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IMPROVED HEAT-TRANSFER PERFORMANCE WITH BOUNDARY-LAYER TURBULENCE PROMOTERS

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Abstract—A substantial improvement in forced-convection heat-transfer conductance is required for the development of advanced steam-cooled and gas-cooled power reactor systems. Boundary-layer turbulence promoters on the heated surfaces are of great interest for these systems because of the large increase in the heat-transfer performance which can be attained. However, much of the experimental data on turbulence promoters has been obtained in annular flow passages, and it is necessary to transform these data in order to apply them to reactor configurations. This investigation of boundary-layer turbulence promoter performance was carried out in arrays of parallel rods, the configuration of greatest interest for engineering applications. Discrete two-dimensional roughness elements, in the form of small fins transverse to the flow, were investigated experimentally to establish the effect of promoter height and promoter spacing. The results are directly applicable for optimization of heat-transfer performance, and also provide a basis for evaluating transformation techniques used for data obtained in annular passages.

NOMENCLATURE

d, rod diameter;
D_H, hydraulic diameter;
f, friction factor;
g_c, gravitational constant;
e, promoter height;
e^+, dimensionless promoter height;
k, thermal conductivity;
Nu, Nusselt number;
p, rod center spacing;
P, pressure;
Pr, Prandtl number;
q'', heat flux;
Re, Reynolds number;
s, promoter spacing;
t, temperature;
T, dimensionless temperature;
V, velocity;
x, axial position.

Greek symbols
ν, kinematic viscosity;
ρ, density;
τ_o, wall shear stress.

Subscripts
m, mean;
o, smooth;
w, wall;
in, inlet;
ii, wall i with wall i heated;
ij, wall i with wall j heated.

INTRODUCTION

Nature of the problem

It is well known that higher heat-transfer coefficients can be achieved with rough surfaces, but this effect is frequently dismissed as a means for improving performance because of the correspondingly higher friction factors. However, when one considers that high power density and/or high cycle thermal efficiency may be the objective, rather than simply an improved heat-transfer effectiveness, and when one allows that not all surfaces need be roughened in order to reach this goal, then surface roughness becomes a very attractive device for improving the heat-transfer performance. Steam-cooled nuclear reactors are a typical example where this has proved to be important. To incorporate surface roughness in practical design applications, it is necessary that basic heat-transfer and fluid-flow data be obtained experimentally.

Surface roughness causes a change in the flow friction mechanism at the wall from that of viscous shear to the more dissipative form drag. This increased flow resistance is accompanied by a corresponding increase in heat-transfer conductance. To optimize this gain in heat transfer, and to try to minimize the corresponding increase in friction, attention has been directed toward discrete, regularly arranged roughness elements. We shall refer to these roughness elements as boundary-layer turbulence promoters because they augment heat transfer by generating turbulent eddies in the high thermal-resistance fluid layers adjacent to the wall.

The velocity field in a flowing fluid is governed by the shape of the particular flow passage and the surface roughness at its boundary. The temperature field is then governed by this velocity field and the heat-transfer boundary conditions. Although the heat-transfer and fluid-flow characteristics of a few simple flow passages may be predicted from data obtained in circular ducts, it is found that the characteristics of more complex flow passage configurations must be determined individually. This investigation considers the effects of various surface roughness boundary conditions applied uniformly to all surfaces in a particularly important flow passage configuration, arrays of parallel rods. The results are therefore directly applicable for design calculations for rod arrays. They also provide a basis for evaluating the transformation techniques which have been proposed to apply to the data obtained from tests in other geometries and tests where all of the surfaces were not roughened.

Method of solution

We are considering the influence of boundary-layer turbulence promoters on turbulent flow through triangularly pitched parallel rod arrays of "infinite" extent. In conducting an experimental investigation of this type, it is necessary to reduce the number of variables in order to focus attention on the primary subject. Consequently, to insure constant properties, the experiments are performed at low heating rates, at temperatures near ambient, and with small pressure gradients. The velocity in the test section is kept low, and the tests are conducted in the particular flow passage of interest. Further, to insure a well defined flow configuration, we are investigating arrays free from large mechanical spacers. Finally, we are limiting our scope to fully developed flow so that the results may be used with the superposition technique to handle the non-uniformly heated rod array.

Boundary-layer turbulence promoters may be any type of protrusion from the surface. The boundary-layer turbulence promoters considered here consist of small fins transverse to the flow and spaced at regular intervals along the rods. The ribs for these tests were formed by winding a fine wire around each rod as shown in Fig. 1, and the rods assembled into an "infinite" array as shown in Fig. 2.

