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THE EFFECT OF THE MOLTEN CORIUM TEMPERATURE ON THE PREDICTED MELT PENETRATION DISTANCE

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ABSTRACT –Two models are developed and used to assess the potential effect of the molten corium temperature on melt penetration distance. This work addresses the impact of melt temperature uncertainties during upcoming experiments. Two sets of results are presented. The first is obtained by adjusting the prediction from an existing melt penetration model developed for saturated liquid melt only. The adjustment accounts for the distance that the initially superheated melt advances through the tube before cooling to saturation temperature. The second is the outcome of a sensitivity study using a different model which inherently accounts for melt superheat.

1. Introduction

Molten fuel relocation through reactor vessel penetrations has been a subject of on-going investigations in reactor safety studies related to severe accidents. A series of experiments at the Canadian Nuclear Laboratories have been planned to determine the extent of molten corium penetration in a well-cooled tube and potential for flow blockage due to solid crust formation on the tube wall. This paper addresses the potential impact of melt temperature uncertainties, commonly recognized in experiments, on the extent of melt penetration distance. The approach taken was to start with two existing and diverse melt penetration models and assess the sensitivity of their results to changes in the melt temperature at the tube inlet.

Nomenclature

A: inner surface area of a tube section	Pr: Prandtl number
B: solidification parameter [1]	Re: Reynolds number
C_p: specific heat	T_f: freezing point of liquid
c_s: heat capacity of crust	T_w: temperature of tube wall
D: tube inner diameter; Fig. 1	T_i, T_o: liquid temperatures at tube inlet and outlet
g: gravitational acceleration	T_{lm} : log mean average temperature difference
h , $\bar{h}$: local and average convective heat transfer coefficients	U: fluid velocity in tube entrance region
H: liquid level in reservoir; Fig. 1	X_p: melt penetration distance used in [1]
k_f: fluid thermal conductivity	X_s: superheat melt penetration distance
L: Latent heat of fusion	X_t: total length of melt penetration in tube
m: mass flow rate	ΔP: Pressure difference over tube length
Nu: Nusselt number	ΔT_i and ΔT_o: (T_i-T_w) and (T_o-T_w)

2. Epstein's Model

Epstein et al present an analysis of saturated liquid (*a liquid at its freezing temperature*) flow into an initially empty horizontal tube (Fig. 1), which is maintained at a temperature below the liquid's freezing temperature [1]. An approximate, closed form, solution was obtained for the potential penetration distance (X_p) of the saturated liquid, based on pre-defined instantaneous shapes of the solid crust formed on the tube wall. In the limit, neglecting the fluid inertia, it was found:

$$X_p = D(0.155)Re^{\frac{8}{11}}\left(\frac{Pr}{B}\right)^{\frac{7}{11}} \tag{1}$$

where D is the inner tube diameter, Re and Pr are Reynolds and Prandtl numbers, and B is a dimensionless solidification parameter, defined in [1] as: $B \equiv \left[1 + \frac{2c_s(T_f - T_w)}{L}\right]^{\frac{1}{2}} - 1$. Here, c_s is the heat capacity of the solid crust; L is the latent heat of fusion; and T_f and T_w are the freezing point of the liquid and the tube wall temperature, respectively.

The results were found to compare well with experimental data as noted in the review in [2], but limited to saturated liquid only.

