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# DISCRETE-HOLE COOLING IN THE PRESENCE OF FREE STREAM TURBULENCE AND STRONG FAVOURABLE PRESSURE GRADIENT

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**Abstract** – Mean velocity and concentration measurements are reported for the injection of carbon dioxide through a plate prepared with discrete holes aligned at 45° with the plate and past which an external stream is flowing. It is shown that a moderate favourable pressure gradient in the external stream produces substantially higher concentration levels at the surface of the plate through its effect in delaying the transition of the injected fluid to turbulent flow. The presence of free-stream turbulence intensities of about 4 per cent reduce the wall concentrations by typically 10 per cent in the case of a favourable pressure gradient but have negligible influence when the free stream velocity of the external stream is uniform.

## NOMENCLATURE

$K$, dimensionless acceleration parameter, $\nu/U_G^2(\mathrm{d}U_G/\mathrm{d}x)$;
$m$, mass fraction of chemical species;
$m$, dimensionless injection rate, $\dot{m}''/\rho_G U_G$;
$\dot{m}''$, mass injection rate through plate averaged over *whole* of porous section of plate;
$T$, temperature;
$U$, streamwise velocity;
$x$, distance in streamwise direction;
$y$, distance normal to wall;
$\nu$, kinematic viscosity;
$\rho$, density.

Subscripts
$C$, hole exit condition;
$G$, local free stream condition;
$W$, wall condition.

## INTRODUCTION

ONE OF the most promising techniques of cooling the outer surface of gas-turbine rotor and stator blades is that of discrete hole cooling, wherein air which has by-passed the combustion chamber is led to the interior of the blade and passed to the exterior through discrete holes in the blade wall. Blades constructed in this way possess far superior strength and blockage-resistant characteristics than do those fabricated from sintered powder or woven metal materials.

A number of recent experimental studies, e.g. [1-4], have sought to provide quantitative information on the external cooling effectiveness of this process. In [4] the investigation was performed on a flat plate (rather than on a curved aerofoil surface) with dimensions roughly ten times as large as would arise on a turbine blade (but with velocities an order of magnitude smaller). The cooling effectiveness was assessed by measuring the dispersion of a foreign gas in the injectant stream, the two streams being at the same temperature. Several geometries of injectant-hole patterns were explored. The main conclusion of the study were that:

(i) a staggered pattern of holes was far superior to an in-line arrangement,
(ii) there was great benefit to orientating the axis of the hole downstream (rather than normal to the plate surface),
(iii) the optimum velocity through the injection holes was about 30 per cent of the free stream velocity,
(iv) the lateral spacing between holes should be appreciably less than the streamwise pitch to avoid "hot spots".

These results were consistent with the findings by the team at the University of Minnesota in so far as the investigations overlapped.

In all the above studies there was negligible streamwise variation of pressure and the level of free-stream turbulence intensity was low (about 0·5 per cent). Neither of these conditions prevail in the case of flow past a turbine blade, however. There are invariably severe favourable gradients over the leading part of the blade and free-stream turbulence intensity levels are commonly estimated to be as high as 30 per cent. Both factors would be expected to have substantial influence on the cooling effectiveness. Severe accelerations are known to reduce turbulent mixing [5] and one might therefore expect a less rapid dilution of coolant than in a uniform-velocity stream. High turbulence levels would tend to enhance the mixing processes causing more rapid dispersion than in a quiescent stream.

In the work reported here exploration has been made of the influence of both the phenomena mentioned above, i.e. free-stream acceleration and free-stream turbulence, employing as test plate the most successful of the geometries examined in [4]. The principal measurement for assessing the cooling performance has been the concentration of the injectant on the plate surface. It is now generally acknowledged that the turbulent Prandtl and Schmidt numbers are equal. Mass transport experiments therefore provide an exact analogy of a heat diffusion process in the same geometry where the wall is adiabatic and frictional heating is negligible. The mass fraction ratio $(m_W - m_G)/(m_C - m_G)$ may therefore be interpreted as the adiabatic wall effectiveness $(T_W - T_G)/(T_C - T_G)$. In addition to wall concentration data, profiles of mean streamwise velocity close to the plate have been measured at a number of positions, to help establish the hydrodynamic character of the flow. A brief description of apparatus and instrumentation is provided in section 2 followed in Section 3 by an examination and discussion of the experimental findings.

