Performance Assessment of the Two-Phase Pump Degradation Model in the RELAP5-3D Transient Safety Analysis Code

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Overview

- Introduction
- Background
  - Current RELAP5-3D two-phase pump performance model
  - Issues that exist with this model
- Purpose of the Present Work
- Methodology
- Results
- Conclusions
- Acknowledgments

Introduction

- Two-phase pump performance becomes important in a reactor system during a large-break Loss-Of-Coolant Accident (LOCA)
  - the system depressurizes
  - this causes the coolant to flash into a two-phase steam/water mixture
  - pump performance has been shown to degrade significantly in these types of situations
- The pump performance during the blowdown phase of these situations directly affects the magnitude of the flow through the core and the resulting core cooling.
- It is important that safety analysis codes, such as RELAP5-3D, accurately predict the pump performance under these conditions to obtain an accurate representation of the resulting core flow and fuel/cladding temperatures.

Introduction

- The ability to generate and verify mechanistic models for predicting two-phase pump performance is impaired by:
  1) the complex flow passages through pumps
  2) the complex physics associated with two-phase flow

- These two factors has made it difficult to characterize the effects of different parameters on two-phase pump performance.

- As a result, the models currently used by safety analysis codes for predicting two-phase pump performance are strictly empirical.

Background

- RELAP5-3D currently calculates pump degradation using model developed by the Aerojet Nuclear Corporation (ANC).
- This model uses a two-phase degradation multiplier as a correction factor to account for the effects of two-phase flow.
- The ANC two-phase pump head model is given as:

$$H_{2\phi}(Q,\alpha_v) = H_{1\phi}(Q) - M(\alpha_v)\left[H_{1\phi}(Q) - H_{fd}(Q)\right] \quad (1)$$

where all the terms are homologous head parameters that are calculated as:

$$H = \frac{h}{\theta^2} = \left(\frac{\Delta P}{\Delta P_R}\frac{\rho_R}{\rho}\right)\left(\frac{\omega_R}{\omega}\right)^2 \quad (2)$$

- Similar formulation used to characterize the two-phase pump torque.

Background

- However, there are three primary issues associated with the ANC model.

  1) The ANC model requires a fully-degraded head to be specified.
    - Physically, the fully-degraded head is defined as the lowest possible two-phase head that can be produced by the pump at a given volumetric flow rate.
    - This is a difficult parameter to define and quantify experimentally.

  2) The ANC model is strictly empirical.
    - The two-phase degradation multipliers are calculated directly from experimental data.
    - Most of the two-phase pump performance data that currently exists was taken at low-pressures using small-scale pumps, some of which were atypical of reactor coolant pumps (i.e. Semiscale Tests).
    - Geometric similarity is difficult to achieve between scaled pumps.

Background

3) The current formulation of the ANC model allows for the two-phase degradation multipliers to be a function of void fraction only.

- Examples of other parameters that have been shown to affect the two-phase pump performance include:

- void fraction	- void distribution	- flow regime
- pressure	- pump type/geometry	- specific speed
- condensation	- compressibility	- slip velocity

- Therefore, even if geometric similarity between the scale and actual pump can be achieved, it is still difficult to reproduce the plant conditions over the wide-range of parameters that have been shown to affect two-phase pump performance and obtain representative data.

- ***As a result, an underlying need still exists for the development of a mechanistic model for the prediction of two-phase pump performance.***

Purpose of the Present Work

- The purpose this work was to model a full-size, two-phase reactor pump test using RELAP5-3D and make an assessment of the code's two-phase pump degradation model by comparing the simulated results to the experimental data.
- The tests that were used in this assessment were conducted by Ontario Hydro Technologies (OHT) in collaboration with Japan Atomic Energy Research Institute in the early 1990s.
- These tests investigated the two-phase performance of a full-size CANDU reactor pump (centrifugal), over a range of pressures (115-930 psia) and void fractions (0-45%).
- The tests were run by specifying, and maintaining, saturation conditions (for a given pressure) within the test loop while slowly bleeding water from the loop, which thereby increased the void fraction.

