Investigations Of Heat And Momentum Transfer in Vapor-Liquid Isobutane Injector

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- **Introduction**
- **Mathematical model of two-phase injector**
- **Analysis of isobutane two-phase injector**
- **Conclusions**

Introduction

Mechanical liquid pump liquid is the only element of the ejector refrigeration system that consume electric power. Without consumption of electric power to drive the system would be <u>fully thermal driven</u>.

The general motivations of application of the two-phase injector pump are:

- two-phase injector operates also as pre-heater of liquid phase supplied to the vapour generator that additionally improve the system efficiency;

- this type of injector is more simple and reliable than mechanical liquid pump since it has no moving parts as well as is not influenced to possible cavitation that may occur in mechanical pumps.

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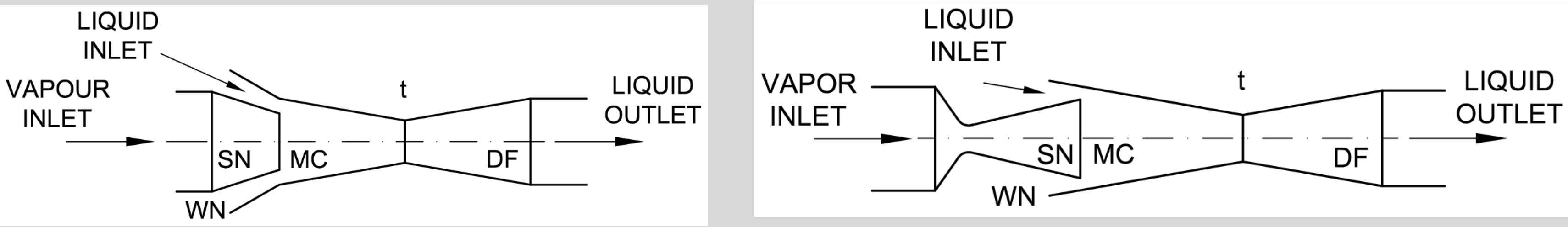
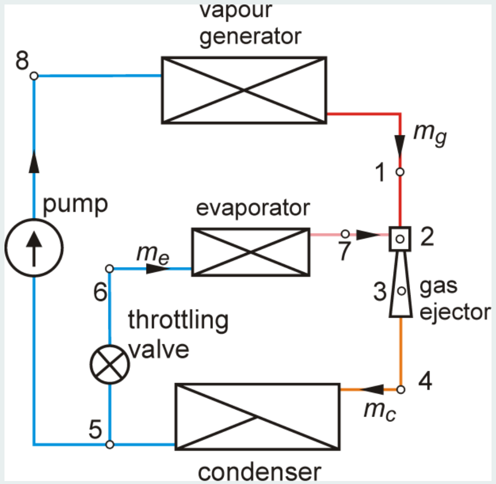
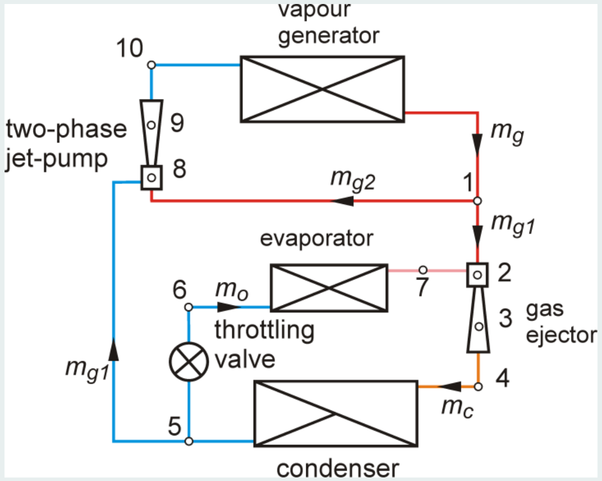


Schematic of vapour-liquid injectors:
a) subsonic; b) supersonic:
SN – vapour motive nozzle; WN – liquid nozzle; MC – mixing chamber; DF – diffuser, t – throat

