Modification to the Condensation Model in the Presence of Noncondensables

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Idaho National Laboratory

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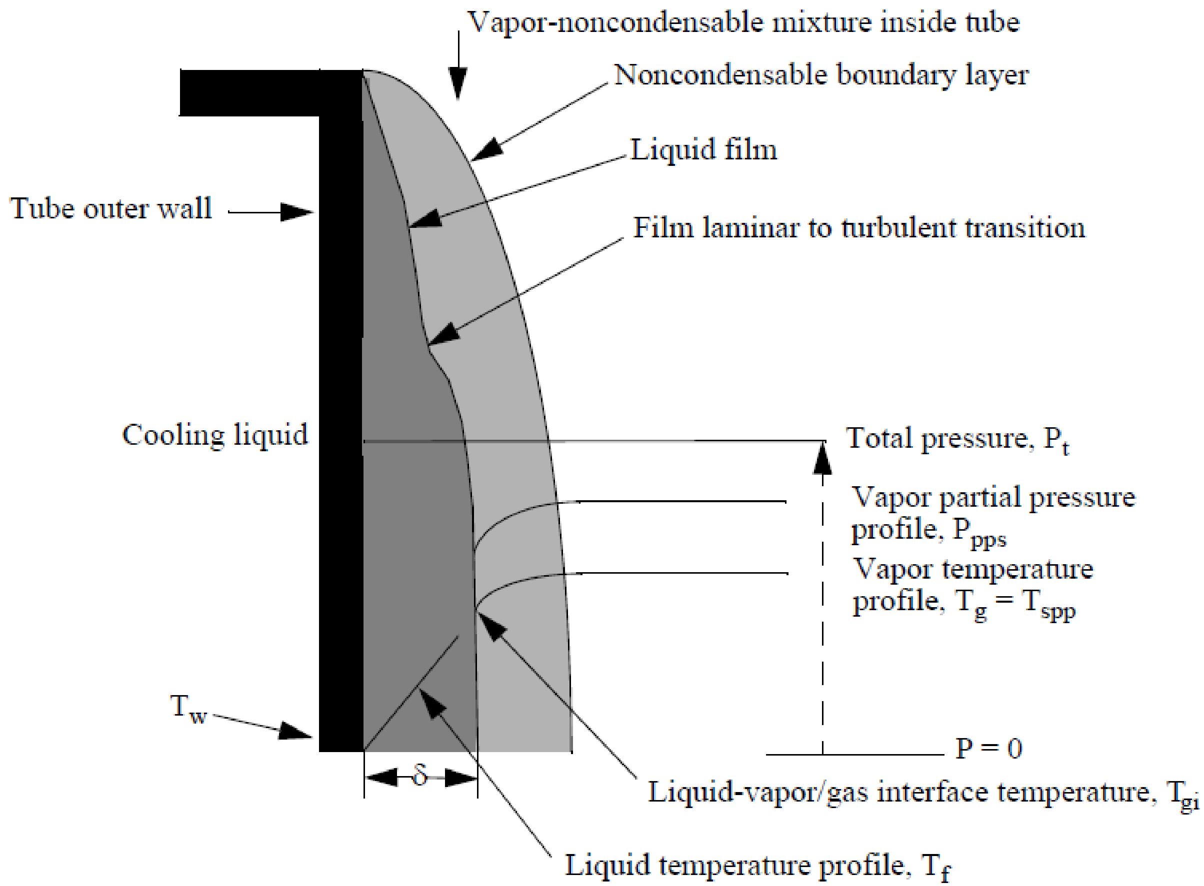
Background

- The presence of noncondensable gases in the wall condensation process has an insulating effect on the heat transfer between the vapor/gas and the wall.
  - This can slow the cooling process by condensation.
- The current RELAP5 default condensation model in the presence of noncondensables was developed by B&W for the RELAP5/MOD2 code.

Background



Vapor-noncondensable mixture inside tube
Noncondensable boundary layer
Liquid film
Tube outer wall
Film laminar to turbulent transition
Cooling liquid
Total pressure, P_t
Vapor partial pressure profile, P_{pps}
Vapor temperature profile, $T_g = T_{spp}$
T_w
P = 0
δ
Liquid-vapor/gas interface temperature, T_{gi}
Liquid temperature profile, T_f

Background

- The heat flux (q”) due to condensation of vapor mass flux (j_v), flowing toward the liquid/vapor-gas interface is:

$$q" = j_v h_{fgb}$$

- where
  - $h_{fgb} = h_{fgsat}(P_{vb})$ vapor minus liquid saturation specific enthalpy based on the vapor partial pressure in the bulk
  - P_{vb} = vapor partial pressure in the bulk.