OHT Test Facility

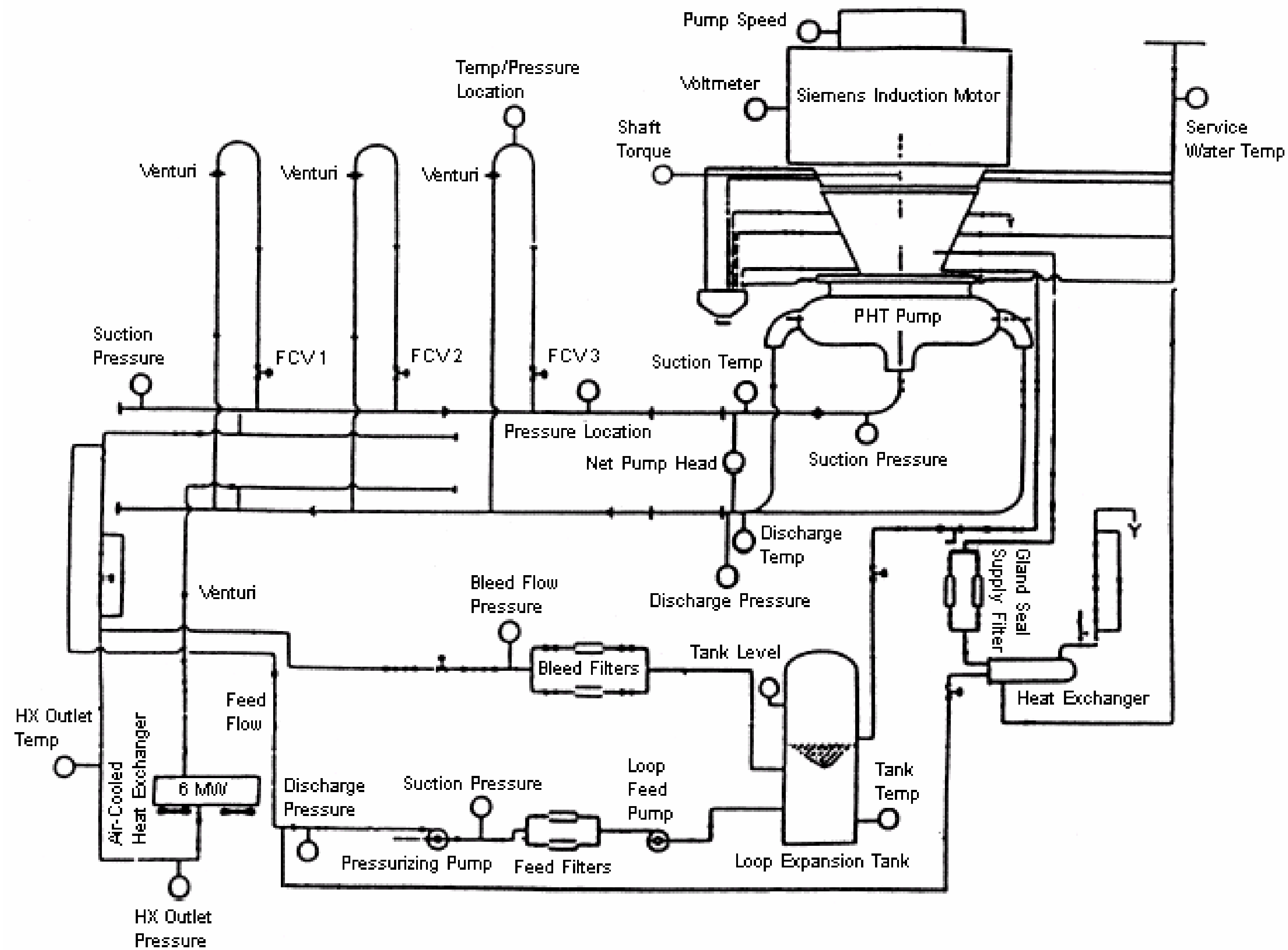

Figure 1: Schematic of the Ontario Hydro Technologies (OHT) Full-Size Two-Phase Reactor Pump Test Loop .

