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HEAT TRANSFER AND AIR FLOW IN A TRANSVERSE RECTANGULAR NOTCH

JAY FOX

National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio

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Abstract—Heat-transfer parameters and recovery factors on all surfaces of transverse rectangular notches, with length-to-height ratios L/H of ¼, to 1¾ are reported for air speeds from 160 to 600 ft/s. Heat-transfer coefficients are proportional to the free-stream mass flux $\rho_e U_e$ raised to the 0·8 power, which continues in a new range of L/H the previous controversy with Larson's measurements in turbulent flow and Charwat's ideas. A tentative proportionality is found between heat-transfer coefficient and notch length raised to the −0·2 power. This proportionality makes possible a dimensionless correlation. Recovery factors are consistent with a previously proposed concept of distinct flow regimes in notches in different ranges of L/H. Temperatures in the flow near the notch surface agree with neither the turbulent boundary layer profiles nor the assumptions of existing theories of heat transfer in notches.

NOMENCLATURE

- C_p, surface pressure coefficient, $(p - p_r)/(\rho_r U_r^2/2)$;
- c, specific heat of air at constant pressure;
- H, notch height;
- h, local heat-transfer coefficient, q_w/t_w;
- k, thermal conductivity of air;
- L, notch length;
- p, surface pressure;
- q_w, heat liberated at surface per unit time and area;
- R, recovery factor, $1 - (t_s - t_a)/(U_r^2/2c)$;
- T, temperature parameter $(tk_s/q_w)(\rho_r U_r/\mu_s)^{0\cdot 8}$ [ft$^{0\cdot 2}$];
- t, temperature *rise* due to heating [degF];
- t^*, $t\rho c\sqrt{(\tau_w/\rho)}/q_w$;
- t_a, unheated surface temperature [°F];
- t_s, stagnation chamber temperature [°F];
- U, mean velocity [ft/s];
- W, heat-transfer parameter, $(h/k_s)(\mu_s/\rho_r U_r)^{0\cdot 8}$ [ft$^{-0\cdot 2}$];
- $\bar{W}$, dimensionless heat-transfer parameter, $(hL/k_s)(\mu_s/\rho_r U_r L)^{0\cdot 8}$;
- X, distance from front side of notch [in];
- X_1, distance along periphery of notch from back edge [in];
- Y, distance above bottom of notch [in];
- Y^*, $Y\sqrt{(\tau_w/\rho)}/q_w$.

Greek symbols

- μ, viscosity;
- ρ, density;
- σ, Prandtl number;
- τ_w, surface shear stress.

Subscripts

- e, edge of free stream bordering upon free shear layer;
- r, reference location 0·25 in ahead of notch;
- s, stagnation chamber;
- w, surface.

INTRODUCTION

A TRANSVERSE rectangular notch in a plane surface causes little change in a uniform free stream that is flowing past the cutout, if the length of the notch in the direction of the free-stream flow is not too great in relation to the height. A shear layer like that of a free jet boundary forms over the cutout on the border of the free stream. Part of this free shear layer is deflected into the notch at the back edge, giving rise to a flow in the notch.

Measurements of heat transfer in cutouts

Short notches with length dimensions L up to 1¾ times their height H had not been investigated for thermal effects prior to the present investigation. Larson [1] measured the average heat-transfer coefficient to longer notches with L/H of 4·8 or more. In laminar flow, average coefficients were about 56 per cent of corresponding coefficients that were measured on models with a straight heated portion in place of a cutout. In turbulent flow, the average coefficients were proportional to the free-stream mass flux $\rho_e U_e$ raised to the 0·6 power, whereas the straight-sided models with turbulent boundary layers engendered average coefficients that were proportional to $\rho_e U_e$ raised to the 0·8 power.

In subsonic flow, Charwat [2] reported local heat-transfer results in long rectangular notches ($L/H > 2$) in turbulent flow at one free-stream condition.

Seban and Fox [3] presented measurements of pressure, recovery factor, and heat-transfer coefficient on the bottom of two notches, $L/H = 1{\cdot}84$ and 3·47. The back sides of the notches were formed by thin fences as shown in Fig. 1. Turbulent flow existed in the notch, adjacent to the subsonic free stream. The heat-transfer coefficients were proportional to the 0·8 power of $\rho_e U_e$, a substantially different exponent from the 0·6 reported by Larson.

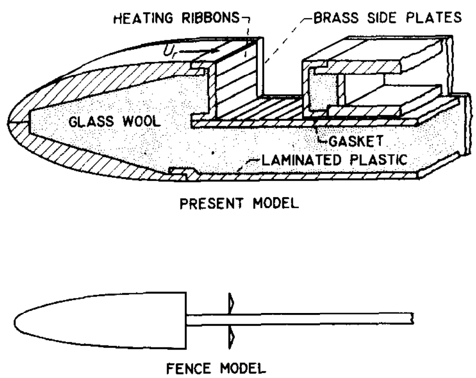

FIG. 1. Present model and Seban–Fox fence model.

