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ON THE DEVELOPMENT OF A GRID-ENHANCED SINGLE-PHASE CONVECTIVE HEAT TRANSFER CORRELATION

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Abstract

A new single-phase convective heat transfer augmentation correlation has been developed using single phase steam cooling experimental data obtained from the Penn State/NRC Rod Bundle Heat Transfer (RBHT) facility. Experimental data obtained from the RBHT single phase steam cooling tests have been evaluated and new findings identified. Previous rod bundle tests showed the importance of spacer grid on the local heat transfer, and that the augmentation in heat transfer downstream of a grid decays exponentially. The RBHT data also shows that the Reynolds number affects the rate at which this augmentation decays. The new correlation includes the strong dependence of heat transfer on both the Reynolds number and the grid blockage ratio. While the effects of both parameters were clearly evident in the RBHT experimental data, existing correlations do not account for the Reynolds number effect. The developed correlation incorporates Reynolds number in the decay curve of heat transfer. The newly developed correlation adequately accounts for the dependence of the heat transfer augmentation decay rate on the local flow Reynolds number.

Introduction

Spacer grids are an integral part of the fuel assembly design in light water nuclear reactors (LWRs). They are used to maintain a constant distance between rods in a tight lattice, secure flow passage, and prevent damage of the fuel assembly from flow-induced vibration. The grid spacers also represent a flow blockage in the channel causing the flow to redevelop downstream of each grid. This has been found to induce turbulent mixing in the flow field, thus increasing the local heat transfer.

It is widely recognized that spacer grids tend to enhance the rate of cooling of fuel rods during the reflood stage of a loss-of-coolant accident (LOCA). To realistically predict the thermal hydraulics response of a rod bundle during reflood transients following a LOCA event in a nuclear power plant, the grid-enhanced heat transfer needs to be adequately accounted for in best-estimate safety analysis codes. In addition to the local enhancement of convective heat transfer, spacer grids can also induce droplet breakup in a dispersed droplet field which further improves the overall heat transfer. These mechanisms can appreciably lower the peak cladding temperatures (PCTs) in a core uncovery.

The importance of single phase convection enhancement downstream of spacer grids on the cooling of fuel rods has been widely recognized and the subject has been studied quite extensively in the past. Kidd and Hoffman [1] were among the first who performed detailed experimental measurements of the temperature distribution and heat transfer characteristics in a rod bundle grid spacer area. They found that the grid-induced convection enhancement was similar to the phenomenon of entrance effect in pipe flows. This observation was confirmed by the subsequent experimental works of Velcek and Weber [2], Krett and Majer [3], Marek and Rehme [4], Bragina et al. [5], Drucker et al. [6], and Chesna and Kolesnikovas [7]. They observed the heat transfer augmentation to exhibit a local maximum at the grid exit whereas downstream of the grid, the amount of heat transfer augmentation decays exponentially in the axial direction.

Using standard support grids with blockage ratios ranging from 0.25 to 0.35, Marek and Rehme [4] successfully correlated the maximum heat transfer with the square of the blockage ratio. When compared with the pressure loss coefficient for standard spacer grids reported by Rehme [8], they concluded that the grid-induced heat transfer enhancement is directly related to the pressure drop across the support grid. Using the expression for the maximum heat transfer reported by Marek and Rehme, Yao et al. [9] developed a correlation for the axial decay of single phase convection enhancement downstream of standard support grids. Based on the axial decay rate of the angular momentum of swirling pipe flow reported by Kreith and Sonju [10], Yao et al. also extended their correlation to the case of a support grid with split-vane pairs to account for the effect of swirling flow in rod bundle subchannels. Their extended correlation with swirling effect was shown to compare well with the data of swirl generator reported by Migay and Goluber [11].

Recently, a convection enhancement correlation was developed by Holloway et al. [12] which was different than the one reported by Yao et al. [9]. While Yao et al. developed their correlation in terms of the grid blockage ratio, Holloway et al. developed their correlation directly in terms of the pressure loss coefficient. The correlation developed by Holloway et al. appears to more adequately capture the first order effects of the pressure drop on the convection enhancement created by the split-vane pair and disc types of support grids. Unfortunately, the working fluid employed in the experiments of Holloway et al. was air rather than steam and as such, their results cannot be readily used for steam during reflood transients.