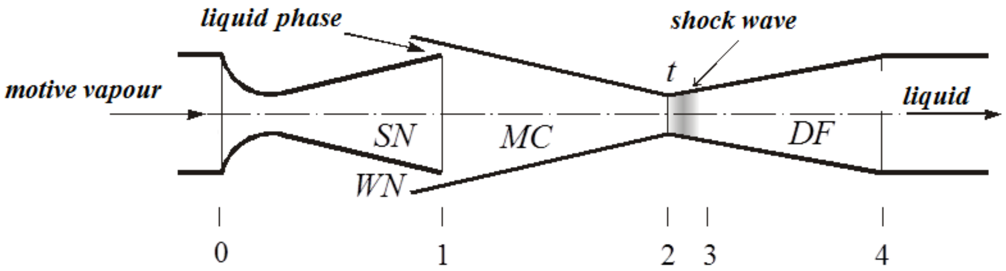


Classic ejection refrigeration system



Modified ejection refrigeration system with two-phase injector as a liquid pump

Mathematical model of two-phase injector



Motive vapour nozzle

nozzle is adiabatic with irreversible losses

continuity balance equation

$$A_{V0}\rho_{V0}w_{V0} = A_{V1}\rho_{V1}w_{V1}$$

energy balance equation

$$h_{V0} + \frac{w_{V0}^2}{2} = h_{V1s} + \frac{w_{V1s}^2}{2} = h_{V1} + \frac{w_{V1}^2}{2}$$

$$h_{V1} = h_{V1s} + \left(1 - c_v^2\right)\frac{w_{V1s}^2}{2} = c_v^2 h_{V1s} + \left(1 - c_v^2\right)\left(h_{V0} + \frac{w_{V0}^2}{2}\right) \qquad c_v = \frac{w_{V1}}{w_{V1s}}$$

Liquid nozzle

$$p_{V1} = p_{L1} = p_1 \qquad \rho_{L1} = \rho(p_{V1}, T_{L0})$$

$$\dot{m}_{L0} = A_{L1}\rho_{L1}w_{L1} \Rightarrow w_{L1}$$

Mathematical model of two-phase injector

Assumptions:
vapour phase is saturated in the mixing chamber
both phases at the throat constitute homogeneous mixture
common velocity w_2, i.e. there is no slip between the phases

$$A_2\rho_2 w_2 = A_{V1}\rho_{V1}w_{V1} + A_{L1}\rho_{L1}w_{L1}$$

$$\dot{m}_2 w_2 + A_2 p_2 + (A_1 - A_2)\,p_{MC} = \dot{m}_{V1} w_{V1} + \dot{m}_{L1} w_{L1} + A_1 p_1$$

$$\dot{m}_2\left(h_2 + \frac{w_2^2}{2}\right) = \dot{m}_{V1}\left(h_{V1} + \frac{w_{V1}^2}{2}\right) + \dot{m}_{L1}\left(h_{L1} + \frac{w_{L1}^2}{2}\right)$$

Mixing chamber

balance equations

The mixture enthalpy h_2 may be evaluated from the relations describing of the thermodynamic properties of homogenous two-phase flow

$$h_2 = h\left(p_2, \rho_2, T_{L2}\right) = x_2 h_{V,sat}(p_2) + (1 - x_2)\,h_{L2}(\rho_{L2}, T_{L2})$$

