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A Methodology to Assess Transient Contact Heat Transfer Coefficient using Contact Boiling Test Data

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A Methodology to Assess Transient Contact Heat Transfer Coefficient using Contact Boiling Test Data

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Abstract

One of the passive safety features present in CANDU® reactors is the heavy-water moderator surrounding the fuel channels. During some postulated loss-of-coolant accidents (LOCAs), pressure tubes (PTs) will deform radially into contact with associated calandria tubes (CTs). The contacted tubes form a radial heat removal path that is additional to the heat removal capability of the heat transport system. The stored heat and the decay heat from the fuel channel are transferred through the CT to the moderator, which acts as a heat sink. To demonstrate the effectiveness of the moderator as a heat sink and to ensure the integrity of the fuel channel, the transient contact heat transfer coefficient (CHTC) between the PT and CT after PT/CT contact is needed for safety analysis.

Since the early 1980s, several series of experiments have been conducted at AECL Whiteshell Laboratories to assess contact boiling heat transfer that occurs when a pressurized PT deforms through a CO_2 annulus gas gap into contact with a CT in a tank of heated water. Such contact boiling tests, in which full-scale PT and CT sections were used, provide sufficient data (i.e., test section temperatures, applied heater power and internal pressure) to infer the transient PT/CT CHTC based on the principles of heat transfer.

A methodology has been developed to assess the transient PT/CT CHTC. The simulation model implements a negative feedback method by comparing contact boiling test data with the corresponding transient simulation results. The effectiveness and applicability of such a CHTC simulation model has been demonstrated with several test cases. The results show that the model has the capability to capture CHTC transient characteristics from the input data including the rapid changes in PT and CT temperatures upon initial contact and associated rapid changes in contact heat transfer coefficients.

The PT/CT CHTC is an important parameter for determining fuel channel behaviour, which changes significantly during the course of a LOCA. With the methodology developed here the PT/CT CHTC transient can be determined using contact boiling test data to meet the needs of safety analysis.

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1. Introduction

One of the passive safety features present in CANDU® reactors is the heavy-water moderator surrounding the fuel channels. Each fuel channel in a CANDU reactor consists of a pressure tube (PT) inside a calandria tube (CT), with a gap that contains CO_2 insulating gas. The PT containing nuclear fuel and pressurized coolant is separated from the CT via garter springs. Cool moderator surrounds the CTs. During the analysis of a postulated large loss-of-coolant accident (LOCA), a break is assumed to occur in the primary heat transport system. A range of such postulated breaks would result in coolant flow stagnation in some fuel channels in the downstream pass; therefore, the event may result in degraded cooling conditions. With insufficient channel coolant flow, the energy that is generated in the nuclear fuel would be partially stored in the fuel, and would cause fuel temperatures to increase. Consequently, the PT temperature may increase, due to convective heat transfer from the hot coolant steam in the channel, and due to radiation from the overheated fuel. If the PT becomes sufficiently hot while the channel pressure is still relatively high, the PT may deform radially (that is, it may exhibit ballooning) until the PT fully contacts its associated CT.

Pressure tube/calandria tube contact would form an outward heat removal path, cool down the PT, and consequently result in the gradual cool-down of the fuel. After contact, the heat, which is stored in the PT and generated in the channel, is transferred to the moderator. The moderator has a large volume of subcooled heavy water that surrounds all the horizontal fuel channels in a CANDU pressurized heavy-water reactor. Because of this configuration, the heat would be transferred radially to the moderator and removed by its cooling system. Therefore, the moderator would act as a supplementary heat sink during postulated LOCA events.

One of the key parameters in the safety analysis is the contact heat transfer coefficient (CHTC) between the PT and the CT after PT/CT ballooning contact. The PT/CT CHTC is required to calculate the heat flux that is transferred from the PT to the CT. This heat flux, together with the heat flux that is transferred from the CT to the moderator, determines CT post-contact behaviour, particularly the boiling regimes on the outside surface of the CT. The PT/CT CHTC is also required to calculate the heat load to the moderator after PT ballooning contact. Both CT post-contact behaviour and moderator heat load are important for assessing fuel channel integrity after PT/CT ballooning contact.

2. Contact Boiling Experiments

A large number of contact boiling experiments were conducted at AECL Whiteshell Laboratories to assess contact boiling heat transfer when a pressurized CANDU PT section deformed through a CO_2 gas gap into contact with a CT in an open tank of heated, stirred water:

1) Thirty-two experiments were originally conducted between 1979 August and 1984 February. The purpose of these experiments was not to simulate reactor conditions, but to obtain an understanding of the thermal-mechanical behaviour of a water-cooled CT as a result of ballooning contact from an overheated PT.