## 2. APPARATUS, INSTRUMENTATION AND TEST PROGRAM

The layout of the open-circuit wind tunnel and design features of the test section are documented in [4]; here therefore only brief details will be given. The permeable section of the $\frac{1}{4}$-in aluminium test plate, shown schematically in Fig. 1, is covered with 0·0625 in dia holes in a staggered arrangement in which the ratio of pitch : diameter is 8 : 1. The axis of the holes makes an angle of 45° with the test plate and is directed downstream. On the back of the test plate were inserted teh steel dividing strips which spanned the width of the plate and between which were affixed sintered bronze strips.

The purpose of the backing strips was to provide a sufficiently high resistance to flow for the flow-rate through the holes to be effectively uniform irrespective of static pressure variations over the plate caused by acceleration of the external stream. The arrangement of the test section, with the permeable section of the test plate inserted, is shown in Fig. 2. For tests with a varying

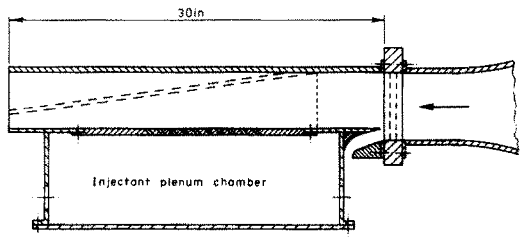


FIG. 2. Test section.

free stream velocity the acceleration is caused by lowering the roof, as indicated. The acceleration parameter $(\nu/U_G^2)(\mathrm{d}U_G/\mathrm{d}x)$ was effectively constant over the permeable section of the test plate with a value of approximately $2{\cdot}0 \times 10^{-6}$. This level of acceleration is known to cause substantial diminution to transport by turbulence close to the wall but is some 50 per cent less than that needed to cause a complete degeneration to laminar flow [5].

In the tests with augmented free-stream turbulence levels the turbulence inducing agents were two-square-mesh grids made from circular sectioned rods 0·1 in and 0·125 in dia which were located a short way upstream from the leading edge of the test plate. These produced a turbulence intensity of 6 per cent at the leading row of holes which fell to about 3·8 per cent at the sixth, as indicated in Fig. 3.

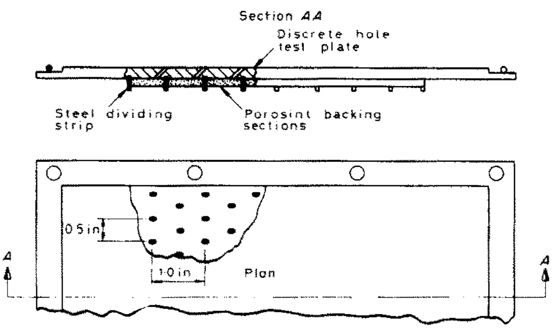


FIG. 1. Discrete hole test plate.

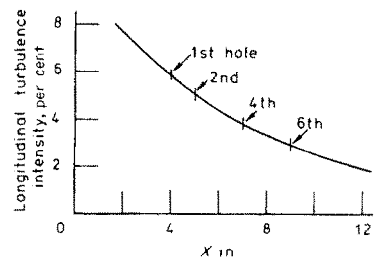


FIG. 3. Variation of free-stream turbulence intensity over test plate.

Velocity profile measurements in the external boundary layer were obtained with a flattened-tip pitot tube mounted on a micrometer traverse; concentration measurements were obtained with a very similar probe and the sample passed through a continuous-sampling katharometer for analysis. The variation of longitudinal free-stream turbulence intensity over the test plate was obtained with a DISA constant-temperature hot wire anemometer employing a standard 90° probe.

In the earlier study on this apparatus [4] air and freon had been employed as injectants, in the former case with a tracer of helium to permit measurement of the dispersion of injectant. The density of freon is more than four times that of air and, while the use of this gas produced very substantial density-ratio effects, it was decided, in the present investigation to use exclusively carbon dioxide as the injected fluid. The choice was made partly on the grounds of cost (the cost per lb of freon being approximately five times that of $CO_2$) and partly because it was now felt preferable to use a fluid whose density vis à vis that of air was closer to the density ratio which would be encountered in gas turbine practice. Three series of experiments are reported in the next section:

(i) parallel flow ($dp/dx \simeq 0$) with low turbulence intensity,
(ii) converging flow ($(dp/dx) - ve$) with low turbulence intensity,
(iii) converging flow with high turbulence intensity.

