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Heat transfer in the stagnation region of the junction of a circular cylinder perpendicular to a flat plate

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Abstract—The heat transfer rate in the stagnation region of the junction of a circular cylinder perpendicular to a flat plate was measured for a range of Reynolds numbers varying from 3.0×10^4 to 7.0×10^5 and a flow Mach number of 0.14. The measurements were performed in a shock-tube facility using a reflected shock-wave technique and thin-film platinum heat gages. The heat flux was measured for both the plate and the circular cylinder. A substantial increase in the heat transfer rate in the junction region was observed. The influence of the cylinder over the flat plate extended beyond 3/4 cylinder diameter for low Reynolds numbers. For high Reynolds numbers the maximum increase in the heat transfer rate was observed to be approximately 100%, but for very low Reynolds numbers a maximum increase in the heat flux to the plate by a factor of 5 was observed. The variations in the heat transfer rate to the stagnation point of the cylinder were very small.

INTRODUCTION

IN THE design of jet engines and gas turbines, a very commonly encountered geometry is the one of a rounded leading-edge component meeting a flat surface, such as vanes supported by a cowl. This geometry can be approximated by a circular cylinder perpendicular to a flat plate. To achieve higher thrust/weight ratios and increase fuel efficiency, higher firing temperatures and higher pressure ratios are required. Under these circumstances the first row of vanes is short in span with a low aspect ratio so that the inner and outer casings make up a substantial part of area exposed to the hot flow.

Given the penalties associated with the cooling processes, namely bleeding the compressed air and injecting cool air into the main flow, it is desirable to reduce the coolant flow to a minimum. To achieve this without compromising the turbine durability, improved methods for predicting the external heat transfer are required.

The flow occurring near the endwall and in the junction region of the vane includes strong gradients and vortex formation. Available analytical techniques are not capable of solving these problems, and numerical schemes with the potential for solving the flow in this region are still being pursued. Some experimental studies related to this problem are described in refs. [1–7].

Han *et al.* [8] investigated the horseshoe vortex effects on the heat transfer distribution on a circular cylinder mounted normal to a flat plate of various lengths. Heat transfer measurements were made with the cylinder surface heated and the endwall plane adiabatic for various Reynolds number. Similar mass transfer measurements were carried out by Goldstein and Karni [9] by using the naphthalene sublimation technique to measure the mass transfer coefficients for a circular cylinder, mounted across the test section, at various distances from the tunnel wall. Recently, Blair [10] investigated the effects of a horseshoe vortex, produced by a rectangular obstruction spanning the tunnel test section, on the heat transfer to the surface beneath the approaching turbulent boundary layer. Upstream of the obstruction along the tunnel centerline, the maximum Stanton number was almost 100% greater than the undisturbed two-dimensional value.

The horseshoe vortex is the dominant flow phenomenon in the junction region of a protrusion from a flat plate [6]. The mechanism for the vortex formation in the junction region is well understood qualitatively. In the undisturbed upstream region, the static pressure of the mainstream is impressed on the boundary layer, so that there is no pressure gradient across the boundary layer far from the protrusion. Since the velocity drops to zero across the boundary layer there is a dynamic pressure variation across the layer. When the flow meets the protruding object and the main flow is slowed down, the dynamic pressure is converted into total pressure. A pressure gradient across the boundary layer is therefore created and a streamwise unfavorable pressure gradient along the boundary layer is produced. This pressure gradient causes the flow to move toward the wall surface near the protruding object and a reverse flow at the region nearest to the wall. This reverse flow of the boundary layer produces the horseshoe vortex that is then carried around the protruding object by the main flow.

In contrast to refs. [9, 10] which used the naphthalene technique and electrical heating of thin-film, stainless-steel foil to measure the local mass and heat transfer coefficients, respectively, in the present work thin-film platinum heat gages with a response time of a few microseconds were used to measure the heat flux distribution under the horseshoe vortex produced by a circular cylinder mounted perpendicular to a flat plate. A shock tube with a reflection plate was used to produce the high temperature air at various pressures and a flow Mach number of 0.14 after the reflected shock wave.