2) Twenty contact boiling experiments were conducted between 1994 November and 1999 February. The purpose of these experiments was to provide additional data on the thermal-mechanical response of a CT to ballooning from an overheated PT, and to provide experimental data on the high-pressure (>5 MPa) deformation behaviour of CANDU fuel channels for the validation of PT deformation models.

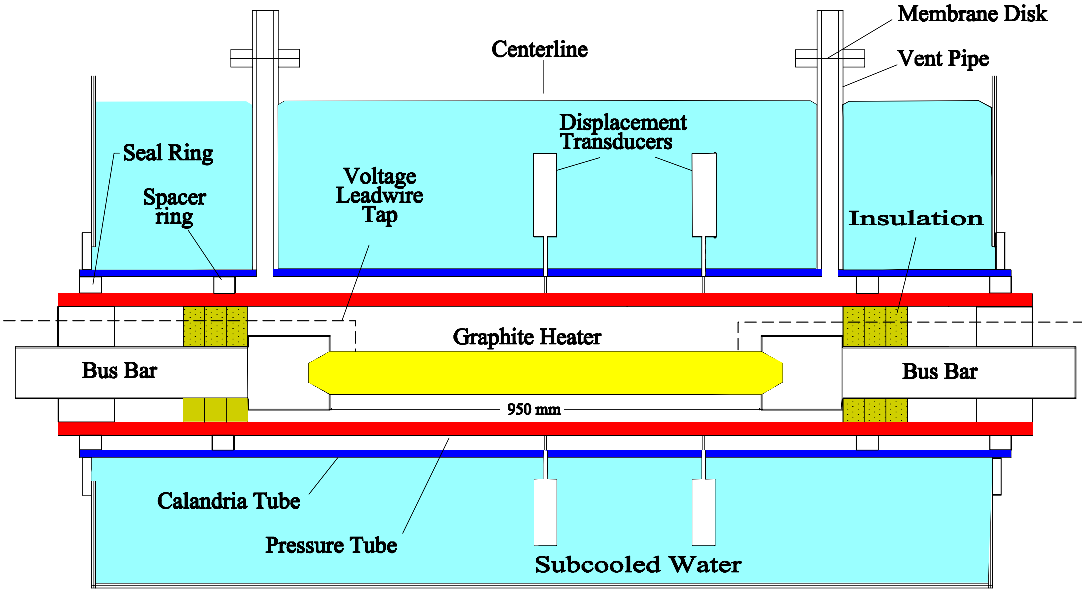
3) Two experiments were conducted between 1999 June and 1999 September. The purpose of these two experiments was to investigate the effect of a modest subcooling shortfall on fuel channel integrity.

A typical experimental apparatus for the contact boiling experiment is shown in Figure 1. The apparatus consisted of a test section with a concentric PT and CT. The CT was submerged in a nearly stagnant, open tank of water, which was heated to a temperature that was dependent upon the individual test design. A heater, graphite rod or other type of heat simulator was located at about the midpoint inside the test section of the assembly. The inside of the PT was pressurized with ultra high purity argon. The annulus gap between the PT and the CT was purged with CO_2 at essentially atmospheric pressure throughout the experiment.

A typical heater was about 950 mm long (see Figure 1). The applied power was determined by multiplying circuit current by the voltage drop measured between voltage taps connected directly to the heater. The spacing between these voltage taps on the heater was 900 mm. Several thermocouples were used to monitor test section temperatures. The thermocouples were axially distributed on a few of particular cross-sections (e.g., 5 rings shown in Figure 1) of the PT/CT system. At particular angular location on each ring, test section temperatures were monitored by a pair of thermocouples—at the middle surface of the PT and on the outer surface of the CT (e.g., pairs of 0-14, 1-16 and 2-18 on Ring 1 in Figure 1).

It is possible that large diameter tubes, such as CTs, may experience nucleate boiling, film boiling or some combination of the two (i.e. patchy film boiling) under certain conditions. Such phenomena are due to a complex combination of the variation in tube-to-tube contact condition as well as the pool boiling variability. The implication of this phenomena for analysis of fuel channel behaviour following ballooning contact is that one must assess the impact of patchy film boiling on fuel channel integrity, rather than using the classical approach of assuming that the tube is undergoing nucleate boiling or film boiling. Patchy film boiling behaviour results in random variations in CT temperature at different locations at any given time. Although a portion of the CT goes beyond the nucleate boiling regime, it does not result in further deformation and failure of the fuel channel, providing that the CT rewetted within a short period of time. At these CT locations, the CT experiences a transient effect due to a shift in the boiling regime. Therefore, the temperature measurement by each pair of thermocouples can be considered as an independent set of experimental temperature data.

