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Heat Transfer Near Spacer Grids in Rod Bundles*

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HEAT TRANSFER NEAR SPACER GRIDS IN ROD BUNDLES

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ABSTRACT

Heat transfer data from several sources have been assembled which show the effect of spacer grids on local heat transfer within a rod bundle. Both single phase (air and steam) data and two phase (steam/water) data show heat transfer augmentation in the grid region. Heat transfer improvement immediately beyond the grid ranges from a few percent to over fifty percent in these experiments, depending on flow conditions. The data is examined using several nondimensional parameters which relate the above effects to known quantities. The relative effect of the grid on local heat transfer is altered by both the Reynolds number, and blockage ratio. Twenty to thirty hydraulic diameters are required before the local effect of the grid dissipates.

Locally, both the single phase and two phase data show the same trends. Comparison of the single and two phase data also show some differences. Some film boiling data indicate that an altered heat transfer regime may exist near the grid. High rod heat transfer coefficients at the grid locations indicate either a rewet of the rods or at least a change from film boiling to transition boiling near the spacer. The comparison also indicates that the film boiling data is affected on a global as well as local basis. This is due to the effect of the grid on the liquid distribution.

The data and analysis show the importance of spacer grids on heat transfer in rod bundles. Evaluation of the data using nondimensional parameters simplify prediction of the various effects operant.

INTRODUCTION

In the construction of many tube or rod bundles, such as shell and tube heat exchangers, or nuclear reactor fuel bundles, spacer grids are required to maintain bundle geometry. Spacers may have many geometric forms ranging from simple "warts" on the tubes or rods which maintain rod separation to "egg-crate" type grids with inserts to induce fluid swirl (separation maintained using specially formed metallic strips) to wire wrapped rods. Besides establishing bundle geometry, these devices also act to alter the bundle hydraulic and heat transfer characteristics. Groeneveld[1] describes the effect of grids on bundle pressure drop and heat transfer. In general, grids tend to increase flow resistance and therefore the bundle pressure drop, while at the same time increasing the local heat transfer in the vicinity of the grid.

Initially, interest in the effect of spacer grids on local hydraulic and heat transfer behavior was stimulated by development of the gas cooled nuclear reactor. Several experiments[2,3,4] using gas as the heat transfer medium were performed in various sized rod bundles. These studies showed an increase in local Nusselt number just downstream of the grid on the order of 20% to 100%. More recently, interest has increased in the effects of spacer grids under light water reactor accident conditions. Data under these conditions have been presented by several authors,[5-8] also showing an increase in heat transfer and perhaps rewet near the grids.

Several mechanisms may be operant near the grids which cause this behavior. The most obvious is the effect of the grid on the thermal and momentum boundary layers. The grid tends to break up the local boundary layer, increasing the local heat transfer in the region downstream of the grid. Since the grid obstructs the flow, coolant velocities at the grid location are higher than those in the unobstructed portion of the bundle. Thus Reynolds numbers and therefore heat transfer coefficients at the grid would tend to be higher than those removed from the grid area. The grids may also act as fins in regions where they contact the rod or tube surface, increasing the local heat transfer. Radiation may also play a role in the local heat transfer if grid surfaces are much cooler than the rod or tube surface. Grids also act as sudden contractions and expansions within the bundle and tend to alter the local heat transfer due to eddy generation. Other effects which are grid design dependent may include the effects of swirl or turbulence generation.

If the fluid is two phase (liquid-vapor) within the bundle, the grids may alter the bundle heat transfer characteristics by means other than those described above. In two phase film boiling, heated surface temperatures are high enough to prevent intimate liquid-surface contact. All heat from the surface is therefore first transferred to the flowing vapor before entering the liquid phase. Thus, some vapor superheat or thermal nonequilibrium is normally present in the film boiling regime. The degree of thermal nonequilibrium is affected by the grids in several ways.

By acting as a flow blockage, liquid may impact the grid and be shattered into small droplets, increasing the heat transfer area. Cold grids may also capture some of the liquid, forming a film on the grid surface. Liquid from this film may detach as droplets, altering the liquid distribution in the flow. These two mechanisms tend to alter the degree of non-equilibrium within the flow. Because vapor velocities at the grid would tend to be higher than those in the region where droplets were formed, the grids would be expected to decrease droplet sizes (increasing surface area), and drive the flow closer to equilibrium.

The effect of the grids on thermodynamic equilibrium in two phase flow is global, i.e., by changing the amount of vapor superheat in the flow, the heat transfer characteristics are altered all along the bundle as well as near the grids. The grids may also have local effects in two-phase flow. Grids can cause liquid rewet on the rod surface by acting as a cooler region within the bundle. They may also tend to cause increased liquid droplet impaction near the grid surface due to increased turbulence generation. All of these mechanisms may play an important role in overall bundle heat transfer.