Theories of heat transfer in notches

Chapman [4] and Korst [5, 6] in laminar and turbulent flow, respectively, visualized an arbitrarily shaped cutout that contained a quiescent fluid at a uniform temperature and pressure. A free shear layer, which was between the quiescent fluid and the free stream, governed both the heat transfer and the momentum exchange of the cutout. The Chapman result was that the average heat-transfer coefficient of a cutout was 56 per cent of the average coefficient of a flat plate with the same length as the cutout. This result was verified experimentally by Larson. Korst concluded that the heat-transfer coefficient at low speeds was directly proportional to $\rho_e U_e$, in contrast with the experimental results by Larson and Seban and Fox.

Charwat [2] visualized the heat exchange from a notch as being governed by a vortex in the back corner. This vortex received fluid intermittently from the free shear layer and ejected it from the notch after it had participated in the vortical motion. Charwat's result was the proportionality of the heat-transfer coefficient to $(\rho_e U_e)^{0{\cdot}6}$, which was measured by Larson (but not Seban and Fox) in turbulent flow.

None of the analyses produce a proportionality of heat-transfer coefficient to $(\rho_e U_e)^{0{\cdot}8}$ as measured by Seban and Fox. Their report also showed the major temperature drop in the turbulent flow to be near the surface, a region that is ignored in the analyses. The nonquiescent nature of the notch flow that belies the assumptions of Korst is well-known in turbulent flow from the results of Roshko [7] and Seban and Fox that show mean velocities near the notch surfaces of the order of 0·4 U_e.

MEASUREMENTS OF SURFACE QUANTITIES

In the present experiment, the two-dimensional model that is shown in Fig. 1 spanned the 6 in width of a 6 by 9 in wind tunnel and divided the air flow into upper and lower streams, each $2\frac{1}{2}$ in thick. The notch was 2·05 in of height, and it was varied in length in multiples of 0·505 in by relocating the back side.

At the reference location $\frac{1}{4}$ in ahead of the notch, ρ_r and U_r were determined by surface pressure measurements and an assumption of isentropic expansion of the flow from stagnation conditions. Stagnation pressure was near atmospheric pressure, while stagnation temperature t_s was near 85°F.

Surface heating was effected by electrical dissipation from resistance ribbons that were cemented on the laminated plastic shell and connected in series. This provided a substantially constant heating rate on the surfaces of the notch. Average gaps of 0·005 in separated the 0·500 in wide ribbons along the periphery except for the 0·030 in wide gaps at the top of the front side and at the bottom of the back side, which accommodated a gasket at the latter location. Thermocouples were located just under the ribbons to provide surface temperatures.

The surface data are presented as heat-transfer parameter $W = (h/k_s)(\mu_s/\rho_r U_r)^{0\cdot 8}$ and recovery factor $R = 1 - (t_s - t_a)/(U_r^2/2c)$. The stagnation and unheated surface temperatures are represented by t_s and t_a, but in all other cases t refers to the temperature *rise* due to heating, as, for example, in the heat-transfer coefficient $h = q_w/t_w$.

FLOW STUDY

The results of a flow study that employed the present wind tunnel and model [8] are summarized as follows. The free stream just ahead of the notch was virtually uniform across its section. The local free-stream velocity U_e adjacent to three notches, $L/H = \frac{1}{2}$, 1, and $1\frac{3}{4}$, was found by mean velocity surveys at $U_r \simeq 160$ ft/s to vary not more than 4 per cent from U_r. Laminar flow ahead of the notches and turbulent flow in the notches were found by mean-velocity and turbulence-intensity surveys at $U_r \simeq 160$ ft/s. Transition to turbulence occurred just after the front edge of the notches. In two ranges of notch geometry, $L/H \leqq 1\frac{1}{4}$ and $L/H = 1\frac{3}{4}$, similar values of L/H in different experiments produced similar values of C_p. Between these ranges, L/H alone did not specify unique values of C_p. Some effects of free-stream compressibility were discernible in the results.

RESULTS FROM THE SURFACE DATA

Surface data from the seven notches are shown in Figs. 2 to 6, where the perimeter of the notch is the abscissa; the front edge is on the left and the back edge is on the right. The front edge, the two bottom corners, and the back edge are each marked by vertical lines. The front and back sides, which form the height of the notch, are 2·05 in, whereas the bottom is a multiple of 0·505 in. Some values of C_p from the flow study

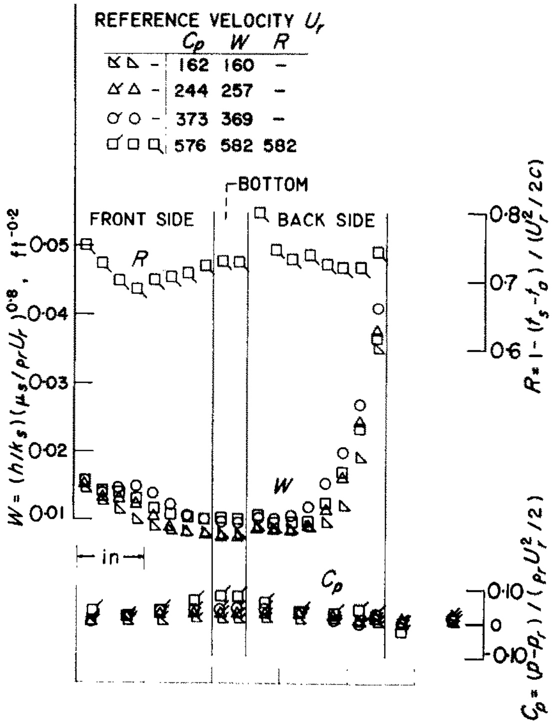

FIG. 2. Results from surface data of $L/H = \frac{1}{4}$ notch displayed along notch perimeter.

are shown in Figs. 2 to 6 for purposes of comparison; those located to the right of the line marking the back edge of the notch were measured on the trailing surface of the model, downstream of the notch.