The contact boiling experiments, in which full-scale PT and CT sections were used, provide sufficient data (i.e., test section temperatures, applied heater power and internal pressure) to infer the transient PT/CT CHTC based on the principles of heat transfer.



Sectional Schematic of Apparatus (not to scale) a)

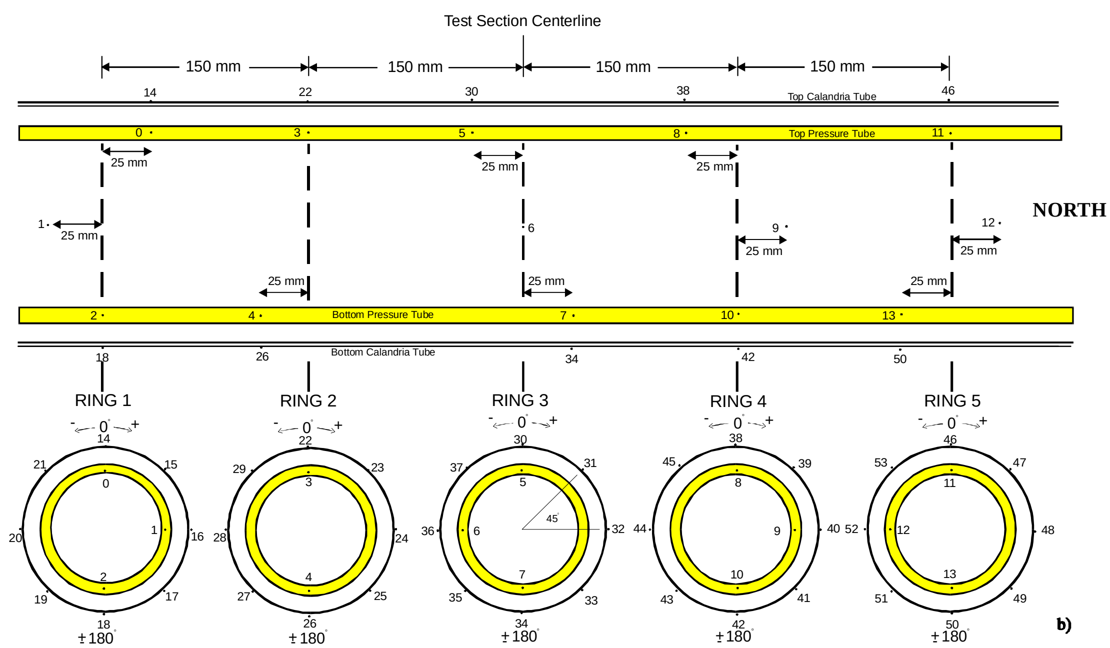


Figure 1. Schematic of (a) Typical Apparatus and (b) Thermocouple Locations in a Contact Boiling Test

3. PT/CT Contact Heat Transfer Coefficient (CHTC)

The measured section temperatures, that is, the PT and CT wall temperatures, can be considered as the PT average temperature and the CT outer surface temperature. The PT and CT temperature distribution in the tube walls and variation in the time after PT/CT contact are not *a* *priori* known; but, they are needed in the assessment of the PT/CT CHTC, since the PT/CT CHTC (also known as contact conductance) directly couples the contact interface temperatures and the contact heat flux, q''_{cont} (W/m^2), see Figure 2. The contact interface temperatures are PT outer surface temperature, T_{PT2} (°C), and CT inner surface temperature, T_{CT1} (°C).

The contact heat flux can expressed in a linear form:

$$q''_{cont} = h_{cont} (T_{PT2} - T_{CT1}) \tag{1}$$

where
h_{cont} ($W/(m^2 \bullet K)$) is the CHTC between the PT and CT.