There have been several attempts to incorporate these effects in spacer grid heat transfer models. Marek and Rehme[9] correlated the maximum Nusselt number ratio at the grid (the Nusselt number ratio is defined as the local Nusselt number divided by a Nusselt number unaffected by the spacer grid) in terms of the grid blockage ratio, ε (defined as the projected grid area perpendicular to the flow direction divided by the unobstructed flow area). The relationship which they found appropriate for smooth tubes was:

$$\frac{Nu_p}{Nu_o} = 1 + 5.55\,\varepsilon^2 \qquad (1)$$

Cluss[5] included several of the mechanisms described above including increased flow velocity beneath the grid, tube to spacer radiation, and wall-droplet heat transfer in a model which he compared to his two-phase tube data. Although the experimental data were affected by conduction in his test section, behavior near the grid followed that of the model.

Yao[10] attempted to combine the model of Marek and Rehme with other mechanisms appropriate to two-phase and single-phase flow. He incorporated an empirical term which allowed the Marek and Rehme model to be used beyond the spacer itself. Also included in the model was the effect of swirl production on heat transfer downstream of the grid.

There have also been a few experimental studies which examine individual mechanisms operant near the grid. Ihle[11] has shown the effect of the grid on global heat transfer in two-phase flow. He first ran two-phase dispersed flow film boiling tests in a 25-rod bundle with all grids in place. He then removed one grid and reran the test at the same conditions. The surface temperatures downstream of the grid, at distances where local grid effects should have damped out, were always lower for the case with the grid in place. This suggests that the grid has altered the nonequilibrium within the dispersed two-phase flow by altering the liquid distribution within the flow.

The effect of grids on the local liquid distribution has been studied by Lee et al.[12,13] using a Laser Doppler technique. A known droplet distribution was injected into a test section which contained a spacer grid. Droplet sizes downstream of the grid were measured to determine the downstream droplet size distribution. It was found that the effect of the grid on droplet sizes was pronounced.

Available data showing grid spacer effects in rod bundles is very limited. Some single phase air experiments were performed in support of the gas cooled reactor, and a limited amount of steam-water experiments show grid effects under light water reactor accident conditions.

A detailed discussion of various grid heat transfer effects has been presented by several of the authors mentioned previously,[5,10] and will therefore not be discussed in detail here. Rather, the object of this paper is to use available data to isolate the parameters effecting grid spacer influence on local heat transfer.

EXAMINATION OF SPACER GRID DATA

Table 1 shows the experiments and grid characteristics included in this presentation. As can be seen from Table 1, the range of grid blockage ratios investigated is relatively narrow (0.2 → 0.4). However, this does cover the range encountered in most nuclear reactor fuel assemblies. Since single phase flow reduces the number of variables required to characterize spacer grid heat transfer, that data will be discussed first.

Blockage Ratio

As stated in the introduction, increasing the blockage ratio decreases flow area, and increases flow velocities. Increased blockage ratio also causes increased turbulence in the grid wake. Both of these effects cause a larger peak Nusselt number ratio. Figure 1 shows air data of Marek and Rehme[9] taken in a three rod bundle using air as the heat transfer medium. The data displays the effect of grid blockage ratio, ε on local heat transfer near the grid for one Reynolds number, Re = 1.27×10^5. Increasing the grid blockage ratio increases the local

Table 1. Spacer grid heat transfer data sources

Investigator	Ref. no.	No. rods	Fluid	Rod dia. (cm)	Pitch to diameter ratio	Blockage ratio, ε	Mass flux (Re) (kg/m^2 s)
Marek	9	3	Air	2.12	1.45	0.253–0.348	1.27×10^4 (Re)
Hassan	14	3	Air	2.12	1.45	0.302–0.348	$(.006\text{–}2.) \times 10^5$ (Re)
Krett	3	7	Air	0.76	–	0.303	$(0.4\text{–}1.5) \times 10^5$ (Re)
Vlcek	2	1	Air	0.8	–	0.24	$(1.3\text{–}2.1) \times 10^5$ (Re)
Hoffman	4	7	Air	1.91	1.33	0.23	1–80
Anklam	16	64	steam	.95	1.34	.30	5–30
Wong	17	161	steam	.95	1.3	.35	3–23
Cluss	5	tube	steam/water	.95	–	.367	25.4
Era	18	1	steam/water	1.5, 1.7	–	.30	22–38
Yoder	19	64	steam/water	.95	1.34	.30	200–800
Yoder	20	64	steam/water	.95	1.34	.30	40–260
Morris	21	64	steam/water	.95	1.34	.30	145–1100
Lee	22	161	steam/water	.95	1.3	.35	1–140

Several single phase gas experiments have been designed to isolate parameters important in grid heat transfer augmentation. Three nondimensional parameters can be identified which effect local heat transfer in the grid region; the blockage ratio, ε, the Reynolds number, Re, and distance downstream of the grid, X/D. Each of these will be discussed separately.