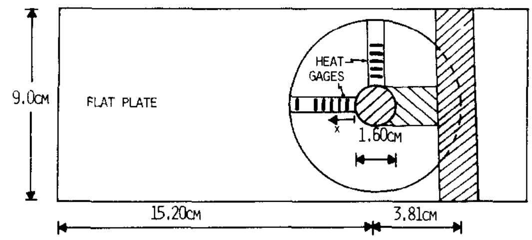

FIG. 2. Flat plate with heat gages.

EXPERIMENTAL FACILITY AND INSTRUMENTATION

The shock tube used in the experiments has a 3.0-m-long driver and a 21.0-m-long driven tube, both with an inside diameter of 10.16 cm and designed for a maximum pressure of 6.7 atm. A constant area transition section is used to convert the circular cross-section of the driven tube to a square cross-section [11].

The 38.1-cm-long square test section with a 9.0 cm side was mounted at the end of the driven tube. A 1.5-m-long section was mounted downstream serving as a dump tank. Piezoelectric crystals and Kistler pressure transducers were mounted on the test section and in the upstream part of the shock tube to monitor the passage of the shock wave and measure the pressure.

The steel flat plate, 22.0 cm long, 9.0 cm wide and 0.63 cm thick, was mounted in the vertical position at a distance of 2.5 cm from one side of the wall as shown in Fig. 1. The leading edge of the plate was tapered on one side forming a 15° half wedge. A reflection plate was mounted 18.7 cm from the leading edge of the plate.

The thin-film platinum heat gages were painted on two Pyrex–glass strips which were mounted at a 90° angle on a 7.62 cm circular disk as shown in Fig. 2. The disk was mounted flush with the plate, the center of the disk being located 15.2 cm from the leading edge of the plate. By rotating the instrumented disk the heat transfer can be measured at all angular positions. The circular cylinder was inserted from the side wall and was supported by a plastic cap bolted to the center of the disk. The circular cylinder was also supported from the back by an aluminum piece mounted to the reflection plate. The aluminum piece with the circular cylinder formed a cylindrically capped plate, Fig. 2.

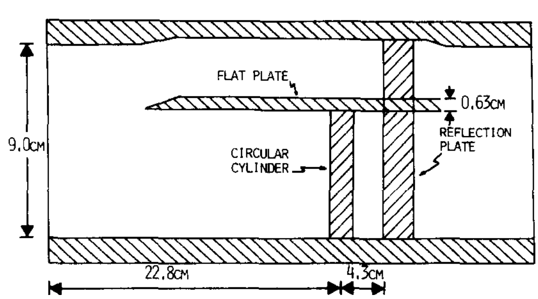

FIG. 1. Test section with flat plate and reflection plate (top view).

HEAT FLUX MEASUREMENTS

The test time in a shock tube is typically of the order of 5–20 ms. This period is long enough for the establishment of steady flow conditions and yet short enough so that the thermal behavior of the wall and models can be described by a semi-infinite wall approximation. This provides for a very accurate and straightforward method of obtaining the local heat transfer rate.

The thin-film platinum heat gage, with a response time of the order of microseconds, is composed of fast-response surface thermometers. A constant electrical current is supplied to the heat gage and a voltage signal proportional to the film resistance is obtained. Since the change of the surface temperature is very small, of the order of 1°C, a linear relation between the surface temperature and the film resistance can be assumed and therefore the voltage signal is proportional to the surface temperature.

The surface temperature history is then used to calculate the surface heat flux by using the semi-infinite body heat conduction solution. A detailed description of thin-film heat gages is given by Schultz *et al.* [12]. Combined with the flexibility of the shock tube in generating a wide range of flow parameters and temperatures this experimental technique constitutes a powerful tool to measure heat transfer rates.

The solution to the unsteady boundary layer developing after the passage of the shock wave over the plate was used as reference for the dynamic calibration of the heat gages. This solution, computed by Mirels [13] and experimentally verified by Dillon and Nagamatsu [14], was observed to be very accurate. A detailed description of the calibration procedure is given in ref. [15].

