Subcooled and Saturated Boiling Heat Transfer Data Compared with Existing Correlations

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Abstract

Subcooled and saturated boiling heat transfer data from experiments performed recently at McMaster University are compared with existing correlations. The test section consisted of a 93.2 cm vertical section of 4.6 mm ID Inconel 600 tubing, electrically heated by a 96 kW DC power supply. Data was collected 4 and 24 cm from the test section outlet at a pressure of 2.0 MPa, for mass fluxes of 1500 and 2000 kg $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$, inlet temperatures of 126, 148, 170, and 180^{o}C, and heat fluxes from 100 to 1100 kW m^{-2}. Maximum equilibrium quality was 0.062. All of the subcooled boiling correlations showed good agreement with the data. The correlation of Thom *et al* predicted approximately 95% of the data within $\pm$30%. The Chen correlation generally overpredicted saturated boiling data by 100–200% while the Steiner-Taborek correlation was able to predict 76% of the data within $\pm$30%.

1. Introduction

Predicting boiling heat tranfer rates accurately is important for the safe operation of nuclear power plants. Boiling heat transfer correlations allow nuclear engineers and safety analysts to predict fuel sheath pellet temperatures. Saturated boiling processes are particularly important in CANDU®and boiling water reactors that operate near or at the saturation point of the primary coolant.

Subcooled nucleate boiling heat transfer is often well represented as a wall superheat expressed as the product of a power function of heat flux and an empirical function of pressure. High heat transfer rates in this regime are due largely due to the near-wall turbulence generated by bubble departure [1]. Heat transfer may also be enhanced by the transport of latent heat away from the wall to the subcooled bulk flow. Guglielmini *et al* evaluated many subcooled boiling correlations against a wide range of experimental data in [2]. The Thom *et al* correlation is shown in Equation 1 below [3].

$$T_W - T_{sat} = 22.65 \left(\frac{\ddot{q}}{1000} \right)^{0.5} \exp\left(-\frac{P}{8.7} \right) \tag{1}$$

When the fluid becomes saturated the bubbles will not condense but rather form two-phase structures called ‘flow regimes’ which may vary from bubbly to annular before the critical heat flux is reached [3]. These flow structures considerably complicate the calculation of heat transfer rates. Both nucleate boiling at the heated surface and direct evapouration at liquid-vapour interfaces, such as from the liquid surface film to the vapour core in an annular flow, contribute to thermal energy transport in saturated flows.

The modified version of the original Chen correlation is widely used, for example in the RELAP5 code [4], in the nuclear industry to predict saturated boiling heat transfer rates [5, 6]. The much more recent Steiner-Taborek correlation is very well documented and based on a large database containing more than 10 000 experimental data points for water alone [7]. The additive form of the Chen correlation and the 'asymptotic' form of the Steiner-Taborek correlation are shown in Equations 2 and 3 respectively.

$$h_{tp} = h_{mic} + h_{mac} = h_{nb}S + h_L F \tag{2}$$

$$h_{tp} = (h_{nb}^3 + h_{cb}^3)^{1/3} = ((h_{nb,o}F_{nbf})^3 + (h_{LO}F_{nbf}^3))^{1/3} \tag{3}$$

At small values of local subcooling—based on the 'local' bulk fluid enthalpy—nucleated bubbles may not condense in the bulk flow. The point of net vapour generation (NVG), and the 'actual' flow quality (x_a)—the local non-equilibrium vapour mass fraction of the flow—can be predicted by the Saha-Zuber correlation [8].

Kandlikar names this region—where NVG has been reached but the flow has not yet reached thermodynamic equilibrium saturation—"significant void flow". He proposed that heat transfer in this region may be accurately predicted by evaluating his saturated boiling correlation using the flow quality, x_a, instead of the equilibrium quality, x_e and obtained good results for a small number of data points [9].

Boiling heat transfer data recently collected during the commissioning of a thermalhydraulic experiment at McMaster University are compared to existing subcooled and saturated boiling correlations in this paper. Subcooled boiling data is compared with five different correlations that are all similar in form. "Significant Void Flow" and saturated boiling data are compared with the modified Chen correlation and the Steiner-Taborek correlation evaluated using both the flow quality, x_a, and the equilibrium quality, x_e. Only the 'macroscopic' or 'convective boiling' components of h_{tp} are affected by x in the modified Chen, and Steiner-Taborek correlations, respectively.

