Int. J. Heat Mass Transfer. Vol. 26, No. 9, pp. 1357–1364, 1983
Printed in Great Britain

0017-9310/83 $3.00 + 0.00
Pergamon Press Ltd.

# A REFUTATION OF KING'S RULE FOR MULTI-DIMENSIONAL EXTERNAL NATURAL CONVECTION

E. M. SPARROW and M. A. ANSARI
Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455, U.S.A.

(*Received* 26 *November* 1982 *and in revised form* 14 *January* 1983)

**Abstract**—Experiments have been carried out to test the validity of King's widely quoted rule for evaluating a characteristic length for problems of multi-dimensional external natural convection. A more recent rule set forth by Lienhard was also tested. Both rules are intended to enable standard textbook-type correlations to be employed to predict natural convection heat transfer from complex bodies. The experiments were performed using a heated vertical cylinder of equal height and diameter, with heat being transferred to the ambient air from all three faces of the body (top, side, and bottom). The use of King's rule led to 40–50% overpredictions of the experimental data, so that its continued citation in textbooks appears inappropriate. Although Lienhard's rule yielded predictions that were somewhat closer to the data than those of King, the level of agreement does not appear to warrant its adoption as the link between multi-dimensional natural convection and the established literature correlations.

## NOMENCLATURE

| | |
|---|---|
| $A$ | surface area of cylinder |
| $D$ | diameter and height of vertical cylinder |
| $g$ | acceleration of gravity |
| $h$ | heat transfer coefficient |
| $k$ | thermal conductivity |
| $L_h$ | horizontal dimension |
| $L_v$ | vertical dimension |
| $L^*$ | characteristic length |
| $Nu$ | Nusselt number, $hL^*/k$ |
| $Pr$ | Prandtl number |
| $Q_{conv}$ | convective heat transfer rate |
| $Q_{rad}$ | radiative heat transfer rate |
| $Ra$ | Rayleigh number, $[g\beta(T_w - T_\infty)L^{*3}/\nu^2]Pr$ |
| $T_w$ | cylinder surface temperature |
| $T_\infty$ | ambient temperature |

Greek symbols

| | |
|---|---|
| $\beta$ | thermal expansion coefficient |
| $\varepsilon$ | emissivity |
| $\nu$ | kinematic viscosity |
| $\sigma$ | Stefan–Boltzmann constant |

## 1. INTRODUCTION

IN A PAPER of historical interest published in 1932 [1], W. J. King set forth all that was known about natural convection at that time. Most of the contents of that paper are no longer reflected in the modern literature. There are, however, two interrelated aspects of King's work which continue to be quoted in the most recently published heat transfer texts. The enduring quality of this vintage information is remarkable, especially since the primary result attributed to King has not been subjected to experimental verification since it was first set forth in 1932. Experiments designed to test the validity of King's results have been performed during the course of the investigation that is reported in this paper.

The primary result of King that is the focus of the present work affords a classic example of how less-than-adequately supported information can attain the status of full acceptance in the modern literature. The process typically begins with the information being quoted in a widely used textbook. Then, a subsequent text borrows the information from the first text, and this borrowing continues from one new text to another. Along the way, modifications or interpretations of the information made in one or another text tend to be carried along in the borrowing process, with the modified form of the information still being attributed to the original source.

For external natural convection about bodies whose vertical dimension $L_v$ and horizontal dimension $L_h$ may both affect the heat transfer, King indicates that a characteristic dimension $L^*$ be defined as

$$\frac{1}{L^*} = \frac{1}{L_v} + \frac{1}{L_h}. \tag{1}$$

As examples of the class of bodies in question, King names small short cylinders, planes, or spheres.

To complement the aforementioned characteristic length, King presented a Nusselt–Rayleigh correlation in graphical form which spans 16 decades in the Rayleigh number. This correlation is purported to be universal for all external natural convection flows, including vertical plates and cylinders, horizontal cylinders, spheres, rectangular blocks, and all other bodies whose characteristic length is given by equation (1). Over a range of Rayleigh numbers (not specified by King), the correlation was expressed algebraically as

$$Nu = 0.55\,Ra^{1/4}. \tag{2}$$

More recent and more accurate experiments have refuted the notion of a universal correlation, so that separate correlations are now employed for the vertical plate, horizontal cylinder, and sphere. Yet, as will be described shortly, the King correlation, particularly equation (2), continues to appear in the modern literature as a companion for equation (1).

