Numerical Analysis of the Bypass Valve in a Loop Heat Pipe

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Outline

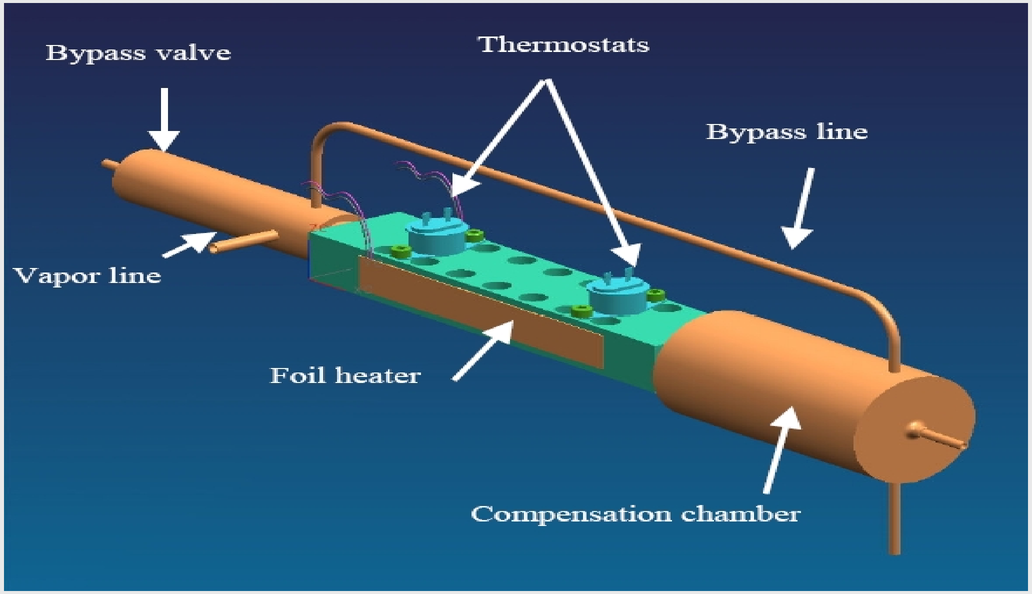
- Background
- Objectives and strategy
- Integral thermodynamical analysis
- FVM analysis: mathematical model
- FVM analysis: status and outstanding tasks

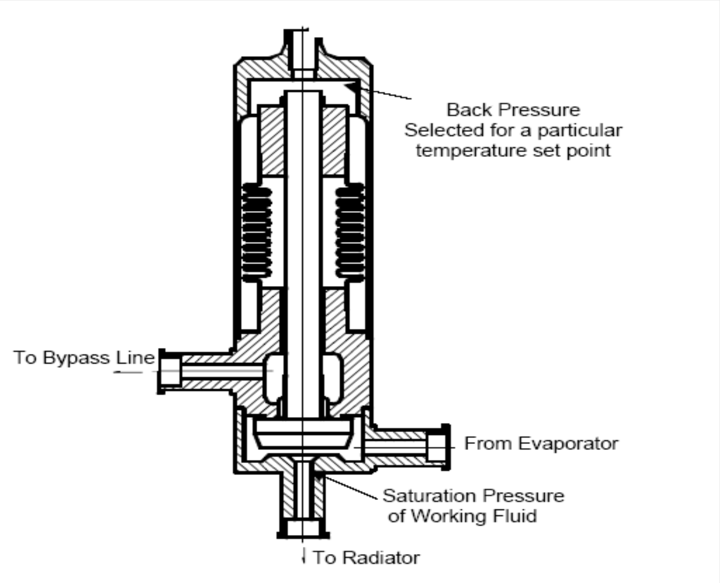
Background

- **Loop Heat Pipe:** thermal control of Alpha Magnetic Spectrometer used for extra-terrestrial studies on anti-matter (see UNIBG-talk)
- **Bypass valve:** prevent freezing of working fluid (Propylene) in liquid line by interrupting circulation:

$p_{sat} > p_{min}$: valve closed; circulation

$p_{sat} \leq p_{min}$: valve open; no circulation





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Objectives and strategy

- **Objective:** more accurate description of the bypass valve in the **SINDA/FlUINT** thermal simulator for the two steady-state operating modes (i.e. open/closed; see before)

- **Strategy:** numerical analysis of fluid flow and heat transfer in bypass valve by FVM-simulations w/ **FLUENT**

