Numerical and Experimental Study of Subcooled Boiling Flows at Low Pressures

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Background

• Application

  - Safety analysis of research reactors
  - High performance heat exchangers
Axial Void Fraction Profile

- Single Phase Flow
- Subcooled Boiling
- Slightly Subcooled Region
- Saturated Boiling

Void Fraction vs. Location

ONB OSV

Heat Flux

Mass flow

Heat Flux
Flow Instability in Multiple Heated Channels
Results & Discussion

Figure 1. Flow Instability Schematic
Results & Discussion

>> Single channel

Figure 5. Pressure drop and void fraction profiles: Inlet T=45°C; Outlet Pressure = 300 kPa; Heat Flux = 4, 3 & 2 MW/m²
Figure 6. Pressure drop plot at OFI with varying heat fluxes

Heat Flux Effect on the Onset of Flow Instability

\( T_{\text{inlet}} = 45 \, ^{\circ}\text{C}; P_{\text{outlet}} = 300 \, \text{kPa} \)
Figure 7. Comparative void fractions at OFI at various heat fluxes

Heat Flux Effect on Void Fractions at the Onset of Flow Instability

$T_{\text{inlet}} = 45 \, \text{C} \; ; \; P_{\text{outlet}} = 300 \, \text{kPa}$

Void Fractions (%)

Heat Flux (MW/m²)

RELAP_old
RELAP_new
Results & Discussion

>> Numerical Simulation: Multi-channel

Figure 8. Inter-channel flow fluctuation diagram
Results & Discussion

Figure 9. Simulated mass flow fluctuation for a two channel system (q = 2 MW/m²)

Mass Flow Fluctuation
2 channels (T=45°C; 300kPa; 2MW)

Inlet Velocity (m/s) vs Mass Flow Fluctuation (%)

- c1_transient
- c2_normal
- voids_c1

Mass Flow Fluctuation (%)

Void Fractions (%)

Inlet Velocity (m/s)
Results & Discussion

>> Numerical Simulation: Multi-channel

Figure 10. Simulated mass flow fluctuation for a two channel system (q = 4 MW/ m²)

Mass Flow Fluctuation
2 channels (T_inlet=45°C; P_outlet=300kPa; Q_w=4MW/m²)
Figure 11. Simulated flow history of a channel with high flow rates subjected to a transient

Mass flow fluctuation

2-channels $T_{\text{inlet}}=45^\circ\text{C}$; $P_{\text{inlet}} = 300\text{kPa}$; $Q_w = 4\text{MW/m}^2$

mass flow rate = 0.9888 kg/s (inlet velocity = 7.3 m/s)

![Graph showing mass flow fluctuation and void fractions over simulation time](image-url)
Results & Discussion

>> Numerical Simulation: Multi-channel

Figure 12. Simulated flow history of a channel with medium flow rates subjected to a transient

\[ T_{\text{inlet}} = 45^\circ C; \; P_{\text{inlet}} = 300\text{kPa}; \; Q_w = 4\text{MW/m}^2 \]
\[ G = 0.7541\text{ kg/s} \; \text{(Inlet Velocity = 5.6 m/s)} \]
Results & Discussion

>> Numerical Simulation: Multi-channel

Figure 13. Pressure drop and void fraction profiles for a 2 channel system indicating critical inlet velocity thresholds when simulation fails.

Flow Instability Profile (Multi-Channel)
\[ T_{\text{inlet}} = 45^\circ \text{C}; \ P_{\text{inlet}} = 300 \text{kPa}; \ Q_w = 4 \text{MW/m}^2 \]
Figure 14. Pressure drop profile for one channel with transient in multi-channel systems
Figure 15. Simulated mass flow fluctuation for the channel with transient in multi-channel systems

Mass Flow Fluctuation in Channel with Transient Multi-channel System

$T_{inlet}=45^\circ C; P_{outlet}=300kPa; Q_w=4MW/m^2$
Results & Discussion

>> Numerical Simulation: Multi-channel

Figure 16. Simulated critical inlet velocity thresholds at OFI
Figure 17. Simulated inlet velocity thresholds prior to code failure
Results & Discussion

>> Experiment: Preliminary Results

Figure 9. Random Bubble Movement
Results & Discussion

>> Experiment: Preliminary Results

Figure 9. Bubble Merging
Results & Discussion

Figure 9. Bubble Break-up ("shearing")
Results & Discussion

>>Experiment: Preliminary Results

Image 609
Results & Discussion

>> Experiment: Preliminary Results

Image 622 Bubble Eruption/ break-up without lift-off; note bubble base expanding
Results & Discussion

>>Experiment: Preliminary Results

Image 631 Bubble Condensation
Results & Discussion

>> Experiment: Preliminary Results

Image 652 Bubble Lateral movement
Results & Discussion

Image 682 Sliding, deforming large bubble

>>Experiment: Preliminary Results
Results & Discussion

Image 693 Sliding, deforming bubble

>>Experiment: Preliminary Results
Results & Discussion

Image 754 Bubbles separating
Conclusion

• The original RELAP5-Mod3.2 code consistently under-predicts the occurrence of the flow instability in low pressure, subcooled boiling flows

• The modified RELAP code provided significant improvement in predicting the occurrence of the flow instability in subcooled boiling flows under low pressures

• Highlights of the numerical simulation of low pressure, subcooled boiling flows in parallel multi-channels:
  – Flow re-direction and/or fluctuations were demonstrated
  – OFI and simulated critical inlet velocity thresholds occur earlier in multi-channel systems
  – Mass flow oscillations can vary by as much as ±20% for the cases considered

• The OFI can manifest sooner in multi-channel systems compared with a single channel system
Thank you