Recovery factor

The recovery factor R in the square notch (Fig. 4) is notably low on the bottom ($R \simeq 0\cdot 6$), but it is not the lowest R that has been measured in separated flow. The present minimum R is lower than those in longer rectangular notches [3] (minimum $R = 0\cdot 65$). It is also lower than those behind a backward facing step [9] (minimum $R = 0\cdot 77$), but it is somewhat higher than those found on a trailing splitter plate behind a circular cylinder [10] ($R = 0\cdot 43$ to $0\cdot 55$).

The local peaks in R on the back side of the $L/H = \frac{1}{4}$ and $\frac{1}{2}$ notches near the bottom are apparently erroneous. These errors seem to be caused by a conduction of heat from the warm interior of the model at a location that has a

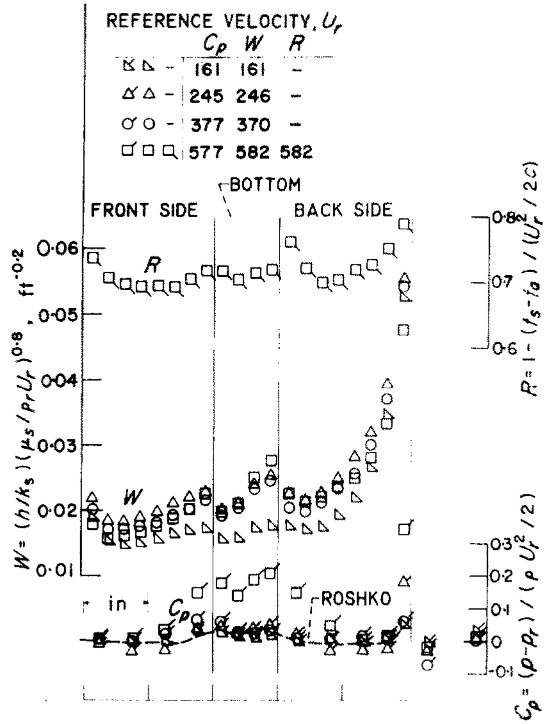

FIG. 3. Results from surface data of $L/H = \frac{1}{2}$ notch displayed along notch perimeter.

small heat-transfer coefficient but a good conduction path through the model structure. The internal temperature of the model is probably near the recovery temperature on a flat plate, corresponding to R near 0·89, due to the extensive lower surface of the model that is exposed to a free stream with $U_e \simeq U_r$.

It is noteworthy that the distributions of R in the $L/H \leqq 1\frac{1}{4}$, $L/H = 1\frac{1}{2}$, and $L/H = 1\frac{3}{4}$ notches are distinctive in magnitude and trend along the periphery. In the aforementioned flow study [8], different flow regimes for these three notch geometries were proposed as a rationalization of the C_p that were measured in different experiments. Agreement between C_p from different experiments was found in the $L/H \leqq 1\frac{1}{4}$ and $L/H = 1\frac{3}{4}$ notches but not in the $L/H = 1\frac{1}{2}$ notch. Additional indications of distinctive flow regimes were found in the velocity measurements. The present distributions of R are consistent with the flow regime concept, as shown by the aforementioned magnitudes and trends. Further consistent features are to be found in the variations of R with speed. In the square notch, R is virtually independent of U_r, whereas R increases with U_r in the $L/H = 1\frac{1}{2}$ notch but decreases with increasing U_r in the $L/H = 1\frac{3}{4}$ notch.

Heat transfer

A correlation of heat-transfer coefficient h with $\rho_r U_r$ raised to the 0·8 power is achieved at nearly all locations in the several notches, as shown by the substantially constant values of $W = (h/k_s)(\mu_s/\rho_r U_r)^{0\cdot8}$ at several speeds. A major departure exists at the top of the back side where a somewhat smaller exponent is indicated in long notches by a decrease of W with increasing speed. In that region the exponent of $\rho_r U_r$ approaches the 0·6 value that was found by Larson to correlate average heat-transfer coefficient in notches, some of which had rounded corners.

This same behaviour of the present results is shown in another manner in Figs. 5 and 6 by the use of a 0·6 exponent in place of the 0·8 exponent in the W formulation. An arbitrary factor is used to place the reformulated results adjacent to the corresponding W values. At some representative locations in Figs. 5 and 6, the scatter of the present results is shown to increase with a 0·6 exponent except near the back edge of the $L/H = 1\frac{1}{2}$ and $1\frac{3}{4}$ notches, where the scatter decreases.