EXPERIMENTAL PROCEDURE

To determine the increase in the heat transfer rate to the flat plate due to the presence of the cylinder in the cross-flow, two sets of experiments were conducted covering the same range of Reynolds numbers. In the first set of experiments the heat transfer rate to the flat plate only was measured at all heat gage locations. The cylinder was then placed against the plate and the experiments were repeated for the same range of Reynolds numbers. The location of the heat gages for the experiments is shown in Fig. 2. The heat gages mounted on the flat plate ahead of the stagnation point of the cylinder were located at the following positions: $x/D = 0.2$, 0.4, 0.6, 0.8, 1.0 and 1.5 where x is the distance from the junction and D is the diameter of the cylinder, 1.6 cm.

THE FLOW CONDITIONS

The hot air flow in a shock tube is generated by a system of shock waves and expansion waves. The flow conditions in the test section are obtained from the test section geometry and from the strength of the shock waves. Fast-response Kistler pressure transducers mounted on the top wall of the test section are used to measure the pressure and monitor the passage of the incident and reflected shock waves, from which the strength of the shock waves can be obtained. By using the reflected-shock technique the desired flow Mach number can be also established. In the present case the incident shock wave was reflected by a slotted wall which had an open area so that the upstream flow Mach number was 0.14, which is approximately the inlet flow Mach number for the first row of vanes in a gas turbine.

The temperatures of the flow is determined by the strength of the incident and reflected shock waves. For the present set of experiments the temperature was in the range, 410–450 K and the flow velocity corresponding to the flow Mach number of 0.14 was approximately 60 m s^{-1}. Steady pressure was observed after both the incident and reflected shock waves, thus indicating steady flow conditions as shown in Fig. 3.

A period of approximately 12 ms of steady-state flow was observed in all experiments. Since the establishment time of the boundary layer over the flat plate was less than 4 ms, the period of steady conditions was quite adequate.

It should be noted that the Reynolds number was changed mainly by changing the operating pressure of the shock tube, since the velocity and length of the plate were kept constant.

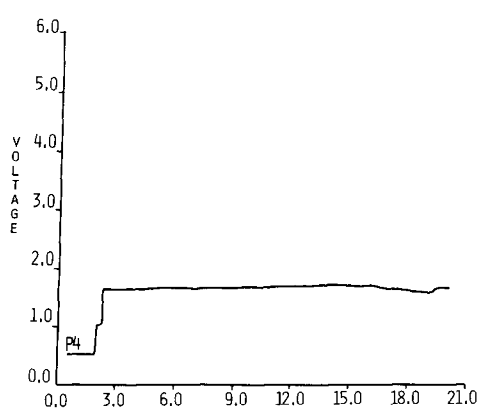

FIG. 3. Pressure trace for incident and reflected regions.

EXPERIMENTAL RESULTS

The heat transfer rates obtained for each gage location are presented in Figs. 4a–f. Analytical correlations for laminar an turbulent boundary-layer heat transfer predictions are also included in the figures for purposes of comparison. The results from the two sets of experiments with and without the cylinder placed against the plate are presented.

As can be observed in these figures, in the experiments performed with the flate plate only, an overlap of the laminar and turbulent experimental data exists for Reynolds numbers between 7.0×10^4 and 2.0×10^5. Over this range of Reynolds numbers the boundary layer over the flat plate was observed to be initially turbulent after the passage of the reflected shock. As the shock wave moved upstream, away from the leading edge of the flat plate, the boundary layer over the plate changed back to a laminar profile. As the Reynolds number increased, the delay in the laminarization of the boundary layer after the passage of the reflected shock wave was also increased. For Reynolds numbers higher than 2.5×10^5 the boundary layer over the flat plate remained turbulent over the entire test time.

This behavior of the boundary layer over the flat plate is attributed to the effect of free-stream turbulence generated by the passage of the reflected shock wave. As the shock wave moves away from the leading edge of the plate the turbulence level of the free stream over the flat plate decays and the boundary layer becomes laminar and stable. A more detailed discussion of the laminarization phenomenon is presented in ref. [15].