Nusselt number. This effect has been correlated by Yao[10] using the empirical equation

$$Nu/Nu_0 = 1 + 5.55\, \varepsilon^2\, e^{-0.13(L/D)} \quad (2)$$

recommended for Reynolds numbers above 10^4. This equation is shown as solid curves on Figure 1. As the Marek data formed part of the data

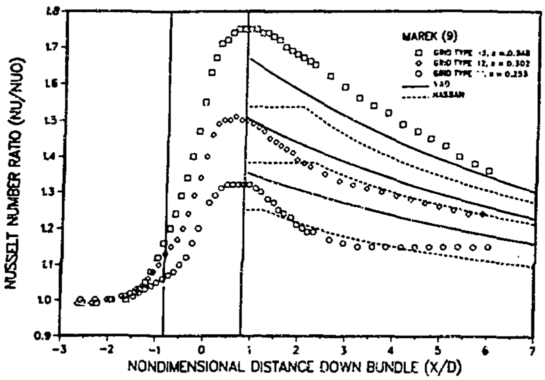

Fig. 1. Data showing the effect of blockage ratio on grid Nusselt numbers (Re = 127,000).

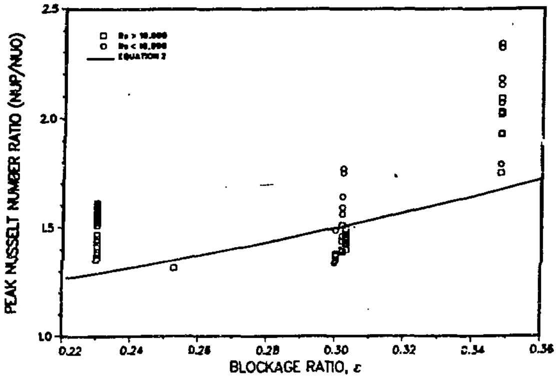

Fig. 2. Effect of blockage ratio on peak Nusselt number ratio.

base upon which Equation 2 was developed, the agreement is very good.

Hassan and Rehme[15] have also developed a correlation for predicting heat transfer near the grids in their gas cooled rod bundle. Their equation for smooth tubes includes Reynolds number, Graetz number, and blockage ratio dependence.

$$Nu/Nu_o = K\ Gz^m \qquad (3)$$

where:

$$m = -1.855 \times 10^{-3}\ Re\ \varepsilon^2 \qquad Re < 3000$$
$$K = 4.42 - 1.05 \log (Re) - 2.25\varepsilon$$

$$m = -30.34\ Re^{-0.253}\ \varepsilon^2$$
$$K = 0.426 + 0.113 \log (Re) - 2.25\ \varepsilon \qquad Re > 3000$$
$$K \geq 0.895 - 2.25\ \varepsilon$$

Agreement between equation (3) and their data was very good. Comparison of equation 3 to the Marek data is shown as dashed curves on Figure 1.

The effect of blockage ratio on peak Nusselt number ratio is presented in Figure 2 for single phase experiments listed in Table 1. Equation 2 (solid line) is also shown for reference. The data shows considerable scatter due to the effect of Reynolds number variation. However, the peak Nusselt number ratio increases with blockage ratio. Equation 2 predicts this effect to within ∿ 20% for Re > 10^4. The scatter in the data shown in figure 2 is partially due to the effect of Reynolds number described in the next section. The data shown as (O) are those for Re < 10^4 and show a much larger variation than those for Re > 10^4 (□).

Reynolds Number

Figure 3 shows air data of Marek and Rehme[9] and Hassan and Rehme[14] for one grid blockage ratio, ε = 0.302, and several Reynolds numbers. Hassan's experiments were performed in the same experimental apparatus as those of Marek. As

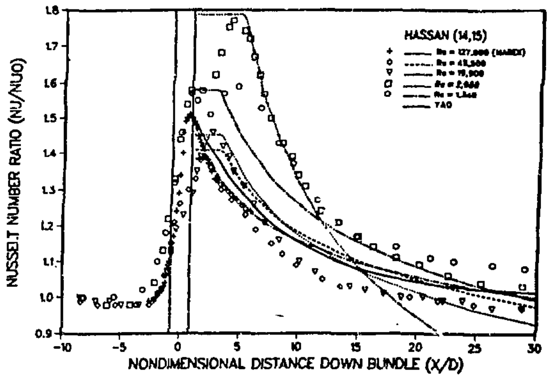

Fig. 3. Data showing the effect of Reynolds number on grid Nusselt numbers (ε = 0.302).

