HEAT TRANSFER PARAMETERS FOR GLASS-PEENED CALANDRIA TUBE IN PRESSURE TUBE AND CALANDRIA TUBE CONTACT CONDITIONS

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Abstract

During a postulated event of large LOCA in CANDU reactors, the pressure tube may balloon to contact with its surrounding calandria tube to transfer heat to the moderator. To confirm the integrity of the fuel channel after the contact with a given moderator subcooling, many experiments have been performed in the last three decades by applying different pressure tube heatup rates, different pressure tube pressures and different moderator subcoolings for calandria tubes with smooth outer surface and glass-peened surface. A concept of Equivalent Moderator Subcooling (EMS) has been put forward to determine integrity of fuel channel upon pressure tube/calandria tube contact based on the existing experiment results. This concept has been presented in another work. In this work, the contact thermal conductance between pressure tube and calandria tube, critical heat flux, minimum film boiling temperature, empirical methods for nucleate boiling and film boiling heat transfer coefficient on the glass-peened calandria tube surface are discussed and estimated based on some experimental results and the EMS concept. These parameters are confirmed by simulating the existing experiments using a computer code. The estimated results may help detailed analyses on fuel channel integrity upon PT/CT contact if necessary.

1. Introduction

During the postulated large loss of coolant accidents (LOCA) in CANDU reactors, pressure tubes (PT) will be heated up and finally the PTs will be so hot that they may balloon to contact the surrounding calandria tubes (CT). Thus heat will be transferred to moderator through the CTs and the moderator is considered as a heat sink. The integrity of the fuel channels after the PT/CT contact was considered to be controlled by the moderator subcooling. To determine the required moderator subcooling to ensure fuel channel integrity after PT/CT contact, PT/CT contact experiments have been performed extensively in last three decades. The first set of data was obtained for low internal pressures and lower heater powers and later on more experiments were performed at high internal pressures (Reference [1]). Recently, more experiments data were obtained at both high internal pressures and high heater powers (Reference [2]). Some experiments for the glass-peened CTs (GCT) were also performed recently (References [3] and [4]). A schematic of the experiment facility and the arrangement of thermal couples are shown in Figure 1 and Figure 2 (from Reference [4]). A summary of the significant experiment results are documented in References [1] and [2]. Presently the condition to ensure fuel channel integrity after PT/CT contact is to prevent sustained film boiling on CT surface after PT/CT contact, which is sufficient but not necessary. Recently a new methodology has been developed and validated against the existing

PT/CT contact experiments to analyze the integrity of the fuel channel after the PT/CT contact with the input of available moderator subcooling (Reference [5]).

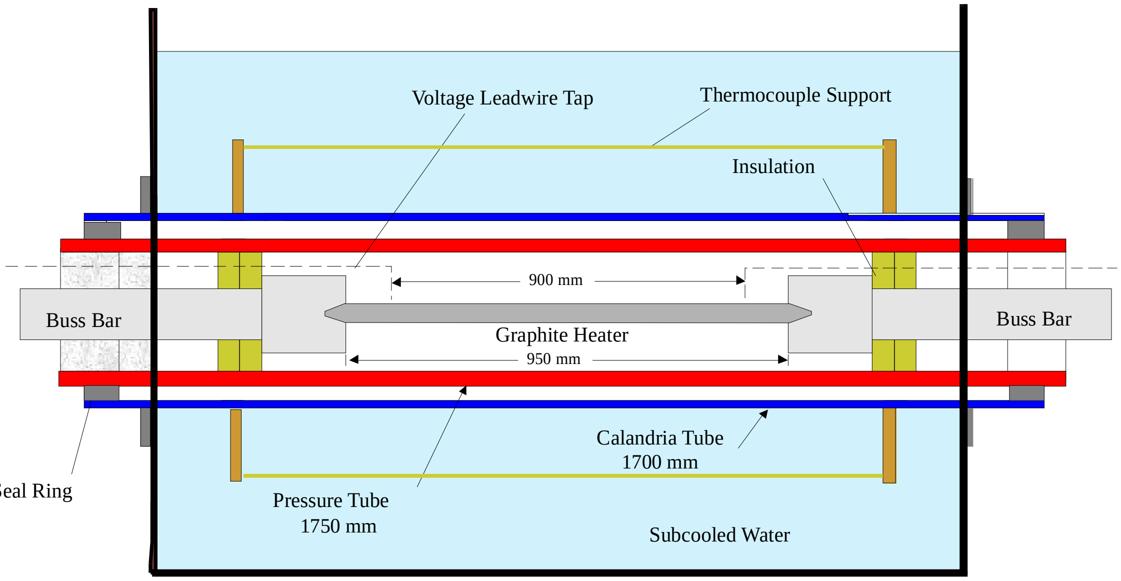

Figure 1 A simplified schematic of PT/CT contact experiment facility (Reference [4])

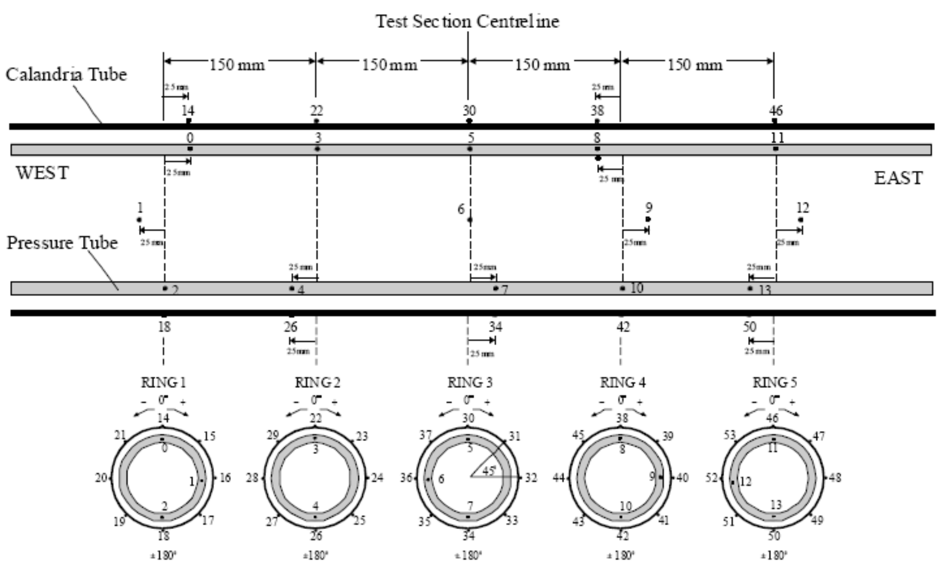

Figure 2 Demonstration of thermal couple arrangement for PT/CT contact experiment (Reference [4])

To ease the future R&D work and safety analysis, a new methodology has been put forward by using a concept of equivalent moderator subcooling (EMS) to determine the integrity of fuel channels upon PT/CT contact (Reference [7]). The EMS is an artificial term combining the impacts of the PT pressure, PT heatup rate, the actual moderator subcooling (AMS) and the CT surface conditions on the CT dryout area and on the maximum CT temperature. In the mean time, in Reference [7] it is determined that with the application of glass-peened calandria tube (GCT), the moderator subcooling can be reduced by 9ºC in comparison with the smooth calandria tube (SCT) for same CT dryout area after the PT/CT contact. In this work, the contact thermal conductance between pressure tube and calandria tube (CTC), critical heat flux (CHF) and minimum film boiling (MFB) temperature for the GCTs are discussed and estimated based on the results for SCTs and the EMS concept. The estimated results may help detailed analyses on fuel channel integrity upon PT/CT contact if necessary. In addition, the nucleate boiling and film boiling heat transfer coefficients (HTC) are also put forward empirically for the purpose of analyses. These parameters are confirmed by simulating the existing experiments.

2. PT/CT Ballooning Temperature

The PT ballooning is essentially a plastic PT deformation with significant PT temperature increase. With high PT temperatures, the PT yield stress decreases significantly, which would result in the PT diameter increase after the onset of strain which can be described using creep equations. The measurement and modelling on the yield stress of pressure tube material (Zr-Nb%2.5) have been performed elsewhere (References [7] and [9]) and the dependence of the yield stress of Zr-Nb%2.5 alloy on temperature is shown in Figure 3, Figure 4 and Figure 5.

