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Towards modeling the impact of the aspect ratio in an energy model describing the transient flow boiling crisis at high subcooling

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Abstract

Boiling crisis under transient heat input is a phenomenon of major interest for the safety of research nuclear reactors. Recently, a model for highly subcooled flow was developed by Nop et al. (2021), which assumes the existence of a homogeneous mantle exchanging with the heating wall and the bulk flow until its saturation. We present an extension of this approach, taking into account the increase of the bulk temperature during the transient. We demonstrate that, if the assumption of an isothermal bulk is valid under the experimental conditions of Nop et al. (2021), it is no longer the case for configurations with high aspect ratios (L/D_h), and thus for the application of the model to reactor geometries.

Introduction

In a Reactivity Initiated Accident (RIA) scenario, the reactor undergoes a high and fast power escalation and the nuclear fuel delivers an exponential heat flux to the coolant with a time period τ on the order of tens of milliseconds. In some cases, the boiling crisis may occur before the power excursion is mitigated by the reactivity feedback. When this happens, a vapor blanket develops at the wall, reducing the heat transfer. Subsequently, the fuel temperature sharply rises, leading to a risk of meltdown and a steam explosion. Therefore, understanding and predicting boiling crisis with transient heating is of key importance for nuclear safety.

Serizawa (1983) and Pasamehmetoglu et al. (1990) developed the mechanistic *Liquid Sublayer Dryout* approach to describe the transient flow boiling crisis by considering the evaporation of a thin layer of liquid between the wall and a vapor blanket. However, during their experiments, Kossolapov et al. (2020) did not observe a behavior suitable for such a phenomenology. Indeed, during the transient heating of a wall in contact with a highly subcooled liquid, the bubbles grow and rapidly collapse in the vicinity of the wall due to the cold surrounding water, rather than coalescing into a vapor blanket.

Recently, Nop et al. (2021) proposed an energy model based on the phenomenology observed under these thermal-hydraulic conditions. This work extends the homogeneous mantle model by introducing heat transfer between the bulk and the mantle. It is shown that the bulk superheat has to be taken into account to accurately model the transient boiling crisis when considering a high aspect ratio rectangular channel as in nuclear reactors.

Physical description of the Homogeneous Mantle Model and extension

The homogeneous mantle model is based on the experimental observations published in Kossolapov et al. (2020), obtained on a thermal-hydraulic loop designed to study transient subcooled flow boiling, described in Richenderfer et al. (2018).

High-speed camera visualizations show that in forced con-

vection at high subcooling ($\Delta T_{sub} > 25 K$), bubbles are confined near the heating element due to high subcooling.

Furthermore, due to both high subcooling and shear stress, the bubbles are remarkably small ($\approx 100 \mu m$) and have a short lifetime ($100 \mu s$). This generates pulsating behavior in the form of "nucleation and condensation cycles" which induces turbulent mixing in the vicinity of the wall. This model assumes that turbulent mixing is strong enough to homogenize the temperature inside a layer of fluid, the so-called mantle, whose thickness is δ .

The bubble density at the wall increases with the heat flux. When the homogeneous mantle reaches the saturation temperature, the bubbles can no longer condense and start coalescing with their neighbours, forming irreversible dry spots. Therefore, this model considers that the triggering of the boiling crisis happens as soon as the temperature of the mantle reaches the saturation value.

As illustrated in Fig.1, the energy balance in the channel flow is modeled as follows. The homogeneous mantle is characterized by its volumetric energy $E_m'''(x, t)$. The bulk is characterized by its volumetric energy $E_b'''(x, t)$. In the model proposed by Nop et al. (2021), the bulk temperature is assumed to be constant and equal to the flow inlet value. In the present study, a variable temperature is assumed in the bulk due to heat exchange with the surroundings.

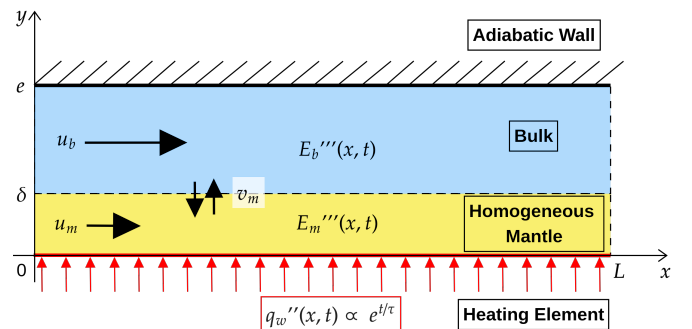


Figure 1: Schematic description of the Homogeneous Mantle Model

The energy balance associated with this model leads to a

coupled system of partial differential equations governing the energy evolution in the system:

$$\begin{cases} \frac{\partial E_m'''}{\partial t} + u_m \frac{\partial E_m'''}{\partial x} + \frac{v_m}{\delta}(E_m''' - E_b''') = \frac{q_w''}{\delta} \\ \frac{\partial E_b'''}{\partial t} + u_b \frac{\partial E_b'''}{\partial x} + \frac{v_m}{e-\delta}(E_b''' - E_m''') = 0 \end{cases}$$

