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Thermal Hydraulic Study of Utilizing Unfinned Plate Fuel in the MITR

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ABSTRACT

A unique feature of the MIT Research Reactor fuel element design is the use of 0.01" x 0.01" longitudinal fins machined into the fuel plate cladding to improve heat transfer. However, there is motivation to transition to flat (unfinned) fuel plates due to added fabrication costs and the potential for crud filling in the grooves. A thermal hydraulic loop has been constructed at MIT with a heated, full-scale coolant channel with prototypic dimensions and operating conditions of that found in the MITR. The experiment is designed to measure single phase heat transfer coefficient and onset of nucleate boiling on a flat plate for mass fluxes ranging from 750 kg/m^2-sec to 5250 kg/m^2-sec and subcoolings from 10 °C to 60 °C. This study provides an overview of the experimental apparatus along with preliminary heat transfer data. The measured convective heat transfer coefficient is compared to existing correlations.

1. Introduction

Several initiatives are underway at the MIT Nuclear Reactor Laboratory in support of the conversion of the MITR-II from highly enriched uranium (HEU) to low-enriched uranium (LEU) fuel. A power uprate from 6 MW to 7MW has been proposed for the converted core in order to maintain the same thermal neutron flux. Unlike the other high performance research reactors in the United States, the MITR fuel plates are finned to improve heat transfer to the coolant. However, there is motivation to implement flat (unfinned) fuel plates in the new LEU core because of concern over crud filling in the grooves and promoting oxide growth. Implementation of unfinned plates would also reduce fabrication costs for the new U10Mo fuel.

Thermal hydraulic studies are being conducted to measure the single phase convective heat transfer coefficient and onset of nucleate boiling in a narrow rectangular channel prototypic of that found in material test reactors (MTR's). The Limiting Safety System Setting (LSSS) criterion for the MITR, and for similar MTR's, is onset of nucleate boiling (ONB). For the MITR, this means that ONB must not be encountered anywhere on the clad during routine 6 MW operation nor during natural convection with heat generation up to 100 kW [1]. Avoidance of onset of nucleate boiling is viewed as a conservative criterion, as the onset of flow instability (OFI) and/or the critical heat flux (CHF) are viewed as the phenomena which could lead to excess clad and fuel temperatures. Narrow channels are more susceptible to localized dryout and a reduction in CHF as a result of two-phase flow instabilities [2], since even a small amount of vapor can lead to high local void fractions.

The Bergles-Rohsenow correlation [3], shown below, is used to predict the onset of nucleate boiling heat flux in the MITR.

$$q''_{ONB} = 1083P^{1.156}[1.8(T_w - T_{sat})]^{2.16/P^{0.0234}} \tag{1}$$

where all variables are in SI units except for P which is in bar. The Bergles-Rohsenow is applicable only for water and 1 bar$<P<$138 bar. Note that equation (1) was developed from data obtained for circular geometries, though it is commonly applied to narrow rectangular channels such as those found in the MITR. In a 1986 study supporting a power uprate of the JRR-3 following conversion to LEU fuel, Sudo et al. [4] note that the Bergles-Rohsenow correlation is conservative in predicting ONB and adopting this correlation increases the safety margin. The study by Sudo et al. has largely been the motivation for continued usage of the Bergles-Rohsenow correlation for MTR safety analyses, including that for the MITR. Basu et al. [5] also note that existing correlations, such as that of Bergles and Rohsenow, tend to underpredict the wall superheat at boiling incipience for most cases.

Selection of an appropriate single-phase heat transfer correlation is necessary for predicting ONB, as the wall superheat in equation (1) is unknown. The ONB heat flux may then be solved iteratively using equation (1) and the correlation for single-phase heat transfer. However, there is no one correlation that may be considered most suitable for high aspect ratio, narrow rectangular coolant channels, whether finned or unfinned. Nonetheless, what is typically referred to as the Dittus-Boelter equation, which is discussed in detail in section 3, is commonly used in calculating single-phase convective heat transfer coefficients. The focus of this paper is the experimental measurement of single phase heat transfer utilizing a flat, unfinned plate in a narrow rectangular channel. Such data are necessary as a baseline regardless of whether transitioning to unfinned plates is found to be feasible with the MITR for the 7 MW uprate. An overview of the experimental facility is provided in the next section.