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Background

- The mass flux is calculated as:

$$j_v = h_m \rho_{vb} \ln\left(\frac{1 - \frac{P_{vi}}{P}}{1 - \frac{P_{vb}}{P}}\right)$$

- where h_m is a mass transfer coefficient, ρ_{vb} is the saturation vapor density at P_{vb}, P_{vi} is the vapor partial pressure at the liquid/vapor-gas interface and P is the total pressure.
- The saturation vapor density can also be written as:

$$\rho_{vb} = (1 - X_n)\rho_{mb}$$

- where ρ_{mb} is the combined vapor and noncondensable gas density in the bulk at the bulk vapor-gas temperature and X_n is the noncondensable mass quality.

Reported Error

- A report by Fu, et al. indicated that the mass flux equation used by RELAP5 did not match what is used in the MELCOR code.
- In the report a derivation of the mass flux was provided which indicated that RELAP5 should use the equation used by the MELCOR code.
- Essentially the equation for the saturation vapor density:

$$\rho_{vb} = (1 - X_n)\rho_{mb}$$

- should be replaced with:

$$\rho_{vb} = \rho_{mb}$$

Review of Model Documentation

- To determine if this change is appropriate for RELAP5, the source documentation of the model was investigated.
- The model description document indicates that the saturation vapor density at the bulk vapor partial pressure (ρ_{vb}) is used.
- In the document it is stated that the equation for the condensation heat flux comes from the 2nd edition of Convective Boiling and Condensation by Collier, but the 3rd edition was consulted.
- In the text book the ρ_{vb} notation is not used. Instead the density is noted as ρ_g, which is interpreted as the combined vapor and gas density in the bulk, or ρ_{mb}.

Review of Model Documentation

- The derivation by Fu, et al. and Collier were compared and the paper by Fu, et al. was found to be incomplete and incorrect in comparison to Collier.
- Despite the observed differences in derivations, the end result in both sources indicates that the combined vapor and gas density in the bulk (ρ_{mb}) should be used.

Assessment of the Modification

- An assessment of how well the condensation models used in RELAP5 match condensation data was performed previously.
- The UCB-Kuhn and MIT-Siddique tests were used to assess how well the code could represent the physics of condensation.
- Input decks representing the conditions for the various tests were previously developed and were located and used for this assessment.
- The code was run both with and without the modification to the condensation model to determine the affect it would have on the results.

UCB-Kuhn Tests

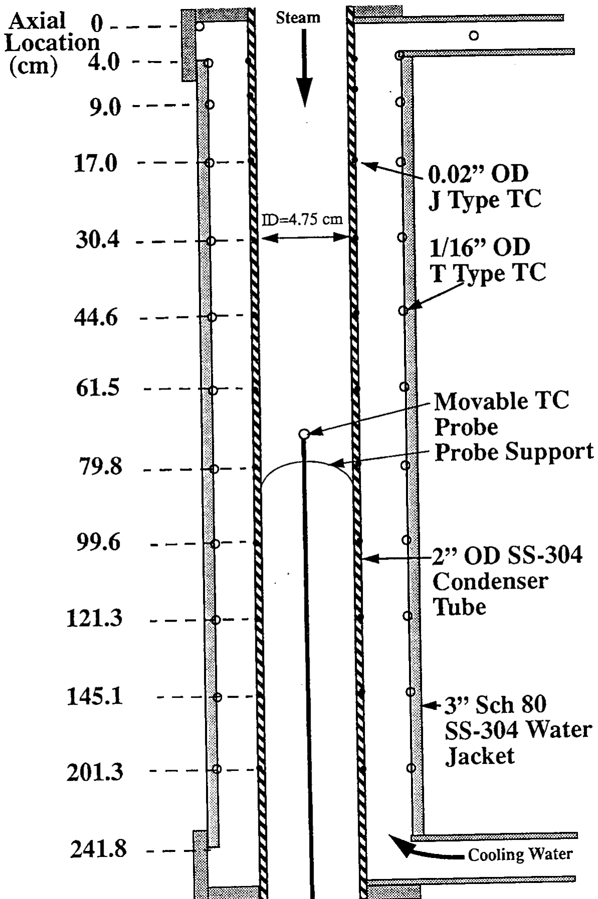


FIGURE 4. UCB-Kuhn test section.

