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AN EXPERIMENTAL STUDY OF HEAT TRANSFER THROUGH GASES CONTAINED BETWEEN TWO VERTICAL COAXIAL CYLINDRICAL SURFACES AT DIFFERENT TEMPERATURES

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Abstract—Experimental heat-transfer studies through gases enclosed between two vertical coaxial cylindrical surfaces are reported. The inside surface is an electrically heated tungsten wire, while the outside surface is a glass tube maintained at a constant temperature by circulating thermostatted water. The wires of two different diameters and the tubes of three different bores have been used in the measurements which extend over argon and nitrogen at various pressures ranging between 11–76 cm of mercury. The wire is heated to temperatures as high as about 700°C above the cold wall temperature. The end heat-transfer effects are carefully determined following Lipkea and Springer, but in an apparatus where the measurement does not perturb the flow field. It is found that such end effects are confined only in the corner regions for all the test gas conditions employed here, and the depths to which these penetrate are approximately equal to the diameter of the outer tube in each case. These conclusions while substantiating those given by Lipkea and Springer, also establish that the same are valid for at least seven fold increase in the temperature difference of the two surfaces. It is found that the average Nusselt numbers for the entire columns as well as for the corner regions are complicated functions of the geometrical constants, temperatures, nature of the gas, etc., in addition to Grashof and Prandtl numbers.

NOMENCLATURE

a, radius of inner cylinder [cm];
A, constant of equation (1) [(deg C)$^{-1}$];
b, radius of outer cylinder [cm];
B, constant of equation (1) [(deg C)$^{-2}$];
Cp, specific heat [W/g deg K];
g, gravitational acceleration [cm/s^2];
H, distance between potential leads [cm];
k, thermal conductivity [W/cm deg K];
l, distance between disks where heat transfer becomes constant [cm];
$\overline{Nu}$, average Nusselt number for the whole column;
$\overline{Nu}_c$, average Nusselt number in the corner region;
p, gas pressure [cm Hg];
Q_T, total heat flow [W];
Q_v, heat flow in vacuum [W];
Q_H, heat flow by conduction and convection [W], $= Q_T - Q_v$;
R, gas constant [cm^3 cm Hg/g deg K];
R_0, resistance of unit length of wire at ice point [Ω/cm];
r, radial co-ordinate [cm];
R_T, resistance of unit length of wire at temperature T [Ω/cm];
Ra, Rayleigh number,

$$= \frac{(2b)^3 p^2 g(T_a - T_b) C_p(T_m)}{R^2 k(T_m) T_m^3 \eta(T_m)};$$

S, distance between disks [cm];
T, temperature [deg C];
T_a, temperature of the inner cylinder [deg K];
T_b, temperature of the outer cylinder [deg K];
T_{am}, arithmetic mean temperature, $= (T_a + T_b)/2$ [deg K];
T_{lm}, log-mean temperature, $= (T_a - T_b)/\ln(T_a/T_b)$ [deg K];

T_m, mean temperature as defined by equation (2) [deg K];
Z_p, depth of penetration [cm];
Z_p^*, reduced depth of penetration, $= Z_p/2b$;
η, viscosity [g/cm s].

INTRODUCTION

SAXENA and coworkers [1] have extensively used two vertical, coaxial, cylindrical surfaces maintained at widely different temperatures (up to about 1200 degC) with the test gas enclosed in between to determine the thermal conductivity of gases. In particular, a platinum wire stretched axially inside a glass tube is heated electrically and the gas conductivity is obtained at the wire temperature from the knowledge of the heat transfer from the heated wire to the surrounding gas. A reliable determination of conductivity involves a very careful analysis of the heat lost by the wire both as regards the magnitude and the mode of transfer. The experiments described here are intended to assist in such an evaluation by direct heat-transfer measurements. It may be recalled, that Saxena and coworkers [2, 3] did find that over a range of gas pressures almost all the energy lost by the heated wire is by conduction and radiation only, and the convection appeared to be confined at the two ends and over a small portion of the wire only. This conclusion was indeed based on the measurements of electrical power required to heat the wires of different lengths to the same temperature in the presence of the gas at different pressures and in vacuum. This led to the conductivity values in good agreement with the data obtained from other techniques and invariance of the experimental thermal conductivities with pressure over a range. The present experiments test this contention by direct heat-transfer measurements in a carefully designed and precisely built apparatus.

