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EFFECTS OF VERY HIGH TURBULENCE ON CONVECTIVE HEAT TRANSFER

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INTRODUCTION

In spite of all the effort expended on heat-transfer research over the past 30 years, gas-turbine designers must still use significantly large "experience factors" for each family of engines to "adjust" predictions based on laboratory data. We believe that turbulence effects may be an important contributor to this situation.

Gas-turbine blade and vane heat-transfer situations are characterized by high free-stream turbulence (20% or more) of large scale compared to boundary-layer thickness, but nearly all of the data in the literature is from tests with little or no turbulence. In fact, it is a point of pride to "clean up" a tunnel until the free-stream turbulence is less than 0.25% before taking data "for record"! By itself, this is evidence that we believe turbulence is important. When turbulence is introduced, it is nearly always "grid-generated" turbulence--in part because its characteristics are reasonably predictable.

In the present research, we are studying the effects of high-intensity, large-scale turbulence on turbulent boundary-layer heat transfer. We are producing flow fields with turbulence intensities up to 40% and length scales up to several times the boundary-layer thickness. In addition, we plan to compare three different types of turbulence (i.e., turbulence generated by three different devices) to see whether they have the same effect on the boundary layer. The three are: (1) the far field of a free jet, (2) flow downstream of a grid, and (3) flow downstream of a simulated gas-turbine combustor.

To characterize the turbulence produced in these different flow fields, we shall use two different hot-wire anemometer systems. High relative turbulence is difficult to measure with conventional hot-wire anemometry. For measurements at a point, we plan to use a real-time triple-wire system developed in our laboratory for recording the instantaneous velocity components u, v, and w. This system has the capability of reporting the measurements of u, v, and w in real time, properly in phase, at up to 10 kHz per channel. It has also demonstrated the ability to measure the velocity components within ± 5% up to 20° angle of incidence of the instantaneous velocity, which corresponds to a very high relative turbulence intensity. For length-scale measurements, two single-wire probes will be used with a correlator. We plan to characterize each turbulence field by several measures: intensity (by component), scale, and spectrum.

Heat transfer will be measured on a 2.5-m-long, 0.5-m-wide flat plate using an energy-balance technique. The same plate will be used in each of four flow fields: a low-turbulence tunnel for baseline data, and the three flow situations mentioned earlier.

By this research, we hope to determine how many descriptors of the system are needed to specify the system well enough to get repeatable heat transfer.

PREVIOUS WORK

A representative collection of experiments on the effects of free-stream turbulence is given in the works of Kestin [ref. 1], Kearney et al. [ref. 2], Slanciauskaus and Pedesius [ref. 3], Brown and Burton [ref. 4], Bradshaw and Simonich [ref. 5], and Blair [ref. 6].

Kestin reported no effect of turbulence level on a constant-velocity turbulent boundary layer. Kearney et al. reported no effect on the constant-velocity boundary layer and also no effect when a strong acceleration was applied to the flow ($K = 2.5 \times 10^{-6}$) for a grid-generated turbulence level of 4%. Slanciauskaus and Pedesius found effects of 10% to 15% with turbulence intensities up to 8%, but obtained a 20% increase when the turbulence intensity rose to 14%. Part of this increase was attributed to changes in the mainstream flow as a consequence of the boundary-layer growth. Brown and Burton confirmed Kestin's results; but then, in 1978, Simonich and Bradshaw reported an increase in Stanton number in response to free-stream turbulence. In a more recent study, Blair (1983) reported increases as much as 20% for grid-generated free-stream turbulence of 7%.

Kestin's (1966) found that the principal effect of free-stream turbulence of 3.8% was to move the transition location upstream. He concluded that there was no effect on the fully developed turbulent layer. This study was followed by Kearney et al., at Stanford. Their data are shown in Fig. 1. Kearney's test section consisted of a duct with a flat-plate floor and a top wall which could be adjusted to produce either a uniform velocity flow or an acceleration at a constant value of K. A uniform velocity section followed the accelerating section. Data were taken in all three sections of the plate, for a low-velocity (6-18 m/s) flow in the tunnel.

