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

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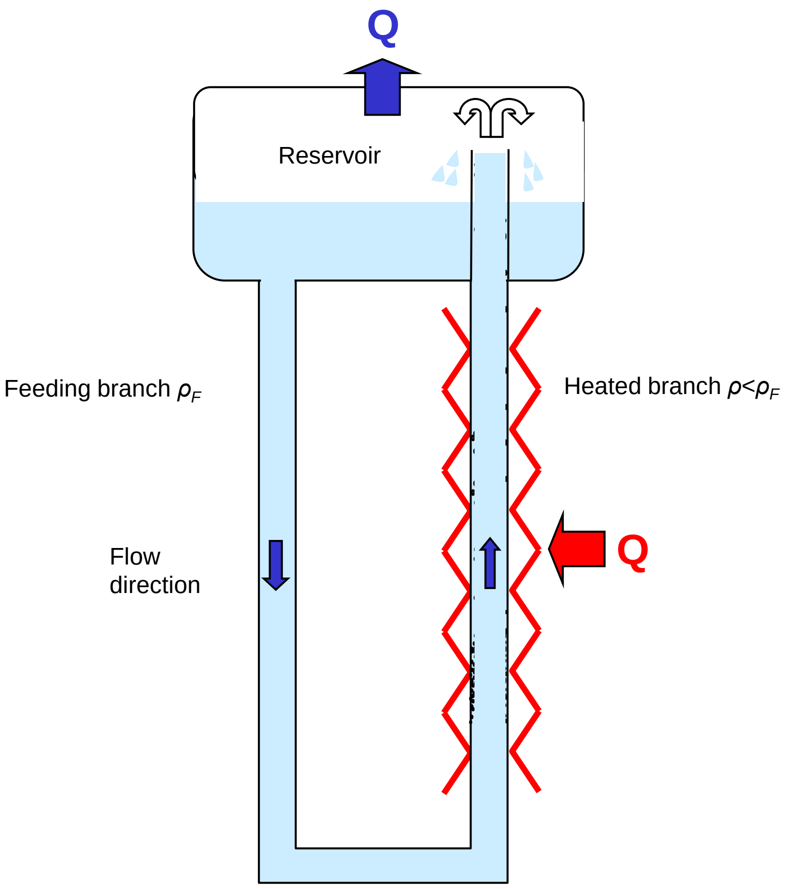
Introduction

- 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

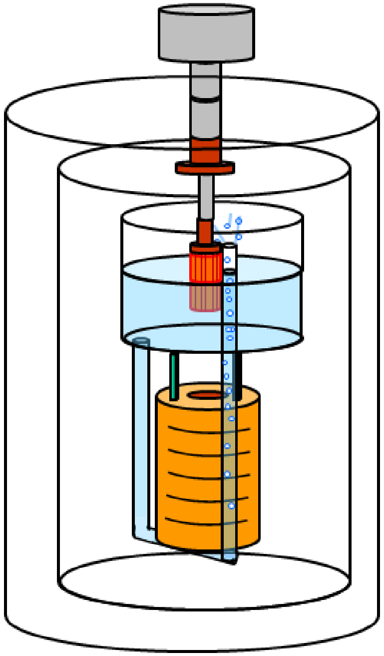
- Ranges of study
  - P=2.3 bar
  - Heat flux up to 1000 W/m^2
  - Mass flow rate from 0.1 to 0.3 g/s
  - Re from 10^3 to $3\ 10^4$



