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PERIODIC HEAT TRANSFER IN DIRECTLY OPPOSED FREE AND FORCED CONVECTION FLOW*

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Abstract—An experimental study of the heat transfer from small circular cylinders placed horizontal to a downward flowing air stream is reported. Based on heat-transfer measurements and flow visualization, a model for directly opposed free and forced convection was developed. Three modes of flow were observed. For very low velocities the free convection, buoyant plume dominates the heat transfer. At a "lower critical" Reynolds number, when the free and forced convections are of the same order of magnitude, a well defined periodic heat transfer was obtained. The periodic heat transfer was due to the build-up of the buoyant forces to a magnitude where they overcame the downward force of the air flow. At an "upper critical" Reynolds number the periodic heat transfer abruptly ceases. For velocities greater than the upper critical limit the forces due to the air flow dominate. A potential like, laminar sheet forms, as a shroud around the thermal layer of the hot cylinder. The average heat transfer from the cylinder decreases with increasing Reynolds number for both the case of dominant free convection and the periodic heat-transfer regime. The minimum value of the heat transfer occurred at the upper critical Reynolds number.

INTRODUCTION

INFORMATION on heat transfer, when both free and forced convection are important, is limited. One area of interest is the use of hot wire anemometers to measure the mean and turbulent flows when the velocity is directed downward. Flows with strong vortex type motion, such as those behind a rearward facing step and atmospheric thermal flows, can produce the downward motion. For downward flows in the range where the free and forced convection are approximately equal it has been observed that the heat transfer from horizontal cylinders can be less than for the case of no flow.

A study of the gross heat transfer from horizontal cylinders in directly opposed free and forced convection was reported by Oosthuizen and Madan [1, 2]. The case of the flow about spheres was reported by Pei [3]. Analytical analysis for these types of flows is extremely difficult. The integral method of Acrivos [4] predicts that the Grashof number divided by the square of the Reynolds number will be the fundamental parameter. Joshi and Sukhatme [5] report an analytical solution based on a coordinate perturbation method for the case of directly opposed free and forced convection flow.

The present paper covers an experimental evaluation of the flow model and heat transfer from horizontal cylinders in directly opposed free and forced convection flows. Although difficulties in control of low speed downward flows can produce unsteady effects, the general phenomenon observed was much larger in scale than any flow perturbations. The periodic phenomenon had time periods from 3 to 15 s, which is much longer than any flow time scales. The periodic phenomenon was not foreseen in previous analytical or experimental free convection studied.

MECHANISM OF DIRECTLY OPPOSED FREE AND FORCED CONVECTION

The phenomenon of either free or forced convection heat transfer from small cylinders is well documented [6]. The case of forced convection can be shown to vary with Reynolds, Mach or Knudsen numbers [7]. For pure free convection a thermal plume is developed. As might be expected, it was found that the directly opposed force convection restricts the thermal plume with the equivalent of a "stagnation point" being developed between the two flow systems.

A small size, low speed, calibration flow facility which was developed mainly to calibrate velocity transducers was used for the present study [8]. This facility is shown in Fig. 1. By careful attention to the screens it was possible to develop a uniform flow velocity over approximately 9 cm of the center of the test section. The velocities in the test section could be set from approximately 10 to 1500 cm/s. In order to visualize the phenomenon, cylindrical sticks of "incense" were employed. The burning incense produces both the heat and smoke for visualization, although it was impossible to obtain a uniform burning along the length. Limited observations with a crude Schlieren system viewing a small (0.001 cm) diameter heated cylinder confirmed that the smoke from the incense closely identifies the heated air.

Figure 2 shows typical photographs of the smoke patterns obtained for the cylinder normal to the flow. Use of the incense stick as a "point" source of heat, rather than as a cylinder normal to the flow, is shown in the photographs of Fig. 3. The point source produces

