Int. J. Heat Mass Transfer. Vol. 9, pp. 729–738. Pergamon Press 1966. Printed in Great Britain

EXPERIMENTS ON THE FLOW OVER A ROUGH SURFACE†

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(*Received* 24 *September* 1965 *and in revised form* 31 *January* 1966)

Abstract—In order to explain the heat transfer in forced convection from a rough surface, a model of the flow over such a surface is required. The present experiments were conducted to provide information which might be helpful in the formulation of a suitable model. Observations were made of the flow over sets of artificial roughnesses consisting of square slots normal to the direction of flow. The boundary layer was turbulent and the experimental conditions could be adjusted so as to produce a relatively thick laminar sublayer. Ratios of slot depth to laminar sublayer as low as 2 or 3 could be obtained with the physical dimensions sufficiently large to allow convenient visualization.

The experiments showed that when the slot exceeded the thickness of the laminar sublayer by a factor of about 20, a more or less steady vortex pattern would form in the slots. This pattern had been observed by several previous investigators. For lower slot depths, however, the flow in the slots was subject to random disturbances. A fairly steady vortex pattern would form periodically, but would be subsequently destroyed. The general appearance of the flow could be described in terms of four fairly well distinguishable patterns.

1. INTRODUCTION

WHEN attempting to interpret the results from studies of heat transfer over rough surfaces, it would be most desirable to have a clear concept of the flow over the roughness elements. Several hypotheses have been advanced as to the nature of the flow about roughnesses and attempts have been made to predict heat-transfer coefficients for rough surfaces on the basis of such flow models. For example, Owen and Thompson [1] in their analysis assumed horseshoe-like vortices wrapped around individual roughness spikes, and Dipprey and Sabersky [2] when considering two-dimensional roughness consisting of transverse slots postulated a vortex pattern in each of the slots.

A significant number of experiments have also been performed to investigate the flow in rectangular cavities of various types. The results of these experiments are pertinent to the understanding of the flow in the type of two dimensional roughness as postulated by Dipprey and Sabersky [2]. In one of the earliest experiments Folsom [3] studied the flow in a pipe having internal annular fins of rectangular cross-section and observed rather steady vortices in the spaces between the fins. Similar patterns were reported by Wieghardt as well as by Knudsen and Katz [4] for the flow past a series of rectangular cavities. Knudsen and Katz in particular investigated a great number of cavities with different ratios of height to width, and showed that for deep cavities two stable counter rotating vortices may exist. In a more recent series of experiments Maull and East [5] detected a certain cellular structure which formed in the slots depending on the width to breadth ratio. Extensive pressure measurements in a single rectangular cavity were performed by Roshko [6] and also by Charwat *et al.* [7, 8], whose experiments extended into the supersonic range. Several attempts to describe the flow in a cavity analytically have also been made. One of the

† This paper is based on a thesis submitted by H. W. Townes in partial fulfillment for the degree of Doctor of Philosophy at the California Institute of Technology. The research was carried out under the sponsorship of the National Science Foundation, NSF Grant No. GP-276.

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first was that by Chapman [9] who used an infinitely deep cavity as a model. This model was subsequently modified and in a recent paper Burggraf [10] has presented a very careful analysis in which he subdivides the flow into three regions, the boundary layer on the cavity walls, the vortex core in the cavity, and the boundary layer on the outside of the cavity.

In all of the foregoing experimental work, the thickness of the boundary layer of the approaching flow did not seem to exert a strong influence on the results. When considering flow over roughnesses of ordinary size, however, it is known, for example from Nikuradse's work, that the ratio of the roughness size to the laminar sublayer plays a key role in determining the friction behavior. It is, therefore, plausible that this ratio should also affect the flow pattern as well as the heat-transfer behavior, and it seemed appropriate to extend the exploration into the range where the laminar sublayer was of the order of the roughness size. It was the purpose of the present investigation, therefore, to investigate what effects a relatively large laminar sublayer might have on the flow in a series of slots. A more detailed account of the work described in this paper may be found in reference [11].

2. EXPERIMENTAL APPROACH

(a) *The velocity profile*

The most effective approach for obtaining a first understanding of the possibly complicated flow patterns in slots or cavities was believed to be that of direct visualization. In order to carry out such observations and to record the flow patterns photographically, it was decided that it would be desirable to work with slot sizes of at least $\frac{1}{8}$ in. This in turn made it necessary to produce a flow with a laminar sublayer of this approximate magnitude. After considering various possible fluids and flow systems, a 60 ft water channel was selected for the purpose. In such a channel a sublayer thickness of about 0·10 inch could be expected at a distance of 45 ft downstream for a mean stream velocity of 0·10 ft/s. A schematic drawing of the channel and its circulation system is shown in Fig. 1. The series of slots was located in the bottom of the channel with the top of the slots flush with the floor. The boundary layer was then developed in the upstream section of the channel and the flow approaching the slot section was to have the characteristics of a developed turbulent boundary layer. To ascertain that the actual profile was of the desired type, the velocity distribution of the approaching stream had to be determined experimentally. Because of the low velocities, the measurement of this profile presented a rather major problem. This task was eventually accomplished by means of a hot film anemometer quite similar in principle to the hot wire sets which are common in aerodynamics. The sensing element itself, a commercially pro-

