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Coherent Structures in the Gaps of Rod Bundles

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Abstract: *The work presented here is part of a research program at the University of Ottawa aimed at studying the detailed characteristics of turbulent flow and heat transfer near narrow gaps of rod bundles. An experimental investigation was conducted in a simplified system, comprising isothermal air flow in a rectangular channel with a height to width ratio of 2/3 and containing a cylindrical rod with its axis parallel to the channel axis and a diameter equal to half the channel height. The rod was suspended to form an adjustable narrow gap with the channel base. The flow Reynolds number, based on bulk velocity and hydraulic diameter, was 140,000. Previously reported measurements include the distributions of the wall shear stress, the mean velocity and the turbulent stresses, as well as the dependence of the spacing and the convective speed of the observed large-scale, quasi-periodic flow pulsations across the gap upon the gap size. These results are now complemented by conditionally sampled measurements of the phase-averaged characteristics of the coherent vortical structures that produce these flow pulsations and a tentative physical model of their typical shapes.*

1. Introduction

Rod bundles form the basic configuration for almost all fuel element designs used in existing and planned nuclear power reactors. Due to the geometric complexity of rod bundles, flows in their subchannels exhibit phenomena not encountered in circular pipe flows. A well known phenomenon in such configurations is that the local friction factor and the local convective heat transfer coefficient in narrow gaps between adjacent rods or a rod and the pressure tube wall maintain relatively large values for a wide range of gap sizes, and diminish appreciably only when the gap becomes extremely narrow. Conventional turbulence analyses, based on local transport concepts, have been grossly inadequate to predict the insensitivity of these parameters, while it is clear that the heat transfer and mixing across the gap occur at a scale much larger than the gap size. Among the various relevant explanations, the most successful one appears to be that cross-subchannel mixing is greatly enhanced by transport due to large-scale, quasi-periodic pulsations, which form across the gap. The existence of such flow pulsations in rod bundle flows was first detected by Rowe et al (1974), followed by several systematic studies by Hooper (1983), Hooper and Rehme (1984), Rehme (1987) and Wu and Trupp (1993), among others. Hooper and Rehme (1984) attributed these flow pulsations to a parallel-channel instability mechanism, while Möller (1991) modelled them by a street of vortices in the gap region. The formation of strong, large-scale, quasi-periodic structures has also been observed in other types of channels containing slot-like narrow regions connected to larger subchannels (Meyer and Rehme, 1994 and 1995). The only available analytical study aimed at predicting coherent structures in narrow gaps is a Large Eddy Simulation by Biemüller et al (1996), in a channel consisting of two rectangular sections connected by slot near the wall. This study was in qualitative agreement with an experiment and

predicted the formation of two counter-rotating vortices with centres on opposite sides of the gap plane of symmetry. Empirical attempts to incorporate the effects of large-scale pulsations in "lumped parameter" types of analyses of inter-subchannel mixing have been made by Rehme (1992), Möller (1992), Wu and Trupp (1994) and Kim and Park (1997).
The above studies have demonstrated beyond doubt the presence and importance of quasi-periodic flow structures in rod bundles, however, they have not yet adequately described the physical features of these structures. In particular, there has been no known attempt to exploit the sophisticated pattern recognition and phase averaging methods that have been applied successfully to the detection of coherent structures in other types of turbulent flows. The objectives of the present study were to fully characterize experimentally the coherent structures in narrow axial regions of compound channels and to develop a physical model that explains their apparent effects. Although motivation for this project was provided by the thermalhydraulic performance of nuclear reactor rod bundles, it was realized that additional phenomena occurring in a channel of excessive geometrical complexity, such as a rod bundle, might obscure the individual gap effects; instead, it was decided to utilize a prototype channel, which contains an adjustable, narrow, axial gap region but is otherwise "simple". The selected geometry consists of a rectangular channel containing a suspended circular rod with a diameter small enough, compared to the channel height and width, for the flow away from the gap region to be relatively free of gap effects. The results reported here are part of an experimental study of the detailed characteristics of turbulent flow near narrow gaps of rod bundles. The present paper focuses on the phase-averaged features of the coherent structures and the presentation of a relevant physical model. It is hoped that the present work will contribute to the understanding of these important flow phenomena and will facilitate the development of methods incorporating their effects in the prediction and design of rod bundles and other complex engineering systems.