2. Experimental Details

The experimental apparatus used to gather the data presented in this paper is thoroughly described in the author's Master's thesis, along with boiling curves of the raw experimental data for single phase and boiling heat transfer [10]. It is briefly described here—a flow diagram is shown in Figure 1.

The 4.6 mm ID Inconel 600 test section was electrically heated by a 96 kW DC power supply with an entrance length of more than 60 diameters and a heated length of 93.2 cm. Flow was vertical and upward. Flow rate was controlled using a needle valve upstream of the flow meter. A 40 kW AC power supply electrically heated a 1.5 m long coiled length of 7.7 mm ID 316 Stainless Steel tubing that was used to control inlet temperature. Heat was removed at the test section outlet by a coiled counterflow tube and shell heat exchanger. The loop was pressurized by charging a

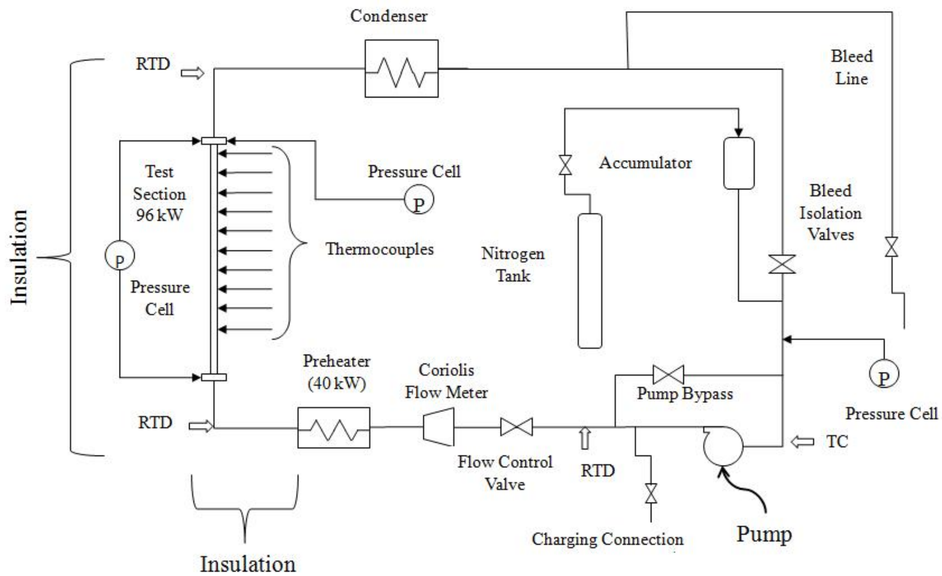

Figure 1: Flow diagram of the experimental apparatus at McMaster University. TC denotes a thermocouple and RTD denotes a resistive temperature device.

bladder with nitrogen inside a 3.79 L accumulator. Pressure was controlled by monitoring the measured TS outlet pressure and adjusting a pressure-reducing and a back-pressure regulator that joined the bladder to a high pressure nitrogen cylinder.

Fluid temperature measurements were made at the test section inlet and outlet using RTDs with an uncertainty of ± 3 K. Wall temperature measurements were made by K-type thermocouples with an uncertainty of ± 3 K. They were electrically isolated by a very thin layer of high temperature ceramic cement. Fluid flow rate mas measured by a coriolis mass flow meter with an uncertainty of approximately $\pm 3\%$—a new, appropriately ranged, flow meter has been installed since these experiments were performed which has improved this uncertainty by an order of magnitude. Outlet pressure was measured by a Rosemount 3051CA absolute pressure transmitter with an uncertainty of ± 12 kPa. All quoted uncertainty values have confidence intervals of 95%.

2.1 Experimental Procedure

The experimental data presented here were gathered at steady state. The tubing was bled of any air or vapour then closed and pressurized. Coolant was then run through the heat exchanger. The pump was then turned on and the flow rate adjusted to the desired value. Inlet temperature was raised until the correct subcooling was reached. Finally, power was applied to the test section. When the desired test section power was reached for each data point, controls were adusted to maintain the desired boundary conditions and all process measurements given time to reach steady state before recording data. This process was repeated for each succeeding higher test section power.

The local enthalpy at each measuring location along the test section was linear extrapolated based on the inlet temperature and mass flow rate. Local qualities were then evaluated based on the local enthalpy. Fluid properties, including temperature, were evaluated at the test section outlet pressure, based on the extrapolated enthalpy. Inside wall temperatures were evaluted based on the measured outside wall temperature and test section power using the thermal conductivity fit to Inconel 600 and the method derived in [11].