Heat-transfer and flow-friction measurements are made in the parallel rod array described in Appendix 1 with air ($Pr = 0{\cdot}7$) past electrically heated rods. The parameters of interest are the promoter height e and the promoter spacing s.

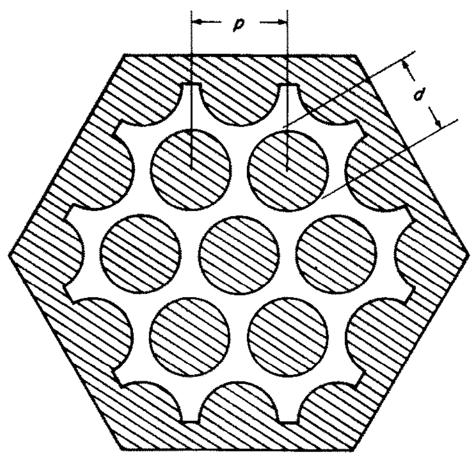

FIG. 2. Parallel rod array test assembly.

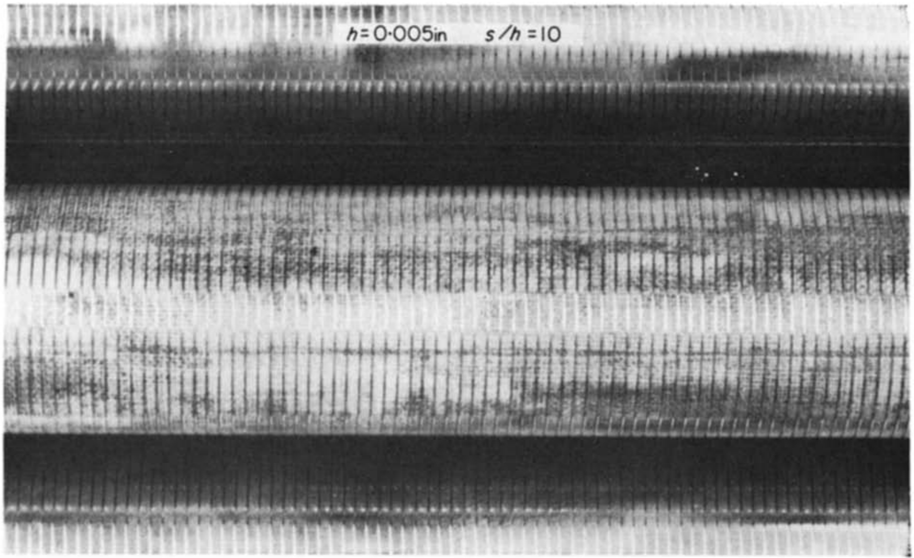

FIG. 1. Turbulence promoters installed in the parallel rod array.

Since the thickness of the low velocity fluid layers at the wall will depend on the Reynolds number, the penetration of these wall layers is investigated by varying the Reynolds number (Re = 5000–150000), and by varying the relative height of the turbulence promoter (e/D_H = 0·00692–0·0349). The nondimensional penetration into the boundary layer is, thereby, varied from e^+ = 5–1000. The relative spacing of the turbulence promoters was varied from s/e = 7·15–14·82, and the tests are carried out with two rod-spacing-to-diameter ratios, p/d = 1·15 and 1·25.

SUMMARY OF PREVIOUS INVESTIGATIONS

A substantial amount of data has been obtained on turbulence promoter performance over the past 10 years. However, a suitable method of correlating all of this data on a common basis has not been developed, and extrapolating these results to new applications is not yet possible. It is not the intention of this paper to review all of this work nor attempt to provide a method for a general correlation; however, some of these papers will be mentioned to show the course of boundary-layer turbulence promoter development.

In order to achieve the flexibility necessary to evaluate more than a few turbulence promoter parameters, many investigators have carried out their experiments in an annular flow geometry. A number of different boundary-layer turbulence promoters can be investigated by applying the promoters to the outer surface of a tube and using this surface as the inner wall of the annular flow passage. However, the unsymmetrical boundary condition of a rough inner wall and a smooth outer wall presents a substantial problem in interpreting the experimental results. A method for handling this unsymmetrical boundary condition was first proposed by Hall [1], and most of the subsequently proposed methods have followed his basic approach. Walker and Rapier [2] and Wilkie [3] have investigated a wide range of size and spacing parameters for transverse rib type turbulence promoters, and the results from these investigations have been transformed by Hall's method. Sheriff and Gumley [4] have reported their results in both the transformed and conventional manner. Gargaud and Paumard [5] have also transformed their results, but with a different definition of the hydraulic diameter.