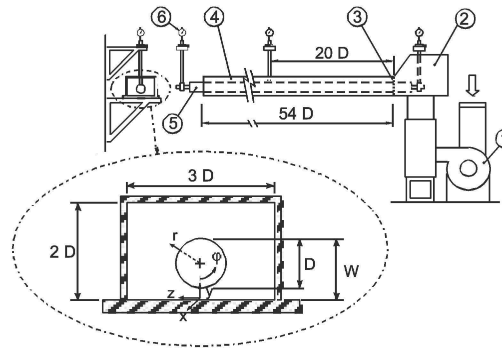

Figure 1. *Sketch of the flow facility; (1): fan, (2): pressure box, (3): screen, (4): test section, (5): rod, and (6): micrometers and rod supports.*

2. Experimental Set-Up and Procedures

A sketch of the experimental facility is shown in Figure 1. The test section consists of a rectangular channel with an aspect ratio of 2/3, containing a suspended, traversable aluminum pipe ("rod") with a diameter of $D = 101$ mm. The rod was positioned so that it would form an adjustable gap with the channel base. The hydraulic diameter and the length of the test section were, respectively, $1.59D$ and $54.0D$. The channel was supplied with air produced by a blower. The detection of coherent structures was made by a triggering hot-wire probe, which was of the cross-wire type and was placed at the centre of the gap, approximately $3D$ upstream of the main hot-wire probe, which had three-sensors and was placed near the exit of the channel. The triggering probe was mainly used to measure the spanwise velocity variation, while the main probe was used to measure simultaneously all three velocity components.
The conditional sampling technique employed in this work is based on the Variable Interval Time Averaging (VITA) technique of Blackwelder and Kaplan (1976). In this technique, the variable-interval time average of a quantity Q is defined as

$$\hat{Q}(x_i,t,T)=\frac{1}{T}\int_{t-T/2}^{t+T/2}Q(x_i,s)\,ds \tag{1}$$

where T is the averaging time interval, which is of the order of the time scale of the phenomenon under study. The conventional time-average of a stationary random variable is obtained as $T \rightarrow \infty$. A localized measure of the turbulent energy is the "localized variance", defined as

$$v\hat{a}r(x_i,t,T) = Q^2(x_i,t,T) - [\hat{Q}(x_i,t,T)]^2 \qquad \textbf{(2)}$$

In the present study, a detection of a coherent event was made when the localized variance of the spanwise velocity, W, in the gap exceeded a certain level, proportional to the mean square value, as

$$v\hat{a}r > k\overline{w^2} \ \ and\ \ \partial W/\partial t > 0 \qquad \textbf{(3)}$$

where k is an adjustable "threshold level"; the condition on the velocity time derivative was added to discriminate between flow accelerations and decelerations to ensure proper phase averaging. In order to phase-match all coherent events before averaging, a "detection time", t_j, corresponding to the same relative instance in the duration of a coherent event, must be defined. This was selected to be the midpoint of each time interval during which equation (3) was satisfied. Then, the conditional average at a particular instance τ during the coherent event j was defined as

$$<Q(x_i\ ,\tau)> = \frac{1}{N}\sum_{j=1}^{N} Q(x_i\ ,t_j{+}\tau) \qquad \textbf{(4)}$$

The optimal averaging time, T, was found to be approximately equal to half the period of the average pulsation, while the optimal threshold level was k = 0.7.