- Vertical test section, down-flowing steam
  - Constant pressure, noncondensable mass fraction (when present)
- Cooling water pumped upward through annular jacket to absorb energy.
- Test section instrumented with thermocouples and pressure transducers.

UCB-Kuhn Tests

- Note: some of the tests were repeated to verify results, but many of the repeated tests fell outside the original error bands. This indicates that the error bands in the test were likely underestimated.
- The input models were developed such that the center of each volume corresponds to the approximate location of a thermocouple.
- A heat structure was attached to the pipe wall with a convective boundary condition.
- The outer wall of the heat structure is set to a fixed temperature boundary condition with temperature values obtained from thermocouple measurements.
- The inlet and outlet pressure conditions correlate to the measured pressure and the measured mass flow rate was specified at the inlet of the test section.

UCB-Kuhn Tests

- There were 27 UCB-Kuhn tests used for the assessment.
  - 9 cases were pure steam
  - 15 cases used air as a noncondensable
  - 3 cases used helium as a noncondensable.
- The inlet pressures varied between 0.11 and 0.52 MPa.
- The gas mass flow rates varied between 0.007 and 0.027 kg/s.
- The noncondensable mass fractions varied between 0.0028 and 0.40.

UCB-Kuhn Tests

- The RELAP5-3D heat flux calculations were compared with data from the UCB-Kuhn tests.
- A root-mean square (RMS) calculation was used to determine how well the RELAP5 results matched the data as follows:

$$RMS = \sqrt{\frac{\sum_{1}^{N} \left| \frac{q''_{predicted} - q''_{measured}}{q''_{measured}} \right|^2}{N - 1}}$$

- where N is the number of data points.

UCB-Kuhn Tests

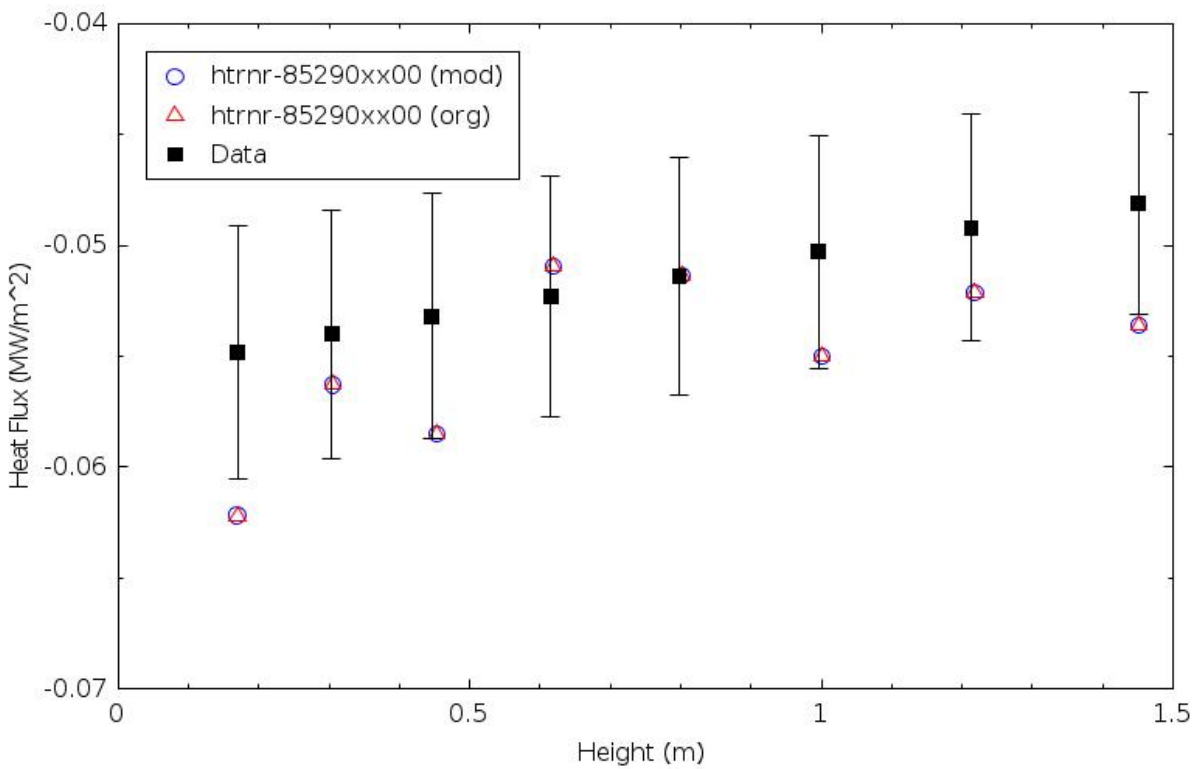
- The results of the RMS calculations are as follows:

RELAP5 Version	RMS value for all 205 points	RMS value steam only 62 points	RMS value air only 119 points	RMS value helium only 24 points
Original	0.178	0.204	0.172	0.139
Modified	0.184	0.204	0.183	0.129

- Results are slightly worse overall.
  - Unchanged for steam cases (as expected)
  - Cases with air as the noncondensable are worse
  - Cases with helium as the noncondensable are improved.

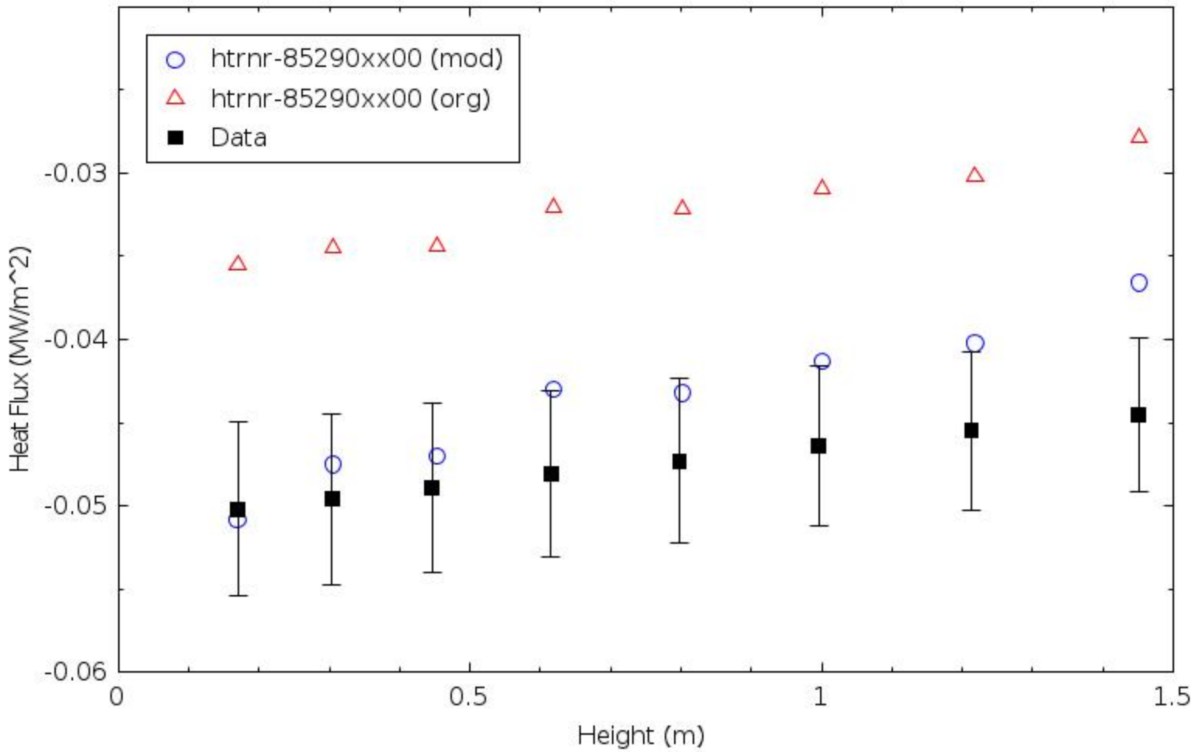
UCB-Kuhn Tests