Kearney's data for low (0.7% and moderate (3.9%) turbulence show no effect on Stanton number. The two data sets are well aligned with each other and agree with the constant-velocity correlation in the approach section. The STAN5 program was fitted with a turbulence kinetic-energy closure and produced results which matched the data: no effect on Stanton number for 4% turbulence. Computer runs for 10% free-stream turbulence, however, indicated a small increase in Stanton number, about 5%. An important aspect of Kearney's work is his use of an enthalpy-thickness Reynolds number to focus on local response, in order to isolate the effect of free-stream turbulence on turbulent boundary-layer heat transfer from its effect on moving the location of transition.

Slanciauskaus and Pedesius tested over a wider range of turbulence levels (1.1% to 13.5%) but tested only the constant-velocity case. Their data are shown in Fig. 2. The effect of turbulence level is clearly discernible and orderly, and suggest an effect approaching 20% on Stanton number. These were the first data to suggest a significant effect due to turbulence.

Simonich and Bradshaw report the largest effects, as shown in Fig. 3. Their data for heat-transfer coefficient represent average values over a flat plate of relatively large size, placed on the centerline of a wind tunnel. It is possible that increasing the turbulence caused a change in the location of the transition zone on the plate. If this occurred, one would expect high turbulence levels to cause the transition location to move upstream, raising the average heat coefficient on the plate by exposing more of the plate to a turbulent boundary layer. If this occurred, it would account for the rather large effects observed.

In 1979, Consigny et al. confirmed that the principal effect of turbulence is to alter the location and extent of transition. Their data showed that changes in turbulence intensity from 1% to 3.6% shifted the transition zone upstream from its original location at x-Reynolds number of 250,000 to a final location at x-Reynolds number of 100,000. This caused drastic changes in the values of h at locations which were originally laminar and finally turbulent, but did not significantly alter the behavior of the already-turbulent region.

In a carefully controlled and documented study, Blair reported that free-stream turbulence has a significant effect on heat transfer for fully turbulent boundary-layer flow. His data (Fig. 4) clearly show both the effect of free-stream turbulence on transition location and on Stanton number in the fully turbulent region. Observe that in the fully turbulent region with free-stream turbulence levels of 4 to 6%, Stanton number is significantly higher than the correlation given by Kays [ref. 7] (Blair's Ref. 23), for low levels of free-stream turbulence.

At the present writing, it appears likely that free-stream turbulence levels up to 10% cause a proportional increase in heat transfer for constant velocity and for accelerating turbulent boundary layers. Large effects on the average values may result if the turbulence affects the location of transition and if the heat-transfer data are compared (with and without turbulence) at constant x-Reynolds numbers or constant positions on the surface. There is a suggestion (Brown and Martin, 1979) that scale or frequency of the turbulence may be as important as intensity in determining the effect. This suggestion remains to be investigated.

THE PRESENT VIEWPOINT

We treat turbulence as a separate property of the flow, measured by a set of attributes such as its intensity components, scale components, spectra, etc. The hypothesis is that, whenever the free-stream turbulence can disrupt the innermost region of the boundary layer, it will affect the heat transfer. Our expectation is that small-scale and large-scale turbulence may act by quite different means to affect surface heat transfer: small-scale turbulence by diffusion and large-scale by pressure and shear interactions in the near-wall region. To illustrate the hypothesis, consider the following situation: A cubical box whose bottom face is a heat-transfer measuring face and which is provided with some means of violently agitating the air inside the box in a purely random manner. A small amount of electric power provided to the bottom plate, will heat it slightly above the surrounding temperature, not enough to cause any significant buoyant effect, but enough to allow the heat-transfer coefficient to be measured. For the first data point in this thought experiment, the air inside the box is at rest. The situation is one of low-Grashof-number free convection, and one would expect a low value of h. For the second data point, the air is agitated moderately. The random motions of small packets of air near the surface will cause the surface heat transfer coefficient to increase. If the scale of the turbulent motions produced is small compared with the size of the box and the events are randomly distributed inside the box, the average heat-transfer coefficient (over some characteristic length) will be uniform over the entire surface. The average h will increase as the vigor of the mixing inside the box is increased.

It seems reasonable to assume that the process discussed above would have an upper asymptote, determined by the no-slip condition and a Couette flow analysis for very high shear rates on a local area of the surface. As a consequence, the variation in h with turbulence intensity might look like that shown in Fig. 5.