Figure 3 indicates, the magnitude of the Reynolds number (based on unobstructed flow area) effects the degree of augmentation, with higher Reynolds numbers decreasing the peak Nusselt number ratio in this instance. Also shown on this figure is the prediction of Equations 2 (solid line), and 3 (broken lines). Figure 4 shows the effect of the Reynolds number on peak Nusselt number

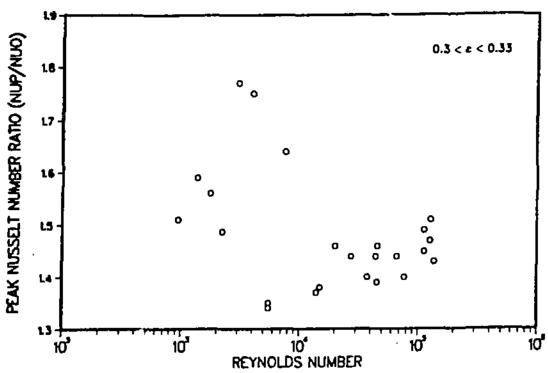

Fig. 4. Effect of Reynolds number on peak Nusselt number ratio.

ratio for gas data listed in Table 1. At low Reynolds numbers, an increase in Reynolds number increases the peak Nusselt number ratio. As Reynolds numbers increase further, the opposite effect occurs. However, the effect tends to diminish as Reynolds numbers increase further. This appears due to the grid's influence on turbulence within the flow. In the laminar region (Re less than $\sim 3 \times 10^3$), increasing the Reynolds number tends to increase the turbulence generated by the grid, increasing the peak Nusselt number, while the undisturbed Nusselt number remains approximately constant. As Reynolds numbers are increased to the bulk flow laminar/turbulent transition region, the undisturbed Nusselt number increases rapidly, while the peak Nusselt number changes little (as the regions under and trailing the grid were likely in turbulent flow at lower Reynolds numbers) and the Nusselt number ratio decreases. Once the entire flow system is in turbulent flow, the increase in peak Nusselt number ratio with Reynolds number is less pronounced, appearing to flatten at higher Reynolds numbers. Turbulence generation by the grid would not be expected to impact the local heat transfer as significantly, once the flow is completely turbulent.

The two points located at Re = 5500, with peak Nusselt number ratios of ~ 1.35, are steam data of Anklam. The small amount of steam cooling data taken near spacer grids makes it impossible to determine whether these low ratios are due to the fluid itself or grid characteristics within his bundle causing a difference in the turbulence generation and transition from laminar to turbulent flow.

An interesting feature of the Hassan data (Figure 3) is that the peak Nusselt number ratio moves downstream of the grid spacer as Reynolds numbers decrease. This behavior is typical of the heat transfer variation seen downstream of sudden expansions.[23,24] The generation of eddies cause flow separation and stagnation immediately downstream of the grid. The flow then reattaches, and the heat transfer again increases. Increased turbulence at higher Reynolds numbers tends to cause the flow to reattach closer to the grid trailing edge, thus reducing this effect.

X/D Ratio

The effect of the grid downstream of the grid itself can be seen by examining Figure 5 which presents the Nusselt number vs. nondimensional distance from the grid, X/D. Within thirty diameters, all effects of the grid appear

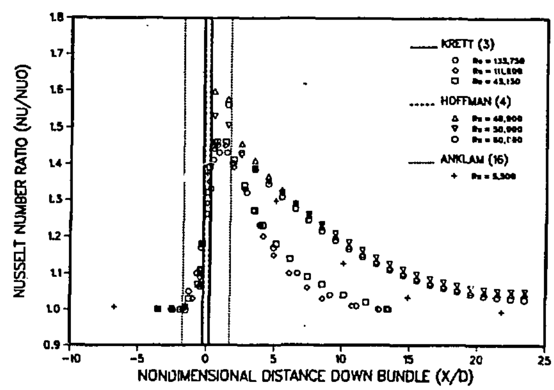

Fig. 5. Data showing the effect of distance downstream of grid.

to dissipate. This is true for even the low Reynolds number cases where it might be expected that longer distances would be required to reestablish fully developed laminar flow (e.g., see Hassan data,[14] Re = 1340). The Krett[3] data show somewhat shorted distances required for the grid effects to dissipate, ~ 15 diameters. This data was taken at relatively high Reynolds numbers (Re > 4.5×10^4). However, the data of Hoffman[4] also taken at higher Reynolds numbers (Re > 4.0×10^4) do not show this decreased dissipation length. Duplicate runs by Hoffman also do not indicate that dissipation lengths decrease to less than about 30 hydraulic diameters downstream of the grid. Steam data taken by Anklam[16] also show similar behavior.