In the present study, data from a series of single phase steam cooling tests performed at the Penn State/NRC Rod Bundle Heat Transfer (RBHT) facility over a range of Reynolds numbers were used to evaluate models and correlations commonly used in best-estimate thermal/hydraulic computer codes. The experimental results of the single phase steam cooling tests were analyzed to identify grid enhanced heat transfer effects. The local Reynold number decreases with elevation in a rod bundle due to the axial increase in steam temperature and its effect on viscosity. However, approximately fully developed flow does occur at points far downstream of a spacer grid just prior to the next downstream grid. At each spacer grid, the flow is disrupted as the hydrodynamic and thermal boundary layers are stripped away and must redevelop. Owing to this flow redevelopment, the heat transfer downstream of the spacer grid was found to be enhanced.

Heat transfer coefficients are significantly increased at the grid and then decrease with downstream distance from the grid.

Development of Enhancement Correlations

The models typically used in best-estimate thermal-hydraulic codes were compared to the experimental results of the RBHT steam cooling tests and were found to significantly under-predict the measured results. From the RBHT steam cooling data, a new correlation has been developed which takes into account the strong dependence of the decay curve of the local heat transfer augmentation on the flow Reynolds number in addition to the grid blockage ratio. The newly developed correlation adequately accounts for the dependence of the maximum heat transfer augmentation at the spacer grid location and the rate of decay of the local heat transfer augmentation on the local flow Reynolds number.

Convective Heat Transfer Correlations

The most widely used turbulent single-phase convective heat transfer correlation for rod bundles is the Dittus-Boelter correlation [13]. This correlation, which is used in COBRA-TF and other thermal-hydraulic codes for fully developed flow heat transfer is given by

$$Nu_{\infty DB} = (0.023)\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{1}$$

where Nu_{∞} is the Nusselt number for fully developed flow, the second subscript "*DB*" refers to Dittus-Boelter, Re is the flow Reynolds number and Pr is the Prandtl number of the fluid.

The Weisman correlation [14] which is judged to be more appropriate for use as a reference basis for the development of a single-phase convection enhancement correlation is given as

$$Nu_{\infty W} = [0.042(P/D) - 0.024]\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{2}$$

where *P/D* is the pitch-to-diameter ratio and the second subscript "*W*" refers to Weisman. Using the pitch-to-diameter ratio of *P/D* = 1.3262 for the rod bundle in the RBHT facility, the above expression reduces to

$$Nu_{\infty W_{RBHT}} = (0.0317)\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{3}$$

It should be noted that there is another correlation developed by Kim and El-Genk [15] for rod bundle geometries given as

$$Nu_{\infty El-Genk} = [0.026(P/D) - 0.006]\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33} \tag{4}$$

which for RBHT bundle, reduces to

$$Nu_{\infty\, El-Genk_{RBHT}} = (0.0285)\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33} \tag{5}$$

In a more recent study, Holloway et al. [12] proposed a new correlation using air rather than steam as the working fluid. Their fully developed correlation is reported in the following form:

$$Nu_{\infty H} = (0.018)\mathrm{Re}^{0.79} \tag{6}$$

The above correlation, however, was developed using air as the working fluid. As such, it requires an additional modifier in order to be applicable for steam under reflood transient conditions.

Fully Developed Heat Transfer Correlations

The RBHT tests produced nearly fully developed heat transfer data at locations downstream of a grid just before the next downstream grid. These data were used to evaluate the existing convective correlations. Figure 1 shows the fully developed data taken from the inner 3x3 bundle of the steam cooling tests performed in the RBHT facility [16]. Also shown in the figure for comparison are the Dittus-Boelter correlation [13] and the Weisman correlation [14]. As can be seen from the figure, the Dittus-Boelter correlation significantly under-predicts the fully developed heat transfer in the rod bundle over the entire range of Reynolds numbers explored in the experiments. As such, it is not suitable for use as a reference basis in the development of the single phase convection enhancement correlation. For laminar flow, the Nusselt number is constant with an approximate value of 27.