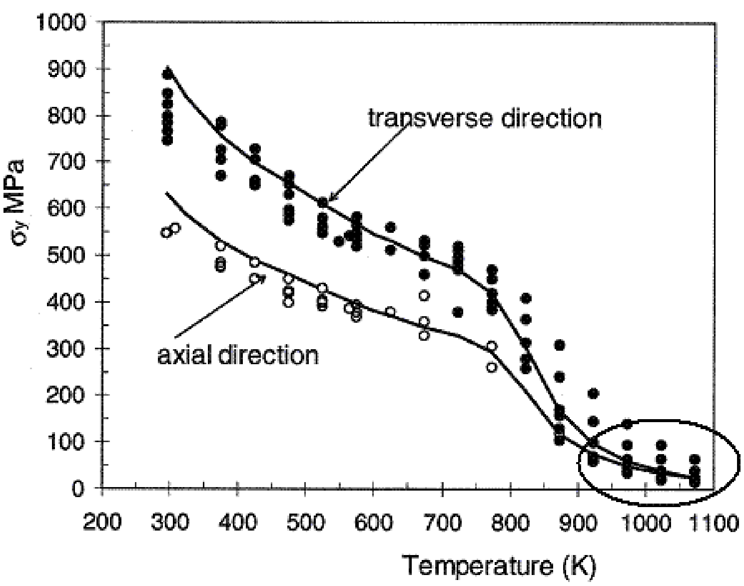

Figure 3 Dependence of the Zr-Nb%2.5 yield stress on absolute temperature for pressure tube material tested in the axial and transverse directions (Figure 8(a) in Reference [7]).

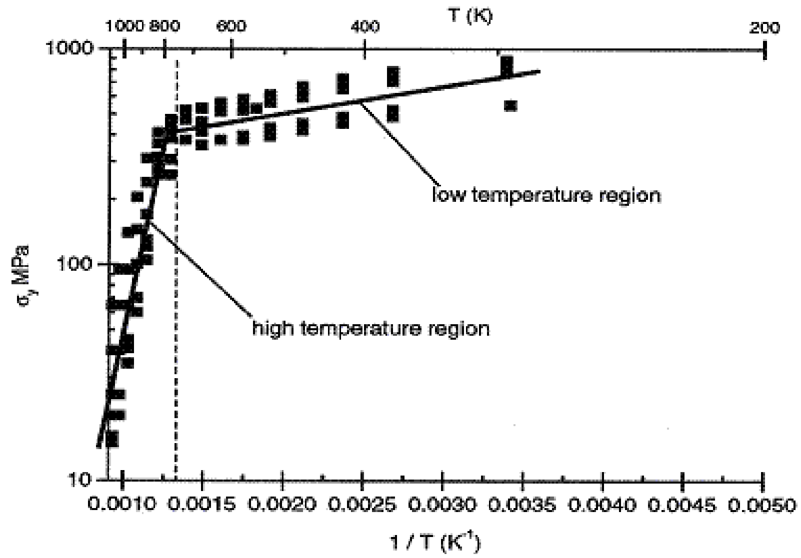

Figure 4 Dependence of the Zr-Nb%2.5 yield stress on the inverse of absolute temperature (Figure 9 in Reference [7])

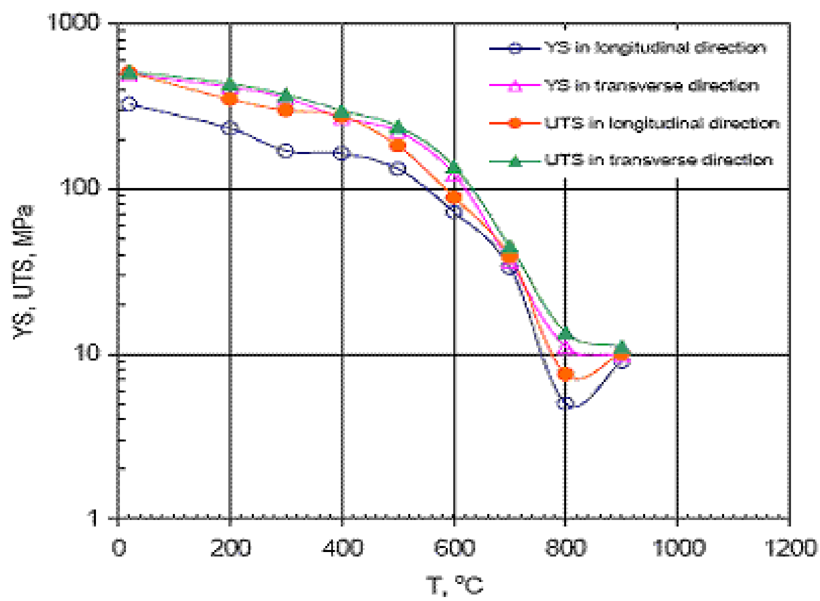

Figure 5 Zr-2.5%Nb alloy temperature dependence of yield strength (YS) and ultimate strength (UTS) (Figure 2(a) in Reference [9])

These results demonstrate that for a given internal pressure, there is a minimum PT temperature for the PT to start a plastic ballooning and this temperature has been termed PTBT in Reference [10]. Based on the results in Figure 3, Figure 4 and Figure 5 and the experimental results in References [1], [2] and [3], the temperatures at which the PTs begin to balloon for different PT pressure (PTBT) are determined approximately as following for PT pressure between 1MPa to 5MPa

$$PTBT = -38.35P + 822 \qquad (1)$$

where *PTBT* is in *ºC* and *P* is the PT pressure in *MPa*. In Reference [10], it has been proved that the average hoop stress in the PT before ballooning is same as the average hoop stress in the PT and CT after PT/CT contact, which implies that Equation (1) is also applicable to CT after PTCT contact. Based on this equation, provided the maximum temperature of CT is smaller than a certain temperature, the stress exerted on it will not exceed the yield stress for the corresponding temperature. Thus the CT will not strain either locally or universally and so the fuel channel integrity can be ensured. This criterion is conservative since if the CT straining can be stopped, i.e., the CT temperature can be decreased sufficiently in time before the fuel channel rupture, the strength of the fuel channel can be recovered and the fuel channel integrity can also be ensured.

3. EMS Methodology

After PT/CT contact in a moderator with a given AMS, the parameters that control the CT dryout areas include the PT pressure, PT heatup rate, the moderator AMS and the outer surface condition of the CT. PT pressure and PT heatup rate impact the PT temperature upon PT/CT contact and the initial PT/CT contact thermal conductance (CTC), while the AMS and the outer surface condition impact the critical heat flux (CHF) on the CT surface for the given AMS.

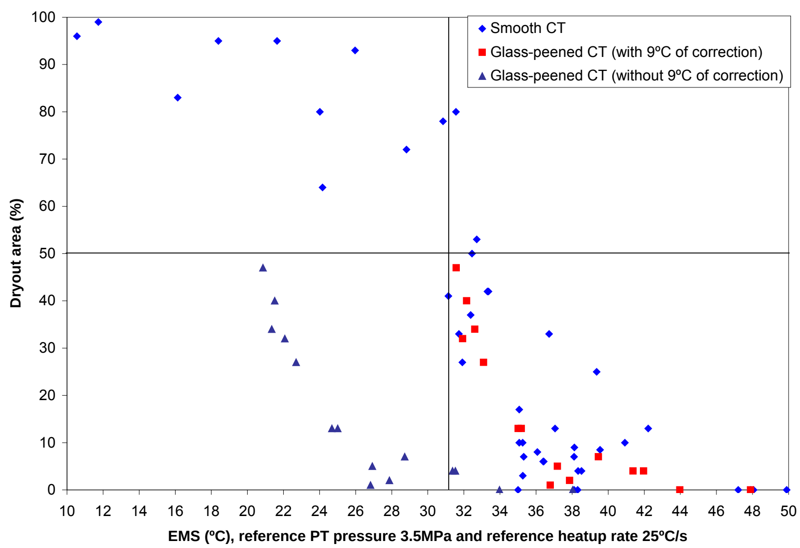

Figure 6: Relationship between CT dryout area and EMS

In Reference [5], it has been proved that same dryout area can be obtained for SCT and GCT if they have same EMS value for a given reference PT pressure and a reference PT heatup rate. The EMS value can be calculated as

$$EMS = AMS - 0.1061(P^2 - P_r^2) + 1.6724(P - P_r) - 0.8477(H - H_r) + E \qquad (2)$$

where EMS is the equivalent moderator subcooling, AMS is the actual moderator subcooling, P is the PT pressure in MPa, H is the heatup rate in ºC/s, E is a parameter depending on the outer surface condition of the CTs, and P_r and H_r are reference PT pressure and reference PT heatup rate which together determine a reference state. For SCTs the value of E is zero while for the GCTs the value of E is 9ºC. After correcting for the impacts of different pressures and different heatup rate to the reference values and correcting for the impact of CT surface conditions (E), the *EMS* value corresponding to the reference parameters are obtained. It seems the CT dryout areas for all cases are obtained by using a SCT with a PT pressure of P_{r}, a PT heatup rate of H_{r} in a moderator with a subcooling of *EMS*. The results of Equation (2) for all the qualified data are shown in Figure 6 where the data for GCTs without correcting for the influence of E is also shown.