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

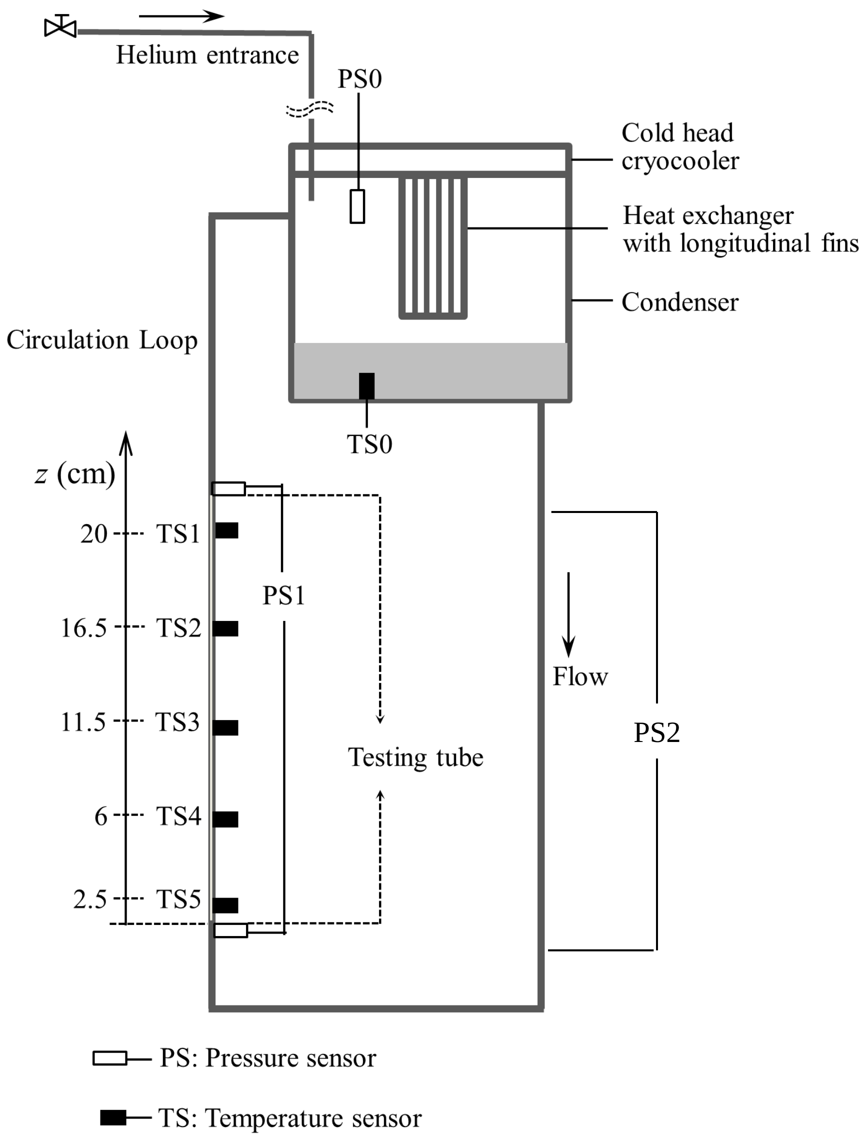


- 35 cm high loop
- Return loop higher than the liquid level

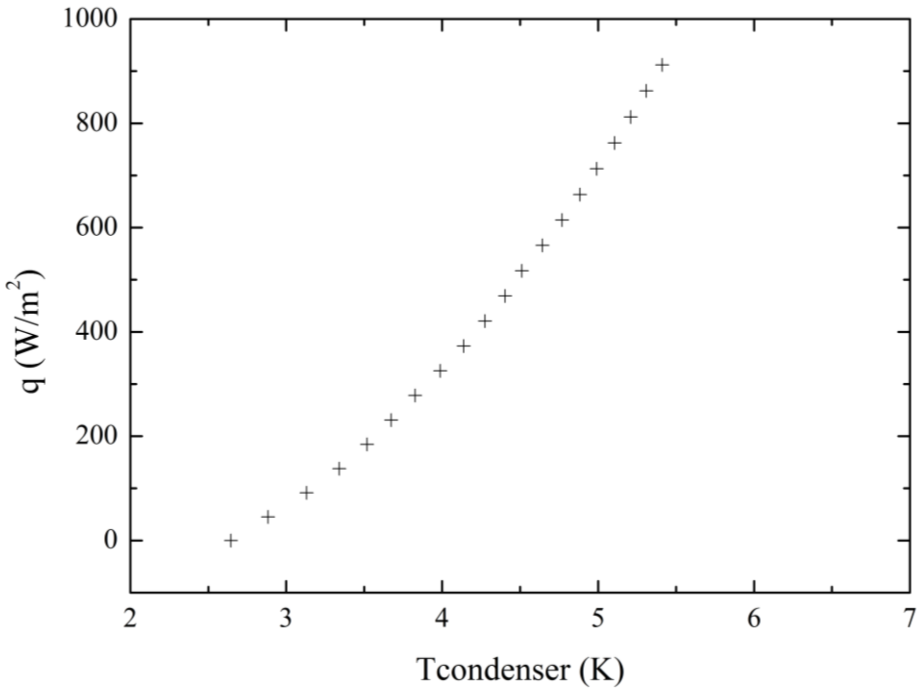
- Loop made of 4 mm inner diameter copper tube
- 23 cm heated length

