APPLICABILITY OF STEADY STATE CHF DATA IN TRANSIENT PROCESSES

L. Sun
Point Lepreau Generating Station, PO Box 600, Lepreau, NB, E5J 2S6

Abstract

An accurate prediction of critical heat flux (CHF) in the 37-element fuel bundle during postulated accident events in CANDU reactor is required to assure fuel sheath integrity. A series of steady-state experiments have been performed using full-scale bundle simulators. To confirm the applicability of the steady-state CHF values in transient processes, analyses to the existing experimental results have been performed in Canadian Nuclear Industry. This work attempts to demonstrate the applicability of steady-state CHF values in transient analyses by using a simple mathematical model based on reasonable assumptions.

1. Introduction

An accurate prediction of critical heat flux (CHF) in the 37-element fuel bundle during postulated accident events in CANDU reactor is required to assure fuel sheath integrity. The CHF correlation (or lookup table) used for Lepreau safety analysis was obtained by fitting the CHF data obtained by performing steady state experiments, rather than transient experiments. The experimental entries, i.e., the parameters controlled during the experiment (References [1] and [2]) are: power level in the fuel channel, flow rate through the channel, inlet temperature of the fuel channel, the outlet pressure of the fuel channel and creeping rate of the fuel channel. These five parameters constitute the experiment matrix. For each series of experiment, the inlet temperature, flow rate, outlet pressure, and the creeping rate were maintained at constant values, and the power was raised step by step. During each step after the system achieved the steady state, the temperatures of the fuel elements were scanned using the movable thermal couples carried by a ceramic carrier to detect the sign of dryout. The applied power to the test section corresponding to the initial dryout occurrence has been referred to as the critical power or dryout power. Local CHF values were calculated using the measured critical power. The local parameters corresponding to the measured CHF such as pressure, mass flux and thermodynamic quality were also determined. The detailed information of the experiment facility, experiment procedure and experiment results can be obtained from References [1] and [2].

A CHF lookup table has been made using the measured CHF values for safety analysis after correcting for the differences in thermophysical properties between the experimental fluids and D_2O which is used as a primary heat transport coolant in the presently operating CANDU reactors (Reference [3]). Within the lookup table, the CHF value is a function of local pressure, mass flux, and thermodynamic quality which were determined using the controlled parameters. The CHF table has been built in thermalhydraulics codes for safety analysis such as CATHENA (Reference [4]). Local pressure, mass flux, thermodynamic quality and heat flux can be determined by CATHENA, which in turn determine the CHF values. A comparison between the local heat flux and the determined CHF will indicate whether dryout occurs or not in the transient.

However, since the CHF values used to make the CHF lookup table were obtained using steady state method mentioned above and the lookup table has been used to analyze transient events, it is necessary to confirm that the CHF values from steady state experiment are applicable in transient processes. To address this issue, some work has been done or in progress in Canadian Nuclear Industry by analyzing the existing experimental data to demonstrate that the CHF values obtained in the steady state experiments are applicable in the transient processes (References [5] and [6]). In this work, it is attempted to demonstrate that the conclusion drawn References 5 and 6 is reasonable using a simple mathematical model. The objective of this study is to certify mechanically that it is conservative or deterministic to apply the CHF data determined in steady state experiments in transient process analyses for CANDU reactor.

2. Methodology

In this work, a mathematical method is developed to assess the effect of transient processes on CHF using a few simple assumptions. At first, the specific enthalpy of coolant will be determined for both steady state and transient state processes by applying the mass and energy conservation equations. Based on the conditions that one of the parameters among inlet temperature, outlet pressure, fuel channel power and inlet coolant flow rate changes transiently while the rest of the parameters are kept constant, the coolant specific enthalpy of the transient process is compared to that of the steady state process when all four controlled parameters including inlet flow rate, inlet coolant temperature, outlet pressure and power level are same for the steady and transient processes. If the coolant specific enthalpy in the transient process is lower than that of the steady state process, the CHF value in the transient process is expected to be higher than that in the steady state process. If the coolant specific enthalpy in the transient process is higher than that of the steady state process, the CHF value in the transient process will be lower than that in the steady state. If it is impossible to determine which is larger of the coolant specific enthalpy in the transient and steady state processes, more detailed analysis will be required either experimentally or analytically. Since pressure tube creeping rate will not change significantly until a long period of high power operation (in years), this factor is not discussed in this work. During the determination of the coolant enthalpy and the discussion on CHF value for transient and steady state processes, the following assumptions were made:

(1) All the heat produced in the fuel was added to the fluid, i.e., the heat transfer process is not considered.