4. Determination of PT/CT contact thermal conductance

Cziraky and Luxat developed a model to calculate the PT/CT CTC (Reference [6]), but the CTC needs to be calculated using a computer program. An empirical correlation of the PT/CTC versus PT pressure will be developed below based on experiment results.

As per Equation (2), for both SCTs and GCTs at constant pressure and EMS values for a given reference state, the following relationship is correct,

$$\left(\frac{\partial AMS}{\partial H}\right)_P = 0.8477 \qquad (3)$$

Equation (3) means that to keep the same dryout area (or same EMS) on SCT or GCT surface upon PT/CT contact with a given PT pressure, if the heatup rate is increased by 1ºC/s, the AMS value has to be increased by 0.8477ºC. Although Equation (3) was only verified against the results of Tests 6, HP3, SC3, SC5, SC8 and SC11 for SCTs whose dryout areas are less than 10% and the PT pressures are around 3.5MPa, it has been justified to be applicable for all other cases provided the PT pressures, CT outer surface conditions and CT dryout areas are same or close. In particular, this relationship is applicable for the cases when the CHF on the CT surface is reached.

As per Equation (1) and Figure 3 to Figure 5, the PT temperature for the onset of PT ballooning is a function of PT pressure. When the PT ballooning begins, the temperature increase upon PT/CT contact is mainly determined by the PT heatup rate and the times it takes for the ballooning PT to contact the CT, i.e., the ballooning time. The ballooning time can be estimated using Equation (1) and Figure 3 to Figure 5 together with the temperature transient of the PT. Assuming the PT heatup rate is increased by 1ºC/s and the ballooning time t_{bl} is not impacted by the small increase in the heatup rate of 1ºC/s, the increase in PT temperature upon PT/CT contact can be calculated as following if the PT ballooning is uniform in the radial direction

$$\Delta T_{PT} = 1\ {}^{o}C/s \times t_{bl} \qquad (4)$$

According to References [11] and [12], the relationship between the critical heat flux and moderator subcooling can be written as

$$q_{CHF} = q_{CHF0}\left[1 + 0.1\left(\frac{C_p(T_{sat} - T_b)}{h_{fg}}\right)\left(\frac{\rho_f}{\rho_g}\right)^{0.75}\right] \tag{5}$$

where,

$$q_{CHF0} = 0.118 h_{fg}\left[\sigma g \rho_g^2 (\rho_f - \rho_g)\right]^{0.25} \tag{6}$$

In the nucleate boiling region, the following correlation can be used to determine the heat flux from the CT outer surface to the moderator (Reference [13])

$$q = \mu h_{fg}\left(\frac{g(\rho_f - \rho_g)}{\sigma}\right)^{0.5}\left(\frac{C_p(T_s - T_{sat})}{C_{sf} h_{fg} \Pr}\right)^3 \tag{7}$$

In Equations (5) and (6), q_{CHF} is the critical heat flux in the subcooled liquid in W/m^2, q_{CHF0} is the critical heat flux in the saturated liquid in W/m^2, h_{fg} is the latent heat of vaporization in J/kg, ρ_f is the saturated liquid density in kg/m^3, ρ_g is the saturated vapour density in kg/m^3, σ is the surface tension in N/m, T_s is the surface temperature, T_{sat} is the saturation temperature in K, T_b is the bulk liquid temperature in K, C_p is the liquid specific heat evaluated at the liquid film temperature in J/(kg·K), μ is the dynamic viscosity of liquid water in kg/(m·s), Pr is the Prandtl number of liquid water, g is the gravity acceleration in m/s^2 and C_{sf} is a coefficient determined by fluid and the surface conditions of wall. Thus if a saturation state is given, Equation (5) and Equation (7) can be simply written in the following

$$q_{CHF} = q_{CHF0}(1 + \chi \times AMS) \tag{8}$$

$$q = E_{sf} \times (T_s - T_{sat})^3 \tag{9}$$

where q_{CHF0}, χ and E_{sf} are constants for the given saturation state.

Table 1: Thermophysical properties of water at ambient pressure

ρ_f (kg/m3)	ρ_g (kg/m3)	h_{fg} (J/kg)	C_p (J/(kg·K))	μ (kg/(m·s))	σ (N/m)	Pr
958	0.59	2.26×10^6	4200	2.8×10^{-4}	0.059	1.73

For ambient pressure, the thermophysical properties of water are listed in Table 1 and based on these values, Equations (8) and (9) are written as following if C_{sf} value is assumed to be 0.013 which is close to that for polished copper, lapped copper, mechanically polished stainless steel and for platinum.

Based on the thermophysical properties of water, Equations (8) and (9) can be rewritten as following

$$q_{CHF} = 994 \times (1 + 0.049 \times AMS) \tag{10}$$

$$q = 145 \times \left(T_s - T_{sat}\right)^3 \tag{11}$$

where q_{CHF} is in kW/m^2 and the temperatures are in ºC. When the temperature point with the CHF value is achieved, Equation (10) and (11) should be equal to each other.

If the moderator subcooling is increased by 0.85ºC, the initial CT temperature will be lower by 0.85ºC. Since the volume ratio of the CT to PT is 0.42 as per the nominal dimension and the CT and PT have similar density and specific heat, to heat up the CT and its surrounding water by 0.85 ºC more to reach saturation temperature will cost at least 0.6ºC of the PT temperature increase (assuming the hot water layer thickness is half of that of the CT at most due to the short heating time). In addition, due to the increase in CHF caused by moderator subcooling increase, when the CHF value is reached, the CT temperature will also be a bit higher than the case of keeping moderator subcooling unchanged, but this increase is only around 0.02ºC. Thus when the heat flux to the moderator reaches the CHF during initial PT/CT contact, the temperature difference between the PT and CT is decreased by 0.62ºC from Equation (4) due to PT heatup rate increase and moderator subcooling increase and the heat flux increase Δq from PT to CT can be calculated using

$$\Delta q = \delta T \times D_T = \left(\Delta T_{PT} - 0.62^oC\right) \times D_T = (1\ ^oC/s \times \Delta t - 0.62\ ^oC) \times D_T \tag{12}$$

The parameter D_T is the total thermal conductance between the PT mid-plane where the PT temperature was measured and the CT outer surface where the CT temperature was measured and δT is the increase in the temperature difference between the mid-plane of the PT and the outer surface of the CT.

To keep the CT surface at the critical point, the increase in the heat flux from PT to CT should be equal to the CHF increase Δq_{CHF} due to the 0.85ºC of decrease in the moderator temperature, thus

$$\begin{aligned}\left(1\ ^oC/s \times \Delta t - 0.62\ ^oC\right) \times D_T &= 994 kW/m^2 \times (0.049 \times 0.85) \\ &= 41.2 kW/m^2\end{aligned} \tag{13}$$

Based Equation (1), Figure 3 to Figure 5 and the pressure tube temperature history listed in Reference [14], the ballooning time are measured from the curve of PT temperature versus time and listed in Table 2. Since the PT ballooning has a complicated 3-D behaviour and different points around the PT have different straining rate and there is a small difference in the times for these points to contact the CT, so the average ballooning time obtained based on different thermal couples is used. In addition, the results were obtained from graphics, so the uncertainty can be as large as 0.25s in the measurement. Figure 7 which are from Reference [10] gives the straining time of the pressure tube material with same stress and material temperature for the experiment of SC7. As shown in the figure, the time period from the moment the ballooning begins until the strain reaches the value corresponding to PT/CT contact value (around 10s) is consistent with the results listed in Table 2.

