ABSTRACT

Counter-current flow limitation (CCFL) of steam and water can occur in several internal regions of Reactor Coolant Systems (RCSs) during the emergency core cooling phase of a loss-of-coolant accident (LOCA). Such regions include the upper core tie plate, downcomer annulus, hot legs, entrance of the steam generator inlet plenum and the U-tubes of the steam generators. When saturated water, condensed in the steam generator (SG) tubes, drains back down towards the reactor vessel via hot leg, it is possible that steam boiled off in the core inhibits partly or totally the backward water flow. This is an important issue to the safety analysis of the pressurized water reactor (PWR). In order to study the CCFL in a PWR hot leg geometry, experiments with air and water were carried out at the Centro de Desenvolvimento de Tecnologia Nuclear (CDTN) and experimental data for the onset of flooding were obtained and analyzed. This work presents a Relap5 nodalization developed for the CDTN's test facility and a comparison between calculated Relap5 results and experimental data. The use of a new CCFL correlation, which can be selected by the user particularly for the hot leg region, is also evaluated.

1. INTRODUCTION

Counter-current flow limitation (CCFL) of steam and water can occur in several internal regions of Reactor Coolant Systems (RCSs) during the emergency core cooling phase of a loss-of-coolant accident (LOCA). Such regions include the upper core tie plate, downcomer annulus, hot legs, entrance of the steam generator inlet plenum and the U-tubes of the steam generators. When saturated water, condensed in the steam generator (SG) tubes, drains back down towards the reactor vessel via hot leg, steam boiled off in the core may inhibits partly or totally the backward water flow. This is an important issue to the safety analysis of the pressurized water reactor (PWR).

In order to study the CCFL in a PWR hot leg geometry, experiments with air and water were carried out at the Centro de Desenvolvimento de Tecnologia Nuclear (CDTN) and experimental data for the onset of flooding were obtained and analyzed.

This work presents a Relap5 nodalization developed for the CDTN's test facility and a comparison between calculated Relap5 results and experimental data.
2. EXPERIMENTAL TEST FACILITY

Fig. 1 shows a schematic diagram of the experimental system used in the study of CCFL. Water and air, at room temperature and atmospheric pressure, are the working fluids. In a typical experiment, the water from the reservoir (ST) is pumped to the upper tank (UT) from where it precipitates by gravity through the test section to the lower tank (LT). The air injected in the lower tank flows in countercurrent through the test section to the upper tank and after that is released into the atmosphere. After the onset of flooding, a portion of the water is impeded by the air of precipitating to the lower tank and accumulates on the right side of the upper tank until a level defined by a separator plate is reached (H). The flow rates of the falling water and of the carried water are measured through the rate of level rise in tanks FT and CT, respectively.

![Figure 1. Schematic diagram of experimental apparatus](image)

Although the experiment matrix included various test section configurations ($L_H$, $L_I$, $D$, $\theta$, $H$), a configuration with the $L_H/D$ close to the PWR ratio was chosen.

An experiment was initiated with the establishment of a specified water flow rate and soon afterwards a low air flow rate. The air flow rate was increased by small increments, until the
beginning of the water drag by the air (onset of flooding) and afterwards until the water was impeded of precipitating in the lower tank (zero liquid precipitation). Finally, the air flow rate was reduced, also gradually, until the total precipitation of the water once again (partial delivery).

3. RELAP5 MODEL

A general CCFL model is implemented in RELAP5/MOD3 that allows the user to select the Wallis form, the Kutateladze form, or a form in between the Wallis and Kutateladze forms:

\[ H_{g}^{1/2} + m H_{f}^{1/2} = c \]  

where the subscript \( f \) is for liquid phase, the subscript \( g \) is for gas phase, \( m \) is a slope and \( c \) is a gas intercept.

The dimensionless fluxes in Eq. (1) have the form:

\[ H_{k} = j_{k} \left[ \frac{\rho_{k}}{g_{W}(\rho_{f} - \rho_{g})} \right]^{1/2}, \quad k = f, g \]  

where \( j_{k} \) is the superficial velocity for each phase, \( g \) is a gravitational acceleration and \( w \) is given by the expression:

\[ w = D^{1-\beta} L^{\beta} \]  

where \( D \) is a junction hydraulic diameter and \( L \) is the Laplace capillary constant, given by

\[ L = \left[ \frac{\sigma}{g(\rho_{f} - \rho_{g})} \right]^{1/2} \]  

In Eq. (3), \( \beta \) can be a number from 0 to 1, and should be correlated to data for the particular geometry of interest. For \( \beta = 0 \), the Wallis form of the CCFL equation is obtained; and for \( \beta = 1 \), the Kutateladze form of the CCFL equation is obtained. For \( 0 < \beta < 1 \), a form in between the Wallis and Kutateladze forms is obtained.

3.1. RELAP5 Nodalization

Fig 2 shows the nodalization of the test facility. The water from the reservoir (TDV 310) is injected into the upper tank (P330) from where it precipitates by gravity through the test section (P100) to the lower tank (P230). The air is injected from the tank (TDV 210) flows in countercurrent through the test section to the upper tank and after that is released into the atmosphere (TDV 360).
3.2. Code Calculations

The RELAP5 calculations followed the experimental procedure of allowing the liquid flow to reach the steady state before increasing the gas injection rate. Water flow is ramped up from zero to a given flow rate corresponding to the dimensionless superficial liquid velocity of the simulated database. While the water flow is maintained constant, the air flow is increased slowly until the onset of flooding is observed.

Two sets of calculations were performed. Relap5’s default data for CCFL model, Wallis form with both gas intercept and slope set to 1, was applied to the first set. In the second set, a linear correlation obtained from Navarro’s data base was applied.

Figure 3. Flooding diagram for different water injection rates
4. RESULTS AND CONCLUSIONS

A typical behavior of water flow rate resulting from slowly increasing the air flow is shown in Fig. 4. At the moment that the water flow rate reaches its limits and shows fluctuation, the onset of CCFL is determined.

![Figure 4. Typical behavior of water flow rate at the onset of CCFL](image)

Fig. 5 shows the superficial velocity behavior of the downward water as a function of the superficial air velocity for the particular configuration of the test section.

![Figure 5. Comparison of RELAP5 calculations with experimental results](image)
The experimental data for the onset of flooding were used to compare the Relap5 predictions of counter-current flow limitation in horizontal-to-inclined pipes simulating a PWR hot leg. It can be observed that for $0.15 < j_f^{1/2} < 0.30$, both the two Relap5 predictions show good agreement with the experimental data. However, by using Wallis correlation for $j_f^{1/2} < 0.15$, the Relap5 predictions led to higher gas flow rates values than those from experimental data. When using Wallis form of the general flooding limit equation, the code user should choose adequate constants applicable to the specific geometry, so that the code provides acceptable results.

REFERENCES