Consider, now, an extension of the tests in which the left and right walls of the box are porous, allowing flow through the box. If the turbulence is zero, the heat-transfer coefficient will be a function of position and velocity given by the usual Reynolds number correlation. Figure 6 represents a typical distribution of heat-transfer coefficient with position along a flat plate for a constant velocity parallel to the plate. The laminar region, the transitional region, and the turbulent region are shown. Figure 7 shows the heat-transfer coefficient (turbulent) at a particular location x as the velocity increases. Both Figures 6 and 7 must be kept in mind while visualizing how the heat-transfer coefficient might vary with turbulence level, position, and velocity.

Now consider a compound case where the turbulence intensity and the free-stream velocity are independent variables. In this case, turbulence is described absolutely in terms of turbulence kinetic energy per unit mass rather than as a fraction of free-stream velocity. Figure 8 shows an operating surface describing the variation of heat-transfer coefficient with turbulence intensity per unit volume and position along a plate for a constant velocity. The individual cases already considered form the bounding planes for this operating surface, and the surface itself is sketched in with the assumption that the heat-transfer coefficient is a smoothly varying function of two variables, all other factors being held constant. Physical arguments lead to the heat-transfer coefficient asymptotically approaching a uniform high value at very high turbulence. The technical literature contains ample evidence that h asymptotically approaches the zero-turbulence state for the fully turbulent boundary layer. The primary effect of low turbulence levels is to advance the location of transition towards the laminar region, a feature not shown in Fig. 8.

There are important engineering applications of heat transfer corresponding to each of the asymptotic states shown on these operating-surface diagrams. In piston engines, the heat transfer to cylinder walls, piston tops, and cylinder heads corresponds quite closely to a case with high turbulence intensity and zero mean convective velocity. There is evidence in work done by the General Motors Research Laboratories linking the value of the measured heat-transfer coefficient to the turbulence kinetic energy measured within the cylinder. These results generally support the shape shown in Fig. 1 for the effect of turbulence in the absence of mean velocity. At the other extreme, years of research on heat transfer in low-turbulence tunnels have produced data along the "front" face of the operating surface in Fig. 8. The modern gas-turbine engine provides an example of a situation in which there are both very high turbulence intensities and high free-stream velocities. The structure of the typical gas-turbine combustion chamber, even in the absence of turbulence generated by the combustion process itself, produces extremely high turbulence intensities in the gas path which are not related to the mean speed in the throughflow direction in the usual way. Typically, air enters the combustion chamber at high velocity perpendicular to the engine axis to enhance mixing. This induces large-scale, high-intensity turbulence, which is then convected downstream by the mean speed. It seems reasonable to expect that the turbulence components (the fluctuating components of velocity) are not so much related to the mean speed as they are to the pressure drop in the combustion chamber and the heat release rate per unit volume. If this is the case, then, in the first stage stator and rotor in particular, a situation exists in which very high fluctuation velocities and large scales could be encountered. The scale of the turbulence at this location is not that dictated by a well-developed channel flow, but is rather the leftover scale from the injection process and the combustion process.

THE PRESENT EXPERIMENTS

Figure 9 shows the test plate ready for installation in HMT-2, a low-turbulence heat-transfer wind tunnel. This plate will be subjected to the four flow fields described in our introduction. It consists of seven 31.12 cm × 31.75 cm aluminum sections thermally isolated from each other by 0.16 cm balsa strips. Each section has five type J thermocouples embedded in its underside to ensure axial and spanwise temperature uniformity. The sections are individually powered by 30.48 × 30.48 cm Electrofilm patch heaters capable of delivering 10 W/m^2. The heated sections are preceded by a 50.8 cm unheated leading edge. The entire plate is to be operated to maintain a constant temperature difference between the plate and the free stream while we measure the power required by each section to determine local average h. Turbulence characteristics will be measured by the anemometry systems already discussed. Once our plate has been baseline tested in HMT-2, we plan to test it in the far field of a free jet.

In a free jet, the turbulence intensity and length scale vary differently with position, and a wide range of combinations can be found by sampling different radial and axial positions. Large-scale structures are present in the outer regions of the jet, and the local relative intensities are very high. Positioning a flat plate parallel to the local mean velocity at different radial locations results in a family of related flow fields. As our free-jet test proceeds, we shall design and build our combustor liner simulators.