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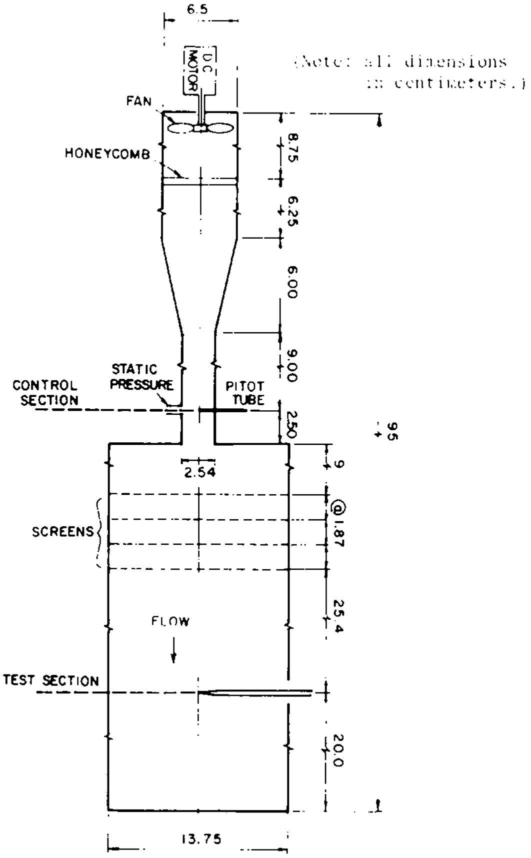

FIG. 1. Low speed flow facility.

a better defined, more stable demonstration of the flow. The photos shown are for cases where forced convection was present. Figures 2(a) and 3(a) show typical cases where a "shroud" of heated air, outlined by the smoke, was formed downstream of the heat source. For these photos [Figs. 2(a) and 3(a)] the forced convection of the downward flowing air is dominant over the buoyant force of the heated air. The shroud around the point source (Fig. 3a) extends further downstream before a vortex "instability" appeared, than is the case for the horizontal cylinder (Fig. 2a). The vortex motion downstream of the horizontal cylinder produced some unsteady motion of the shroud directly around the cylinder.

When the downward air velocity was reduced, a point was reached where the buoyant force of the heated air caused the shroud to move upward, as shown in Figs. 2(b) and 3(b). Once the heated air reaches a sufficient height above the heat source it appears to break up, as shown in Fig. 2(c). The motion above the heat source becomes disorganized and was quickly swept downstream by the air flow. A new shroud was formed around the heat source and the "bubbling" effect repeats in a periodic manner. Further reduction of the downward flowing air increases the bubbling frequency. At very low velocities the periodic motion changes to a "plume" like upward flow of heated smoke. The plume is quite unstable and appears to lose its organized motion at small distances above the heat source. No doubt the plume motion was extremely sensitive to any unsteady motion of the air stream. While the visualization of the horizontal cylinders was subject to three-dimensional effects, the basic phenomenon associated with directly opposed free and forced convection is demonstrated.

A number of small cylinders of varying diameter from 0.4 mm to 0.01 mm were employed to measure the heat transfer [9]. Only heat-transfer results from the 0.01 mm dia cylinder will be discussed. The effect of cylinder length was also investigated. A length of the order of 8 mm or longer was found to have negligible three-dimensional flow effects for the 0.01 mm cylinder. The cylinders were heated electrically by Joulean heating, and the resistance of the cylinder material was measured to determine the cylinder temperature. Use of constant temperature or constant current techniques [7] to operate the cylinders did not appear to greatly alter the heat transfer characteristics [9]. Figure 4 shows a typical set of voltage outputs vs time, obtained for a number of different velocity settings for a cylinder operating at a constant temperature condition. This particular set of data at a high cylinder temperature was selected because the periodic effects were the most prominent observed in the study. The constant temperature was maintained by a commercial, feedback, constant temperature anemometer. The heat transfer from the cylinder is proportional to the square of the voltage. Note that for the low velocity traces of Fig. 4 the heat transfer is less than the free convection (no flow) trace.

The voltage traces of Fig. 4 became progressively more unsteady with increasing velocity (see for example the $U = 16.6$ cm/s trace). In this flow region the free convection plume is being impeded by the downward flow. Once the forced convection was strong enough the random fluctuations are replaced by periodic heat transfer. The frequency of the periodic heat transfer progressively decreases with increasing downward velocity. At a well defined critical velocity ($U = 21.09$ cm/s for the measurements shown on Fig. 4) the periodic heat-transfer excursions reach a maximum. A slight change in the flow, which was too small to measure, completely stops the periodic heat transfer. Note that the steady heat transfer was the same as the minimum of the periodic heat transfer. The heat-transfer rate for velocities above 21.90 cm/s progressively increase. The high velocity traces were steady, similar to the trace shown for 21.09 cm/s.