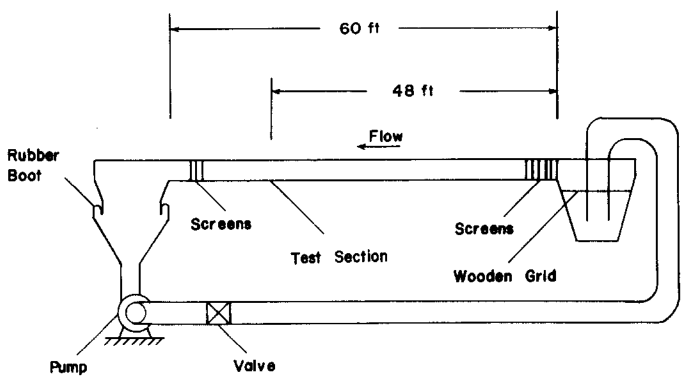

FIG. 1. Diagram of the test channel and its circulation system.

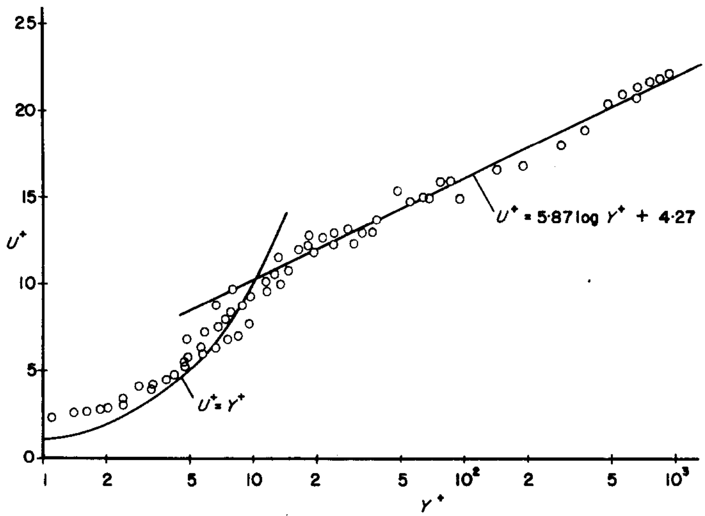

FIG. 2. Mean velocity profile for a free stream velocity of 0·254 ft/sec.

cured item, was made of a small glass tube (about 0·001 inch dia.) on which a platinum film was deposited. This film in turn was covered by a protective layer of quartz to prevent corrosion as well as electrolysis. In addition an unusually sensitive and stable amplifier was required. This became necessary because in water the sensing element has to be operated at considerably lower temperatures than is usual for air, in order to avoid gas evolution and/or boiling. As a consequence the electrical output of the probe becomes very small compared to that of the air anemometers. As an additional feature the electronic system included a circuit which could average the velocity readings over a desired period of time. This feature was of great convenience, because the periods of the fluctuations at the very low water velocities were quite long, necessitating average times of the order of minutes. The hot film instrument had to be calibrated, of course, and this was accomplished by towing the probe at a known velocity in a tank filled with still water.

Velocity profiles were determined for each channel flow rate, and a few typical profiles are shown in Figs. 2 and 3. The curves are plotted on semi-log scales, with the dimensionless variables u^* and y^* as coordinates. As usual, u^* is defined as

$$u^* = u/\sqrt{(\tau_0/\rho)}$$

and y^* as

$$y^* = y\sqrt{(\tau_0/\rho)}/\nu$$

where

u = local velocity;
τ_0 = wall shear stress;
ρ = density;
y = distance from the wall;
ν = kinematic viscosity.

The profiles clearly show the characteristics of a turbulent boundary layer, and the regions of the turbulent core, the transition, and the laminar sublayer are easily distinguishable. It may be noted that the measurements extend well into the laminar sublayer to values of y^* as low as 1 or 2, where, for comparison, a value of $y^* = 5$ is generally taken as the limit for the laminar sublayer. In fact, the slope of the velocity profile in this laminar layer could be determined with sufficient accuracy to allow direct computation of the wall shear τ_0.

It should be pointed out that the slope of the

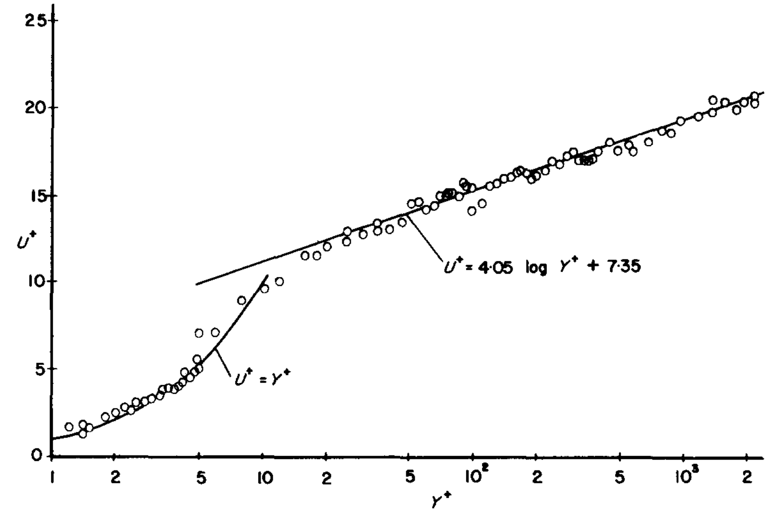

FIG. 3. Mean velocity profile for a free stream velocity of 0·498 ft/sec.

velocity profile in the region of the turbulent core differs somewhat from the accepted value for the so-called "universal profile", which represents the velocity distribution near the wall of a flat plate or of a circular pipe. The difference may well have been caused by the presence of the side walls of the channel, which alters the conditions from those for the ideal flat-plate flow. The differences, however, were not considered significant for the present experiments. The velocity profiles which were produced in the channel were believed adequate for exploring the flow in the slots when exposed to an approaching flow with a typical turbulent boundary layer.

