ANALYTICAL MODEL FOR THE BYPASS VALVE IN A LOOP HEAT PIPE

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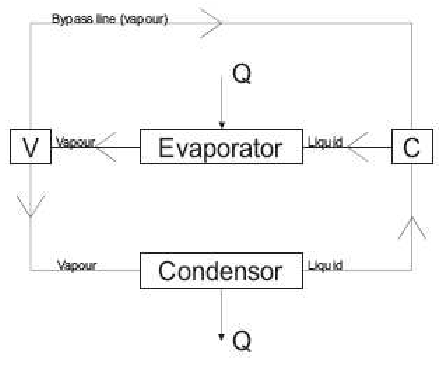
Introduction

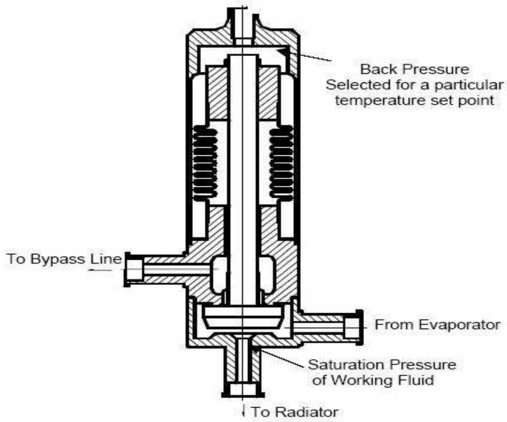
The loop heat pipe (LHP) is part of the cryo-cooling system for the thermal control of the Alpha Magnetic Spectrometer used for extra-terrestrial studies on anti-matter. The LHP basically comprises a conventional cooling cycle (i.e. heat intake by an evaporator; heat release by a condensor) following the schematic in Figure 1a. The circulation of the working fluid (propylene) is set up by capillary forces in the evaporator according to the heat-pipe principle (hence the denotation "LHP"). In order to avoid freezing of the working fluid and, consequently, cessation of the circulation – and thus termination of the cooling process – a bypass valve (component "V" in Figure 1a; cross-section in Figure 1b) has been placed between evaporator and condensor that interrupts the circulation in case the evaporator pressure p_e (typically the saturation pressure) drops below a certain lower limit p_{min} ("back pressure"). The system has two steady-state operating modes:

- $p_e > p_{min}$: only liquid-vapour phase change possible; no risk of freezing. The bypass valve is closed and the circulation is enabled. The LHP is operational.
- $p_e \leq p_{min}$: solid-vapour phase change possible; risk of freezing. The bypass valve is opened and the circulation is halted; the working fluid (vapour) is redirected into the evaporator through the compensation chamber (component "C" in Figure 1a). The LHP is not operational.

To date a poor description exists of the thermodynamical behaviour of the bypass valve. Better description is essential so as to better describe the behaviour of the LHP as a whole, however. To this end the thermodynamical behaviour of the bypass valve in its two steady-state operating modes is to be performed, first, through an analytical integral analysis and, as a follow-up on the latter, through a detailed numerical analysis using the finite-volume method (FVM). The discussion hereafter concerns the analytical integral analysis. Results of the FVM analysis are communicated separately.



a) Schematic of the LHP.



b) Cross-section of the bypass valve.

Figure 1: *The Loop Heat Pipe (panel a) and the bypass valve (panel b). Components "V" and "C" in panel a indicate the bypass valve and compensation chamber, respectively.*