2. Experimental

A heated thermal hydraulic loop has been designed and built to accommodate a test section prototypic of a single fuel assembly subchannel in a MTR. A schematic of the flow loop is shown in Figure 1. All wetted parts consist of stainless steel and hard fluoroelastomers to reduce contaminants in the de-ionized water stream. A bellows-type accumulator acts as a system pressurizer and thermal expansion compensator. A one horsepower centrifugal pump allows for mass fluxes up to 6500 kg/m^2-sec through the test section. A four pass shell-and-tube heat exchanger transfers heat to the building chilled water system. System flow rate is measured using a vortex meter. Test section and heat exchanger inlet and outlet temperatures are measured using four-wire RTD's. A dissolved oxygen meter allows for the quantification of the dissolved gas content of the fluid stream. Pressure transducers after the test section inlet and before the outlet allow for measurement of pressure drop across the flow channel. A solenoid valve on the chilled water system, along with a preheater, allow for fully automated control of the test section inlet temperature via a full PID controller.

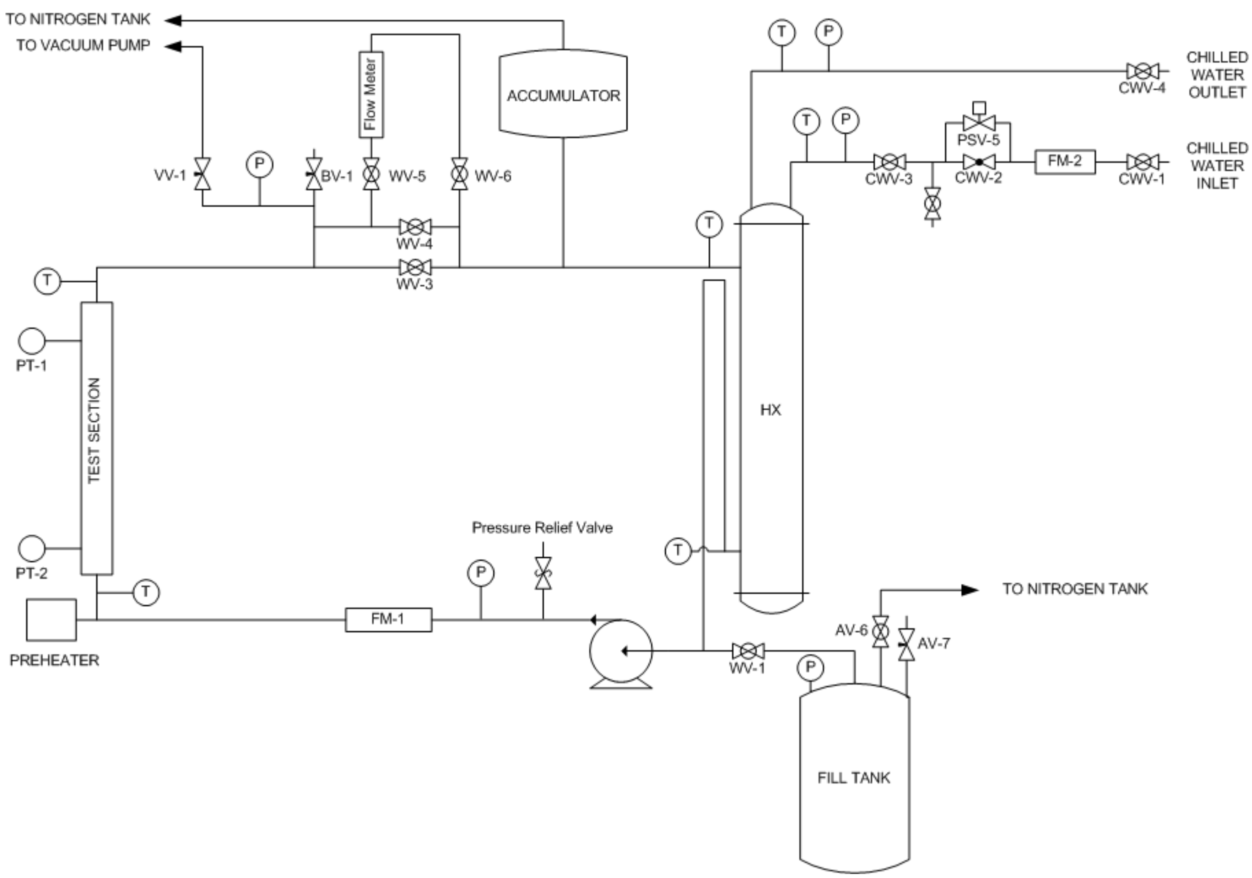

Figure 1: Schematic of the Thermal Hydraulic Test Loop.

The test section consists of a vertical, narrow rectangular channel uniformly heated on one side with a viewing window on the front to allow for visualization of ONB using high speed videography. The inlet and outlet of the flow channel have smooth transition regions, fabricated using wire electrical discharge machining, to reduce vortex shedding and ensure that flow becomes fully developed within