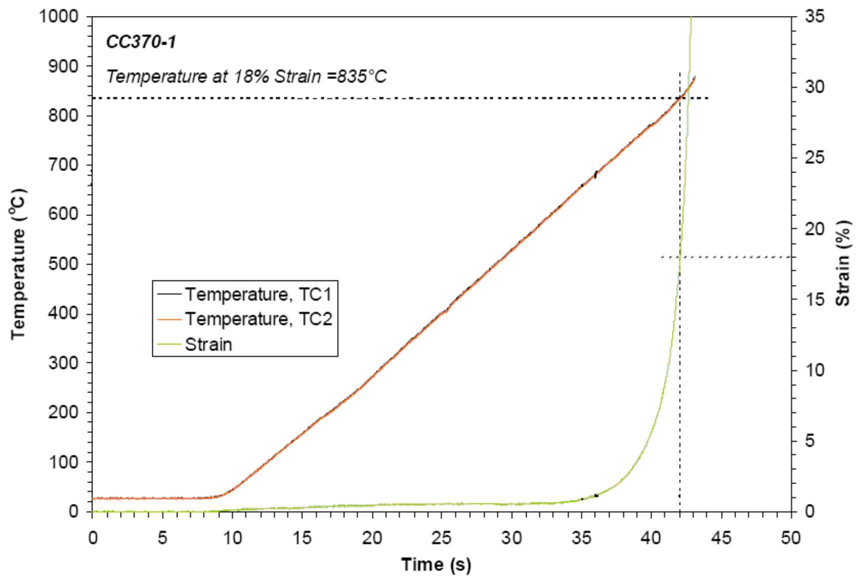

Figure 7: Measured temperatures and strains for sample CC370-1 (Figure C1 in Reference [15] and the thick dashed lines were added for discussion of this work)

Table 2: PT ballooning time and ballooning temperature

Pressure (MPa)	Temperature (ºC)	Tests Used	Ballooning Time(s)	CTC (kW/(m^2·C))
1	784	3, 9, D1	15.11	5.1
2	745	20	11.43	9.1
2.5	726	7, 8	10.76	10.7
3.6	684	SC2,SC8	9.76	14.3
4	670	HP11, HP18	9.35	16.6
5	653	HP1, HP9	9.02	19.3
6.6	630	HP2, HP12	8.45	25.7
8.5	620	HP4, HP5	8.19	30.5

Upon PT/CT contact, heat is transferred from the high temperature PT to the low temperature CT and the heat transfer equations can be written as following

$$\rho C_p \frac{\partial T_{PT}}{\partial t} = \lambda \left(\frac{1}{r} \frac{\partial T_{PT}}{\partial r} + \frac{\partial^2 T_{PT}}{\partial r^2} \right) \tag{14}$$

$$\rho C_p \frac{\partial T_{CT}}{\partial t} = \lambda \left(\frac{1}{r} \frac{\partial T_{CT}}{\partial r} + \frac{\partial^2 T_{CT}}{\partial r^2} \right) \tag{15}$$

with boundary conditions of

$$\begin{aligned} & r = r_0, \quad -\lambda \left(\frac{\partial T_{PT}}{\partial r} \right)_{r=r_0} = q_0 \\ & r = r_2, \quad -\lambda \left(\frac{\partial T_{PT}}{\partial r} \right)_{r=r_2} = -\lambda \left(\frac{\partial T_{CT}}{\partial r} \right)_{r=r_2} = D(T_{PT} - T_{CT}) \\ & r = r_3, \quad -\lambda \left(\frac{\partial T_{CT}}{\partial r} \right)_{r=r_3} = h(T_{CT} - T_M) \end{aligned} \tag{16}$$

In the above equations, t denotes time, q_0 denotes heat flux at the inner PT surface, T_{PT}, T_{CT} and T_M denote the temperature of the PT, CT and the moderator, λ, ρ and C_p denote thermal conductivity, density and specific heat of PT and CT, D denotes contact thermal conductance between the PT inner surface and the CT outer surface, r_0, r_2 and r_3 denote the radii of PT inner surface, PT outer surface (or CT inner surface) and the CT outer surface, h denotes the heat transfer coefficient between the CT and the moderator. For cases where the maximum heat flux from the CT to the moderator equals to the CHF value corresponding to the moderator subcooling (AMS), when the CT temperature reaches the maximum, the changing rate of the CT temperature will be zero and decreasing rate of the PT temperature will be small, too. Thus the heat transfer process from the PT to CT will be close to the steady state process and the average heat flux is close to the heat flux at the outer surface of the CT. The steady state heat transfer equation between the PT and the CT upon PT/CT contact can be calculated as

$$\Delta T = \frac{Q}{2\pi\lambda} \ln \frac{r_2}{r_1} + \frac{Q}{2\pi\lambda} \ln \frac{r_3}{r_2} + \frac{Q}{2\pi D r_2} \tag{17}$$

where Q is the heat flow from the PT to the CT, r_1, r_2 and r_3 are the radii of mid-plane of the PT (where PT temperature is measured), PT outer radius (or CT inner radius) and CT outer radius (where dryout may occur) respectively, and ΔT is the temperature difference between the mid-plane of the PT and outer surface of the CT. Based on the calculation in Reference [10], the values of r_1, r_2 and r_3 are 0.06304m, 0.06491m and 0.06635m respectively. For the PT contact temperature increase due to the heatup rate increase, Equation (12) can be written as

$$\begin{aligned} \delta T &= (2\pi r_3 \Delta q) \left(\frac{1}{2\pi\lambda} \ln \frac{r_2}{r_1} + \frac{1}{2\pi\lambda} \ln \frac{r_3}{r_2} + \frac{1}{2\pi D r_2} \right) \\ &= \Delta q \left(\frac{r_3}{\lambda} \ln \frac{r_3}{r_1} + \frac{r_3}{D r_2} \right) \end{aligned} \tag{18}$$

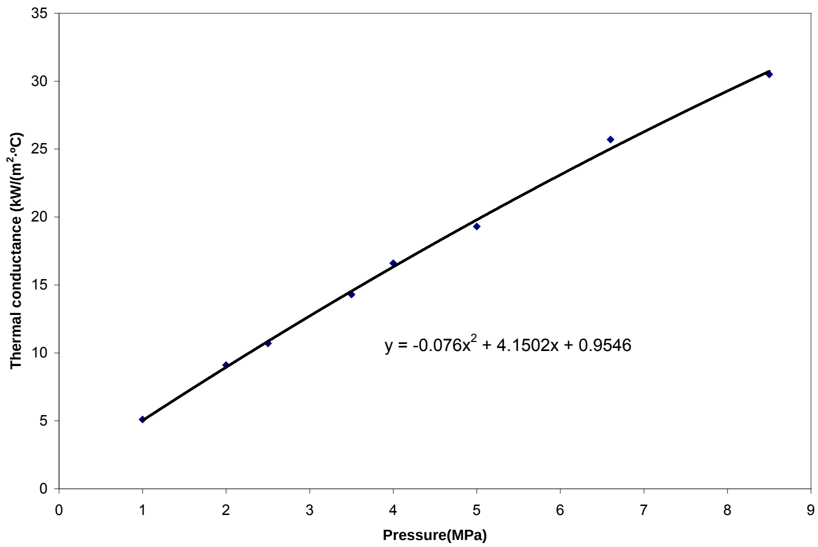

Figure 8: Relationship between estimated thermal conductance and PT pressure

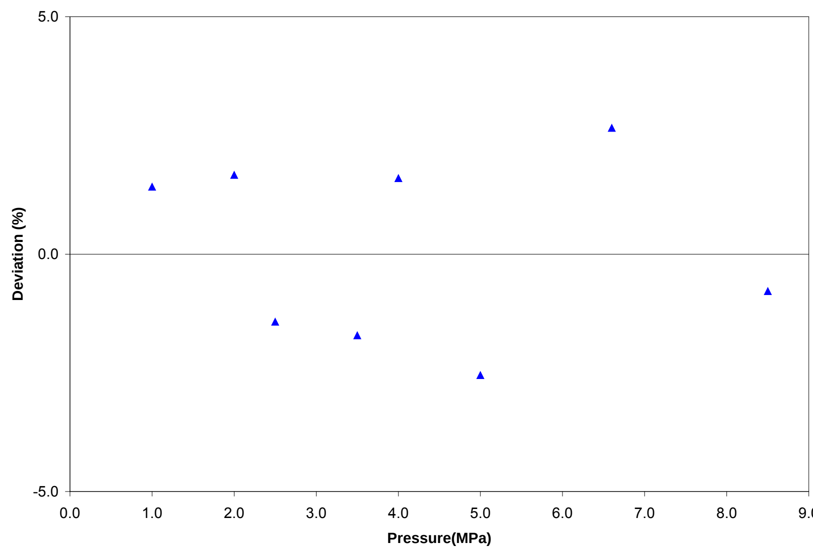

Figure 9: Deviation of contact thermal conductance data from correlation

Based on Equations (12), (13) and (18) and the PT ballooning times in Table 2, the values of *D* (CTC) are estimated and are also listed in Table 2. The relationship between the obtained CTCs and pressure is shown in Figure 8 . The contact thermal conductance data is correlated versus pressure as

$$D = -0.076P^2 + 4.1502P + 0.9546 \tag{19}$$

The deviation of the data from the correlation are shown in Figure 9 which shows the maximum deviation is less than 2.6% and standard deviation is determined to be 1.5%.