Indeed, there exist several related theoretical and experimental investigations of heat transfer in the literature, but those having the most direct bearing on our experiments to be described are due to Eckert and Carlson [4] and Lipkea and Springer [5]. The former workers [4] performed an interferometric study of an air layer enclosed between two vertical plates at different temperatures, and confirmed the theoretical analysis of Batchelor [6]. They [4] found that below a certain Grashof number and thickness to height ratio, heat transfer is by pure conduction in the central region and convection is confined in the four corner regions only. Lipkea and Springer [5] have more recently examined the gas layer enclosed between two coaxial cylindrical surfaces at different temperatures, and found that as long as the Rayleigh number and the length to diameter ratio are below certain critical values, most of the heat lost is by conduction and end effects are confined at the ends over a length of the order of the diameter of the outer cylinder only. The temperature differences between the two surfaces were varied between 10 and 160 deg F at 25 deg intervals in one case [4], and were 10, 50, and 100 deg C in the other [5]. In both the studies [4, 5], the average temperature of the gas was taken as the arithmetic mean of the temperatures of the two surfaces.

In the experiments described here, the temperature difference between the two surfaces has ranged up to about 700 deg C, and the average temperature of the gas is computed on the basis of the equation of state for an ideal gas and the energy equation. As test gases, prepurified varieties, 99·97 per cent argon and 99·997 per cent nitrogen, supplied by Matheson Scientific Co., have been used, and the choice of eight test gas pressures range between 11·0 and 76·0 cm of mercury. The preliminary phase of this program on argon and covering a maximum temperature difference between the two surfaces of 480 deg C only was described in detail by Ganti *et al.* [7]. Here we present briefly the improved version of the experimental facility used to take measurements over an extended temperature range and describe the new results, as well as an improved interpretation of the earlier experimental data on argon.

PENETRATION DEPTHS

It is clear from the above brief reference to the works of Eckert and Carlson [4] and Lipkea and Springer [5] that the heat transfer through an enclosed layer of gas between two surfaces at different temperature under certain conditions is predominantly by Fourier conduction except at the top and bottom ends where it is much more complicated. The analytical calculations of Saxena and Davis [8] also show that for two coaxial cylindrical surfaces, where the inner wall is heated with its ends maintained at the same temperature as the outer cold wall, the nonradial heat transfer is confined at the two ends only, and most of the central part is at a uniform temperature. The nonisothermal regions in this analysis owe their origin to the axial heat flow at the ends because of a steep temperature gradient in this direction. The investigations of Eckert and Carlson [7] on an air layer confined between two vertical plates at different temperatures indicate that the local heat-transfer conditions are different in the opposite corners and are similar in the diagonally opposite ones. The heat-transfer mechanisms in the end regions are further complicated in the experiments of the type described by Lipkea and Springer [5] and in the present work, because of the presence of disks, potential leads, etc.

In the light of the above comments it is clear that the heat-transfer conditions are quite complicated at the top and bottom ends of the experimental columns. In these regions there will be nonradial heat flow and local turbulent flow may result under unfavourable conditions. However, the general design and dimensions of the experimental heat-transfer surfaces are such that nonradial heat flow as well as any mechanical hindrance to the laminar motion of the gas is confined at the very ends and so it is logical to assume that the end effects penetrate only over a small portion, and the thermal energy transport from the remaining portions are via the Fourier type radial conduction. These end segments of length Z_p will be referred to as penetration depths and represent the distance from the ends over which only the end effects are confined and pure conduction regime governs the heat flow over the remaining portion of the heat transfer surfaces. In the next section, we describe an experimental facility and the procedure which enables the determination of Z_p under different conditions of the test gas enclosed between the two cylindrical surfaces.