(2) The coolant is always flowing forward, i.e., there is no backward flow during the transient process.

(3) The coolant at the inlet of the channel is always liquid and the enthalpy of the liquid does not change significantly with pressure.

(4) The coolant is flowing through a pipe simulating the fuel channel as shown in Figure 1 and the heat is added through the wall of the pipe.

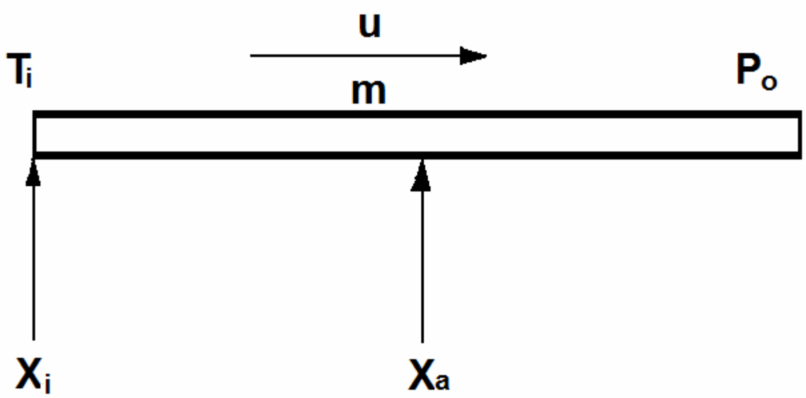

Figure 1 A Simplified Schematic of the Flow Pipe

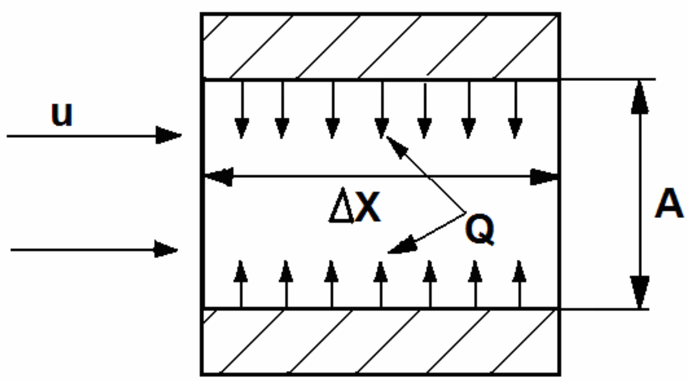

Figure 2 A Segment of the Pipe to Show Analysis Control Volume

3. Determination of coolant specific enthalpy

A segment of the pipe through which the coolant is flowing with a length of Δx is shown in Figure 2 as a control volume for analysis. Based on the mass conservation, the change of the mass in the control volume equals to the mass entering the control volume minus that exiting the control volume and the change of coolant enthalpy in the control volume equals to the enthalpy flowing into the control volume from upstream minus that flowing out of the control volume plus the energy added from the wall, i.e.

$$\frac{\partial(\rho A\Delta x)}{\partial t} = \rho Au - \left(\rho Au + \frac{\partial(\rho Au)}{\partial x}\Delta x\right) \tag{1}$$

$$\frac{\partial(Ah\rho\Delta x)}{\partial t} = Auh\rho - \left(Auh\rho + \frac{\partial(Auh\rho)}{\partial x}\Delta x\right) + Q(x)\Delta x \tag{2}$$

In equations (1) and (2), ρ is the density of the coolant, A is the area of the intersection of the pipe simulating the fuel channel, Δx is the length of the pipe segment, u is the flow velocity of the fluid, $Q(x)$ is the energy input per unit length of the pipe as a function of the position along the fuel channel and t is the time. Equations (1) and (2) can be simplified to the following formats

$$\frac{\partial \rho A}{\partial t} + \frac{\partial(\rho Au)}{\partial x} = 0 \tag{3}$$

$$\frac{\partial(\rho Ah)}{\partial t} + \frac{\partial(\rho Auh)}{\partial x} = Q(x) \tag{4}$$