In addition to the tests performed in annular flow passages, turbulence promoters have been investigated in various other flow passage shapes; some of these tests have been specifically designed to evaluate the method for transforming data from one geometry to another. Round tubes have been investigated by Sams [6, 7], and rectangular channels have been investigated by Edwards and Sheriff [8]. Tests have also been run in prototype reactor fuel bundles with spiral wire spacers by Kattchee and Mackewicz [9]. It can be concluded from these tests that the transformation techniques, such as the one proposed by Hall, are very useful for handling the unsymmetrical boundary condition imposed by adjacent smooth and rough walls. However, the variation introduced by large differences in flow passage geometry is not completely correlated by this method in its current state of development. Further data from the flow passages of interest for application is necessary in order to evaluate transformation techniques.

SUMMARY OF INVESTIGATION

Heat-transfer results

The method we have used to evaluate heat-transfer performance employs the technique of superposition of fundamental solutions developed in [10]. The Nusselt number data obtained in this manner has less experimental uncertainty than is possible from more common data evaluation procedures, and the fundamental solutions themselves are useful for handling the arbitrary heat flux distribution problem.

The fundamental solution represents a normalized wall temperature, and is defined with respect to the difference between the fluid inlet temperature and the wall temperature as

$$T_w = \frac{t_w - t_{in}}{q'' \, D_H/k}. \tag{1}$$

This parameter has the advantage of being directly measurable in the experiment. The experimentally determined values of T_w are correlated as a function of Reynolds number for each of the four axial positions in the test assembly, as shown for a typical case in Fig. 3.

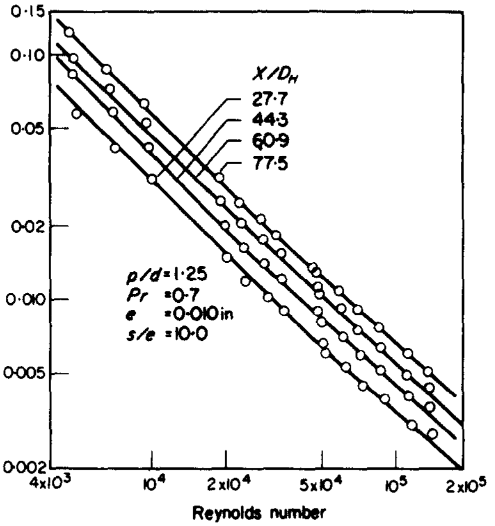

FIG. 3. Wall temperature measurements for a uniformly heated parallel rod array with boundary-layer turbulence promoters.

Measurements were made for one rod in the array heated alone, six rods in a ring heated, and again for uniformly heating the array. The results from these three heating conditions are plotted as a function of length for a given Reynolds number, as shown in Fig. 4, and the best value is determined over the length. The superposition of solution technique, which is described in Appendix 2, is then used to combine the data obtained from these three heating conditions. The Nusselt number results presented are therefore a composite of wall temperature measurements made at four positions in the rod array, under each of the three different heating conditions, and over the extended Reynolds number range.

Nusselt number as a function of Reynolds number has been determined in this way for each of the turbulence promoter parameters investigated. The effect of promoter height for boundary-layer turbulence promoters having

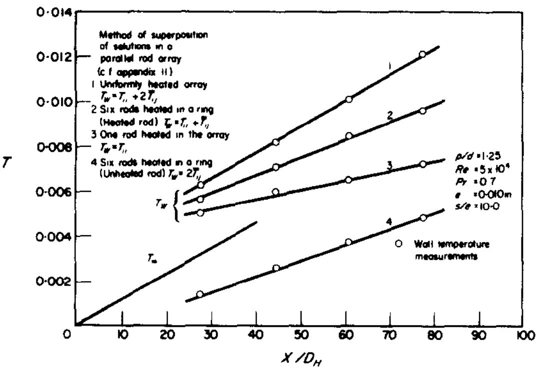

FIG. 4. Wall temperature measurements for a parallel rod array under different heating conditions.

the same relative spacing (i.e. $s/e = 10{\cdot}0$), is shown in Fig. 5. As one would expect, the largest promoters (i.e. those with the greater relative roughness parameter) penetrate through the laminar sublayer and, thereby, increase the heat-transfer coefficient at a lower Reynolds number. The increase in heat transfer is seen to rise as the turbulence promoters penetrate further into the buffer layer, and then remain relatively constant when the surface exhibits "fully rough" characteristics. This is because further penetration into the turbulent core by the turbulence promoters does not appreciably affect the flow characteristics at the heated surface (cf. [8]). These characteristics can also be seen in the results of other investigators (e.g. [3, 4]).