3. Results and Discussion

Experimental results were compared with the predictions of correlations by converting predicted values of wall temperature and/or heat transfer coefficient into a local Nusselt number—$Nu = {}^{h_{tp}L}/_{k_b}$. Note that the fluid thermal conductivity was evaluated at the local *bulk* fluid temperature. For saturated boiling correlations evaluated using the equilibrium quality, x_e, zero was assigned to negative values of x_e for calculation of h_{tp}.

3.1 Subcooled Boiling

A formal onset of nucleate boiling (ONB) correlation was not used to select subcooled boiling data. Rather, based on qualitative observation of the boiling curves generated by the experiments, $T_w - T_{sat} > 5\ K$ and $x_e < 0.0$ were used as the subcooled boiling data selection criteria.

The correlations of Jens-Lottes, Thom *et al* [3], Thom as modified by Novog [12], Rassokhin *et al* and Labuntsov [2] were compared with 77 experimental data points. The results are summarized in Table 1.

$L - z$ (# data) ${}^{\pm 20\%}/_{\pm 30\%}$	24 cm (45)	4 cm (32)	All (77)
Jens-Lottes	65.6 / 84.4	71.1 / 88.9	68.8 / 87.0
Thom *et al*	84.4 / 100	80.0 / 97.8	81.8 / 98.7
Thom *et al*[12]	93.8 / 100	64.4 / 91.1	76.6 / 94.8
Rassokhin *et al*	84.4 / 100	60.0 / 77.8	70.1 / 87.0
Labuntsov	84.4 / 96.9	68.9 / 93.3	75.3 / 94.8

Table 1: Percentage of subcooled heat transfer data predcited within 20% and 30% for each correlation at two different test section locations.

The Thom correlation, plotted against the experimental data in Figure 2, had the best overall agreement with the data. However, the modified Thom and Labuntsov correlations also predicted more than 90% of the data within ±30%. It is evident that these simple correlations capture the major governing phenomena during subcooled nucleate boiling: heat flux and pressure—the latter may be interpreted as a highly empirical way of representing a function of fluid properties.

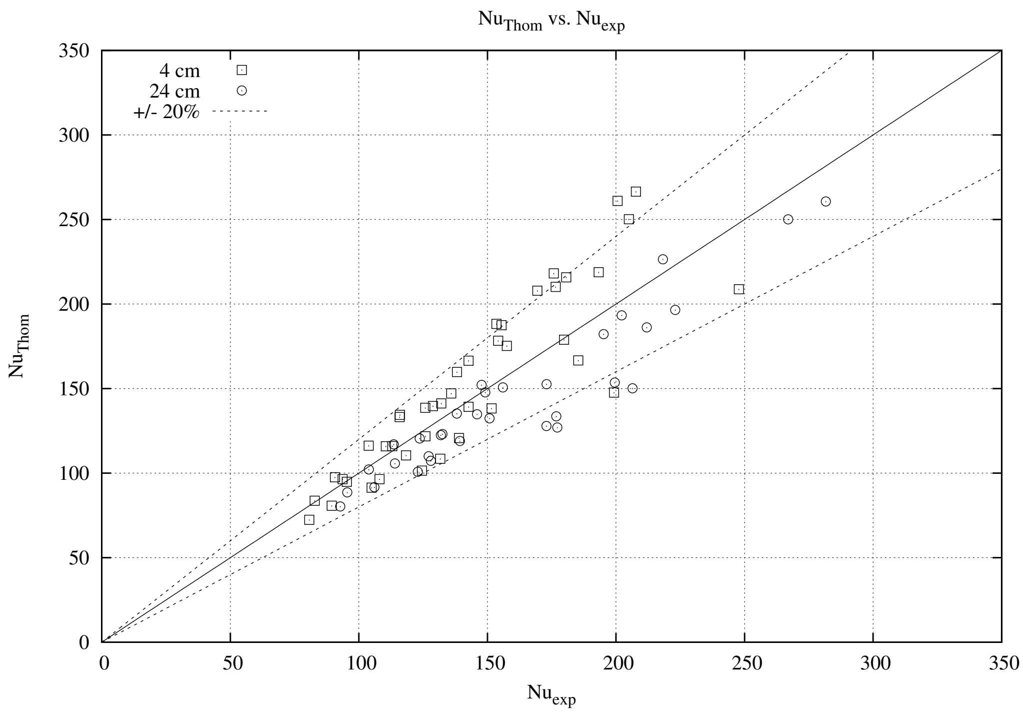

Figure 2: Comparison of Nu_{exp} with the prediction of the Thom correlation for subcooled boiling

3.2 Saturated Boiling

A relatively small number of data points were gathered where the local fluid temperature had reached saturation. Local *flow* quality, evaluated using the Saha-Zuber correlation, greater than zero was the saturated boiling data selection criteria.