Where e is the channel thickness. Heat transfer with the unheated wall is assumed to be negligible (adiabatic boundary condition) compared to the energy transfer with the heated wall q_w'' . The quantity u_m is the streamwise velocity in the mantle. It is calculated using the classical law of the wall for a turbulent channel flow. The bulk streamwise velocity u_b is obtained by mass conservation in the flow. The quantity v_m represents the characteristic velocity of the turbulent velocity fluctuations carrying energy from the mantle to the bulk. More details are available in Nop et al. (2021).

Results and Discussion

We applied the extended Homogeneous Mantle Model to the database used by Nop et al. (2021) and to recent experimental data obtained by Chavagnat et al. (2022) at higher pressure and for different channel geometries (1 – 4 cm length and 2 – 10 mm thickness). The increase of the bulk temperature (ΔT_{bulk}) as a function of the channel aspect ratio (L/e) for various thermo-hydraulic conditions (168 distinct flow configurations are investigated) is shown in Fig. 2.

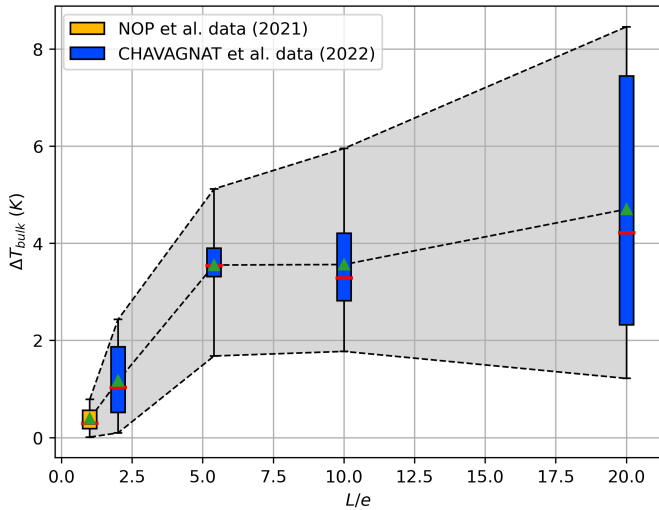


Figure 2: Boxplot of the predicted bulk temperature rise ΔT_{bulk} as a function of channel aspect ratio L/e for all 168 thermo-hydraulic conditions investigated.

For all Nop et al. (2021) data ($L/e = 1$ in orange), the temperature rise is negligible (< 1 K). This confirms the constant bulk temperature assumed in the model of Nop et al. (2021). However, for some experimental conditions of Chavagnat et al. (2022) (in blue), the temperature rise becomes significant when the aspect ratio increases (up to 8 K for $L/e = 20$).

A rise in the bulk temperature reduces heat transfer between the mantle and the bulk. This effect promotes a premature triggering of the boiling crisis and thus decreases the critical heat flux as compared to the Nop et al. (2021) model. This specific

effect plays a key role for channels with a high aspect ratio. In particular, this coupling should be integrated into the homogeneous mantle model in order to accurately predict the boiling crisis in a reactor whose aspect ratio is one to two orders of magnitude higher than in the experiments of Chavagnat et al. (2022).

Conclusion

The introduction of the coupling between the mantle and the bulk in the homogeneous mantle model developed by Nop et al. (2021) reveals that under some operating conditions, the homogeneous mantle model predicts a significant increase in the bulk temperature, despite the limited length of the heating element.

Since the aspect ratio at the reactor scale is considerably greater than in the experiments investigated in this paper, a significant temperature rise in the bulk is expected to trigger the boiling crisis much earlier in the channel and at lower heat fluxes. This confirms the relevance of considering the mantle-bulk coupling to describe the boiling crisis at the reactor scale for nuclear safety applications.

Finally, this work constitutes a first step in taking into account the variations of the fluid properties along the channel in order to model the reactor length scale. Upcoming work will highlight the effect of pressure variations on the boiling crisis. In particular, one expects pressure drops in the reactor to decrease the saturation temperature along the channel, thereby reducing the energy required to trigger the boiling crisis. Furthermore, viscosity variation due to temperature increase in the liquid flow needs to be accounted for as it modifies the flow distribution and therefore the characteristic velocities u_m , u_b and v_m during the transient.

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