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A COMPARISON OF THE HEAT TRANSFER AND FRICTION FACTOR PERFORMANCE OF FOUR DIFFERENT TYPES OF ARTIFICIALLY ROUGHENED SURFACE

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Abstract—A comparison is made of the heat transfer and friction factor performance of four different types of artificially roughened surface. Each surface has near-optimum thermal performance for its own particular type of roughness. These roughened surfaces have been developed and tested as part of nuclear reactor research programmes with the object of improving the rate of heat removal from fuel pins in gas-cooled reactors. The empirical data are taken from single pin tests using gaseous coolants. The comparison of thermal performance is made on the basis of transformed data, with some extrapolation using roughness parameter techniques. A discussion is included on other factors which may be important in the selection of an artificially roughened surface for practical use.

NOMENCLATURE

d_{pin}, pin diameter;
de, equivalent diameter;
e, g, 3-dim. surface parameters, Fig. 1(d);
f, friction factor;
h, roughness height;
h^+, roughness Reynolds number, $(h/de_1)Re_1(f_1/2)^{1/2}$;
p, roughness pitch;
w, roughness width;
Bi, Biot number;
Pr, Prandtl number;
Re, Reynolds number;
St, Stanton number;
St_∞, Stanton number for $Bi = 0$;
T_b, bulk gas temperature;
T_w, wall temperature.

Subscripts
1, refers to transformed values for inner roughened flow zone;
S, smooth;
R, rough;
A, square transverse ribbed surface;
B, helically ribbed surface;
C, trapezoidal transverse ribbed surface;
D, 3-dim. surface.

1. INTRODUCTION

Artificially roughened surfaces have been used to enhance the thermal performance of fuel pins in gas-cooled nuclear reactors for many years. These roughened surfaces take the form of regularly spaced ribs or studs which act as turbulence promoters, breaking up the viscous sublayer near the roughened wall. Roughened surfaces increase the heat transfer performance but also have the disadvantage of increasing the friction factor and hence the required pumping power. For this reason a concept of thermal performance is introduced which takes into account both the enhanced heat transfer performance and the increased friction factor.

The purpose of this paper is to compare the performance characteristics of four different examples of this type of roughened surface. Two of these surfaces were developed as part of the U.K. Advanced Gas-cooled Reactor (AGR) research programme and two were developed as part of the Gas-Cooled Fast Reactor (GCFR) research programme.

The reactor fuel assemblies for both AGRs and GCFRs consist of clusters of fuel pins, though for reasons of convenience and economy much of the basic testing of roughened surfaces is achieved in single pin tests. In these tests a roughened pin is placed centrally in a smooth outer channel forming a concentric annular flow passage. In the region of interest the flow is fully developed and turbulent with Reynolds numbers up to 5×10^5. For heated tests, the central roughened pin is heated electrically but the outer surface is not heated directly. The empirical data from each of these tests are expressed in terms of friction factor, Stanton number and Reynolds number. The coolant property variation across the channel is taken into account using the wall-to-bulk gas temperature ratio.

These annulus data have to be 'transformed' to remove the effect of the outer smooth wall. The aim of the transformation analysis is to 'separate' the flow along the no shear surface and to calculate a friction factor, equivalent diameter and Reynolds number for the annular region bounded by the roughened wall and the no shear surface. The Stanton number is then transformed to give the value as if there were the same heat flux through the roughened wall but no heat flux through the no shear surface. These transformed values of friction factor and Stanton number can then be used more readily for predictions of cluster performance.

A number of different transformation methods have been suggested for analysing single pin experiments (e.g. ref. [1]) and it is not the purpose of this paper to dwell on this aspect of the subject. However, the uncertainty caused by the method of analysis will be assessed by using two methods which are based on different approaches; the first is based on a logarithmic velocity and temperature profile method [1, 2] and the second is based on an eddy diffusivity concept [3].

The surfaces chosen for this comparison are described in Fig. 1. They are each near the optimum

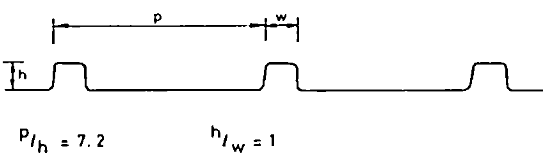

Fig. 1a. Square transverse ribbed surface.