The behavior of the data vs. distance from the grid is very much like that of boundary layer growth behavior, and the distances involved (X/D ∿ 20-30) are similar to those noted in entrance length investigations.[25,26] This behavior is caused by grid destruction of the existing boundary layer, and consequent rebuilding downstream of the grid.

The effect of the grid at and upstream of the grid location can be seen by examining Figures 1, 3, and 5. These effects are limited to approximately 2-4 hydraulic diameters upstream of the grid and are due to both conduction within the rod and the effect of the flow disturbance upstream of the grid. These effects have been incorporated into correlations by both Yao[10] and Hassan,[15] who have used linear interpolation between upstream and peak Nusselt number values.

Azimuthal Location

Several investigators, including Marek,[9] Hassan,[14,15] and Hoffman,[4] have measured the azimuthal variation of surface temperature in the vicinity of the grid. This was accomplished by using spring loaded moveable thermocouples within the rod itself. Temperature measurements could then be made at any axial and azimuthal location. As would be expected, results of these experiments are highly dependent on the grid design. An example of measurements beneath the grid taken by Marek are shown in Figure 6 as a temperature map near the grid. Temperature differences of about 10°C can be noted. These azimuthal effects, however, appear to dissipate within about 5 hydraulic diameters beyond the grid trailing edge. The distortion in the temperature profile seen at X/D = -2.1 is caused by the bundle geometry. The effects downstream of the grid are clearly noted as temperatures at the contact locations are depressed by about 10°C from the "average" temperature at a given location. These depressions are caused by local turbulence and eddy generation at X/D = 1.34 due to the grid contact points. The average rod temperatures in this example are depressed by about 25°C due to the presence of the grid.

Two Phase Flow - Local Effects

Because of the complicated nature of two phase flows, and the increased difficulty of measuring local fluid conditions, much less detailed information is available for two phase, film boiling spacer grid heat transfer effects. However, there have been some rod bundle heat transfer measurements taken near the grids under two phase flow conditions. Grids appear to affect the local heat transfer in two phase

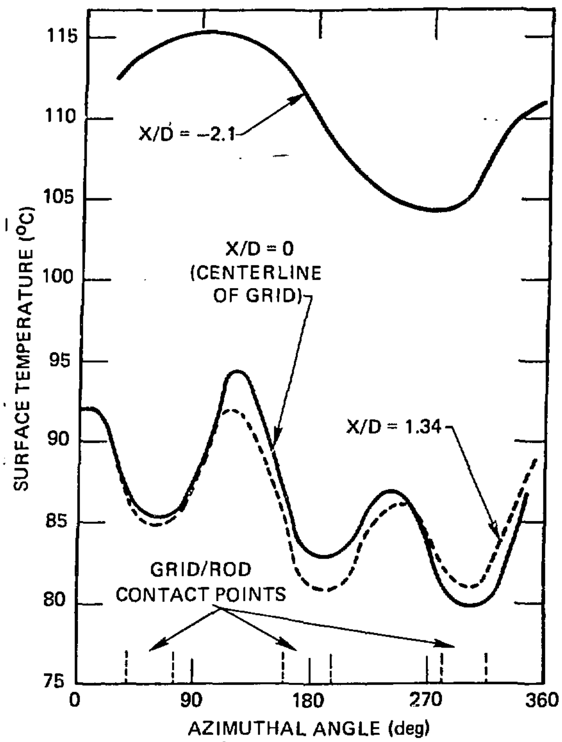

Fig. 6. Temperature distribution near the grid [9] (trailing/leading edge of grid = ±0.9).

flows in much the same way as they do single phase flow. Many of the same mechanisms which influence single phase heat transfer will also affect the local axial profile downstream of the grid in two phase flows.

Figure 7 shows Nusselt number ratios for two phase data. The effect of non-equilibrium within the flow was eliminated by examining the behavior of dNu/d(X/D). Several slopes were calculated for each data set. Each set presented in Figure 7 (except Cluss) contained data from two consecutive grid locations (only one is shown in the Figure 7). Slopes were determined using two data points located the same distance downstream of each grid. This was done at several positions. If the slopes vaired by more than ∿10%, the data set was not presented. If the slopes varied by less than ∿10%, the average slope value was used to extrapolate the local Nu_0 from the last data point upstream

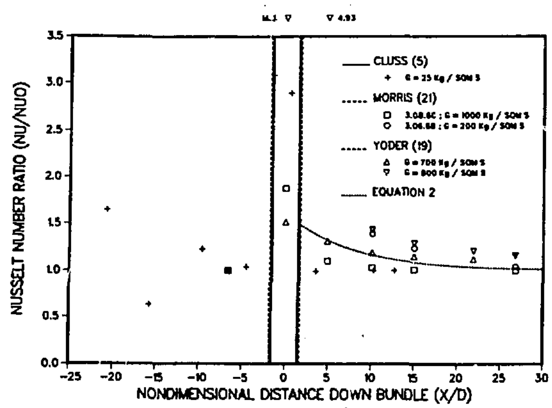

Fig. 7. Two phase heat transfer data near the grid spacers.

of the grid shown in Figure 7. Errors in Nu/Nu_o introduced due to this extrapolation are estimated to be approximately 5-10% at the peak Nusselt number ratio location, and 10-15% at the end of the heated length. Cluss' Nusselt numbers had similar values at points away from the grid and away from the test section ends. These values were therefore averaged to determine Nu_o.