Integral thermodynamical analysis

The bypass valve corresponds in both operating modes with an open two-port thermodynamical system, i.e. having one inlet (denoted by 'i'") and one outlet (denoted by "o") (Shavit & Gutfinger (1995)). Important to note is that viscous effects and inhomogeneous property distributions on the ports are not taken into account in the integral analysis. These issues are dealt to be with in the abovementioned FVM analysis. The integral thermodynamical behaviour of the bypass valve is in both operating modes governed by the integral conservation laws for mass and energy. These laws are given by

$$\dot{m} = \rho_i A_i V_i = \rho_o A_o u_o, \qquad \frac{\dot{Q}}{\dot{m}} + h_i + \frac{V_i}{2} = h_o + \frac{V_o}{2}, \tag{1}$$

with $\dot{m}$, ρ, A, V and h signifying mass flow, density, cross-sectional area, velocity and specific enthalpy, respectively, and $\dot{Q} \leq 0$ representing heat loss by radiation. Closure of the problem requires specification of the state of the working medium (propylene) as a function of the thermodynamical variables. Propylene may to good approximation be considered an ideal gas (Chao & Zwolinksi (1975)). This completes the integral model with the equation of state and the enthalpy relation,

$$\frac{p}{\rho} = RT, \qquad h = c_p(T)T, \qquad c_p(T) = \sum_{k=0}^{3} a_k T^k, \tag{2}$$

respectively, with R the specific gas constant and $c_p(T)$ the temperature-dependent specific heat with coefficients a_k following Çengel & Boles (2002).

Relevant quantities are the thermodynamic variables p, ρ and T and the fluid-dynamical variables V and $\phi = AV$ (volumetric flow rate) at the inlet and outlet of the bypass valve. Given are the mass flow $\dot{m}$, the radiative heat loss $\dot{Q}$, the cross-sectional areas A_i and A_o and the inlet conditions p_i, T_i and V_i. This straightforwardly leads to

$$\phi_i = AV_i, \qquad \rho_i = \frac{p_i}{RT_i}, \tag{3}$$

and thereby fully determines the state at the inlet. The state at the outlet is determined as follows. Recasting relations (1)-(2) yields

$$A_o \rho_o V_o = \dot{m}, \qquad \frac{p_o}{\rho_o} = RT_o, \qquad c_p(T_i)T_i + \frac{\dot{Q}}{\dot{m}} = c_p(T_o)T_o + \frac{V_i^2}{2}\left\{\left[\frac{p_i T_o A_i}{p_o T_i A_o}\right]^2 - 1\right\}, \tag{4}$$

providing three equations for the four unknown outlet quantities p_o, ρ_o, T_o and V_o. Imposing the pressure gradient $\Delta p = p_o - p_i < 0$ fixes the outlet pressure p_o and, via expressions (4), fully determines the state at the outlet as a function of Δp. This is elaborated below.

The state at the outlet depends on the relative share of the three energy contributions (radiative heat loss; kinetic energy; enthalpy flux) in the total energy balance (nonlinear relation in (4)). Consider to this end relations (4) in the non-dimensional form

$$1 - \Pi_1 = \bar{c}_p(\Theta_T)\Theta_T + \Pi_2\left\{\left[\frac{\Lambda\Theta_T}{1+\Theta_p}\right]^2 - 1\right\}, \qquad \Theta_\rho = \frac{1+\Theta_p}{\Theta_T}, \qquad \Theta_V = \frac{\Lambda}{\Theta_\rho}, \qquad \Theta_\phi = \frac{1}{\Theta_\rho}, \tag{5}$$

in terms of the non-dimensional outlet conditions

$$\Theta_p = \frac{\Delta p}{p_i}, \qquad \Theta_T = \frac{T_o}{T_i}, \qquad \Theta_\rho = \frac{\rho_o}{\rho_i}, \qquad \Theta_V = \frac{V_o}{V_i}, \qquad \Theta_\phi = \frac{\phi_o}{\phi_i}, \tag{6}$$

with $\bar{c}_p(\Theta_T) = c_p(T_i\Theta_T)/c_p(T_i)$. (Form (5) readily follows from rescaling (4)). The corresponding parameters read