Measurements of the free-stream turbulence level during the whole test time and also within the boundary layer itself will be conducted to further clarify this laminarization phenomenon. Turbulence measurements performed by Trolier [16], indicated an amplification of turbulence level across the reflected shock wave by a factor of 2–3.

The variation of the heat transfer rate in the junction region with the Reynolds number and the distance from the line of junction of the cylinder against the plate are also illustrated by Figs. 4a–f.

Close agreement with theoretical predictions for laminar and turbulent boundary layers were obtained for all heat gages in the experiments conducted without the cylinder placed against the plate. With the cylinder placed against the plate the heat gages located

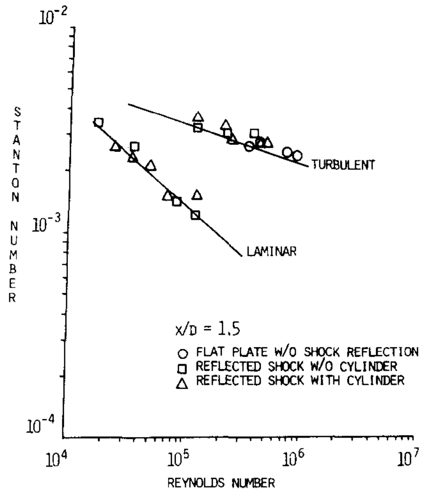

Fig. 4a. Heat transfer rate for heat gage located at $x/D = 1.5$.

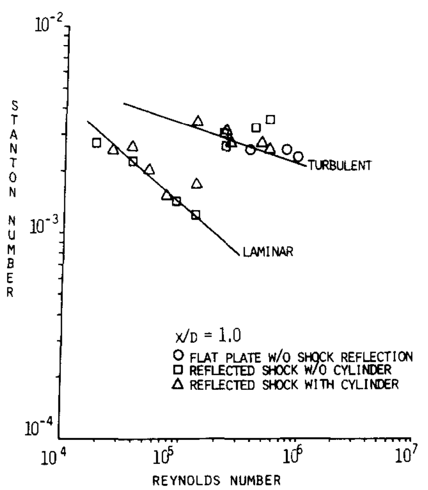

Fig. 4b. Heat transfer rate for heat gage located at $x/D = 1.0$.

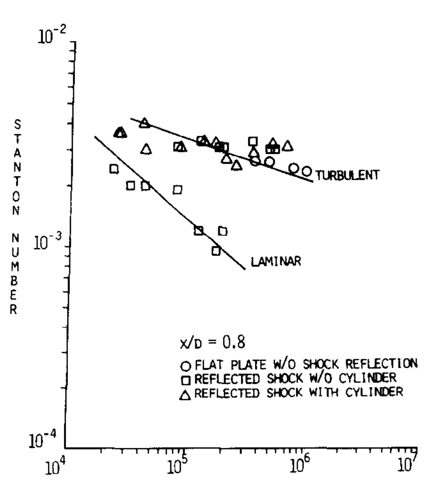

Fig. 4c. Heat transfer rate for heat gage located at $x/D = 0.8$.

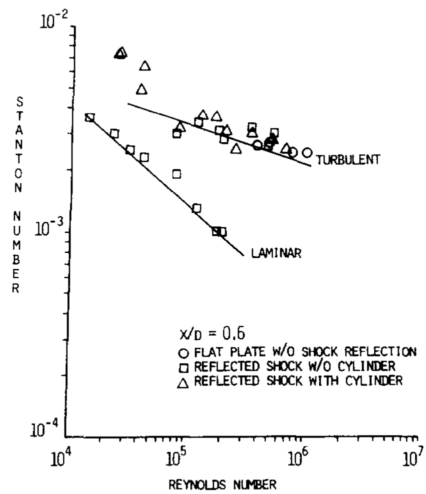

Fig. 4d. Heat transfer rate for heat gage located at $x/D = 0.6$.

