Transient Heat Pipe Modeling Using THROHPUT

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This presentation and additional information can be found on the THROHPUT home page at

http://www.lanl.gov/THROHPUT

Outline

- History
- Current Capabilities
  - Modeled Phenomena
  - Numerical Models
- Main Equation Set
- Results
- Future Work

History

- THROHPUT stands for Thermal Hydraulic Response Of Heat Pipes Under Transients

- Developed as a Research Code for my Ph. D. Thesis (Thesis copies available on request)

- Initial Problem:

  – Cylindrical Lithium Heat Pipe (SP-100)

  – Startup from a Frozen State to Steady State Operation

  – Space-based or Terrestrial

  – Three Phases of Lithium & Noncondensable Gas

  – Sintered or Annular Screen Wick

  – Molybdenum Wall

History (cont)

- Some problems matching experiments —
  Kinetic evaporation/condensation model to blame? No ...

- Phillips Laboratory — 0.4 man-year additional work

  - Determined problem: liquid in tension (negative liquid pressure)

  - Much better experimental matches

  - Added additional fluids: potassium, sodium, mercury and silver

- Additional research by a doctoral student into Boltzmann Transport Equation solutions

- Currently a research code, not a production code

- Simplifications / Improvements / Additions are possible

Current Capabilities:
Modeled Phenomena

- Radial and Axial Convection
- Radial and Axial Conduction
- Mass & Heat Transfer at Wick Surface
- Surface Tension (Capillary Pressure)
  via separate gas and liquid pressures
- Liquid Recession into the Wick
- Pooling into the Core
- Axial Diffusion and Effusion

Current Capabilities:
Numerical Models

- Main Equation Set
  - Area-Averaged Navier Stokes Equations
  - Fully-Implicit Transient Solution

- Auxiliary Models
  - Parabolic Radial Temperature Distribution
  - Two Capillary Pressure Models
  - Radial and Axial Melt Front Propagation
  - Diffusion – Dusty Gas Model
  - All auxiliary models solved implicitly with main equation set

Main Equation Set:
Mass Conservation

Mixture Continuity:

$$\frac{\partial}{\partial t}(\alpha_m \rho_m) + \frac{\partial}{\partial z}(\alpha_m \rho_m V_m) = \sum_{x=l,s} \Gamma_{xg}$$

Noncondensable Continuity:

$$\frac{\partial}{\partial t}(\alpha_m \rho_m X_n) + \frac{\partial}{\partial z}(\alpha_m \rho_m X_n V_m) = \frac{\partial}{\partial z}\left(\alpha_m D_n^X \frac{\partial X_n}{\partial z}\right) + \frac{\partial}{\partial z}\left(\alpha_m D_n^\rho \frac{\partial \rho_m}{\partial z}\right)$$

Liquid Continuity:

$$\epsilon_v \frac{\partial}{\partial t}(\alpha_l \rho_l) + \epsilon_v \frac{\partial}{\partial z}(\alpha_l \rho_l V_l) = \sum_{x=g,s} \Gamma_{xl}$$

Solid Continuity:

$$\epsilon_v \frac{\partial}{\partial t}(\alpha_s \rho_s) = \sum_{x=g,l} \Gamma_{xs}$$

Main Equation Set:
Energy Conservation

Mixture Internal Energy:

$$\frac{\partial}{\partial t}\left(\alpha_m \rho_m U_m\right) + \frac{\partial}{\partial z}\left(\alpha_m \rho_m U_m V_m\right) =$$
$$-P_m\left(\frac{\partial}{\partial z}\left(\alpha_m V_m\right) + \frac{\partial \alpha_m}{\partial t}\right)$$
$$+\frac{\partial}{\partial z}\left(\alpha_m D_n^X\left(h_n - h_g\right)\frac{\partial X_n}{\partial z}\right)$$
$$+\frac{\partial}{\partial z}\left(\alpha_m D_n^\rho\left(h_n - h_g\right)\frac{\partial \rho_m}{\partial z}\right)$$
$$+\frac{\partial}{\partial z}\left(\alpha_m k_m \frac{\partial T_m}{\partial z}\right) + \sum_{x=l,s}\left(Q_{xm} + Q_{xg}^\Gamma\right)$$