The time averaged mean values of the Nusselt number as a function of Reynolds number is shown on Fig. 5 (for the data of Fig. 4). Also shown on the insert of Fig. 5 is the variation of the periodic frequency with Reynolds number. The Reynolds number was based on the flow properties at ambient temperature, free stream velocity, and on the cylinder diameter. The thermal conductivity of air employed in the Nusselt number was based on an average temperature between the cylinder and the ambient air temperature. If the thermal conductivity at ambient air temperature were used, the values of Nusselt number would be increased by a factor of 2.2. For a low value of cylinder tem-

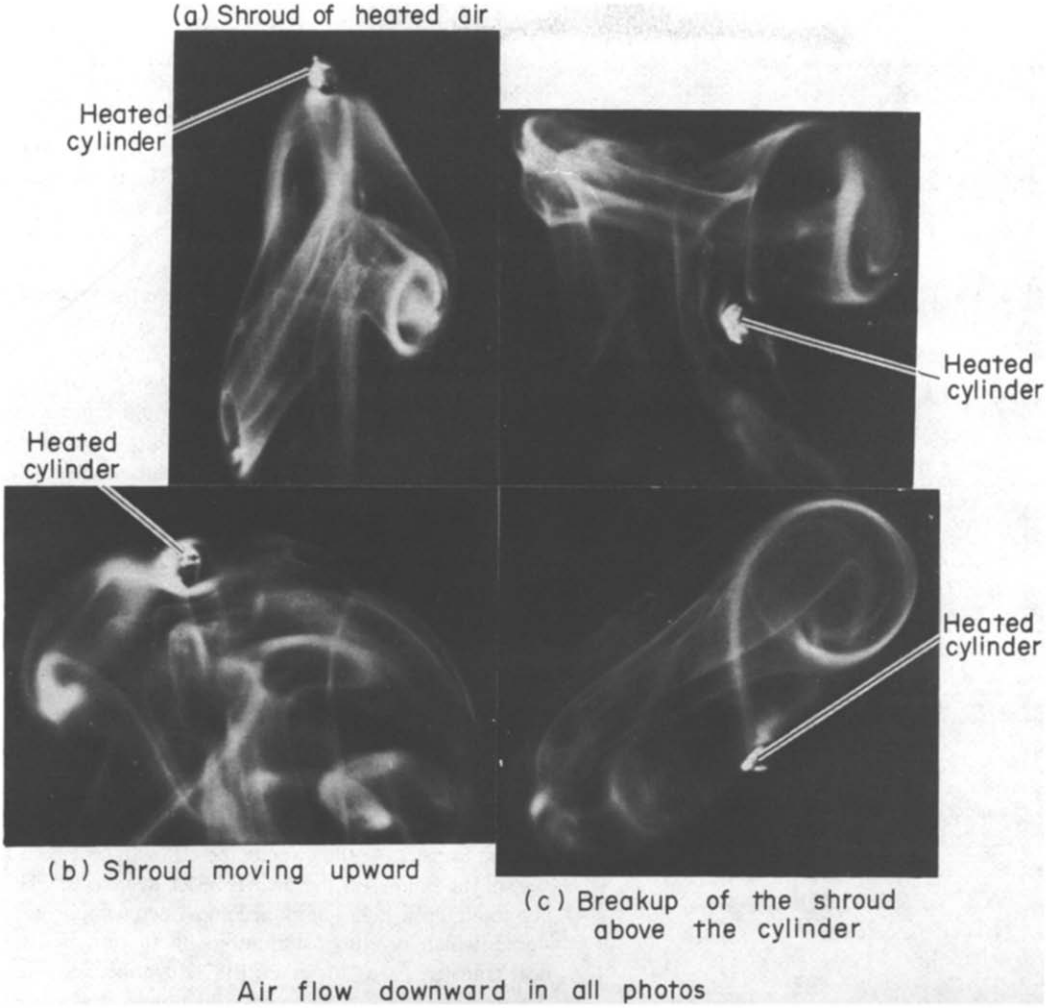

FIG. 2. Smoke visualization of heat flow from a horizontal cylinder in a downward flowing airstream. (a) Shroud of heated air; (b) Shroud moving upward; (c) Breakup of shroud above the cylinder.