The above method detected individual structures producing signals varying not only in magnitude, but also in period and waveform. As a result, the computed ensemble averages had weak magnitudes and erroneously large periods, the values of which seemed to depend on the threshold level. This prompted the development of an iterative enhancement method, which utilized the above conditional sampling technique only to obtain a first estimate of the ensemble running average. In a second pass through the same data, this average was correlated with the signals of detected structures and the optimum time shift, corresponding to the time of the maximum correlation, was determined. Then, the same average was correlated with the optimally shifted signals, having their time-axis scaled by a factor α, and the optimum α, corresponding to the correlation with the highest maximum, was determined. Thus, the signals of all detected events were time-shifted and scaled optimally, with respect to the average event, to account for variations in phase and periods of the detected events. At the end of the second step, a new, "enhanced", ensemble average was obtained by scaling the previous average by the average scaling factor, α_a. The new average was used during a third pass through the same signals and the procedure was repeated until convergence of successive ensemble averages was achieved. In most cases, three passes were sufficient for convergence. The enhancement method reduced substantially the dependence of the results on the threshold value, thus improving the objectivity of the technique, as far as individual structures are concerned. On the other hand, the enhancement method also distorted the structures that preceded or followed the detected one, but not optimally. For this reason, reconstructed views of a sequence of structures were based on the classical VITA method and not the enhanced one.

Two different decompositions of the turbulent flow fields were used in the present analysis, depending on the information to be extracted. These are the "double decomposition" and the "triple decomposition". According to the double decomposition, the instantaneous value, Q, of a random process is decomposed into a coherent component and an incoherent component, respectively, as follows

$$Q(x_i\ ,t) = <Q(x_i\ ,t)> + q_r(x_i\ ,t) \qquad \textbf{(5)}$$

According to the triple decomposition, the instantaneous value is decomposed into a time-average component, a coherent component, and an incoherent component, respectively, as follows

$$Q(x_i,t) = \overline{Q}(x_i) + \tilde{Q}(x_i,t) + q_r(x_i,t) \qquad \textbf{(6)}$$

The time-average component is equal to the conventional Reynolds average; the incoherent components in the double and triple decompositions are identical; finally, the coherent component in the triple decomposition can be obtained from that in the double decomposition, as

$$\tilde{Q} = <Q> - \overline{Q} \qquad \textbf{(7)}$$

3. Measurements and Discussion

All measurements presented here were performed at a Reynolds number, based on the bulk velocity and hydraulic diameter, of 140,000 and a $W/D = 1.100$ (see Figure 1). The average convective speed of the structures was used to convert the time signals obtained with fixed probes into streamwise variations. Previous studies (Guellouz and Tavoularis, 1995) have demonstrated that coherent structures were convected downstream relatively unchanged. Samples of the coherent velocity components, according to the triple decomposition and obtained by the enhanced VITA technique using the same detection time, are shown in Figure 2. 110,000 structures were detected and scaled. The distribution of optimum α was nearly Gaussian, with the relatively small standard deviation of $0.28\alpha_a$, which shows that the structures were fairly repeatable. It can be seen that the spanwise coherent velocity component has its largest amplitude close to the centre of the gap, while the streamwise coherent velocity component has essentially the same amplitude up to 0.6 D from the channel centerline, but a shifting phase, relative to that of the spanwise component.

The coherent velocity field, in a frame moving with the average convection speed of the structures and reconstructed using the classical VITA method, is visualized in Figure 3, using software-generated pathlines (TECPLOT, Amtec Engineering Inc.). It can be seen that the structures are vortices with cross-sections elongated in the streamwise direction and encroaching well into the open subchannels, where they curve away from the plane wall. A cross-section of the above flow field at a height equal to half the gap width is shown in Figure 4. The pathlines clearly indicate the presence of a street of counter-rotating vortices, with axes alternating on either side of the gap. The streamwise spacing of the axes of the vortices, at this plane of observation, is about $2.1D$, while their spanwise spacing is roughly equal to D.