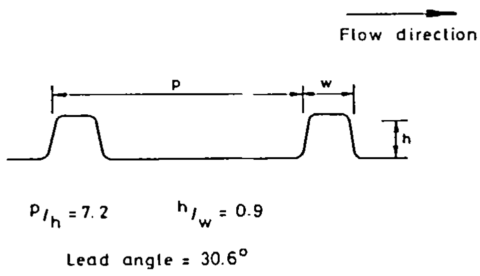

Fig. 1b. Helically ribbed surface.

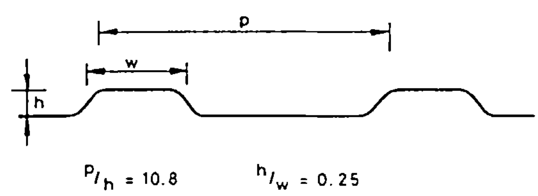

Fig. 1c. Trapezoidal transverse ribbed surface.

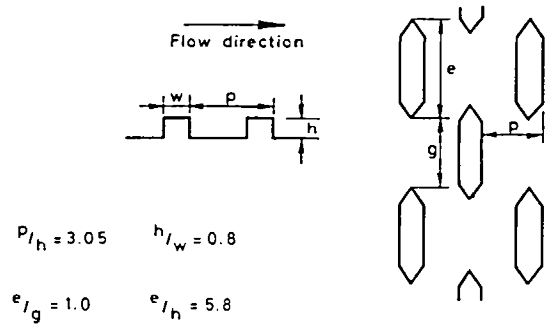

Fig. 1d. Three-dimensional surface roughness.

thermal performance for their particular type of surface roughness. The square transverse ribbed surface is similar to that used in AGRs for many years. Helically ribbed surfaces of a similar form to that shown in Fig. 1(b) are undergoing irradiation trials in AGRs but are not yet used on a large scale [4]. The trapezoidal ribbed surface is similar to the standard design proposed for the GCFR. The 3-dim. surface is a more recent development in the GCFR research programme [5, 6].

2. FRICTION FACTORS AND STANTON NUMBERS

The empirical data used in this comparison are:

(1) Square transverse ribbed surface data [7].
(2) Helically ribbed surface data [7].
(3) Trapezoidal transverse ribbed surface data [8].
(4) Three-dimensional surface data from surface 2 ref. [9].

All these data are taken from single pin tests using gaseous coolants. For the square transverse rib surface, the data are taken from four separate experiments using different pins with a nominally identical form of roughness, although with different scales of roughness geometry. For the remaining surfaces, the data are each taken from an experiment which used the same roughened pin throughout.

The data have been corrected to zero Biot number using the formulae recommended in the above reports. This correction makes allowance for the finite conductivity of the pin material. Biot number is defined here as

$$Bi = h \times \frac{\text{(heat transfer coefficient)}}{\text{(thermal conductivity of pin material)}}. \quad (1)$$

The recommended corrections take the form

$$E_\infty = 1 - \lambda Bi \quad (2)$$

where $\lambda = 0.79$ for square transverse ribs, $\lambda = 0.50$ for helical ribs and $\lambda = 0.4$ for the trapezoidal and 3-dim. surfaces. (Note that these corrections are specific to the particular surface geometries, wall thicknesses and method of heating.) In order to make the correction from the experimental Stanton numbers, defined using nominal outer wall temperatures, to Stanton number, St_∞, with $Bi = 0$,

$$St_\infty = St/E_\infty. \quad (3)$$

It should be noted that the data used in this paper have been interpreted using a volumetric definition of pin diameter, i.e. the roughness root diameter plus an allowance for the roughness as though the volume of the roughness were evenly spread over the pin surface.

All the annular channel data, noted above, have been analysed using both eddy diffusivity methods [3] and logarithmic profile methods [1, 2]. The output from both of these methods can be expressed in terms of roughness parameters which describe the flow characteristics near the roughened surface. A discussion on the usage of roughness parameters can be