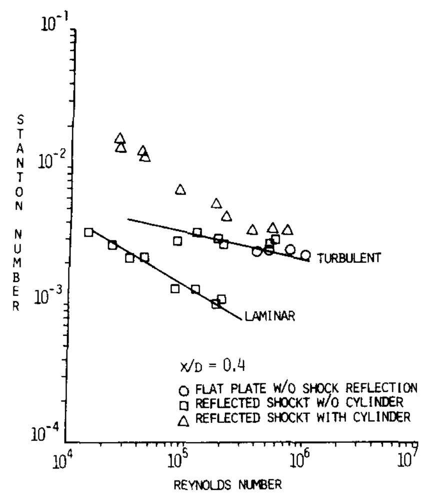

Fig. 4e. Heat transfer rate for heat gage located at $x/D = 0.4$.

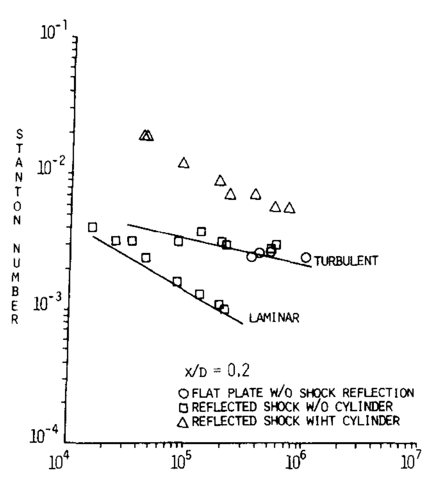

Fig. 4f. Heat transfer rate for heat gage located at $x/D = 0.2$.

further than 0.8 cylinder diameters did not show any substantial difference as compared to the experiments conducted without the cylinder, Figs. 4a–c.

The heat transfer results obtained for the heat gage located at $x/D = 0.6$, Fig. 4d, also did not show any noticeable difference due to the presence of the cylinder for Reynolds numbers higher than 1.0×10^5. The only difference occurred for the low Reynolds number when the boundary layer over the flat plate was laminar.

The heat transfer data obtained from heat gages located at $x/D = 0.4$ and $x/D = 0.2$ are presented in Figs. 4e and f. An increased heat transfer rate was observed for the case of the cylinder placed against the flat plate as compared to the measurements taken with the flat plate only. The qualitative behavior of the Stanton number with the Reynolds number was approximately the same for both locations, but the magnitude of the increase in the heat transfer rate was substantially different. For the higher range of the Reynolds number the increase in the heat transfer rate due to the presence of the cylinder was approximately 25% for the location $x/D = 0.4$, while at $x/D = 0.2$ an increase of approximately 100% was observed. As the Reynolds number decreased the effect of the cylinder became even more pronounced with an increase by a factor of 5 being observed for the heat gage located at $x/D = 0.2$.

The effect of the Reynolds number and the distance from the junction are more clearly shown by the heat transfer results in a normalized form presented in Fig. 5. For high Reynolds number, the boundary layer over the flat plate became turbulent and the Stanton number near the stagnation point of the cylinder, $x/D = 0.2$, was approximately twice the value for the plate without the cylinder. But at lower Reynolds numbers—with a laminar boundary layer—the increase in the heat flux due to the horseshoe vortex was much greater. Blair [10] tripped the boundary layer at the entrance to the test section to produce a

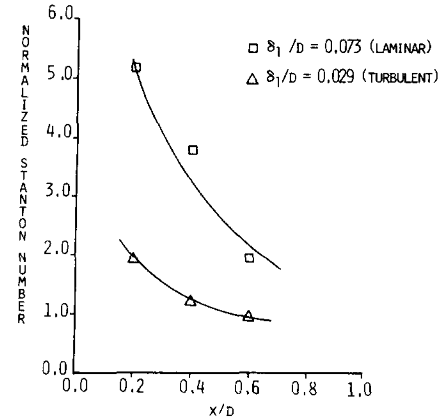

Fig. 6. Normalized heat transfer rate as function of distance from junction and displacement thickness.

turbulent boundary layer ahead of the rectangular obstruction. Stanton numbers as much as 100% greater than the undisturbed two-dimensional level were recorded upstream of the obstruction along the tunnel centerline.