Methodology

- The approach used was to employ a once-through system with a control system where:
  - the suction side pressure, void fraction and mass flow rate measured during the OHT experiments was provided as input.
  - RELAP5-3D calculated the resulting pump head and corresponding pressure rise through the pump.
  - the calculated pressure rise was then be compared to the experimental data to assess the performance of the RELAP5-3D two-phase pump performance model.
- A total of 6 sets of experimental data were available and used in this analysis taken from 2 different references.
- All cases had an initial single-phase flow rate and pump speed equal to the rated conditions for the pump.

Methodology

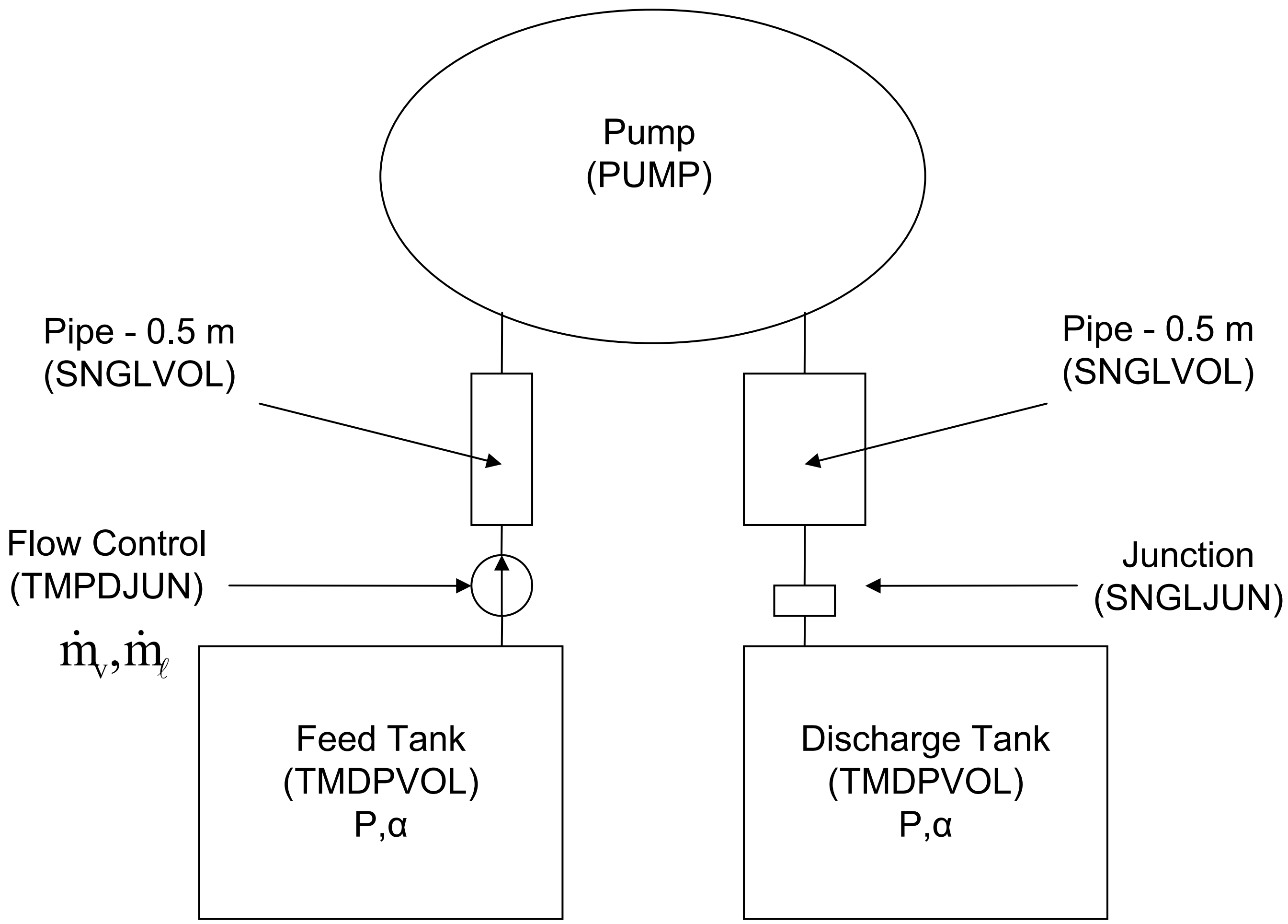

Figure 2: Schematic of RELAP5-3D Model of the OHT Test Facility.

Methodology

- OHT developed pressure specific sets of two-phase head degradation multipliers from their experimental data.
- This is unlike the current approach since the Semiscale two-phase head degradation multipliers are assumed to apply at all pressures.
- Therefore, in this assessment the appropriate set of OHT multipliers was provided as input to RELAP5-3D based upon the system pressure for the tests.
  - Note: the Semiscale two-phase torque degradation multipliers were used throughout this assessment since no new sets have been developed or suggested.