(b) *Visualization techniques*

As mentioned earlier, one of the purposes of the present work was to make the flow in the slots visible. Several different techniques were tried for this purpose, among them the addition of aluminum particles, the electrolytic generation of hydrogen bubbles, and the injection of dye. After various attempts with methods of this kind, the simple dye injection technique proved to be the most suitable. A solution of black aniline dye with water was prepared, the density of which was essentially equal to that of the water in the channel. The dye solution was introduced through probes made of hypodermic tubing or through orifices of similar size located on the walls of the slot or at the bottom of the channel. All orifices were flush with the surface.

(c) *Experimental procedure*

A series of experiments were then conducted for channel velocities from 0·12 ft/s to 0·83 ft/s and for slot sizes from 0·125 in to 1·0 in. A sketch of a set of slots is shown in Fig. 4. The cross-section of each slot is square and the wall between adjacent slots is equal to one half the slot width. The number of slots varied from 8 for the 1·0 in size to 20 for the $\frac{1}{8}$ in size. The flow in each set of slots was investigated for several channel velocities. At each flow rate the flow patterns in the slots were recorded by still photographs as well as by motion pictures. Essentially all observations were made for the center of the slot, midway between the channel walls. This location was selected because the effects of secondary flows were expected to be a minimum at this point. As the channel was 33·5 in wide, the camera lens was set at a distance of about 15 in from the

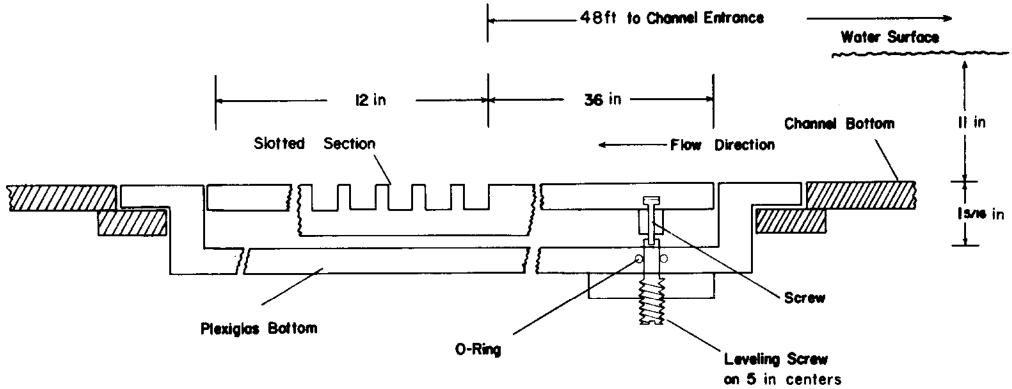

FIG. 4. Detailed sketch of slotted test section as installed on channel floor.

object plane. An enlargement by a factor of two could be obtained by means of a lens with a focal length of about 12 in.

3. FLOW OBSERVATIONS

In discussing the observations, reference will be made to the parameter ϵ^* which is defined as

$$\epsilon^* = \frac{\epsilon \sqrt{(\tau_0/\rho)}}{\nu}$$

where ϵ is the depth of the slot and the other quantities have been defined earlier in connection with the definition of y^*. The two quantities are, of course, closely related and ϵ^* is a measure of the slot size in terms of the reference distance $\nu/\sqrt{(\tau_0/\rho)}$. Letting $y^* = 5$ represent the extent of the laminar sublayer, the ratio of the slot depth to the sublayer is given by $\epsilon^*/5$. The parameter ϵ^* may also be regarded as a Reynolds number governing the flow in and about the slot. One may then argue that this Reynolds number should be the principal factor governing the flow in the region of the slot, at least as long as the dimensions of this region are small compared to those of the channel cross-section.

In the present test series the obtainable values of ϵ^* were governed by the size of the slots and the free stream velocity of the channel. The highest value of ϵ^* ($\epsilon^* = 259$) was reached with the 1·0 in slots at a channel velocity of 0·788 ft/s and the lowest value ($\epsilon^* = 11{\cdot}8$) was obtained with $\frac{1}{8}$ in slots at 0·255 ft/s.

As mentioned earlier the work of previous investigators corresponds mostly to the higher values of ϵ^*, far in excess of 500. In Fig. 5 a typical flow is shown which corresponds to the upper range of ϵ^* ($\epsilon \approx 250$) for the present investigation. The figure shows a rather well established, fairly steady vortex occupying the main portion of the slot. The flow across the opening of the slot had a very turbulent appearance, much like that of a free turbulent jet. Active fluid exchange seemed to take place at this surface and the flow gave the appearance of frequently crossing the plane of the slot opening. This was particularly evident at the downstream edge of the slot where the "flutter" of the stream in respect to the edge could be observed clearly and the rate of flutter could be determined. It should be added that most of these observations were made in the fourth downstream slot; however, no major differences were observed for the flow in the several slots of the set. These observations of the steady vortex as well as of the "flutter" agree well with the findings of previous investigators.