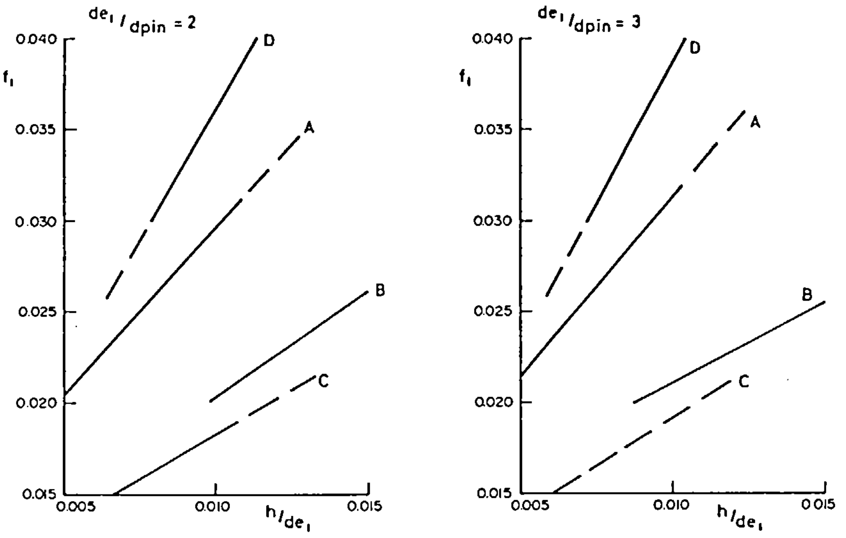

FIG. 2. Friction factor as a function of h/de_1 ($Re_1 = 2 \times 10^5$, $T_w/T_b = 1.2$).

found in ref. [10]. The roughness parameters derived from each of the two methods have been used as a basis for extending the range of the experimental data to the conditions of interest. (For completeness it should be noted that the non-dimensionalised mainstream eddy diffusivity variation for the 3-dim. surface data was taken to be $0.07 + 9.5h/de_1$ and that the logarithmic method used the variable slope option, where appropriate, together with the STT* transformation method of ref. [11].)

Figure 2 shows the variation of friction factor as a function of h/de_1 and de_1/d_{pin}. The curves shown in Fig. 2 are the best estimates obtained from the two different methods of analysis. The difference due to the method of analysis is less than $\pm 2\%$, with this decreasing near the centre of the range of parameters tested in the experiment. The dashed lines represent extrapolated values, where the level of uncertainty may exceed 2%. Figure 3 shows the Reynolds number dependence of the friction factors for the four surfaces.

The relative levels of the friction factor shown in Figs. 2 and 3 can be explained in the following way. The trapezoidal transverse ribs have a lower friction factor than the square transverse ribs because the rib height to width ratio is lower and there is more ribrounding. The helically ribbed surface has a lower friction factor than the transverse ribs because of the reduced 'angle of attack'. The 3-dim. surface has the highest friction factor because of the higher density of effective leading surface which can be obtained with alternate stud surfaces.

Figure 4 shows Stanton number as a function of h/de_1 and de_1/d_{pin} and Fig. 5 shows Stanton number as a function of Reynolds number for the four different surfaces. The relative levels of the four surfaces which were established for friction factor remain the same for the Stanton number plots also. In these graphs, the difference due to the method of analysis is less than $\pm 3\%$.

Figure 6 is a plot of the Stanton multiplier against the

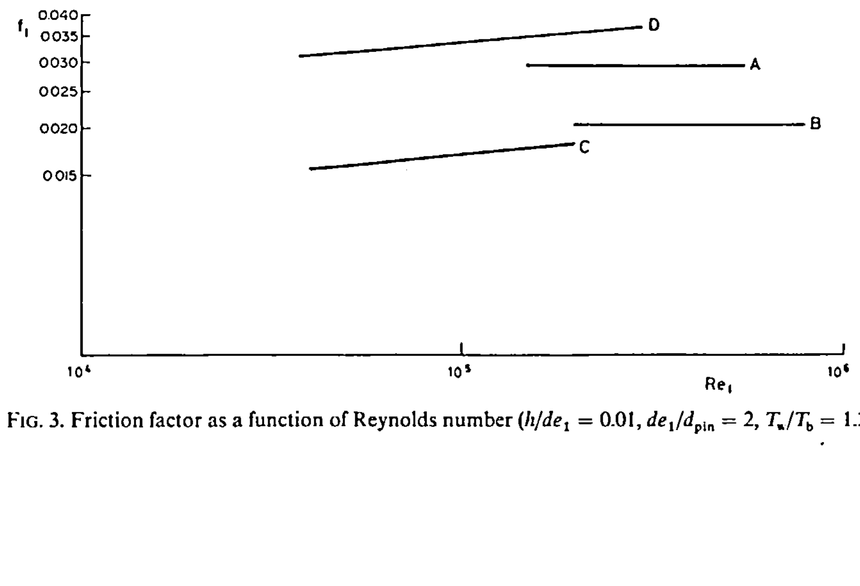

FIG. 3. Friction factor as a function of Reynolds number ($h/de_1 = 0.01$, $de_1/d_{pin} = 2$, $T_w/T_b = 1.2$).