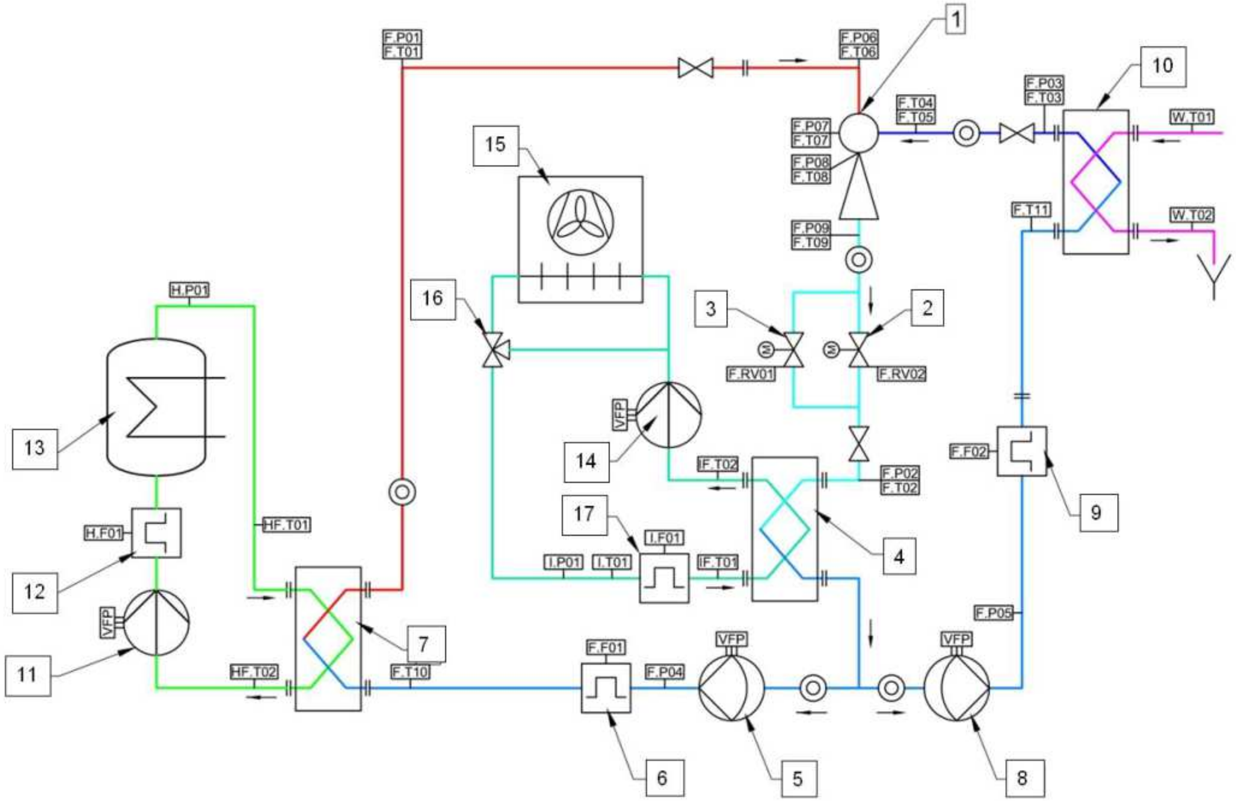
temperature T_{L2} of liquid phase is below the saturation temperature since subcooled liquid enters the injector

$$x_2 = \varphi_2 \frac{\rho_{V,sat}(p_2)}{\rho_2}$$

$$\varphi_2 = \frac{\rho_2 - \rho_{L2}(p_2, T_{L2})}{\rho_{V2} - \rho_{L2}(p_2, T_{L2})}$$

$$\Delta T_{L2} = T_{V,sat}(p_2) - T_{L2}$$

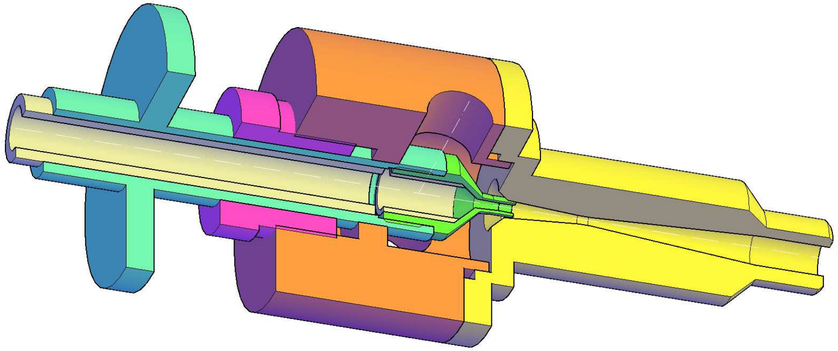
Testing stand



1 – tested injector; 2,3 – control valve; 4 – condenser; 5,8 – circulating pump of working fluid; 6,9 – mass flow meter; 7 – vapour generator; 10 – liquid subcooler; 11 – circulating pump of glycol; 12 – mass flow meter; 13 – electric heater; 14 – circulating pump of glycol, 15 – fan cooler; 16 – control valve; 17 – mass flow meter