➢ detailed determination of physical quantities (pressure drops, temperature changes, flow rate, …) so as to better parameterise bypass valve in **SINDA/FlUINT**

Integral thermodynamical analysis

Mass conservation: $\dot{m} = \rho_i A_i V_i = \rho_o A_o V_o \overset{A_i = A_o}{\Leftrightarrow} \rho_i V_i = \rho_o V_o$

Energy conservation: $h_i + \frac{V_i^2}{2} = h_o + \frac{V_o^2}{2}$

Equation of state: ideal gas: $\rho(p,T) = \frac{p}{RT},\ h = c_p(T)T$

- **Relevant quantities:** $p, \rho, T, V, \phi = AV$ at inlet/outlet

- **Given:** $\dot{m},\ p_i, T_i,\ \Delta p = p_o - p_i < 0$ => determine quantities

Inlet conditions: trivial; outlet conditions: above yields:

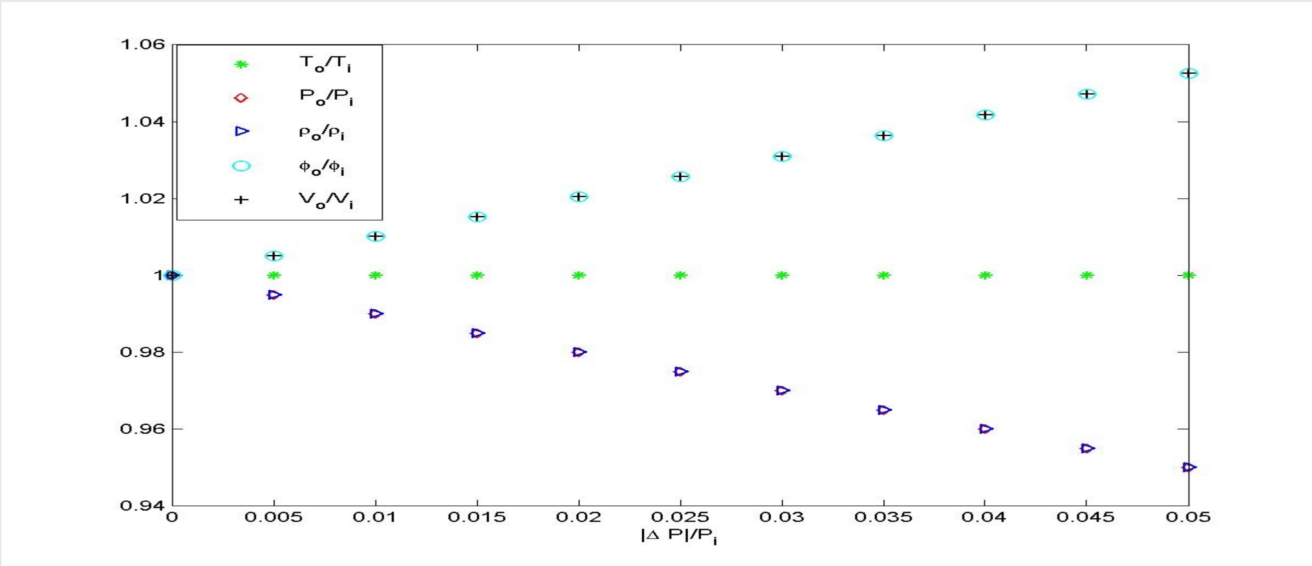
$$\frac{V_i^2}{2}\left[\frac{p_i}{p_o T_i}\right]^2 T_0 + c_p(T_o)T_o - c_p(T_i)T_i - \frac{V_i^2}{2} = 0 \Rightarrow T_o \Rightarrow p_o, \rho_o, T_o, V_o, \phi_o$$

($c_p(T)$: empirical relation in Çengel & Boles (2002))

Integral thermodynamical analysis: an example

$$T_i = 245\,K, p_i = 2.3\,bar, \dot{m} = 68\,\frac{mg}{s},\ -\frac{p_i}{20} \leq \Delta p \leq 0,\ c_{p,i} = 1.3\frac{kJ}{kgK}$$

- **Inlet:** above $+\ \rho_i = 4.7\frac{mg}{cm^3},\ V_i = 3.6\frac{m}{s},\ \phi_i = 14.5\frac{cm^3}{s}$
- **Outlet:**



- **Analysis suggests isothermal conditions**
- **Limitations:** uniform inlet/outlet conditions; **no viscous effects**
- **Realistic (non-uniform) conditions => numerical simulations**