When the flow is reduced to lower values of ϵ^*, however, a definitely new phenomenon comes into play. The vortex pattern can no longer be maintained continuously, but it is periodically dispersed and reformed. The unsteady flow sequence can be described fairly adequately by introducing four typical flow phases which have been called "strong exchange", "weak exchange", "inflow", and "divide". Examples of each are shown in Figs. 6–9. Next to each photograph a somewhat idealized sketch of the streaklines is given to clarify the definition of the various phases. The "strong exchange" implies a very noticeable outflow of fluid from the slot sufficient to destroy any previously existing vortex pattern; the "weak exchange" designates outflow of fluid in such a way that the streaklines of the outflowing fluid form a rather shallow angle with the channel floor and the flow in the slot remains relatively undisturbed. During the "inflow" phase the streaklines from the upstream edge bend into the slot; and in the "divide" phase a streakline leads from the upstream edge to the downstream edge of the slot across the open surface. Except for the "strong exchange" the basic vortex pattern remains recognizable, and during the two phases mentioned last, the vortex tends to reform. It is clear that except for the "divide" phase the flow must be three dimensional in nature, but the description is here limited to the components in one plane. The classification of the flow into these four phases leads, of course, only to an approximate description of the complicated unsteady flow.

For values of ϵ^* below about 150, these four phases follow each other in random succession. A motion picture sequence for $\epsilon^* = 49{\cdot}3$ taken at 10 frames/s is shown in Fig. 10. The duration of each phase is difficult to determine with any accuracy, because the specification of the precise moment at which one phase stops and the next begins is somewhat arbitrary. The number of different phases which occur over a fixed period of time can, however, be determined accurately and a frequency, f, of phase changes can be defined in this way. The corresponding dimensionless frequency may be written as

$$S = \frac{\epsilon f}{\sqrt{(\tau_0/\rho)}}$$

which is in the form of a Strouhal number. Throughout this presentation the point of view has been taken that the quantity ϵ^* is the essential parameter determining the flow in a slot exposed to a turbulent boundary layer. If this point of view is correct, the dimensionless frequency S should be a function of ϵ^* only. In Fig. 11, S is plotted against ϵ^*. The graph, which contains data for several stream velocities and

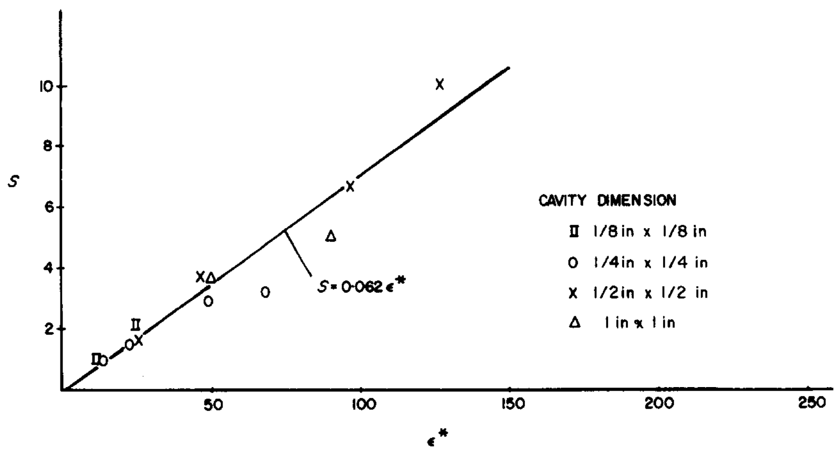

FIG. 11. The Strouhal number $(\epsilon f)/\sqrt{(\tau_0/\rho)}$ vs. ϵ^* where f represents the number of flow phases observed per unit time.