It should be noted that the uncertainty in the average CTC obtained above can be larger than 20% due to the uncertainty in the PT ballooning time measurement and the assumptions. Considering the CTC values after the dryout quenching drops to the order of 1kW/(m^2·C) and the PT ballooning times do not differ each other significantly at same PT pressure, it is expected that the average CTC may not change significantly with the PT and CT temperatures at the initial period of time after PT/CT contact. The obtained correlation should be applicable to both the SCT and the GCT cases since the contact surface conditions of these two kinds of tubes are same.

5. Assessment on CHF of Glass-Peened CT

For an ideal transition boiling case, assuming the dryout area proportion on the CT surface is A_d and the dry patches are distributed uniformly thus the average heat flux from the CT surface to the moderator can be calculated as

$$q_a = q_{chf}(1 - A_d) + A_d q_{mfb} \tag{20}$$

where q_a, q_{chf} and q_{mfb} stand for the average heat flux, critical heat flux and minimum film boiling heat flux respectively. Thus the expression of A_d can be written as

$$A_d = \frac{q_{chf} - q_a}{q_{chf} - q_{mfb}} = \frac{1 - q_a / q_{chf}}{1 - q_{mfb} / q_{chf}} \tag{21}$$

Since the ratio of q_{mfb} to q_{chf} is smaller than 10% after assessing using the existing correlations and this value does not vary significantly for different AMS values, it is expected that the cases with same dryout area will have similar ratio of q_a to q_{hf}. Furthermore, if the ratio of the ratio of q_{mfb} to q_{chf} is ignored, Equation (21) can be written as

$$A_d \approx 1 - q_a / q_{chf} \tag{22}$$

Equation (22) indicates if the dryout areas are same for the SCT case and the GCT case, the ratios of the actual heat fluxes to the corresponding critical heat fluxes will also be same.

Assuming a Case S with the SCT and a Case G with the GCT have same PT heatup and PT pressure, thus the AMS value of the Case G is 9ºC lower than that of Case S. With these conditions, the following relationships are tenable and the two cases have same EMS with the reference PT heatup rate and PT pressure, for example, 25ºC/s and 3.5MPa

$$EMS = AMS_s \tag{23}$$

$$EMS = AMS_g + 9\,^{o}C \tag{24}$$

where the subscripts ‘s’ and ‘g’ stand for the SCT and GCT respectively.

With same EMS values, the two cases will have same dryout area as per Figure 6. The relationship between the maximum measured CT temperature and CT dryout area is shown in Figure 10 (Reference [7]) which demonstrates that if the CT dryout areas are same for the two cases, the maximum measured CT temperatures are also same for dryout areas higher than 5%, though below 5% and close to zero dryout area, the maximum GCT temperatures are apparently higher than the maximum SCT temperatures.

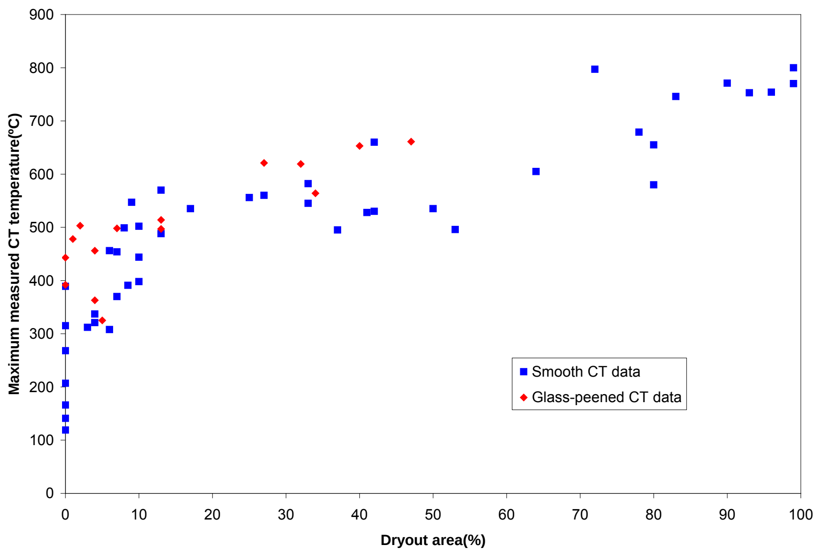

Figure 10: Relationship between maximum measured CT temperature and CT dryout area

The relationship between the time for the CT temperatures to be above 220ºC (termed as rewet time) for SCT cases and GCT cases is shown in Figure 11 (Reference [7]) for EMS value higher than 30ºC (reference PT pressure of 3.5MPa and reference heatup rate of 25ºC/s) where the GCT data is available. The figure demonstrates that if the EMS values are same for Case G and Case S, the rewet times are also same or close for the two cases.

Based on the observation for Figure 6, Figure 10 and Figure 11, it is expected the average CT temperatures are same for Case G and Case S provided their EMS values are same. As per the discussion in the preceding section, the contact thermal conductance between PT and CT only change significantly with PT pressure in the initial PT/CT contact period. Since the PT heatup rates and PT pressures are same for Case S and Case G, the average PT temperatures upon PT/CT contact are same for the two cases.

With same PT temperature, same CT temperature and same contact thermal conductance, it is expected the heat fluxes from PT to CT are same. Considering the average CT temperatures are same for the two cases, which implies the energy desposited in the CTs are same, the heat flux to the moderator should also be same.

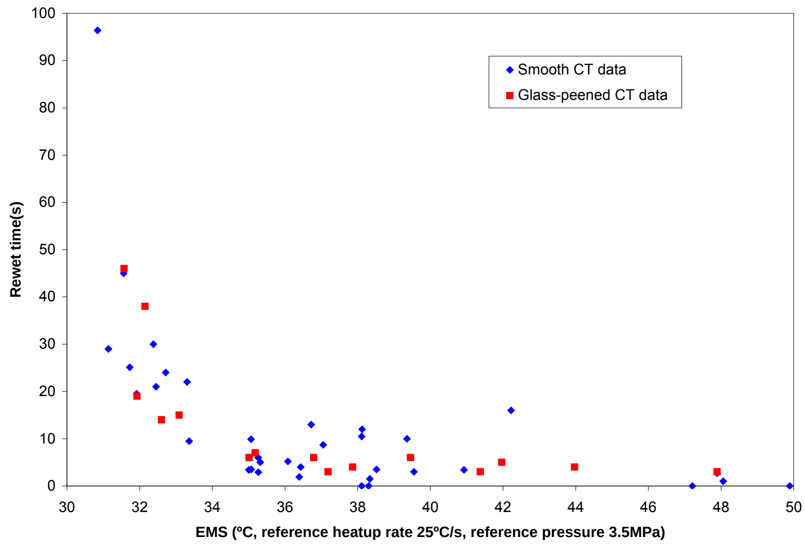

Figure 11: Relationship between rewet time and EMS

Based on Equation (22) the CHF values for Case S and Case G are same, i.e., the CHF of a SCT is same as that of a GCT with the same EMS value. Since the AMS value of Case G is 9ºC lower than that of Case S, the CHF for Case G following based on Equation (24)

$$q_{GCHF} = q_{SCHF0}\left[1+\chi\left(AMS_G + 9\right)\right] \tag{25}$$

At ambient pressure for water, the CHF for Case G can be written as following

$$\begin{aligned} Q_{GCHF} &= 994\times[1+0.049(9+AMS_G)] \\ &= 994\times[1.44+0.049AMS_G] \\ &= 1431\times(1+0.034AMS_G) \end{aligned} \tag{26}$$