For a steady state, i.e., the inlet temperature, T_{i}, flow rate, m, outlet pressure Po and the heating power Q are given, the term with the derivative versus time disappears and Equation (4) can be written as

$$\rho Au\frac{\partial h}{\partial x} = Q(x) \tag{5}$$

Assuming the inlet coordinate is x_{i}, an integral for Equation (5) between x_{i} and any downstream position, x_a, can be obtained as equation as

$$\int_{x_i}^{x_a} \rho Au\frac{\partial h}{\partial x}dx = \int_{x_i}^{x_a} Q(x)dx \tag{6}$$

Considering the flow rate m can be written as $m = \rho Au$, Equation (6) can be written as

$$\int_{x_i}^{x_a} m\frac{\partial h}{\partial x}dx = \int_{x_i}^{x_a} Q(x)dx \tag{7}$$

For a given flow rate at the inlet of the fuel channel, m_{i}, which is a constant along the channel, a given inlet specific enthalpy, h_{i} which is also considered a constant at a given temperature T_{i}, a given power level $Q_i(x)$, the above equation can be written as

$$m_i h(x_a) - m_i h_i = \int_{x_i}^{x_a} Q_i(x)dx \tag{8}$$

Thus the specific enthalpy at position x_a downstream from the inlet for a steady state process can be obtained as

$$h(x_a) = h_i + \frac{1}{m_i}\int_{x_i}^{x_a} Q_i(x)dx \tag{9}$$

For a transient process an integration can be performed between the inlet position x_i and any position downstream the inlet, x_a, for Equation (3), the mass conservation equation, as

$$\int_{x_i}^{x_a} \frac{\partial(\rho A)}{\partial t}dx + \int_{x_i}^{x_a} \frac{\partial(\rho A u)}{\partial x}dx = 0 \tag{10}$$

Thus the mass flux through the intersection of the fuel channel can be obtained as

$$\rho(x_a)Au(x_a) = -\int_{x_i}^{x_a} \frac{\partial(\rho A)}{\partial t}dx + \rho(x_i)Au(x_i) \tag{11}$$

At the same time an integration can also be performed between the inlet position x_i and any position downstream from the inlet, x_a, for Equation (4), the energy conservation equation, as

$$\int_{x_i}^{x_a} \frac{\partial(\rho A h)}{\partial t}dx + \int_{x_i}^{x_a} \frac{\partial(\rho A u h)}{\partial x}dx = \int_{x_i}^{x_a} Q(x)dx \tag{12}$$

Equation (12) can be further expanded to the following format

$$\int_{x_i}^{x_a} \frac{\partial(\rho A h)}{\partial t}dx + \rho(x_a)Au(x_a)h(x_a) - \rho(x_i)Au(x_i)h(x_i) = \int_{x_i}^{x_a} Q(x)dx \tag{13}$$

After substituting Equation (11) into Equation (13), the following equations can be obtained

$$\int_{x_i}^{x_a} \frac{\partial(\rho A h)}{\partial t}dx + \left(-\int_{x_i}^{x_a} \frac{\partial(\rho A)}{\partial t}dx + \rho(x_i)Au(x_i)\right)h(x_a) - \rho(x_i)Au(x_i)h(x_i) = \int_{x_i}^{x_a} Q(x)dx \tag{14}$$

Considering the coolant flow rate at the fuel channel inlet can be written as $m(x_i) = \rho(x_i)Au(x_i)$, Equation (15) can be written as

$$\int_{x_i}^{x_a} \frac{\partial(\rho A h)}{\partial t}dx + \left(-\int_{x_i}^{x_a} \frac{\partial(\rho A)}{\partial t}dx + m(x_i)\right)h(x_a) - m(x_i)h(x_i) = \int_{x_i}^{x_a} Q(x)dx \tag{15}$$

From Equation (15), the specific enthalpy of coolant at location x_a downstream from the inlet of the fuel channel can be obtained as

$$h(x_a) = h(x_i) + \frac{1}{m(x_i)} \int_{x_i}^{x_a} Q(x)dx + \frac{h(x_a)}{m(x_i)} \int_{x_i}^{x_a} \frac{\partial A\rho}{\partial t} dx + \left(-\frac{1}{m(x_i)} \int_{x_i}^{x_a} \frac{\partial(\rho A h)}{\partial t} dx \right) \quad (16)$$