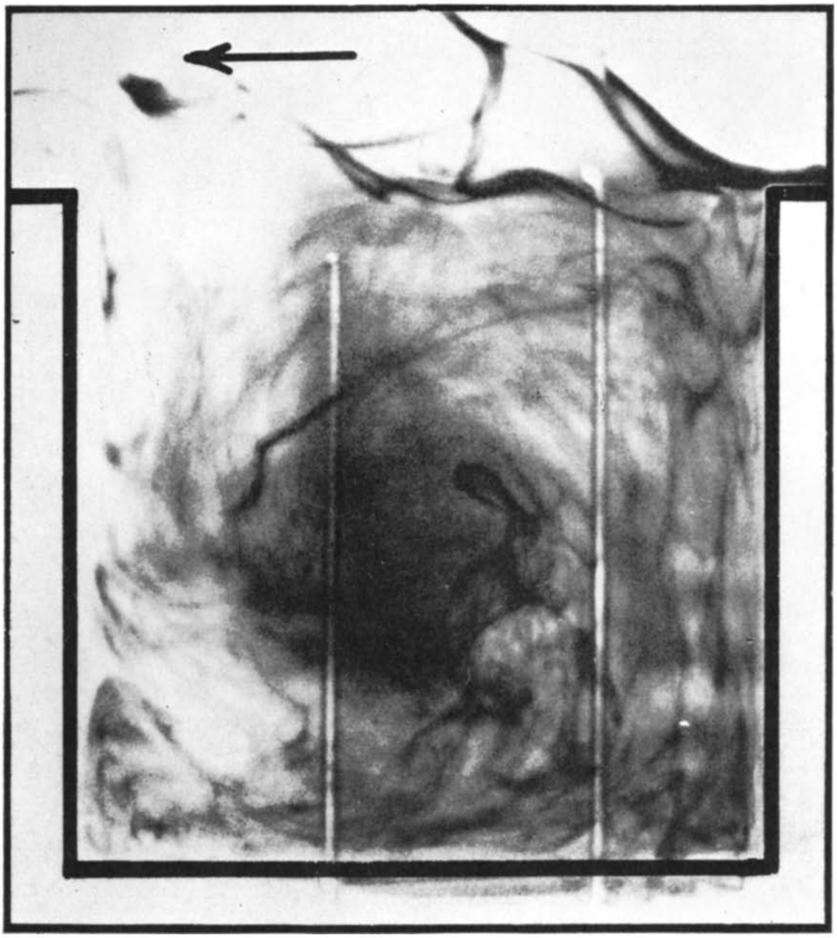

FIG. 5. Typical flow pattern for high values of ϵ^*. The flow has the general characteristics of a vortex and the appearance does not change with time. The slot shown is 1 × 1 in and the free stream velocity is 0·259 ft/s. The corresponding value of ϵ^* is 201.

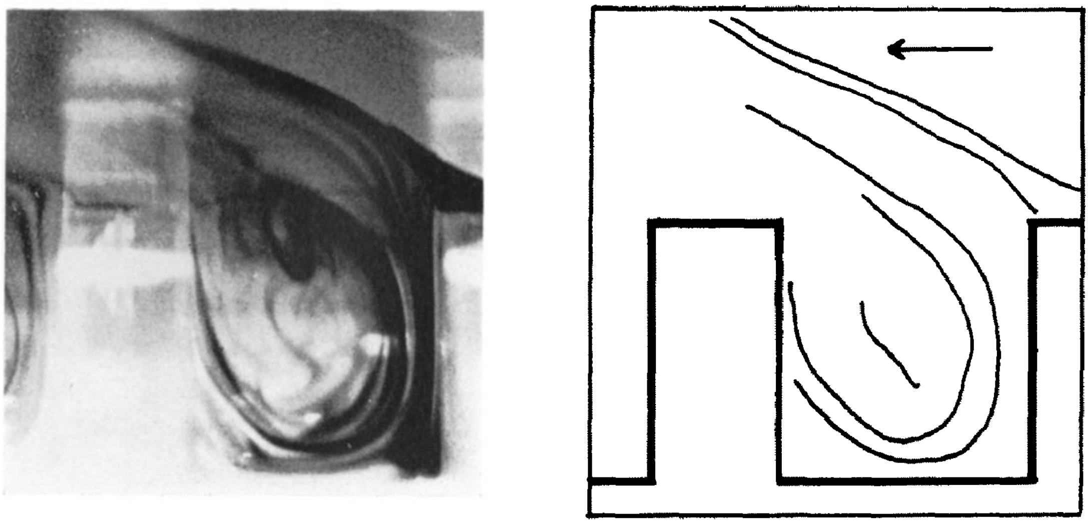

FIG. 6. Example of the so-called "strong exchange" phase. Slot size ¼ × ¼ in, free stream velocity 0·520 ft/s, $\epsilon^* = 49{\cdot}3$. An idealized sketch is shown on the right.

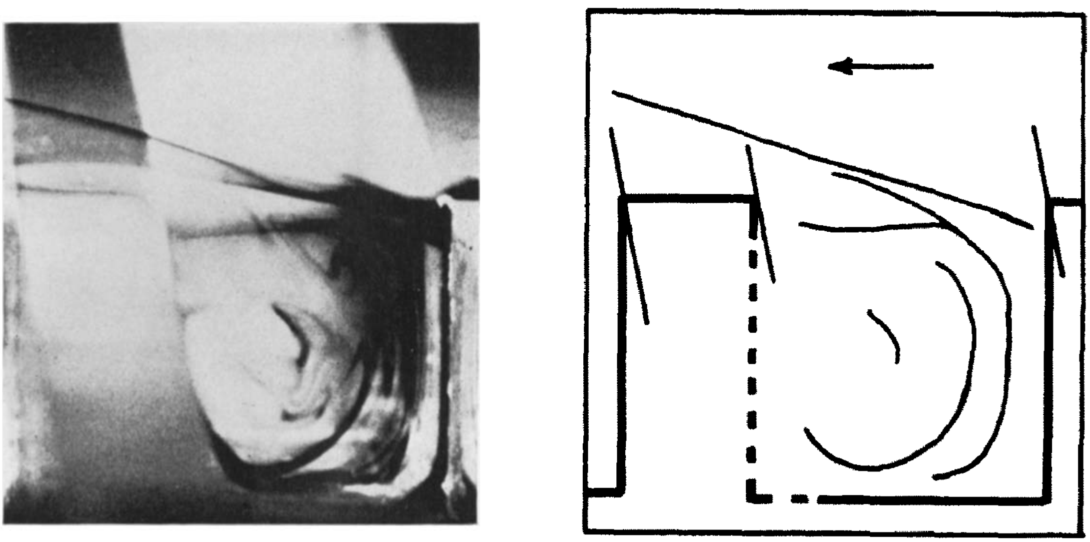

FIG. 7. Example of the so-called "weak exchange" phase. Slot size ½ × ½ in, free stream velocity 0·252 ft/sec, $\epsilon^* = 46{\cdot}6$. An idealized sketch is shown on the right.