Equation (1) is quoted in at least four of the recently published heat transfer texts [2–5]. In all of these texts, the equation is specifically earmarked for use for rectangular blocks, which represents a case not mentioned by King among his examples. Further embellishments, also attributed to King (but not appearing in his paper) are that $L_h$ is the longer of the two horizontal dimensions of the block [2] or that $L_h$ and $L_v$ are respectively taken as the average of the horizontal and vertical dimensions of the block [5].

All of the cited texts specify that equation (1) for $L^*$ is to be employed in conjunction with equation (2) [2, 5] or with a modified form where the coefficient 0.55 is replaced by 0.60 [3, 4], with the modified form again attributed to King although it nowhere appears in his paper. Furthermore, these texts append the range $10^4 \leqslant Ra \leqslant 10^9$ to equation (2) (or its modified form) and, by implication, also to equation (1). This implied limitation on equation (1) is not found in King's paper, where equation (1) is presented as an adjunct to the all-encompassing Nusselt–Rayleigh correlation.

There are reasons to doubt the validity of equation (1). First of all, King's advocacy of this definition of the characteristic length was based on its success in bringing together data for odd geometries with data for regular geometries to yield a universal correlation. However, as was noted earlier, King's universal correlation has subsequently been found not to be universal, thereby eliminating the main basis for the characteristic length of equation (1).

Perhaps of greater concern is that equation (1) takes no account of the specifics of the various configurations to which it might be applied. In this connection, consider, for instance, a short, heated vertical cylinder, with heat being transferred from all three surfaces (top, bottom, and side) to the surrounding fluid. The natural-convection-induced flow on the bottom surface is directed radially outward, while that on the top surface moves radially inward. By way of further contrast, the bottom surface is washed by fresh fluid (i.e. from the surroundings), whereas the top surface is washed by fluid that has been heated by contact with the other surfaces of the cylinder. Notwithstanding these major differences, no distinction is made between the two surfaces, and they are jointly represented by $L_h = D$ ($D$ = diameter) in equation (1).

Considering the broad acceptance of equation (1) and the virtual absence of definitive data supporting its validity, there is ample motivation to undertake careful experiments on multi-dimensional external natural convection. The present research was undertaken in response to this motivation. The experiments were performed using a heated vertical cylinder of equal height and diameter. A cylinder was employed because it afforded a clean-cut application of equation (1), which would not have been true had a rectangular block with two different horizontal dimensions been employed.

The experiments were carried out in air under conditions conducive to the attainment of data with an accuracy in the 1% range. Nusselt and Rayleigh numbers were evaluated from the data for several choices of the characteristic dimension, one of which is King's equation (1). Another characteristic dimension that was investigated is that recommended by Lienhard [6], namely, the length of travel of the fluid in the boundary layer. A third characteristic dimension, based on purely geometrical considerations, was also considered. These results were compared with a number of literature correlations in addition to that of King (and those attributed to him). These many comparisons provide perspectives about how the Nusselt numbers for a multi-dimensional body relate to literature information for simpler geometries.

## 2. THE EXPERIMENTS

The experimental apparatus and the test environment will now be described. The description of the apparatus is facilitated by reference to Fig. 1, which shows a cross-sectional view of the vertical cylinder used in the experiments. As seen there, the height and the outside diameter of the cylinder are equal—the finished dimension being 3.119 cm. The cylinder was assembled from three parts, all made of aluminum, with a uniform thickness of 0.635 cm for all walls. Aluminum was chosen because of its high thermal conductivity (to facilitate the attainment of a uniform surface temperature) and because it is capable of being polished to an enduring mirror-like surface finish (to minimize radiative heat transfer).

The lower portion of the cylinder was a cup-like piece made from a solid rod into which a cavity had been machined concentric with the axis. The cavity served to house a specially fabricated heating element, the core of which was an aluminum shell. Forty equally spaced longitudinal grooves were milled into the core, 20 on the outer surface and 20 on the inner surface. The heating wire (0.0076 cm diameter chromel wrapped with 0.0076 cm thick Teflon insulation) was laid in series in the grooves in a back and forth pattern and then fixed in place by copper oxide cement. The choice