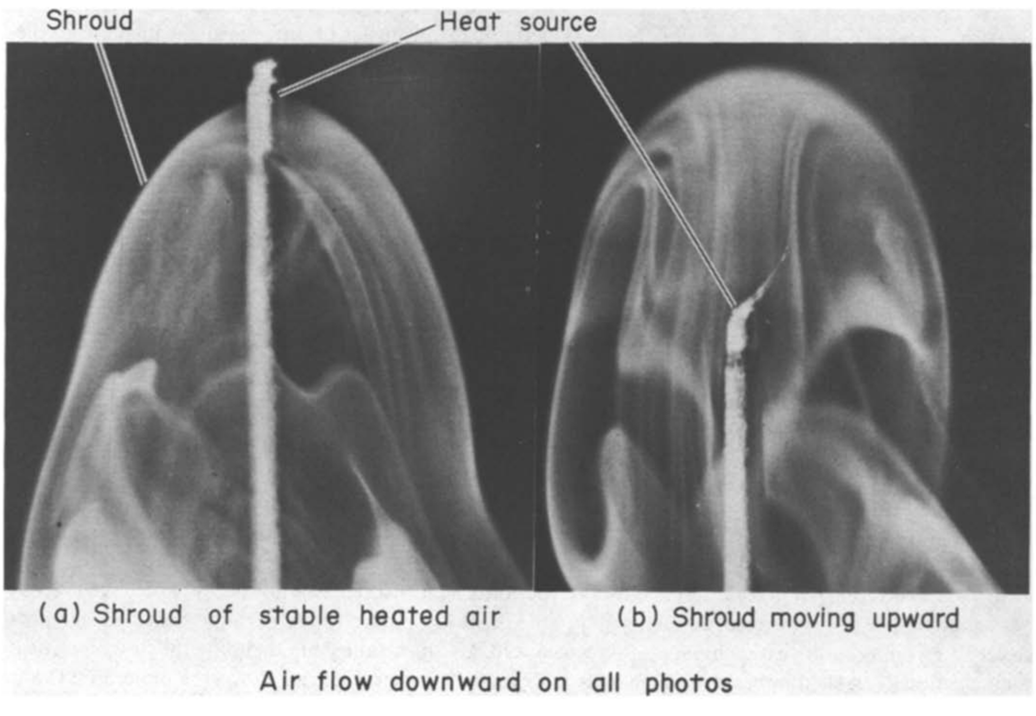

FIG. 3. Point source of heat in a downward flowing airstream. (a) Shroud of stable heated air; (b) Shroud moving upward.

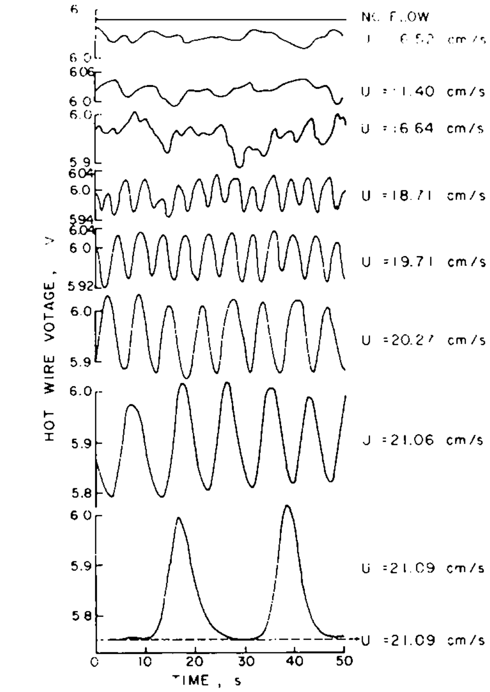

FIG. 4. Typical voltage output traces for a horizontal cylinder in a downward flow. Diameter 0.01 mm, temperature 1066°C.