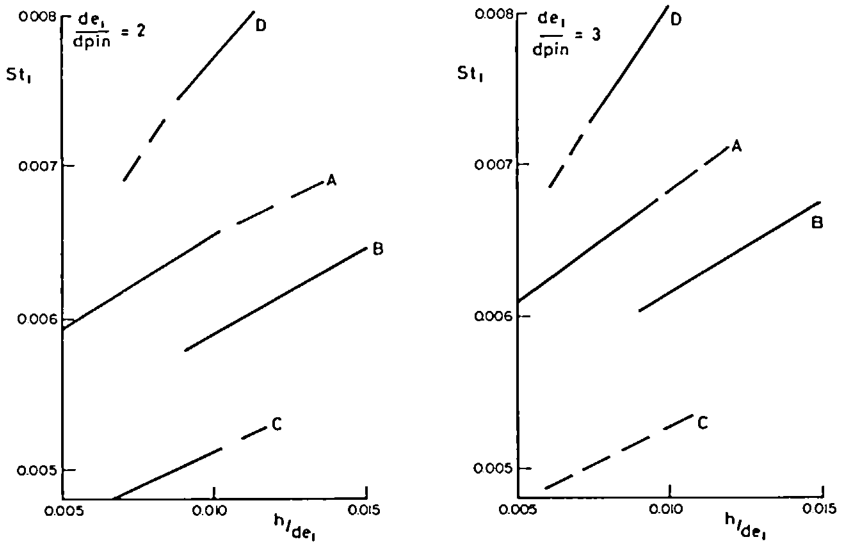

FIG. 4. Stanton number as a function of h/de_1 ($Re_1 = 2 \times 10^5$, $T_w/T_b = 1.2$, $Pr = 0.7$).

friction multiplier with smooth tube values of friction factor and Stanton number given by

$$f_S = 0.0014 + 0.125Re^{-0.32}$$
(Drew, Koo and McAdams),

$$St_S = 0.023Re^{-0.2}Pr^{-0.6}$$
(Dittus–Boelter).

The Stanton numbers shown in Figs. 4–6 are for a Prandtl number of 0.7. These values would decrease by $\sim 2\%$ if the value of the Prandtl number were increased to 0.74, for example.

The values of friction factor and Stanton number are calculated using $T_w/T_b = 1.2$. The T_w/T_b ratio is used to monitor the effect of coolant property variations in the flow. Changes in the T_w/T_b ratio can result in significant changes in both friction factor and Stanton number and these changes are functions of the gaseous coolant used and also of the type of surface. The tendency is for friction factor and Stanton number to decrease as T_w/T_b increases. Some details of this variation can be found in refs. [9–11].

It should be noted that extrapolation of these data in Figs. 2–6 to lower values of h^+, where the surface is not acting as fully roughened, is likely to lead to relatively large errors.

3. COMPARISON OF THERMAL PERFORMANCE

The enhanced heat transfer performances of artificially roughened surfaces are gained at the expense of increased friction factors, and therefore increased pumping power. The concept of thermal performance is introduced as a method of allowing for this increase in pumping power in assessing the performance [12–14]. Measures of thermal performance generally consider all aspects of the performance together, including the pitching of the rods in a cluster, parasitic pressure drop losses due to grids and braces, in addition to the surface

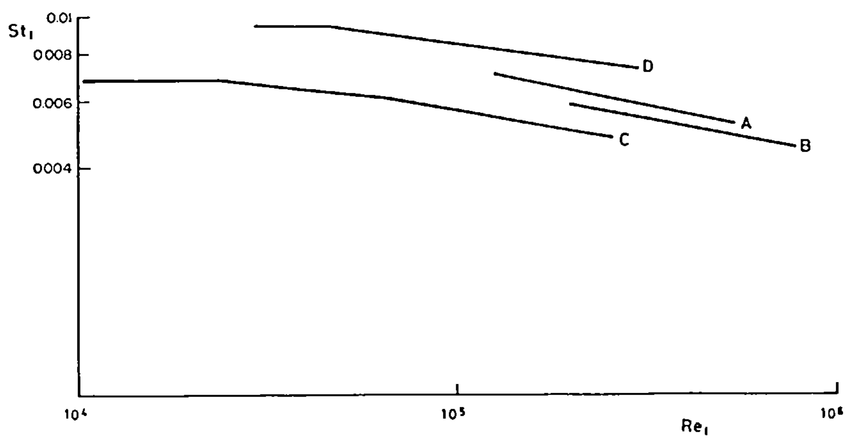

FIG. 5. Stanton number as a function of Reynolds number ($de_1/d_{pin} = 2$, $h/de_1 = 0.01$, $T_w/T_b = 1.2$, $Pr = 0.7$).