$$\Pi_1 = \frac{|\dot{Q}|}{\dot{m}c_p(T_i)T_i} = \frac{\text{radiative heat loss}}{\text{enthalpy flux}}, \quad \Pi_2 = \frac{V_i^2}{2c_p(T_i)T_i} = \frac{\text{kinetic energy}}{\text{enthalpy flux}}, \quad \Lambda = \frac{A_i}{A_o}, \tag{7}$$

with parameters $\Pi_1 \geq 0$ and $\Pi_2 \geq 0$ relating the three energy contributions as indicated; the independent outlet variable $-1 < \Theta_p \leq 0$ controls the pressure drop over the bypass valve. The ratio of cross-sectional areas is fixed at $\Lambda = 1$, and thus $\Theta_V = \Theta_\phi$, hereafter.

Figure 2 gives a visual representation of the thermodynamical behaviour of the bypass valve. Shown are the dependent outlet variables Θ_T and $\Theta_\rho(= \Theta_V^{-1})$ as a function of Θ_p and Π_2 with growing non-dimensional radiative heat losses Π_1. The graphs clearly demonstrate the changes in outlet conditions with changing Θ_p and Π_2.

Correlations for normal operating conditions

Typical values for the various quantities under normal operating conditions are (Bodendiek et al. (2005)): $T_i \approx 245\ K$, $V_i \sim \mathcal{O}(10^{-5}\ m/s)$, $\dot{m} \sim \mathcal{O}(10^{-5}\ kg/s)$, $\dot{H}_i = \dot{m}c_p(T_i)T_i \sim \mathcal{O}(30\ W)$. This gives $\Pi_2 \sim \mathcal{O}(10^{-5})$ and thus implies that kinetic effects are negligible. Under this proviso relations (5) simplify to

$$1 - \Pi_1 = \bar{c}_p(\Theta_T)\Theta_T, \quad \Theta_\rho = \frac{1 + \Theta_p}{\Theta_T}, \quad \Theta_V = \frac{\Theta_T}{1 + \Theta_p}, \tag{8}$$

resulting in a constant outlet temperature for given Π_1 and, consequently, proportional and inversely-proportional dependence of Θ_ρ and Θ_V, respectively, upon Θ_p. The non-dimensional outlet temperature Θ_T is to good approximation given by $\Theta_T = 1 - \Pi_1$. This admits further simplification of (5) to the practical correlations

$$\Theta_T = 1 - \Pi_1, \quad \Theta_\rho = \frac{1 + \Theta_p}{1 - \Pi_1}, \quad \Theta_V = \frac{1 - \Pi_1}{1 + \Theta_p}, \tag{9}$$

that conveniently relate the inlet and outlet conditions of the bypass valve for given Π_1. Figure 3 gives the outlet conditions as a function of Θ_p according to (8) (heavy) and approximated by (9) (dashed) with growing non-dimensional radiative heat losses Π_1. The correlations (9) progressively depart from relations (8) with increasing Π_1. However, deviations remain sufficiently small for correlations (9) to provide an adequate description of the thermodynamical behaviour of the bypass valve.

Conclusions and outlook

The above study concerns an integral thermodynamical analysis of the bypass valve in its two steady-state operating modes. This study resulted in the practical correlations (9) between the inlet and outlet conditions of the bypass valve. Omitted in this analysis are irreversible effects occurring in the interior of the bypass valve due to viscosity. The influence of such effects on the relations between the several thermodynamical quantities depends essentially on the operating mode and is to be investigated through a detailed numerical analysis of the bypass valve using the finite-volume method (FVM). Results of the FVM analysis are presented in a forthcoming communication.