Testing stand – tested injector

throat diameter of the motive nozzle: 1.5 mm;
diameter of the mixing chamber: 2.2 mm



Definitions

compression efficiency – power of isochoric compression of liquid in reference to motive power

$$\boxed{\eta_c = U\frac{p_d - p_{sL}}{\rho_{dL}\left(h_V - h_{dL}\right)}}$$

injector efficiency – power of liquid compression + powier of liquid heating in reference to motive power

$$\boxed{\eta_e = \frac{U}{h_V - h_{dL}}\left[\frac{p_d - p_{sL}}{\rho_{dL}} + h_{dL} - h_{sL}\right]}$$

compression ratio

$$\boxed{\pi_e = \frac{p_d}{p_{sL}}}$$

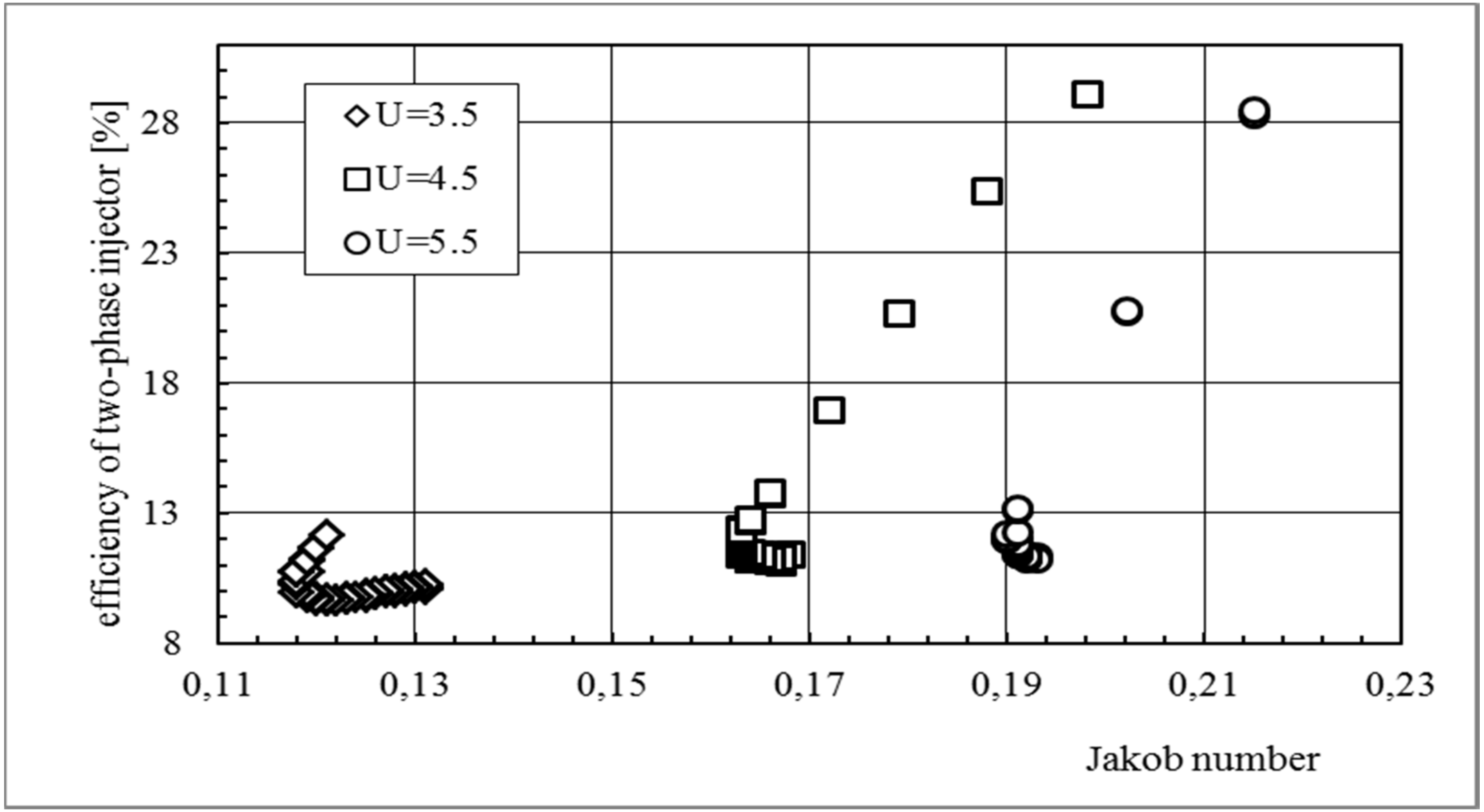
superheating of liquid

$$\boxed{\Delta T_L = T_{dL} - T_{sL}}$$

Jakob number

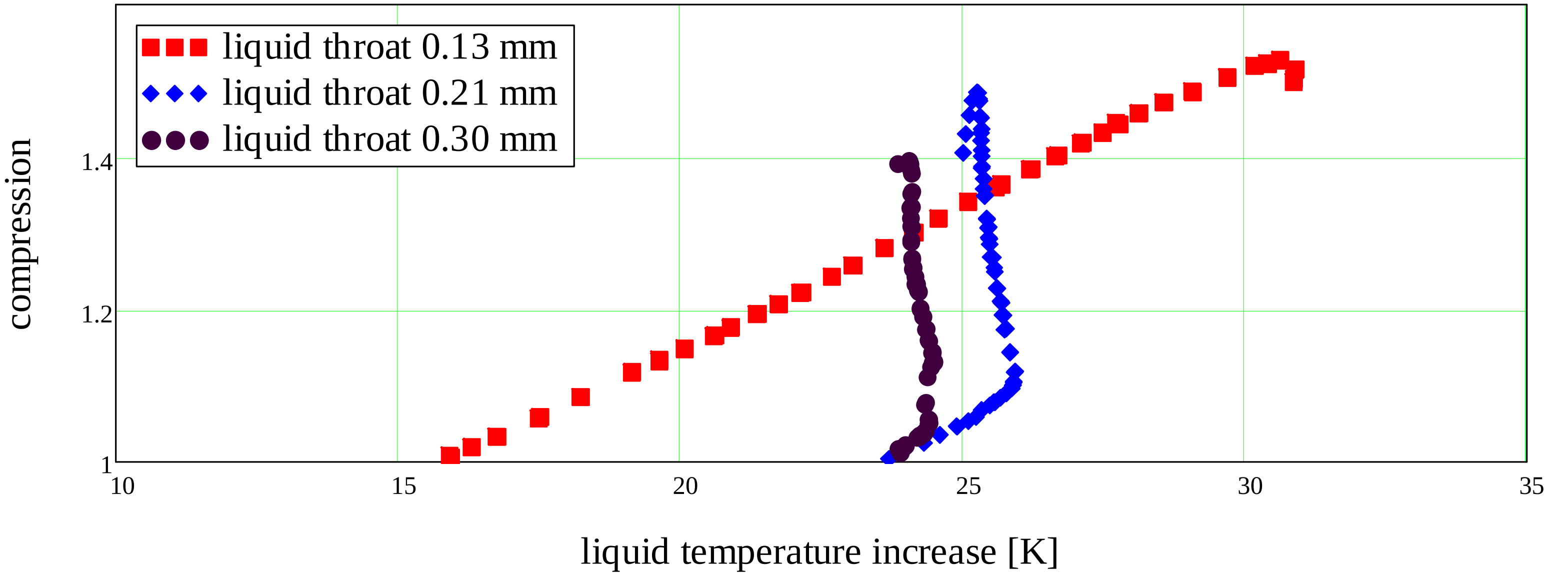
$$\boxed{Ja = \frac{c_{pL}\Delta T_L}{h_{fg}}}$$