In each set of tests attention was directed to two regions of the test plate: the areas behind the leading row and the sixth row of holes.* The main emphasis of the measurements was on the level of $CO_2$ concentration at the surface, the reason being that this produced the mass-transfer counterpart of the plate temperature in the absence of frictional heating and heat transfer. As remarked in the Introduction, the mapping of surface concentration patterns was supplemented by velocity-profile measurements to help infer the structure of the flow adjacent to the plate.

### 3. PRESENTATION AND DISCUSSION OF RESULTS

The case of parallel flow with low free stream turbulence has been extensively explored in [4] for air and freon injection. We re-examined this flow condition (with $CO_2$ injection) here simply to provide a base to which variations caused by acceleration and free stream turbulence could be referred. Figure 4 compares the variation of injectant mass fraction with dimensionless injection rate $M$ for positions eight diameters

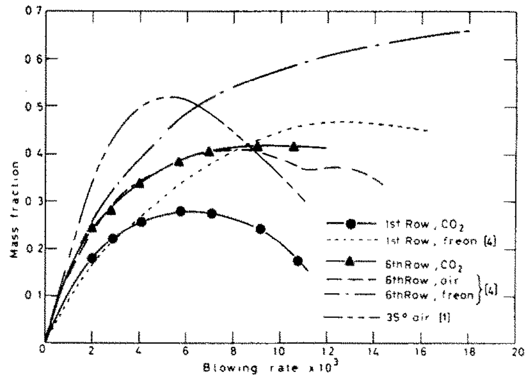


FIG. 4. Effect of density ratio and position on concentration 8 diameters behind hole.

directly behind a hole in the first and sixth row respectively. For the leading row, the concentration level rises steeply at first then shows little variation over the range $4 \times 10^{-3} < M < 8 \times 10^{-3}$. Further increase of injectant rate causes the concentration level to fall sharply. The behaviour is seen to be qualitatively the same as the 35° air injection data of [1]* and the freon injection data of [4]; the maximum level of concentration is 50 per cent higher for freon, however, and occurs at a much larger injection rate.

The above variation of wall concentration with injection rate suggests that substantial changes must be taking place in the external boundary-layer. Confirmation is provided by Fig. 5 which shows the near-

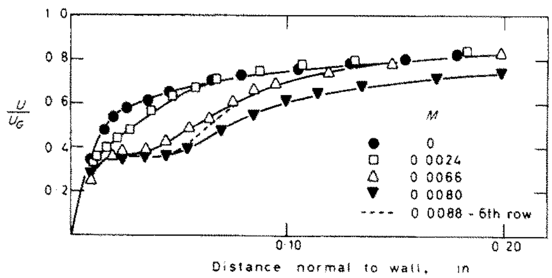


FIG. 5. Effect of injection rate on near wall velocity profile four diameters behind first row.

wall velocity profiles four diameters behind a hole for three levels of injection. For $M = 0{\cdot}0024$ the profile exhibits only slight departure from that for zero injection; at $M = 0{\cdot}0065$ there is a much increased velocity defect close to the wall but little effect further away from it; and at $M = 0{\cdot}0080$ there is a large velocity deficit extending over the whole of the region shown in Fig. 5. The above patterns are respectively indicative of:

*No special significance attaches to the sixth row; it was selected simply as representative of a region where the injection pattern had become well established.

*The data of [1] were in fact for a *single* hole; we have evaluated an equivalent $M$ value assuming the same pitch : diameter ratio as in the present tests.

a carbon dioxide jet remaining attached to the plate on leaving the hole; a jet separating from the plate at exit but reattaching a short way downstream; a separated jet which has not attached to the plate. It seems highly probable that in practice one would want to operate a discrete-hole cooling system in the "attached-jet" mode; for this reason most of the detailed exploration has been made at a low level of $CO_2$ injection ($M = 0{\cdot}0027$).

The dependence of concentration level on $M$ is somewhat different at the downstream station. From Fig. 4 it is seen that the concentration of $CO_2$ again levels off above a certain injection rate but does not display the sharp decrease with $M$ observed behind the leading row of holes. There seems to be two main reasons for the behaviour: firstly by the sixth row of holes the process has augmented the effective viscosity of the fluid and thus acts to reduce the degree of separation of the jet as indicated by the velocity profile in Fig. 5 for the sixth row; secondly some of the fluid from the *upstream* rows of jets eventually finds its way (through convection and diffusion) to the surface, thus providing a "background" concentration level which increases monotonically with injection rate.

