachment. For length-depth ratios greater than 7, a definite pressure gradient exists on the cavity floor and recompression takes place along the entire cavity length.

5) The recovery factor is virtually constant within the cavity and downstream of reattachment, and it is very close to the laminar attached flow value. The recovery factor distribution does exhibit a slight peak at reattachment but is only about 5% higher at this point than elsewhere.

6) The heat-transfer coefficient is very low on the cavity floor, falling to a minimum value of about 10 to 20% of the attached flow heat-transfer coefficient. This pronounced local heat-transfer reduction might well be useful in practical applications.

7) The heat-transfer coefficient is high in the immediate vicinity of reattachment, where a maximum value several times higher than the attached flow heat-transfer coefficient is obtained. In the present work, however, the theory of Chung and Viegas was found to overestimate the average heat-transfer coefficient in the reattachment region by a factor of 2.

8) The theoretical analysis of Chapman for the integrated heat-transfer rate in a laminar cavity flow is in excellent agreement with experiment, at least for short, deep cavities with relatively thin boundary layers at separation.

9) Although the heat-transfer rates over most of the cavity surface are very much lower than the attached flow heat transfer, the considerable increase in the heat-transfer rates in and downstream of the reattachment region nullifies most of the heat-transfer reduction obtained in the separated flow region. Although the total reduction in heat-transfer rate in the cavity was 45% of the attached flow value, this was reduced to 20% or less when the integration included at least one cavity length downstream.

10) Within certain limits, changes in the geometry of the reattachment region have little effect on the basic characteristics of a laminar cavity flow. However, if the reattachment shoulder of a cavity configuration is sufficiently lowered, the type of reattachment changes and a flow pattern more typical of that over a rearward facing step will be obtained.

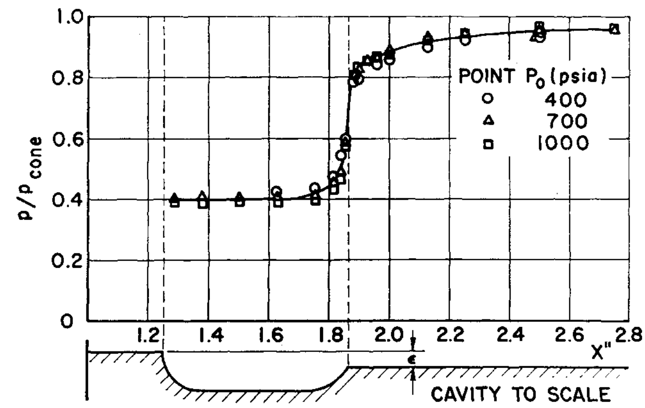


Fig. 12 Pressure distribution, $L = \frac{5}{8}$ in., $D = \frac{1}{8}$ in., $\epsilon/D = -0.4$.

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