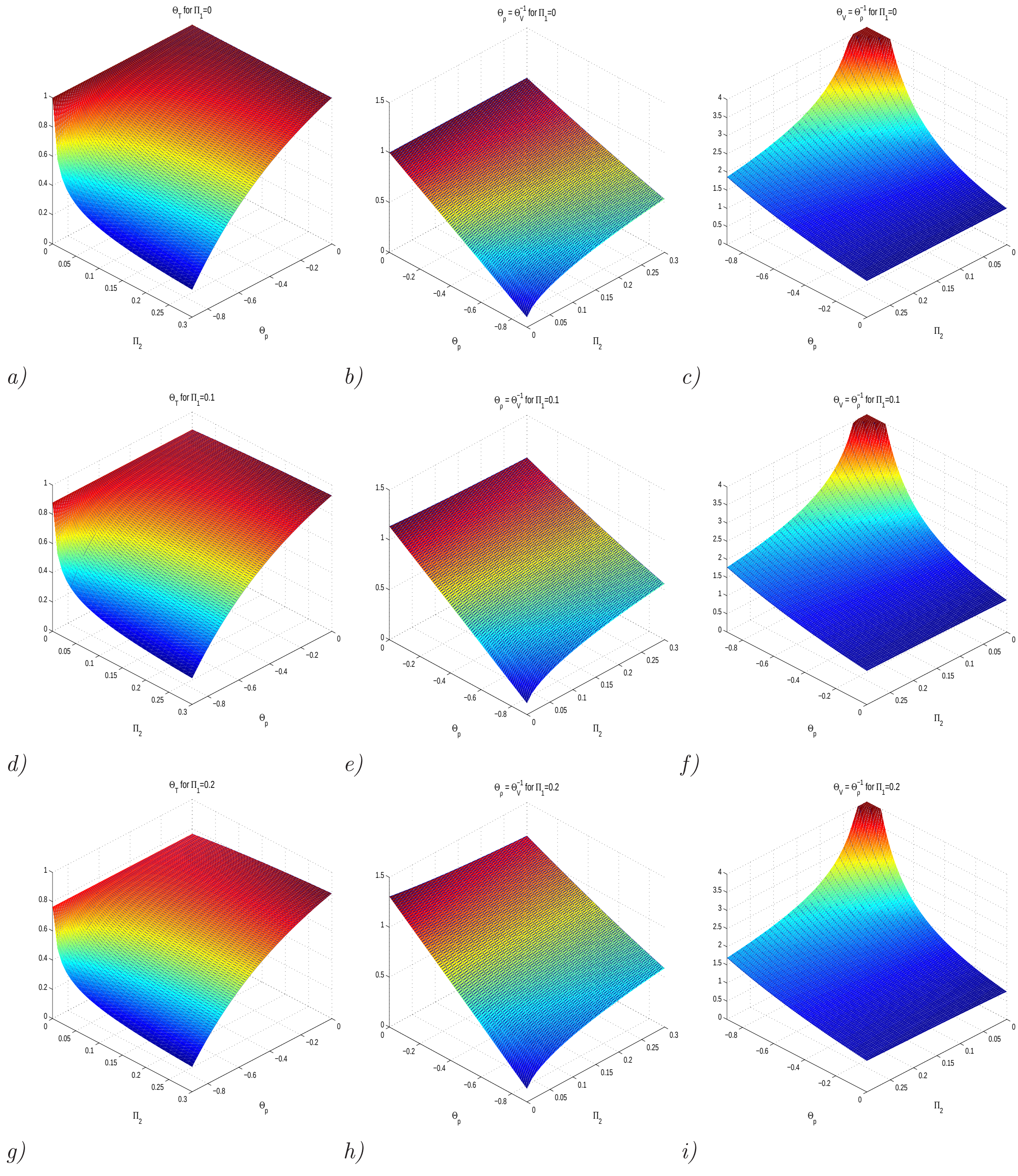


Figure 2: *Visual representation of the thermodynamical behaviour of the bypass valve. Shown are the dependent outlet variables Θ_T and $\Theta_\rho (= \Theta_V^{-1})$ as a function of Θ_p and Π_2 with growing non-dimensional radiative heat losses Π_1.*