EXPERIMENTATION

The principal component of this heat transfer study is the heat transfer column, and its top half section is shown in Fig. 1 as the bottom half

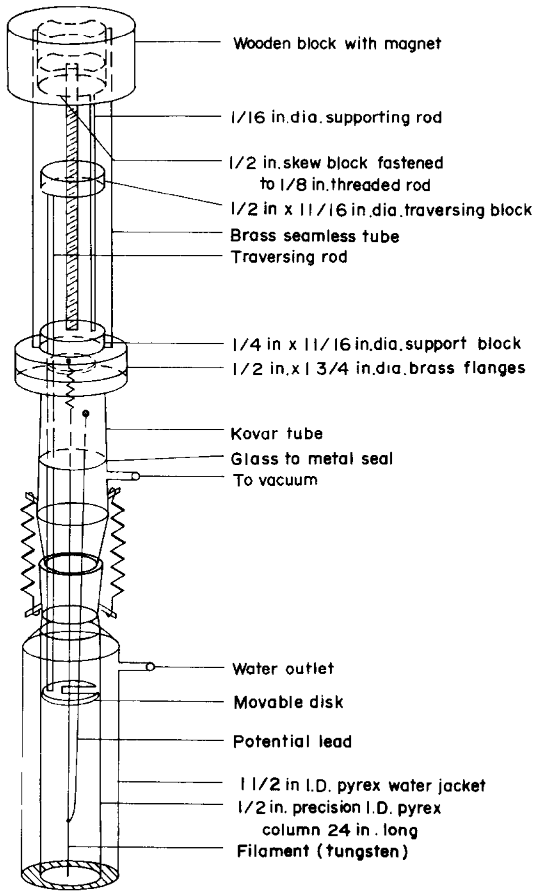

FIG. 1. Schematic of the heat-transfer column III (top half section).

is identical. Three such columns are used of different dimensions listed in Table 1. The column consists of a jacketed precision bore pyrex glass tube ($\pm 0{\cdot}0009$ cm), along the axis of which is run a tungsten wire (B.S., black and straight; C.S., chemically clean and straight, supplied by General Electric). The wire is mounted specially to ensure its axial alignment and that it remains taut, but not unduly stretched when heated to different temperatures as shown in the figure. Two potential leads ($0{\cdot}0260 \pm 0{\cdot}0012$ cm) are silver soldered to the central tungsten wire and this constitutes the test section for the heat-transfer studies. The glass column temperature is maintained constant within $\pm 0{\cdot}2$ degC by circulating water from a constant temperature bath. The latter consists of a water bath, a heater circulation motor and a "Rota Set Regulator." The wire is heated to different temperatures by a Hewlett and Packard d.c. power supply having a continuously variable 0–60 V and 0–15 A output.

As explained by Lipkea and Springer [5], the determination of penetration depths require the free movement of a disk from either end into the heat transfer column to any desired position. Whatever device is employed, it is essential not to introduce any material hindrance inside the test section so that the flow pattern of the test gas remains uninfluenced. A special disk movement mechanism is designed to accomplish this requirement and is operated completely from outside by the rotation of a magnet. The design is shown in the figure and is described in detail by Ganti *et al.* [7]. The top housing, which accomodates the disk movement mechanism, is connected to the heat transfer column by a vacuum tight flange joint. The latter is designed so that the same unit can work with columns of different dimensions. Further, because each disk is individually moved, it remains possible to position them symmetrical with reference to the middle point even when the wire experiences different elongations as its temperature is increased. Briefly, through this sophisticated design, we are able to meet the ideal requirements in our experiments while determining the depths to which the end effects penetrate. This is a unique feature of our work in comparison to the earlier effort of Lipkea and Springer [5]. In the latter design of the heat-transfer column [5], support rods were used to guide the motion of the disks in the column and these physically blocked, to some extent, the flow of the gas.

Table 1. Constants of the heat-transfer columns and the test gas conditions

	Column I	Column II	Column III
Total length (cm)	60·0	60·0	60·0
Internal diameter (cm)	2·54	1·95	1·27
Hot wire	Tungsten (B.S.)	Tungsten (B.S.)	Tungsten (C.S.)
Diameter of the hot wire (cm)	0·025	0·025	0·030
Distance between the potential leads (cm)	30·50	30·05	30·2
Temperature of the cold wall (°C)	30·0	30·0	30·0
Test gas	Argon	Argon	Nitrogen
Various gas pressures (in cm of mercury)	30·4	19·0	11·0
	40·0	76·0	21·0
	53·0	—	52·2
Constant A of tungsten wire (deg C^{-1})			$4{\cdot}265 \times 10^{-3}$
Constant B of tungsten wire (deg C^{-2})			$0{\cdot}7650 \times 10^{-6}$
Resistance of the column wire at 0°C (Ω/cm)			$7{\cdot}9035 \times 10^{-3}$

The distance between the teflon disks while performing experiments under different test conditions is measured by a cathetometer within $\pm 0{\cdot}01$ mm.