The effect of turbulence promoter spacing along the heated surface has been investigated with 0·010-in-high promoters spaced at s/e = 7·15, 10·0 and 14·82. Typical of the results found are the wall temperature measurements at the first axial position in the test section which are shown in Fig. 6(a) and 6(b). From this investigation there does not appear to be a significant

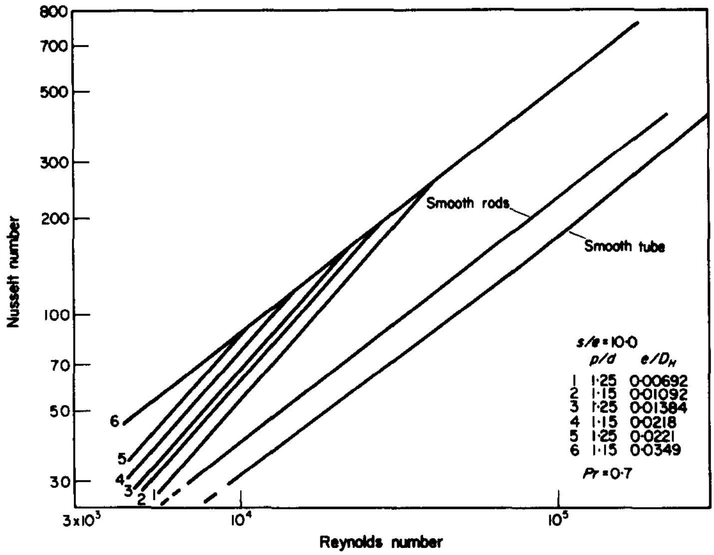

FIG. 5. Heat-transfer performance of turbulence promoters with various relative roughnesses.

effect on heat-transfer performance within this range of promoter spacing.

Fundamental solutions have been measured for each of the six relative roughnesses tested, and a general correlation developed for application to the asymmetric heating problem as described in Appendix 2. For the case of smooth rods, spaced in the range of $p/d = 1{\cdot}15$–$1{\cdot}25$, the general correlation developed in [10] is

Friction factor results

The pressure gradient is determined by static pressure measurements made every 6 in along the 60-in test section length. The friction factor is then calculated from

$$f = \left(\frac{\Delta P}{\Delta x}\right)\frac{D_H}{4}\frac{2g_c}{\rho V^2} \tag{4}$$

The results of varying the relative roughness,

$$\left.\begin{aligned} T_{ii} &= 53{\cdot}9\, Re^{-0{\cdot}810} + 1{\cdot}151\, Re^{-0{\cdot}922}\left(\frac{x}{D_H}\right) \\ \bar{T}_{ij} &= 2{\cdot}99\, Re^{-1{\cdot}063}\left(\frac{x}{D_H} - 17\right) \end{aligned}\right\}\ \text{smooth rods.} \tag{2}$$

For parallel rods with turbulence promoters, the general correlation developed from this investigation is

$$\left.\begin{aligned} T_{ii} &= 25{\cdot}5\, Re^{-0{\cdot}810} + 1{\cdot}660\, Re^{-0{\cdot}975}\left(\frac{x}{D_H}\right) \\ \bar{T}_{ij} &= 2{\cdot}16\, Re^{-1{\cdot}019}\left(\frac{x}{D_H} - 10\right) \end{aligned}\right\}\ \text{fully rough rods.} \tag{3}$$

For the transition between smooth surfaces and fully rough surfaces, the first term in equation (5) is a function of relative roughness, i.e.

$$25{\cdot}5\, Re^{-0{\cdot}810} \leqslant 121\left(\frac{e}{D_H}\right)^{-0{\cdot}307} Re^{-1{\cdot}097} \leqslant 53{\cdot}9\, Re^{-0{\cdot}810} \quad \text{transition.} \tag{3a}$$

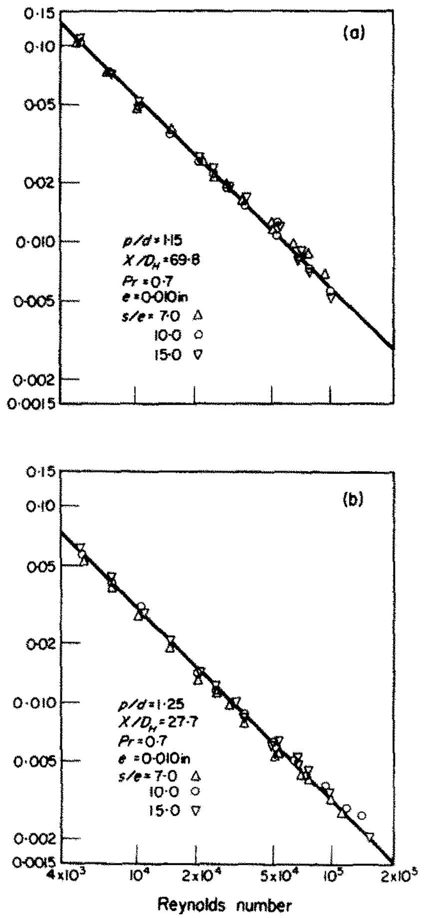

FIG. 6. Influence of turbulence promoter spacing on heat-transfer performance.