The reason for the disparity on most of the notch periphery between Larson's 0·6 exponent and the present 0·8 exponent, which was also found in the Seban–Fox experiment [3], is not clear. Differences in surface heating conditions and geometry that were utilized by Larson as compared with the present conditions of experiment, namely, constant surface temperature and axisymmetric models as contrasted with the present constant heat rate and plane model, do not appear significant enough to cause the difference between exponents.

The direction of decreasing magnitude of W indicates the general direction of flow along the perimeter of most notches to be toward the front edge of the notch from the back edge. This is the same direction as that measured by Roshko at the midpoints of the surfaces that formed a square notch. Velocity measurements on the

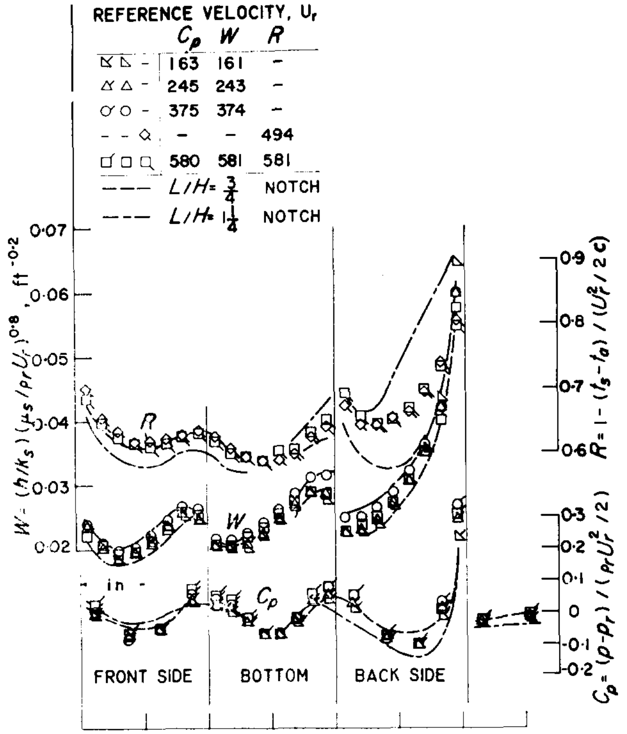

FIG. 4. Results from surface data of $L/H = 1$ notch and averaged results from $L/H = \frac{3}{4}$ and $1\frac{1}{4}$ notches.

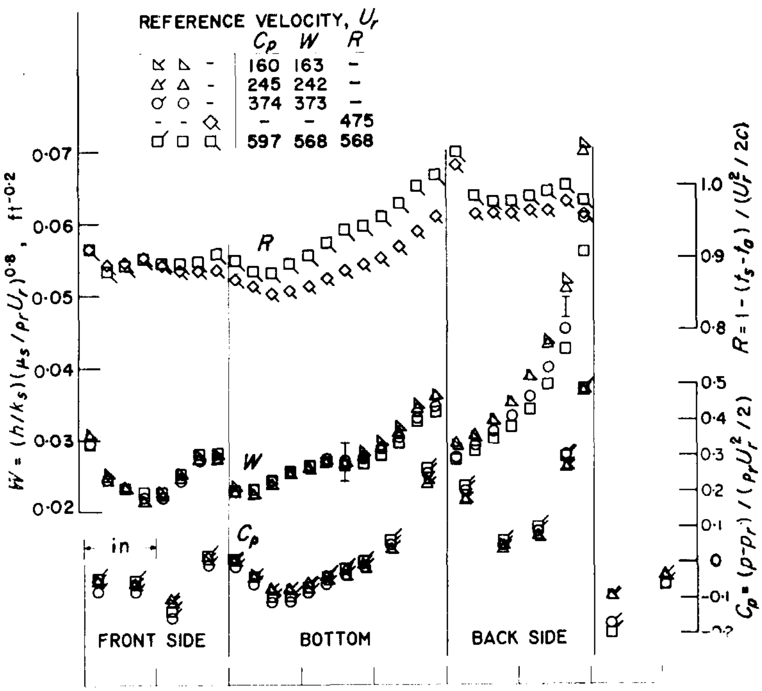

FIG. 5. Results from surface data of $L/H = 1\frac{1}{2}$ notch displayed along perimeter. The I symbols show the range of the measurements when a 0·6 exponent is used in place of the 0·8 exponent in the W formulation.