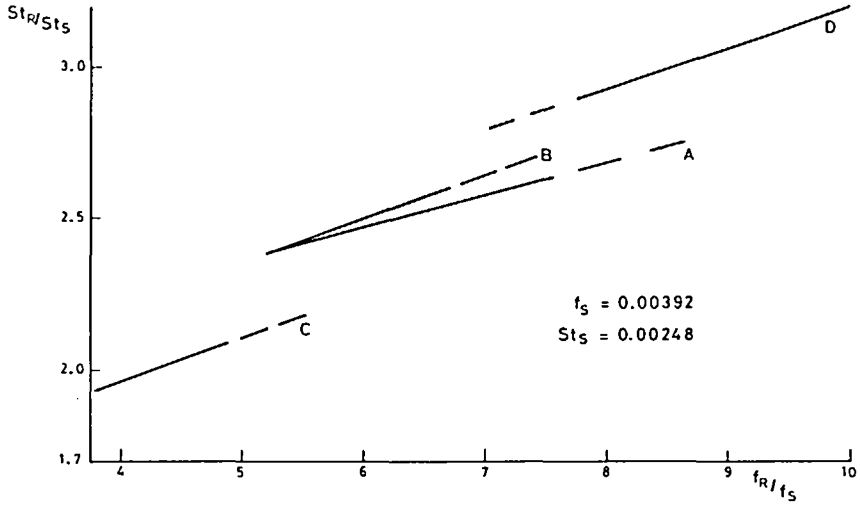

FIG. 6. Stanton vs friction factor multiplier ($Re_1 = 2 \times 10^5$, $de_1/d_{pin} = 2$, $T_w/T_b = 1.2$, $Pr = 0.7$).

roughening. In the present comparison, our attention is specifically on the relative merits of the surface roughness with everything else being equal. For this case it is sufficient to consider the relative heat transfer performance as a function of friction factor and Reynolds number. In this case the relative thermal performance, whether it is assessed as $St/f^{1/3}$ or $St/f^{1/4}$ [14], is identically equal to the relative heat transfer performance.

Figure 7 shows the relative thermal performances of the four different surface roughnesses under consideration. The comparison has been made against the square transverse ribbed surface for $Re_1 = 2 \times 10^5$ and 6×10^5. This comparison is insensitive to changes in de_1/d_{pin} and T_w/T_b in the ranges $2 \leqslant de_1/d_{pin} \leqslant 3$ and $1.0 < T_w/T_b \lesssim 1.5$.

The comparisons show that the performance of the trapezoidal transverse ribbed surface is substantially

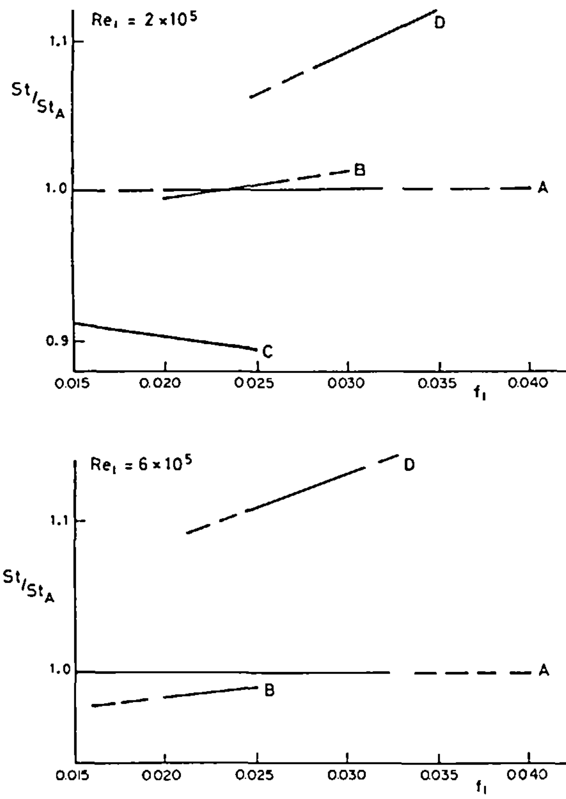

FIG. 7. Relative thermal performances ($2 \leqslant de_1/d_{pin} \leqslant 3$).

lower than all the other surfaces being considered for the given range of parameters. The square transverse ribbed surface and the helically ribbed surface have comparable levels of thermal performance. The 3-dim. surface shows a substantially improved thermal performance over the other surfaces particularly for higher values of h^+, i.e. higher friction factors and/or higher Reynolds numbers.