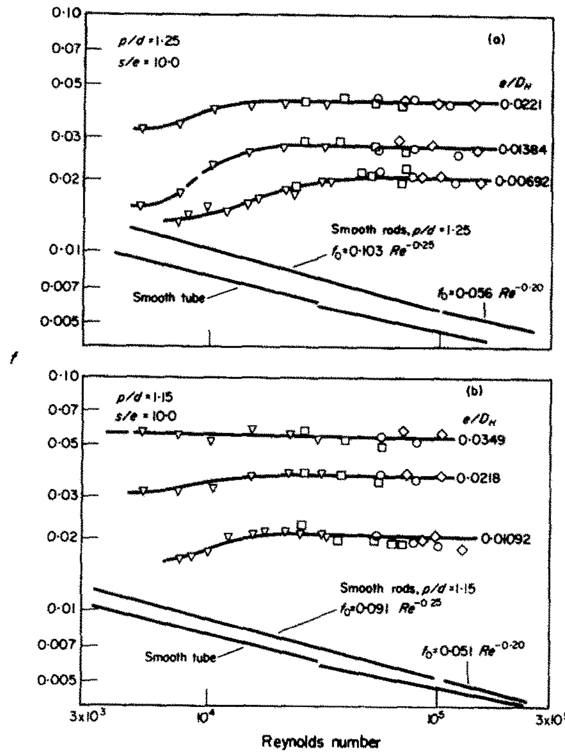

FIG. 7. Flow friction of turbulence promoters with various relative roughnesses.

e/D_H from 0·00692 to 0·0349, at a constant relative spacing $s/e = 10{\cdot}0$ is shown in Fig. 7. To avoid interference between closely spaced curves, the data are shown separately for the rod spacing $p/d = 1{\cdot}25$ and the rod spacing $p/d = 1{\cdot}15$. It should be noted that the smooth rod friction factors are different for these two rod spacings. The influence of varying promoter relative spacing s/e from 71·5 to 14·82 is shown in Fig. 8. The "fully rough" friction characteristics are independent of Reynolds number because the mechanism has changed from viscous shear to form drag, and whereas further penetration by the turbulence promoters into the turbulent core does not increase the heat transfer, it does increase the form drag.

Performance of boundary-layer turbulence promoters

The influence that boundary-layer turbulence promoters will have on the heat-transfer and flow-friction characteristics in a flow passage will depend on the penetration of the promoters into the flow. Since the penetration is relative, depending on the Reynolds number as well as the promoter height, it is reasonable to correlate to results on the basis of a nondimensional height. For this purpose, the nondimensional height is defined as

$$e^+ = \frac{e\sqrt{(g_c\,\tau_o/\rho)}}{\nu} \tag{5}$$

where $\sqrt{(g_c\,\tau_o/\rho)}$ is the shear velocity grouping

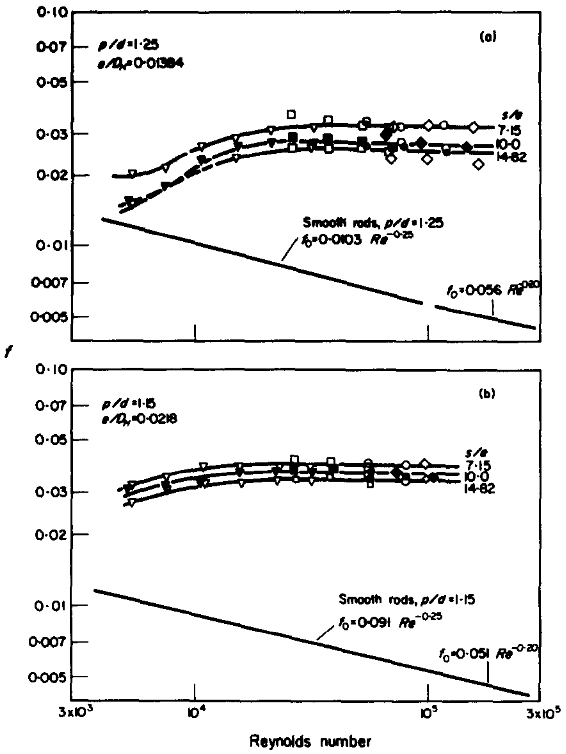

FIG. 8. Flow friction of turbulence promoters with various relative spacings.