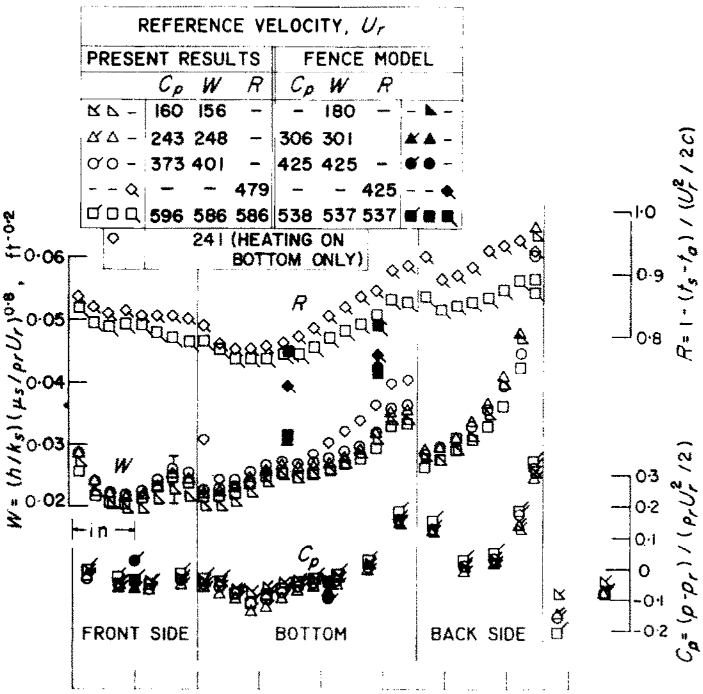

FIG. 6. Results from surface data of $L/H = 1\frac{3}{4}$ notch and Seban–Fox fence model. The I symbol shows the range of the measurements when a 0·6 exponent is used in place of the 0·8 exponent in the W formulation.

present model [8] ascertained that the flow direction along the bottom of the $L/H = 1$ and $1\frac{3}{4}$ notches is mainly from back to front, which is the same as the other indicated flow directions.

The abrupt increase of W at the corners of most notches can reasonably be associated with a local mixing and cooling of the flow along the periphery. The flow that approaches a corner along the back side or bottom seems to be heated like the flow in a boundary layer, that is, the fluid temperature increases and W decreases in the direction of flow. If the flow in the corner were similar to potential flow, the fluid temperature next to the surface would continually increase and W decrease in the direction of flow. It seems more likely, in view of the abrupt increases in W at the corners of the $L/H \geqq \frac{1}{2}$ notches, that the flow that approaches the corner separates in the manner of a boundary layer in an adverse pressure gradient. This separation allows the main notch flow to round the corner and subsequently reattach. It follows that an increased turbulent mixing, such as that in a free shear layer, exists in the locally separated corner region. The fluid temperature is therefore lower at reattachment than at separation because the cooler fluid away from the surface is mixed with the hotter fluid before reattachment. This reduced fluid temperature and the accompanying increased turbulence evidently cause the increase of W that is shown in the corners of the $L/H \geqq \frac{1}{2}$ notches.

In the $L/H = \frac{1}{4}$ notch, values of W are markedly low. On and near the bottom, W is essentially constant, which indicates that there is no mean velocity along the surface in that region. Yet, the successful correlation of the results by $(\rho_e U_e)^{0.8}$ indicates that turbulence is present in the notch. This latter feature could not be verified by turbulence-intensity measurements of the notch flow because the presence of a probe altered the flow. This alteration was shown by large changes in the surface measurements when the probe was inserted.

An inflection in the trend of W on the bottom of the $L/H = 1\frac{1}{2}$ and $1\frac{3}{4}$ notches, at about $1\frac{1}{2}$ in from the front side, exists for reasons that are not clear. This point plays a major role in the changes that occur in W on the bottom when the sides of the notch are unheated. A comparison of W with and without side heating in the $L/H = 1\frac{3}{4}$ notch is shown on Fig. 7. In the absence of side heating, a marked increase in W exists in the region in back of the inflection but not in front.

The values of W, in Fig. 7, from the Seban–Fox fence model with $L/H = 1{\cdot}84$ and unheated

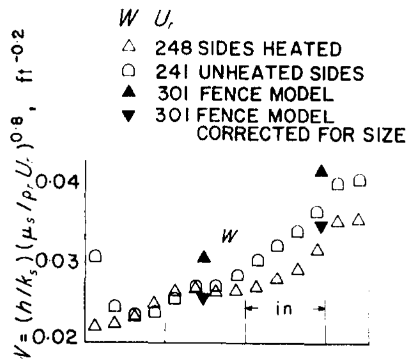

FIG. 7. Effect of size with unheated sides on heat transfer of $L/H = 1\frac{3}{4}$ notch.

sides are greater than the values from the present model with unheated sides. The facts that W has dimensions of length and that the Seban–Fox model is smaller than the present model can be used in a search for an improved correlation that is dimensionless. It seems necessary to experimentally determine a characteristic length before a truly reproducible correlation can be established. Unfortunately, the existing experimental evidence, which is shown in Fig. 7, pertains to just one notch geometry ($L/H = 1\frac{3}{4}$) and one heating condition (uniform heating on the bottom only).

Notch length L is proposed as the characteristic length. Its combination with W produces a dimensionless heat-transfer parameter

$$\bar{W} = \frac{hL}{k_s}\left(\frac{\mu_s}{\rho_r U_r L}\right)^{0\cdot 8}.$$

A separate figure for $\bar{W}$ is avoided herein by a consideration of corrected values of W in Fig. 7. A ratio of $L^{0\cdot 2}$ for the Seban–Fox fence model to that for the present model is used as a correction factor for the fence model results. In effect, the fence model results are corrected to the values of W that would be found on a fence model as large as the present model, if $\bar{W}$ were the valid form of reproducible correlation. In Fig. 7, the improved agreement between the corrected results and the present results supports the role of L as the characteristic length for heat transfer in notches.