Test 1.1-1



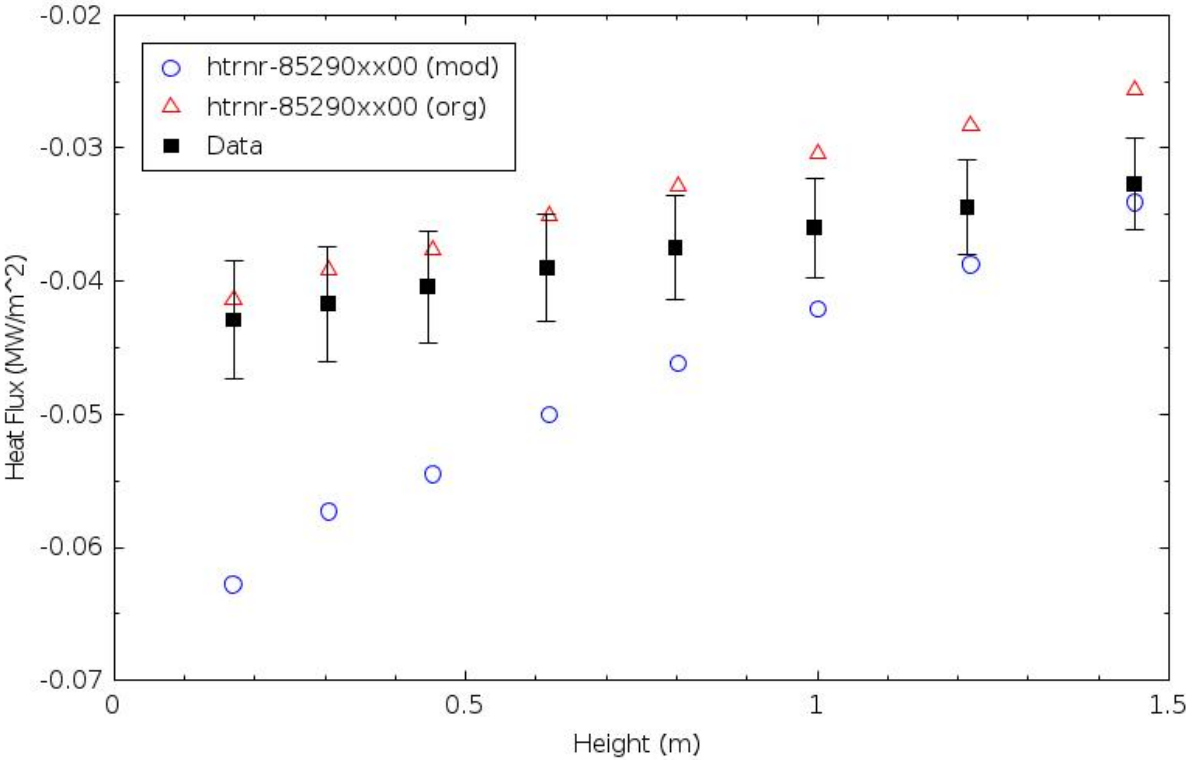
UCB-Kuhn Tests

Test 3.5-2



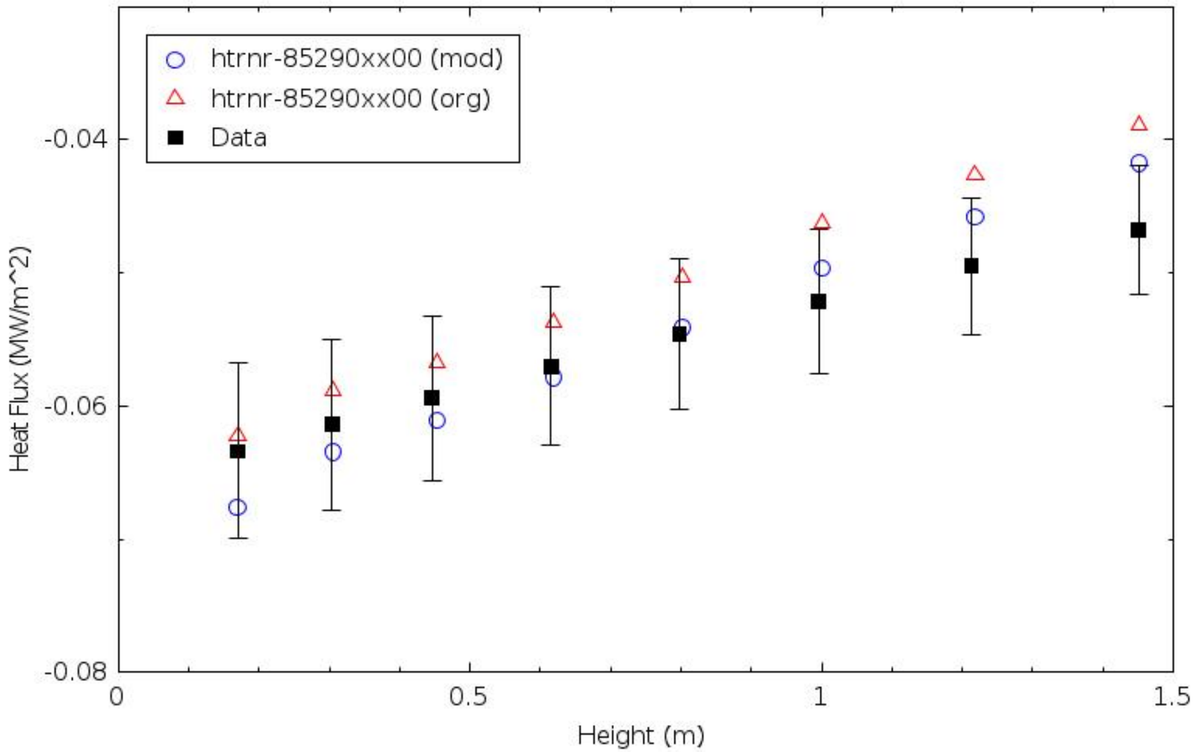
UCB-Kuhn Tests

Test 4.5-2

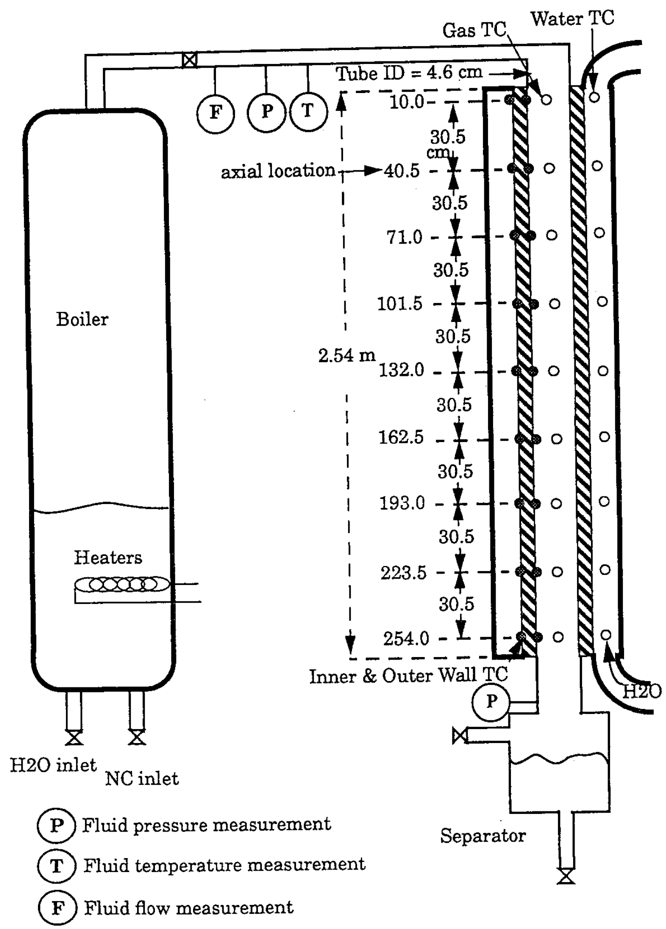


UCB-Kuhn Tests

Test 5.2-6



MIT-Siddique Tests



- Similar to the setup for the UCB-Kuhn tests.
- Test section consisted of downward flowing mixture of steam and noncondensable (helium or air).
- Cooled by concentric jacket.

MIT-Siddique Tests

- The RELAP5 input decks for these tests were developed by modifying the UCB-Kuhn decks to the slightly different geometry and conditions.
- There were 18 MIT-Siddique tests used for the assessment.
  - 11 tests used air as the noncondensable
  - 7 tests used helium as the noncondensable.
- The inlet pressure varied between 0.11 and 0.47 MPa.
- The gas mass flow rate varied between 0.0025 and 0.01 kg/s.
- The noncondensable mass fraction varied between 0.021 and 0.36.