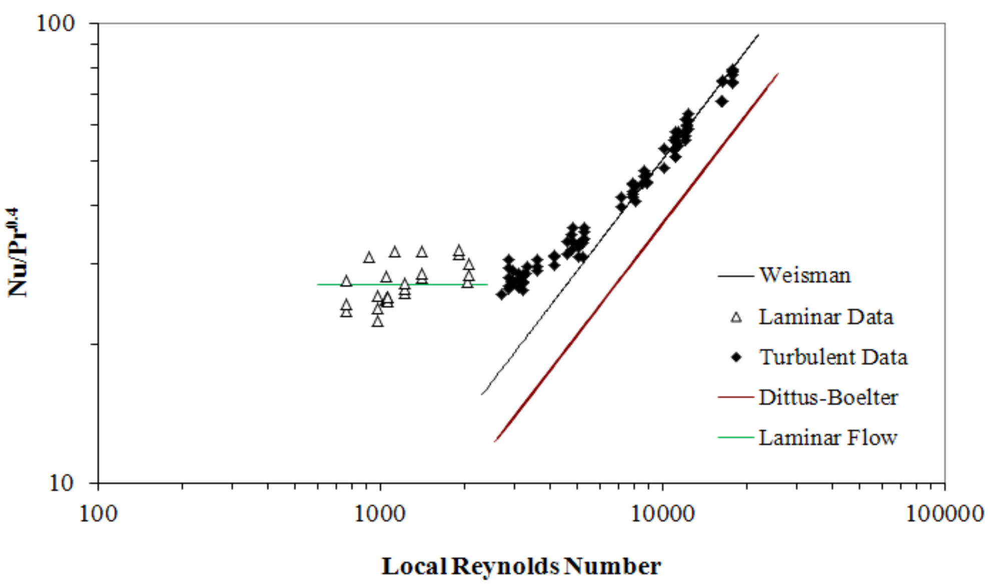

Figure 1. Comparison of Existing Correlations with the RBHT Fully Developed Data

The Weisman correlation [14] fits the RBHT turbulent data very well, especially at high Reynolds numbers. Note that Weisman attempted to correct the Dittus-Boelter correlation by adding the dependence on the pitch-to-diameter ratio which is more appropriate for rod bundle geometry. The Weisman correlation was developed from data having a pitch-to-diameter ratio ranging from 1.1 > *P/D* > 1.3 for square lattice rod bundles similar to the rod array used in the RBHT test section. The Weisman correlation does however under-predict the heat transfer coefficients over much of the mixed convective regime (3000 < Re < 7000).

Maximum Grid-Enhanced Heat Transfer Correlation

Because of the flow redevelopment, heat transfer downstream of a grid spacer is enhanced relative to fully developed heat transfer. The maximum heat transfer augmentation is expected to occur right at the exit of the grid where $x = 0$. Based on the analogy of momentum and heat transport, the maximum heat transfer augmentation should have the same form as the grid effect on the pressure drop or equivalently, the loss coefficient of a grid spacer. The latter was found by Rehme [8] to be proportional to the square of the grid blockage ratio ε. Accordingly the following correlation form can be obtained for the maximum single-phase convection enhancement at the grid exit:

$$[Nu_{max} - Nu_{\infty}]/Nu_{\infty} = a\,\varepsilon^2 \qquad (7)$$

The augmentation of the heat transfer has been shown in several studies, as summarized by Yao et al. [9] to be an exponential decay from a maximum at the grid spacer location to near fully developed flow heat transfer several *x/D* downstream of the grid. The maximum augmentation Nu_{max} at a grid location has been correlated by Yao et al. [9] which is expressed as

$$\left(Nu_{\max}\right)_Y = \left(Nu_{\infty}\right)_{DB}\left[1 + 5.55\varepsilon^2\right] \qquad 0.156 \le \varepsilon \le 0.348 \qquad (8)$$

where the subscript "*Y*" refers to the correlation of Yao et al., ε is the grid blockage ratio and $(Nu_{\infty})_{DB}$ is the fully developed Nusselt number based on the Dittus-Boelter correlation given by Equation (1).

It is desired to develop a more suitable heat transfer correlation for the maximum augmentation so as to adequately account for not only the grid blockage ratio but also the flow Reynolds number. This is done by using the following form for the correlation as expressed in Equation (7) as

$$\left(Nu_{\max}\right)_{RBHT} = \left(Nu_{\infty}\right)_{W}\left[1 + a\varepsilon^2\right] \qquad 0.156 \le \varepsilon \le 0.362 \qquad (9)$$

where the subscript "*RBHT*" refers to the new correlation to be developed using the RBHT single phase steam cooling data. In developing the new correlation, "a"is not assumed to be constant as in the Yao-Hochreiter-Leech correlation [9] but is treated as a function of the flow Reynolds number. A preliminary value of "a" can be obtained by applying a linear curve fit to the maximum heat transfer observed from the various tests. Figure 2 presents the maximum

Nusselt numbers measured in the RBHT steam cooling tests and in the tests employed by Yao et al. [9]. In the figure, the Weisman correlation is employed as the reference basis for determining the maximum enhancement.

In each case, the intercept is fixed to the coefficient of the applicable correlation such that for blockage ratio of zero there is no augmentation and fully developed flow conditions are maintained. This stands to reason as a smaller blockage will disrupt the flow less, resulting in less mixing and a lower heat transfer rate. Using a least square technique, the curve fit yields a preliminary value of a =5.02.