The maximum concentration at this downstream station occurs at values of $M$ of $6{\cdot}5 \times 10^{-3}$, $10 \times 10^{-3}$ and $26 \times 10^{-3}$ respectively* for air, carbon dioxide and freon; this corresponds to exit velocities from the holes of 53 per cent; 53 per cent and 49 per cent of the external stream velocity $U_G$. Behind the leading row, the maximum $m_W$ for $CO_2$ and freon injection occurs when the injection velocities are respectively 31 per cent and 25 per cent of the free stream value. These two sets of results suggest that, at a given row, the ratio of hole-exit velocity: external stream velocity is the main factor in determining whether or not the emerging jet remains attached to the plate; the density ratio *per se* has little effect.

We now examine the effect of flow acceleration on the concentration pattern. Figure 6 which again shows the variation with $M$ of the $CO_2$ concentration eight diameters behind a hole indicated that, for the leading row, the acceleration brings about a marked increase of mass fraction relative to the parallel flow case; the improvement ranges between 25 per cent and 40 per cent according to the injection rate. There is also an increase in concentration level behind the sixth row of 20–25 per cent. It is perhaps not appropriate in this case to draw detailed conclusions about the result for, in the accelerating flow, $M$ varies appreciably along the plate whereas for parallel flow it is sensibly uniform.

*For carbon dioxide and freon there is an uncertainty of about 10 per cent in the quoted values because these curves are very flat in the neighbourhood of the maximum.

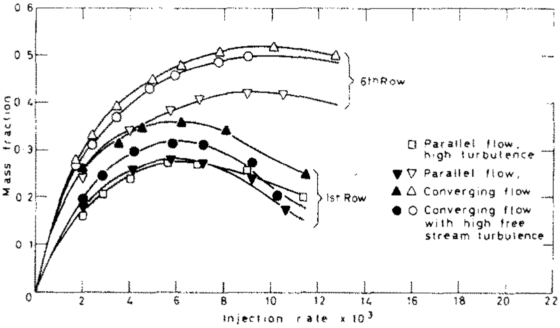


FIG. 6. Effect of acceleration and free-stream turbulence on concentration levels 8 diameters behind injection hole.

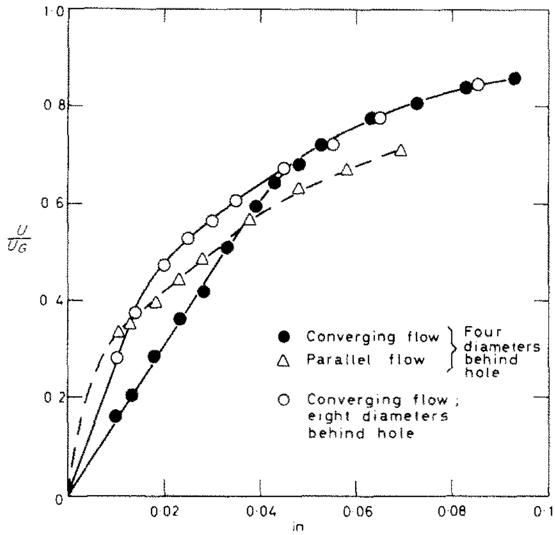


FIG. 7. Near wall velocity profile behind first row; comparison of converging and parallel flow.

The cause of the higher concentration levels will shortly be inferred from Fig. 7 which shows the development of the mean velocity profile behind a hole in the first row. We first remark, however, that at exit from the hole the jet fluid will not be turbulent for the Reynolds number based on hole diameter for $M = 0{\cdot}0027$ is only 325. The attached jet becomes turbulent at some distance downstream from the hole through mixing with and agitation by the turbulent fluid in the external boundary layer. In the case of parallel flow this transition occurs swiftly for there is nothing to suggest in Fig. 5 that the near-wall flow four diameters behind the holes is laminar even at the lowest injection rate. In contrast, at the same position for the accelerating flow (Fig. 7) the velocity increases nearly linearly with distance to a height of 0·05 in above the wall suggesting unequivocally that turbulent mixing is negligible in this region. Even at eight diameters behind the hole the laminar region still extends over about 0·02 in which is about twice as large as that at four diameters behind a hole for parallel flow. Thus, the basic cause of the higher concentration levels is that the acceleration tends to diminish turbulent mixing in the external boundary layer and offers a stabilizing environment to the laminar jet emerging from the hole. In these conditions the jet undergoes transition to turbulent flow much less rapidly than it does in parallel flow; the streamwise dilution rate of the $CO_2$ is thereby reduced.