The contact heat transfer coefficient is composed of three heat transfer components: solid-to-solid conduction, radiation across the annulus gap and conduction through the annulus gas between the PT/CT tube contact interfaces. The parameters that influence the contact heat transfer coefficient include:

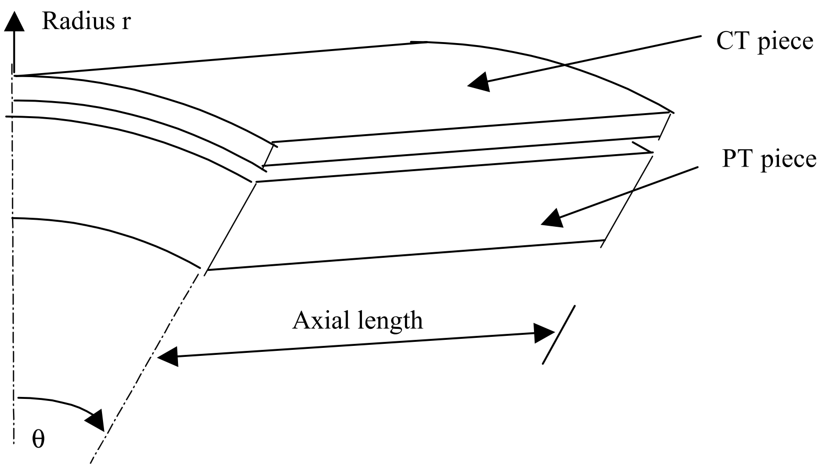
- the surface roughness of the interfaces,
- the surface hardness of the interfaces,
- the yield strength of the tube walls,
- the PT surface profiles (striation) formed during PT ballooning deformation,
- the contact force,
- the thermal conductivity of the annulus gas, and
- the emissivity of the contact-surfaces.

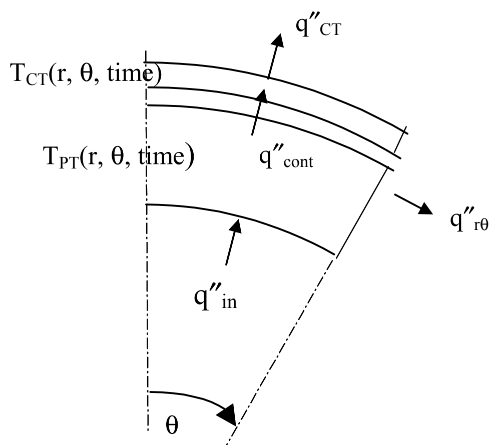
As the temperature of the contact surfaces increases and the materials become more plastic under contact pressure, solid-to-solid contact heat transfer increases at the expense of the other two components. The actual solid-to-solid contact area increases as the size of the annulus gaps decreases. Heat transfer through small (microscopic) gaps by free convection is insignificant compared to conduction across the same interface at a given time. Radiation heat transfer could only be significant at high PT temperatures compared to conduction across the same interface at a given time. However, radiation, conduction and convection are lumped into a single term to simplify the analysis.

Considerable research efforts have been expended to expand the understanding of the thermal contact phenomenon after PT/CT contact, including the PT/CT CHTC. For example, a minimum contact conductance between the PT and CT was identified to prevent CT dryout at various PT contact temperatures and moderator subcooling [2]. Also, analytical calculations based upon wavy-surface concepts of conductance for multiple contacts were performed with experimental verification on small sections of PT/CT taken from a contact boiling experiment [3, 4]. These previous works suggested the magnitude of the PT/CT CHTC. Attempts have also been made to derive transient contact conductance-induced methodologies tied with moderator subcooling. Although a general correlation of PT/CT CHTC is not yet available, CHTC is understood to vary during the course of PT/CT contact, including after PT/CT contact. The CHTC is directly dependent on PT and CT contact surface conditions, the interface pressure between the tubes, and the temperatures of the PT and CT. These surface temperature conditions and interface pressure, in turn, are implicitly dependent upon the PT internal channel pressure, the heat transfer for the PT temperature at the time of contact, the incident heat flux and the moderator subcooling.

4. Derivation of CHTC Transient using Contact Boiling Test Data

The methodology to assess the CHTC using contact boiling test data can be established to be based on the heat transfer principle from the experimental data of contact boiling tests, in which full-scale PT and CT sections were used. The modelling detail focuses on the radial heat transfer between the contacted PT and CT (see Figure 2).





q''_{in}: Incident heat flux to the PT inner surface
q''_{cont}: Contact heat flux on the PT/CT interface
q''_{CT}: CT heat flux to the moderator from the CT outer surface
$q''_{r\theta}$: Circumferential heat flux towards the adjacent portion of the tubes
(r, θ): Local point location inside PT or CT
The tube temperature change rate depends on the net heat balances at a given location in the tube.

