Int. J. Heat Mass Transfer. Vol. 36, No. 4, pp. 961–965, 1993
Printed in Great Britain

0017-9310/93 $6.00 + 0.00

Some measurements of the penetration of turbulence into small cavities

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(*Received 5 December 1991 and in final form 24 April 1992*)

Abstract—Within a cavity, bordering a fluid in turbulent flow, mass and heat transport, along with phenomena which depend on them (such as corrosion), are likely to be affected by penetration of turbulence from without. Experimental measurements of velocities within cavities have been carried out by hot film velocimetry. Measurements were carried out in a wind tunnel with cavities of various shapes, of width 2–10 mm. Turbulence was generated by a grid upstream of the cavity and velocity fluctuations were observed in the cavity for all but the smallest cavities. It is suggested that an eddy will penetrate a cavity if the cavity is larger than the Prandtl eddy length.

INTRODUCTION AND PREVIOUS INVESTIGATIONS

CONVECTIVE mass transport within cavities can influence the rate of several phenomena of scientific and engineering interest. Examples are corrosion within crevices in metals, chemical vapor deposition in the processing of semiconductors, solute transport between dendrite arms in solidification processing, electrodeposition into holes and heat and mass transport at rough surfaces.

There have been many investigations of mass transport in cavities where the fluid within is stationary or in laminar (or even Stokesian) flow. Examples particularly relevant to corrosion have been the papers of Alkire and co-workers who examined both the stationary case [1–6] and the case where the flow is laminar [7–9]. This group also treated the effect of (Stokesian) flow on convective transport encountered in processing of printed circuit boards [10, 11], a topic also examined by Shin and Economou [12]. The papers by Beck [13] and by Beck and Chan [14] are amongst other examples of publications examining the connection between flow and corrosion within small pits and crevices.

While the studies cited above have been concerned with cavity sizes such that flow is laminar, it should be recognized that under other conditions (larger cavities, higher free stream velocities) turbulence may penetrate a cavity with consequent effect on mass and heat transport. It has long been recognized that turbulence generated upstream of an object can affect heat or mass transfer to the surface of the object. A classical example is the work of Lavender and Pei [15] who measured the effect of turbulence, generated by an upstream grid, on heat transfer at a sphere placed in a wind tunnel. This led the present authors to the conjecture that turbulence, penetrating into a cavity, may influence mass transport, and to the investigation described herein. Indirect evidence in support of this conjecture is provided by studies of heat and mass transfer at rough or grooved surfaces. For example, Cornet *et al.* [16] measured the rate of mass transfer of dissolved oxygen to rotating discs with different roughnesses. In laminar flow, the effect of surface roughness was merely one on electrode surface area. Beyond the laminar-to-turbulent transition (itself effected by roughness) the rough discs showed greatly enhanced mass transport (beyond that explicable merely in terms of area).

Penetration of turbulence into large openings (for example open aircraft doors) has long been of interest to the aerospace community, but there appear to have been no studies of the penetration of turbulence into cavities of an intermediate size (i.e. comparable to the length scale of the turbulence). The closest studies have been those of unsteady flows in cavities, for example those of Amon and Patera [17], of Amon and Mikic [18], and of Ghaddar *et al.* [19, 20]. Bogatyrev and Gorin [21] have measured velocities in such cavities under both laminar and turbulent conditions. Those theoretical and experimental investigations have been concerned with behaviour at high Reynolds numbers where unsteady behavior is engendered within the cavity itself. The present study is concerned with much lower Reynolds numbers (0.1–3) where turbulence is convected into the cavity from the outside.

The flow in the present investigation bears a superficial resemblance to lid-driven cavity flow described by many authors (e.g. Ghia *et al.* [22], Schreiber and Keller [23], Thompson and Ferziger [24], Prasad and Koseff [25], and Aidun and co-workers [26]. Again those investigators studied flow at much higher Reyn-

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olds numbers and any turbulence was generated within the cavity rather than being convected in from the outside.

EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments were carried out in a small wind tunnel (approximately 0.46 m in diameter by 13 m long) designed to operate in the weakly turbulent regime. Turbulence was generated by a grid upstream of a cavity set into the tunnel wall, as shown schematically in Fig. 1. The grid was placed 50 mm from the cavity and consisted of a perforated plate (2.5 mm diameter holes on 5 mm spacing). Preliminary smoke tests showed that the flow was in the direction shown in Fig. 1 with no gross recirculation.

The cavities were machined in various shapes and sizes into interchangeable 'cavity pieces'. The cavities were cylindrical holes (height/diameter = 1), square section trenches, and triangular section trenches (the last with two different height-to-width ratios). The trenches were 27 mm long with their lengths perpendicular to the tunnel axis. The widths of the cavities ranged from 2 to 10 mm. Each cavity had a small hole opposite its mouth through which a miniature hot film probe could be passed. The probe was secured by an o-ring and the probe position adjustable so that measurements could be made along the center line (or plane) of the cavity.