a reasonable distance. Figure 2 shows a photograph of the test section. Table 1 lists detailed specifications for the test section and flow loop. The heated side of the channel consists of a plate seated in a high performance fluoropolymer insulator. The plate is heated resistively using a 72 kW DC power supply capable of supplying 4500 A at 16 V. Current is measured using a Hall effect current transducer, while voltage is measured from taps on the heater electrodes. Current is delivered to the heater plate using a copper busbar and four 2000 MCM welding cables. Eighteen Type E thermocouples measure the temperature on the backside of the heater plate, with the front side temperature being calculated by:

$$T_{surf} = T_{meas} - q'''_{elec}\frac{t_{plate}^2}{2k_{plate}} + \left[q'''_{elec}t_{plate} - q''_{therm}\right]\frac{t_{plate}}{k_{plate}} \qquad (2)$$

National Instruments LabVIEW is used to control the facility, with data collected through an Agilent 34980A Multifunction Measurement Unit. Single phase heat transfer tests were conducted by first degassing the fluid and subsequently setting the surface heat flux at 200 kW/m^2. The channel mass flux was increased step-wise, with sufficient waiting time to reach thermal equilibrium. Heat loss was determined by comparing the electric power to the thermal power, and was typically between 5% and 10%. Measurement uncertainty in the heat transfer coefficient was typically 10% or less, except at high mass fluxes where the temperature drop was small.

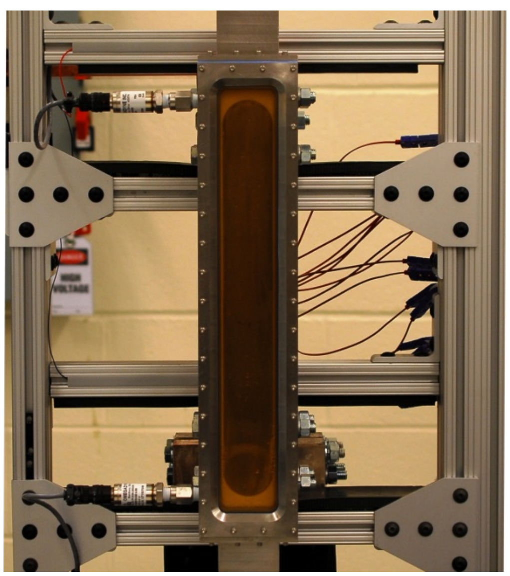

Figure 2: View of the Test Section From the Front.

Table 1: Design Parameters of the Thermal Hydraulic Loop and Test Section.