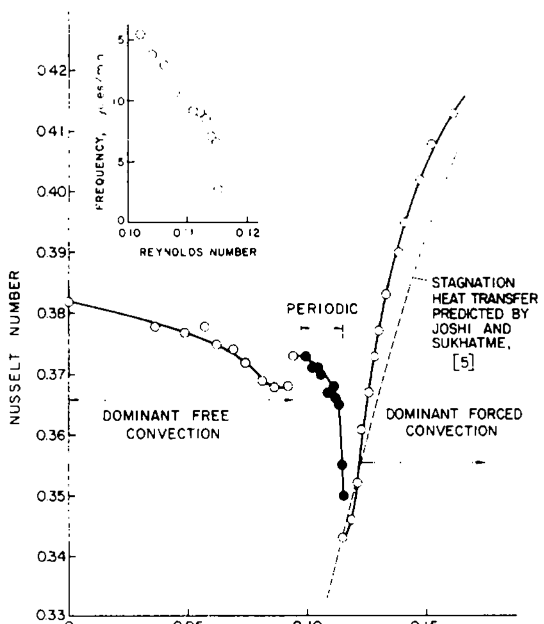

FIG. 5. Heat transfer from a horizontal cylinder in a downward airflow. Diameter 0.01 mm, temperature 1066°C.

perature ($T = 107°C$), [9], the free convection (no flow) Nusselt number, based on ambient air temperature, has a value of 0.43. The value, $Nu = 0.43$, agrees closely with values reported for hot wire measurements [7] (p. 64). The very high temperature case, shown on Fig. 5, has a free convection Nusselt number, based on ambient air temperature, of 0.82. This higher value of Nusselt number is due to an increase of a factor of ten in the Grashof number and also a marked increase in the radiation heat loss.

The dashed curve shown on Fig. 5 is the stagnation heat-transfer variation based on free stream conditions predicted by Joshi and Sukhatme [5]. The theoretical results of Joshi and Sukhatme do not indicate the increase in heat transfer at the very low Reynolds numbers. The theoretical prediction is strictly a square root of Reynolds number variation, since the Grashof over Reynolds number squared range from 0.04 to 0.08 is too small for the theory to predict a change. The reasonable agreement between the theory and the forced convection dominated region, would appear to justify the use of the "film" temperature evaluation of the thermal conductivity for the measurements.

The present measurements are for Reynolds-, Grashof-, and Nusselt-numbers several orders of magnitude smaller than those reported by Oosthuizen and Madan [2]. The basic characteristic of a minimum in the heat transfer at a finite value of Reynolds number is also found by Oosthuizen and Madan. They did not report observations of periodic heat transfer.

FLOW MODEL

The present study identifies three basic regimes of directly opposed free and forced convection flow. At very low velocities the free convection plume dominates the heat transfer. As the velocity increases, the effectiveness of the plume on the heat transfer decreases. The plume-air flow interaction becomes increasingly unstable, which produces a random fluctuation in the heat transfer. At a "lower critical" Reynolds number the downward flow stagnates the plume flow. The stagnated hot fluid surrounding the cylinder builds up with time until the buoyant force overcomes the force of the downward flowing air. Initially the start of the periodic heat transfer produces a slight increase in the mean heat transfer. As the velocity increases the frequency of the periodic heat transfer decreases, and the mean heat transfer also decreases. Once the flow increases to the point where the shroud of heated air around the cylinder cannot build up sufficiently to move upward, a minimum heat transfer is obtained (upper critical Reynolds number). A very stable flow condition is established at Reynolds numbers greater than the upper critical value. This higher flow velocity decreases the heated shroud and a systematic increase in the heat transfer occurs.

The values of the "lower critical" and "upper critical" Reynolds numbers are plotted vs the Grashof number on Fig. 6. The Grashof number is based on the free-stream viscosity, cylinder diameter and the temperature difference between the cylinder and the air. A minimum value of Grashof and Reynolds number might be indicated from the measurements, below which the periodic heat transfer will not occur. The change from the unsteady plume to the periodic heat transfer produced an uncertainty in defining the lower critical Reynolds number. Figure 7 shows the upper and lower critical points correlated in terms of Nusselt number and Grashof number divided by the square of the

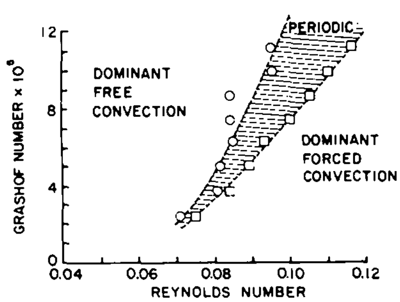

FIG. 6. Limits of the periodic heat transfer for the 0.01 mm diameter cylinder.

