Investigation of Two-Phase Flow Instability under SMART-P Core Conditions

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1. Introduction

An integral-type advanced light water reactor, named SMART-P, is being continuously studied at KAERI. The reactor core consists of hundreds of closed-channel type fuel assemblies with vertical upward flows. The upper and lower parts of the fuel assembly channels are connected to the common heads. The constant pressure drop imposed on the channel is responsible for the occurrence of density wave oscillations under local boiling and/or natural circulation conditions. The fuel assembly channel with oscillatory flow is highly susceptible to experience the CHF which may cause the fuel failure due to a sudden increase of the cladding temperature. Thus, prevention of the flow instability is an important criterion for the SMART-P core design.

Experimental and analytical studies have been conducted in order to investigate the onset of flow instability (OFI) under SMART core conditions. The parallel channel oscillations were observed in a high pressure water-loop test facility. A linear stability analysis model in the frequency-domain was developed for the prediction of the marginal stability boundary (MSB) in the parallel boiling channels.

2. Experiments

2.1 Test Facility and Experimental Procedure

Experiments for the measurement of the local flow instabilities in the parallel channels have been conducted in a high-pressure high-temperature water-loop test facility located at EREC (Electrogorsk Research and Engineering Center) in Russia. The test section consists of two identical vertical parallel channels connected with collectors at the inlet and outlet parts of the channels. Each channel consists of an unheated inlet part with a throttling valve, heated part, and an unheated riser at the outlet part. The influence of axial power shape (APS) and unheated riser were investigated by employing three different test sections: TS-1 with a uniform APS and short riser (riser length is 200 mm), TS-2 with a non-uniform APS and short riser, and TS-3 with a uniform APS and long riser (riser length is 800 mm). The test range covers the pressure from 6 to 16 MPa. The heated channels were made of round tubes with 8 mm inner diameters and 800 mm heated lengths. In addition, a test section consisting of two-parallel 19 SSF(Self-sustained Square Finned) rod bundles was employed to examine the bundle effects on the stability boundaries.

The oscillatory conditions were investigated by decreasing the total flow rate (or by increasing the channel inlet temperature) under fixed pressure, power, and inlet temperature (or flow rate) conditions.

2.2 Experimental Findings

As a result of the experiments it was observed that the cosine APS stabilized the boiling channel system at the low subcooling conditions as shown in Fig. 1. The long riser destabilized the system, and a type-I density wave oscillation[1] was observed at the high subcoolings. In this figure the dimensionless inlet subcooling means the absolute value of the inlet quality, and the dimensionless enthalpy rise means the quality difference between the channel outlet and the inlet.

Under the high channel power and low subcooling conditions, it was observed that the CHF occurred simultaneously with the flow oscillations (represented by the solid legends in the figure). The onset of CHF was reasonably predicted by a static CHF prediction model[2]. At the intermediate subcoolings, it was observed that the CHF occurred after a certain period of flow oscillations. In a boiling channel, CHF becomes more limiting than the flow instability as the system pressure increases or the inlet subcooling decreases. Under these conditions the MSB moves to higher quality conditions.

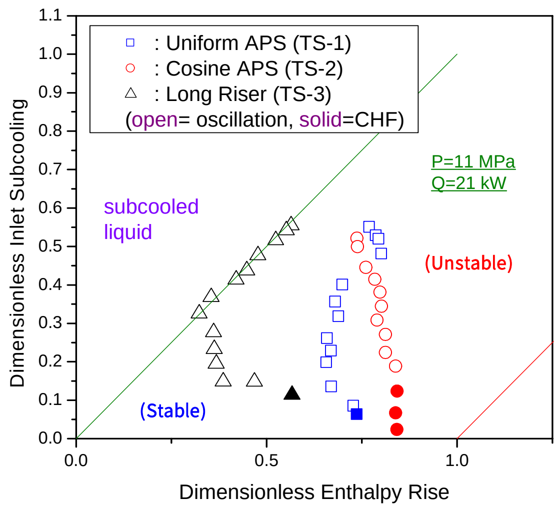

Figure 1. Influence of axial power shape and unheated riser on the MSB in two-parallel channels.