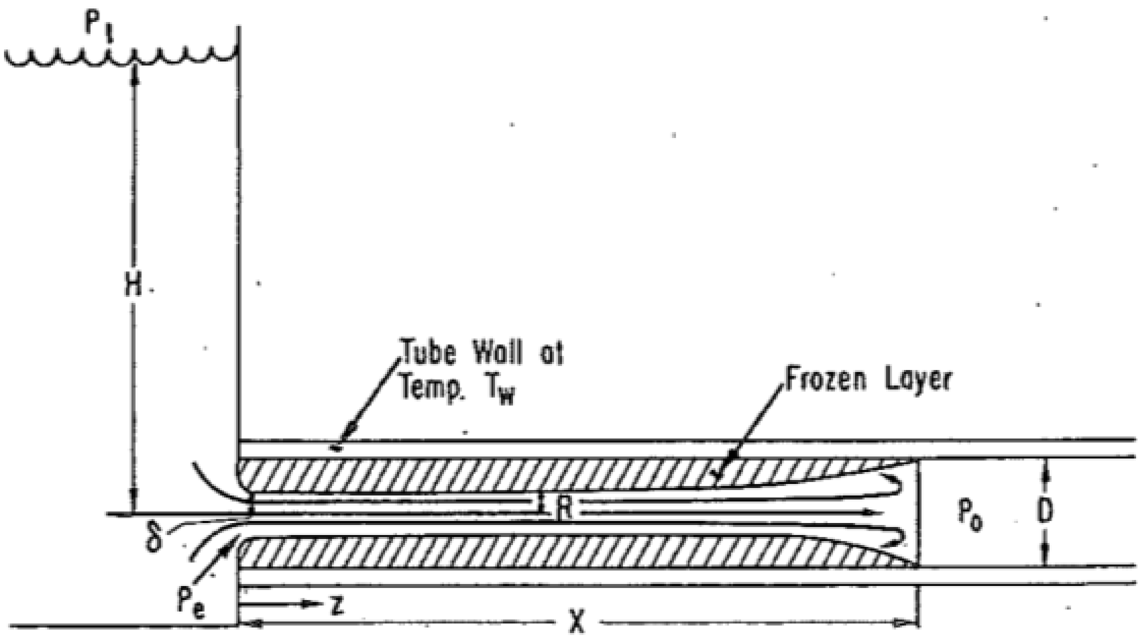

Figure 1: Schematic of physical configuration and instantaneous frozen layer profile presented in Epstein's paper [1].

For a liquid being initially superheated (i.e., at a temperature higher than its freezing temperature), the melt penetration distance would be expected to be greater than that predicted using equation (1), and the total penetration distance, X_t , could be expressed as:

$$X_t = X_s + X_P \tag{2}$$

as seen in Fig. 2, with X_s being the penetration distance of the initially superheated liquid before being cooled to saturated temperature due to radial heat convection. X_p obtained from equation (1) representing in this case the downstream section of X_s, i.e., starting from the point where the liquid temperature has reached its melting point. Although equation (1) was originally developed in [1] for the entire tube starting from its inlet, it is reasonable to be used in the context of equation (2), i.e., to represent the distance of melt penetration in a downstream section of the tube, because the hydraulic entrance effect had been assumed negligible in [1]. Additionally, the thermal initial condition imposed in [1], i.e., the liquid temperature at the tube inlet being radially constant, is also accommodating the proposed model using bulk energy balance for section X_s as in the following.