The ratio of Equation (26) and Equation (10) can be written as

$$\frac{q_{GCHF}}{q_{SCHF}} = 1.44\times\frac{1+0.034AMS_G}{1+0.049AMS_S} \tag{27}$$

The parameters q_{GCHF} and q_{SCHF} stand for critical heat flux for Case G and Case S, respectively, AMS_G and AMS_S stand for the actual moderator subcooling for Case G and Case S respectively. For subcooling values from 0 to 35ºC, the improvement of the subcooling is from 44% to 17% respectively, i.e., the larger is the subcooling the smaller is the improvement. Comprehensively for the subcooling range of 20 to 30ºC, the improvement in CHF is around 20%. Thus the critical heat flux improvement is a function of the moderator subcooling. As per References [3] and [17], the CHF value in the saturation water is 860kW/m^2 for the as received CT surface with spiked power ramp case. While for the glass-peened CT surfaces, the corresponding CHF value is 1350kW/m^2. The improvement in CHF is 58% which is higher than 44%. If the as received CHF value is assumed to be same as that calculated using Equation (6), the improvement would be 36%. Thus 44% improvement in CHF estimated in this work is considered close to the in Reference values.

The CHF for a GCT is obtained by using Case G and Case S with EMS value with a reference PT heatup rate of 25ºC/s and PT pressure of 3.5MPa, but the CHF is independent of these two parameters and is only a function of AMS. Since the results are indirectly from the PT/CT contact experiments, larger error may exist.

6. Assessment on Boiling HTC of Glass-Peened CT

So far there is no any information about the convective and nucleate boiling heat transfer coefficients available for GCTs and it is necessary to estimate this parameter in order for a detailed analysis. The relationship between the maximum CT temperature and the CT dryout area is shown in Figure 10. In this figure and along the vertical axis, the highest CT temperature for SCT case is 389ºC (Case SC6 with AMS of 50ºC) and the highest CT temperature for GCT case is 443ºC (Case Q4 with AMS of 22ºC). These two points can be considered to be at the verge of critical area or where the heat flux is close to the critical heat flux. Based on the discussion in Section 5, the CHF for case SC6 and Case Q4 can be calculated to be 3417kW/m^2 and 2501kW/m^2. Thus the ratio of the boiling heat transfer coefficient for Case Q4 to that for Case SC6 can be calculated as following for the two hot spot region

$$\frac{HTC_G}{HTC_S} = \frac{(2501kW/m^2)\big/(443^\circ C - 100^\circ C)}{(3417kW/m^2)\big/(389^\circ C - 100^\circ C)} = 0.63 \qquad (28)$$

As shown in Figure 10, with dryout area less than 5%, the maximum GCT temperatures are always higher than SCT temperatures and this is expected being caused by the lower boiling HTC on the GCT surface. Based on the results of Equation (28) and other points, if the maximum measured CT rewet time is to be predicted, the value of 0.76 is recommended as the empirical correction factor to the Modified Chen convective and boiling HTC correlations to obtain the HTC on the GCT surface in water. For the best estimate simulations for the average CT rewet time and CT temperatures, the value of 0.85 is recommended for use by assuming a uniform PT ballooning and uniform heat transfer among the PT, CT and the moderator along the circumferential direction.

7. Assessment on Rewet Temperature for Glass-Peened CTs

After observing Figure 10, it is determined that for dryout area higher than 5%, the maximum GCT temperature is close to the maximum SCT temperature with same dryout area. According to Figure 6, same dryout area basically implies same EMS, thus it is expected when the EMS value are same, the maximum CT temperature should also be same. For cases with dryout area sufficiently large, it is very probable the maximum measured CT temperature is or is close to the MFB temperature.

In many occasions, the SCT MFB temperature at which the film boiling begins to occur is often used and expressed in a linear function of the AMS, i.e.

$$T_{SMFB} = C_1 \times AMS_S + C_2 \tag{29}$$

In Equation (29) C_1 and C_2 are two constants and T_{SMFB} is the MFB temperature or rewet temperature for a SCT. As discussed before, with same EMS values for a given reference PT heatup rate and PT pressure for a relatively large CT dryout area, the maximum CT temperatures are same, thus it can be inferred that the MFB temperatures for the two cases are also same. Thus the MFB temperature for the GCT, T_{GMFB} can be written as

$$\begin{aligned} T_{GMFB}(AMS_G) &= T_{smfb}(AMS_G + 9) \\ &= C_1(AMS_G + 9) + C_2 \\ &= C_1 AMS_G + 9C_1 + C_2 \end{aligned} \tag{30}$$

Similar to the CHF, the MFB temperature correlations are obtained based the EMS with a reference PT heatup rate and PT pressure, but the results are independent of the reference PT heatup rate and reference PT pressure. Since the results are indirectly from the PT/CT contact experiments, large error may exist.

8. Film Boiling HTC

Simulations on the obtained PT/CT experiments were performed by applying GCTs, where the Modified Berenson ([18]) film boiling heat transfer correlation is used. However, it is discovered, that the heat transfer coefficient has to be doubled to make the simulation results consistent with the experiments. It is empirically recommended a correction factor calculated using the following equation to be used for AMS value between 20ºC to 28ºC, which is obtained based on two experiment cases with 20ºC and 28ºC of AMS:

$$C = 0.0459 \times AMS + 1.2608 \tag{31}$$

9. Confirmation of Results

9.1 Simulation of SCT experiments

To confirm the obtained Equation for PT/CT contact thermal conductance at different PT pressures, simulations for Test 12 (1MPa), Test 20 (2MPa), Test SC2 (3.5MPa), Test 2 (4MPa), Test HP1(5MPa), Test HP12 (6.5MPa) and HP5 (8.5MPa) are simulated using CATHENA ([18]). The methodology is same as that used in Reference [14] but the following:

(1) Constant heat flux is applied on the inner surface of the PT at the beginning to achieve the required PT heatup rate and the PT/CT contact temperature.

(2) For simulation of Test 12, it is discovered that the simulated PT ballooning time is much shorter than that observed from experiment and the PT temperature upon PT/CT contact is much lower than that obtained in the experiment. Thus to achieve the target PT temperature, a higher initial PT temperature is applied.

(3) The CTC value upon PT/CT contact is obtained using Equation (19) and considered constant. This assumption will not impact the CT temperatures. If the dryout does not quench, the PT/CT CTC is not expected to decrease as shown in the experiment results. If the dryout quenches in a short time, the nucleate boiling will occur on the CT surface and the heat transfer will be steady. Thus even if the PT/CT CTC decreases, as shown in the experiments, only the PT temperature will be influenced, but not the CT temperature which is determined by the nucleate boiling.

(4) The Modified Berenson correlation is used for film boiling heat transfer without using any correction factor (Reference [18]).

The simulation results for SCTs with PT pressures from 1MPa to 8.5MPa are shown in Figure 12 and Figure 13. The simulated rewet time and maximum SCT temperature results are very close to those documented in References [1] and [2]. Since the results are only for the average CT temperatures, the maximum CT temperature values shown in these figures may be smaller than those shown in the experiment graphics, especially for those tests with dryout areas around 50% where the temperature distribution may not be very uniform. However, after comparing the simulated and experiment average CT temperatures, it is discovered that they are very close.

