Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)

Experimental investigation of nitrogen flow boiling heat transfer in a single mini-channel

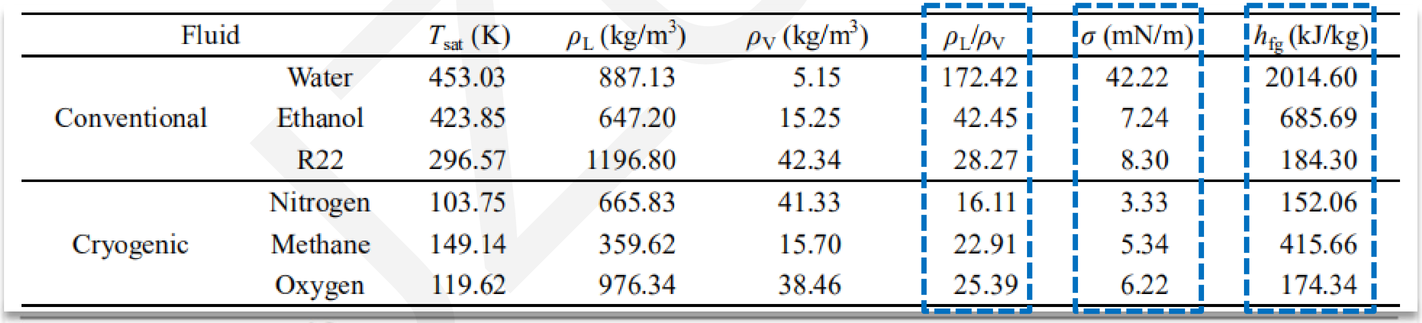
Key words: Mini-channel; Nitrogen; Flow boiling; Heat transfer; Regenerative cooling

Cite this as: Bei-chen Zhang, Qing-lian Li, Yuan Wang, Jian-qiang Zhang, Jie Song, Feng-chen Zhuang, 2020. Experimental investigation of nitrogen flow boiling heat transfer in a single mini-channel. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(2):147-166. https://doi.org/10.1631/jzus.A1900468

Introduction

- The application of phase-change heat transfer of cryogenic propellant in mini-channels to regenerative cooling of a rocket engine has scarcely been studied.;
- Compared with conventional fluids, cryogenic fluids have some unique thermophysical properties, which would influence the flow boiling heat transfer process:
  - Because of the low liquid-gas density ratio of nitrogen, a homogeneous model could be used to predict the pressure drop of nitrogen two-phase flow;
  - For cryogenic fluids, the bubbles can be easily created and depart with smaller bubble size at lower surface tension;
  - For nitrogen and oxygen, the latent heat of evaporation is relatively low, so the vapour quality of flow boiling changes rapidly along the tube;

Table 1 Thermophysical property comparison of cryogenic and conventional fluids at p_{sat}=1000 kPa



Fluid		T_{sat} (K)	ρ_L (kg/m^3)	ρ_V (kg/m^3)	ρ_L/ρ_V	σ (mN/m)	h_{fg} (kJ/kg)
Conventional	Water	453.03	887.13	5.15	172.42	42.22	2014.60
	Ethanol	423.85	647.20	15.25	42.45	7.24	685.69
	R22	296.57	1196.80	42.34	28.27	8.30	184.30
Cryogenic	Nitrogen	103.75	665.83	41.33	16.11	3.33	152.06
	Methane	149.14	359.62	15.70	22.91	5.34	415.66
	Oxygen	119.62	976.34	38.46	25.39	6.22	174.34

- As a safe alternative working fluid, liquid nitrogen has similar thermophysical properties to liquid methane and/or oxygen and was used to study the heat transfer process and characteristics of vertical mini-channel flow boiling under high pressure.

Introduction

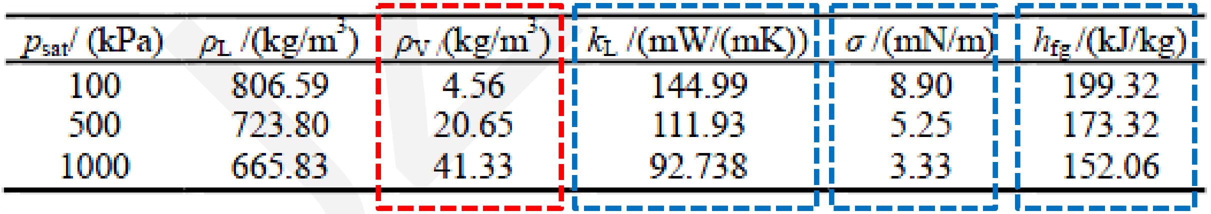
☐ For flow boiling of nitrogen in mini/micro-channel, limited studies were carried out based on a survey on the open literature, among which the tested inlet pressures were at a relative low level;

☐ Considering the practical regenerative cooling background, it is necessary to explore the nitrogen flow boiling characteristics under high pressure, the study of which, according to the existing literature, has been very limited;

☐ The differences brought by the variation of pressure conditions should be highlighted.