Results



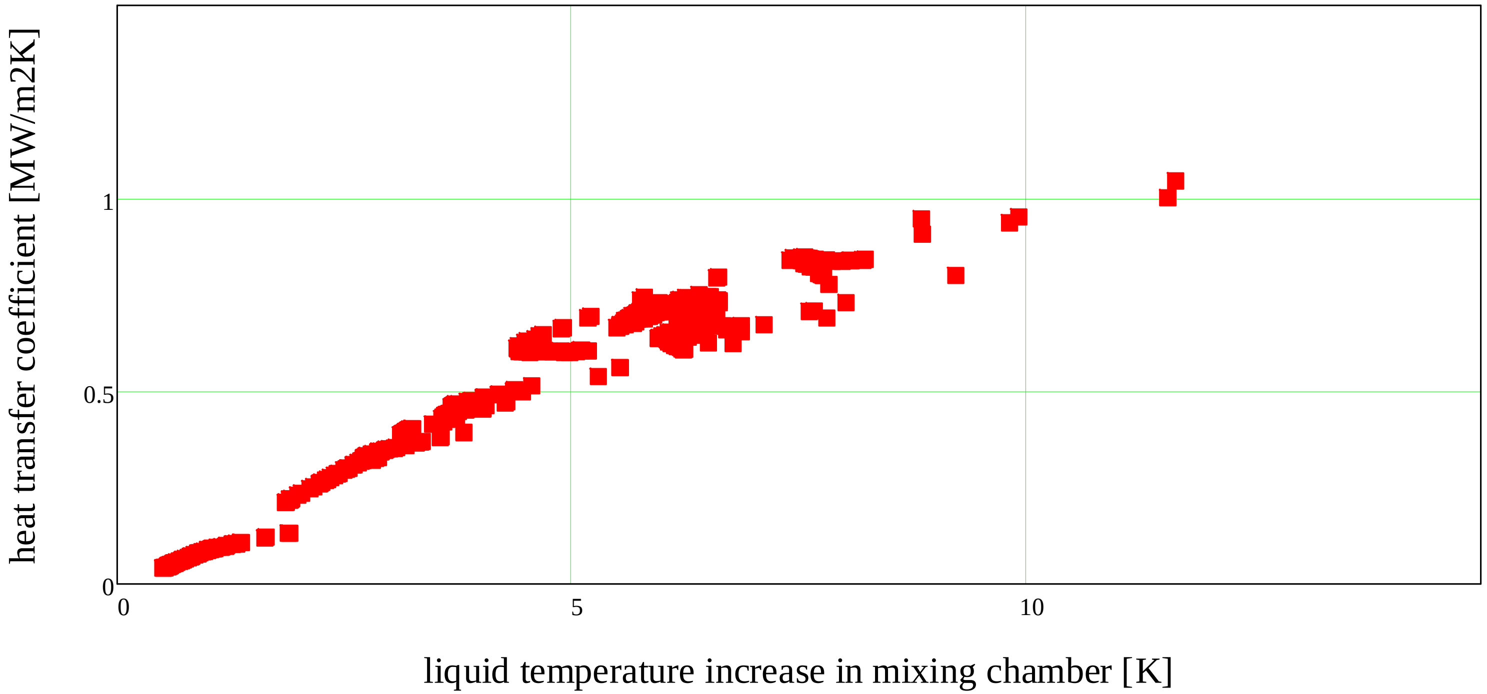
Relationship between total injector efficiency η_e versus Jakob number *Ja*