The strength of the horseshoe vortex is better correlated with some measure of the boundary-layer thickness than with the Reynolds number itself. Since the horseshoe vortex is the dominating phenomenon for the heat transfer rate in the junction region, a measure of the vortex strength such as the displacement thickness is probably also a better correlation parameter for the heat transfer rate in the junction region than the Reynolds number. Such a correlation is presented in Fig. 6. The displacement thickness was chosen over the boundary-layer thickness because of its better ability of accounting for the fact that turbulent and laminar boundary layers of the same thickness have difference velocity profiles and will create vortices of different strengths.

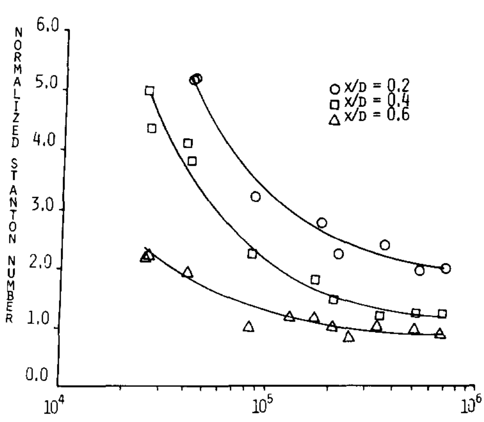

Fig. 5. Normalized heat transfer rate in the junction region as function of Reynolds number and distance from junction.

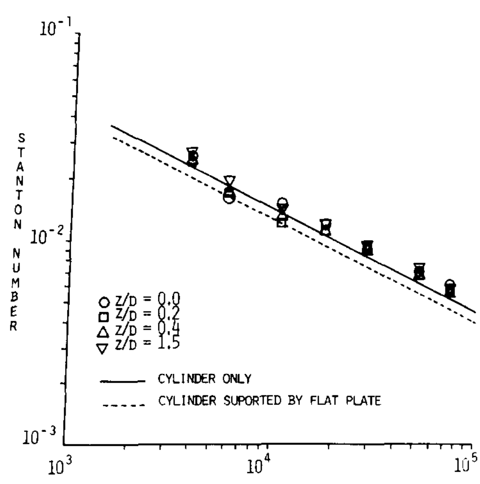

Fig. 7. Heat transfer rate at the stagnation point of the cylinder in the junction region.

The heat transfer results obtained for the stagnation point of the cylinder in the junction region are presented in Fig. 7. In this figure, z represents the distance along the axis of the cylinder from the junction. Thin-film platinum heat gages with a width of 1 mm and a length of 2.8 mm, which covered approximately 20° of the 1.6-cm-diameter cylinder, were used to measure the stagnation region heat flux along the cylinder. Thus, the large mass transfer coefficient observed by Goldstein and Karni [9] about 0.066 cylinder diameters from the tunnel was was not recorded by the heat gages because of the width of the platinum film compared to the diameter of the cylinder. Han *et al.* [8] did not observe the large heat transfer increase with the foil-type resistance heater at the cylinder–wall junction region. Further investigation must be conducted with narrower platinum heat gages to determine the heat flux to the cylinder in the junction region.

SUMMARY

Thin-film platinum heat gages combined with the shock tube to generate hot flow form a versatile and reliable technique for measuring local heat transfer rates.

The presence of a cylinder perpendicular to a flat plate and the associated horseshoe vortex produced a large increase in the heat transfer rate to the plate in the junction region ahead of the stagnation point of the cylinder, as compared to the measurements performed with the flat plate only. The increase in the heat transfer rate was shown to depend on the boundary-layer thickness and on the type of boundary layer ahead of the cylinder.

The displacement thickness of the boundary layer is recommended as the correlating parameter for the heat transfer rate in the junction region, since it can account for both the boundary-layer type and the boundary-layer thickness. It also gives a better measurement of the vortex strength which is the dominant flow phenomenon in the junction region.