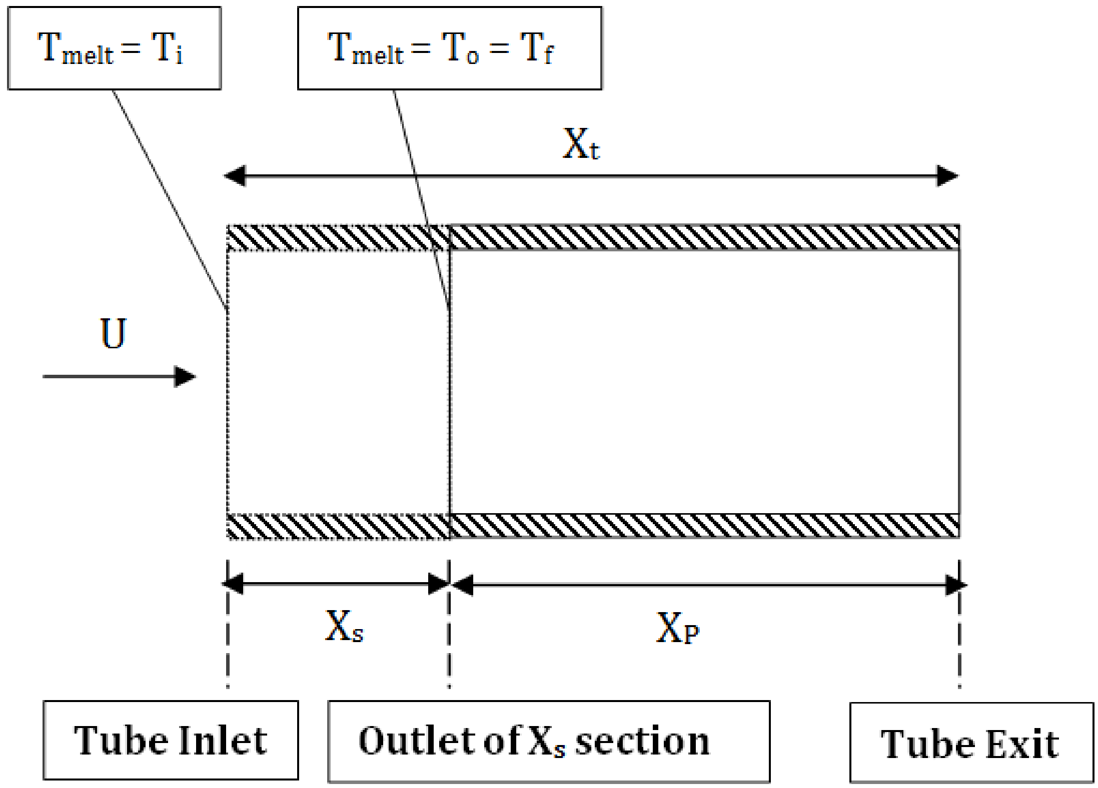

Figure 2: Schematic illustrating the relationship between X_s , X_p and X_t

An expression for X_s has been developed based on the bulk balance between the rate of energy being transported into a tube section (section X_s in Fig. 2) as liquid superheat, and the rate of heat being convected radially outward to the tube wall:

$$\dot{m}c_p(T_o - T_i) = \bar{h}AT_{lm} \tag{3}$$

with T_{lm} as the log mean temperature difference [3]:

$$T_{lm} = \frac{\Delta T_o - \Delta T_i}{\ln\frac{\Delta T_o}{\Delta T_i}} \tag{4}$$

Noting that surface area A in this case can be expressed as:

$$A = \pi D X_s \tag{5}$$

As the result, an expression for X_s can be derived from equation (3) as:

$$X_s = \frac{\dot{m}c_p(T_o - T_i)}{(\pi D)\bar{h}T_{lm}} \tag{6}$$

The convective heat transfer coefficient can be evaluated [3] using:

$$Nu_D = \frac{hD}{k_f} = 5.0 + 0.025(Re_D \mathrm{Pr})^{0.8} \tag{7}$$

The variation of X_s with the initial melt temperature can be obtained using equation (6), considering $\bar{h} \sim h$, as in [1]. Applying the model to an approximation of the experiments planned at CNL, we have a constant corium pile of 2 cm height driving the melt through an horizontal tube of 1 cm in diameter, with the tube wall temperature being maintained at 400 K. The mass flow rate $(\dot{m})$ in this example is calculated using an approximate average velocity, U, based on the height of the corium pile and pressure differential over the pipe length, as described in [1]:

$$U = \left[\left(\frac{2\Delta P}{\rho}\right) + 2gH\right]^{1/2} \tag{8}$$

Considering the melting point of corium being at 2600 K, a range of superheat melt temperatures used in this sensitivity study is from 2600 K to 3000 K, as could be expected following a severe accident. Fig. 3 shows the linear increase of the total melt penetration distance over a span of 400K increase in initial corium temperature.