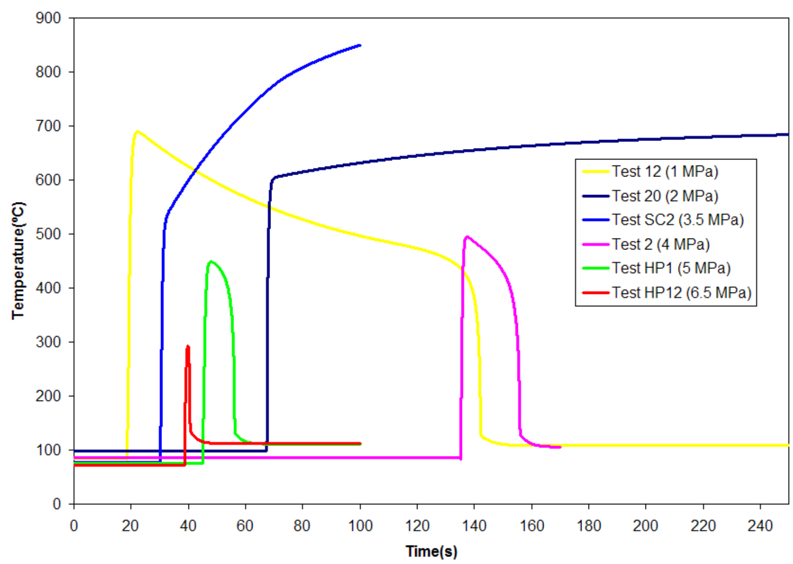

Figure 12: Simulated SCT temperatures for PT/CT contact experiments (PT pressure from 1MPa to 6.5MPa)

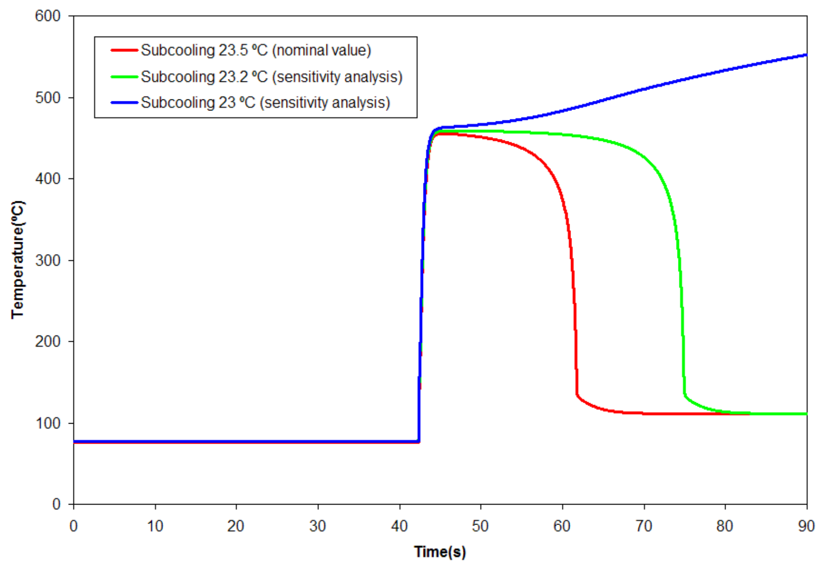

Figure 13: Simulated SCT temperatures for PT/CT contact test HP5 (PT pressure = 8.5MPa)

For Test HP5 with an EMS value of 32ºC (reference pressure of 3.5MPa and reference PT heatup rate of 25ºC/s), the sensitivity simulations of rewet time and maximum CT temperature versus the moderator subcooling are also performed. As shown in Figure 13, with the decrease in moderator subcooling by 0.2ºC and 0.5ºC (EMS values decreases to 31.8ºC and 31.5ºC, respectively), the rewet time is increasing or there is no quenching, i.e., the rewet time is infinite. As shown in Figure 8 and Figure 11, the EMS values of the cases lie in between 30ºC and 34ºC which is the so called transition dryout region (Reference [7]), thus a tiny decrease in the EMS value will cause a dramatic increase in the rewet time, and the results are not surprising.

9.2 Simulation of GCT experiments

To confirm the obtained correlations for GCT CHF and rewet temperature and the correction factors obtained empirically for nucleate boiling and film boiling HTC, simulations for GCTs experiments are performed for AMS from 20ºC to 28ºC. Equations (25) and (29) are used for critical heat flux and CT rewet temperature, the Modified Chen (Reference [18]) correlation is used for nucleate boiling heat transfer with a multiplying correction factor and the modified Berenson Correlation (Reference [18]) is used for film boiling heat transfer with a multiplying correction factor calculated using Equation (31). The Bjornard-Griffith correlation ([16]) is assumed to be applicable on the GCT surface for transition boiling heat transfer and applied in this work.

The simulated CT temperatures versus time for AMS values from 20 to 28ºC are shown in Figure 14 when the multiplying correction factor of 0.85 is used for nucleate boiling coefficient. The rewet times are close to the experiments except Test Q11 and Q13 whose maximum rewet time is 46s and 38s respectively while the simulated average rewet times are only 28s and 15s respectively.

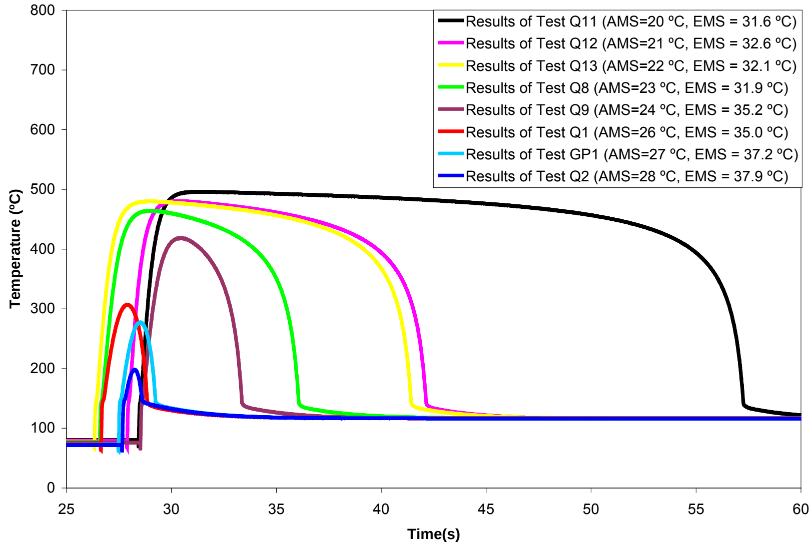

Figure 14: Simulated GCT temperatures upon PT/CT contact (AMS from 20ºC to 28ºC, nucleate boiling HTC correction factor of 0.85)

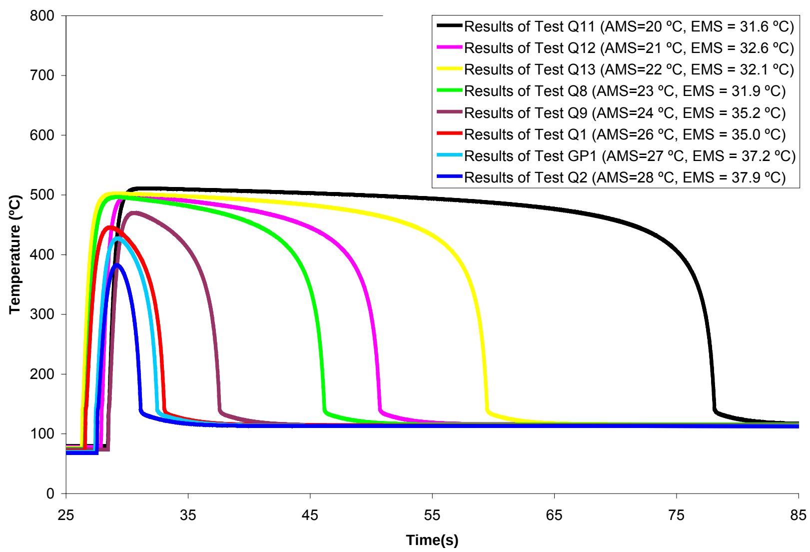

Figure 15: Simulated GCT temperatures upon PT/CT contact (AMS from 20ºC to 28ºC, nucleate boiling HTC correction factor of 0.76)

To make the simulated CT rewet time match the maximum CT rewet time in the experiments, the multiplying correction factor of 0.76 is tried for nucleate boiling coefficient and the results are shown in Figure 15. Although the predicted rewet times are almost identical with the maximum CT rewet times obtained in the experiments, the simulated CT temperatures are still lower than the maximum experimental CT temperatures. Since the simulation assumes that the PT ballooning and heat transfer among the PT, the CT and moderator is uniform along the circumferential direction, the obtained rewet time is only the average rewet time, rather than the maximum rewet time. Thus, the factor of 0.76 is overly conservative in prediction the average rewet time and the correction of 0.85 is recommended for simulation of average CT temperature and CT rewet time. The impacts of the non-uniformity in the heat transfer along the circumferential direction can be assessed using uncertainty analysis as demonstrated below.