For completeness, we should note that comparing roughened surfaces with smooth surfaces gives the thermal performance ratio, $(St/f^{1/3})_R/(St/f^{1/3})_S$ which is ~ 1.36 for $Re_1 = 2 \times 10^5$ and ~ 1.29 for $Re_1 = 6 \times 10^5$, using the square transverse ribbed surface.

4. DISCUSSION

In the previous sections, attention has been concentrated on the averaged data obtained from single pin tests. It is also pertinent to consider the size of experimental uncertainties, the effect of modifying the surface geometry, the accuracy of using single pin data to predict cluster performance and additional effects of importance in the application of this work to use for fuel pins in commercial nuclear reactors. The intention of the following discussion is to give some perspective to the comparisons that have been made in the previous section.

For the purposes of the present work, the square transverse rib data have been used to estimate experimental uncertainties. These data are taken from a number of different experiments using a nominally similar roughness geometry. The standard deviation of the friction factor is 3.5% and that of the Stanton number is 2.8%. These should include both random uncertainties from within the experiments and systematic uncertainties between different experiments, although it is probable that the latter uncertainty will have been underestimated by the process of data selection for the present comparison.

The uncertainty due to the methods of analysis has been indicated above but it is worthwhile giving some more detail here. The discrepancy between the two methods in the centre of the parametric range used in the experiment is $\lesssim 2\%$ for friction factor and this increases to $\lesssim 4\%$ within the range shown by solid lines in Fig. 2. This discrepancy for Stanton numbers is $\lesssim 3\%$ in the centre of the parametric range used in the experiment and this increases to $\lesssim 6\%$ within the range shown by the solid lines in Fig. 4. The diffusivity method of analysis gives higher values of transformed Stanton number for the three ribbed surfaces but lower values for the 3-dim. surface. This has the important implication that the relative levels of thermal performance in Fig. 7 have a difference due to the method of analysis of less than $\pm 1\%$ for the three ribbed surfaces whereas the difference for the 3-dim. surface is $\pm 3.5\%$.

Changes in the surface geometry of the roughnesses have a direct effect on thermal performance. For example, a reduction of 25% in the rib height for the square ribbed surface (keeping all other parameters constant) would decrease the thermal performance $(St/f^{1/3})$ by $\sim 2\%$ (using data from ref. [10]). For 3-dim. surfaces this effect is more important, for example, a reduction of 25% in roughness height (keeping all other parameters constant) reduces the thermal performance by 12% ($10^5 \lesssim Re \lesssim 3 \times 10^5$) [2], though it should be noted that a full parametric study has not yet been undertaken for this type of surface.

The roughness geometry can also be affected by rounding of the ribs or studs. For practical purposes, this rounding affects the thermal performance by only a few percent in the case of ribbed surfaces; the effect for 3-dim. surfaces has not been examined. It is general practice to test the surface rounding which will be used rather than to attempt to make a correction for this effect.

Throughout this paper the surfaces used have been described as being near-optimum rather than actually being the optimum surface. It is acknowledged that small improvements, of the order of a few percent, could be gained by additional experiments though it has not been considered worthwhile to refine the optimisation of the roughened surfaces any further at this stage.

It has already been noted that a Biot correction has been made to allow for the finite conductivity of the cladding material in deriving the above Stanton numbers. Clearly, in applying the data, this correction must be performed in reverse to allow for the conductivity of the particular cladding material of interest.

In the analysis of the present data, no account has been taken of the expected increase in friction factor and Stanton number of a roughened flow zone for a rough surface facing a rough surface compared to those of a rough surface facing a smooth surface. In the former case there is no net interaction of the flow zones which results in an effective increase of the friction factor and Stanton number in the roughened flow zone compared to the rough/smooth case. This effect is difficult to quantify in practice but has been estimated to represent a 6% change in friction factor for the square transverse ribbed surface [15].