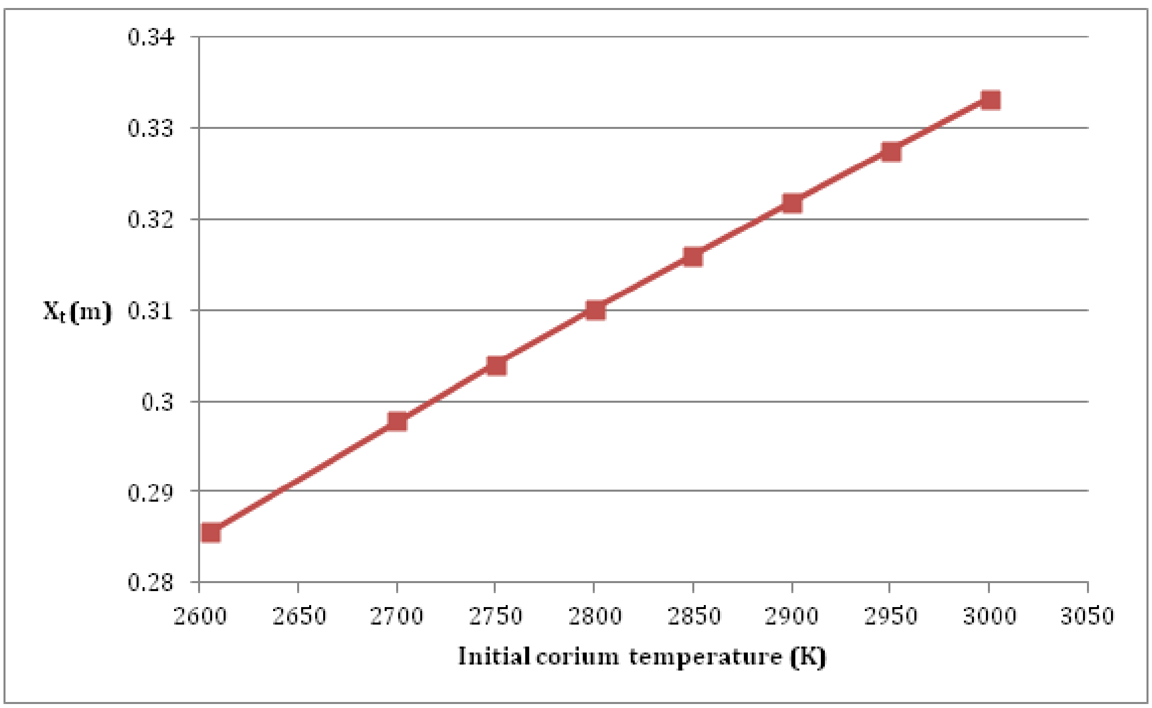

Figure 3: Effects of initial corium temperature on total melt penetration distance

In Fig. 4 are the results of the potential increases (in %) of the penetration distance for increases in the initial melt temperature.