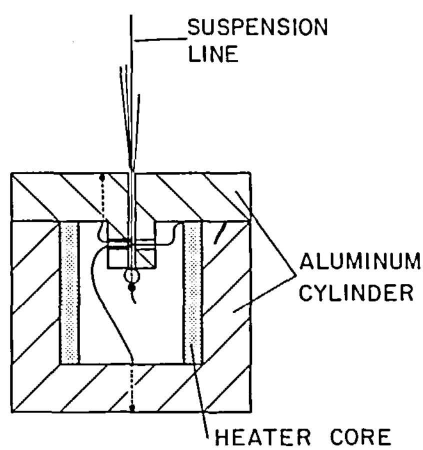


FIG. 1. Cross-sectional view of the vertical cylinder used in the experiments.

of the wire type, diameter, and length was made to achieve low electric current flows ($<0.18$ A), enabling the use of small diameter copper lead wires to deliver power to the heater.

The upper portion of the cylinder was a disk machined from a solid rod, with an integral cylindrical extension which penetrated downward into the hollow space within the heater core. As seen in Fig. 1, a 0.1 cm diameter hole was drilled along the axis of the disk and the cylindrical extension. The line used to suspend the cylinder was passed through the hole. The end of the line which emerged from the bottom of the hole was threaded through a small hollow spherical ball (from a key chain) and knotted below the ball. When the cylinder was suspended, the ball centered itself in the mouth of the hole.

The hole also served to convey the heater lead wires and the thermocouple wires from the interior to the exterior of the cylinder. However, owing to the blockage of the mouth of the hole by the spherical ball, lateral access to the hole was provided as shown in the figure.

Two thermocouples were installed in the wall of the cylinder to detect the outside surface temperature. The holes for the thermocouples were drilled from the rear side and penetrated to within 0.076 cm of the surface, with copper oxide cement used to fix the thermocouples in place and fill the holes. The positions of the thermocouples are indicated in the figure—one in the lower wall and the other in the upper wall. These locations were chosen since it was expected that any wall temperature differences would show themselves most strongly there. For most of the data runs, no temperature difference could be detected within the 1 $\mu$V resolving power of the instrumentation. At the highest heat input, the temperature difference between the measurement points was 0.1% of the wall-to-ambient temperature difference. In light of this, it can be concluded that the desired uniform-wall-temperature boundary condition was achieved.

A major issue in the design of the apparatus was the minimization of extraneous losses by conduction along the suspension line and lead wires and by radiation from the surface of the cylinder. With regard to conduction, the suspension line was made of catgut, a low conductivity material of great strength. (It is used for bows in high-performance bow and arrow sets.) In view of the low levels of electric current, it was sufficient to use 0.0076 cm diameter copper lead wires to supply the heater. A survey of the thermal conductivities of commonly available thermocouple-wire pairs showed that chromel–constantan has the lowest value (as well as the highest thermoelectric output). Therefore, chromel–constantan thermocouples were employed for the experiments, the wire being of the smallest diameter that could be handled conveniently (0.0076 cm).

To diminish the radiative heat transfer to its smallest possible value, the cylinder surface was subjected to a succession of painstaking polishing and lapping operations, concluding with 1200 grit. The final surface finish was that of a high quality mirror, so that it can be safely assumed that the surface can be regarded as 'highly polished' from the standpoint of radiation properties.

In addition to the two thermocouples used to measure the cylinder surface temperature, three additional thermocouples of the same type were employed for the determination of the temperature of the ambient air. These thermocouples were positioned about 30 cm to the side of the cylinder, with one at the same height as the cylinder and the other two at 15 cm above and below this height. Aluminum-foil shields were used to block direct radiation from the heated cylinder to the ambient-air thermocouples. All thermocouples had been calibrated prior to their installation.

Power to the cylinder heating element was provided by a programmable DC supply whose voltage output was constant to at least one in the fourth significant figure over the 8 h duration of a data run. The heater voltage was read directly, while the current was read in terms of the voltage drop across a calibrated shunt.

The laboratory in which the experiments were performed was ideally suited for high-precision natural convection work. The walls, ceiling, and floor of the laboratory are insulated with 46 cm of cork, and there are no ducts, pipes, or vents leading in or out. It is situated in a basement, is windowless, and is away from external walls (i.e. a room within a room). The total volume of the laboratory is about 70 $m^3$, and it contains various objects of large aggregate heat capacity. The combination of thermal isolation and large heat capacity makes for unusual thermal stability. Thermal stratification, as detected by the ambient-air thermocouples, was negligible.

The power supply and all instrumentation were situated outside the laboratory. It was never entered during a data run nor were lights turned on.