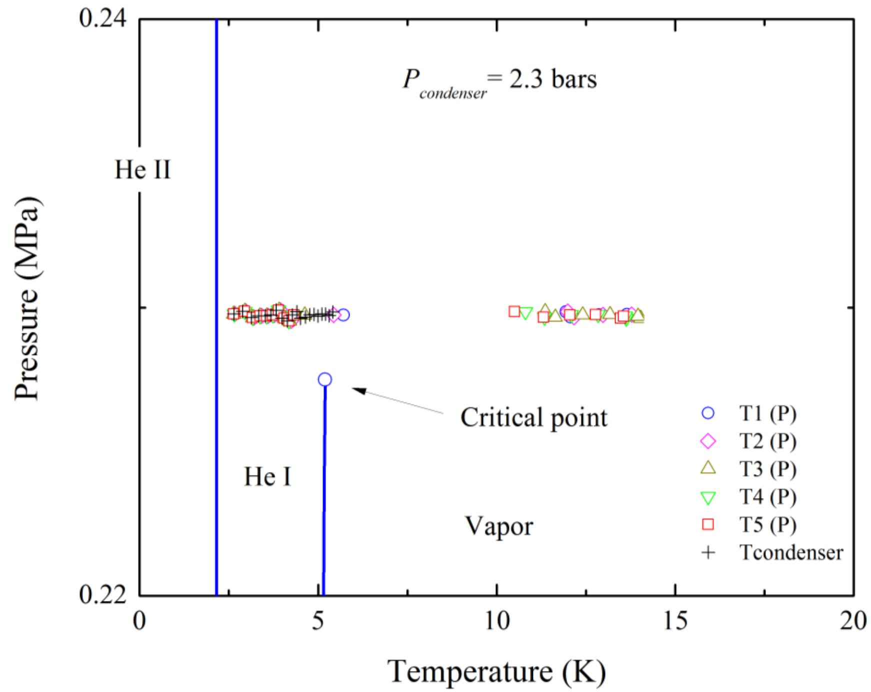
Instrumentation

- Condenser
  - 1 absolute pressure
  - 1 temperature sensor
- Loop
  - 1 ΔP (PS2)
  - 2 temperature sensors
- Testing tube
  - 1 ΔP (PS1)
  - 5 cernox sensors
- Pressure constant within 5 mbar