In our combustor simulators, we plan to achieve independent control of the intensity and scale of the turbulence by using generators which produce an array of high-velocity jets at right angles to the mean flow. We are particularly interested in large-scale turbulent structures (on the order of the boundary-layer thickness or greater) and highly energetic ones. These structures will closely resemble the secondary injection holes used in most gas-turbine combustion chambers. It would be simplistic to say that we are simply going to put a scaled-up burner liner in our tunnel and see what it does to the heat transfer, but that is what it will look like.

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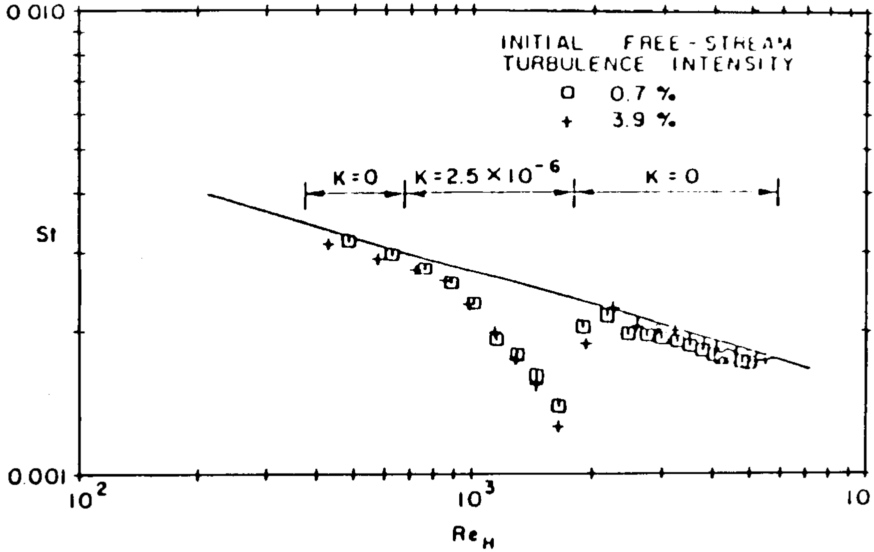

Fig. 1. Effect of free-stream turbulence on heat transfer through turbulent boundary layer with strong acceleration (Kearney et al., 1970).

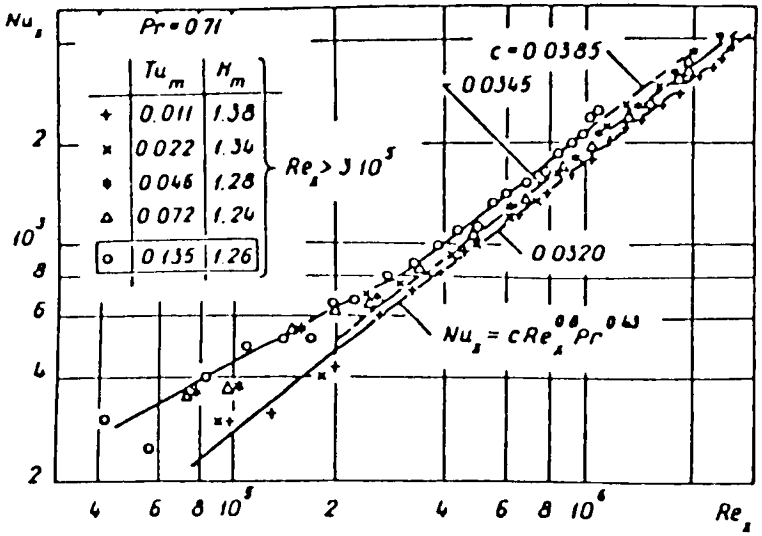

Fig. 2. The effect of free-stream turbulence on heat transfer with no pressure gradient (Slanciauskaus & Pedesius, 1977).

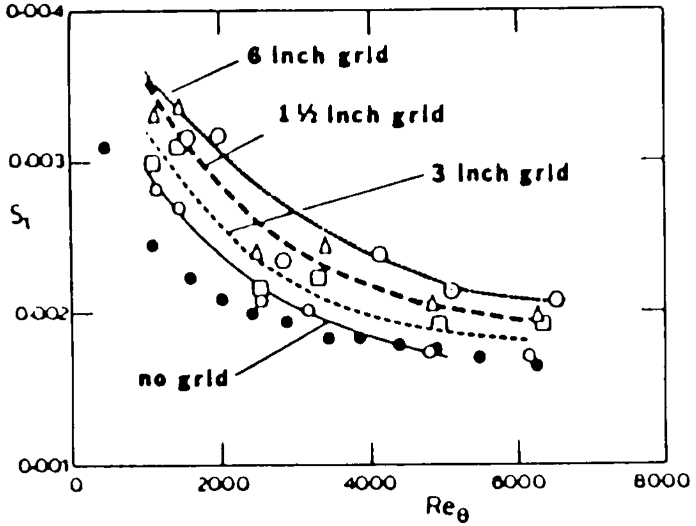

Fig. 3. Simonich & Bradshaw (1978) results concerning the effects of turbulence on heat transfer.