## 3. DATA REDUCTION

The cylinder heat transfer coefficient and Nusselt number were evaluated from the defining equations

$$h = (Q_{conv}/A)/(T_w - T_\infty), \quad Nu = hL^*/k. \tag{3}$$

In the $h$ equation, $A$ is the surface area including the top, side, and bottom faces of the cylinder. Since the cylinder height was equal to its diameter, $A = (3/2)\pi D^2$. Both the wall and ambient temperatures $T_w$ and $T_\infty$ needed as input to equation (3) were directly measured.

The convective heat transfer, $Q_{conv}$, was determined from the measured heater power corrected for extraneous losses. For the calculation of the radiation heat loss, the cylinder is accurately modeled as a small body in a large isothermal enclosure. Correspondingly,

$$Q_{rad} = A\varepsilon\sigma(T_w^4 - T_\infty^4) \tag{4}$$

where $\varepsilon$ is the graybody emissivity of the cylinder, taken as 0.05 for the highly polished aluminum. In equation

(4), $T_\infty$ denotes the temperature of the walls of the laboratory, which is assumed equal to the air temperature. The calculated values of $Q_{rad}$ ranged from 5 to 7% of the electric power input.

The conduction losses along the lead wires were also estimated. Owing to the small diameter of the wires (0.0076 cm), these losses were less than 0.5% of the input power and were therefore neglected. Consequently, the convective heat transfer $Q_{conv}$ was obtained by subtracting $Q_{rad}$ from the input power.

In the Nusselt number definition of equation (3), the quantity $L^*$ denotes the characteristic length of the cylinder. If King's prescription, equation (1), is used, then

$$(L^*)_{King} = \tfrac{1}{2}D. \quad (5)$$

Lienhard, as noted earlier, suggested that the characteristic length be taken equal to the length of travel of the fluid in the boundary layer. For the cylinder used here, the Lienhard length is

$$(L^*)_{Lienhard} = 2D \quad (6)$$

with contributions $\frac{1}{2}D$, $D$, and $\frac{1}{2}D$, respectively for the bottom, side, and top.

As a third alternative, the characteristic length was taken to be $D$ itself, i.e.

$$L^* = D. \quad (7)$$

This choice was motivated by the fact that the geometry of the present cylinder is characterized by $D$ alone.

The Nusselt number results will be presented as a function of the Rayleigh number defined as

$$Ra = [g\beta(T_w - T_\infty)L^{*3}/\nu^2]Pr \quad (8)$$

where $L^*$ is the same characteristic length as for the Nusselt number. The thermophysical properties appearing in equations (8) and (3) were evaluated at the film temperature $T_f = \frac{1}{2}(T_w + T_\infty)$, with $\beta$ as $1/T_f$ (absolute temperature for the $\beta$ calculation).

## 4. RESULTS AND DISCUSSION

Before presenting the experimental results, it is relevant to establish their level of accuracy. High accuracy is to be expected because of the features built into the apparatus to minimize extraneous losses and to obtain stable and uniform operating conditions. Also contributing to this expectation is the ideal nature of the available test environment. To help provide a quantitative measure of the expected accuracy, it may be noted that the heated cylinder used in the present experiments had also been employed in the study of a fully enclosed natural convection flow which was amenable to solution via numerical finite differences [7]. Of the 22 experimentally determined Nusselt numbers which were compared with the numerical predictions, the majority agreed to within 1%, and the maximum deviation was 3%. There is no reason why the present results should not be equally accurate.

### *Tests of proposed characteristic lengths*

The present heat transfer data, evaluated in terms of $Nu$ and $Ra$ based on King's prescription for the characteristic length (i.e. $L^* = \frac{1}{2}D$), are plotted in Fig. 2. The data are seen to be remarkably free of scatter, and for $Ra \geqslant 1800$ they fall on a straight line,

$$Nu = 0.597\,Ra^{0.208}, \quad L^* = \tfrac{1}{2}D, \quad (9)$$

which was determined by least squares. Overall, the Rayleigh numbers of the data span a forty-fold range. However, because of the factor 1/8 which enters the Rayleigh number through the characteristic dimension $L^* = \frac{1}{2}D$, the values of the Rayleigh number are limited to about 16 000.