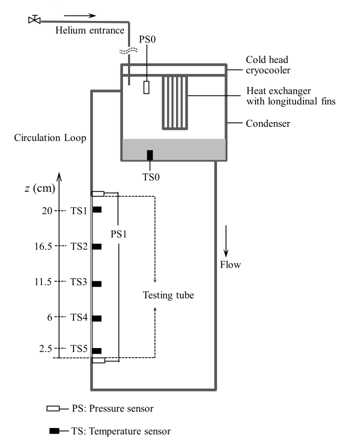


Temperatures evolution

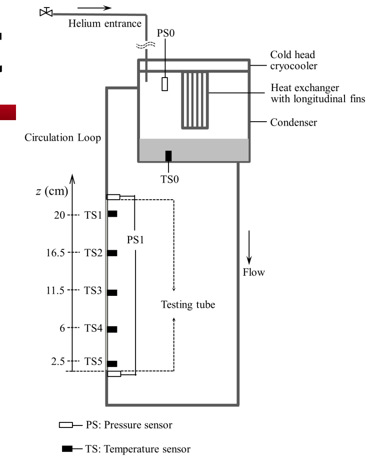


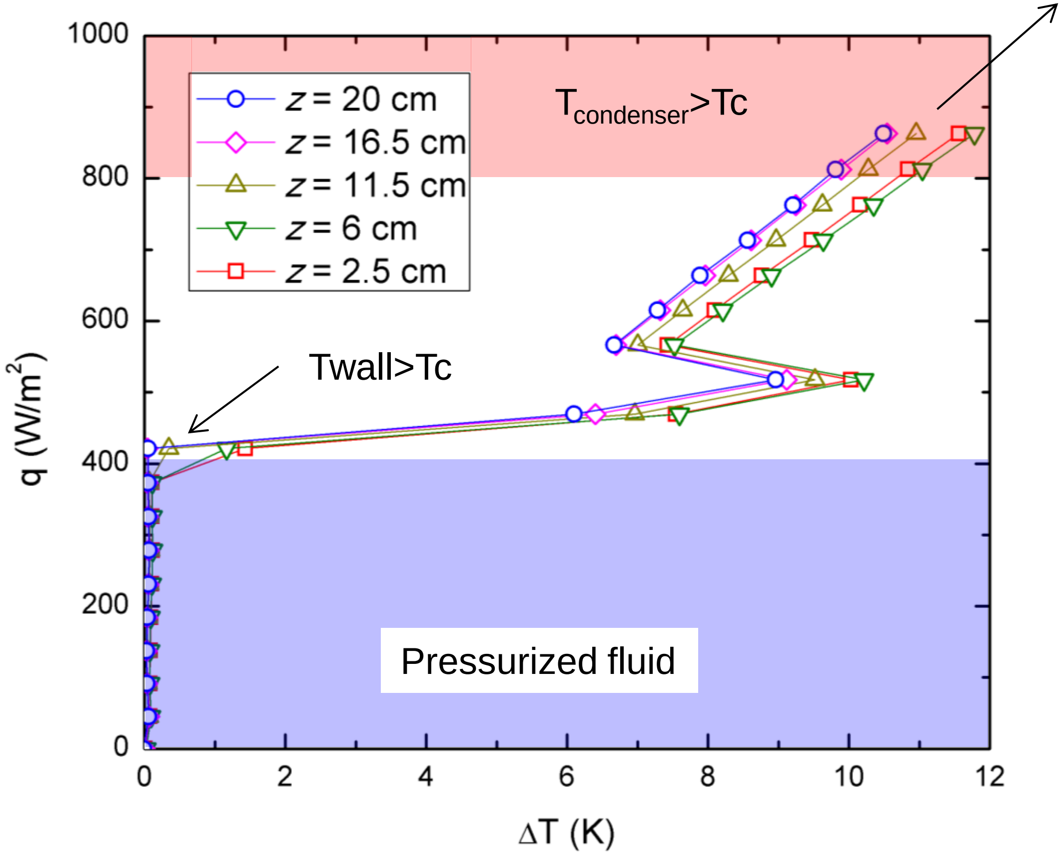


P_c=2.27 bar
T_c=5.195 K



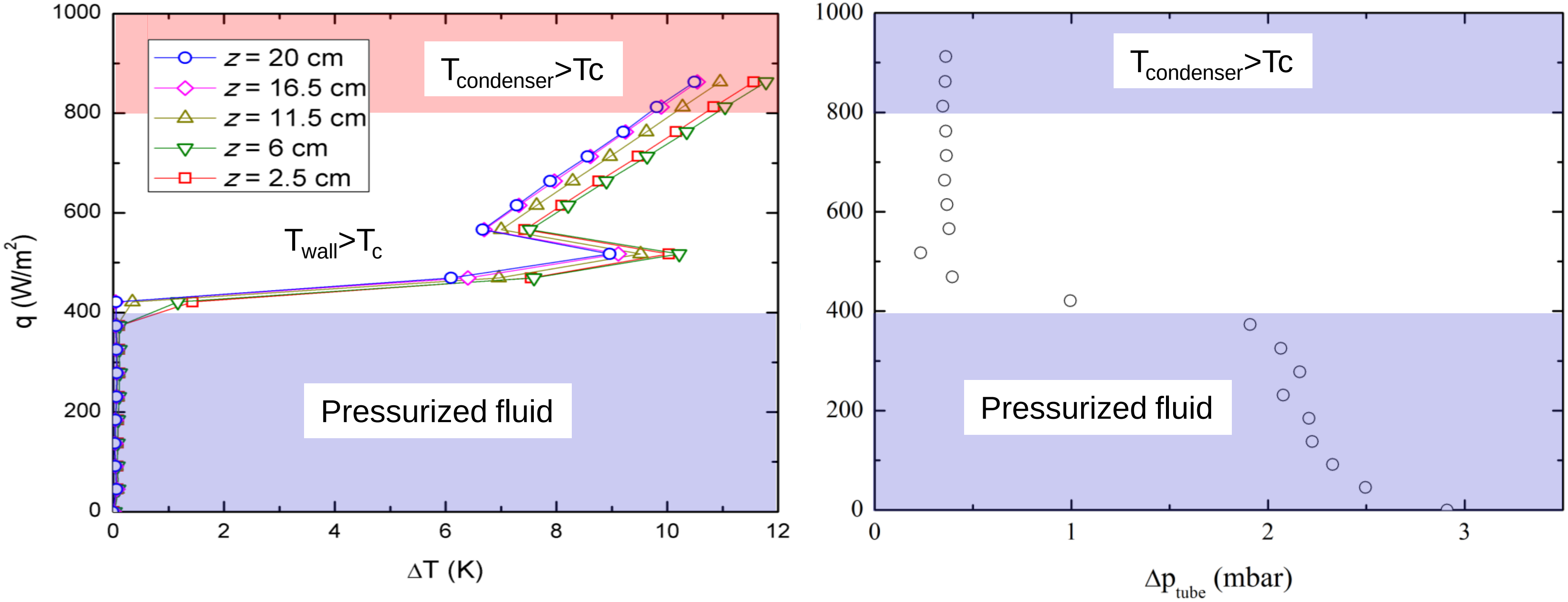
Wall temperature difference with height





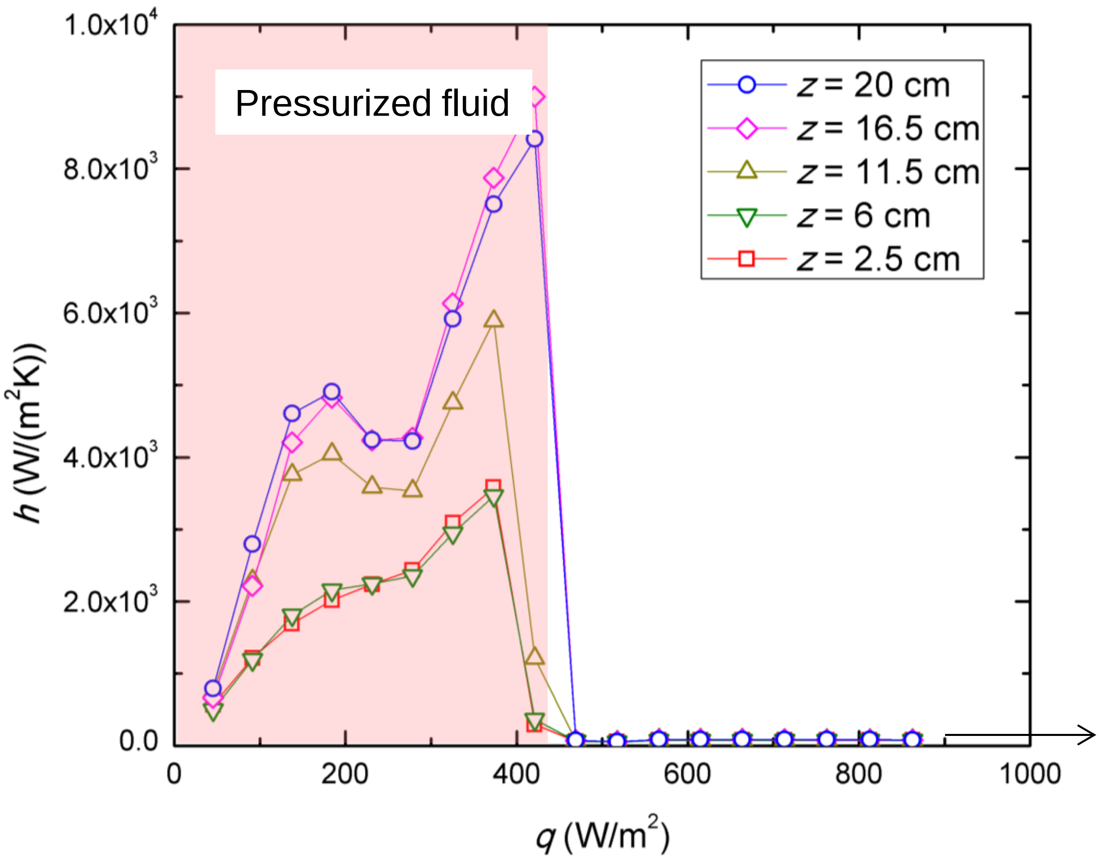
- Evolution almost identical with height
- Better heat transfer at higher location
- T_{walls} go over T_c around 400 W/m^2 while $T_{condenser}$ is still below T_c
- $T_{condenser}$>T_c above 800 W/m^2
- Above 800 W/m^2 the q-ΔT is monotonous and linear up to 1000 W/m^2

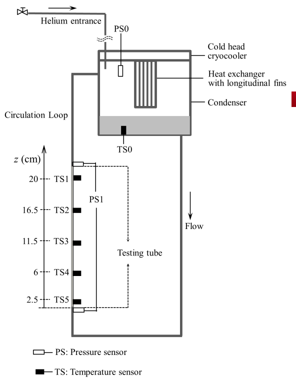
Pressure drop along the heated tube



- Δp_{tube} ↘ due to ↘ ρ in pressurized fluid region
- Δp_{tube} ↘ ↘ due to ↘ ↘ ρ when $T_{wall} > T_c \rightarrow T_{fluid} > T_c$ in the heated section?
- Δp in descending tube ↘ ↘ due to ↘ ↘ ρ when $T_{wall} > T_c \rightarrow T_{fluid} > T_c$ too?