The results from single pin test are applied to cluster predictions using computer codes such as CLUHET [16], HELCAL [17], HOTSPOT [18], SAGAPO [19, 20], SCANDAL [21] and SCRIMP [22]. The size of uncertainty between computer predictions and cluster rig experiments is typically of the order of 5%.

In the case of helically ribbed pins there is a secondary flow induced by the ribs which has a greater effect in a cluster than in an axisymmetric single pin test. This is particularly important if the helical roughnesses are 'geared' to enhance the production of secondary flow. The enhanced secondary flow has been shown to cause an increase in thermal performance by up to 5% for the present helically ribbed surface [23].

It is interesting to note that a cluster test using a 3-dim. surface also showed an enhanced heat transfer performance compared with that predicted from single pin data [24]. In this case the enhancement was as high as 9% [25], although the reason for this difference is not fully apparent. There has not been a cluster test using the present 3-dim. surface which, in fact, has a thermal performance (from the single pin tests) which compares closely with the performance of the cluster test noted above.

In considering which roughened surface should be used for a particular application there are a number of factors which are not directly related to thermal performance. Since the present work is part of two nuclear reactor research programmes, we shall discuss some of the considerations relevant to these cases.

It is desirable to reduce the cross-cluster temperature gradient, within nuclear reactors, as much as possible. This helps to maximise reactor performance whilst not exceeding peak cladding temperature limits due to cladding corrosion rates. The mainstream diffusivity of heat is significantly higher for the 3-dim. surface than for transverse ribbed surfaces and this could have a beneficial effect in reducing cluster gradients. For helically ribbed surfaces, there is not only a substantially higher diffusivity level than for all the other surfaces (for a given friction factor) but of greater importance is the secondary flow created by the ribs which also serves to reduce cross-cluster temperature gradients.

In nuclear reactors there is a penalty on fuel performance due to the amount of material used in the cladding and spacers etc. within the cluster. The amount of material in the surface roughness forms a small but significant part in these calculations. This would be a point against the trapezoidal ribbed surfaces which have high density of surface roughness and require relatively high ribs (for a given friction factor).

Surface corrosion and deposition are both potential causes of impaired heat transfer performance. In both cases these effects would be expected to be larger in an AGR with a carbon dioxide coolant than in a helium cooled GCFR. Corrosion of the surface would tend to cause roughness rounding which has already been considered above. Deposition has the effect of decreasing the effective rib height and consequently changing the geometry of the surface roughness. The effect of deposition on the 3-dim. surface would be to reduce its performance markedly because of its sensitivity to changes in surface geometry. The effect on ribbed surfaces is less significant, particularly for the higher ribbed surfaces, i.e. the trapezoidal and helically ribbed surfaces which require ribs about twice the height of the other surfaces to give the same friction factor. The helically ribbed surface has the additional advantage that the inter-rib flow has a greater tendency to remove particulate deposits than is the case for flow over transverse ribs.

A more immediate consideration to the practical use of these roughened surfaces on a commercial scale is the cost of manufacture. The three ribbed surfaces should have comparable manufacturing costs but the present 3-dim. surface is considerably more expensive to produce, although it is conceivable that these costs could be reduced by developing the necessary technology.

The important point to emerge from the above discussion is that, although four different types of surface have been considered, only the trapezoidal ribbed surface can be excluded on grounds of relatively poor performance which cannot be countered by other advantages. The 3-dim. surface shows a generally improved thermal performance. However, this benefit must be weighed against the high manufacturing costs and the susceptibility to deposition. The square transverse ribbed surface and the helically ribbed surface have a comparable thermal performance, although the helically ribbed surfaces appears to have a number of additional advantages (see also ref. [4]).

Thus, although we are making a comparison of four different types of surface, there does not appear to be one surface which is clearly superior to the others and the final choice of which one to use in a particular application must be decided on a case by case basis.

5. CONCLUSIONS

A comparison has been made of the heat transfer and friction factor performance of four different types of artificially roughened surface. Each surface has near-optimum thermal performance for its own particular type of roughness.

(1) There is no advantage in using a transverse trapezoidal roughness. If a roughness is required with a low friction factor but without a reduction in rib height then it is recommended that the best alternative is a helically ribbed surface, possibly with a higher lead angle than the one described here. If the friction factor and rib height are not constrained then any of the other surfaces would perform significantly better than the trapezoidal surface.