The column could be evacuated to a vacuum of 10^{-6} torr by a three stage mercury diffusion pump (10 l/s at 10^{-6} torr) backed by a rotary pump (21 l/min at full air). The columns are also attached to a glass handling unit with a provision to prepare gas mixtures as desired and transfer the same or a pure gas to any test column at the specified pressure up to one atmosphere. An electrical measuring circuit comprising of a Leeds and Northrup K-3 potentiometer, a null detector, a standard cell, a standard resistance, a volt box to scale down the unknown potentials, a digital voltmeter, etc., are used to obtain accurate values of the electrical energy dissipated through the tungsten wire. The latter is used both as a heater as well as a thermometer. To accomplish the latter, the resistance of a known length of wire is determined at the fixed freezing points of ice, zinc and aluminium. The latter two temperatures were obtained in 8411 fixed temperature standard unit supplied by Leeds and Northrup. The constants R_0, A, and B of the quadratic relation giving the variation of resistance with temperature are thus obtained:

$$R_T = R_0(1 + AT + BT^2). \qquad (1)$$

In the earlier effort [7], the temperature of the tungsten wire was identified on the basis of a curve of R vs T, supplied by the manufacturers. We have, therefore, re-interpreted the raw data [7], and these results are included in this paper.

A typical run consists in evacuating the column and annealing the wire carefully. Great care is necessary to ensure that the electrical circuit is satisfactory and the wire resistance is reproducible within a high degree of accuracy, better than $\pm 0{\cdot}1$ per cent. The measurements of the electrical power required to heat the wire to different temperatures is determined in vacuum and in the presence of the gas at a certain pressure, and for a fixed distance between the disks. The gas pressure changes by about 1 per cent as the wire is heated to the highest temperature, but in our present calculations we have ignored this change in pressure. Keeping the gas pressure constant, the disks are located at different positions in relation to the potential leads and the measurements are repeated. Such a series of measurements is essential to determine the depths of penetration, and the same are repeated for various initial values of the test gas pressure. In Table 1, are reproduced the experimental conditions for the various sets of data on the three columns and the two test gases. A typical plot of electrical power for the potential lead section of the tungsten wire in column III for nitrogen at 11·0 cm of mercury pressure as a function of its temperature for various distances between the disks is shown in Fig. 2. Also shown in this figure is the electrical power required to

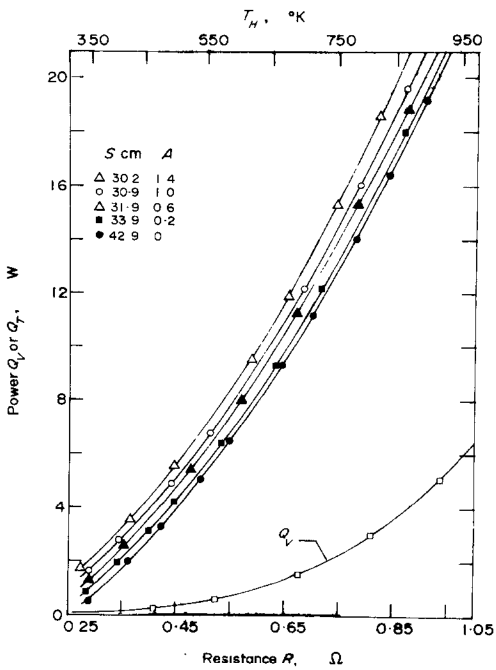

FIG. 2. Plot of the electrical power Q_v or Q_T, as a function of resistance, R, for different distances between the disks, S. The curves are arbitrarily displaced by the amount A to avoid overlapping.

heat the same section of the wire in vacuum to different temperatures. Typically, at each pressure, the measurements are taken for five to seven symmetrical positions of the disks in relation to the potential lead section of the tungsten wire.