Figure 2. Tube Temperature Fields and Surface Heat Fluxes

Based on the basic heat equations, the approach taken to assess the PT/CT CHTC here involves using the incident heat flux (see Figure 2) on the inner surface of the PT to estimate the contact heat flux. The incident heat flux, q''_{PT}, on the PT is not directly measured in contact boiling experiments. It can be estimated based on the radiation model from heater to PT and on the applied V_{tap} power for a given contact boiling experiment. The contact boiling experiment used argon gas to fill in the channel of the test section. The effect of free convection is lumped into the radiation heat transfer model through the emissivities of the heater and inner surface of the PT. The incident heat flux predicted for the contact boiling experiments is a steady value that gradually increases over time during the course of a contact boiling experiment. Thus, the incident heat flux is less sensitive to variations in PT and CT temperatures.

In the detail, the approach here uses measured CT temperatures as known boundary conditions, which have taken into account the transient effect of the moderator heat removal conditions. The incident heat flux mentioned in the previous paragraph is used as a known boundary condition on the inside surface of the PT. On the contact interfaces, the heat flux out of the PT outside surface is equal to the heat flux into the CT inner surface at any time. The measured PT temperatures are used as one of the targets for simulation control. This approach reduces the dependency on modelling the moderator and on utilising the CT/moderator heat transfer correlations for critical heat flux and heat transfer coefficients. A calculation model for the PT/CT CHTC, named the "CHTC simulation model", is derived based on the basic heat equations for both PT and CT as

$$h_{n+1} = h_n + (C_1 \bullet h_n \bullet \Delta T + C_0 \bullet C_2 \bullet \rho C_\rho \bullet \Delta(dT/dt)) \bullet (\Delta t_{cal}/\Delta t_{test})/(T_{PT2} - T_{CT1}), \quad (2)$$

where,

- h_n and h_{n+1} (both in $W/(m^2 \bullet K)$) are the estimated PT/CT CHTCs at time steps n and n+1, respectively.
- ΔT (K) is the PT temperature difference between calculation, T_{PTC}, and measurement, T_{PTM}, at the current time, i.e., $\Delta T = T_{PTC} - T_{PTM}$. Since the PT temperature measurement is at about the middle of the PT wall cross-section, the PT temperature calculated at the middle of the PT wall cross-section is used. Between any pair of measurement times, the PT temperature is linearly interpolated.
- $\Delta(dT/dt)$ (K/s) is the difference of the PT temperature change rate between calculation and measurement at the current time, which is calculated based on the ΔT change rate over the calculation time step.
- $\Delta t_{cal}/\Delta t_{test}$ is a time-step controller, the ratio of the calculation time step length to the measurement time step length in the test.
- ρC_ρ ($J/(m^3 \bullet K)$) is the volumetric heat capacity of the PT wall materials.
- C_0 (in m) is the ratio of the PT volume to the contact interface area, about the same as the PT wall thickness after PT/CT contact.
- C_1 and C_2 are dimensionless numerical control factors. Sensitivity study results show that higher values for the control factors may result in a fast convergence, but may lead to overshooting, followed by unstable results. Results also show that using a reference value of 1.618 for both C_1 and C_2 can give a reasonable convergence and stable results for the time-step controller ($\Delta t_{sim}/\Delta t_{test}$) of 0.01/0.125.

The CHTC simulation model uses a negative feedback method based on PT temperature. Therefore, a reasonable convergence and stable results are expected within a certain time lag. If the simulation results agree well with the experimental measurements of both the PT temperature value and its trend (i.e., $\Delta T = 0$ and $\Delta(dT/dt) = 0$), then the PT/CT CHTC remains unchanged. Since the CT temperature measurement has been used as the boundary, no significant difference is expected for the CT temperature value and its trend between calculation and measurement. In addition, the effect of the CT temperature value and its trend on the PT/CT CHTC has been taken into account in the CHTC simulation model, with the usage of the PT/CT interface temperature.

There are other approaches to assess the PT/CT CHTC using experimental data. For example, a classical approach is to take the average of the heater power and heat removal from the tank to estimate contact heat flux (see Figure 2). This approach is suitable for cases with low channel pressure, where the heat flow changes little with time and varies little at a given location across the PT and CT wall. The other approach involves the CT heat flux (see Figure 2), which is the CT/moderator heat transfer correlation that is employed in the computer code and related to the CT surface temperature. This second approach is suitable for cases where the CT stays in a single boiling regime, and requires an accurate correlation of CT/moderator heat transfer. The approach presented in this report is to give a model which has the capability to capture CHTC transient characteristics from the input data including the rapid changes in PT and CT temperatures upon initial contact and associated rapid changes in contact heat transfer coefficients.