It should be noted that the various data points shown in the figure were obtained at different blockage ratios and flow Reynolds numbers. It is evident that the blockage ratio is not the only parameter affecting the maximum heat transfer augmentation. The Reynolds number also effects the maximum augmentation and should be adequately accounted for. As can be seen from Figure 2, there is considerable scattering of the data without accounting for the Reynolds number effect. Physically, this is expected because the maximum augmentation depends on the turbulent mixing level. At a higher Reynolds numbers corresponding to a stronger turbulent mixing, the grid effect may result in less heat transfer enhancement than at a lower Reynolds number corresponding to a weaker turbulent mixing. As such, the coefficient "a" cannot be treated as a constant as it would vary from one Reynolds number to another.

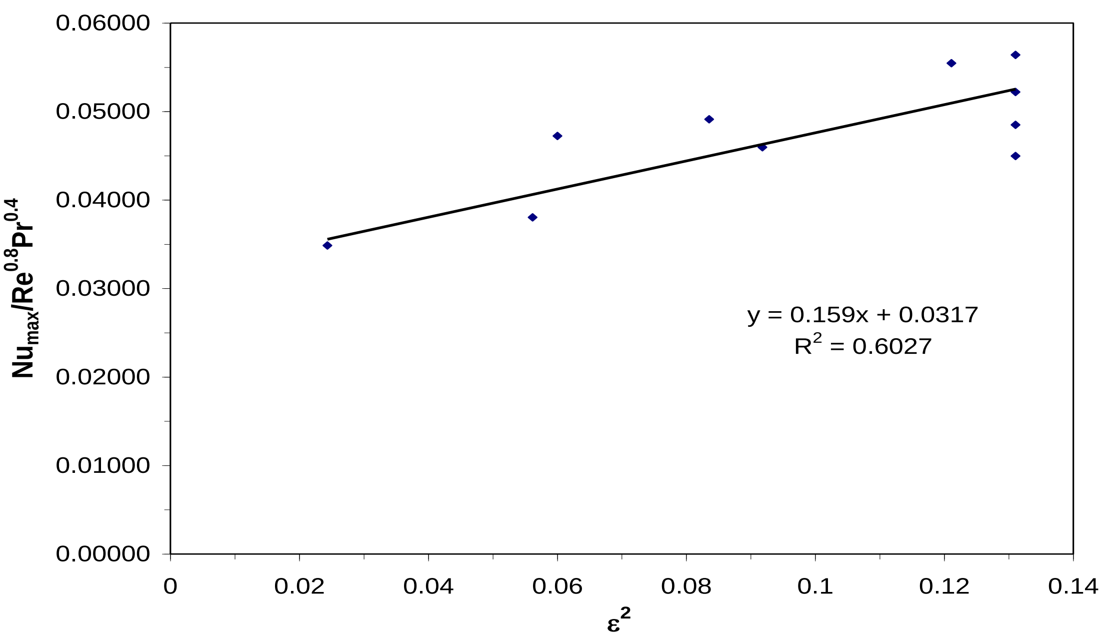

Figure 2. Variation of the Maximum Nusselt Numbers with the Grid Blockage Ratio

Using the current form of the correlation given by Equation (9), the Reynolds number dependence can be added to fine-tune the value of the coefficient "a"as follows:

$$Nu_{MAX_{RBHT}} = (Nu_{\infty})_W \left[1 + 5.02 a \varepsilon^2\right] \qquad 0.156 \le \varepsilon \le 0.362 \qquad (10)$$

Utilizing the RBHT steam cooling data [16] for which the blockage ratio is fixed, the Reynolds number dependence can be correlated as

$$a = \frac{\left[\frac{Nu_{MAX_{RBHT}}}{(Nu_\infty)_W} - 1\right]}{5.02\varepsilon^2} = a(\mathrm{Re}) \qquad (11)$$

Figure 3 presents the maximum augmentation coefficient as a function of the local flow Reynolds number. From the result of the curve fit shown in the figure, the maximum heat transfer augmentation can be obtained as

$$Nu_{MAX_{RBHT}} = (Nu_\infty)_W \left[1 + 4.65\left(\mathrm{Re}/10^4\right)^{-0.50} \varepsilon^2\right] \qquad 0.156 \le \varepsilon \le 0.362 \qquad (12)$$

Note that the maximum augmentation coefficient "a" is inversely proportional to the square root of the flow Reynolds number. As previously discussed, this behavior is physically sound. As the Reynolds number is increased, the turbulence level of the flow becomes higher and thus the maximum augmentation caused by the grid effect relative to the fully developed flow value becomes smaller.