Results



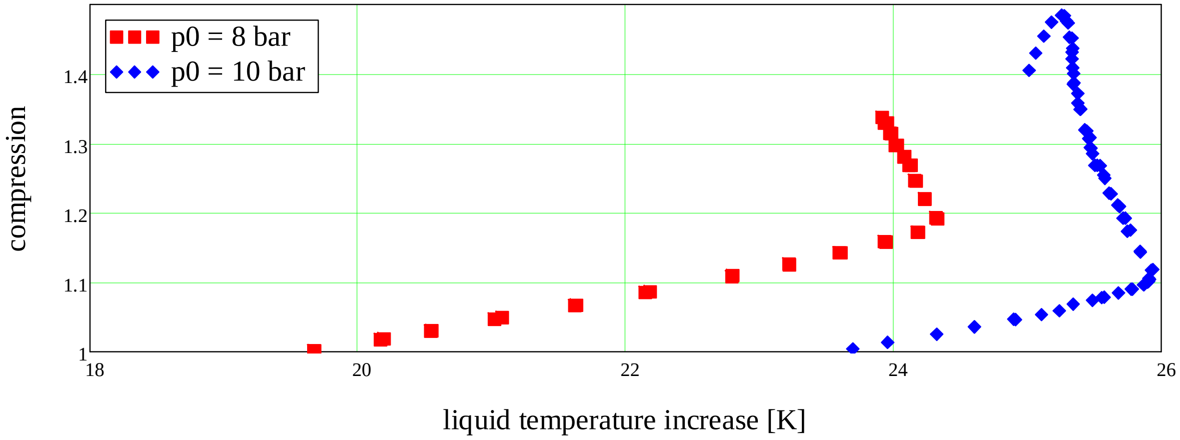
Performance characteristics of the injector operations for various liquid nozzle gaps thickness

Results



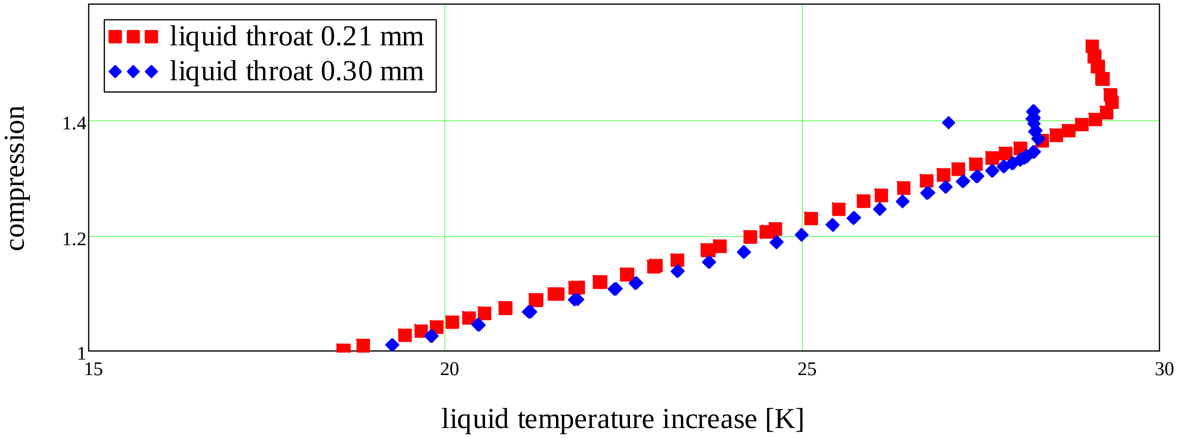
Condensation film heat transfer coefficient versus temperature increase of liquid phase.