Methodology

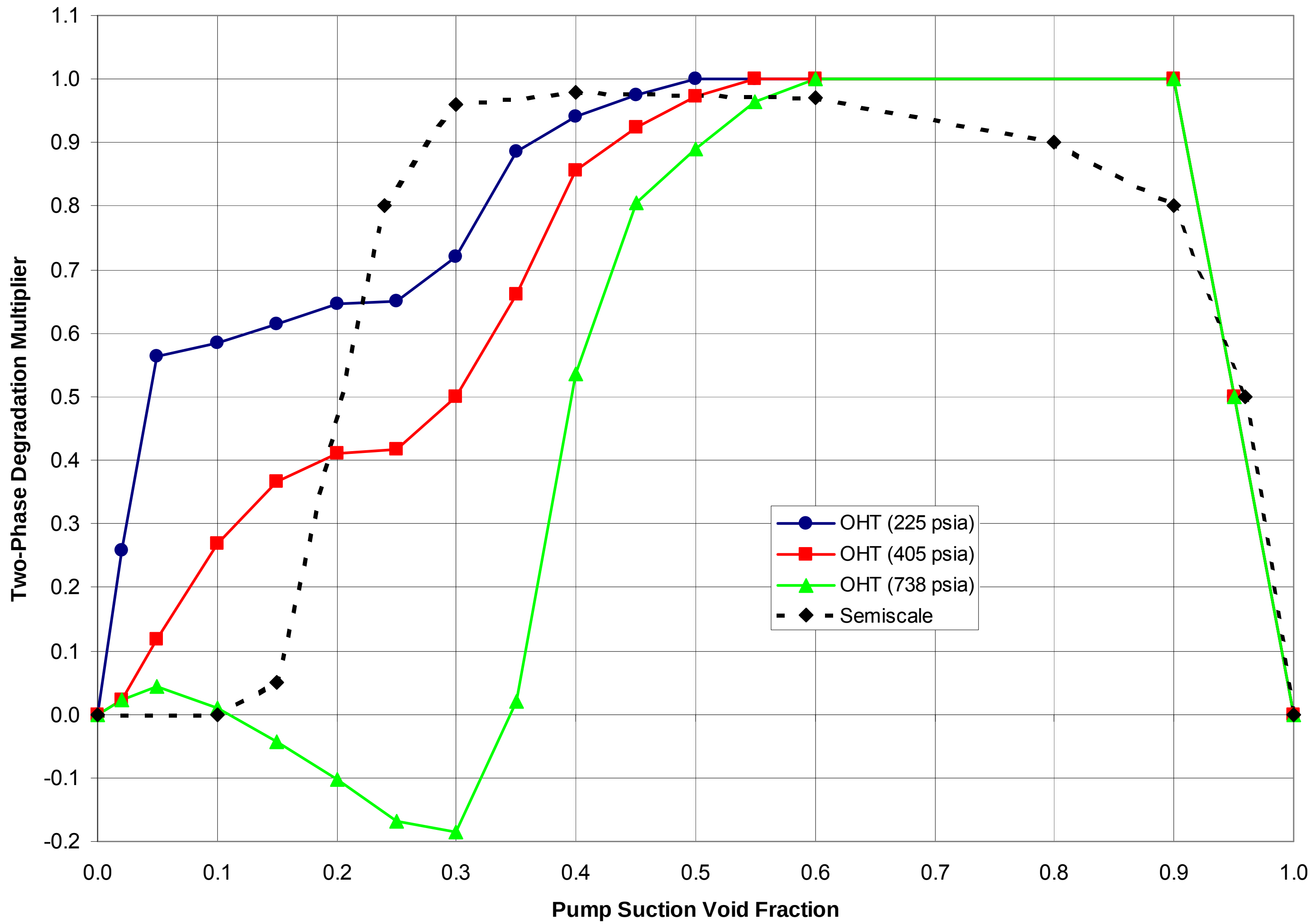

Figure 3: Two-Phase Head Degradation Multipliers.

Methodology

- Additionally, the pump curves that were used by RELAP5-3D for the calculations were systematically changed throughout the analysis to determine the parameters that had the greatest effect on the solution.

Table 1: RELAP5-3D Simulation Test Matrix.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Single-Phase Homologous Curves	Semiscale	OHT	OHT	OHT	OHT
Two-Phase Difference Curves	Semiscale	Semiscale	OHT	OHT	OHT
Two-Phase Head Degradation Multipliers	Semiscale	Semiscale	Semiscale	OHT - uncorrected for pump average void fraction	OHT – "corrected" for pump average void fraction

Results

- The experimental data from the OHT tests and results of this assessment both indicate that the effect of pressure, in addition to void fraction, cannot be neglected by safety analysis codes when predicting two-phase pump performance.

- Overall, the RELAP5-3D predicted results using the widely-adopted Semiscale two-phase head degradation multipliers did a poor job of predicting the experimental data.

- Significant improvement was obtained when the pressure specific two-phase head degradation multipliers developed by OHT from their experimental data were used.

