Experimental study on helium heat transfer in a small natural circulation loop above the critical pressure

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Introduction

• Study the thermal performance of a small circulation loop coupled with a cryocooler at different thermodynamical conditions

• Circulation loop coupled with a cryocooler
  – Natural self-adaptation
  – Autonomous working conditions

• Heat transfer and flow measurement
  – Measurement of wall temperatures
  – Determination of the pressure drop
  – Determination of the mass flow rate

• Ranges of study
  – P=2.3 bar
  – Heat flux up to 1000 W/m²
  – Mass flow rate from 0.1 to 0.3 g/s
  – Re from $10^3$ to $3 \times 10^4$
Experimental set-up

- Cryocooler Gifford-MacMahon
  - 1.5 W at 4.2 K

- Stainless-steel condenser can with a horizontal fins copper heat exchanger
- Heat exchanger connected to the second stage of the cryocooler
- Pre-cooling with a heat exchanger connected with the first stage of the cryocooler

- 35 cm high loop
- Return loop higher than the liquid level

- Loop made of 4 mm inner diameter copper tube
- 23 cm heated length
Instrumentation

- Condenser
  - 1 absolute pressure
  - 1 temperature sensor

- Loop
  - 1 \( \Delta P \) (PS2)
  - 2 temperature sensors

- Testing tube
  - 1 \( \Delta P \) (PS1)
  - 5 cernox sensors

- Pressure constant within 5 mbar
Temperatures evolution

\[ P_c = 2.27 \text{ bar} \]
\[ T_c = 5.195 \text{ K} \]
Wall temperature difference with height

- Evolution almost identical with height
- Better heat transfer at higher location
- $T_{\text{walls}}$ go over $T_c$ around 400 W/m$^2$ while $T_{\text{condenser}}$ is still below $T_c$
- $T_{\text{condenser}} > T_c$ above 800 W/m$^2$
- Above 800 W/m$^2$ the $q$-$\Delta T$ is monotonous and linear up to 1000 W/m$^2$
Pressure drop along the heated tube

- $\Delta p_{\text{tube}} \downarrow$ due to $\downarrow \rho$ in pressurized fluid region
- $\Delta p_{\text{tube}} \downarrow \downarrow$ due to $\downarrow \downarrow \rho$ when $T_{\text{wall}} > T_c \rightarrow T_{\text{fluid}} > T_c$ in the heated section?
- $\Delta p$ in descending tube $\downarrow \downarrow$ due to $\downarrow \downarrow \rho$ when $T_{\text{wall}} > T_c \rightarrow T_{\text{fluid}} > T_c$ too?
Heat transfer coefficient

- \( h = \frac{q}{(T - T_{\text{condenser}})} \)
  - Acceptable in the pressurized fluid region and when \( T_{\text{condenser}} > T_c \)
  - Questionable when \( T_{\text{wall}} > T_c \)

- In pressurized fluid, heat transfer better with higher height
  - \( T_{\text{fluid}} \uparrow \) due to heating

- When \( T_{\text{wall}} > T_c \) heat transfer goes down to 100 W/m²

- \( q > 800 \text{ W/m}^2 \), the heat transfer is not different than in the \( T_{\text{wall}} > T_c \) region
**Nu-correlations**

- Nu-correlation have been tried
  - Most of them developed for forced flow supercritical in large diameter in water and Co$_2$
  - Only the Bald correlation was developed for helium

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Expression</th>
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<tbody>
<tr>
<td>Dittus and Boelter (1930)</td>
<td>$Nu_b = 0.0243Re_b^{0.8}Pr_b^{0.4}$</td>
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<tr>
<td>Jackson and Fewster (1975)</td>
<td>$Nu = 0.0183Re_b^{0.82}Pr^{0.5}(\rho_w/\rho_b)^{0.3}$</td>
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<td>Bishop (1964)</td>
<td>$Nu = 0.0069Re^{0.9}Pr^{0.66}(\frac{\rho_w}{\rho_b})^{0.43}(1 + 2.4\frac{D}{x})$</td>
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<td>Yaskin (1977)</td>
<td>$\frac{Nu}{Nu_0} = (1 - 0.2\frac{Nu}{Nu_0}\beta(T_w - T_b))^2$</td>
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<td>Griem (1996)</td>
<td>$Nu_b = 0.0169Re_b^{0.8356}Pr_b^{0.432}$</td>
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<tr>
<td>Bald (1973)</td>
<td>$Nu = 0.0259Re_D^{0.8}Pr_D^{0.4}(T_w - T_{\text{average}})^{-0.716}$</td>
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Comparison between Experiment and Nu

• Huge discrepancies in the pressurized fluid region
  – Small Re number, non developed flow and turbulence, small effect of natural convection

• Better results for the Bishop and Jackson-Fewster correlations in the $T_{\text{wall}}>T_c$ and supercritical region but still not satisfactory
  – $\text{Gr}/\text{Re}^2 > 1 \rightarrow \text{Natural convection effect}$
Conclusions and future

• Measurements in pressurized and supercritical helium in a small circulation loop

• Larger heat transfer coefficient in pressurized fluid region than in the supercritical region or $T_{\text{wall}} > T_c$

• Huge drop in heat transfer when $T_{\text{wall}} > T_c$ as expected

• Several heat transfer correlations tried
  – None are acceptable
  – Non developed flow and influence of the natural convection

• Next
  – Measurement (in progress) in full supercritical region with $T_{\text{condenser}} > T_c$
  – Computation of the temperature of the fluid in the entire loop with a forced flow model
  – Influence of the natural convection