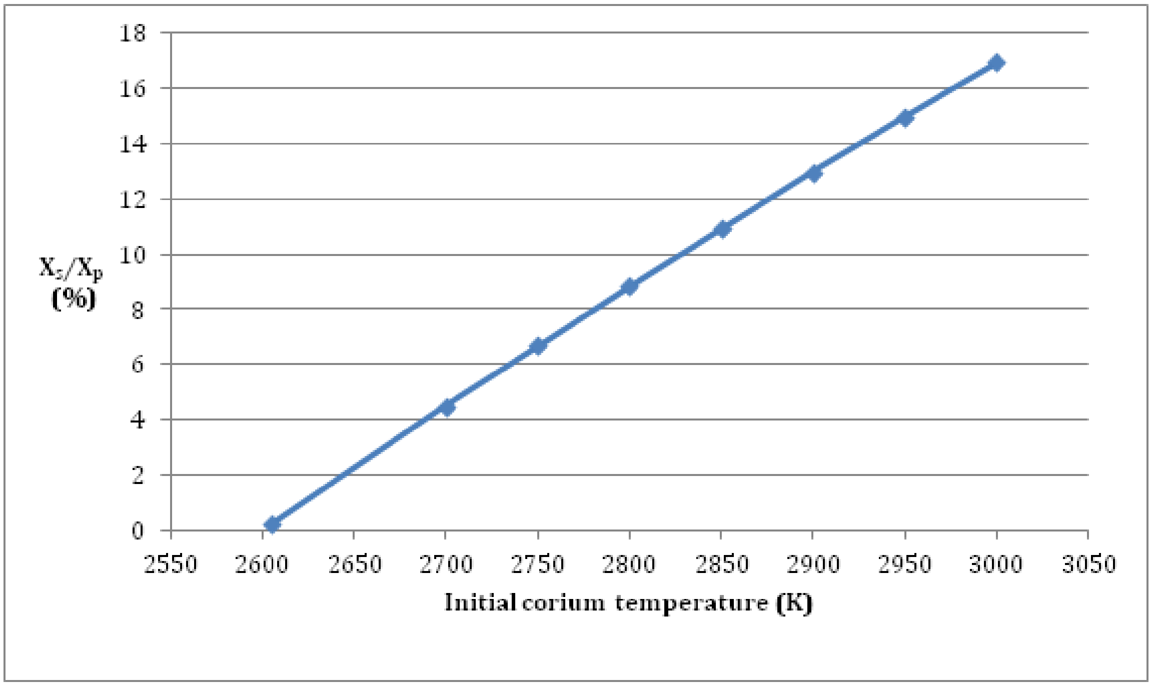

Figure 4: Effects of initial corium temperature on melt penetration distance expressed in term of percentage of X_s over X_p

3. Sampson's Model

In reference 4, Sampson and Gibson present a mathematical model for solidification with crust formation in an existing liquid metal flow in circular pipe, as illustrated in Fig. 5. The model can be used to determine the potential for flow blockage, and estimate the blockage time where applicable. Although both laminar and turbulent flows are addressed [4], a more explicit solution for turbulence is described in [5]. An approximate analytical solution was obtained mainly by solving the energy equation established for a moving control volume at the interface of the liquid-melt/solid-crust region, which is subjected to satisfy the initial and boundary conditions as well as the generic quasi-steady state conservation equations for mass, energy and momentum transfer.

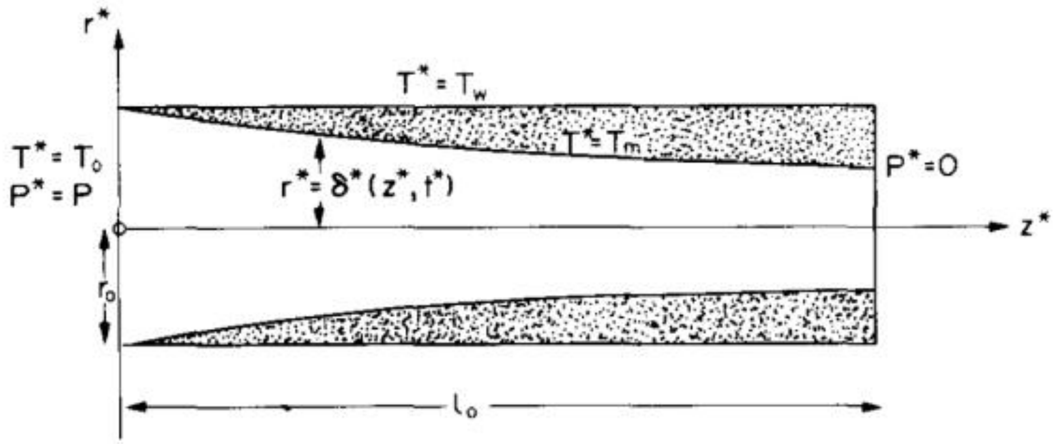

Figure 5: Horizontal tube with crust growth schematic from Sampson's paper [4]. (For illustration of the model configuration only. Notation in the figure is different from that used in this paper)

The model in [4] has been re-coded in C++ and validated against the original results. Sensitivity runs were performed and the results on the effect of blockage time for various initial corium temperatures can be seen in Fig. 6. Unlike Epstein's model [1], Sampson's [4] addresses only cases with corium temperature being above its melting point. This mathematically presents a singularity in the solution at the melting point. To circumvent this issue the first data point was calculated for initial corium temperature at 2605K (instead of 2600K). The approximation near the singularity may have accounted for the slight deviation from the linear shape of the curve.

