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
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.
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**

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

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

\[ c_v = \frac{w_{V1}}{w_{V1s}} \]

**Liquid nozzle**

\[ \rho_{V1} = \rho_{L1} = \rho_1 \quad \rho_{L1} = \rho(p_{V1}, T_{L0}) \]

\[ m_{L0} = A_{L1} \rho_{L1} w_{L1} \quad w_{L1} \]
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

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

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

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

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

\[
h_2 = h(p_2, \rho_2, T_{L2}) = x_2 h_{V,\text{sat}}(p_2) + (1 - x_2) h_{L2}(\rho_{L2}, T_{L2})
\]

\[
x_2 = \frac{\rho_{V,\text{sat}}(p_2)}{\rho_2} \quad \varphi_2 = \frac{\rho_2 - \rho_{L2}(p_2, T_{L2})}{\rho_{V2} - \rho_{L2}(p_2, T_{L2})}
\]

\[
\Delta T_{L2} = T_{V,\text{sat}}(p_2) - T_{L2}
\]
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
<table>
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<tr>
<th>Term</th>
<th>Description</th>
<th>Formula</th>
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<tr>
<td>compression efficiency</td>
<td>Power of isochoric compression of liquid in reference to motive power</td>
<td>$\eta_c = U \frac{p_d - p_{sL}}{\rho_{dL} (h_V - h_{dL})}$</td>
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<tr>
<td>injector efficiency</td>
<td>Power of liquid compression + power of liquid heating in reference to motive power</td>
<td>$\eta_e = \frac{U}{h_V - h_{dL}} \left[ \frac{p_d - p_{sL}}{\rho_{dL}} + h_{dL} - h_{sL} \right]$</td>
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<tr>
<td>compression ratio</td>
<td></td>
<td>$\pi_e = \frac{p_d}{p_{sL}}$</td>
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<tr>
<td>superheating of liquid</td>
<td></td>
<td>$\Delta T_L = T_{dL} - T_{sL}$</td>
</tr>
<tr>
<td>Jakob number</td>
<td></td>
<td>$Ja = \frac{c_{pL} \Delta T_L}{h_{fg}}$</td>
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Results

Relationship between total injector efficiency $\eta_e$ 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.
Compression ratio versus liquid phase temperature increase for various motive pressures:

- p₀ = 8 bar
- p₀ = 10 bar

Compression ratio versus liquid phase temperature increase for: U = 3.5, pᵥ = 10 bar
Compression ratio versus liquid phase temperature increase for various vapour superheating: $U = 4.5$, $p_V = 8$ bar, $\delta_1 = 0.21$ mm

Compression ratio versus vapour superheating: $U = 4.5$, $p_V = 8$ bar, $\delta_1 = 0.21$ mm
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.