frequently used in boundary-layer studies. From the definition of friction factor cf. equation (4), equation (5) reduces to

$$e^{+} = \frac{e}{D_H} Re \sqrt{\frac{f}{2}}\,. \tag{5a}$$

The relative improvement of heat-transfer performance can be determined directly from the measured wall temperature in the uniformly heated array. As shown in Appendix 2 the ratio of heat-transfer coefficients becomes

$$\frac{Nu}{Nu_o} = \frac{T_{wo} - T_m}{T_w - T_m} = \frac{\dfrac{T_{wo}}{T_m} - 1}{\dfrac{T_w}{T_m} - 1}. \tag{6}$$

The wall temperature data at a series of Reynolds numbers for each of the six different relative roughnesses have been evaluated in this manner at the first axial position. The result is a general correlation for all the roughnesses, as shown in Fig. 9(a). The maximum increase by a factor of 2·23 in heat-transfer coefficient corresponds with that shown in Fig. 5 for Nusselt numbers determined by a somewhat different method.

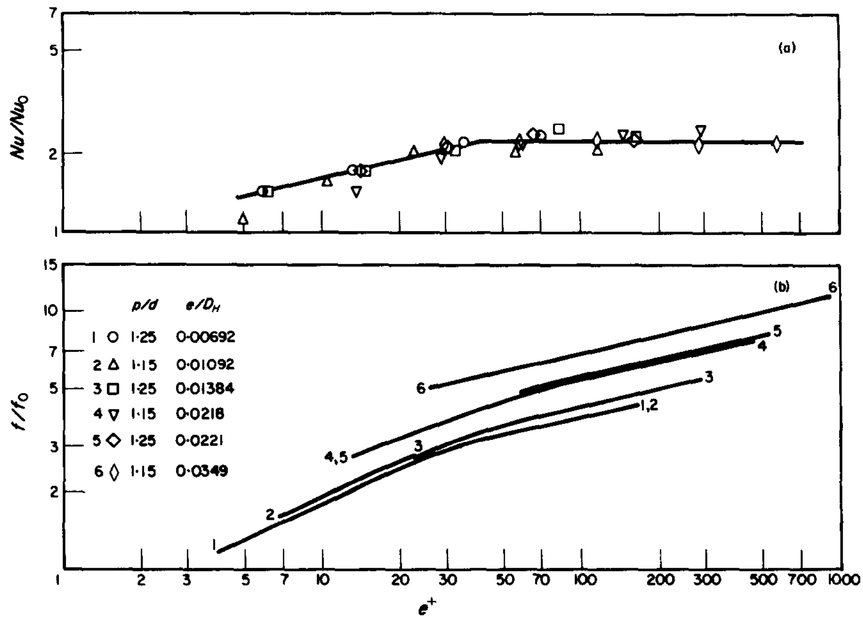

FIG. 9. Performance of turbulence promoters—$s/e = 10{\cdot}0$.

Results of two other investigations are shown for comparison in Fig. 10. Sheriff and Gumley [4] investigated promoter heights from 0·002 to 0·040 in spaced $s/e = 10$, in an annular test section. Their untransformed data fell within about 5 per cent of the curve shown in Fig. 10, which is in good agreement with the results of this investigation. Wilkie's [4] tests were also conducted in an annular test section, but his results show a substantial relative roughness effect which was not apparent in either [4] or in this investigation.

CONCLUSIONS

In this report we have established the performance of boundary-layer turbulence promoters in parallel rod arrays. Discrete two-dimensional roughness elements have been investigated, and the heat-transfer and flow-friction performance has been determined for relative roughnesses and relative promoter spacings in the range of interest. The results are directly applicable to thermal performance prediction and optimization in rod bundles. It is found that the relative roughness of the turbulence promoters determines the Reynolds number at which the promoters become effective; but that once fully rough conditions have been established, the heat-transfer performance is the same for all promoter sizes. Further, the heat-transfer performance is not as sensitive to relative spacing of promoters as has previously been supposed.

Data evaluation on the basis of boundary-layer penetration has advantages as a means for comparing the relative increase in Nusselt number and friction factor for various turbulence promoter parameters and the dimensionless promoter height e^+ is seen to be a very useful parameter for this purpose. The maximum improvement in heat-transfer performance is found to occur for promoter height $e^+ \geqslant 40$, which suggests that the increased heat transfer is due to tripping the laminar and buffer layers.