Simple phenomenological energy balances for Q_T and Q_v are discussed by Lipkea and Springer [5]. Assuming the heat losses due to axial conduction along the wire and or leads, and radiation to the surrounding from the wire are the same in the presence of the gas and in vacuum, $Q_T - Q_v = Q_H$ will be a good measure of the thermal energy transfer from the wire by conduction through the gas and due to end effects. Recent calculations of the temperature profiles of the hot wire of Saxena and Davis [8] provide a substantial support for the adoption of such an approach to analyze the end effects for a thermally transparent gas. These calculations did reveal that the nonisothermal portions of the wire at the ends are small and are independent of its length provided it is sufficiently long. However, these calculations do not account for convection and nonradial heat losses. In Fig. 3, a typical plot of Q_H vs the distance between the disks is shown for a fixed value of the gas pressure and temperature of the tungsten wire. It is seen that Q_H becomes constant beyond a certain value of the distance between the disks. Once this value, say 1, is obtained experimentally, the depth of penetration is obtained simply by $(1 - H)/2$. This is consistent with the simplified definition used by Lipkea and Springer [5] and indeed used here for the penetration depth from the more general concept given by Eckert and Carlson [4].

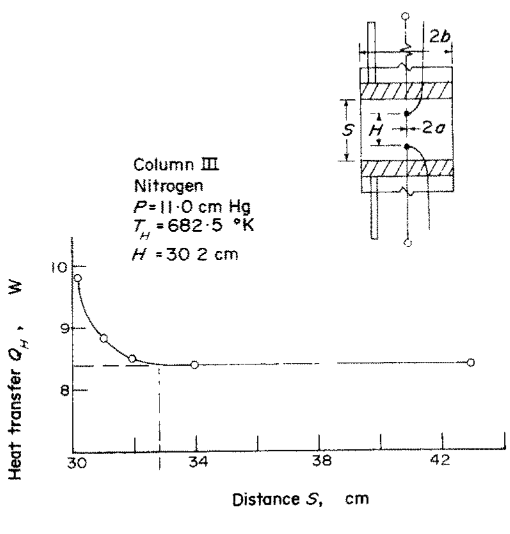

FIG. 3. Plot of the heat-transfer rate, Q_H, as a function of distance, S, for a fixed value of the resistance, R.

Now we are able to physically visualize how this experimental procedure determines the penetration depths, the concept of which is already explained above at length. The isolation of a central portion, H, of the wire and continuous monitoring of the heat-transfer rate, Q_H, from it as the disks are symmetrically moved apart in steps while all the other conditions are held constant, enables us to track down the specific portion of the end region, $(l - H)/2$, which is capable of influencing the heat transfer in the central region. In fact, this procedure enables us to assimilate realistically the heat-transfer conditions of an actual heat-transfer column of length l, and establishes that only its central portion of length H is transferring thermal energy via Fourier conduction, while at each of the two ends a portion of length $(l - H)/2$, referred to here as the penetration depth, experiences more complicated heat transfer conditions. Thus, this experimental device offers the flexibility of determining the varying penetration depths as the experimental conditions are changed and thereby the heat-transfer rates are considerably influenced. Indeed, this is the major theme of the present series of measurements, the results of which are described below.

In Fig. 4, we plot the reduced depth of penetration $Z_p^*(=Z_p/2b)$ as a function of the Rayleigh number based on the column diameter and the mean gas temperature, T_m. The latter is obtained by considering the gas to be ideal and the energy equation in which the gas conductivity is assumed to vary linearly with

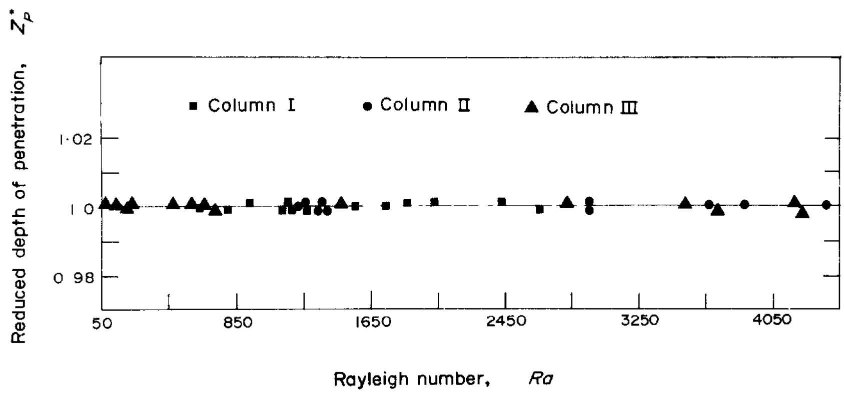

FIG. 4. Plot of the reduced depth of penetration, Z_p^*, as a function of Rayleigh number, Ra.