Liquid Internal Energy:

$$\epsilon_v \frac{\partial}{\partial t}\left(\alpha_l \rho_l U_l\right) + \epsilon_v \frac{\partial}{\partial z}\left(\alpha_l \rho_l U_l V_l\right) =$$
$$-\epsilon_v P_l\left(\frac{\partial \alpha_l V_l}{\partial z} + \frac{\partial \alpha_l}{\partial t}\right) + \epsilon_v \frac{\partial}{\partial z}\left(\alpha_l k_l \frac{\partial T_l}{\partial z}\right)$$
$$+\sum_{x=m,s,w} Q_{xl} + \sum_{x=g,s} Q_{xl}^\Gamma$$

Main Equation Set: Energy (cont) & Momentum Conservation

Solid Internal Energy:

$$\epsilon_v \frac{\partial}{\partial t}\left(\alpha_s \rho_s U_s\right) = \epsilon_v \frac{\partial}{\partial z}\left(\alpha_s k_s \frac{\partial T_s}{\partial z}\right) + \sum_{x=m,l,w} Q_{xs} + \sum_{x=g,l} Q_{xs}^{\Gamma}$$

Wall Internal Energy:

$$\rho_w c_{p_w} \frac{\partial T_w}{\partial t} = \frac{\partial}{\partial z}\left(\alpha_w k_w \frac{\partial T_w}{\partial z}\right) + Q_{in} + \sum_{x=l,s} Q_{xw}$$

Mixture Momentum:

$$\frac{\partial}{\partial t}\left(\alpha_m \rho_m V_m\right) + \frac{\partial}{\partial z}\left(\alpha_m \rho_m V_m^2\right) = -\alpha_m \frac{\partial P_m}{\partial z} - \mathcal{F}_m V_m + \alpha_m \rho_m g_z$$

Liquid Momentum:

$$\epsilon_v \frac{\partial}{\partial t}\left(\alpha_l \rho_l V_l\right) + \epsilon_v \frac{\partial}{\partial z}\left(\alpha_l \rho_l V_l^2\right) = -\epsilon_v \alpha_l \frac{\partial P_l}{\partial z} - \mathcal{F}_l V_l - \Delta P_{cap}^{\nu} \frac{\partial \alpha_l}{\partial z} + \epsilon_v \alpha_l \rho_l g_z$$

Main Equation Set:
Constitutive Equations

Mixture State:

$$P_m = \rho_m T_m \left(X_n R_n + (1 - X_n) R_g \right)$$

Liquid State:

$$\rho_l = \rho_l \left(P_l, T_l \right)$$

Solid State:

$$\rho_s = \rho_s \left(T_s \right)$$

Volume Fraction Sum:

$$\sum_{x=m,l,s} \alpha_x = 1$$

Capillary Pressure Relation:

$$P_m - P_l = \mathcal{L} \left(\Delta P_{cap} \left(\alpha_m \right) \right)$$

System variables are: ρ_m, ρ_l, ρ_s, X_n, α_m,α_l, α_s, P_m, P_l, V_m, V_l, T_m, T_l, T_s and T_w.

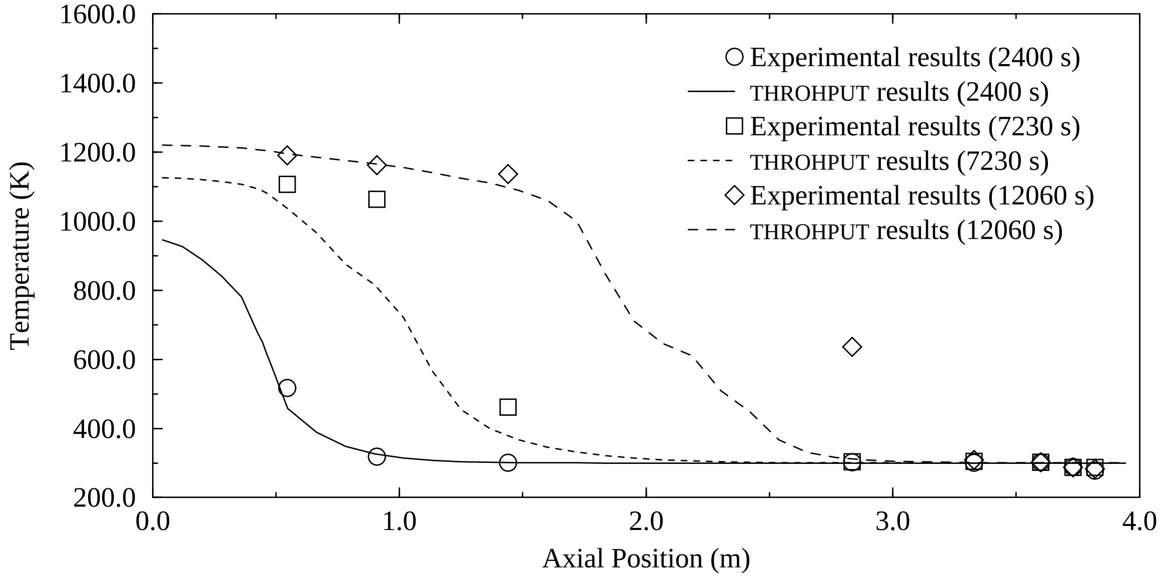
The interphase transfer terms $(\Gamma_{xy}, Q_{xy}, Q^{\Gamma}_{xy})$ are all functions of $\rho_m, X_n, T_m, T_l, T_s$, and T_w and are defined implicitly in the Radial Model.