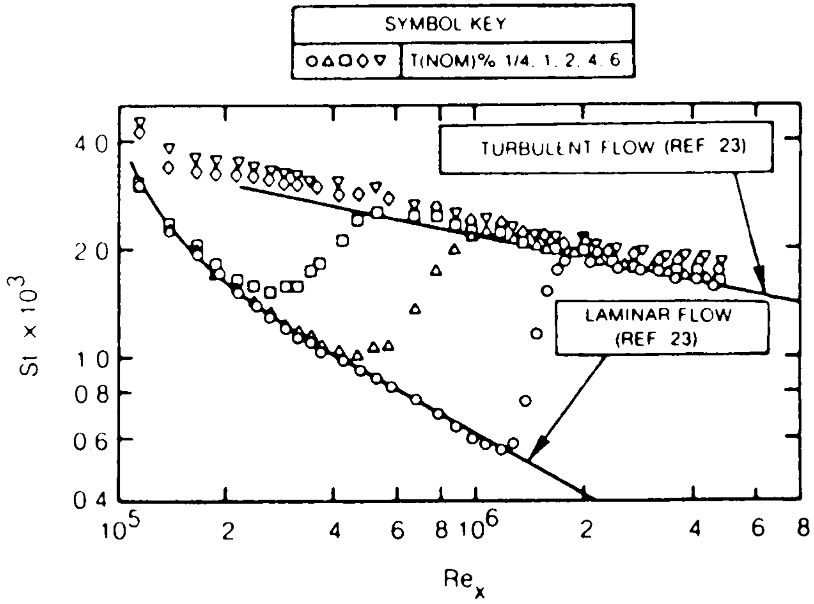

Fig. 4. Heat transfer distributions along a flat plate for five free-stream turbulence levels (Blair, 1983).

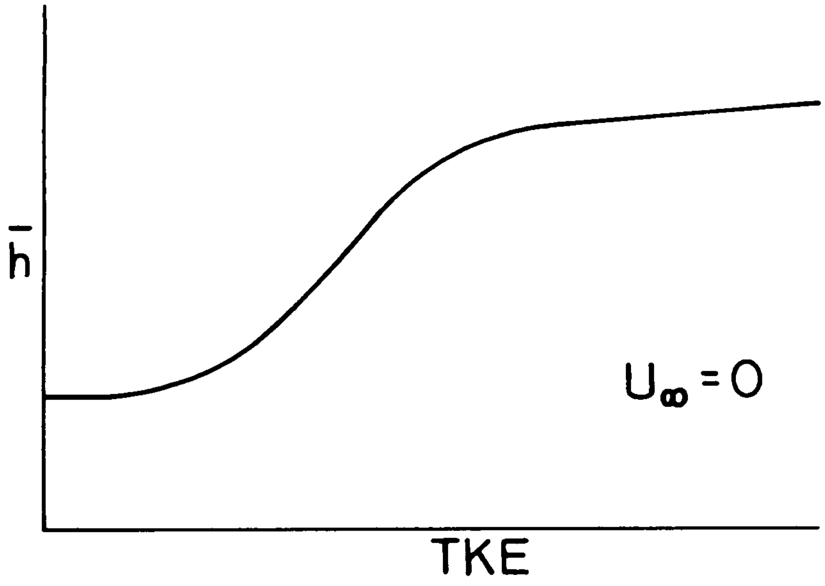

Fig. 5. Sketch of h vs. TKE for $U_\infty = 0$.