Results

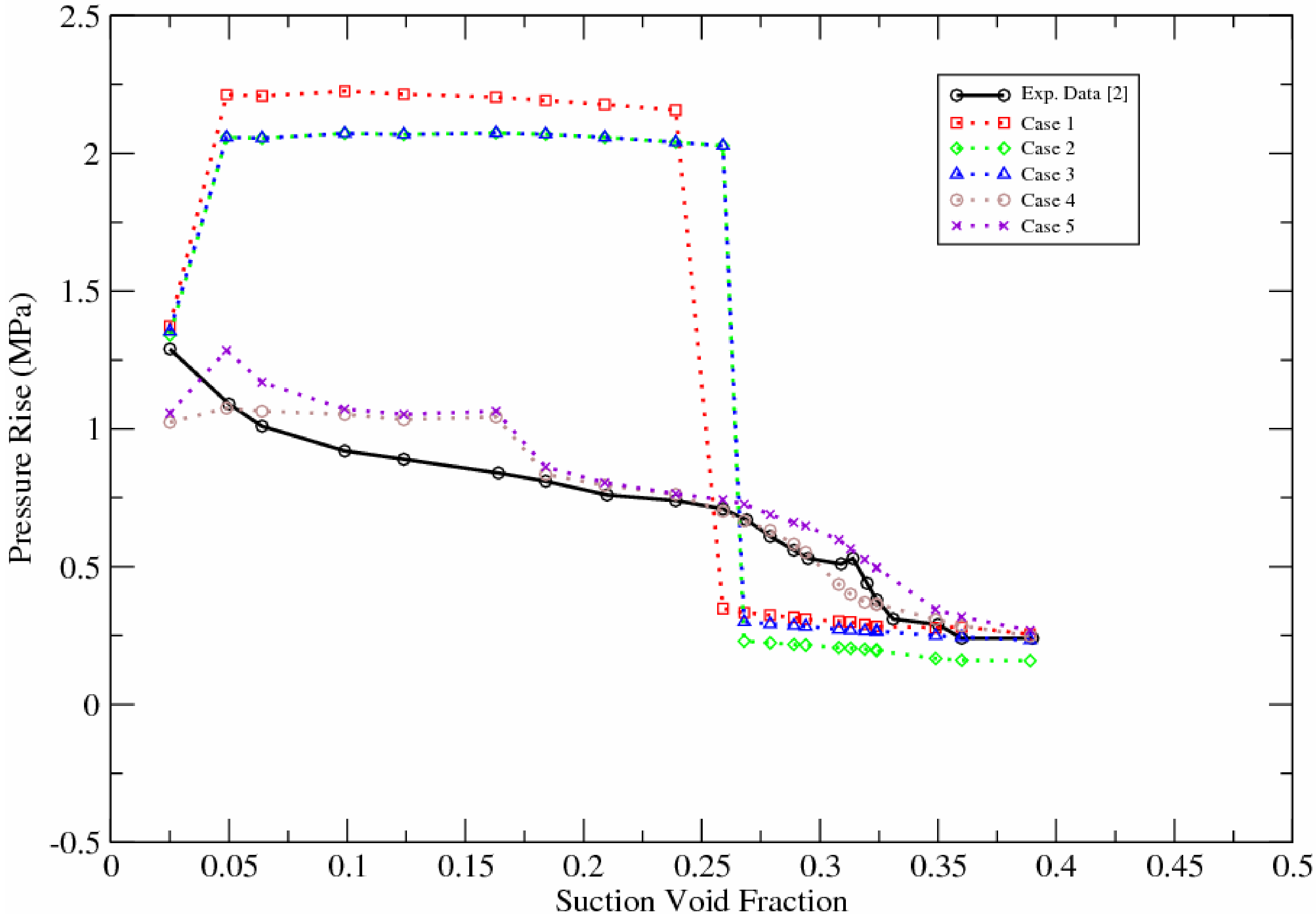

Figure 4: Comparison of the RELAP5-3D Simulation Results for the Different Cases to the Experimental Data at 1.55 MPa.