In addition to the experimental data, Fig. 2 contains several curves representing literature correlations. The most pertinent of these is that of King and those attributed to him (i.e. the power laws appearing near the right-hand margin of the figure). It is seen that there is a large gap between the experimental data (based on

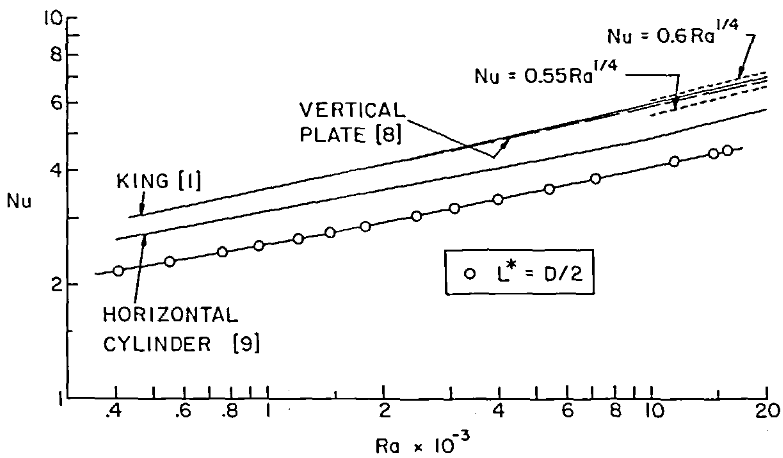


FIG. 2. Comparison of experimental $Nu$, $Ra$ data based on King's characteristic length ($L^* = \frac{1}{2}D$) with King's and other literature correlations.

$L^* = \frac{1}{2}D$) and the King-related curves. Indeed, the curves lie 40–50% above the data. This finding stands in strong opposition to the use of King's rule [equation (1)] to determine $L^*$ and to its subsequent use in conjunction with either King's correlation or the power laws frequently attributed to him in the modern literature.

It is relevant to observe that King's rule overpredicts the data regardless of the literature correlation with which it is used. In this connection, the Churchill–Chu equation for the vertical plate [8] and the Morgan equation for the horizontal cylinder [9] are plotted in Fig. 2. (The selection of these particular correlations for the comparison will be discussed shortly.) It is seen from the figure that the vertical plate correlation overpredicts the data by 40–45%, while the cylinder curve lies 20–25% above the data.

The aggregate of the results presented in Fig. 2 argues persuasively against the use of King's rule [equation (1)] for evaluating the characteristic length for multi-dimensional natural convection problems. Moreover, its continued citation in textbooks appears inappropriate.

Attention is next turned to the characteristic length suggested by Lienhard (the length of travel of the fluid in the boundary layer). This yields $L^* = 2D$ for the present problem. According to Lienhard, the use of this definition of $L^*$ in conjunction with the expression

$$Nu = 0.52\,Ra^{1/4} \tag{10}$$

should predict the natural convection heat transfer from any submerged body within about 10% if $Pr$ is not $\ll 1$.

When the present data are evaluated with $L^* = 2D$, the Rayleigh number range extends from about $2 \times 10^4$ to $10^6$. These data are plotted in Fig. 3 along with the Lienhard equation (10). The figure shows that the Lienhard prescription underpredicts the data, which is just opposite to the behavior of King's prescription for $L^*$. At the lower end of the Rayleigh number range, the data lie about 30% above equation (10). On the other hand, at the upper end of the range, the data are within 8% of the prediction, which fulfils Lienhard's stated accuracy band. Overall, however, the gap between the prediction line and the data is too large to encourage acceptance of Lienhard's prescription as the sought-for link between multi-dimensional natural convection and the established literature correlations.

*Final form of the Nu, Ra data*

Up to now, the presentation of results has been focused on evaluating the credentials of various proposals for the characteristic length. Now, the data will be presented in their own right, as basic information for a case not heretofore investigated. For this purpose, it appears reasonable to take $L^* = D$, since, with the cylinder diameter equal to the height, $D$ is the only geometric parameter of the problem. The resulting Nusselt–Rayleigh data are plotted in Fig. 4, with the range of the Rayleigh number extending from about $3 \times 10^3$ to $1.3 \times 10^5$. For $Ra > 1.4 \times 10^4$, the data lie on a least-squares straight line

$$Nu = 0.775\,Ra^{0.208}, \quad L^* = D \tag{11}$$

virtually without deviation.