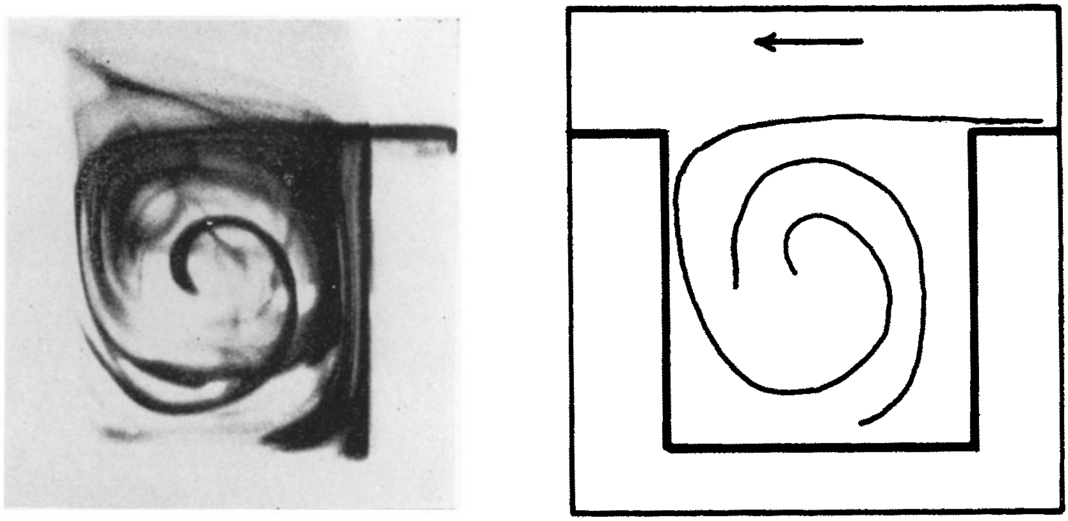

FIG. 8. Example of the so-called "inflow" phase. Slot size $\frac{1}{4} \times \frac{1}{4}$ in, free stream velocity 0·520 ft/s, $\epsilon^* = 49\cdot3$. An idealized sketch is shown on the right.

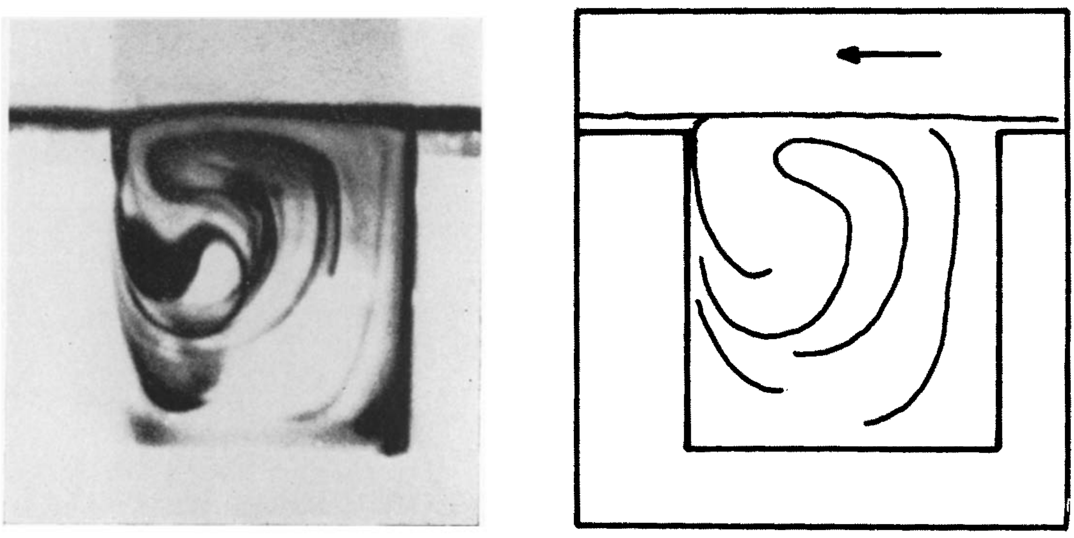

FIG. 9. Example of so-called "divide" phase. Slot size $\frac{1}{4} \times \frac{1}{4}$ in, free stream velocity 0·520 ft/s, $\epsilon^* = 49\cdot3$. An idealized sketch is shown on the right.