temperature for simplicity. The explicit relation is:

$$T_m = \frac{b^2 - a^2}{2}\left[\int_a^b \frac{r}{T(r)}\,\mathrm{d}r\right]^{-1}. \tag{2}$$

It is clear that T_m depends upon the geometry of the column and in those cases where the radius of the inner cylinder is much smaller than that of the outer cylinder, T_m is much closer to T_b. Consequently, it is necessary to choose the proper mean temperature of the gas, and the same may not be approximated arbitrarily by the average temperature, T_{av}, or the log-mean temperature, T_{lm} [9]. To illustrate the point in Table 2, we list the values of T_{av}, T_{lm} and T_m for

Table 2. Computed values of T_{am}, T_{lm} and $\bar{T}$ for T_b = 303·2°K and arbitrarily chosen values of T_a(°K)

T_a	T_{av}	T_{lm}	T_m
353·2	328·2	329·3	307·6
413·2	358·2	356·0	314·2
493·2	398·2	390·9	324·8
573·2	438·2	424·1	338·7
673·2	488·2	463·9	361·7
773·2	538·2	502·1	392·1
873·2	588·2	538·9	433·0
923·2	613·2	556·8	455·1
973·2	638·2	574·5	490·9

a fixed value of T_b and arbitrarily chosen values of T_a. The Rayleigh numbers vary in our experiments from 55 to 4400, and for this entire range the penetration depth is approximately equal to the tube diameter. This implies that the end effects do not penetrate much farther than the tube diameter, even when the two surfaces are maintained at as large a temperature difference as 700 deg C, provided the Rayleigh number does not exceed at least 4400. These experimental results obtained on a carefully built apparatus are not only in conformity with the work of Lipkea and Springer [5], but also establish that the same conclusion is valid even when the temperature difference between the two surfaces is almost seven times larger than in the earlier work [5].

Now in an attempt to estimate the energy transfer in the corner region, we calculate the average Nusselt number according to the procedure outlined by Lipkea and Springer [5], the expression being:

$$\overline{Nu}_c = \{Q_{cv}/[2\pi k(T_m)\,Z_p(T_b - T_a)]\} + 2/\ln(b/a). \tag{3}$$

Q_{cv} is the difference of the two experimentally obtained values of Q_H, referring to the physical situations when the disks are located at the leads and at a distance Z_p from them. The results so obtained for the three columns and two test gases are displayed in Fig. 5. It is seen that the average Nusselt number in the corner region for a given gas and column is approximately constant for the range of test conditions employed in our experiments, the latter being represented collectively through Rayleigh number. The $\overline{Nu}_c$ are 0·491, 0·523, and 1·843 for the heat-transfer columns I, II, and III respectively. This result is not sufficient for practical use in general, particularly from the heat transfer point of view for it simply points out that the actual form for Nu_c may be quite complicated and its dependence on various factors such as b/a, $H/2b$, Ra, test gas, etc., may be quite involved. The average Nusselt numbers for the three columns are 0·444, 0·471 and 0·646 respectively and these are computed according to the following expression given by Lipkea and Springer [5]:

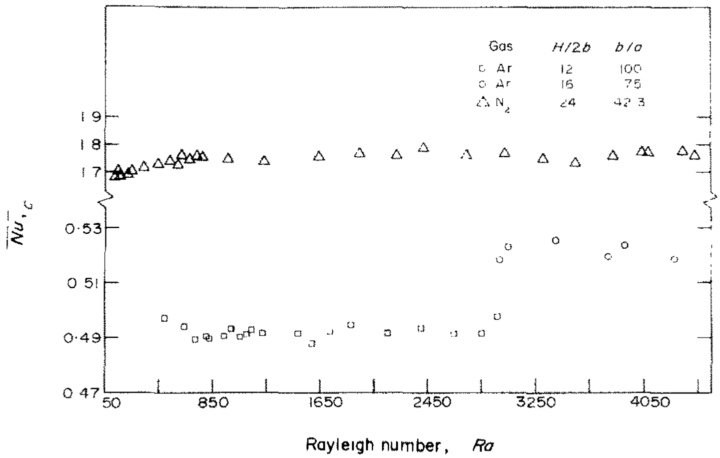

FIG. 5. Plot of the average Nusselt number in the corner region, $\overline{Nu}_c$, as a function of Rayleigh number Ra.

$$\overline{Nu} = \frac{2}{\ln(b/a)} + \frac{Z_p}{H}\left(2\overline{Nu}_c - \frac{4}{\ln(b/a)}\right). \quad (4)$$

These results lend confirmation to the pioneer work of Nusselt [9] in as much as Nu is likely to be a function of many quantities in addition to Grashof and Prandtl numbers such as b/a, S/H, temperature ratio, and difference in the temperatures of the two surfaces, etc.