No single length can fully specify a flow situation in which several lengths are needed for a complete description. In this instance, the boundary-layer thickness ahead of the notch and the height of the free stream are additional relevant lengths of unknown significance in relation to the notch length. However, the major heat-transfer effects seem, from the limited evidence at hand, to be a function of the length of a rectangular notch when the unheated laminar boundary layer is thin compared with H at separation and the flow in the notch is turbulent, which is the case in the present and Seban–Fox experiments. Charwat's emphasis of the importance of the boundary-layer thickness, which was of the order of H in his experiment, is an indication that the significant length varies with the flow configuration.

Spatial variation of heat-transfer coefficient

Spatial variations of W, especially on the back side of the notches, show a certain degree of similarity. In Fig. 8, W is plotted logarithmically as a function of the distance on the back side from the top edge X_1. Power law relations, which, of course, are evidenced in logarithmic coordinates as straight lines, can approximate the spatial variation between $X_1 = 0{\cdot}5$ and $1{\cdot}5$ in in notches with $L/H \geqq \frac{1}{2}$. The largest values of W on the back side occur in the $L/H = 1\frac{1}{2}$ notch. Since W on the front side is also largest in the $L/H = 1\frac{1}{2}$ notch, the heat-transfer performance of this notch is remarkable, as are C_p and R.

FLOW MEASUREMENTS

Velocity and temperature traverses in the $L/H = 1$ and $1\frac{3}{4}$ notches at low speed ($U_r \simeq 160$ ft/s) were accomplished along lines that were normal to the notch bottom. Velocity was measured by a hot-wire anemometer that sensed the

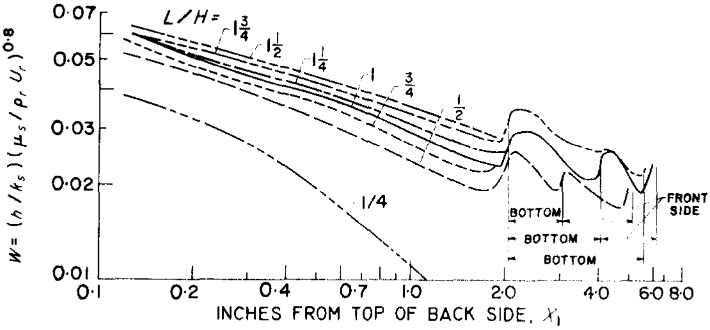

FIG. 8. Average heat-transfer results along notch perimeter from back edge.

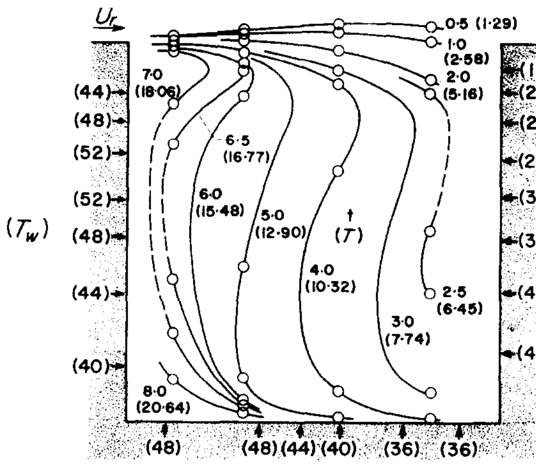

FIG. 9. Temperature contours in square notch. Lines of constant temperature rise due to heating drawn through circled measurements.

magnitude of the velocity including components both normal and parallel to the notch bottom. One display of velocity ratios is shown in Fig. 10 for purposes of comparison, but the major portion of the velocity results is included in [8]. Temperatures in the flow were sensed by a nichrome–constantan thermocouple that was strung between sewing needles.

Temperatures in square notch flow

Temperature rise due to heating is displayed in Fig. 9 as isotherms or temperature contours that are identified both as t [degF] and T [$ft^{0.2}$], where $T = (tk_s/q_w)(\rho_r U_r/\mu_s)^{0.8}$. A simple relation between T and W exists at the surface, namely, $T_w \equiv 1/W$. Values of T_w are shown in Fig. 9.

Temperatures in the square-notch flow are quite low compared with surface temperatures. This implies that the major resistance to heat transfer is at the surface where the major temperature drop occurs.

There are some trends in the temperatures in the square notch that correlate with Roshko's concept of the flow, which consists of one large vortex in the body of the notch and two small vortices that counterrotate in the corners. Temperatures increase in the direction of the main vortical flow along the perimeter, which was found in [7] and [8] to be from the back edge to the front edge. Another consistent feature is the relatively low fluid temperature near the back side where the fluid from the free shear layer enters the notch.