In most cases the miniature hot film probe was a TSI platinum film probe (1276-10A) which has a sensing length of 0.25 mm and a diameter of 25 μm. Instrumentation used with the probe consisted of a TSI IFA 100, a Solartron computing voltmeter (7071) and a Rapid Systems digital oscilloscope (4 × 4) plus spectrum analyzer (R360). Preliminary experiments led to the selection of a 200°C film temperature and a data acquisition time of 40 s as suitable. The probes were calibrated in the wind tunnel (with the grid removed) against calibrated pitot tubes over a velocity range of 0–8 m s^{-1}. Over this range the measurements were reproducible and were a good fit to the King equation.

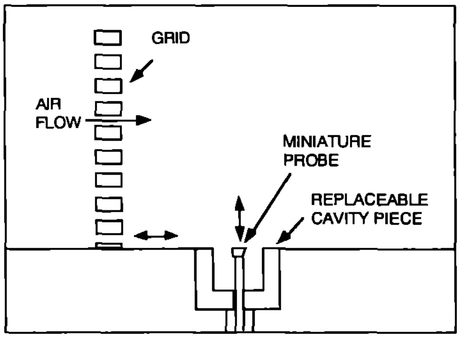

FIG. 1. Experimental apparatus for the wind tunnel system.

RESULTS AND DISCUSSION

The results reported here principally are the time-averaged velocity ('mean velocity' in the figures below) and the root mean square deviation ('r.m.s. velocity') measured along the axis (or center plane) of the cavity, i.e. along a line perpendicular to the tunnel wall. It should be recognized that a single film hot film velocimeter is insensible to the direction of the velocity (within a plane perpendicular to the film). Consequently 'velocity' appearing on the ordinate of Figs. 2–6 should be regarded as the magnitude of the velocity. Under conditions of fluctuating flow, the inability of the hot film probe to distinguish positive from negative flows may artificially increase the magnitude of the mean velocity. This is not thought to be a difficulty in the present investigation where the mean velocity is significantly higher than the typical fluctuations (r.m.s. velocity < mean velocity), i.e. flow reversals are uncommon. It should also be recognized that, in the case of the cylindrical cavities, the mean flow will be three-dimensional. In the case of the trench cavities the flow is expected to be almost two-dimensional with a primary vortex running clockwise when (as in Fig. 1) the free stream air flow is from left to right. For the wider trench cavities wall effects may introduce a third velocity component into the mean flow. The depth of the measurement point within the cavity has the following convention: negative depths are positions within the cavity with zero being the

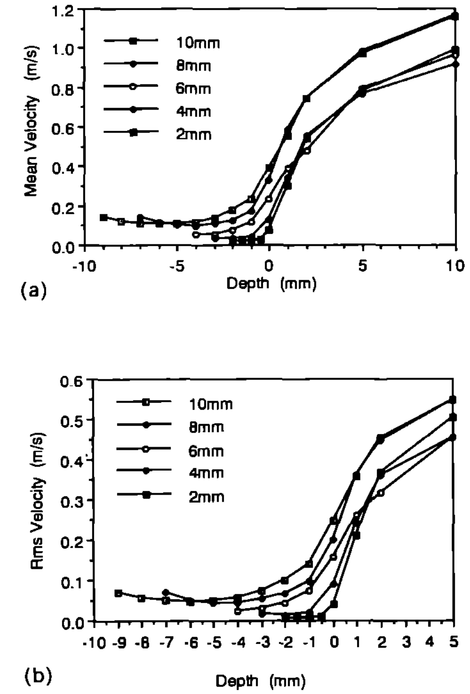

FIG. 2. (a) Dependence of mean velocity on cavity size for cylindrical cavities at various positions along cavity axis. (b) Dependence of r.m.s. fluctuation on cavity diameter.

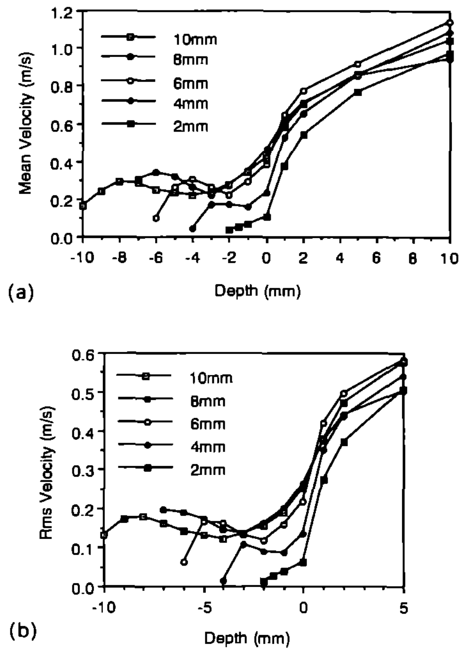

FIG. 3. (a) Dependence of mean velocity on width for rectangular trenches. (b) Dependence of r.m.s. deviation on trench width.

