Int. J. Heat Mass Transfer. Vol. 11, p. 1573. Pergamon Press 1968. Printed in Great Britain

LETTERS TO THE EDITORS

IMPROVED HEAT-TRANSFER PERFORMANCE WITH BOUNDARY-LAYER TURBULENCE PROMOTERS

In this paper [1] are presented the results of a series of experiments on roughened rod cluster performance. The tests have obviously been very carefully carried out, and provide useful data on the performance of that type of surface. However we feel that the statement that "Wilkie's results show a substantial relative roughness effect which was not apparent in either Sheriff and Gumley or in Sutherland's investigation" needs further elaboration. For instance, we would ask whether Wilkie's results are directly comparable with the other two bearing in mind that the former were carried out on integral square ribs, whereas the latter were both done on wire wound surfaces. It seems to us that a wire-wound surface can be correctly referred to as a turbulent promoter, since the uncertain contact of the wire with the rod would make any direct contribution of the roughness to the rod performance unlikely. But this is certainly not the case with integral ribs where not only is there a significant change in surface area over the range of surfaces tested by Wilkie (143–251 in^2/ft) but there is also a relatively high heat-transfer coefficient on top of the rib [2]. It appears to us therefore that the performance of an integrally ribbed surface can be influenced considerably by the shape and dimensions of the rib and in fact results of work which we are carrying out at the present time support this argument, although not perhaps to the extent indicated by Wilkie's results. Thus we suggest that it is most important to emphasise that Sutherland's conclusion "once fully rough conditions have been established, the heat-transfer performance is the same for all promoter sizes" has, in his paper, only been demonstrated for wire winding and does not apply to integral ribs.

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Int. J. Heat Mass Transfer. Vol. 11, pp. 1573–1575. Pergamon Press 1968. Printed in Great Britain

IMPROVED HEAT-TRANSFER PERFORMANCE WITH BOUNDARY-LAYER TURBULENCE PROMOTERS

The paper by Sutherland [1] is very relevant to our own heat-transfer investigations in connection with roughened rod cluster fuel elements for gas-cooled nuclear reactors, and we have studied it with interest but some difficulty. The difficulty perhaps arises from over-compression and a certain looseness of definition which leave a number of points obscure even after reference to an earlier paper by Sutherland and Kays [2]. For example:

(a) On p. 1590 it is stated that "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". Subject to reservations to be made later, the data given will handle a non-uniformly heated array, i.e. non-uniform *across* the array. They will also handle non-uniformity of heat flux in the *axial* direction provided the starting-point for heating is not in the hydrodynamic entry region. Superposition is also applicable to the hydrodynamic entry region provided experiments have been carried out to establish the basic solutions for a step-change in heat flux starting at various points in the hydrodynamic entry region. The overall experimental programme would of course be very much larger than that reported by Sutherland.

(b) When measurements were made for "uniformly heating the array" did that include the ring of partial rods?

(c) The discussion of the superposition technique in the Appendix is not easy to follow. The mixture of specific suffices 1, 2, 3 (undefined) and general ones i, j in equation (A.2) is confusing as is the statement below the equation that "$\bar{T}_{ij}$ indicates the average temperature around the 60° segment of the circumference facing the rods of interest".

(d) By promoter "spacing" (s) does the author mean the gap between neighbouring turns of wire or the reciprocal of the number of turns per unit length? If the latter, then the well-defined term "pitch" would have avoided ambiguity.

We now turn to a discussion of the two main topics of the paper, i.e. the superposition technique and the heat-transfer and friction characteristics of roughened passages.

SUPERPOSITION TECHNIQUE

With gas- and steam-cooled rod cluster fuel elements the coolant temperature rise over the length of the fuel channel and the clad-coolant temperature difference are quite large, and the maximum design clad temperature is usually not far below the permitted maximum for the material. Therefore a really accurate method is required for estimating the surface temperature distribution along and around the fuel rods for various power distributions across and along the fuel channel. The most common approach to this problem has been to develop experimentally-based calculation methods, by which estimates are made of the distribution of the channel coolant flow between the various cluster passages, of the coolant temperature rise in each passage, of the heat interchange between adjacent passages, and of local heat-transfer coefficients. A number of computer programmes with differences in detail, for example in the degree of subdivision of the flow area, have been written. The implication of Sutherland's paper is that superposition of experimentally determined fundamental solutions offers an alternative approach.

The data published by Sutherland apply at best to an infinite cluster. Finite clusters have an outermost coolant zone with a smooth, adiabatic outer boundary. Further tests would be needed to provide data for that coolant zone. Moreover, it is to be expected that over the length of a reactor coolant channel there will be a significant temperature change in the outermost zone owing to heat generation in the inner zones and vice versa, in other words it is unlikely that a central region of the cluster can be isolated and treated as part of an infinite array. It follows that the basic experiments to provide data for a superposition approach may have to be carried out on a particular fuel cluster configuration, with the usefulness of the data limited to the treatment of different power distributions in the same configuration. Even in that limited context the superposition technique would seem to involve a number of approximations which could lead to significant errors:

(a) It is assumed that the entire flow pattern is independent of the magnitude and distribution of the heat flux, i.e. that the coolant physical properties are constant. However even the basic experiments cannot avoid finite temperature differences and physical property changes. Incidentally the temperature differences employed by Sutherland are not quoted.