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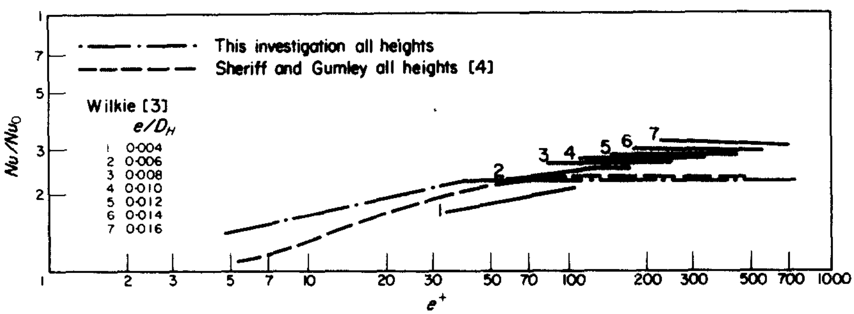

FIG. 10. Heat-transfer performance of turbulence promoters—$s/e = 10{\cdot}0$.

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APPENDIX

1. *Experimental Apparatus*

This investigation was made with air flow past electrically heated rods. The air is circulated by a lobe-type blower with a capacity of 350 ft^3/min at 6 psi differential. Heat exchangers are provided to control the inlet temperature to the test section, and a flow tube is used to meter the flow rate. To extend the Reynolds number range the fluid density is increased by operating the system as a closed loop at pressures up to 100 psig. Power to the test section is supplied by a 50 kVA step-down transformer and is metered by a calibrated voltmeter and ammeter.

Test sections are assembled from 1-in dia. rods, 60-in long. The triangularly pitched arrays, with center spacing to diameter ratio $p/d = 1{\cdot}15$ and 1·25, consist of a seven-rod cluster surrounded by the next ring of partial rods to simulate an infinite array (cf. Fig. 2). Rod spacing is maintained by small stand-off spacers every 20 in along the length which have been shown [10] to cause a negligible disturbance to the flow. All rods, including those in the outer ring, have turbulence promoters, as shown in Fig. 1, which are applied by winding a fine wire around the rod. The heat flux is determined on the basis of the surface area of a rod without promoters, and any increased heat transfer due to a fin effect is lumped into the overall promoter performance. The rods consist of a laminated phenolic resin core supporting a 0·002-in thick stainless steel sheath. The rods are heated by electric resistance heating in the sheath. Heat generation in the promoters is negligible since the wire resistance is more than 500 times that of the sheath. The wall temperatures are measured by thermocouples on the inner surface of the sheath. (The temperature drop through the wall is less than 0·1 degF.) The pressure gradient is measured by static taps located every 6 in along the length.

2. *Experimental Procedure*

Local heat-transfer coefficient cannot be determined directly in any experimental investigation of internal flow because it is not possible to measure the mean fluid temperature along the length. The usual procedure is to calculate this temperature from heat input data. However, since fundamental solutions do not require knowledge of the local mean fluid temperature, they can be determined directly, with a corresponding reduction in experimental uncertainty.

Superposition of fundamental solutions has been developed in [10] as a method to handle the variety of heat-transfer boundary conditions which may be applied in a parallel rod array. We have made use of this technique here to obtain two independent checks of the basic heat-transfer measurement. By heating one rod in the array, we determine the fundamental solution

$$T_w = T_{ij} = \frac{t_i - t_{in}}{q_j'' D_H/k}. \qquad \text{(A-1)}$$

where the index "i" indicates the rod of interest, and the index "j" indicates the rod being heated. The rod temperature on a wall due to arbitrarily heating in the array then becomes

$$t_i - t_{in} = \frac{D_H}{k}[q_1'' T_{ii} + q_2'' \overline{T}_{ij} + q_3'' \overline{T}_{ij}]. \qquad \text{(A-2)}$$

where $\overline{T}_{ij}$ indicates the average temperature around the 60° segment of the circumference facing the rods of interest. A superposition of fundamental solutions is established by equally heating six rods in a ring. The nondimensional wall temperatures on the heated rods will then be

$$T_w = T_{ii} + \overline{T}_{ij}. \qquad \text{(A-3)}$$

and the nondimensional wall temperature in the unheated rod in the center of the ring will be

$$T_w = 2\bar{T}_{ij}. \quad \text{(A-4)}$$

Finally, when all rods in the array are uniformly heated, the wall temperature will be the superposed solution

$$T_w = T_{ii} + 2\bar{T}_{ij}. \quad \text{(A-5)}$$

The data from each of these three types of runs are correlated as a function of Reynolds number, and the results plotted as a function of length. An example from a typical set of data is shown in Fig. 4.