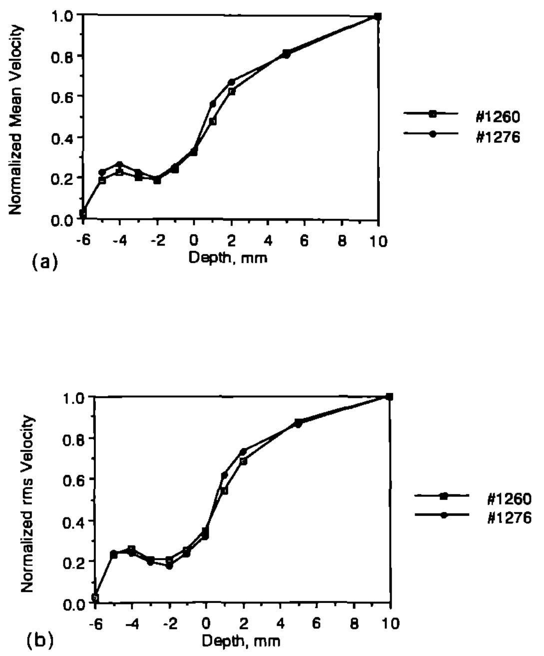

FIG. 5. (a) Mean velocity, 6 mm rectangular trench, probe 1260 vs 1276. (b) r.m.s. velocity, 6 mm rectangular trench, probe 1260 vs 1276.

mouth of the cavity. In all cases the probe was aligned so that the film was perpendicular to the tunnel axis and parallel to the tunnel wall.

Figure 2 depicts the results for cylindrical cavities of various diameters ranging from 2 to 10 mm. Scatter of the measurements outside the mouth of the cavity is due to the imprecision of the speed controller on the tunnel's fan which, although maintaining a steady speed, was too coarse to permit repeating experiments at exactly the same velocity. It can be seen that, with the possible exception of the 2 mm cavity, appreciable velocities occurred in these cavities.

More significant from the viewpoint of these studies is that turbulence, reflected in non-zero r.m.s. deviation from the mean value, appeared in all but the smallest cavity.

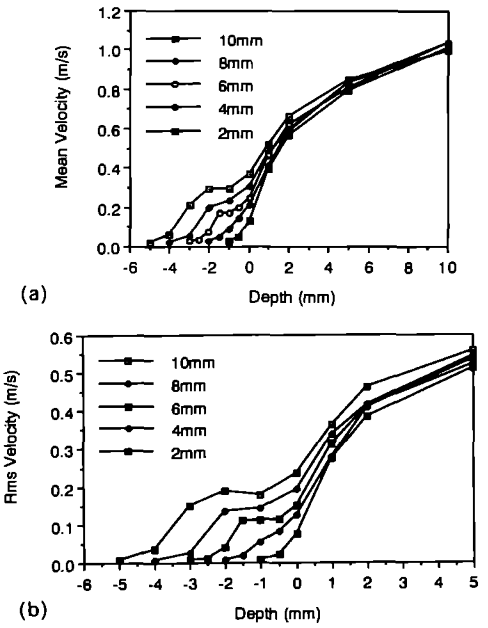

FIG. 4. (a) Dependence of mean velocity on trench width for triangular section trenches. (b) Dependence of r.m.s. velocity on triangular trench width.

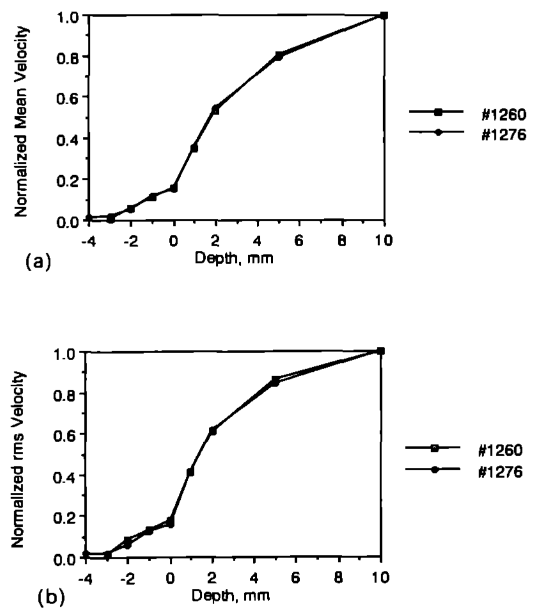

FIG. 6. (a) Mean velocity, 4 mm 53°C V-trench, probe 1260 vs 1276. (b) r.m.s. velocity, 4 mm 53° V-trench, probe 1260 vs 1276.