FVM analysis: governing equations

Mass conservation: $\nabla \cdot (\rho \boldsymbol{u}) = 0$

Momentum conservation: Re~O(3,000): laminar; steady, compressible Navier-Stokes equations: $\rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \nabla \cdot \{\mu[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T]\}$

Energy conservation: Pe~O(300): advection-dominated heat transfer:

$\rho c_p \boldsymbol{u} \cdot \nabla T = \nabla \cdot \{\lambda \nabla T\}$, $\rho(p,T)$: ideal gas; $c_p(T), \lambda(T)$: empirical

Equation of state: ideal gas: $\rho(p,T) = p/RT$

Rheology: Newtonian fluid w/ temperature-dependent viscosity following Sutherland's viscosity law:

$$\mu(T) = \frac{1.45 T^{3/2}}{T+110} \cdot 10^{-6}$$

FVM analysis: boundary conditions

Inlet: Poiseuille flow; saturation conditions

$$u_z(r) = 2V_i \left(1 - \left[\frac{r}{R}\right]^2\right) \quad p_i = p_{sat}, \; T_i = T_{sat}$$

Solid boundary: no-slip; adiabatic: $(u, v) = (0, 0), \; \nabla T \cdot n = 0$

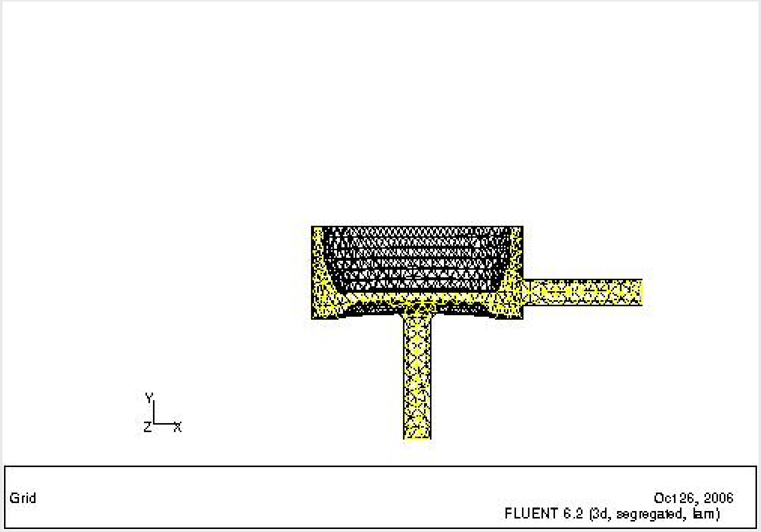
Outlet: prescribed pressure (via pressure drop)

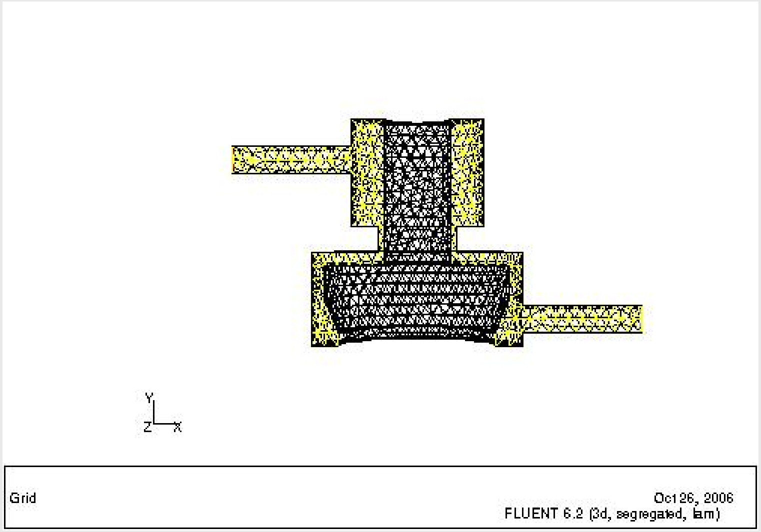
- **Relevant quantities: inlet/outlet conditions**
- **Similar to integral analysis; yet now with non-uniform conditions and viscous effects**

FVM analysis: status and outstanding tasks

Tasks:

➢Meshing of two operating modes (current status)





➢Implementation of model (in progress)

➢Incompressible isothermal simulations (in progress)

➢Compressible isothermal simulations (possibly sufficient; see before)

➢Compressible non-isothermal simulations (double-check)

➢Evaluation SINDA/FLUINT parameters