A close scrutinizing on the experimental graphics about the PT and GCT temperature transients, it is found that the rewet times at the other locations are around 10s for these two cases, but the rewet times at the top are much longer. Thus it is expected that hot regions are formed at the top of the CTs for these two cases. Considering due to the free convection effect of the heated argon, it is assumed that a symmetrical hot region of around one quarter of the top half of the tube and a same size of symmetrical cold region is formed at the bottom half of the tube due to the non uniform heat flux distribution. The ratios of the local heat flux to average heat flux at the hot and cold spot are shown in Figure 16.

The simulation results for Test Q11 with the hot and cold regions and the boiling HTC correction factor of 0.85 are shown in Figure 17. The results for Test Q13 with same configuration are similar. Figure 17 indicates that when a hot spot and a cold spot are formed at the top and bottom of the fuel channel due to the free convection of gas, the maximum temperature at the top increases dramatically and it takes a much longer time for this region to rewet in comparison with other spots. The simulated rewet time and GCT temperatures shown in Figure 17 are close to the experiment results for test Q11.

It should be noted that in the reactor with large LOCA event, when the fluid flowing through the fuel channel is steam only, the non-uniformity in energy distribution will be much less severe than that met in the experiment. This is because in the large LOCA event, the steam is still flowing to the break with a significant speed and the force convection effect will dominate the free convection, while in the experiments, the major heat transfer coefficient between the gas (helium or argon) and the PT is free convection and it is very easy to form a large temperature gradient from top to bottom. Thus the situation met in safety analyses will not be worse than the experiments and it is conservative to judge fuel channel integrity based on the criteria determined using experimental data. The ballooning of PT in the experiments is never uniform and this process uncertainty always makes the fuel channel rupture more easily. In addition, in the reactor event, the pressure tube begins ballooning at a higher pressure which will yield a lower contact temperature and after the contact occurs, the PT pressure has decreased to a lower value which will yield a lower PT/CT contact conductance. These factors will make the actual EMS value higher than the case where PT ballooning is caused by a constant pressure, thus the experiment results can cover the safety analysis situation.

Similar to the sensitivity simulation for SCT case HP5, sensitivity simulations for Test Q11 with AMS value of 19ºC and 19.5ºC with other parameters unchanged are also performed to understand the impact of the change EMS on the rewet time. The results for the nominal case and the two sensitivity cases are shown in Figure 18 which indicates with the tiny decrease in the moderator subcooling, the rewet time increases dramatically until sustained dryout occurs. As shown in Figure 8 and Figure 11, the EMS values of the cases lie in between 30ºC and

34ºC which is the so called transition dryout region (Reference [7]), thus a tiny decrease in the EMS value will cause a dramatic increase in the rewet time and the results are not surprising.

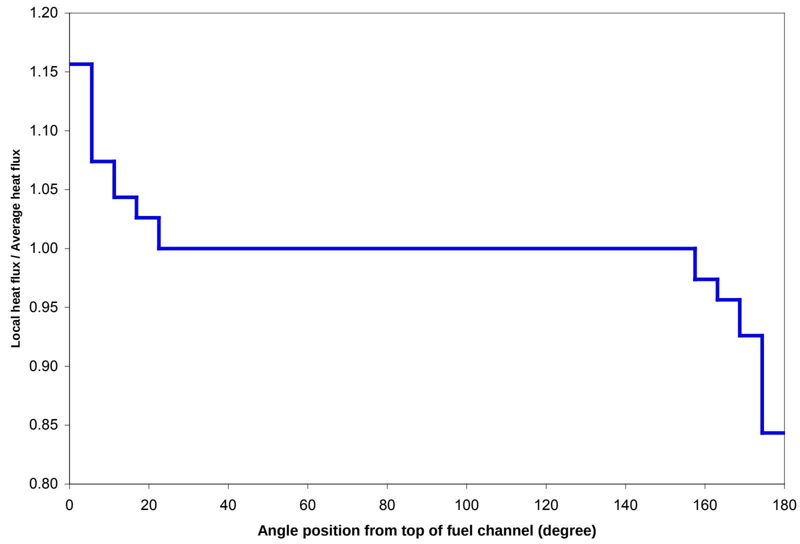

Figure 16: Ratios of local heat fluxes to average heat flux at the artificial hot and cold regions for Test Q11

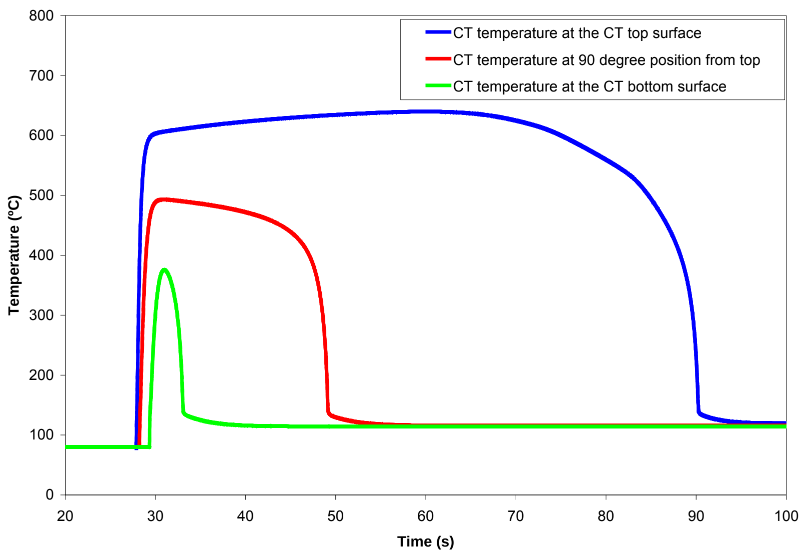

Figure 17: Simulated GCT temperatures for Test Q11 with the assumed hot spot and cold spot

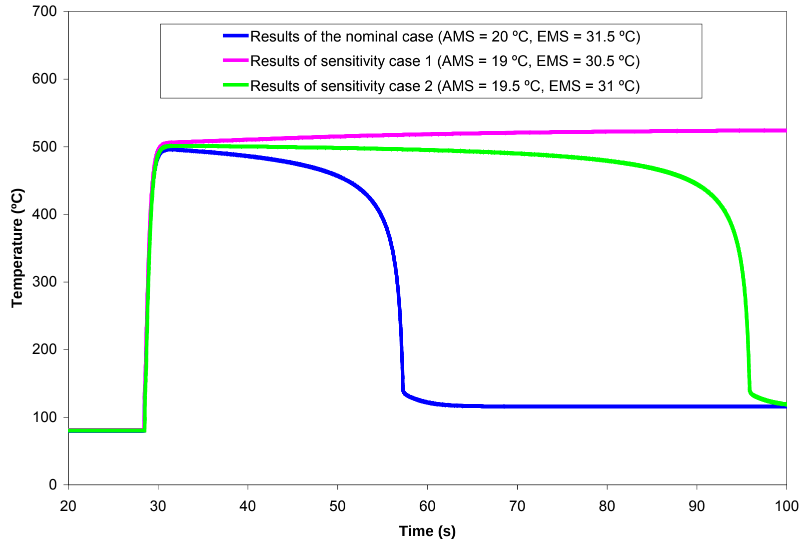

Figure 18: Simulated GCT temperatures for PT/CT contact test Q11 (PT pressure = 4.7MPa)

10. Conclusions

Based on the methodology of equivalent moderator subcooling, the contact thermal conductance upon PT/CT contact, critical heat flux and the rewet temperature of GCTs in the moderator are estimated. The empirical methods to calculate the nucleate boiling heat transfer coefficient and film boiling heat transfer coefficient on the GCT surface in water are proposed. The correlations for these parameters are derived based on estimation and the correlations for SCTs and these estimates may help in detailed analysis on the PT/CT contact to determine the integrity of fuel channels. The obtained correlations are confirmed by simulating some typical tests using both smooth calandria tubes and glass-peened calandria tubes. Some sensitivity simulations are also performed to confirm the sensitivity of the rewet time to EMS change in the transition dryout region. The impact of the non-uniformity in energy distribution along the CT surface is also discussed for the GCT cases. Since the applied parameters are highly empirical, if accurate correlations are needed, more detailed experiments or mechanistic models may still be necessary.

11. Acknowledgements

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