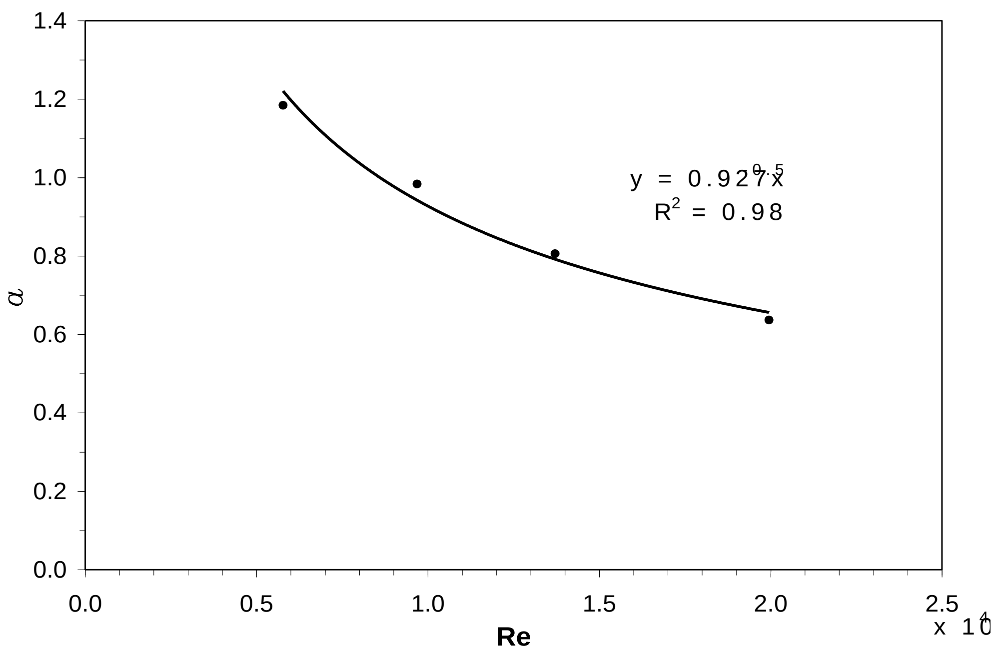

Figure 3. Coefficient for the Maximum Heat Transfer Augmentation Using RBHT Data

Single-Phase Convection Enhancement Correlation

Upon exiting the spacer grid, the flow continues to restructure and redevelop in the downstream locations. At sufficiently far downstream locations, the local Nusselt number will approach its fully developed value. Thus the local Nusselt number is expect to decay from its maximum value at the grid exit to the fully developed flow value far downstream of the grid. Using an exponential decay function to correlate the decay of the local heat transfer augmentation, the following expression can be obtained for the local Nusselt number:

$$[Nu(x) - Nu_\infty]/[Nu_{max} - Nu_\infty] = \exp[-b\,(x/D)] \tag{13}$$

where "b" is a dimensionless coefficient and D is the hydraulic diameter of the channel. The latter is used to normalize the local axial location measured from the grid as all terms in the above equation must be dimensionless. Substituting Equation (7) into Equation (13) results in the following form for the local single-phase convection enhancement at the downstream location x:

$$[Nu(x) - Nu_\infty]/Nu_\infty = a\,\varepsilon^2 \;\exp[-b\,(x/D)] \tag{14}$$

From the RBHT steam cooling tests, the decay curve was observed to be Reynolds number dependent as given by Equation (15), such that the exponential term "b" is a function of the Reynolds number, where

$$Nu_{RBHT} = \left(Nu_\infty\right)_W \left[1 + 4.65\left(\mathrm{Re}/10^4\right)^{-0.50} \varepsilon^2 e^{-b(x/D)}\right] \qquad 0.156 \le \varepsilon \le 0.362 \tag{15}$$

Solving for "b" yields

$$b = \left(\frac{1}{(x/D)}\right) \ln\left\{\frac{4.65\left(\mathrm{Re}/10^4\right)^{-0.50}\varepsilon^2}{\left[\frac{Nu_{RBHT}}{(Nu_\infty)_W} - 1\right]}\right\} = b(\mathrm{Re}) \tag{16}$$

Figure 4 presents the calculated "b" for the RBHT steam cooling tests to obtain an expression for the Reynolds number dependency. According to the results shown in the figure, an expression for "b" can be written as

$$b = 0.291\left(\frac{\mathrm{Re}}{10^4}\right)^{1.15} \tag{17}$$

Note from the above expression that "b" is an increasing function of the flow Reynolds number. This result is physically sound as the local convection enhancement downstream of the grid should decay faster at a higher turbulent mixing level corresponding to a higher flow Reynolds number.