As might be expected, the data show considerable scatter; however, the behavior is very similar to that of the single phase data. Also shown in Figure 7 is equation 2 for $\varepsilon = 0.3$. As shown, prediction is reasonable, with an error of $\sim$ 30% at points beyond the grid.

One set of data shown in Figure 7 as ∇'s, show very high heat transfer coefficients beneath the grid. These coefficients are an order of magnitude larger than film boiling coefficients under the same conditions, and indicate that the grid has caused the rod surface to rewet, or at least return to transition boiling. The local effects of the grids appear to dissipate within approximately 30 hydraulic diameters, the same length required for dissipation in single phase flows. Boundary layer disruption by the grid and consequent rebuilding downstream of the grid also explain this two-phase behavior. Two-phase flows, however, are complicated by the presence of droplets. Several analyses[27,28] have shown that droplets tend to depress the boundary layer rebuilding process by acting as heat sinks within the thermal boundary layer. The available data for grid effects on film boiling, however, are not sufficiently detailed to show this phenomenon. Droplets emerging from the grid area may also tend to have higher velocities perpendicular to the rod surface due to grid turbulence generation and may, therefore, cause increased rod surface/droplet heat transfer, which is normally negligible without the presence of grids.

Two Phase Flow - Global Effects

The most difficult grid effect to either measure or predict is the influence of the grid on thermal nonequilibrium within dispersed flow film boiling. As was stated in the introduction, this effect is global in nature, influencing the heat transfer much farther beyond the grid than the local effects described above. Ihle et al.[11] has shown this global influence dramatically. Figure 8 shows film boiling data taken during two transient experiments. The first

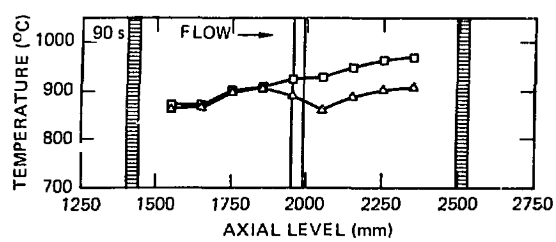

Fig. 8. Data of Ihle [11] showing the global effect of grid spacers on two phase film boiling heat transfer.

experiment was run with a full compliment of grid spacers within the bundle. The second was run under the same conditions, except that the mid bundle spacer was removed. Temperature differences of $\sim$ 75°C can be seen well downstream of the spacer. The test performed with all spacers in place indicates lower surface temperatures due to the effect of the grid on the liquid distribution and therefore the degree of nonequilibrium existing within the flow.

Lee et al.[12,29] has used Laser Doppler measurements to examine the liquid redistribution due to the presence of a wetted spacer grid. Droplet size measurements (air/water) were taken both before and after the spacer grid in their unheated four-rod bundle. Two different egg crate type spacer grid designs were used. It was shown that both grids altered the droplet size distribution, reducing average droplet diameters, and therefore increasing vapor/liquid interfacial area. Lee[29] described the droplet breakup mechanism by dividing the droplets into two groups, "large" and "small", at his measurement sites.

The ratio of "large" droplet Sauter mean diameter downstream of the grid to those upstream of the grid was given by

$$\frac{d_{L,2}}{d_{L,1}} = 0.162 \text{ We}^{0.75} \left(\frac{h}{d_{L,1}}\right)^{0.062} \qquad (4)$$

where We is the Weber number based on the injected air velocity, and h is the length of the grid spacer. The ratio of "small" droplet Sauter mean diameters was found to be uniform and given by

$$d_{s,2} = 1.489 \times 10^{-4} \frac{\mu_f^2}{\rho_f \sigma} \qquad (5)$$

The ratio of the interfacial area for the "small" droplets after the grid spacer to that before the grid spacer for his experiments ranged from 10 to 13, indicating a very substantial effect of the grid on droplet characteristics. These measured effects would tend to decrease the degree of non-equilibrium present in heated dispersed flows. These results illuminate the results of Ihle presented earlier, showing decreased surface temperatures with all grids in place. Larger interfacial area tends to reduce the degree of thermal nonequilibrium, lowering surface temperatures.