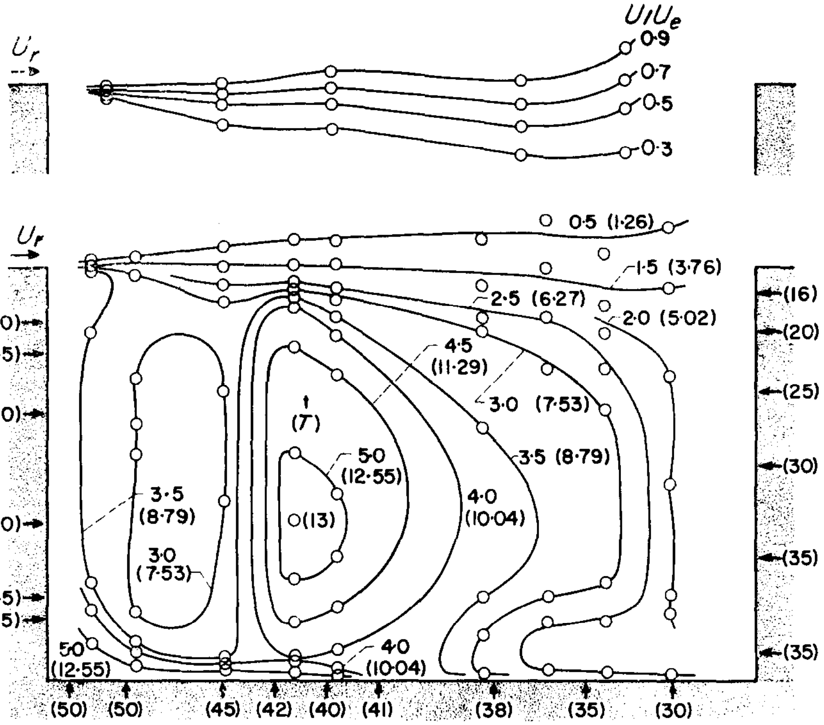

FIG. 10. Temperature and velocity in $L/H = 1\frac{3}{4}$ notch.

Temperatures in the $L/H = 1\frac{3}{4}$ *notch*

A temperature peak (or hot spot) in the central region of the $L/H = 1\frac{3}{4}$ notch is shown by the isotherms in Fig. 11. A peak at such a location gives the appearance of a source of heat in the flow because of the common physical concept that heat always diffuses in the direction of declining temperature. Heat transfer is also unusual on the bottom beneath the temperature peak; $W(= 1/T_w)$ shows a local peak and valley there. This location on the bottom is also the limit of the alterations of W that results from not heating the notch sides; W is increased toward the back but changed little toward the front, as shown in Fig. 7. Maximum velocities along the bottom are about 0·4 U_r in back of this location, but they are lower in front of this location. All these measurements, however, serve to just identify a site of unusual effects; they do not combine to produce a coherent explanation of the phenomena there. It does seem possible, however, that these phenomena may be associated with a three-dimensional effect, such as those discussed in [11], since one of the present phenomena, the temperature peak, is not consistent with two-dimensional flow effects.

TEMPERATURES NEAR THE BOTTOM SURFACE

In the $L/H = 1$ and $1\frac{3}{4}$ notches, the temperatures in the flow near the bottom are compared in Fig. 11 to the von Kármán analogy profile from turbulent boundary layers. The measured quantities, $t^* = t\rho c\sqrt{(\tau_w/\rho)}/q_w$ and $Y^* = Y\sqrt{(\tau_w/\rho)}/\nu$, utilize the shear results from [8]. No agreement is shown between the measurements and either the von Kármán laminar sublayer ($t^* = \sigma Y^*$; $Y^* \leqq 5$) or the von Kármán intermediate layer