	$x_a > 0$			$x_e > 0$
$L - z$ (# data) $^{\pm 20\%}/_{\pm 30\%}$	24 cm (7)	4 cm (29)	All(36)	4 cm (17)
Chen (x_e)	0 / 0	0 / 0	0 / 0	0 / 0
Chen (x_a)	0 / 0	0 / 0	0 / 0	0 / 0
Steiner-Taborek (x_e)	85.7 / 100	48.3 / 65.4	55.6 / 63.9	58.8 / 76.5
Steiner-Taborek (x_a)	71.4 / 100	37.9 / 53.8	44.4 / 55.6	47.1 / 58.8

Table 2: Percentage of heat transfer data for $x_a > 0$ and $x_e > 0$ predicted within 20% and 30% for each correlation at two different test section locations.

Table 2 summarizes the comparison of the experimental results with the Chen and Steiner-Taborek correlations evaluated using both the flow quality, x_a, and the equilibrium quality, x_e for all data with $x_a > 0$ and for the data gathered near the test section exit with $x_e > 0$. The modified Chen correlation predicts none of the data within $\pm 30\%$ while the Steiner-Taborek generally overpredicts the data.

The data is plotted against the modified Chen correlation in Figure 3, and against the Steiner-Taborek correlation in Figure 4. It is evident that the Chen correlation generally overpredicts the data on the order of 100–200%. The relative magnitude of the two terms in each correlation—the nucleate boiling and convective boiling terms, respectively—are on the same order of magnitude in both correlations. The Steiner-Taborek correlation includes a diameter correction for the nucleate boiling term while the Chen correlation does not. However, the diameter correction predicts an *increase* in heat transfer with diameter, so this correction actually makes the prediction worse in this case, since the test section diameter, 4.6 mm, is smaller than the 'reference' diameter, 10 mm, in the correlation.

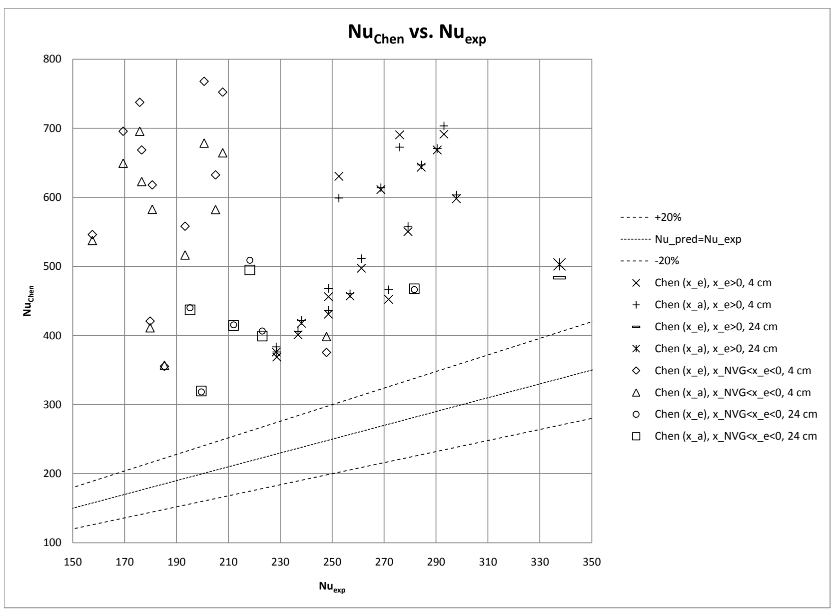

Figure 3: Nu_{exp} compared with the Chen correlation evaluated using x_e and x_a.

3.2.1 The Region of $x_{NVG} \leq x_e < 0.0$

For the subset of data that had $x_{NVG} \leq x_e < 0.0$ the saturated boiling correlations were compared against one another and the Thom correlation which gave the best results overall for subcooled boiling. The results are summarized in Table 3.