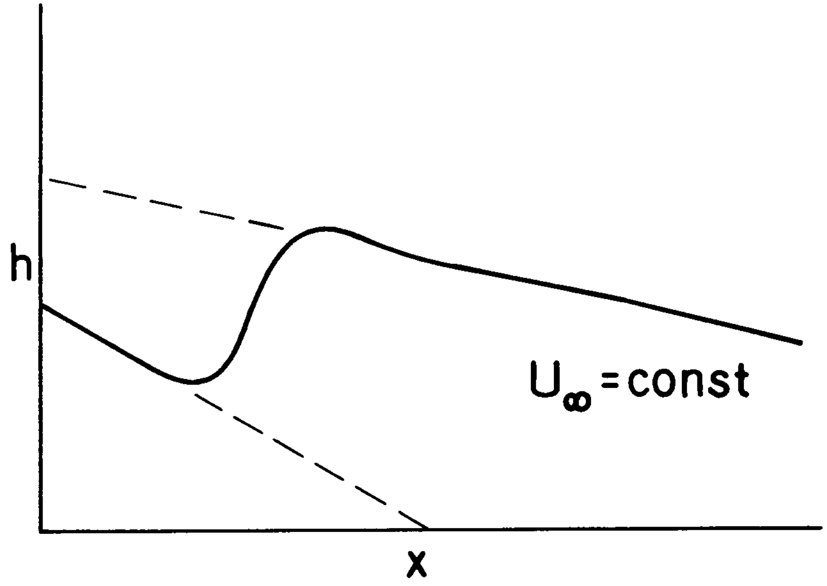

Fig. 6. Sketch of h vs. x for U_∞ = const.

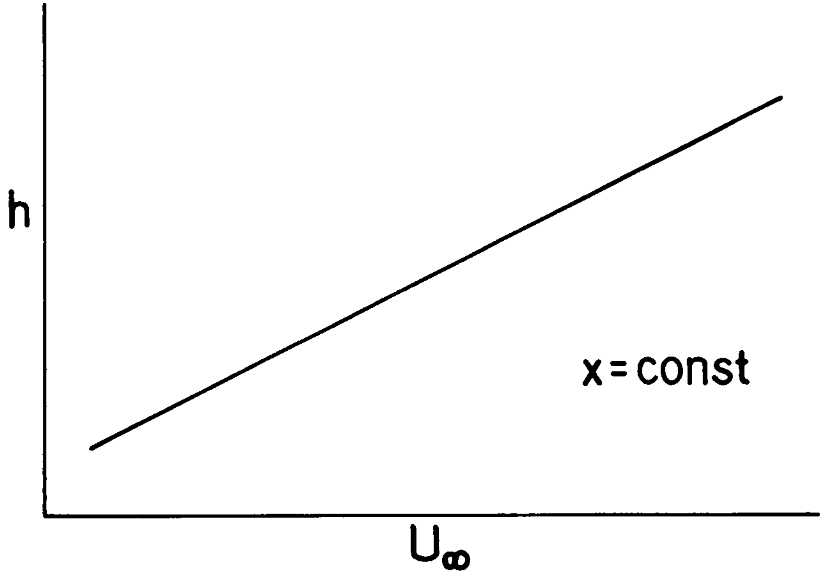

Fig. 7. Sketch of h vs. U_∞ for x = const.

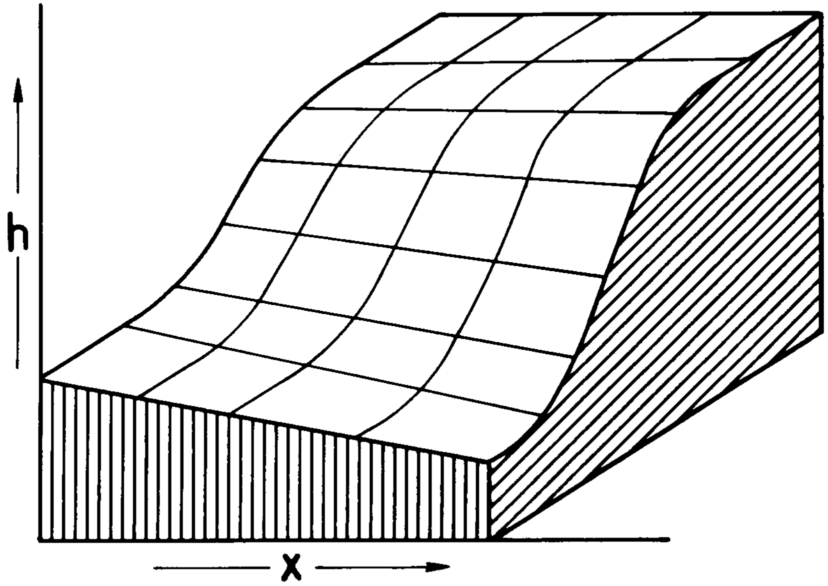

Fig. 8. Sketch of the operating surface h vs. x and TKE at constant free-stream velocity.