Results

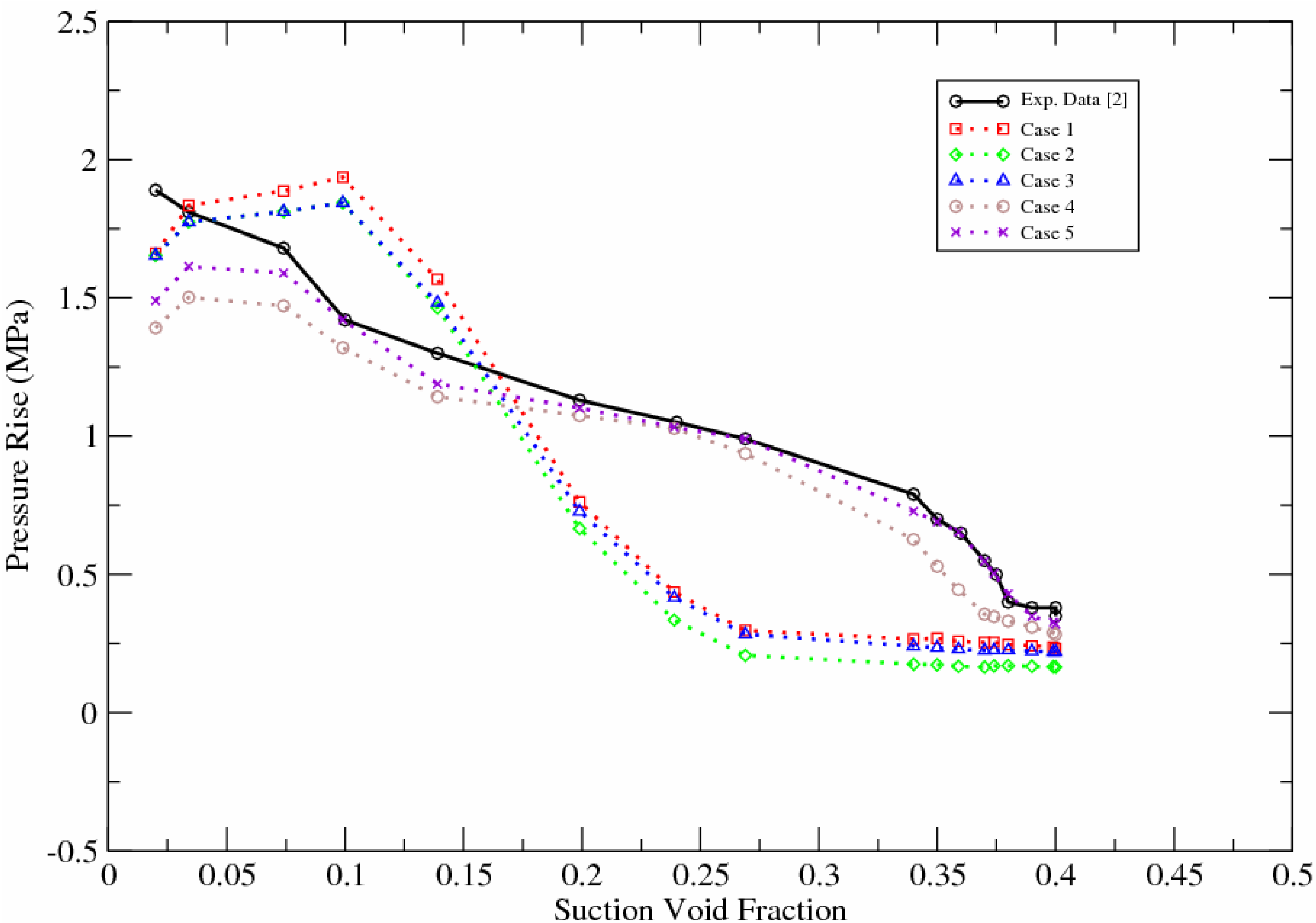

Figure 5: Comparison of the RELAP5-3D Simulation Results for the Different Cases to the Experimental Data at 2.80 MPa.