The horseshoe vortex increased the stagnation point heat transfer for the circular cylinder only in a very thin region adjacent to the flat plate.

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TRANSFERT DE CHALEUR DANS LA REGION D'ARRET A LA JONCTION D'UN CYLINDRE CIRCULAIRE ET D'UN PLAN PERPENDICULAIRE

Résumé—Le flux de chaleur convecté dans la région d'arrêt à la jonction d'un cylindre circulaire et d'un plan perpendiculaire est mesuré pour un domaine de nombre de Reynolds compris entre 3×10^4 et 7×10^5 et un nombre de Mach de 0,14. Les mesures sont effectuées dans un tube de choc et elles utilisent la technique de l'onde de choc réfléchie et des jauges à film mince de platine. Le flux de chaleur est mesuré sur le plan et sur le cylindre. Un accroissement sensible du flux thermique est observé à la jonction. L'influence du cylindre sur le plan s'étend jusqu'à 3/4 diamètre du cylindre pour les nombres de Reynolds faibles. Pour les grands nombres de Reynolds l'acroissement maximal du flux thermique atteint approximativment 100%, mais pour les très faibles nombres de Reynolds un accroissement maximal correspond à un facteur de 5. Les variations du flux thermique au point d'arrêt du cylindre reste très petites.

DER WÄRMEÜBERGANG IN DER STAUZONE EINES KREISZYLINDERS, DER SENKRECHT AN EINER EBENEN PLATTE BEFESTIGT IST

Zusammenfassung—Der Wärmeübergangskoeffizient in der Stauzone eines senkrecht auf einer ebenen Platte befestigten Kreiszylinders wurde für die Reynolds-Zahlen von $3{,}0 \times 10^4$ bis $7{,}0 \times 10^5$ und für Mach-Zahlen von 0,14 gemessen. Die Messungen wurden in einer Stoßrohr-Apparatur durchgeführt, wobei die Technik der reflektierten Stoßwellen und ein Platin-Dünnfilmheizer benutzt wurden. Die Wärmestromdichte wurde an Platte und Zylinder gemessen. Eine starke Erhöhung des Wärmeübergangskoeffizienten wurde in der Befestigungszone beobachtet. Der Einflußbereich des Zylinders auf die Platte reichte bei kleinen Reynolds-Zahlen bis 3/4 Zylinderdurchmesser. Bei großen Reynolds-Zahlen wurde eine maximale Erhöhung des Wärmeübergangskoeffizienten von ca. 100% festgestellt. Für sehr kleine Reynolds-Zahlen wurde eine Erhöhung der Wärmestromdichte zur Platte bis zum Faktor 5 beobachtet. Die Veränderungen des Wärmeübergangs im Staupunkt des Zylinders waren sehr klein.

ТЕПЛОПЕРЕНОС В ЗАСТОЙНОЙ ЗОНЕ ВБЛИЗИ СОЕДИНЕНИЯ КРУГОВОГО ЦИЛИНДРА С ПЛОСКОЙ ПЛАСТИНОЙ

Аннотация—Интенсивность теплопереноса в застойной зоне вблизи присоединения кругового цилиндра, перпендикулярного плоской пластине, измерялась в диапазоне чисел Рейнольдса от $3{,}0 \times 10^4$ до $7{,}0 \times 10^5$ и числа Маха для потока, равном 0,14. Измерения проводились в ударной трубе методом отраженной ударной волны и с помощью тонкопленочного платинового датчика. Величина теплового потока измерялась как для пластины, так и для кругового цилиндра. Наблюдался существенный рост скорости теплопереноса в зоне соединения. При малых числах Рейнольдса влияние цилиндра на теплоперенос в пластине проявляется на расстоянии, равном 3/4 диаметра цилиндра. Для больших чисел Рейнольдса максимальное увеличение скорости теплопереноса составляло приблизительно 100%, хотя для очень малых значений числа Рейнольдса наблюдалось пятикратное увеличение теплового потока на пластину. Изменения интенсивности теплопереноса в точке застоя цилиндра были очень малы.