Parameter	Value
Gap thickness	1.96 mm
Channel length	483 mm
Channel width	56 mm
Heated length	305 mm
Heated width	51 mm
Hydraulic diameter	3.78 mm
Aspect ratio	0.035
Inlet pressure	Up to 3 bar
Mass flux	Up to 6500 kg/m^2-sec
Reynolds number	Up to ~50,000
Surface heat flux	Up to 3.8 MW/m^2

3. Preliminary Results and Discussion

In this study, the single phase heat transfer coefficient was measured for mass fluxes ranging from 750 kg/m^2-sec up to 5250 kg/m^2-sec with inlet conditions slightly above 1 bar and an inlet temperature of ~42 °C. These conditions correspond to $Pr \approx 4$ and Re ranging from approximately 5000 to 32,000. For a smooth entrance, the critical Reynolds number, that is, the Reynolds number below which flow is laminar, ranges from 3400 for parallel plates to 4300 for a rectangular channel with an aspect ratio, α^*, of 0.1 [6]. Therefore, it is expected that flow will be turbulent for the conditions tested. Preliminary results from these experiments are presented in the following figures. Figure 3 shows the local Nusselt number plotted against dimensionless length for a fixed mass flux of 750 kg/m^2-sec. It would appear that the flow is fully developed thermally once the dimensionless length, z^+, equals 30.

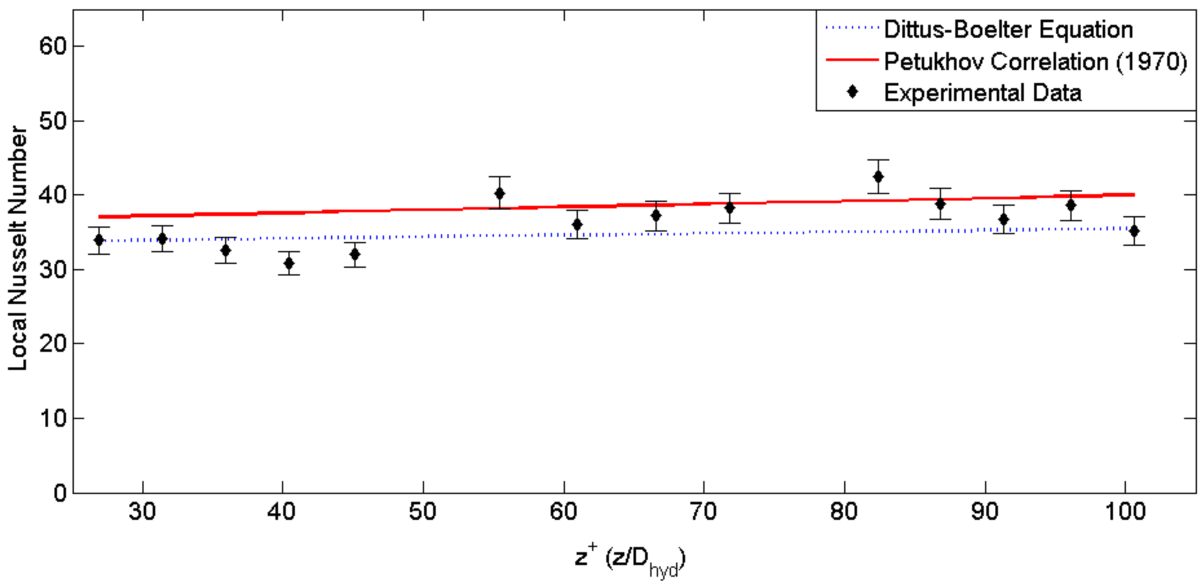

Figure 3: Local Nusselt Number versus Dimensionless Length for G=750 kg/m^2-sec and Pr_{avg}=3.9. Local values for the Dittus-Boelter equation and Petukhov Correlation, discussed below, are plotted for comparison. Note that these correlations are typically applied for Re>10,000.