It is interesting to see where these results lie with respect to the totality of the available information in the present Rayleigh number range for external natural convection. To this end, Fig. 4 includes the vertical plate and horizontal cylinder correlations that were mentioned earlier as well as the correlations for the sphere [10] and for the up-facing, heated horizontal plate [11].

All of the cases included in Fig. 4 display a tendency toward a flattening of the slope of the $Nu$, $Ra$ distribution as the Rayleigh number decreases. At the upper end of the depicted Rayleigh number range, the literature correlations tend toward a $\frac{1}{4}$-power slope, whereas the present data display a 0.208-power slope [equation (11)]. This lesser slope is believed due to a thickening of the thermal boundary layers on the side and top surfaces of the cylinder due to what is, in effect, a preheating of the air. The preheating occurs when the air passes over the bottom face of the cylinder before reaching the side and when it passes over the side en route to the top face. This effect is also believed to be responsible, at least in part, for the fact that the present data lie below that for the vertical plate.

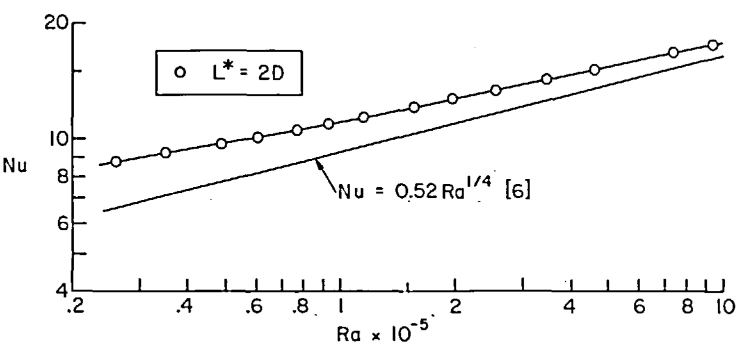


FIG. 3. Comparison of experimental $Nu$, $Ra$ data based on Lienhard's characteristic length ($L^* = 2D$) with Lienhard's correlation.

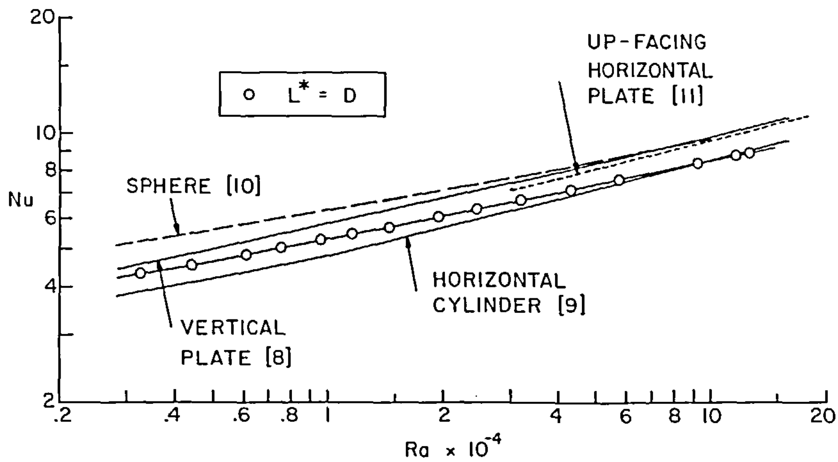


FIG. 4. Experimental $Nu$, $Ra$ data based on the characteristic length $L^* = D$ and comparisons with literature correlations.

*Choice of comparison cases*

As a final matter, the selection of the literature correlations used for comparison with the present data will be discussed. For the vertical plate, up-facing horizontal plate, and sphere, there is, for each case, only one modern correlation, and that one was used here. For the horizontal cylinder, there are several modern correlations, so that considerable care was exercised in the choice of the one used here for comparison purposes.

To facilitate a rational choice, a set of data for the horizontal cylinder was obtained using an apparatus that is described in ref. [12]. These horizontal cylinder data were collected subsequent to the completion of the work described in ref. [12], with the experiments being carried out in the same test environment as employed in the present experiments. The data obtained are plotted in Fig. 5, which also shows the modern correlations of Morgan [9], Churchill and Chu [13], and Fand *et al.* [14], with the venerable McAdams correlation [15] included for perspective. Churchill and Chu actually give two correlations—the upper of the two curves in Fig. 5 corresponds to their equation (10) and the lower to their equation (6). $Nu$ and $Ra$ which appear in this figure are based on the diameter of the horizontal cylinder.