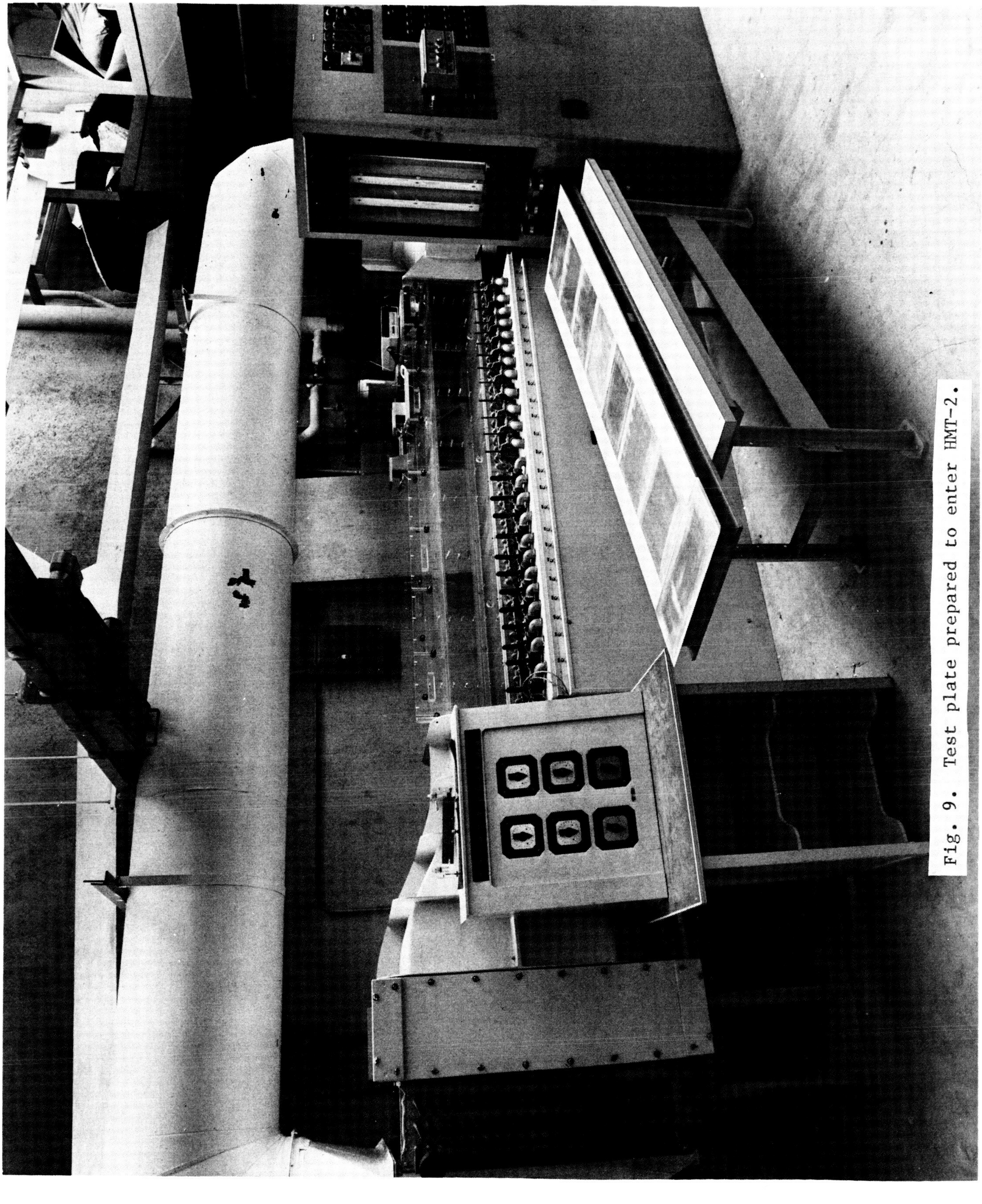

Fig. 9. Test plate prepared to enter HMT-2.