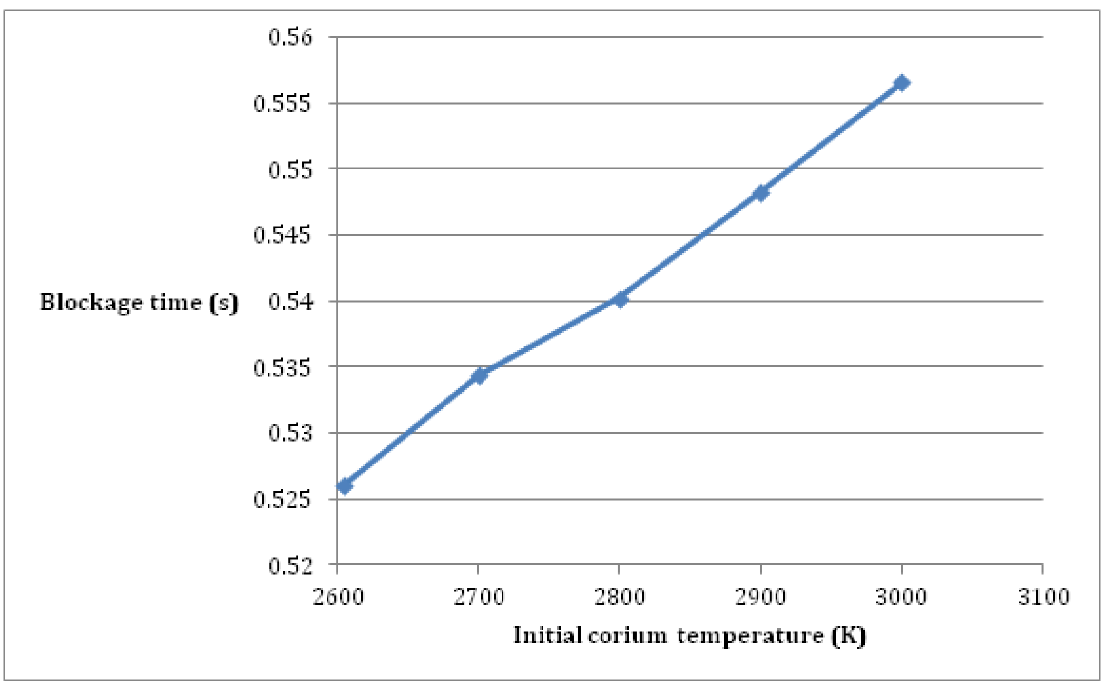

Figure 6: Effect of initial corium temperature on the time required for complete flow blockage using Sampson's model.

4. Conclusions

The effects of initial corium temperature on the predicted melt penetration distance and flow blockage time have been assessed using two diverse mathematical models. It was found that for the representative physical configuration, the melt penetration distance could be increased by almost 17% for an increase in melt temperature of 400 ^{0}C, as predicted by the revision of Epstein's model. For a similar melt temperature increase, Sampson's model would predict an increase of at most 5.5% in blockage time.

It should be noted that due to the differences in the referenced models, both in the physical configurations and assumed inital conditions, there may not be a one-to-one comparison between the increases in the melt penetration distance predicted by Epstein's model and the blockage time estimated by Sampson's model. The diversity in the models, however, could be considered as providing confirmation on the extent of the effects of the initial melt temperature described in this paper.

These results are valuable in establishing the impact of melt temperature uncertainty in the planned experiments at CNL. Within a reasonable range of temperature uncertainty, it appears that variation in the penetration distance can be expected to be of moderate magnitude.

5. References

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