An improved single-phase convective heat transfer correlation, accounting for spacer grid effects, thus can be obtained as

$$Nu_{RBHT} = \left(Nu_{\infty}\right)_W \left[1 + 4.65 \left(\mathrm{Re} / 10^4 \right)^{-0.50} \varepsilon^2 e^{-0.291 \left(\frac{\mathrm{Re}}{10^4} \right)^{1.15} (x/D)} \right] \qquad 0.156 \le \varepsilon \le 0.362 \tag{18}$$

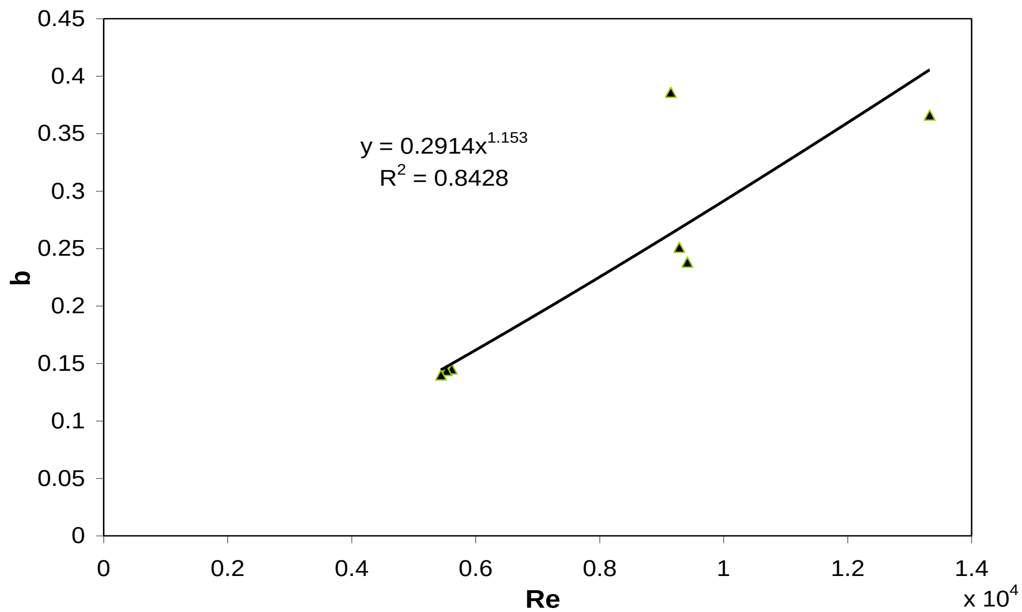

Figure 4. Heat Transfer Augmentation Decay Curve Dependence on Reynolds Number

Note that the swirling effect has not been included in the new correlation given by equation (18) but can readily be incorporated in a similar fashion as done by Yao et al. [9].

Comparisons with Experimental Data

Figure 5 to Figure 8 present comparisons of the existing correlation and the newly developed correlation predictions of the RBHT steam cooling experimental data [16]. As can be seen from these figures, over the range of Reynolds numbers from 10,000 to 30,000, the Yao-Hochreiter-Leech correlation [9] always under-predicts the measured local Nusselt numbers at all downstream locations. On the other hand, the upgraded single-phase convection enhancement correlation given by Equation (18) provides a much better predictions for the local Nusselt numbers at various downstream locations.

The new correlation represents an improved correlation over existing correlations such as the one reported by Yao et al. [9] for predicting the local Nusselt number. As shown in Figures 5 to 8, over the range of flow Reynolds numbers explored in the present study, the new correlation provides a better prediction for (i) the maximum Nusselt number at the grid exit, (ii) the rate of decay of the convection enhancement downstream of the grid, and (iii) the fully developed value at locations far downstream as observed in the RBHT single phase steam cooling tests.