Rearranging the last two terms, Equation (16) can be written in the following format.

$$\begin{aligned} h(x_a) &= h(x_i) + \frac{1}{m(x_i)} \int_{x_i}^{x_a} Q(x)dx + \frac{1}{m(x_i)} \int_{x_i}^{x_a} h(x_a) \frac{\partial(A\rho)}{\partial t} dx \\ &- \frac{1}{m(x_i)} \int_{x_i}^{x_a} h(x) \frac{\partial(\rho A)}{\partial t} dx - \frac{1}{m(x_i)} \int_{x_i}^{x_a} \rho(x) \frac{\partial(Ah)}{\partial t} dx \\ &= h(x_i) + \frac{1}{m(x_i)} \int_{x_i}^{x_a} Q(x)dx + \frac{1}{m(x_i)} \int_{x_i}^{x_a} \left[h(x_a) - h(x) \right] \frac{\partial(A\rho)}{\partial t} dx + \left(-\frac{1}{m(x_i)} \int_{x_i}^{x_a} \rho(x) \frac{\partial(Ah)}{\partial t} dx \right) \end{aligned} \quad (17)$$

At the moment when the inlet flow rate, inlet temperature, power level and outlet pressure are same for a transient process and a steady state process, Equations (16) and (17) can be rewritten using the controlled parameters for the steady state as:

$$h(x_a) = h_i + \frac{1}{m_i} \int_{x_i}^{x_a} Q_i(x)dx + \frac{h(x_a)}{m_i} \int_{x_i}^{x_a} \frac{\partial A\rho}{\partial t} dx + \left(-\frac{1}{m_i} \int_{x_i}^{x_a} \frac{\partial(\rho A h)}{\partial t} dx \right) \quad (18)$$

$$h(x_a) = h_i + \frac{1}{m_i} \int_{x_i}^{x_a} Q_i(x)dx + \frac{1}{m_i} \int_{x_i}^{x_a} \left[h(x_a) - h(x) \right] \frac{\partial(A\rho)}{\partial t} dx + \left(-\frac{1}{m_i} \int_{x_i}^{x_a} \rho(x) \frac{\partial(Ah)}{\partial t} dx \right) \quad (19)$$

4. Applicability of steady state CHF in transient processes

The specific enthalpy of coolant at any location downstream from the inlet of fuel channel have been obtained as shown in Equations (9) and (18) (or Equation (19)) for steady state and transient state processes when the inlet flow rates, the inlet specific enthalpy and power level are same for these processes. Equations (18) and (19) are same as Equation (9) except for the two transient terms, i.e., Term 3 and Term 4 in Equation (18) and Equation (19). The focus of the following analysis is to compare the coolant specific enthalpy within the channel between the steady and transient processes when all four controlled parameters including the inlet flow rate, inlet coolant temperature, outlet pressure and power level are same for steady and transient processes.

The following four different transient processes which are of interest in safety analysis to ensure fuel sheath integrity, are discussed:

(1) The inlet temperature, fuel power and outlet pressure are constant, but the flow rate at the inlet decreases from a higher initial value, m_0, to the steady state value, m_i.

(2) The inlet temperature, outlet pressure and flow rate at the inlet are constant, but the fuel power increases from a lower initial value, $Q_0(x)$ to the steady state value, $Q_i(x)$.

(3) The inlet flow rate, fuel channel power and outlet pressure are constant, but the inlet temperature is increased from a lower value, T_0, to the steady state T_i.

(4) The outlet pressure (Po) change with other parameters from initial value P_0 to the steady state value P_i.