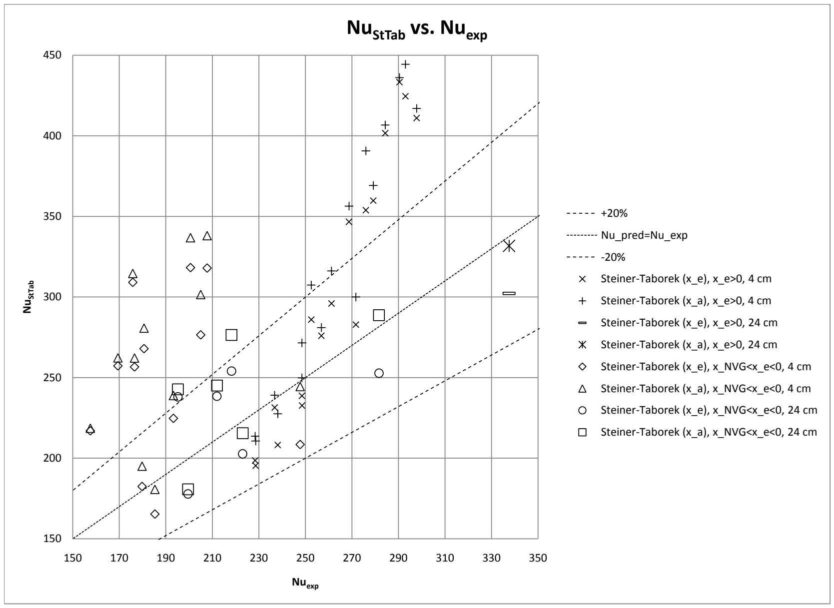

Figure 4: Nu_{exp} compared with the Steiner-Taborek correlation evaluated using x_e and x_a.

Similarly to the data set with $x_a > 0$, the Chen correlation does not predict any of the data within $\pm 30\%$. The Steiner-Taborek correlation performs slightly worse in this regime than it does for the satured-only data, as can be seen by comparing Table 3 with the $x_e > 0$ column in Table 2. The Thom correlation predicts the data far better than either of the saturated boiling correlations in this regime.

Figures 3 and 4 demonstrate the goodness of prediction for the saturated boiling correlations in each of the ranges $x_e > 0.0$ and $x_{NVG} \leq x_e < 0.0$, for each of the thermocouple locations. The data for $x_a > 0.0$ consists of the two ranges together. It is evident that evaluating Nu using the flow quality worsens the overprediction of both correlations. This makes sense since both correlations predict increasing h_{tp} as quality increases based on the premise—and the evidence on the data sets used for derivation of the correlation—that vapour moving at very high velocities will enhance heat transfer.

Based on these results it is likely that for all of the data presented here that nucleate boiling may be the dominant mode of heat transfer. This is corroborated by the fact that the maximum equilibrium quality for the entire data set is less than 6.5% which is likely too small to form an annular flow regime where liquid-vapour interface evapouration and convective enhancement of heat transfer of high velocity vapour would play a larger role.

$L-z$ (# data) $^{\pm 20\%}/_{\pm 30\%}$	24 cm (6)	4 cm (12)	All (18)
Chen (x_e)	0 / 0	0 / 0	0 / 0
Chen (x_a)	0 / 0	0 / 0	0 / 0
Steiner-Taborek (x_e)	83.3 / 100	33.3 / 33.3	50.0 / 55.6
Steiner-Taborek (x_a)	66.7 / 100	25 / 33.3	38.9 / 55.6
Thom	83.3 / 100	58.3 / 91.7	66.7 / 94.4

Table 3: Percentage of heat transfer data for 'significant void flow' region predicted within 20% and 30% for each correlation at two different test section locations.

4. Conclusion

All of the subcooled boiling correlations that were evaluated showed good agreement with the data. The Thom correlation gave the best results. It was found that the Chen correlation significantly overpredicted the saturated boiling data and subcooled data taken where the local flow quality was greater than zero. The much more recent Steiner-Taborek correlation showed reasonable but not excellent agreement with the saturated data, predicting about 75% of the data within $\pm 30\%$. In the region of 'significant void flow', the Thom correlation had very good performance, predicting over 94% of the data, while the Chen and Steiner-Taborek correlations generally overpredicted the data.

5. References

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