(2) The best overall thermal performance is given by the 3-dim. surface, which shows an improvement of over 15% compared with the trapezoidal transverse ribbed surface. The improvement of the 3-dim. compared to the other two ribbed surfaces is $\gtrsim 8\%$, increasing with Reynolds number. This improvement could be even larger for clusters than for single pin tests. The 3-dim. surface has the important disadvantage that the thermal performance is more sensitive to changes in the surface geometry. This implies that a tight specification is required, with the resulting higher manufacturing costs. Further, any deposition or corrosion will tend to have a relatively large effect in reducing thermal performance, although these are more likely to be important factors with cooling by carbon dioxide than cooling by helium.

(3) The square transverse ribbed surface has an overall performance which compares well with the other surfaces considered.

(4) The helically ribbed surface has a thermal performance which compares closely with the square transverse ribbed surface. The relatively high radial

diffusivity levels and the presence of a strong secondary flow induced by the helical ribs all serve to give this surface some advantage over the square transverse ribbed surface in practical applications.

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UNE COMPARAISON DU TRANSFERT THERMIQUE ET DU FROTTEMENT POUR QUATRE TYPES DIFFERENTS DE SURFACE ARTIFICIELLEMENT RUGUEUSE

Résumé—On compare les performances de transfert thermique et de frottement pour quatre types différents de surface artificiellement rugueuse. Chaque surface a une performance thermique proche de l'optimum pour son type particulier de rugosité. Ces surfaces rugueuses sont réalisées et testées dans un programme de recherche relatif au réacteur nucléaire pour évaluer le flux de chaleur quittant les aigulles combustibles dans des réacteurs à gaz. Les données empiriques sont relatives à une aiguille unique et des réfrigérants gazeux. La comparaison des performances thermiques est faite sur la base de données transformées, avec une extrapolation utilisant les techniques du paramètre de rugosité. Une discussion est faite sur d'autres facteurs qui peuvent être importants dans la sélection d'une surface artificiellement rugueuse pour utilisation pratique.

EIN VERGLEICH DER WÄRMEÜBERTRAGUNGS UND REIBUNGSEIGENSCHAFTEN VON VIER VERSCHIEDENEN ARTEN KÜNSTLICH AUFGERAUHTER OBERFLÄCHEN

Zusammenfassung—Vier verschiedene Arten von Künstlich aufgerauhten Oberflächen werden in Bezug auf ihre Wärmeübertragungs—und Reibungseigenschaften verglichen. Jede der vier Rauhigkeiten liegt in ihrer Klasse in der Nähe des Optimums an Wärmeuebertragungsfähigkeit. Diese rauhen Oberflächen wurden unter verschiedenen Forschungsprogrammen entwickelt und experimentell untersucht mit dem Ziel, die Wärmeuebertragungsrate von Brennelementstäben in gasgekülten Reaktoren zu erhöhen. Die experimentellen Daten wurden in Einzelstabmessungen mit gasförmigen Kühlmittel gewonnen. Der Vergleich der Wärmeuebertragungsfähigkeit wird auf der Basis von transformierten Daten durchgeführt, wobei die Methode der Rauhigkeitsparameter zur Extrapolation verwendet wird. Der Beitrag enthält auch eine Diskussion über andere Faktoren, die bei der Auswahl einer künstlichen Rauhigkeit für die praktische Anwendung von Bedeutung sind.

СРАВНЕНИЕ ВЕЛИЧИНЫ ТЕПЛОВОГО ПОТОКА И КОЭФФИЦИЕНТА ТРЕНИЯ ПОВЕРХНОСТЕЙ ДЛЯ ЧЕТЫРЕХ РАЗЛИЧНЫХ ВИДОВ ИСКУССТВЕННО НАНЕСЕННОЙ ШЕРОХОВАТОСТИ

Аннотация — Проведено сравнение величины теплового потока и коэффициента трения поверхностей с четырьмя различными видами искусственно нанесенной шероховатости. Для данного вида шероховатости каждая поверхность характеризовалась почти оптимальным тепловым режимом. Такие поверхности были созданы и испытывались в соответствии с программой исследования ядерных реакторов, разработанной с целью улучшения интенсивности отвода тепла от топливных стержней в газоохлаждаемых реакторах. Использовались экспериментальные данные, полученные в опытах с единичными стержнями при охлаждении их газовыми теплоносителями. Для сравнения тепловых режимов проводилось преобразование данных с некоторой экстраполяцией по параметру шероховатости. Рассмотрены также другие факторы, которые могут играть существенную роль при выборе поверхности с искусственной шероховатостью для практического использования.