References

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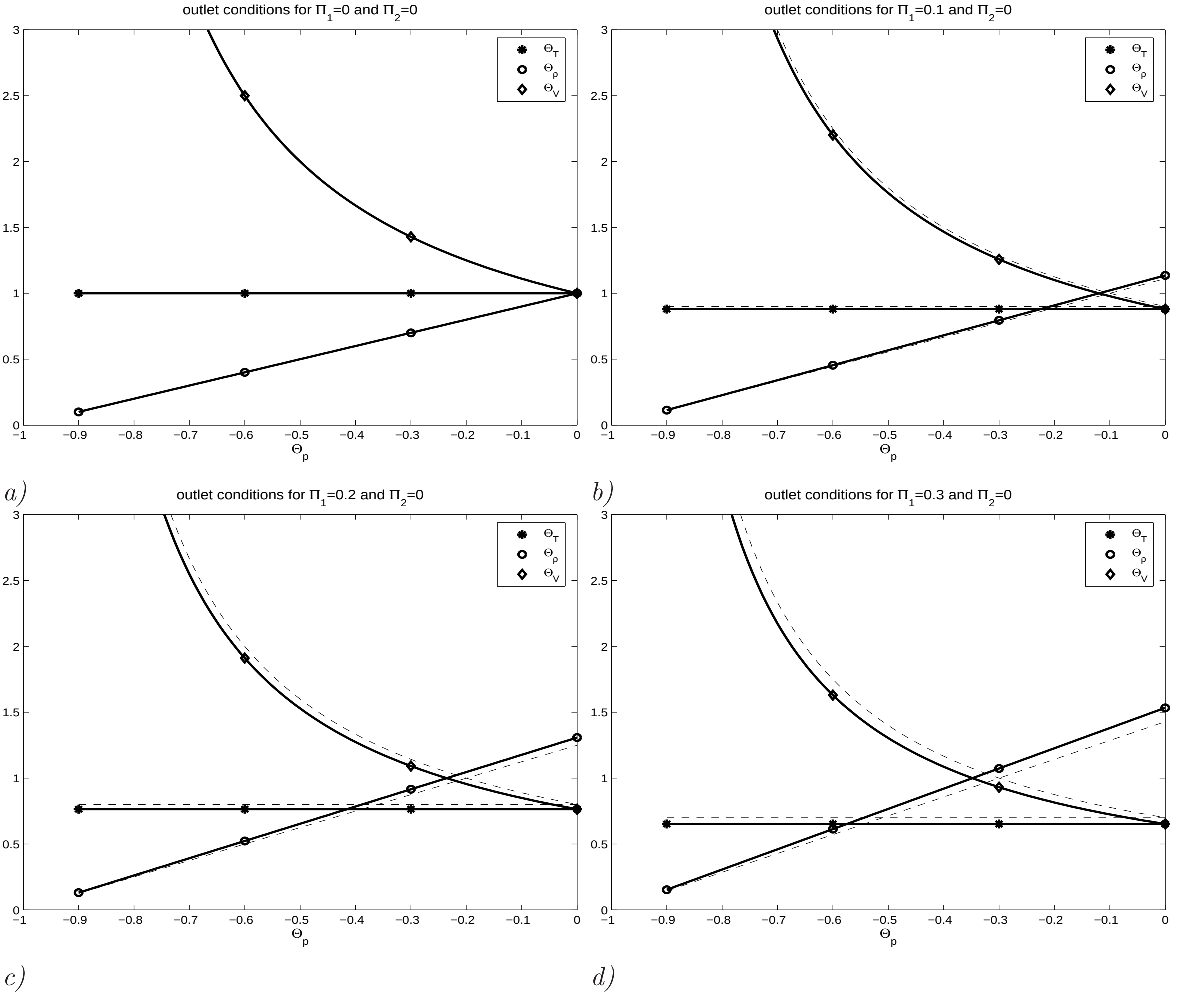

Figure 3: *Relations between inlet and outlet conditions of the bypass valve with increasing radiative heat losses* Π_1. *Heavy lines correspond with relations* (8)*; dashed lines correspond with the practical correlations* (9).

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