5. Computer Code

The CATHENA code [5] is used in the assessment of the PT/CT CHTC using contact boiling test data.

CATHENA uses a transient, one-dimensional, two-fluid representation of two-phase flow in piping networks [5]. CATHENA also provides a comprehensive solid heat transfer package, GENHTP (GENeralised Heat Transfer Package), which is used to model pipe walls or fuel that are in contact with fluid [5]. The heat transfer model includes radial and circumferential conduction, thermal radiation and contact conduction between solid surfaces. The heat transfer model also includes a deformation model to account for the PT expansion that may result in contact with the CT. The heat transfer package allows the connection of multiple solid surfaces of a heat transfer model to a single thermalhydraulic node, or multiple thermalhydraulic nodes. As a result, very detailed modelling of a CANDU channel can be performed. The testing of CATHENA/GENHTP has demonstrated high computational efficiency, as well as the advantage of closely coupling thermalhydraulic, fuel and fuel channel behaviour. A single code, CATHENA, may be used for modelling the system thermalhydraulics, as well as the detailed heat transfer modelling of a CANDU fuel channel.

Extensive validation work on CATHENA has been done including work on the phenomena of PT/CT heat transfer and CT/moderator heat transfer.

6. Empirical Form of the PT/CT Contact Heat Transfer Coefficient

The PT/CT CHTC is understood to vary during the course of PT/CT contact. The PT/CT CHTC is directly dependent on PT and CT contact surface conditions, the interface pressure between the tubes and the temperatures of the PT and CT. The interface pressure and surface temperature conditions, in turn, are implicitly dependent upon the PT internal channel pressure. Thus, the PT/CT CHTC will be a function of the interface pressure and interface profile condition, for a given type of tube. The interface pressure and interface profile condition are themselves functions of the wall temperatures. Therefore, as a simple form of an analytical approach [3], the empirical correlation would be

$$H_{cont} = C*k*(K_P P) + h_0 \qquad (3)$$

where

- P (MPa) is the channel pressure, which is known in an experiment or safety analysis case;
- $K_P P$ (MPa) gives the interface pressure value;
- K_p is a dimensionless pressure factor to be determined;
- C (1/(m•MPa)) is a material constant to be determined, which is a lumped parameter influenced by the contact surface profile, wavy shape and other tube geometrical data;
- k (W/(m•K)) is the tube material thermal conductivity, which is assumed to be a known function of tube temperature; and
- h_0 (W/(m^2•K)) is a lumped heat transfer coefficient for the heat transfer due to mechanisms other than solid-solid contact (e.g., CO_2 conductive and radiative effect). This constant is to be determined, and the value is expected to be small.

In this empirical correlation, the contact interface pressure is considered to be a key parameter. The contact interface pressure is also the pressure load on the CT. Since only the channel pressure (that is, the pressure load on the PT) is measured, the contact interface pressure is represented by the channel pressure, using a pressure factor K_p. Although K_p is to be determined, the magnitude of this pressure factor is expected to vary as follows.

Upon PT/CT contact, the pressure factor K_P would be ≥ 1, when considering the contact dynamic effect. Upon PT/CT contact, the PT has little strength to balance the channel pressure.

After PT/CT contact, the pressure factor K_P would be stabilized as a small fraction ($\ll 1$). After PT/CT contact, the PT will gain strength and the dynamic effect will be 'damped' out (relaxation) within a very short period. Then, the contact interface pressure will decrease and will not be greater than the channel pressure for static equilibrium. The PT may still creep and thermally contract at the same time, after PT/CT contact. However, the composite materials (PT and CT) would be assumed to deform together circumferentially, regardless of whether the PT and CT are in plastic or elastic regions. The ratio of the CT wall thickness to the composite PT/CT wall thickness is about ¼. With the assumption of small additional straining and the same PT and CT temperatures (though in general the PT temperature remains higher than the CT temperature), the possible pressure factor would be ¼ after PT/CT contact. The tube surface profile and other surface geometrical conditions will vary after contact, due to micro-deformation of the contact surfaces (elastic or plastic) under high temperature and interface pressure.

However, variation of the geometrical influence after PT/CT contact will be taken into account by the interface pressure factor.