Figure 3 presents corresponding results for the square section trench and again it is seen that, except for the smallest trench, there is considerable velocity fluctuation within the cavity.

Results for a triangular section trench, of depth equal to half its width at the mouth, are shown in Fig. 4. This trench is much more confining than the cavities of Figs. 2 and 3 and, as might be expected, the mean velocities and r.m.s. deviations are smaller than in those earlier cases. Nevertheless, significant penetration of turbulence into the cavity appears to be taking place for cavities of opening 4 mm or more. A limited amount of measurement was carried out using a second type of triangular section trench with a depth equal to its mouth width. For the 4 and 6 mm trenches studied, the results were intermediate between those of Figs. 3 and 4.

Based on the mean velocity at the cavity mouth and the width of the mouth, Reynolds numbers for the flows of Figs. 2–4 range from 0.1 to 3, i.e. well below the range at which unsteady flow would be caused by the flow within the cavity itself. To further ensure that what was being detected in the measurements was turbulence penetrating the cavity from outside, rather than turbulence generated within the cavity, some measurements were carried out with the grid removed. These were conducted using 4 and 6 mm rectangular cavities at a flow rate sufficient to give a velocity of approximately 1 m s^{-1} at 10 mm above the cavity (i.e. the same free stream velocity profile as when the grid was present). The maximum r.m.s. velocities within the trench were 0.0013 and 0.0012 m s^{-1} in the 4 and 6 mm trenches, respectively. These values, which may be below the precision of the probe, are one or two orders of magnitude below the r.m.s. values appearing in Figs. 2–4. It appears that the turbulence within the cavity seen in those figures is penetrating the cavities from the outside, rather than being generated within the cavity.

Although the hot film probe is a miniature one, nevertheless its length (0.25 mm) is a significant fraction of the cavity dimension, particularly for the smaller cavities. It might therefore be hypothesized that the measurements are appreciably affected by the measuring device. To test this hypothesis a limited number of experiments were done with a second probe, a TSI 1260 hot film probe which has slightly more than twice the length (of the cylindrical sensor) of the probe normally used. These experiments were conducted with the grid in place. Results for the two probes appear in Fig. 5 for a 6 mm square section trench and Fig. 6 for a triangular trench 4 mm wide by 4 mm deep. In both cases velocities were normalized by dividing by the measurements at 10 mm so as to avoid the fan speed control problem described above. Differences between mesurements with the two probes in other geometries (4 and 6 mm cylindrical cavity) were comparable with those seen in Fig. 5 and are not reproduced here. It appears that the results are insensitive to probe size for these miniature probes and therefore that the probe is likely to have had negligible effects on the velocities.

The spectral analysis of the velocity signal showed a distribution within the cavity that was similar to that outside: a broad peak at approximately 25 Hz descending to background noise at approximately 250 Hz. The peak at the mouth of the cavity appears somewhat broader than at higher or lower positions. The spectra from measurements within a 4 mm cavity were indistinguishable from background.

A simple understanding of the ability of turbulence to penetrate a cavity may be reached as follows. A plausible mechanism for the 'penetration' of turbulence into the cavity is convection of the turbulence into the cavity by the mean velocity. This suggests that an eddy with a length scale significantly greater than the cavity size would be unable to penetrate it.

The Prandtl eddy length can be obtained from [27]

eddy length

= fluctuating velocity/'frequency' of turbulence.

From the spectral analysis, 50 Hz would be an approximate average for the frequency; 0.1 m s^{-1} is a representative value for the velocity at the mouths of the cavities. Hence the eddy length is estimated to be 2 mm. The experimental data revealed that turbulence had penetrated the 4 mm cavity to some extent (and the 2 mm cavity to an even smaller extent) but would readily penetrate 6 mm and larger cavities. This simple analysis is seen, therefore, to be in agreement with the data.

CONCLUDING REMARKS

Experimental measurements of velocities within small cavities have been carried out using hot film velocimetry. The results suggest that turbulence in the stream external to the cavity can penetrate the cavity when the Prandtl length scale is smaller than the size of the cavity mouth. It is concluded that studies of mass and heat transport within such cavities must allow for the penetration of turbulence under these circumstances.

The investigation described here was a preliminary one; it is hoped that measurements with a greater spacial and temporal resolution can be carried out in the future by laser Doppler velocimetry.

Acknowledgements—Mr Joseph Han assisted with some of the experimental measurements. One of the authors (Y.T.) was supported by Nippon Mining Corp. throughout the period of this investigation. Professor Malcolm McPherson is thanked for the use of the wind tunnel.

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