Representations of the flow field, such as those in Figures 3 and 4, though very useful in visualizing a complicated three-dimensional flow structure, cannot be relied upon to estimate the typical shape of the structures. The software generated pathlines present the same limitations as physical flow visualization using, for example, smoke injection: a reduction of the smoke streak amplitude does not necessarily indicate a decrease of the cross-sectional area of the vortices, as the same effect could be caused by a weakening of the vortex strength and/or the increasing local convection speed (Guellouz and Tavoularis, 1995). Similarly, Contours of the coherent velocity components are not helpful in identifying the coherent structure boundaries (Hussain, 1983). For these reasons, the discussion below will be based mostly on the coherent vorticity and coherent velocity traces.

The coherent vorticity field was estimated from the coherent velocity field, using polynomials fitted to typically five neighbouring points. Figure 5 shows contours of constant transverse (i.e. normal to the plane wall) vorticity, on a plane containing the midpoint of the gap and calculated according to the double decomposition. These contours confirm the presence of counter-rotating vortices with axes alternating on either side of the gap. The direction of rotation, as indicated by the sign of the vorticity in the y direction, is such that, at the vortex front, the structure would transport fluid from the high velocity region towards the lower velocity region, i.e. the gap.

4. Towards a Physical Model of the Coherent Structures

In an attempt to construct a physical model of the structures, we compared the traces of the coherent velocity components with velocity variations that would be produced by sequences of two-dimensional, counter-rotating, potential vortices with different cross-sectional shapes and different spatial configurations. The only vortex pattern that produced velocity traces qualitatively similar to those in the range $-0.6 \leq z/D \leq 0.6$ (Figure 2) is one in which the cross-section of the vortices was set to be very elongated, with an "ellipse-like" shape, and in which the vortices were arranged so that their