A less desirable consequence of the acceleration emerges in Fig. 8 which shows concentration contours around a leading-row hole for both converging and parallel flow. Although the contours for converging flow extend appreciably further downstream than do the corresponding ones in parallel flow, the lateral spread of the 25 per cent contour is definitely less. It is believed that the effect is due to the reduction of the turbulent mixing in the boundary layer close to the wall in the accelerated flow.

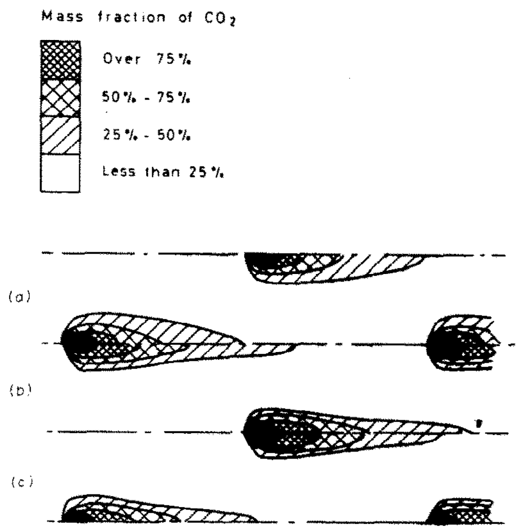


FIG. 8. Concentration contours around leading-row hole, $M = 0{\cdot}0027$. (a) Parallel flow; (b) Converging flow; (c) Converging flow with high free-stream turbulence.

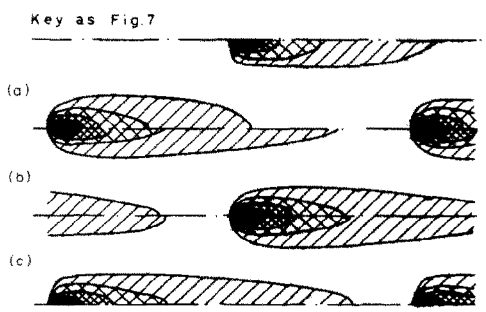


FIG. 9. Concentration contours around sixth row hole, $M = 0{\cdot}0027$. (a) Parallel flow; (b) Converging flow; (c) Converging flow with turbulence.

Comparable measurements for the sixth row are shown in Fig. 9. For parallel flow the 25 per cent contour encloses about twice as large an area as at the leading row mainly due to the steady build-up in the background concentration—about 13 per cent at this station.* The contours for the accelerating flow extend a little further downstream than for parallel flow but do not show a significantly different lateral penetration.

The insertion of the turbulence generating grids raises the level of longitudinal turbulence intensity at the first row of holes from 0·8 per cent to 5·8 per cent. Figure 6 shows that at the "standard" position eight diameters behind a hole the turbulence reduces the concentration level by about 10 per cent for the accelerating flow but insignificantly for parallel flow. The result seems consistent with our conclusion above that the higher levels of concentration in accelerating flow (with low turbulence) are due to the jets remaining laminar or semi-laminar for a greater distance downstream from the hole than for parallel flow; for free stream turbulence is usually held to affect directly only the laminar flow region and the position where transition to turbulent flow occurs. (When a boundary layer is turbulent such intense turbulence generation takes place close to the wall that effects of free-stream turbulence are swamped.) Thus, the high turbulence level in these experiments promotes the transition of the injected fluid to turbulent. Only in the converging flow case does this have noticeable affect on concentration levels, however, for, with parallel flow, transition already occurs very close to the hole exit.

We had thought that the high level of turbulence might have caused greater lateral spreading of the wall concentration contours for accelerating flow, partly compensating thereby for the faster streamwise decay rate. Figure 8 shows that the expectation was not borne out, however; indeed there is rather less lateral penetration than with low free stream turbulence. The probable reason is that the turbulence raises the effective diffusion coefficient substantially in the outer part of the boundary layer but less and less as the

*It is interesting to compare this value of background wall concentration with the data of Baker and Launder [7] on a uniformly porous plate. At a similar Reynolds number their $m_W$ was about 45 per cent (interpolating between their data to get the appropriate value of $M$). Their injectant was freon which leads to slightly higher values of $m_W$ than with $CO_2$ (see Fig. 4); but one nevertheless concludes that the uniformly porous surface gives concentrations about three times as high as the present one.

wall is approached. Thus transport of $CO_2$ away from the surface is aided and, as a consequence, leaves less to be transferred laterally.