Results: Problem Description

- SPAR-8 heat pipe (3/8/85 test)
- lithium working fluid, molybdenum pipe
- Lengths: 0.4 m evaporator, 0.09 m adiabatic, 3.51 m condenser
- Outside radius $\approx$ 1 cm.
- Heat output used as heat input

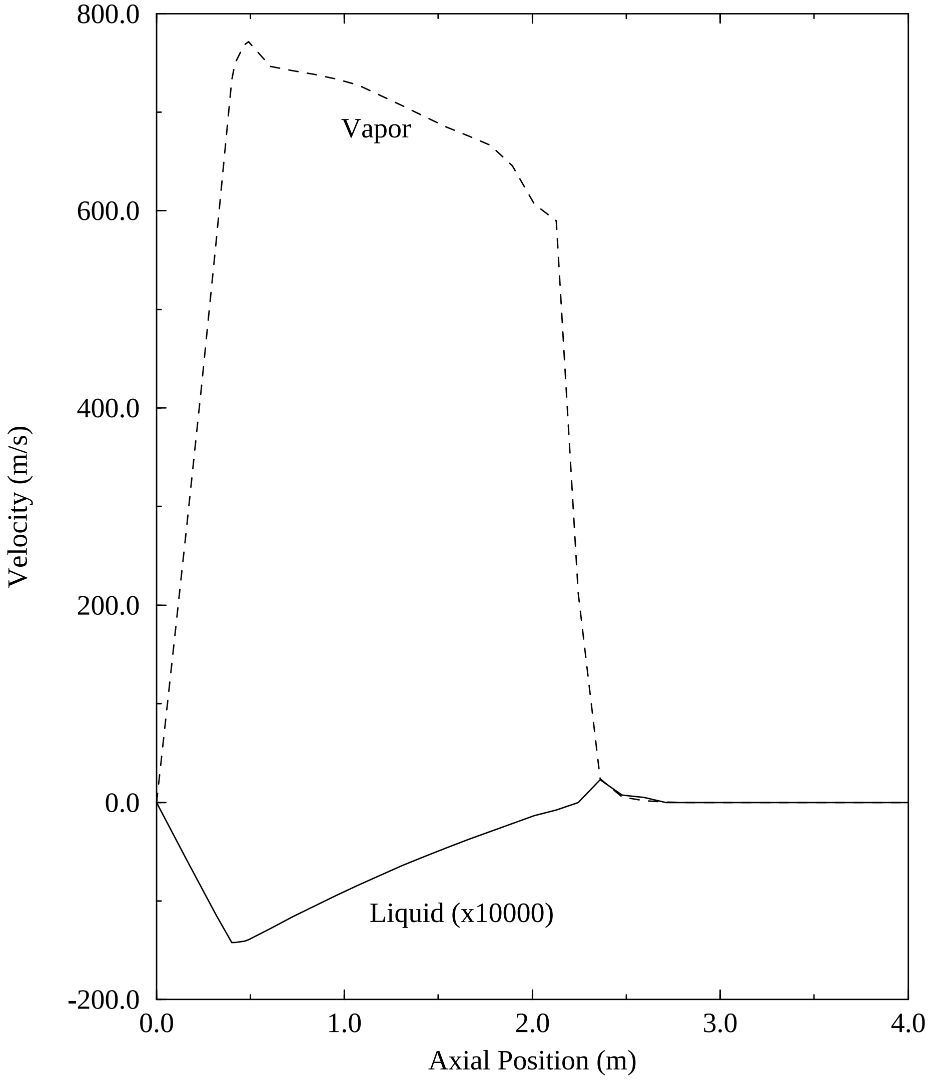
Results:

SPAR-8 Experimental Comparison

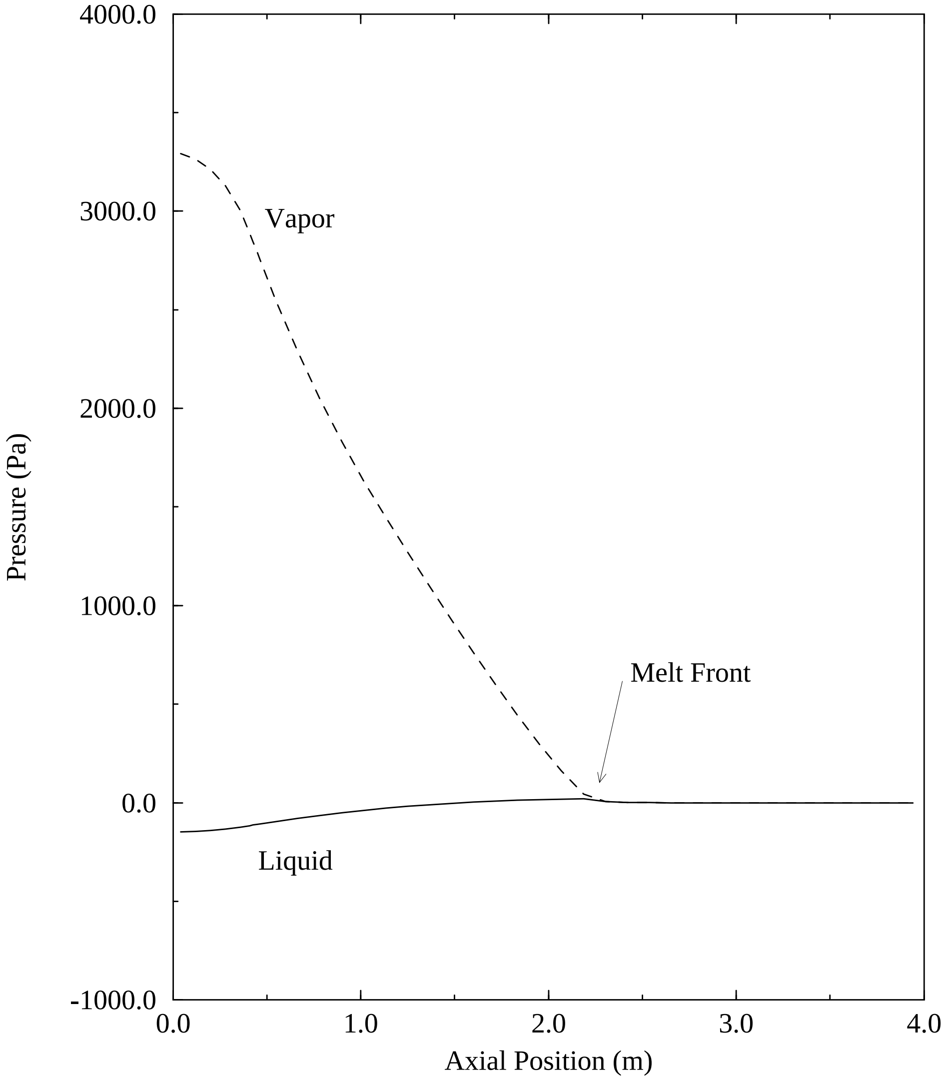


Time lag thought to be caused by using the experimental heat output value as the heat input value in THROHPUT.

Results:
SPAR-8 Velocity Distributions
at 13,260 s



Results:
SPAR-8 Capillary Pressure
Differences at 13,260 s



Experimental Comparison Problems

- Not much experimental data
- No intrusive measurements
- Only exterior temperatures are available
- Numerical modeler not present at experiments; experimenters not aware of measurement needs
- Only global heat output is known; heat input is needed

Future Work

- Production version of THROHPUT
- Additional wick geometries (groove, arterial, slab)
- Arbitrary heat pipe cross-section (e.g. square)
- Two- or three-dimensional model
- Additional fluids and wall materials
- Entrainment model
- Graphical output
- User-specified heat pipe failure criteria
- Limit prediction (sonic, viscous, entrainment, capillary, boiling)