FIG. 10. Series of motion picture frames taken for a period of 2 s at 10 frames per second. Slot size $\frac{1}{4} \times \frac{1}{4}$ in, free stream velocity 0·520 ft/s, $\epsilon^* = 49{\cdot}3$. The series illustrates the unsteady character of the flow and shows several of the flow phases.

slot sizes, shows that S is indeed well represented as a function of ϵ^*. This fact is a reassurance that ϵ^* is the proper parameter for the flow under consideration. The graph shows furthermore that S depends almost linearly on ϵ^*, for values of ϵ^* below about 150. For higher values of ϵ^* the exchange of the various patterns no longer occurs and a rather steady vortex flow is established as stated earlier. The line of S vs. ϵ^* for the frequency of exchange ends, therefore, at about $\epsilon^* = 150$.

It is possible to define a second frequency which applies to the type of flow which exists beyond $\epsilon^* = 150$. This frequency is based on the rate at which the free jet over the opening of the slot "flutters" in respect to the downstream edge of the slot. (In determining the frequency a count is made each time the jet dips into the cavity and forms a stagnation point at the downstream wall.) In the range of the present experiments the Strouhal number for this frequency was found to be constant and equal to about 10.

4. DISCUSSION

As mentioned earlier, the intention of the present experiments was to obtain a concept of the flow about roughness elements under conditions similar to those which might occur in a typical heat-transfer application. The roughness was produced by a set of rectangular grooves, and friction experiments on other grooved surfaces have shown that the characteristic curves of *friction coefficient vs. Reynolds number* are quite comparable to those obtained for surfaces roughened by sand grains. In particular at high Reynolds numbers both types of surfaces show a region of "fully rough" behavior in which the friction coefficient is independent of Reynolds number, and as the Reynolds number is lowered, the friction coefficient usually drops. This region of lower Reynolds numbers has been called the "roughness transition" region as it forms the transition between the laminar flow regime and the range in which the roughnesses have no effect on the friction coefficient (i.e. the "fully rough" flow regime). In view of this similar behavior, it was concluded that the flow observations that have been made for the grooved surface may properly be related to the heat-transfer results obtained with sand grain roughnesses.

The various sets of roughnesses were exposed to flows having velocity profiles typical of a turbulent boundary layer, and the information was coordinated in terms of the wall parameter ϵ^*. This parameter was based on the slot depth ϵ. (It should be noted that this selection of the depth as the characteristic roughness dimension is essentially arbitrary. Any fraction of ϵ—say $0{\cdot}5\epsilon$—would have been equally suitable. Accordingly the absolute numerical values of ϵ^* as such are not of basic significance.) For values of ϵ^* above 200 a rather well established vortex pattern was observed in each slot. This observation is in agreement with those of other investigators who studied the flow in slots and cavities for high values of ϵ^*. In this region the flow pattern is very insensitive to changes in ϵ^* and this region may be identified with the "fully rough" regime. The experiments were then extended to lower values of ϵ^*, into a region in which, to the knowledge of the authors, no prior observations on flow patterns had been made. It is in this region, for values of ϵ^* below about 150 that the unsteady behavior of the flow was noticed. The flow regime at those values of ϵ^* corresponds most likely to that in the "roughness transition" region.

One may next wish to speculate on the cause of the unstable behavior of the flow in the slots at the lower values of ϵ^*. The explanation which appears most plausible is that the disturbances originate in the boundary layer itself and then penetrate into the slots. The disturbances in question are the turbulent fluctuations generally present in the boundary including the unstable longitudinal vortex filaments observed by Kline *et al.* [12]. In flows over a smooth surface these vortices have been observed to break up and to eject clusters of fluid into the outer portions of the boundary layer thereby causing disturbances in these layers. It appears quite possible that this type of motion can similarly cause disturbances within the slots. The range of these disturbances may well be expected to be governed by a dimensionless number proportional to ϵ^*. One may imagine then that for slots of large ϵ^* the disturbances cannot penetrate deeply enough to alter the main flow pattern. For low values of ϵ^* on the other hand the disturbances are capable of bringing about a complete change of pattern and cause the successive appearance of the various flow phases which were defined earlier.

Although the above explanation for the unsteady flows in the slots appears to be the most plausible, there are other possible causes. In particular it may be that the vortex-like flow in a slot may itself become unstable for certain boundary conditions. One observation which favors the first-mentioned mechanism, however, is that changes in flow phases often occur simultaneously in several adjacent slots. This gives the impression that the initiating mechanism lies within the boundary layer rather than within the individual slot. Nevertheless, the question cannot be answered conclusively at this time, and may well form the subject of a separate investigation.

Let us speculate finally on what effect the observed flow behavior might have on the heat transfer from the walls to the main body of the stream. For this purpose we may divide the heat-transfer process into two steps: the transfer from the walls of the slot through the boundary layers of these walls to the central portion of the slot; and from these central regions to the main stream outside the slots. Since all observations indicate that transfer processes across the opening of the slot are very effective, one may expect that the principal resistance to the heat transfer is offered by the boundary layers on the cavity walls. During the change of flow phases which occur for $\epsilon^* < 150$, these layers are, however, being severely disturbed, and the average resistance to heat transfer may, therefore, be effectively reduced. It was also shown in the graph of S vs. ϵ^* that the frequency with which the changes in flow phases occurs continuously increases as ϵ^* increases towards 150. The resistance to heat transfer through the boundary layers of the slot should then be expected to reach a minimum for ϵ^* values near 150, or more generally for ϵ^* values which correspond to that part of the "roughness transition" region which is just below the regime for "fully rough" flow.