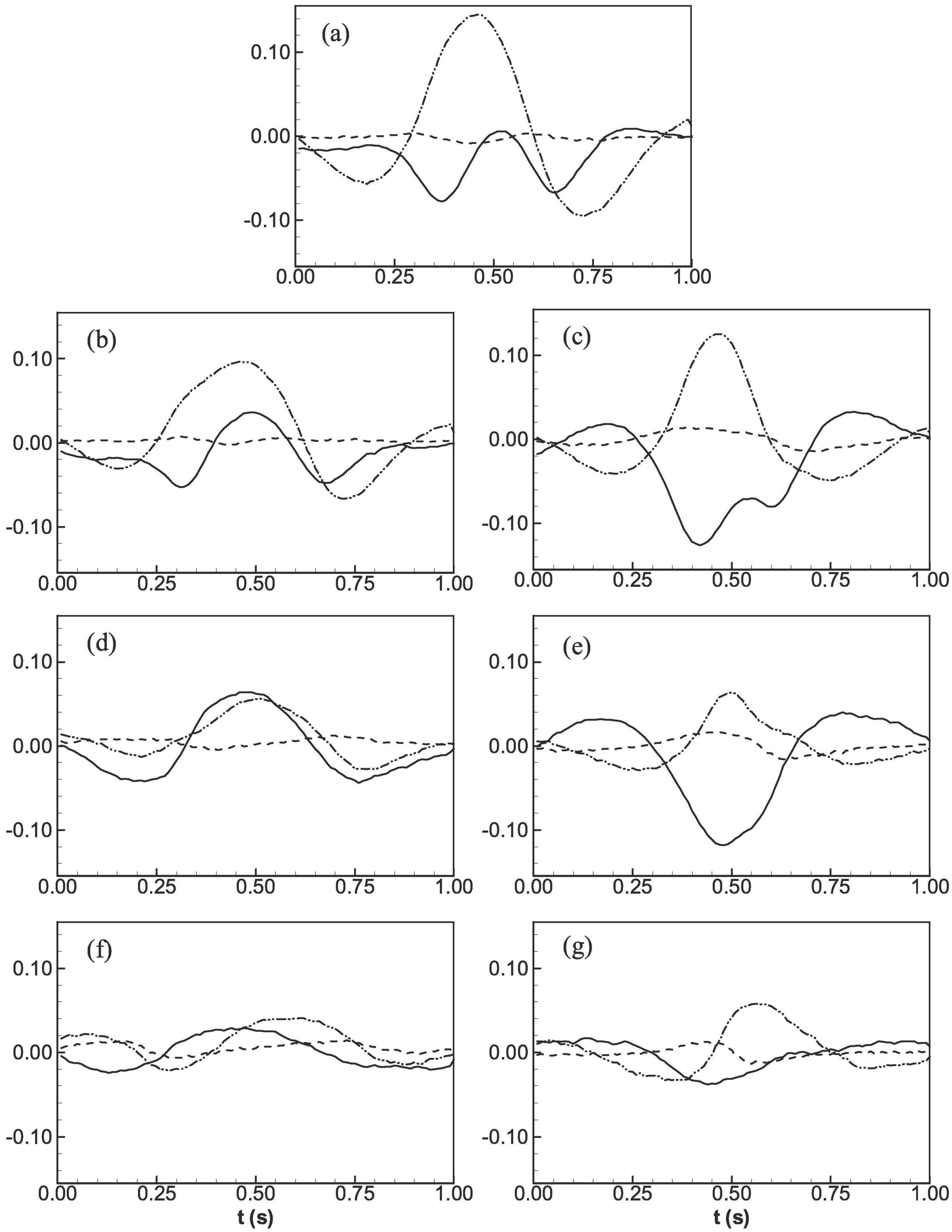

Figure 2. *Examples of coherent velocities, educed by the enhanced VITA technique,* $\tilde{U}/U_b$ *(——),* $\tilde{V}/U_b$ *(----) and* $\tilde{W}/U_b$ *(-··-··-) at (a) y/D=0.050 and z/D=0.000, (b) y/D=0.050 and z/D=-0.200, (c) y/D=0.050 and z/D=0.200, (d) y/D=0.050 and z/D=-0.400, (e) y/D=0.050 and z/D=0.400, (f) y/D=0.050 and z/D=-0.600, and (g) y/D=0.050 and z/D=0.600.*

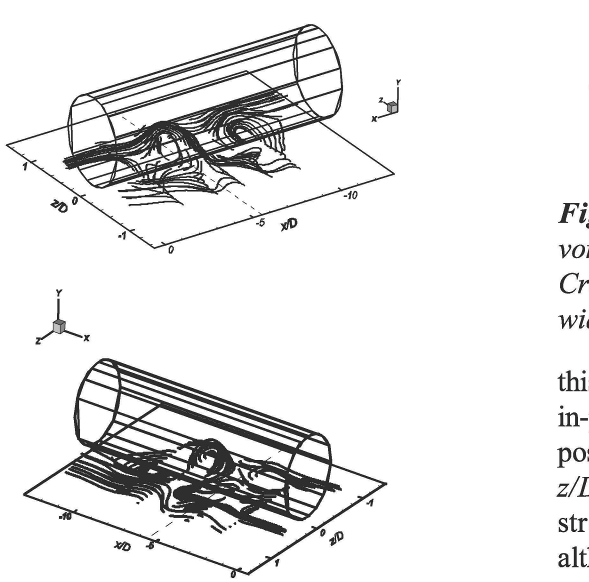

Figure 3. Software generated pathlines, based on the measured coherent velocity field, as seen by an observer travelling with the convective speed of the structures.

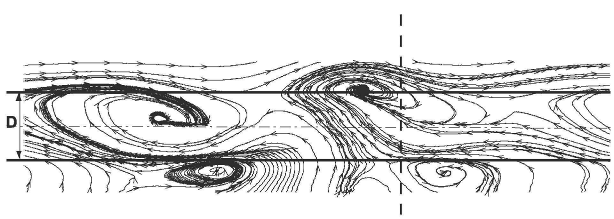

Figure 4. Software-generated "pathlines" of the measured coherent velocity field on a plane equidistant from the rod and plane wall.