$$\{t^* = 5\sigma + 5 \log [(\sigma Y^*/5) + 1 - \sigma];$$

$$5 \leqq Y^* \leqq 30\},$$

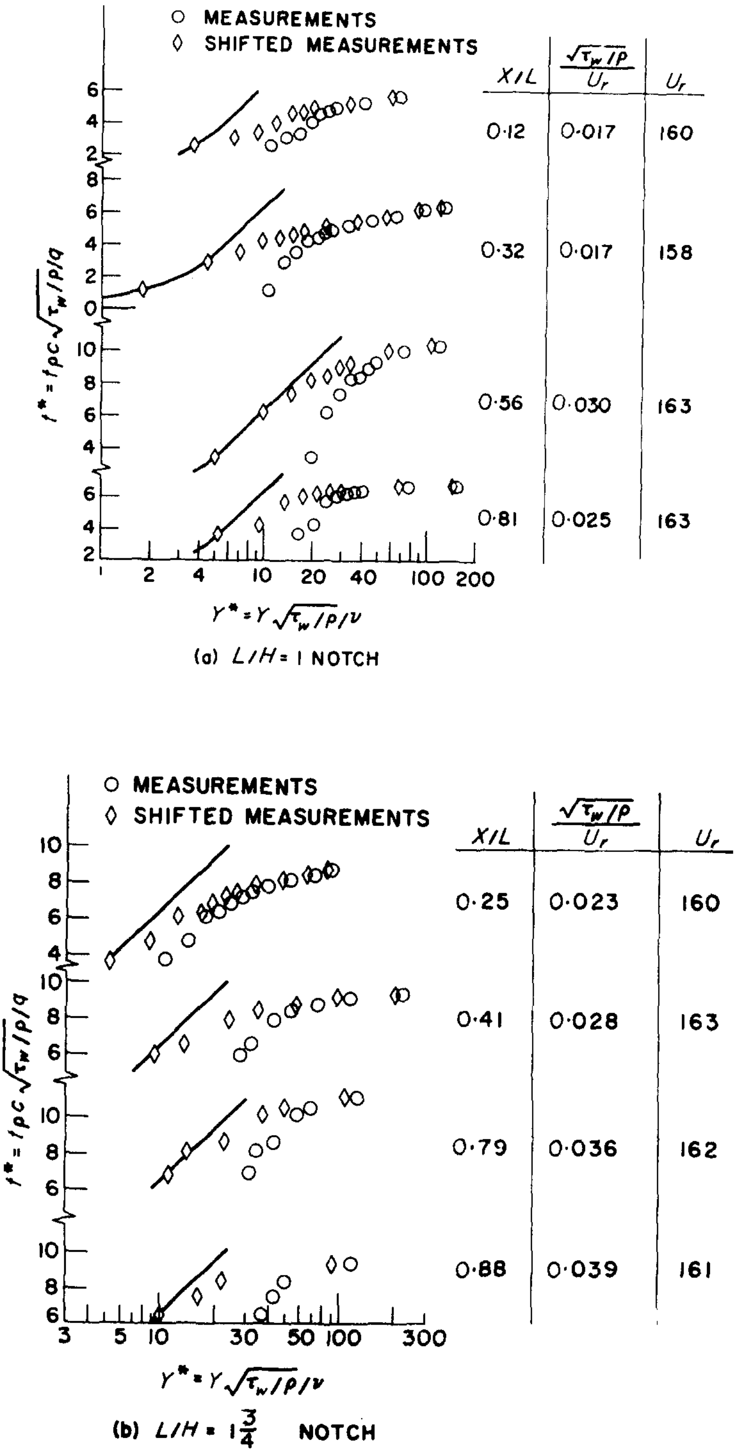

FIG. 11. Temperatures near bottom surface. Curve is von Kármán profile from turbulent boundary layers.

for a Prandtl number σ of 0·70. In Fig. 11, the measurements are also shown after they have been shifted toward the surface so that the first measurement matches the von Kármán profile. In some instances, the second shifted measurement also matches the profile; but in all other respects, the measurements are not similar to those in fully-developed turbulent boundary layers, as described by the von Kármán profile.

ACKNOWLEDGEMENTS

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Note added in proof, 9 December 1964: H. H. Korst reports that his analysis of a nonquiescent notch flow will soon be published in a Rutgers symposium proceedings.

Zusammenfassung—Für Luftgeschwindigkeiten von 49 bis 183 m/s werden Wärmeübergangsparameter und Rückgewinnfaktoren an allen Oberflächen einer quer zum Strom verlaufenden rechteckigen Vertiefung mit einem Verhältnis Länge zu Höhe L/H von ¼ bis 1¾ angegeben. Die Wärmeübergangszahlen sind der Massenstromdichte des Freistroms $\rho_e U_e$ hoch 0,8 proportional, wodurch die frühere Kontroverse mit den Messungen von Larsen in turbulenter Strömung und mit den Vorstellungen Charwat's für einen neuen Bereich von L/H fortgesetzt wird. Eine vorläufige Proportionalität wurde zwischen Wärmeübergangszahl und Vertiefungslänge hoch $-0{,}2$ gefunden. Die Proportionalität ermöglicht die Aufstellung einer Beziehung mit dimensionslosen Grössen. Die Rückgewinnfaktoren entsprechen dem vorhergehenden Vorschlag über deutlich ausgeprägte Strömungsarten in Vertiefungen mit verschiedenen Bereichen von L/H. Die Temperaturen in der Strömung nahe an der Oberfläche der Vertiefung stimmen weder mit den Profilen der turbulenten Grenzschicht noch mit den Annahmen bestehender Theorien über den Wärmeübergang in Vertiefungen überein.

Аннотация—Приводятся теплообменные характеристики и коэффициенты восстановления для всех поверхностей поперечного прямоугольного желоба с отношением длины к высоте L/H от ¼ до 1¾ и при скорости воздуха от 48,768 м/сек до 182,88 м/сек. Коэффициенты теплообмена пропорциональны массовому расходу невозмущенного потока $\rho_e U_e$ в степени 0,8, что в новом диапазоне величины L/H продолжает противоречить измерениям Ларсона для турбулентного течения и представлениям Чаруота. Ориентировочно найдена пропорциональность между коэффициентами теплообмена и длиной желоба в степени $-0{,}2$. Эта пропорциональность делает возможной безразмерную корреляцию. Коэффициенты восстановления совместимы с ранее предложенным представлением о различных режимах потока в желобах для различных диапазонов L/H. Температура потока у поверхности желоба не согласуется ни с профилями турбулентного пограничного слоя, ни с предположениями, сделанными в существующих теориях, о теплообмене в желобах.