MIT-Siddique Tests

- The RELAP5 heat flux calculations were compared to the MIT test data and an RMS value was calculated.
- The original assessment report presented the RMS value for heat flux points above 1, 2, and 5 kW/m^2.
- The assessment report noted that the experimental error values became large at the lower heat fluxes, so the data is considered less reliable at the lower heat fluxes.

MIT-Siddique Tests

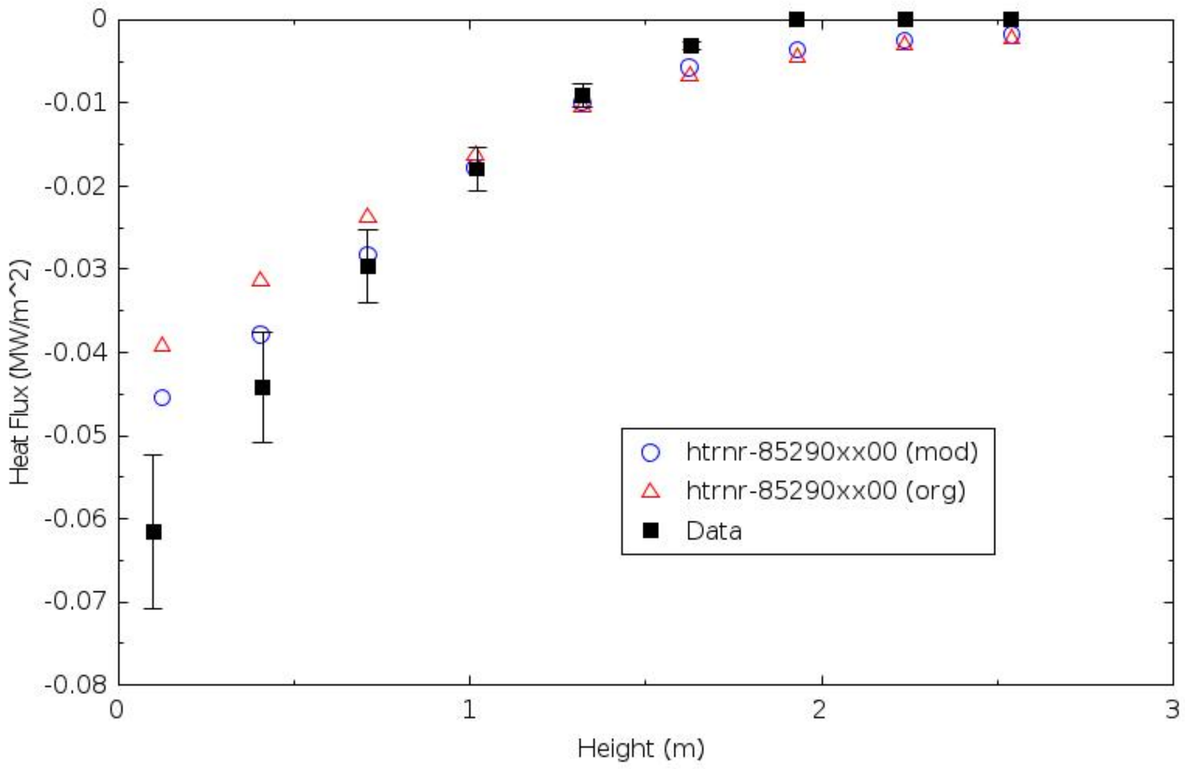
- The results are presented below

RELAP5 Version	RMS Value with 136 points above q”=1 kW/m^2	RMS Value with 132 points above q”=2 kW/m^2	RMS Value with 123 points above q”=5 kW/m^2	RMS Value with 61 air points above q”=5 kW/m^2	RMS Value with 62 helium points above q”=5 kW/m^2
Original	1.66	1.04	0.368	0.279	0.4412
Modified	1.74	1.08	0.344	0.209	0.4407

- The results show very poor agreement with data at the lower heat fluxes. However, only 13 points are below the 5 kW/m^2 threshold where the results significantly improved.
- The results are better above 5 kW/m^2 but worse below this value.