Results

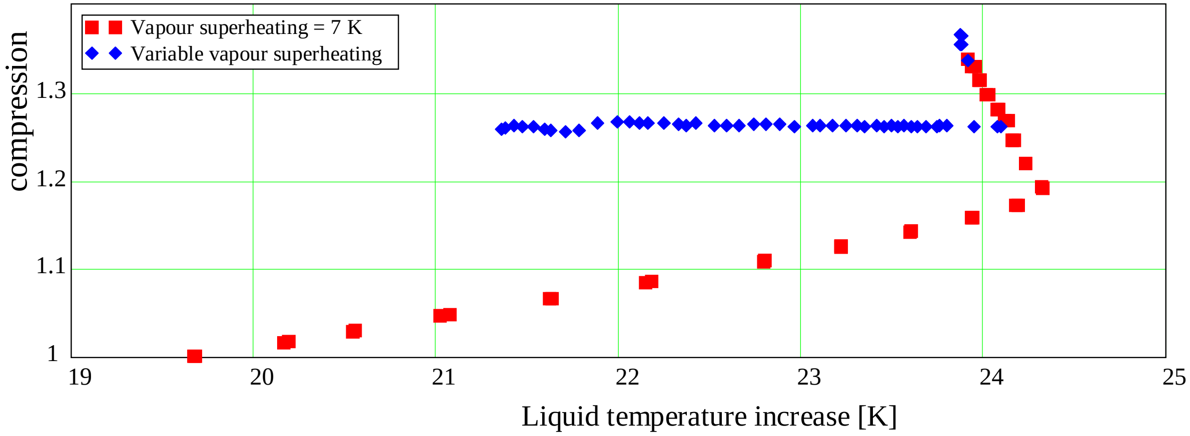


Compression ratio versus liquid phase temperature increase for various motive pressures

Compression ratio versus liquid phase temperature increase for: U = 3.5, p_V = 10 bar



Results



Compression ratio versus liquid phase temperature increase for various vapour superheating:

U = 4.5, p_V = 8 bar,

δ_1 = 0.21 mm

Compression ratio versus vapour superheating:

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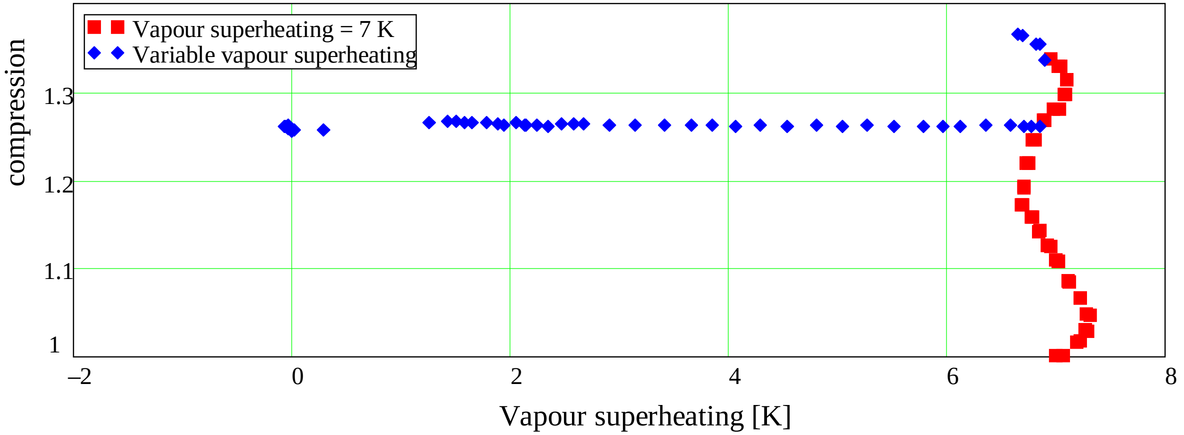
δ_1 = 0.21 mm



Conclusions

- The experimental investigations covered the measurement of the performance of the two-phase injector for isobutane as working fluid in terms of the compression ratio, heat transfer, and mass entrainment ratio. It was shown that intensive condensation heat transfer occurs inside the mixing chamber of the injector in spite of the unfavourable thermokinetic properties of isobutene as working fluid.
- The effect of the liquid gap thickness lays crucial role on momentum and heat transfer in the mixing chamber of the injector.
- The effect of incomplete condensation process strongly affects heat and momentum transfer inside the injector.
- Exceptionally high level of heat transfer coefficient was achieved in the injector so that the tested device may be thought not only as an alternative thermally driven liquid pump but also an effective direct contact condenser