Lee et al.[22] has used aspirated thermocouples within a 161 rod bundle to measure the degree of nonequilibrium within dispersed flow film boiling. During these experiments, droplet size measurements were also taken. Data was taken with all grids in place, and the effect of the grid on thermal nonequilibrium could therefore not be ascertained.

Very few models have been developed to account for two-phase grid effects. The model developed by Cluss[5] was described in a preceding section. Chiou et al.[30] have also developed a two-phase spacer grid model which includes many of the effets discussed previously, including radiation, convection from the grid, and the grid's effect on droplet size. This model was compared to FLECHT/SEASET data with the conclusion that grid/droplet breakup behavior was important in characterizing heat transfer within the bundle. However, more information was needed to completely verify the algorithm.

More experimentation is necessary to completely identify grid effects under two phase film boiling conditions. Both measurements of two phase vapor temperatures and droplet sizes are needed to completely characterize the grid's influence on nonequilibrium.

SUMMARY

The effect of spacer grids on heat transfer within a rod bundle has been discussed using data from previous experiments. Data from single phase experiments show that three factors influence the local heat transfer in the wake region of the grid. Increased grid blockage ratio tends to increase the peak Nusselt number ratio. Reynolds numbers affect the peak Nusselt number differently, depending on the turbulence within the bulk flow. Approximately 30 hydraulic diameters are required for grid effects to dissipate. Two phase film boiling data show the same local grid characteristics as do the single phase data. However, grids also affect two phase flows by altering the degree of nonequilibrium within the flow.

Nomenclature

D	– hydraulic diameter (undisturbed by grid)
Gz	– Graetz number (Z/D/Re/Pr)
L	– distance from grid trailing edge
Nu	– local Nusselt number
Nu_p	– peak Nusselt number
Nu_o	– Nusselt number undisturbed by grid
Re	– Reynolds number (GD/μ)
X	– distance from grid centerline
We	– Weber No.
Z	– distance from grid leading edge
ε	– blockage ratio

REFERENCES

1. D. C. Groeneveld and W. W. Yousef, "Spacing Devices for Nuclear Fuel Bundles, A Survey of Their Effect on CHF, Post-CHF Heat Transfer and Pressure Drop," Proc. ANS/ASME/NRC Int. Topl. Mtg. Nuclear Reactor Thermal Hydraulics, Saratoga Springs, New York, October 5-8, 1980, U.S. Nuclear Regulatory Commission 1980.

2. J. Vlcek and P. Weber, "The Experimental Investigation of a Local (Spot) Heat Transfer Coefficient in the Fuel Spacers Area," Australian Atomic Energy Commission Research Establishment, LIB/TRANS 250, February 1970.

3. V. Krett and J. Majer, "Temperature Field Measurement in the Region of Spacing Elements," ZJE-114, Skoda Works, Pilsen, Czechoslovakia, 1971.

4. H. W. Hoffman et al., "Experimental Studies of the Heat Transfer and Fluid Dynamic Characteristics of Rod-Cluster-Type Nuclear Reactor Fuel Elements," ORNL-4356, Oak Ridge National Laboratory, May 1970.

5. E. M. Cluss, Jr., "Post Critical Heat Flux Heat Transfer in a Vertical Tube Including Spacer Grid Effects," MS Thesis, Massachusetts Institute of Technology, June 1978.

6. D. G. Morris et al., "A Preliminary Evaluation of Rod Bundle Post-CHF Heat Transfer to High Pressure Water in Transient Upflow," ORNL/CF-81/265, Oak Ridge National Laboratory, Nov. 9, 1981.

7. P. Ihle, "Flooding E.periments in Blocked Arrays FEBA Recent Results and Future Plans," "Proc. Mtg Water Reactor Safety Research Information," Gaithersburg, Maryland, October 27-31, 1980, U.S. Nuclear Regulatory Commission, 1980.

8. G. L. Yoder, D. G. Morris, C. B. Mullins, L. J. Ott, "Dispersed-Flow Film Boiling Heat Transfer Data Near Spacer Grids in a Rod Bundle," Nuclear Technology, Vol. 60, pp. 304-313, February 1983.

9. J. Marek and K. Rehme, "Heat Transfer in Smooth and Roughened Rod Bundles Near Spacer Grids," Fluid Flow and Heat Transfer Over Rod or Tube Bundles, S. Yao and P. Pfund, Eds., American Society of Mechanical Engineers, 1979.

10. S. C. Yao, L. E. Hochreiter, and W. J. Leech, "Heat Transfer Augmentation in Rod Bundles near Grid Spacers," Journal of Heat Transfer, Vol. 104, Feb 1982, pp. 76-81.

11. P. Ihle, K. Rust, and S. L. Lee, "Experimental Investigation of Reflood Heat Transfer in the Wake of Grid Spacers," Joint NRC/ANS Meeting on Basic Thermal Hydraulic Mechanisms in LWR Analysis, Bethesda, MD, Sept. 14-15, 1982, pp. 417-43.