In the above discussion, we have based the calculation of Nusselt number (both $\overline{Nu}_c$ and $\overline{Nu}$) on the following general relation and based on the diameter of the heat-transfer column ($2b$):

$$\overline{Nu} = \bar{h}\,.\,2b/k \quad (5)$$

where

$$\bar{h} = Q_H/(2\pi b)\,.\,H\,.\,(T_a - T_b). \quad (5a)$$

Alternatively, coupling $\bar{h}$ with a characteristic distance, very often the artificial idea of effective thermal conductivity is introduced so that

$$\overline{Nu} = \frac{k_{\text{effective}}}{k} \quad (6)$$

$k_{\text{effective}}$ obviously is composed of two parts, one due to conduction and the other due to convection. It may be noticed that we have isolated the influence of radiation from Q_H through Q_v and further only the pure molecular conduction part is represented by k. Thus, the two procedures of computing Nusselt numbers are equivalent and if anything, the one based on equation (5) is slightly preferable for heat-transfer studies, and more often used. The reason being that based on equation (5a) the idea of the heat transfer coefficient is quite realistic and physically understandable.

CONCLUSIONS

The most important conclusion from this experimental work is that the heat transfer from a heated wire in the presence of a gas to its surrounding cylindrical surface is mostly by radial conduction from the central portion of the wire, and the end effects (not limited by convection only) are confined at the ends approximately over a length equal to the diameter of the tube, as long as the test conditions are described by Rayleigh numbers lying at least in the range 55–4400. Further, we find that the energy associated with the corner region for the same Rayleigh number range is approximately constant for a given column and the test gas. These conclusions are of direct relevance to the conductivity column method for measuring the thermal conductivity of gases at high temperatures being developed in this laboratory [10], and indeed provided the incentive to undertake this heat-transfer study.

This study further lends confirmation to the analytical treatment of free convective laminar flow for a gas enclosed between two coaxial vertical cylinders maintained at widely different temperatures given by Blais and Mann [11]. Under the condition when the axial temperature gradient is much smaller than the radial temperature gradient, they found by the numerical integration of the momentum equation that the convected energy is negligible in comparison to the energy conducted radially. This is further substantiated by the calculations of Lipkea and Springer [5]. For such a case, Q_H, measured as the difference of Q_T and Q_V, represents effectively the thermal energy transport via Fourier conduction and hence appropriate for determing gas conductivity.

The error introduced in the conductivity values because of the neglect of end effects may be determined from equation (4). Thus, for a typical geometry [10] where $Z_p = 2b = 0{\cdot}800$ cm, $H = 96$ cm, $2a = 0{\cdot}03048$ cm, for nitrogen gas the Nusselt number is 0·611 when the end effects are ignored, and is 0·619 including such effects. Thus, an error of about one percent is introduced in the conductivity measurements if the end effects are completely neglected.

ACKNOWLEDGEMENTS

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UNE ETUDE EXPERIMENTALE DE TRANSFERT THERMIQUE A TRAVERS DES GAZ ENTRE DEUX SURFACES CYLINDRIQUES COAXIALES ET VERTICALES A DIFFERENTES TEMPERATURES

Résumé—On rapporte des études expérimentales de transfert thermique à travers des gaz compris entre deux surfaces cylindriques verticales coaxiales. La surface interne est un filament de tungstène chauffé électriquement tandis que la surface externe est un tube de verre maintenu à température constante par une circulation d'eau thermostatée. On a utilisé des filaments de deux diamètres différents et des tubes de trois calibres différents pour des mesures qui concernent l'argon et l'azote à diverses pressions variant de 11 à 76 cm de mercure. Le fil est chauffé jusqu'à des températures de 700°C au-dessus de celle de la paroi froide. L'influence des extrémités est soigneusement determinée suivant Lipkea et Springer mais dans un montage où les mesures ne perturbent pas le champ d'écoulement. On trouve que pour toutes les conditions d'essais réalisées ici, de tels effets d'extrémités sont confinés seulement dans des zones dont la profondeur est approximativement égale au diamètre du tube extérieur. Ces conclusions qui matérialisent celles données par Lipkea et Springer sont valables jusqu'à une différence de température entre surfaces sept fois plus grande. Les nombres de Nusselt moyens pour les colonnes entières aussi bien que pour les régions de coin sont des fonctions compliquées des constantes géométriques des températures de la nature du gaz, etc. en plus des nombres de Grashof et de Prandtl.