axes alternated on each side of a plane of symmetry, with the major axis of the ellipse inclined with respect to the streamwise direction. The above vortex pattern is compatible with the vorticity contours and pathline shapes, but only in the region with $-0.6 \leq z/D \leq 0.6$ and on a plane equidistant from the rod and the plane wall ($y/D = 0.05$). Further away from the gap, it was observed that the measured coherent velocity components were essentially zero on the equidistant plane, but had a measurable variation for larger y/D. The most striking characteristic, in these regions of the flow, was the distinct variation of the transverse (i.e. in the y-direction) coherent velocity component, which, in contrast, was essentially zero close to the gap centre. This variation became stronger with increasing distance from the plane wall. In addition to

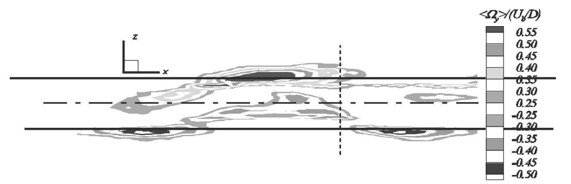

Figure 5. Contours of the coherent transverse vorticity according to the double decomposition. Cross-section at a height equal to half the gap width.

this, the transverse coherent velocity component was in-phase with the spanwise coherent velocity for positive z/D and out-of-phase with it for negative z/D. The above observations indicate that the streamlines produced by the coherent vortices, although essentially planar on the equidistant plane and near the plane of symmetry, they would gradually lift out of this plane and away form the plane wall, as they move away from the plane of symmetry.

The above discussion leads to a tentative physical model for the coherent structures that form in the gap between a cylinder and a plane wall. It consists of a street of three-dimensional counter-rotating vortices with axes located, in an alternating sequence, on either side of the plane of symmetry. The cross-sections of these vortices in the vicinity of the gap are elongated in the streamwise direction with an ellipse-like shape, the major axis of which is inclined by an angle of approximately 28°. The direction of rotation is such that, at its downstream end, each vortex transports fluid from the open flow region towards the gap region and, at its upstream end, transports fluid from the gap to the open flow region. The velocity fields of vortices with axes on one side of the gap extend well into the opposite side. Although the vortices appear to be two-dimensional in the gap region, they are three-dimensional, producing streamlines curving away from the plane wall and away from the gap. As a vortex cannot end abruptly, it is speculated here that the axes of these vortices merge with the boundary layers over the plane wall and the rod surface. This model results in a sequence of continuous vortex tubes with consistent directions of rotation along their entire lengths.

5. Conclusions

The present study has documented, through conditional sampling measurements, the occurrence of large-scale coherent structures in the rod-wall gap region of a rectangular channel containing a circular rod. These structures were shown to vary in size, with the standard deviation of their streamwise extents equal to 0.28 times the corresponding average. The vortical motions cross the gap and extend well into the opposite subchannel. In the immediate vicinity of the gap, streamlines due to these vortices are essentially two-dimensional and parallel to the channel plane wall. Away from the gap, the streamlines curve away from the plane wall. A physical model of the coherent structures was formulated, consisting of a street of three-dimensional counter-rotating vortices with axes alternating on each side of the plane of symmetry, and with directions of rotation such that the vortex front transports fluid from the subchannel core towards the gap.

In view of the previous literature, one may plausibly expect that the present findings, although based on measurements in the specific channel of this study, would qualitatively apply to rod bundle flows. In any channel containing relatively open subchannels connected through narrow gaps, one would expect the formation of large coherent structures, which would transport fluid from the core of an open subchannel, across the gap and well into the opposite subchannel. Unlike small-scale turbulence, coherent structures transport momentum and heat over distances that are much larger than the local scale, i.e. the gap width, thus tending to reduce velocity and temperature differences in the channel. In a reactor rod bundle, the coherent structures would significantly enhance the local convective heat transfer in the gap and the intersubchannel mixing, replenishing the hotter fluid in the gap regions with relatively cooler fluid from the subchannel cores, and thus capable of extracting more heat from the rod surface.

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