An indication that the heat transfer does behave in this manner is provided by the measurements of Dipprey [2]. The data obtained from experiments with tubes with sand-grain roughnesses show that the heat-transfer coefficient does indeed reach a maximum at the end of the "roughness-transition" region just before the flow becomes "fully rough".

5. CONCLUSION

For turbulent flow over a series of slots, it has been shown that at least two general flow regimes can exist. In the region which corresponds to "fully rough" behavior, a fairly steady vortex pattern is established in each slot. In the region corresponding to the "roughness-transition" regime, the flow in the slots is unsteady and may be described by several typical flow phases which follow each other in random succession. The disturbances leading to the unsteady flow are believed to come from the turbulent boundary layer passing over the slots. Based on the flow observations some estimates may be made about the trends of the heat-transfer coefficient for rough surfaces. The results of Dipprey and Sabersky [2] indicate such trends.

In future work it is intended to obtain a more complete understanding of the cause for the unstable flow in the slots. The three dimensional aspects of the flow are then to be explored and the flow behavior for other types of roughnesses is to be studied. Eventually it is hoped to obtain a sufficient understanding of the flow over roughnesses so as to be able to predict more adequately the heat-transfer characteristics of such surfaces.

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Résumé—On a besoin d'un modèle d'écoulement sur une surface rugueuse afin d'expliquer le transport de chaleur par convection forcée sur une telle surface. Les expériences actuelles ont été effectuées afin d'obtenir des informations qui peuvent aider à établir un modèle convenable. On a observé l'écoulement sur des ensembles de rugosités artificielles consistant en rainures de profil carré perpendiculaires à la direction de l'écoulement. La couche limite était turbulente et les conditions expérimentales pouvaient être modifiées de telle façon que l'on ait une sous-couche laminaire relativement épaisse. On a pu obtenir des valeurs du rapport de la profondeur des fentes à l'épaisseur de la sous-couche laminaire aussi faibles que 2 ou 3 avec des dimensions suffisantes pour permettre une visualisation convenable.

Les expériences ont montré que lorsque la profondeur de la fente était supérieure à environ 20 fois l'épaisseur de la sous-couche laminaire, une configuration tourbillonnaire plus ou moins permanente se formait dans les rainures, configuration déjà observée par plusieurs chercheurs. Cependant, pour de plus faibles profondeurs de rainures, l'écoulement était sujet à des perturbations aléatoires. Une configuration tourbillonnaire permanente se formait périodiquement, mais se détruisait par la suite. L'aspect général de l'écoulement pouvait être décrit à l'aide de quatre configurations bien distinctes.

Zusammenfassung—Um den Wärmeübergang an einer rauhen Oberfläche bei Zwangskonvektion erklären zu können, ist ein Modell der Strömung über eine derartige Oberfläche erforderlich. Die gegenwärtigen Versuche wurden durchgeführt um Kenntnisse zu erhalten, die zur Darstellung eines geeigneten Modells nützlich sind. Beobachtet wurde die Strömung über eine Reihe künstlicher Rauhigkeiten aus Rechteckschlitzen quer zur Strömungsrichtung. Die Grenzschicht war turbulent und die Versuchsbedingungen konnten so angepasst werden, dass eine relativ dicke laminare Unterschicht entstand. Das Verhältnis von Schlitztiefe zu laminarer Unterschicht konnte bis auf 2 oder 3 heruntergebracht werden, wobei die physikalischen Dimensionen noch hinreichend gross waren, um eine bequeme Beobachtung zu gestatten.

Die Versuche zeigten ein mehr oder weniger stationäres Wirbelmuster in den Schlitzen, wenn der Schlitz die Dicke der laminaren Unterschicht um einen Faktor von etwa 20 überschritt. Diese Muster sind von einigen früheren Beobachtern bemerkt worden. Bei geringeren Schlitztiefen war die Strömung im Schlitz willkürlichen Störungen unterworfen. Ein ziemlich stationäres Wirbelmuster baut sich periodisch auf und wird wieder zerstört. Das allgemeine Strömungsbild kann auf Grund von vier ziemlich gut zu unterscheidenden Mustern beschrieben werden.

Аннотация—Для выявления влияния шероховатости поверхности на явление переноса тепла при вынужденной конвекции необходимо создать модель течения. Настоящие опыты были проведены с целью получения данных, которые могли бы оказаться полезными для составления соответствующей модели. Наблюдения проводились за течением на поверхности с искусственно созданной шероховатостью в виде квадратных пазов, расположенных перпендикулярно направлению течения. Пограничный слой был турбулентным, и условия эксперимента можно было видоизменять таким образом, чтобы создавать сравнительно большой по величине ламинарный подслой. Самые малые значения отношения глубины паза к толщине ламинарного подслоя, порядка 2–3, можно

было получить при физических размерах, достаточно больших для удобства наблюдения.

Опыты показали, что когда толщина паза превышала толщину ламинарного подслоя в 20 раз, в пазах наблюдалась картина более или менее стационарного вихревого движения. Эта картина наблюдалась ранее несколькими исследователями. Однако при меньшей глубине паза течение в нем нарушалось произвольно. Периодически образуется картина довольно стационарного вихревого течения, которая затем нарушается. Общий вид течения можно было бы описать в виде четырех хорошо различимых картин течения.