The empirical PT/CT CHTC may be represented in other forms. However, these forms mainly reflect the pressure transient influence on the PT/CT CHTC, implicitly considering the transient effect of the tube temperatures.

7. CHTC Simulation Model Testing

Two sets of test problems are designed for the CHTC simulation model:

Test Problem A (Step Function Disturbances)

The CT outer surface temperature remains at a constant value of 120°C. The PT is subjected to an incident heat flux of 300 kW/m^2 and has an initial PT temperature of 321.6°C. A step function disturbance of the PT/CT CHTC is added to the constant PT/CT CHTC.

Using the PT and CT temperature simulation results of the above problem as inputs without specifying the PT/CT CHTC, the above problem is re-simulated using the CHTC simulation model, in order to trace the PT/CT CHTC. The input data time step of 0.125 seconds is used, since most contact boiling experiments logged the data at 8 scans/second after PT/CT contact.

Three cases are designed for this test problem using different step functions:

a. a step of 1.0 kW/(m^2•K) over 1.0 second,
b. a step of 2.0 kW/(m^2•K) over 0.5 seconds, and
c. a step of 4.0 kW/(m^2•K) over 0.25 seconds, adding to the constant of 2.0 kW/(m^2•K).

Test Problem B (Idealized PT/CT Contact Heat Transfer)

The PT is subjected to an incident heat flux of 300 kW/m^2 and has an initial PT temperature of 700 °C. The PT/CT CHTC is given an initial value of 0.1 kW/(m^2•K) until 1.0 s, and then linearly increases up to 10.0 kW/(m^2•K) at 2.0 s, after which it linearly decreases down to 1.0 kW/(m^2•K) at 3.0 s, remaining at 1.0 kW/(m^2•K) after 3.0 s. The CT outer surface temperature is given in a similar way, in the same time frame: 100°C initially, linearly increasing up to 130 °C between 1.0 s and 2.0 s, then linearly decreasing down to 120°C between 2.0 s and 3.0 s, and remaining at 120 °C after 3.0 s.

Using the PT and CT temperature simulation results of the above problem as inputs without specifying the PT/CT CHTC, the above problem is re-simulated using the CHTC simulation model, in order to trace the PT/CT CHTC.

The objective of the model testing is to show the effectiveness and limitations of the CHTC simulation model to handle CHTC variations. Test Problem A is designed to demonstrate the capability to trace up and down for CHTC with the most severe numerical variation. Test

Problem B is designed to demonstrate the capability to handle PT/CT contact impact with a rapid change in CHTC, as well as with a rapid change in PT and CT temperatures.

The two test problems are solved with different simulation time steps to verify convergence in the time steps. Figures 3–6 show the results of the above test problems.