Figure 4 shows the fully developed, channel average Nusselt number, Nu, plotted against the Reynolds number, Re. The Dittus-Boelter equation and Petukhov correlation are shown for comparison. Note that the Prandtl number for all data points is approximately 4. A power fit to the experimental data for $Pr\approx4$ yields:

$$Nu = 0.036Re^{0.83} \tag{3}$$

where 95% confidence intervals on the leading coefficient and exponent are [0.019, 0.054] and [0.79, 0.88], respectively. The Dittus-Boelter equation, which is widely used in the predicting the single-phase heat transfer coefficient, is:

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{4}$$

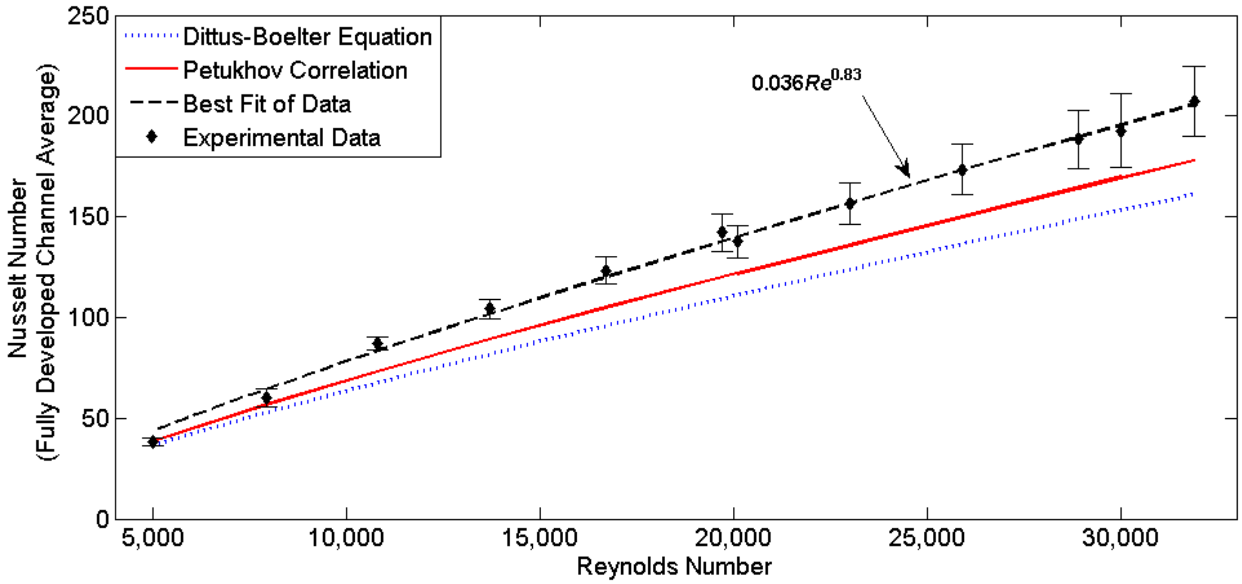

Figure 4: Fully Developed, Channel Average Nusselt Numbers for a Narrow Rectangular Channel with α*=0.035 and Pr_{avg}=4.0. Error bars reflect measurement uncertainty. Note that the Nusselt numbers measured in this study are, on average, about 25% higher than those predicted by the Dittus-Boelter equation. Also note that both correlations are typically applied for *Re*>10,000.

It should be noted that this is not the original form presented by Dittus and Boelter, but rather represents an equation presented by McAdams, as noted by Winterton [7]. Equation (4) is typically valid for smooth conduits with *Re*>10,000. Note that the properties in equation (4) are evaluated at the bulk mean temperature. Petukhov presents the following correlation, where the properties are evaluated at the bulk fluid temperature [8]:

$$Nu = \frac{(f/8)RePr}{1.07 + 12.7\sqrt{f/8}(Pr^{2/3} - 1)} \tag{5}$$

Equation (5) is typically applicable for $10{,}000<Re<5\text{x}10^6$. For smooth pipes, Petukhov recommends the following for calculating the friction factor:

$$f = \frac{1}{1.82log_{10}(Re) - 1.64} \tag{6}$$

Note that the surface finish of the plate used for this study was prepared to have an RMS roughness, ε, of approximately 0.5μm, which is similar to that measured on aluminum 6061 cladding coupons from the Advanced Test Reactor. Referring to the Moody diagram [9], a roughness of 0.5 μm would not be expected to have an appreciable effect on the friction factor and therefore should have little effect on the heat transfer coefficient.