The turbulence decays rapidly over the plate and by the sixth row is only 2·9 per cent. As Figs. 5 and 7 suggest, there is very little influence of free-stream turbulence at this position on the wall concentration level.

## 4. CONCLUDING REMARKS

The main finding to emerge from this experimental study is that steep streamwise accelerations can substantially improve the streamwise effectiveness of discrete-hole cooling systems by delaying the transition of the jet from laminar to turbulent. In the present experiments a level of $K$ of approximately $2 \times 10^{-6}$ led, typically to a 30 per cent improvement in effectiveness eight diameter downstream from the injection point in the leading row of holes. It is expected that still higher values of effectiveness could be recorded on an actual turbine blade for the acceleration level is often high enough to maintain laminar flow over much of the blade surface (Turner [6]).

A secondary effect of the acceleration was that the lateral rate of spread was reduced somewhat. In reference [4], on the basis of parallel-flow tests, it was suggested that the maximum acceptable lateral spacing of holes was about five diameters. In the light of the present experiments, it looks as though, when severe streamwise pressure gradients are present, the maximum lateral spacing should not exceed three diameters if "hot spots" are to be avoided.

The main influence of free stream turbulence seems to be through its effect on the transition point of the jet. Thus, for the accelerating flow, concentration levels behind the first row were reduced by typically 10–15 per cent. Consistently, there was hardly any effect for parallel flow because, even with a quiescent free stream, the injected fluid rapidly becomes turbulent. We could thus regard the parallel flow data as providing a lower bound to the levels of concentration that might occur in accelerating flow, the lower limit being reached only for extremely high levels of free stream turbulence.

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## REFROIDISSEMENT PAR DES PERFORATIONS EN PRESENCE DE TURBULENCE DANS L'ECOULEMENT LIBRE ET D'UN FORT GRADIENT DE PRESSION FAVORABLE

**Résumé**—On rapporte des mesures de vitesse moyenne et de concentration pour l'injection de gaz carbonique à travers une plaque percée de trous alignés à 45° par rapport à un écoulement externe. On montre qu'un faible gradient de pression favorable dans l'écoulement externe produit des niveaux de concentration nettement plus élevés à la surface de la plaque et un effet de retardement sur la transition du fluide injecté vers le mouvement turbulent. La présence d'une intensité de turbulence, de l'ordre de 4 pour cent dans l'écoulement libre, réduit de 10 pour cent les concentrations pariétales dans le cas d'un gradient de pression favorable, mais a une influence négligeable lorsque la vitesse de l'écoulement libre externe est uniforme.

## WÄRMEÜBERGANG AN BEWEGTE GRANULATE

**Zusammenfassung**—Der konvektive Wärmeübergang von einer Platte an vorbeifließende Granulate wurde untersucht. Es wurde ein analytisches Näherungsverfahren unter Einbeziehung der speziellen Eigenschaften des Mediums entwickelt und experimentelle Untersuchungen durchgeführt. Die Ergebnisse zeigen, daß die Nusselt-Zahl für diese Anordnung unter bestimmten Bedingungen wesentlich durch die Inhomogenität des Mediums beeinflußt wird. Gestützt auf Versuchsergebnisse mit vier verschiedenen Granulaten wird eine halbempirische Beziehung angegeben.

# ОХЛАЖДЕНИЕ ПЛАСТИНЫ С ПОМОЩЬЮ ИНЖЕКЦИИ ОХЛАДИТЕЛЯ ЧЕРЕЗ ДИСКРЕТНЫЕ ОТВЕРСТИЯ ПРИ НАЛИЧИИ ТУРБУЛЕНТНОСТИ ВО ВНЕШНЕМ ПОТОКЕ И БОЛЬШОМ ОТРИЦАТЕЛЬНОМ ГРАДИЕНТЕ ДАВЛЕНИЯ

**Аннотация** — Проведены измерения средней скорости и концентрации при вдуве углекислого газа через пластину с дискретно расположенными отверстиями, просверленными под углом 45° к пластине, обтекаемой внешним потоком. Показано, что средний отрицательный градиент давления во внешнем потоке создает существенно большие уровни концентрации на поверхности пластины за счет его влияния на задержку турбулизации инжектируемой жидкости. При этом турбулентный свободный поток интенсивностью около 4% способствует снижению концентрации на стенке на 10%, но в то же время степень турбулентности не влияет на концентрацию при отсутствии градиента давления.