12. S. L. Lee, S. K. Cho, and H. J. Sheen, "Reentrainment of Droplets from Grid Spacer in Mist Flow Portion of LOCA Reflood of PWR," Joint NRC/ANS Meeting on Basic Thermal Hydraulic Mechanisms in LWR Analysis, Bethesda, MD, Sept. 14-15, 1982, pp. 477-92.

13. S. L. Lee and J. Srinivasan, "An LDA Technique for In Situ Simultaneous Velocity and Size Measurement of Large Spherical Particles in Two-Phase Suspension Flow," International Journal of Multiphase Flow, Vol. 8, pp. 47-57, February 1982.

14. M. A. Hassan and K. Rehme, "Heat Transfer Near Spacer Grids in Smooth and Roughened Rod Bundles," Fifth GCFR Heat Transfer Specialists Meeting, May 14-16, 1979, Würenlingen.

15. M. A. Hassan and K. Rehme, "Heat Transfer Near Spacer Grids in Gas-Cooled Rod Bundles," Nuclear Technology, Vol. 52, pp. 401-414, March 1981.

16. T. M. Anklam, R. J. Miller, and M. D. White, "Experimental Investigations of Uncovered-Bundle Heat Transfer and Two-Phase Mixture-Level Swell Under High-Pressure Low Heat-Flux Conditions, ORNL-5848, March 1982.

17. S. Wong and L. E. Hochreiter, "Analysis of the FLECT SEASET Unblocked Bundle Steam Cooling and Boiloff Tests," NUREG/CR-1533, January 1981.

18. A. Era, G. P. Gaspasi, A. Hassid, A. Milani, R. Zavattarelli, "Heat Transfer Data in the Liquid Deficient Region for Steam-Water Mixtures at 70 kg/cm^2 Flowing in Tubular and Annular Conduits," Topical Report No. 11, CISE-R-184, June 1966.

19. G. L. Yoder, D. G. Morris, C. B. Mullins, L. J. Ott, D. A. Reed, "Dispersed Flow Film Boiling in Rod Bundle Geometry-Steady State Heat Transfer Data and Correlation Comparisons," ORNL/5822, Oak Ridge National Laboratory, March 1982.

20. G. L. Yoder, T. M. Anklam, D. G. Morris, C. B. Mullins, "High Dryout Quality Film Boiling and Steam Cooling Heat Transfer Data From a Rod Bundle," ORNL/TM-8794, Oak Ridge National Laboratory, December 1983.

21. D. G. Morris, C. B. Mullins, G. L. Yoder, "An Analysis of Transient Film Boiling of High Pressure Water in a Rod Bundle," ORNL-5848, March 1982.

22. N. Lee, S. Wong, H. C. Teh, and L. E. Hochreiter, "PWR FLECT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Evaluation and Analysis Report, NUREG/CR-2256, November 1981.

23. P. P. Zemanick and R. S. Dougall, "Local Heat Transfer Downstream of Abrupt Circular Channel Expansion," ASME Journal of Heat Transfer, Vol 92, pp. 53-60, February 1970.

24. R. S. Amano, "A Study of Turbulent Flow Downstream of an Abrupt Pipe Expansion," AIAA Journal, Vol 21. No. 10, pp. 1400-1405, October 1983.

25. L. M. K. Boelter, G. Young, and H. W. Iversen, "An Investigation of Aircraft Heaters XXVII-Distribution of Heat Transfer Rate in the Entrance Section of a Circular Tube," NACA Technical Note No. 1451, National Advisory Committee for Aeronautics, October 1930.

26. R. G. Deissler, "Analysis of Turbulent Heat Transfer and Flow in the Entrance Region of Smooth Passages," NACA Technical Note No. 3016, National Advisory Committee for Aeronautics, October 1953.

27. A. Rane and S. Yao, "Heat Transfer of Evaporating Droplet Flow in Low Pressure Systems," Canadian Journal of Chemical Engineering, Vol. 58, pp. 303-308, June 1980.

28. L. M. Hull, "Post Critical Heat Flux Heat Transfer; the Region of the Initial Temperature Rise," Masters Thesis, MIT, July 1980.

29. S. L. Lee, S. K. Cho, H. J. Sheen, "A Study of Droplet Hydrodynamics Across a Grid Spacer," NUREG/CR-4034, 1984.

30. J. Chiou, L. E. Hochrieter, D. B. Utton, M. Y. Young, "Spacer Grid Heat Transfer Effects During Reflood," Joint NRC/ANS Meeting on Basic Thermal Hydraulic Mechanisms in LWR Analyisis, Bethesda, MD, Sept. 14-15, 1982, pp. 445-476.

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