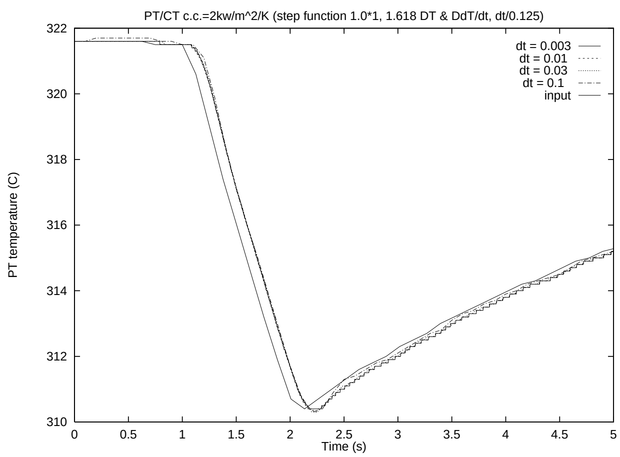


Figure 3. Comparison of Calculated and Input PT Temperatures for Test Problem A

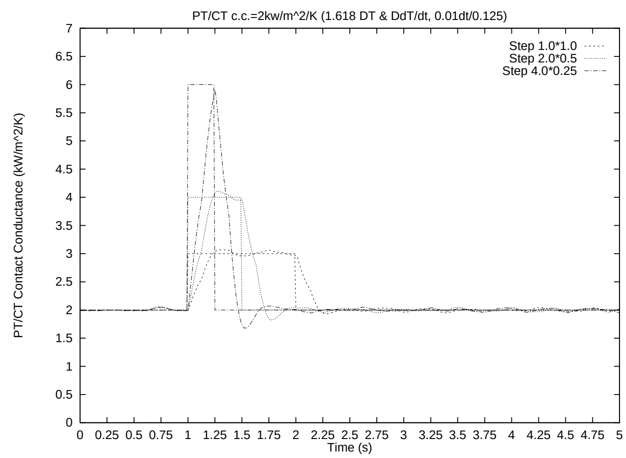


Figure 4. Comparison of Calculated and Given PT/CT CHTC for Test Problem A

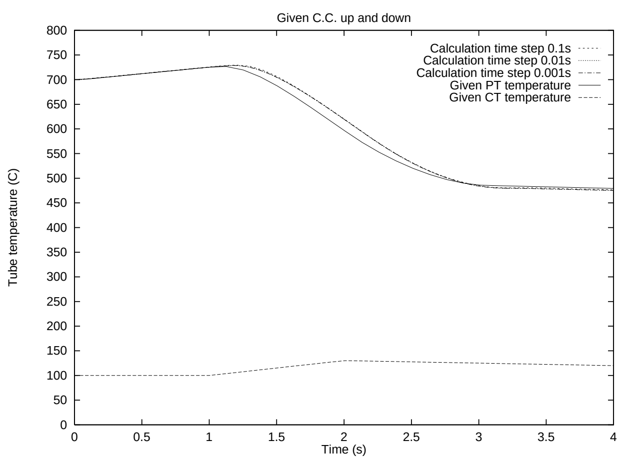


Figure 5. Comparison of Calculated and Input PT and CT Temperatures for Test Problem B

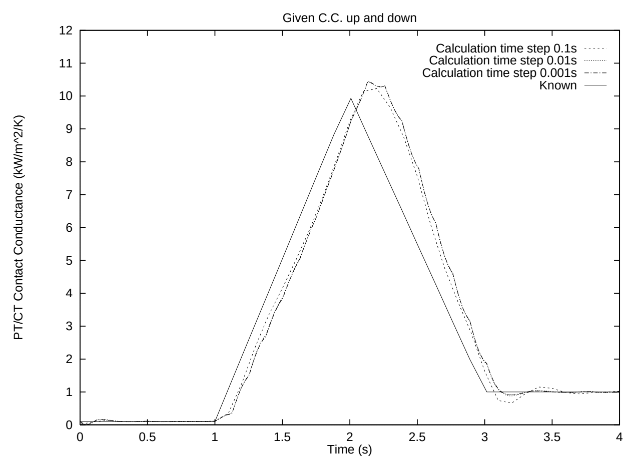


Figure 6. Comparison of Calculated and Given CHTCs for Test Problem B

Figures 3 and 5 show that, when the CHTC simulation model is used, the PT temperature calculation agrees well with the input values and the trend at a given time. Figures 4 and 6 show that, when the CHTC simulation model is used, the PT/CT CHTC can be traced very well.

Figures 3 to 6 also show that a reduction in the simulation time step has no significant effect on the calculation results, provided that the time step is less than 0.03 s when the input data time step of 0.125 s is used. Therefore, a simulation time step of 0.01 s is recommended to be used for assessing the PT/CT CHTC from the contact boiling experiment data. A time lag of up to two input data time steps (2*0.125 s) is noticed, which is expected due to feedback delay.

Figure 4 shows that when the CHTC simulation model is used, a dynamic change in PT/CT CHTC will be traced down, even with only two data points for Test Problem A, case (*c*). The results show that the peak values and half bandwidths of the dynamic changes (step function disturbances) agree well with the input data. Again, the results show that a time lag up to two input data time steps (2*0.125 s) would be expected.

The above model testing results show that the transient PT/CT CHTC can be reasonably obtained using the CHTC simulation model with a pair of PT/CT temperatures measured in a contact boiling experiment. Therefore, the database for that coefficient can be formed after assessing more PT/CT temperature experiment data pairs in the same test, or in a different test.

8. Conclusions

A methodology has been developed to assess the transient PT/CT CHTC. The simulation model implements a negative feedback method by comparing contact boiling test data with the corresponding transient simulation results. The effectiveness and applicability of such a CHTC simulation model has been demonstrated with several test cases. The results show that the model has the capability to capture CHTC transient characteristics from the input data. Since contact boiling test data were logged as fast as 8 scans/s, the model has been shown to handle PT/CT contact impact with a possible rapid change in the CHTC, including a possible rapid change in PT and CT temperature.

The PT/CT CHTC is an important parameter for determining fuel channel behaviour, which changes significantly during the course of a LOCA. With the methodology developed here, the PT/CT CHTC transient can be determined using contact boiling test data to meet the needs of safety analysis.

9. Acknowledgements

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