Heat transfer coefficient





- $h = q/(T-T_{condenser})$
  - Acceptable in the pressurized fluid region and when $T_{condenser} > T_c$
  - Questionable when $T_{wall} > T_c$
- In pressurized fluid, heat transfer better with higher height
  - T_{fluid} ↗ due to heating
- When $T_{wall} > T_c$ heat transfer goes down to 100 W/m^2
- $q > 800\ W/m^2$, the heat transfer is not different than in the $T_{wall} > T_c$ region

Nu-correlations

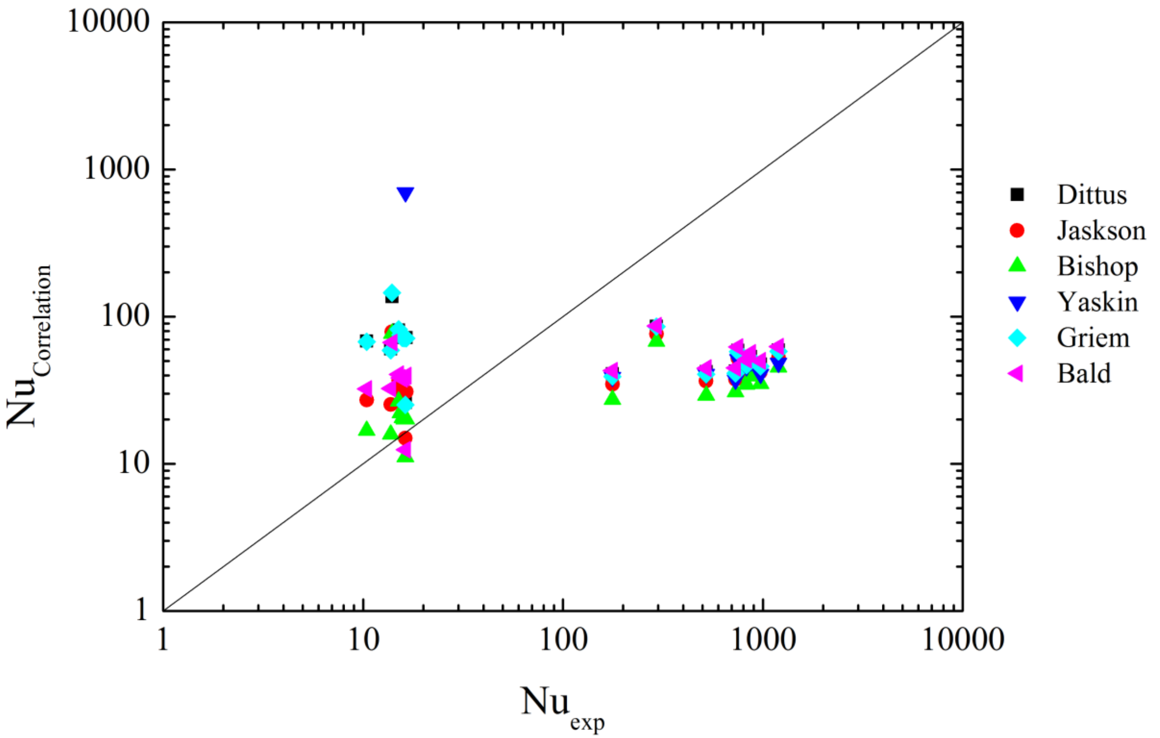
- Nu-correlation have been tried
  - Most of them developed for forced flow supercritical in large diameter in water and Co_2
  - Only the Bald correlation was developed for helium

Correlations used in calculating the heat transfer coefficient

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

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 $T_{wall}>T_c$ and supercritical region but still not satisfactory
  - $Gr/Re^2 > 1 \rightarrow$ 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 $T_{wall}>T_c$
- Huge drop in heat transfer when $T_{wall}>T_c$ 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 $T_{condenser}>T_c$
  - Computation of the temperature of the fluid in the entire loop with a forced flow model
  - Influence of the natural convection