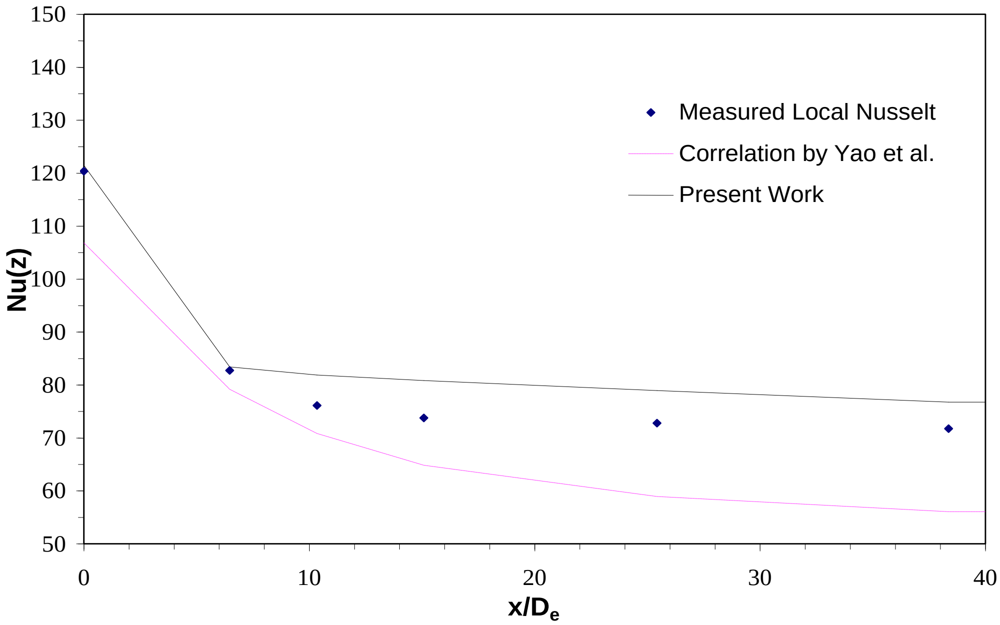

Figure 5. Heat Transfer Augmentation Downstream of Grid Spacer 5 at Re = 30000

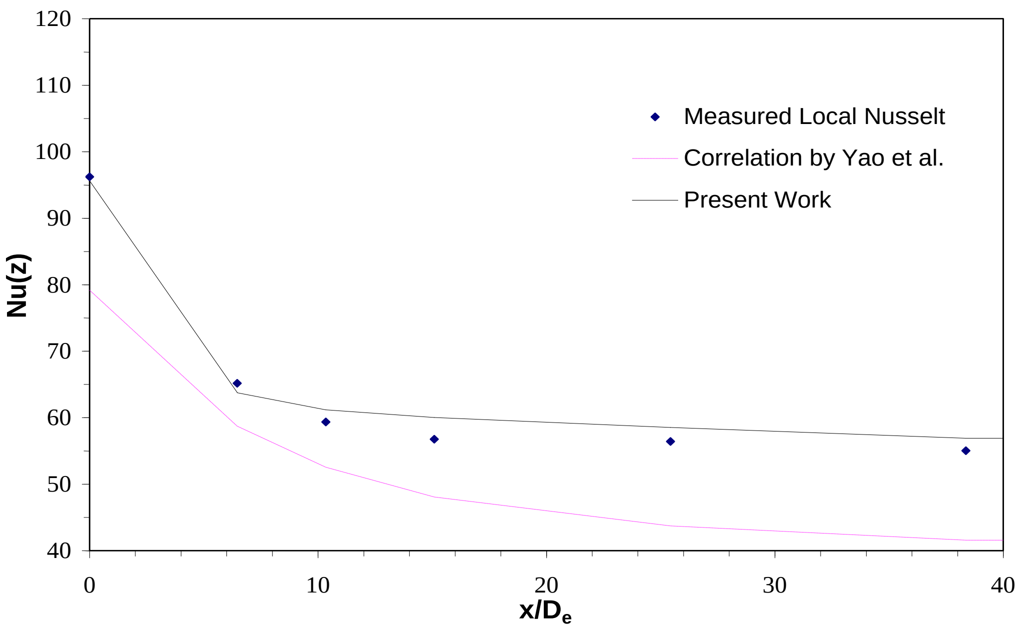

Figure 6. Heat Transfer Augmentation Downstream of Grid Spacer 5 at Re = 20000

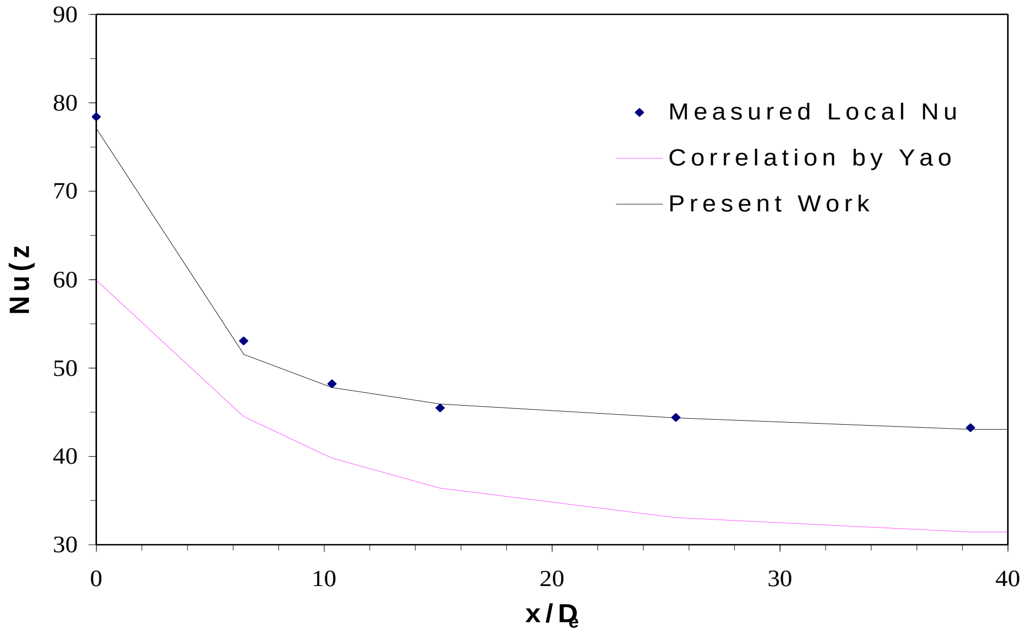

Figure 7. Heat Transfer Augmentation Downstream of Grid Spacer 5 at Re = 15000

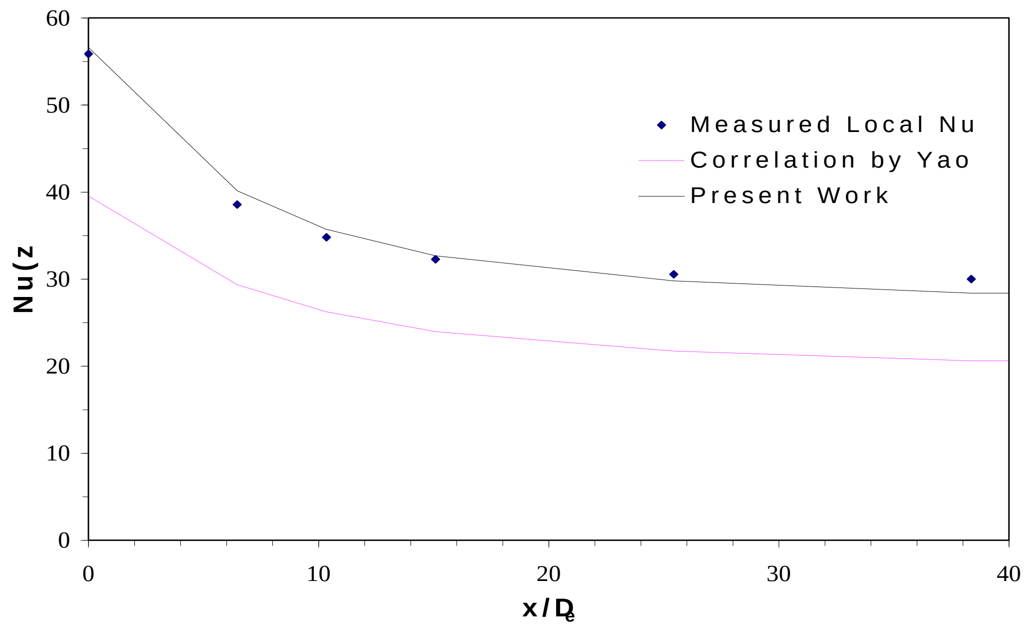

Figure 8. Heat Transfer Augmentation Downstream of Grid Spacer 5 at Re = 10000

Summary and Conclusions

The effect of spacer grids on single phase convection enhancement has been investigated using the steam cooling test data obtained at the RBHT facility where the local heat transfer was determined from instrumentation placed downstream of the grid. The measured local heat transfer exhibited a maximum right at the exit of the grid. As the flow moved downstream of the grid, it became more fully developed, causing the heat transfer augmentation to diminish. An improved single-phase convective heat transfer correlation accounting for heat transfer enhancement at a grid spacer has been developed. The new correlation accounts for the dependence of local heat transfer enhancement on both the flow Reynolds number and grid blockage ratio.

The maximum convective heat transfer enhancement at a grid spacer location which has not been fully investigated in the past has been carefully investigated in this study. It is found that the maximum convective enhancement depends strongly on the flow Reynolds number in addition to the grid blockage ratio. This finding is radically different from all existing correlations which treat the maximum convective heat transfer enhancement to be function of the grid blockage ratio alone, independent of the Reynolds number.

The exponential decay of the local heat transfer augmentation, which has been treated to be independent of the flow Reynolds number in the past, is also found to be Reynolds number dependent. The present results are more physically sound than those reported by previous investigators as the process of flow restructuring can be strongly affected by the local turbulent level. Physically, the flow tends to restructures more quickly at higher Reynolds numbers owing to stronger turbulent mixing effects. As such, the flow would reach fully developed behavior faster which in turn would exhibit faster decay of the local grid-enhanced heat transfer augmentation.

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