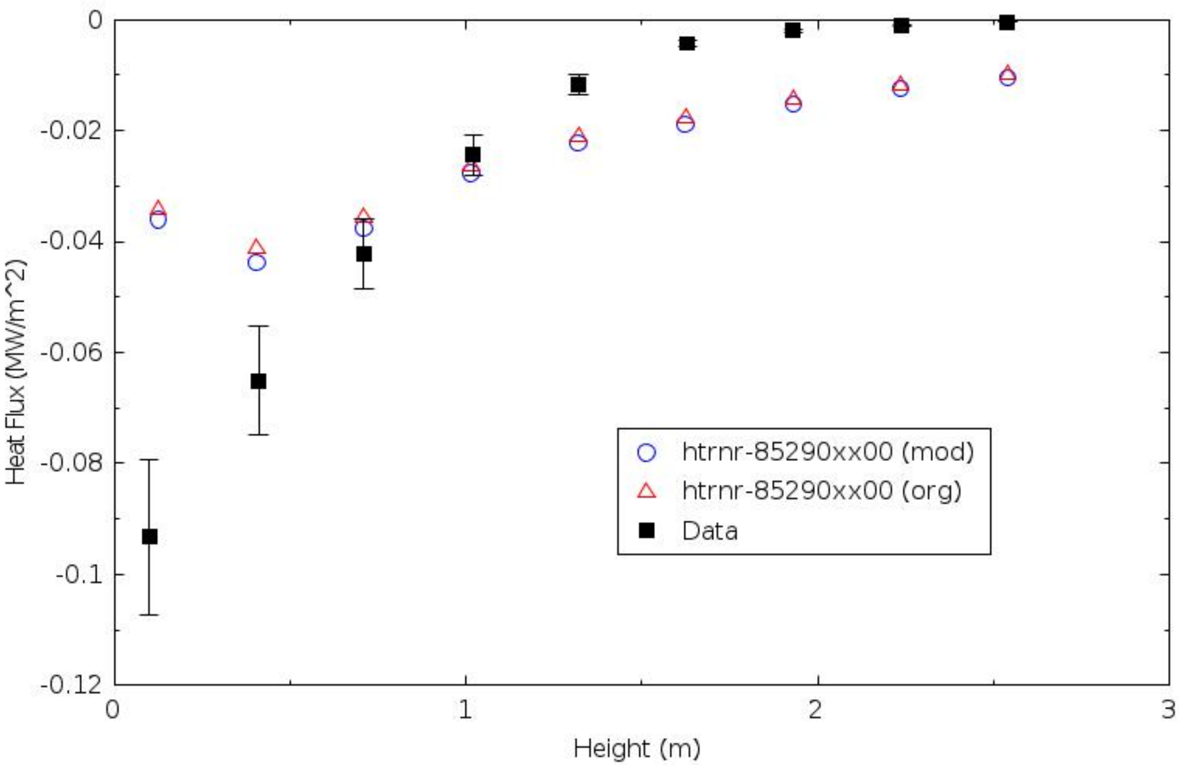
MIT-Siddique Tests

Test 8A



MIT-Siddique Tests

Test 18H



Conclusions

- The calculation of the condensation heat flux in the presence of noncondensable gases was reported to be incorrect.
- After reviewing the documentation it was found that the calculation of the vapor mass flux should be changed to use the combined vapor and gas density in the bulk at the bulk vapor/gas temperature.
- This change has been made in the code.
- The changed code was assessed against the UCB-Kuhn tests which showed slightly worse code performance overall and the MIT-Siddique tests which showed improved predictions above a heat flux of 5 kW/m^2.

References

- Collier, J. G. and Thome, J. R. *Convective Boiling and Condensation, 3rd ed.* Oxford University Press, 1994.
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- RELAP5-3D, Code Development Team. *RELAP5-3D Code Manual, Volume IV: Models and Correlations.* Idaho Falls: INL, 2015.
- Shumway, R. W. *Assessment of RELAP5/MOD3.2 Condensation Models.* Developmental Assessment Test Report, Idaho Falls: INEL, 1995.
- Siddique, M. *The Effects of Noncondensable Gases on Steam Condensation Under Forced Convection Conditions.* PhD Thesis, Department of Nuclear Engineering, MIT, 1992.

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Questions?