Inspection of Fig. 5 shows that the data agree very well with the Morgan and the Fand correlations. The Churchill-Chu correlations lie below the data, and examination of their paper indicates that in the Rayleigh number range considered, the correlating lines lie below the data on which they are based.

The foregoing comparisons, plus the fact that the Morgan correlation has a substantially larger data base than that of Fand, led to Morgan being chosen. The McAdams correlation lay well above the data.

## 5. CONCLUDING REMARKS

The experimental evidence presented here stands in opposition to the use of King's rule, equation (1), for evaluating the characteristic length for multi-dimensional natural convection problems. In view of the present findings, its continued citation in textbooks appears inappropriate.

Lienhard's prescription for the characteristic length (the length of travel of the fluid in the boundary layer) leads to a prediction that is somewhat closer to the data than that of King. Overall, however, the gap between the predicted Nusselt numbers and the experimental values is too large to encourage acceptance of the Lienhard prescription as the sought-for link between multi-dimensional natural convection and the established literature correlations.

Thus, neither of the aforementioned proposals brings the data for the present case into congruence with predictions obtained from literature correlations for standard cases. This outcome appears quite plausible when cognizance is taken of the distinctive and specific nature of the pattern of fluid flow associated with the present body or with any multi-

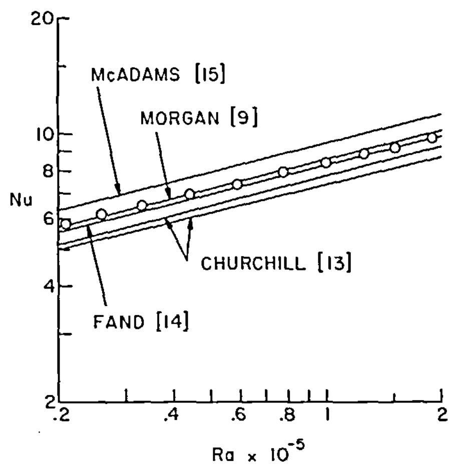


FIG. 5. Results of supplementary horizontal cylinder experiments and comparisons with literature correlations.

dimensional body. These distinctive features may include one or more zones of flow separation and buoyant plumes which are spawned by one or more faces of the body and which may screen another face from the ambient. The preheating of the fluid which arrives at a surface of a multi-dimensional body after passing over other surfaces of the body also affects the heat transfer characteristics. In view of these factors, it would appear unlikely that the selection of a single characteristic length would be sufficient to bring data from multi-dimensional bodies into congruence with literature correlations.

## REFERENCES


1. W. J. King, The basic laws and data of heat transmission—III. Free convection, *Mech. Engng* **54**, 347–353 (1932).
2. B. V. Karlekar and R. M. Desmond, *Heat Transfer* (2nd edn), pp. 624–625. West, St. Paul (1982).
3. J. P. Holman, *Heat Transfer* (5th edn), p. 281. McGraw-Hill, New York (1981).
4. F. Kreith and W. Z. Black, *Basic Heat Transfer*, p. 259. Harper and Row, New York (1980).
5. L. C. Thomas, *Fundamentals of Heat Transfer*, p. 444. Prentice-Hall, Englewood Cliffs, NJ (1980).
6. J. H. Lienhard, *A Heat Transfer Textbook*, pp. 361–362. Prentice-Hall, Englewood Cliffs, NJ (1981).
7. M. Charmchi, Experimental and analytical study of natural convection in the enclosed space between finite length cylinders, Ph.D. thesis, Department of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota (1981).
8. S. W. Churchill and H. H. S. Chu, Correlating equations for laminar and turbulent free convection from a vertical plate, *Int. J. Heat Mass Transfer* **18**, 1323–1329 (1975).
9. V. T. Morgan, The overall convective heat transfer from smooth circular cylinders, in *Advances in Heat Transfer*, Vol. 11, pp. 199–264 (1975).
10. T. Yuge, Experiments on heat transfer from spheres including combined natural and forced convection, *J. Heat Transfer* **82**, 214–220 (1960).
11. J. R. Lloyd and W. R. Moran, Natural convection adjacent to horizontal surfaces of various planforms, *J. Heat Transfer* **96**, 443–447 (1974).
12. E. M. Sparrow and J. E. Niethammer, Effect of vertical separation distance and cylinder-to-cylinder temperature imbalance on natural convection for a pair of horizontal cylinders, *J. Heat Transfer* **103**, 638–644 (1981).
13. S. W. Churchill and H. H. S. Chu, Correlating equations for laminar and turbulent free convection from a horizontal cylinder, *Int. J. Heat Mass Transfer* **18**, 1049–1053 (1975).
14. R. M. Fand, E. W. Morris and M. Lum, Natural convection heat transfer from horizontal cylinders to air, water, and silicone oils for Rayleigh numbers between $3 \times 10^2$ and $2 \times 10^7$, *Int. J. Heat Mass Transfer* **20**, 1173–1184 (1977).
15. W. H. McAdams, *Heat Transmission* (3rd edn), p. 177. McGraw-Hill, New York (1954).