EINE EXPERIMENTELLE UNTERSUCHUNG DES WÄRMEDURCHGANGS DURCH SENKRECHTE, KOAXIALE ZYLINDRISCHE GASSCHICHTEN BEI UNTERSCHIEDLICHER TEMPERATUR DER BEGRENZUNGSFLÄCHEN

Zusammenfassung—Es wird über experimentelle Untersuchungen des Wärmetransportes durch Gase zwischen senkrechten, abgeschlossenen zylindrischen Oberflächen berichtet. Die innere Oberfläche wird durch einen elektrisch beheizten Wolframdraht dargestellt, während die äussere Oberfläche ein Glasrohr bildet, das durch umgewälztes Thermostatwasser auf konstanter Temperatur gehalten wird. Drähte zweier verschiedener Durchmesser und Rohre mit drei verschiedenen lichten Weiten wurden für die Versuche mit Argon und Stickstoff in einem Druckbereich von 110–760 mm Hg benutzt. Die maximale Übertemperatur der Drähte gegenüber der kalten Rohrwand betrug 700°C. Die Randeinflüsse auf den Wärmeübergang wurden nach der Methode von Lipkea und Springer in einer Apparatur, die das Strömungsfeld beeinflusst, sorgfältig bestimmt. Solche Randeffekte beschränken sich, wie die Untersuchung ergibt, auf die Eck-Zonen und zwar für alle hier verwendeten Gase. Dieser Bereich erstreckt sich auf eine Tiefe, die ungefähr gleich dem äusseren Zylinderdurchmesser ist. Diese Feststellungen bestätigen die von Lipkea und Springer und gelten für den zumindest 7-fachen Anstieg der Temperaturdifferenz der beiden Oberflächen. Weiter wurde gefunden, dass die Nusselt-Zahlen für die gesamte Säule, wie auch für die Randzonen komplizierte Funktionen der geometrischen Abmessungen, der Temperaturen, der Art des Versuchsgases usw., sowie der Grashof- und Prandtl-Zahlen sind.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПРОЦЕССА ПЕРЕНОСА ТЕПЛА ЧЕРЕЗ ГАЗЫ, ЗАКЛЮЧЕННЫЕ МЕЖДУ ДВУМЯ ВЕРТИКАЛЬНЫМИ КОАКСИАЛЬНЫМИ ЦИЛИНДРИЧЕСКИМИ ПОВЕРХНОСТЯМИ РАЗЛИЧНОЙ ТЕМПЕРАТУРЫ

Аннотация—Сообщается об экспериментальном исследовании процесса переноса тепла через газ, заключенный между двумя вертикальными коаксиальными цилиндрическими поверхностями. Внутренней поверхностью служит нагретая вольфрамовая нить, а наружной-стеклянная трубка, поверхность которой поддерживается при постоянной температуре. Эксперименты проводились с аргоном и азотом при различных давлениях (от 11 до 76 см рт. ст.), использовались нити двух и трубки трех различных внутренних диаметров. Нить нагревалась до температуры, примерно на 700°C выше температуры стенки трубки. По методике Липки и Шпрингера тщательно определялись утечки тепла с концов нити, измерения проводились в таком аппарате, в котором они не могли нарушить температурного поля. Найдено, что для всех режимов течения газа, исполь-

зуемых в опытах, концевые эффекты наблюдаются только в угловых зонах, а глубина их проникновения в каждом случае приблизительно равна диаметру наружной трубки. Помимо того, что выводы Липки и Шпрингера подтвердились, было также установлено, что они будут справедливы и при семикратном увеличении разности температур между двумя поверхностями. Найдено, что средние значения числа Нуссельта для всего столба газа, а также для угловых зон представляют собой сложные функции постоянных, характеризующих геометрию прибора, температур, природы газа и т.д., помимо чисел Грасгофа и Прандтля.