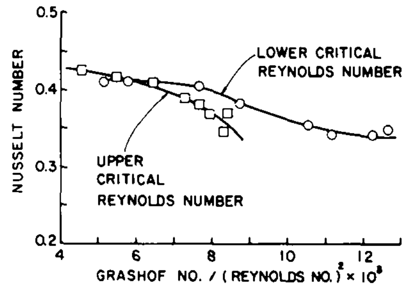

FIG. 7. Upper and lower critical Reynolds number correlated with Nusselt and Grashof numbers.

Reynolds number. The measurements on Figs. 6 and 7 are all for the same cylinder, with only the temperature being varied.

The variation of the periodic frequency of the heat transfer in terms of the Strouhal number (frequency times cylinder diameter divided by flow velocity) vs the ratio of the Reynolds number divided by the upper critical Reynolds number is shown on Fig. 8. The data

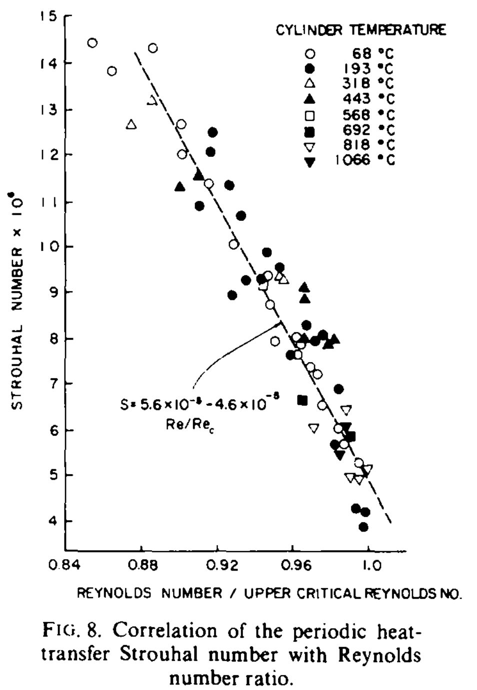

FIG. 8. Correlation of the periodic heat-transfer Strouhal number with Reynolds number ratio.

for the different temperatures appears to define a single curve. The scatter was too great to justify other than a linear relation between the Strouhal and Reynolds number ratio.

The present study demonstrates the effect for the simplest case of directly opposed flows. During the course of the experiments it was noted that slight angles of yaw of the cylinder appeared to increase the magnitude of the periodic heat transfer. It is conceivable that angles of yaw can produce a more concentrated heat plume which will lead to the build up of larger buoyant forces. The results demonstrate that downward flowing air can produce an insulation effect on the heat transfer from horizontal cylinders. Depending on the particular flow geometry, the periodic heat transfer could lead to major problems. The application of such heat-transfer devices as hot wire anemometers must be limited to flows where the forced convection is dominant.

CONCLUSIONS

It is experimentally demonstrated that a periodic heat transfer exists from horizontal cylinders in directly opposed free and forced convection flow. A physical model, based on the observation of a shroud of heat that builds up around the hot cylinder, is proposed for the flow. At very low downward flow velocities the free convection plume determines the heat transfer. As the velocity is increased the plume is impeded to produce a periodic bubbling of the heated air. Once an upper critical Reynolds number is reached, the periodic shedding stops abruptly. The upper critical Reynolds number produces the minimum value of heat transfer from the cylinder.

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TRANSFERT DE CHALEUR PERIODIQUE DANS UN ECOULEMENT DE CONVECTION NATURELLE ET DE CONVECTION FORCEE EN OPPOSITION