For the flow reduction process, i.e., the first kind of transient process, the flow rate at the inlet will be same as that of the steady state process after the flow rate at the inlet decreases from a higher initial value, m_0, to the steady state value, m_i, so $m(x_i) = m_i$, $h(x_i) = h_i$, $Q(x) = Q_\mathrm{i}(x)$, and $P\mathrm{o} = P_i$. With the flow decrease, more energy will be absorbed by every unit mass of coolant and at the same time the decrease in flow implies a decrease in the inlet pressure since the outlet pressure is kept a constant, so the density of the coolant will decrease and Term 3 in Equation (18) is negative. At the same time, with the decrease in flow, less energy is transported out of the channel, so the total enthalpy in each segment of the channel will increase and this means Term 4 in Equation (18) is also negative. The above discussion indicates that the coolant specific enthalpy for this transient process is lower than that for the steady state process when all the four controlled parameters including inlet flow rate, inlet temperature, outlet pressure, and fuel power are same for the transient and steady state processes, thus it can be estimated that dryout will occur earlier in the steady state process than in the flow reduction transient process, i.e., the transient process has a higher CHF than the steady state process.

For the power increase process, i.e., the second kind of transient process, $m(x_i) = m_i$, $h(x_i) = h_i$, $Q(x) = Q_\mathrm{i}(x)$, and $P\mathrm{o}= P_i$ after the power level increases to the steady state value $Q_\mathrm{i}(x)$ from a lower initial value $Q_0(x)$. With the power increase, more energy will be added to every unit mass of coolant and at the same time the pressure will not change significantly since the flow and outlet pressure are kept constant, so the density of the coolant will decrease and Term 3 in Equation (18) is negative. At the same time, with the increase in power, more energy is added to the coolant in each segment of the channel, so the total enthalpy in each segment of the channel will increase and this means Term 4 in Equation (18) is also negative. The above discussion indicates that the coolant specific enthalpy for this transient process is lower than that for the steady state process when all the four control parameters including inlet flow rate, inlet temperature, outlet pressure, and fuel power are same for the steady and transient state processes, thus it can be estimated that dryout will occur earlier in the steady state process than in the power increase transient process, i.e., the transient process has a higher CHF than the steady state process.

For the inlet temperature increase processes, i.e., the third kind of transient process, the inlet specific enthalpy of the transient process will be same as that of the steady state process after the transient inlet temperature increases to the steady state value T_i from a lower initial value T_0, so $m(x_i) = m_i$, $h(x_i) = h_i$, $Q(x) = Q_\mathrm{i}(x)$, and $Po = P_i$. With the inlet temperature increase, the downstream coolant specific enthalpy will also increase which means Term 4 in Equation (19) is negative. If the inlet temperature increase rate is not very large, the coolant specific enthalpy at position x_a will be larger than any other upstream position. At the same time, since the pressure in the system is basically constant (because the flow rate and outlet pressure are constant), the downstream coolant density will also decrease, implying that Term 3 in Equation (19) is also negative. Thus the coolant specific enthalpy for the transient process is lower than that in the steady process, i.e., the transient process has a higher CHF than the steady state process when all the four control parameters including inlet flow rate, inlet temperature, outlet pressure, and fuel power are same for the steady and transient state processes. If the inlet header temperature increase is huge, Term 3 in Equation (19) may be positive. However, a larger increase rate of inlet temperature will make Term 4 more negative to eliminate all or partial influence of Term 3 and thus the steady state CHF value may also be applicable to the transient process.

For the coolant pressure change in the process, i.e., the fourth kind of process, $m(x_i) = m_i$, $h(x_i) = h_i$, $Q(x) = Q_i(x)$, and $Po = P_i$ after the outlet pressure Po changes from initial value P_0 to the steady state value P_i. This situation is a bit complicated. In the postulated accident events, it is pretty hard to keep the other parameters like inlet flow rate, fuel channel power and inlet temperature constant while changing the outlet pressure only. In the postulated accidents events, pressure change often occurs along with the change in other parameters, such as flow and power. But quite often, the interested increase in pressure is often caused by increase in the specific enthalpy of coolant (as in loss of flow event and loss of boiler feedwater event), but not by the increase in coolant density, and the interested decrease in pressure is often caused by the decrease in the coolant density, rather than in the decrease in coolant specific enthalpy (as in small LOCA event). The cases where the pressure increase is caused by coolant density increase are often considered in primary heat transport system overpressure protection while the cases where the pressure decrease is caused by the decrease in coolant specific enthalpy is generally not of a concern in perspective of dryout which is a jeopardy to fuel sheath integrity. Since pressure change are often caused by changes in flow, density, or coolant specific enthalpy, thus its influence on CHF may have been played by the originally changing parameters such as flow, power and inlet header temperature already and may not need to be considered in particular. For confirmation, the two pressure transient processes which may be met in design basis events in CANDU reactor are discussed below to show the impact.