Equation (4) and equation (5) were developed for circular tubes under fully developed flow. While many studies have been performed for rectangular channels, few approach aspect ratios as small as that studied here or investigate heating conditions identical to this study (one wall at uniform heat flux with the other walls insulated). However, parallel plate studies (where $\alpha^* \rightarrow 0$) should also be considered. Sparrow and Cur [10] conduct experiments for a channel with $\alpha^*=0.0556$, where $10{,}000<Re<45{,}000$. Their configuration includes heating on both sides and heating on one side only as in this study. However, their investigation is limited to a fluid with $Pr=2.5$, and the heated wall condition is isothermal. For the asymmetric heating case in which only one wall is heated, they find:

$$Nu = 0.0464Re^{0.76} \tag{7}$$

The results of Sparrow and Cur indicate that the Nusselt number will be about 8% lower when their channel is heated on one side only versus on both sides. Kays and Leung [11] reach a similar finding for parallel plates, with Nusselt numbers being about 10% less for channels heated on one side only. From the investigation by Kays and Leung, Bhatti and Shah [12] note that, in the range $10{,}000<Re<30{,}000$, the Nusselt number for parallel plates is up to 1.23 times that predicted by circular conduit correlations.

4. Conclusion

A heated thermal hydraulic loop has been constructed to measure the single phase heat transfer coefficient and onset of nucleate boiling in a prototypic MTR fuel coolant channel. Experimental measurements using this facility will directly support the LEU conversion and power uprate of the MITR. Preliminary single phase heat transfer data were presented for de-ionized water in the unfinned, narrow rectangular channel heated on one side with $\alpha^*=0.035$. Mass fluxes ranged from 750 kg/m^2-sec up to 5250 kg/m^2-sec for a Prandtl number of ~4. Measured heat transfer coefficients are, on average, about 25% higher than those predicted by the Dittus-Boelter equation, which is consistent with results found in the literature for narrow rectangular channels. In general, the Petukhov correlation more closely predicts experimental Nusselt numbers than the Dittus-Boelter equation.

Further verification of these preliminary results will be performed and onset of nucleate boiling will be studied in the facility to obtain experimental values of the ONB heat flux. An analysis of the MITR using RELAP5 will be performed to determine the maximum achievable operating power using unfinned fuel elements.

5. Acknowledgements

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6. Nomenclature

A	area, m^2
c_p	specific heat at constant pressure, J/(kg K)
D_{hyd}	hydraulic diameter $\equiv 4A_{flow}/P_w$, m
f	Darcy friction factor
G	mass flux, kg/m^2-sec
h	heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
Nu	Nusselt number $\equiv hD_{hyd}/k_l \equiv$ ratio of convective to conductive heat transfer
P	pressure, bar
Pr	Prandtl number $\equiv \mu c_p/k_l \equiv$ ratio of momentum diffusivity to thermal diffusivity
q''	heat flux, W/m^2
q'''	volumetric heat generation, W/m^3
Re	Reynolds number $\equiv GD_{hyd}/\mu \equiv$ ratio of inertial forces to viscous forces
T	temperature, ºC or K
t	thickness, m
z	axial coordinate, m
z^+	dimensionless length $\equiv z/D_{hyd}$

Greek symbols

α^*	aspect ratio $\equiv$ channel gap/channel width
ε	root mean square roughness, μm
μ	dynamic viscosity, kg/(m sec)

Subscripts

elec	electric

l	liquid
meas	measured
sat	saturation
therm	thermal
w	wall

7. References

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