Résumé On présente une étude expérimentale du transfert de chaleur autour de cylindres circulaires de faible diamètre placés horizontalement dans un écoulement d'air descendant. Sur la base des mesures de transfert thermique et de la visualisation de l'écoulement, un modèle est développé pour la convection naturelle et la convection forcée en opposition directe. Trois régimes d'écoulement sont observés. Aux très faibles vitesses, le transfert de chaleur est dominé par la convection naturelle dans le sillage thermique. Pour un nombre de Reynolds "critique inférieur", lorsque la convection naturelle et la convection forcée sont du même ordre de grandeur, un transfert de chaleur périodique bien défini a été obtenu. Le transfert de chaleur périodique est provoqué par le développement des forces de gravité qui parviennent à vaincre la force de l'écoulement descendant d'air. Pour un nombre de Reynolds "critique supérieur", le transfert de chaleur périodique cesse brutalement. Aux vitesses supérieures à la limite critique supérieure, les forces dûes à l'écoulement d'air dominent. Une nappe laminaire semblable à un écoulement potentiel se forme et enveloppe la couche limite thermique autour du cylindre chaud. Le transfert de chaleur moyen autour du cylindre diminue lorsque le nombre de Reynolds croît à la fois dans le cas à convection naturelle dominante et dans le cas du régime thermique périodique. La valeur minimale du transfert de chaleur se produit pour le nombre de Reynolds critique supérieur.

PERIODISCHER WÄRMEÜBERGANG BEI DIREKT ENTGEGENGERICHTETER FREIER UND ERZWUNGENER KONVEKTIONSSTRÖMUNG

Zusammenfassung Es wird über eine experimentelle Untersuchung des Wärmeübergangs von kleinen, horizontal angeordneten Zylindern an eine abwärts gerichtete Luftströmung berichtet. Auf der Grundlage von Wärmeübergangsmessungen und der Sichtbarmachung der Strömung wurde ein Modell für direkt entgegengerichtete, freie und erzwungene Konvektionsströmungen entwickelt. Die Strömungsformen wurden beobachtet. Bei sehr geringen Geschwindigkeiten überweigt der Wärmeübergang durch die von der freien Konvektion bedingten Auftriebsströmung. Bei einer "unteren kritischen" Reynolds-Zahl, bei der die freie und die erzwungene Konvektion von der gleichen Größenordnung sind, wurde deutlich ein periodischer Wärmeübergang beobachtet. Der periodische Wärmeübergang wurde verursacht durch das Anwachsen der Auftriebskräfte, bis diese die Kräfte der abwärts gerichteten Luftströmung übersteigen. Bei einer "oberen kritischen" Reynolds-Zahl bricht der periodische Wärmeübergang abrupt ab. Für Geschwindigkeiten oberhalb dieser oberen kritischen Grenze überwiegen die Kräfte infolge der Luftströmung. Es bildet sich eine potentialartige, laminare Schicht als Mantel um die thermische Grenzschicht des heißen Zylinders. Der mittlere Wärmeübergang am Zylinder nimmt sowohl für den Fall der überwiegend freien Konvektion wie für den Fall des periodischen Verhaltens mit zunehmender Reynolds-Zahl ab. Der minimale Wärmeübergang trat bei der oberen kritischen Reynolds-Zahl auf.

ПЕРИОДИЧЕСКИЙ ПЕРЕНОС ТЕПЛА В ПОТОКЕ ПРИ ПРОТИВОПОЛОЖНО НАПРАВЛЕННЫХ СВОБОДНОЙ И ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация — Доклад содержит результаты экспериментального исследования переноса тепла от небольших цилиндров круглого сечения к нисходящему воздушному потоку. На основе измерений переноса тепла и визуализации потока, разработана модель для описания течения при противоположно направленной свободной и вынужденной конвекции. Наблюдаются три вида течения. Для очень низких скоростей (явление свободной конвекции) свободно-конвективная струйка оказывает доминирующее влияние на перенос тепла. При «самом низком критическом» числе Рейнольдса, когда свободная и вынужденная конвекция сравнимы по порядку величин, получен установившийся периодический перенос тепла. Последний обусловлен нарастанием выталкивающих сил до величины, превышающей градиент давления нисходящего воздушного потока. При «высоком критическом» числе Рейнольдса периодический перенос тепла резко прекращается. Для скоростей выше верхнего критического предела доминирующее влияние имеют силы, обусловленные воздушным потоком. Подобно потенциальному обтеканию, образуется ламинарный слой как экран вокруг теплового пограничного слоя на горячем цилиндре. Средний коэффициент переноса тепла от цилиндра уменьшается с увеличением числа Рейнольдса, как при доминирующей свободной конвекции, так и при периодическом режиме переноса тепла. Минимальный перенос тепла имеет место при «высоком критическом» числе Рейнольдса.