If the pressure increase is caused by coolant specific enthalpy increase and increases to P_i from an initial value P_0, the density either does not change dramatically or decrease (this situation often occurs in the initial stage in loss of flow events), and thus Terms 3 in Equation (19) will be zero or negative since the coolant specific enthalpy increases along the channel and Term 4 in Equation (19) will be negative. If the pressure decrease is caused by the coolant density decrease and decrease to P_i from an initial value of P_0, the coolant specific enthalpy either does not change significantly or increases and thus Term 3 in Equation (19) will be negative since the coolant specific enthalpy increases along the channel and Term 4 will be either zero or negative since the specific enthalpy should either be a constant or increase. In both situations, the coolant specific enthalpy in the transient process is lower than that in the steady state process and thus the CHF value in the transient should also be higher than that in the steady state process.

In the postulated accident events for CANDU 6 unit, e.g., loss of flow events, small LOCA events, loss of boiler water events and loss of regulation events, the flow reduction, power increase and pressure transient and inlet temperature transient may occur simultaneously. However, as per the discussion above, Term 3 and Term 4 in Equation (18) or Equation (19) are still negative and so the CHF value in this kind of transient processes will still be higher than that obtained using steady state methodology in literatures when the four controlled parameters are same for the steady state process and the transient process.

5. Limitation in the analyses

The discussion and conclusion in this work are based on the assumptions made in Section 2. However, these assumptions may not always be true. Next, the influence of the effectiveness of each assumption will be discussed.

(1) All the heat produced in the fuel was added to the fluid, i.e., the heat transfer process is not considered. In steady state and slow transient processes, this assumption can be true with sufficient accuracy. However, in a fast transient process, i.e., a dramatic decrease in flow or dramatic increase in power in a short time, the heat transfer process will be influenced. Although Term 2 in Equation (18) or Equation (19) will be smaller than that in Equation (9) to make the coolant specific enthalpy in the transient process smaller than that in the steady state process, under these situations, a large temperature gradient will be established between the fuel sheath and the coolant and across each coolant sub-channel. Thus although the average coolant specific enthalpy across the fuel channel is lower than that in the steady state process, the coolant specific enthalpy adjacent to the fuel sheath may be much higher and dryout may be easier to occur. It is impossible to quantify the influence by applying the simple 1-demensional model and more detailed analytical, numerical or experimental analysis may be needed.

(2) The coolant is always flowing forward, i.e., there is no backward flow during the transient process. All the steady state CHF values were obtained by keeping the coolant flowing from the inlet to the outlet. For transient events where a backward flow at the inlet may occur, it is hard to evaluate using this method, since in this discussion it is always assumed that the flow rate changes from an initial value to the steady state flow value, which is always positive.

(3) The coolant at the inlet of the channel is always liquid and the enthalpy of the liquid does not change significantly with pressure. In this work, it is assumed that the coolant specific enthalpy at the fuel channel inlet is only a function of temperature. This assumption is only valid with moderate pressure change for liquid. If steam is present at the inlet, this assumption will not be valid any more. Thus for the events where steam appears at the fuel channel inlet, the discussion in this work is not applicable.

(4) The coolant is flowing through a pipe standing for the fuel channel as shown in Figure 1 and the heat is added through the wall of the pipe. This assumption is made since the heat transfer between fuel and the pressure tube and the heat transfer between the

coolant and the pressure tube are not considered. It is estimated that at the initial stage of the transient, this assumption is effective.

6. Conclusion

Based on the mass conservation and energy conservation equations, the specific enthalpy of coolant downstream from the fuel channel inlet was obtained for both the steady state and transient state processes. After comparing some specific transient processes to the steady state process, especially flow reduction processes with constant power, constant inlet temperature and constant outlet pressure and power increase process with constant inlet temperature, constant flow and constant outlet pressure, it is concluded that for a slow transient process applying the CHF results obtained from steady state experiments in the transient process events like loss of flow and small LOCA will give a more conservative results in determining dryout of fuel sheath, though the conservative margin cannot be determined quantitatively using this methodology.

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8. References

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