The mean fluid temperature is normalized in the same manner as the wall temperature

$$T_m = \frac{t_m - t_{in}}{q'' D_H/k}, \quad \text{(A-6a)}$$

which for a uniformly heated array with no heat loss* reduces to

$$T_m = \frac{4}{Re\,Pr}\,\frac{x}{D_H}. \quad \text{(A-6b)}$$

The Nusselt number in a uniformly heated array is then evaluated by

$$Nu = \frac{1}{T_w - T_m}. \quad \text{(A-7)}$$

3. *Experimental Uncertainty*

The experimental uncertainty in the fundamental solution, the Nusselt number, and the Reynolds number have been estimated with the method described by Kline and McClintock [11]. From the estimated uncertainty in each measurement, the probable uncertainty in the calculated variables are as shown in Table A-1.

Table A-1. *Experimental uncertainty*

w	0·73–1·06 per cent
q	1·0 per cent
Nu	6·5–7·4 per cent
T	3·2–4·7 per cent
Re	2·4–5·8 per cent
Nu/Nu_o	10·0–13·3 per cent

* The fact that the wall temperature is observed to rise parallel to the calculated bulk temperature in the uniformly heated array (cf. Fig. 5) shows that the heat loss from the test apparatus is negligible.

Résumé—On a besoin d'une amélioration substantielle de la conductance de transport de chaleur par convection forcée pour le progrès de systèmes de réacteurs de puissance d'avant-garde refroidis par de la vapeur ou un gaz. Des déclencheurs de turbulence dans la couche limite placés sur les surfaces chauffées sont d'un grand intérêt pour ces systèmes à cause de l'augmentation importante des performances en transport de chaleur qui peut être obtenue.

Cependant, la plupart des données expérimentales sur les déclencheurs de turbulence a été obtenue dans des conduites annulaires, et il est nécessaire de transformer ces résultats afin de les appliquer à des configurations de réacteurs. Cette étude des performances des déclencheurs de turbulence dans la couche limite a été conduite sur des rangées de barreaux parallèles, configuration du plus grand intérêt pour des applications techniques. Des éléments bidimensionnels de rugosité discontinue, sous la forme de petites ailettes placées transversalement à l'écoulement, ont été étudiés expérimentalement pour établir l'effet de la hauteur des déclencheurs et de leur espacement. Les résultats sont directement applicables pour l'optimisation des performances de transport de chaleur et fournissent également une base pour évaluer les techniques de transformation employées pour les résultats obtenus dans les conduites annulaires.

Zusammenfassung—Eine wesentliche Verbesserung des Wärmeübergangs bei Zwangskonvektion ist erforderlich für die Entwicklung fortschrittlicher dampf- oder gasgekühlter Reaktorkraftanlagen. Grenzschichtturbulenz-Promotoren auf den beheizten Flächen sind für derartige Anlagen von grösstem Interesse wegen der dadurch erreichbaren Grössenzunahme des Wärmeübergangs. Viele der experimentellen Werte für Turbulenz-Promotoren wurden in Ringkanälen erhalten und es ist deshalb erforderlich, diese Werte für die Anwendung in Reaktoranordnungen zu transformieren. Diese Untersuchung von Grenzschichtturbulenz-Promotoren wurde in Anordnungen von parallelen Stäben durchgeführt, die von grossem Interesse bei ingenieurmässigen Anwendungen sind. Unstetige zweidimensionale Rauhigkeitselemente in

Form kleiner Rippen quer zur Strömung wurden experimentell untersucht, um den Einfluss von Promotorhöhe und Promotorabstand festzustellen. Die Ergebnisse lassen sich direkt zur Optimierung des Wärmeübergangs anwenden und liefern auch eine Grundlage zur Ausübung von Transformationsverfahren für Werte, die an Ringräumen erhalten wurden.

Аннотация—Для создания усовершенствованных энергетических реакторов с паровым и газовым охлаждением необходимо существенно интенсифицировать теплообмен при вынужденной конвекции. Для таких систем представляет большой итнерес турбулизаторы пограничного слоя на поверхности нагрева, что значительно повышает теплообмен. Однако, полученное большое количество экспериментальных данных для течений в кольцевых каналах требует специального анализа для применения к геометрии упомянутых типов реакторов. Данное исследование эффективности турбулизаторов пограничного слоя проведено в пучках параллельных стержней, т.к. именно эта конфигурация представляет наибольший интерес для практических целей. Для определения влияния высоты турбулизаторов и расстояния между ними проведено исследование дискретных двумерных элементов шероховатости в виде небольших ребер, расположенных поперек потока. Результаты исследования можно применить для оптимизации теплообмена, а также для создания на их основе метода преобразования данных, полученных в кольцевых каналах.