(b) There may be a significant difference in Biot number between the experiments and the application, affecting the redistribution of surface heat flux by conduction in the fuel pins. This aspect does not seem to have been considered.

For these reasons—the fact that the data in the paper is not by itself adequate for the analysis of any particular fuel cluster design, that the extension of the method to a particular design including the hydrodynamic entry region would involve a major experimental programme, that data for a particular design may be restricted to that design, and that superposition in practice involves substantial approximations—we do not feel that the superposition approach is a practical alternative to the experimentally based computer calculations that we have previously referred to.

We believe that the most useful part of Sutherland's paper is that related to the performance of roughened heat-transfer surfaces in the shapes of passage found in a rod cluster. As he has correctly pointed out a great deal of work has been done on the comparison of a variety of roughened surface forms in simple passage shapes, and on the treatment of mixed boundary conditions, but information on the effect of departures from simple passage shapes is still very limited.

HEAT-TRANSFER CHARACTERISTICS OF ROUGHENED CLUSTER PASSAGES

A number of investigations have been made to determine the temperature variation around closely-pitched rods in a cluster for the case of smooth surfaces, for example [3]. There are no comparable papers dealing with roughened surfaces. Since Sutherland employed a thin (0·002 in) stainless steel sheath on 1-in dia. rods, any tendency to circumferential temperature variations would presumably not be strongly damped by heat conduction. Does the fact that there is no mention of a circumferential temperature variation, i.e. the sixth harmonic for rods in triangular array, mean that such variations were insignificant even for the p/d of 1·15?

If the ring of partial rods was not heated how were the air mass velocity and temperature for the centre zone of the experimental array isolated to enable Nusselt numbers for that zone to be calculated? There would be some mass flow displacement to the outer zone consequent upon the reduced gas density in the centre zone. Also would it be justified to assume no heat interchange with the outer zone especially with helical ribs?

Sutherland drew the conclusion that in the range seven to fifteen the effect of promoter spacing (s/e) variation on heat transfer was not significant. This conclusion may have a restricted range of validity. At most it has been established for circular cross-section promoters, for rather large values of the promoter height (e/D_H), and, perhaps most important, for a particular method of applying the promoter in which the thermal contact between the wire and the tube must be poor.

In a practical case the rib is likely to be integral with, or well bonded to, the tube. Referring to the sketch, and taking a square-section rib rather than a circular one, the effective heat-transfer perimeter for a well-bonded rib is $(s + 2e)$, for an un-bonded rib $(s - e)$.

s/e	$\frac{s - e}{s + 2e} = \frac{s/e - 1}{s/e + 2}$
7	0·67
10	0·75
15	0·82

Although this is only a very approximate calculation it illustrates the obvious fact that heat transfer must be most affected by a poor bond for small s/e, particularly if one were to allow for the fact that heat-transfer coefficients over the rib itself are known to be large. This may be the main explanation of Sutherland's disagreement with the conclusion of our own work that an s/e of seven gives significantly better heat transfer than ten and fifteen.

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Int. J. Heat Mass Transfer. Vol. 11, pp. 1575–1576. Pergamon Press 1968. Printed in Great Britain

NOTE ON THE MEANING OF "HEAT"

(DISCUSSION OF A PAPER BY M. TRIBUS [1])

Tribus [1] raises the question of the proper definition of the concept "heat" and suggests that the usual definition as found in many textbooks of classical thermodynamics should be revised or generalized.

In classical thermodynamics, heat is defined as a special type of energy flux through the boundaries of "systems". Tribus distinguishes between the "C" system (as used in thermodynamics) as a region of space and the more general "Q" system, which includes: (a) the "C" system, (b) a subset of particles mixed with other particles, and (c) a subset of possible states of a "C" system. He argues that the limitation to "C" systems in thermodynamics is too restrictive. Now, type (b) is actually identical to type (a). It is only necessary to note that the region of space may be multiply connected or *unconnected*, e.g. the space including the particles of the subset but excluding other particles. The boundary of the system may be fixed or moving with respect to any spatial coordinates. In fact, in no book on thermodynamics, the restriction of simply connected or fixed space has been invoked in the definition of a system.

To illustrate his type (c), Tribus mentions two examples, namely the "relaxation" of the vibrational state and two-temperature plasma. Relaxation phenomena, namely the energy redistribution from one mode of motional state to another, are certainly not to be considered as heat transfer, in the sense used in this journal or as understood by any heat-transfer engineer. The transport phenomena of the two-temperature plasma refer to the transfer from the system ["C" or "Q", type (b)] of the plasma to another system, so that the legitimate usage of the term "heat" here is never contested.

Whether one chooses to consider certain energy flow phenomena as heat depends on the choice of the system boundary. Guggenheim [2] explained at pain how an electrical heater may or may not be considered as converting the kinetic energy of electrons into heat, and this is analogous to the "heating" of a ceramic moderator. Thus the energy flow between the molecules of H_2O and N_2 may or may not be considered as heat depending on the choice of the system ["Q" type (b)] boundary.

Tribus' last example is a paper by Gollnick [3] in which the "heat flux to the wall" is divided into a "conduction contribution and that due to thermal diffusion". This is also quite in order in the "thermodynamical" sense, provided the system boundary is taken at the wall.

The case of negative (absolute) temperatures is not in conflict with the classical definition. Once the system boundary is properly defined, the interaction of two systems at temperatures of opposite signs involves no principle distinction from the interaction of systems at temperatures of the