## UNE REFUTATION DE LA REGLE DE KING POUR LA CONVECTION NATURELLE EXTERNE MULTIDIMENSIONNELLE

Résumé—Des expériences éprouvent la validité de la règle de King, largement citée, pour évaluer une longueur caractéristique pour les problèmes de convection naturelle externe multidimensionnelle. On vérifie aussi une règle plus récente proposée par Lienhard. Les deux règles prétendent permettre aux formules d'être employées pour prédire la convection naturelle thermique autour de corps complexes. Dans les expériences est utilisé un cylindre chaud, vertical, de hauteur égale au diamètre, avec la chaleur transférée à l'air ambiant par les trois faces du corps (sommet, coté et base). L'utilisation de la règle de King conduit à 40–50 pour cent de surestimation sur les résultats expérimentaux si bien qu'elle est inappropriée. Bien que la règle de Lienhard conduisent à des prévisions plus proches des données que celle de King, le niveau d'accord ne semble pas garantir son adoption comme chaînon entre la convection naturelle multidimensionnelle et les formules données dans la littérature.

## EINE WIDERLEGUNG DER KING'SCHEN REGEL FÜR MEHRDIMENSIONALE ÄUSSERE FREIE KONVEKTION

Zusammenfassung—Es wurden Versuche durchgeführt, um die Gültigkeit der viel zitierten King'schen Regel zu prüfen, mit der man bei mehrdimensionaler äußerer freier Konvektion die charakteristische Länge bestimmen kann. Eine etwas neuere Regel von Lienhard wurde ebenfalls überprüft. Beide Regeln haben zum Ziel, die Anwendung üblicher, einfacher Gleichungen auf die Berechnung der freien Konvektion an komplexen Körpern zu ermöglichen. Die Versuche wurden an einem vertikalen Zylinder, bei dem Durchmesser und Höhe gleich waren, durchgeführt. Die Wärme wurde dabei von allen drei Flächen des Körpers (Oberseite, Mantel und Unterseite) an die umgebende Luft übertragen. Die Anwendung der King'schen Regel führte hierbei zu 40 bis 50% zu hohen Voraussagen gegenüber den Meßwerten, so daß ihre fortgesetzte Zitierung in Lehrbüchern nicht gerechtfertigt erscheint. Obgleich die Regel von Lienhard Voraussagen liefert, die den Versuchswerten etwas näher kommen, so scheint das Ausmaß der Übereinstimmung doch nicht dazu zu berechtigen, diese Regel als Bindeglied zwischen der mehrdimensionalen freien Konvektion und den etablierten Literaturbeziehungen anzusehen.

# ОБ ИСПОЛЬЗОВАНИИ ПРАВИЛА КИНГА ДЛЯ РАСЧЕТА МНОГОМЕРНОЙ ВНЕШНЕЙ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ

**Аннотация**—Выполнены эксперименты по проверке справедливости правила Кинга, широко используемого для оценки характеристической длины в задачах с многомерной внешней естественной конвекцией. Было проверено также правило, выведенное позже Линхардом. Оба правила предназначены для получения стандартных и надежных соотношений и их использования для расчета теплопереноса естественной конвекцией от тел сложной формы. Эксперименты проводились с нагреваемым вертикальным цилиндром, у которого высота равнялась диаметру. Тепло отводилось в окружающий воздух со всех трех его поверхностей (верхней, боковой и нижней). Правило Кинга приводит к занижению расчетных данных по сравнению с экспериментальными на 40–50%, так что его дальнейшее цитирование в учебниках кажется нецелесообразным. Хотя правило Линхарда позволяет получать расчетные значения несколько ближе к измеряемым, тем не менее степень соответствия результатов недостаточна для рекомендации этих соотношений при расчетах многомерной естественной конвекции.