3. Analysis

3.1 Linear Model in the Frequency-Domain

A distributed parameter linear stability analysis model was developed for a boiling channel with a constant pressure drop boundary condition. A drift-flux partially non-equilibrium model was employed for simulating the dynamics of the two-phase flow inside the channel. With the assumption of constant thermodynamic properties along the channel for a given system pressure, the momentum equation can be decoupled from the mass and energy conservation equations. The governing equations were linearized using the first-order perturbation technique. The linearized time-domain differential equations were converted to an equivalent set of algebraic equations in the frequency-domain by the Laplace transformation. The stability of the system was examined by employing the Nyquist stability criterion[3]. The propagation of the inlet velocity perturbation (δv_{in}) to the single and two phase pressure drop perturbations was accounted for the linear model as shown in Fig. 2.

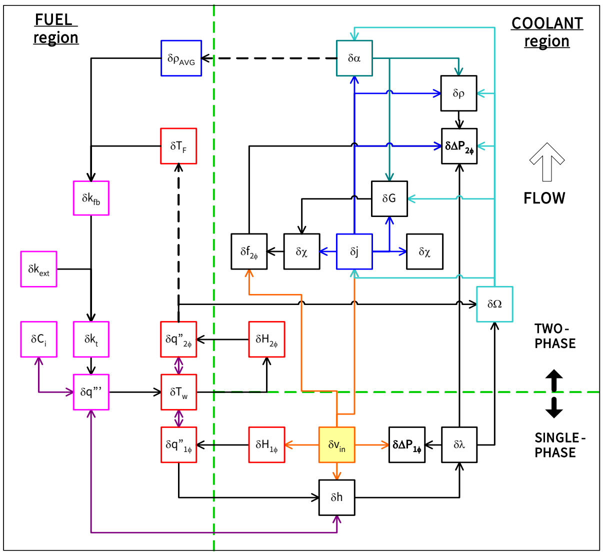

Figure 2. Propagation of the perturbed parameters.

3.2 Analysis of Experimental Data

The experimentally observed MSBs were compared with those predicted by a linear stability analysis model. As shown in Fig. 3, it is revealed that the linear model reasonably reproduces the MSB for the round tube channels. It is also revealed that the linear model conservatively predicts the MSB for SSF test bundles. The periods of flow oscillations in the boiling channels are presented in Fig. 4 at the OFI conditions. For a given pressure and channel power, it was observed that the oscillation period tends to increase as the channel inlet subcooling increases. This trend is reasonably predicted by the linear model as shown in Fig. 4.

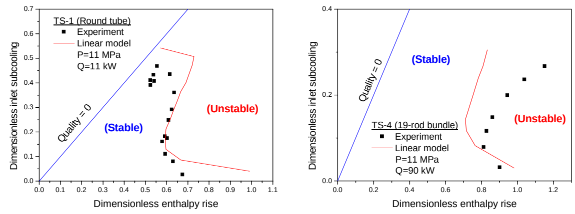

Figure 3. Prediction of marginal stability boundaries by the linear model for round tube and rod bundle test sections.

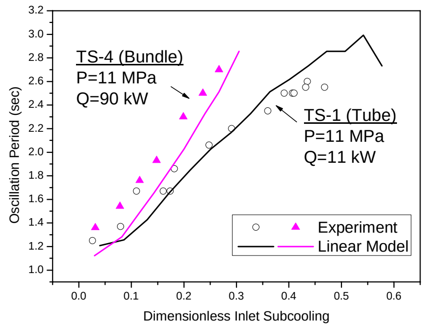

Figure 4. Oscillation periods of channel flow at the onset of flow instability conditions.

4. Conclusion

The OFI conditions have been measured for the two-parallel vertical channels with reference to the SMART-P core conditions. The parametric effects of the APS and unheated riser were observed in three different round tube test sections. The bundle effect was examined by employing a test section with 19-rod SSF bundles. The relationship between the flow oscillation and the CHF was observed at various operating conditions. The marginal stability boundaries and oscillation periods of the experimental findings were compared with those calculated by a linear model. It was found that the linear model conservatively predicted the OFI conditions for the bundle test section which simulates the SMART-P fuel assembly.

ACKNOWLEDGEMENTS

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