Results

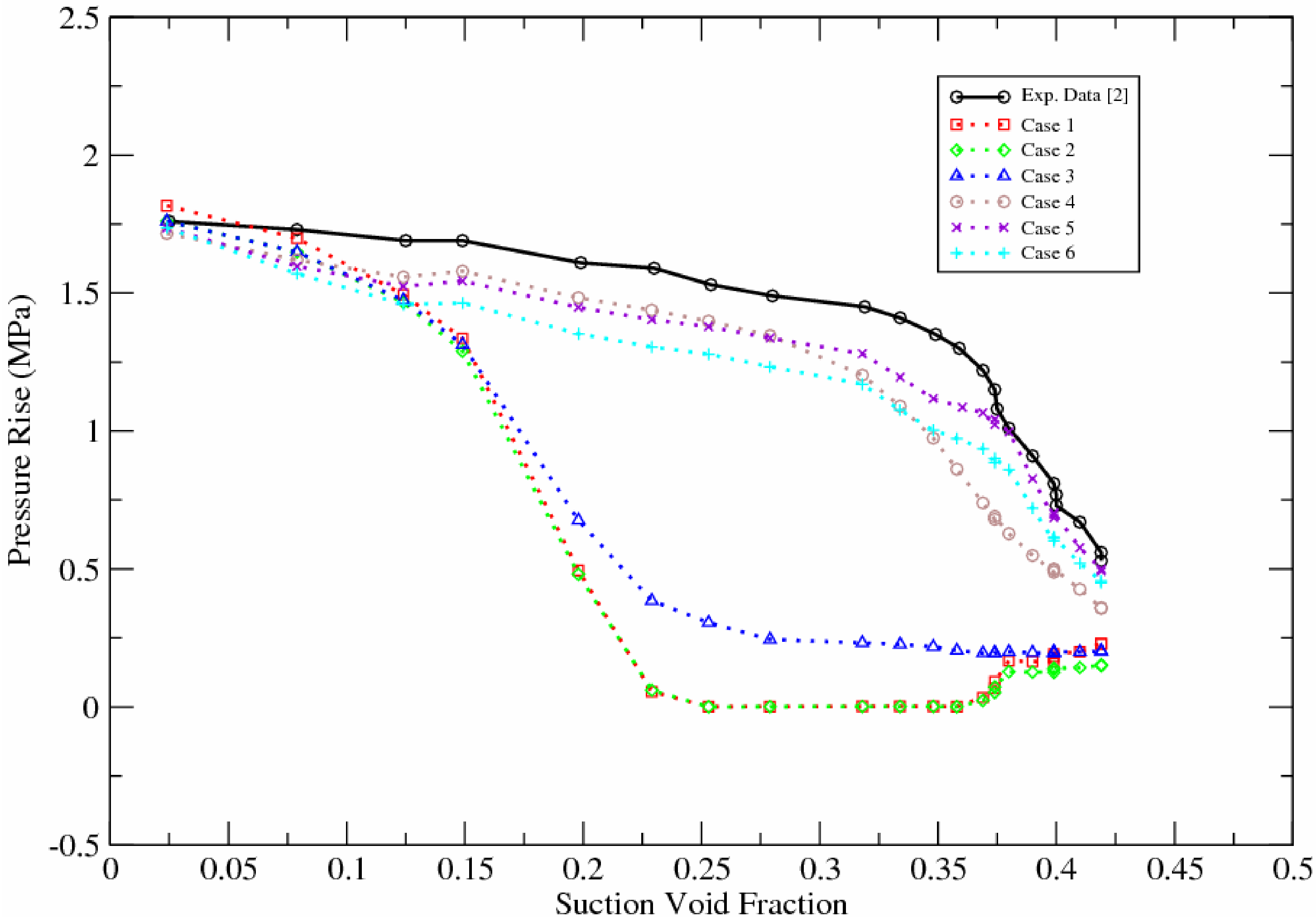

Figure 6: Comparison of the RELAP5-3D Simulation Results for the Different Cases to the Experimental Data at 4.69 psia.

Conclusions

- The results of this analysis expose:
  1) the inaccuracies of using the Semiscale two-phase degradation multipliers.
  2) a weakness in the present formulation of the ANC model since it does not currently consider pressure effects.
  3) the limited usefulness of empirical models.

- It is recommended that at a minimum pressure should be added as a secondary parameter for formulating two-phase degradation multipliers in addition to void fraction.
  - Adding a second term of dependence to the ANC formulation would most likely require two-dimensional interpolation between different sets of multipliers, which are a function of void fraction, and developed over the range of pressures of interest.

Conclusions

- Also, in future two-phase pump testing programs it is important to:

  1) characterize the change in void fraction through the pump over a range of pressures to correct experimental data for pump average void fraction.

  2) characterize the pump degradation behavior at finer pressure increments to assess the validity of linearly interpolating between different sets of degradation multipliers formulated at different pressures.

  3) characterize the shaft torque degradation behavior to develop an improved set of two-phase torque degradation multipliers.

Conclusions

- Finally, it since the OHT two-phase head degradation multipliers were developed directly from the OHT experimental data it should be expected that the code's predictions would agree with the experimental data.

- However, the applicability of these two-phase head degradation multiplier values to other situations is unknown and two-phase pump performance has been shown to be highly pump specific.

- Therefore, the OHT two-phase head degradation multipliers should be assessed using an independent set of experimental data before being utilized.

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