- When the saturation pressure increases, the surface tension and the latent heat of evaporation decrease, which results in the intensification of the nucleate boiling heat transfer;
- When the saturation pressure increases,the density of the vapour increases while the liquid film conductivity decreases with increasing saturation pressure, which weaken the convective boiling contribution.

Table 2 Nitrogen thermo-physical property at p_{sat}=100, 500, and 1000 kPa

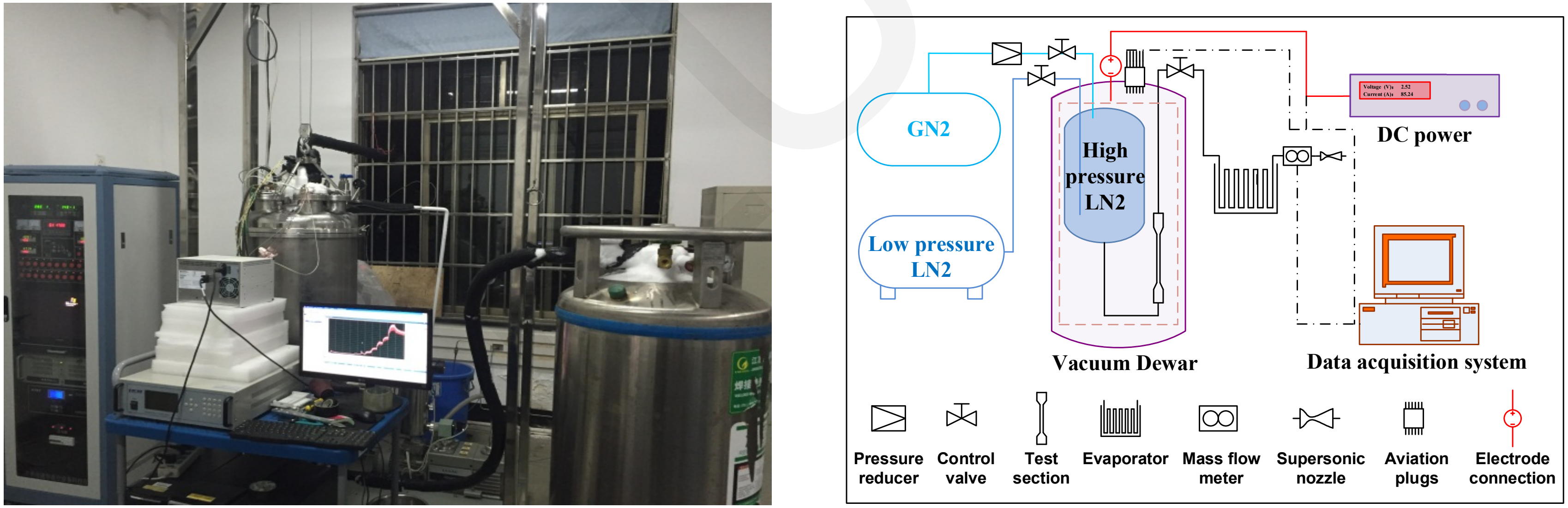


p_{sat}/ (kPa)	ρ_L /(kg/m^3)	ρ_V /(kg/m^3)	k_L /(mW/(mK))	σ /(mN/m)	h_{fg} /(kJ/kg)
100	806.59	4.56	144.99	8.90	199.32
500	723.80	20.65	111.93	5.25	173.32
1000	665.83	41.33	92.738	3.33	152.06

p The present study conducted experiments of nitrogen flow boiling in a vertical mini-channel at high subcritical pressure (630–1080 kPa) in order to determine the heat transfer mechanism of liquid nitrogen under high pressure and verify the experimental correlation.

Experimental system and test section

- An integrated cryogenic experimental system includes the gas nitrogen source (GN_2), the self-pressurization nitrogen storage tank (low pressure LN_2), the vacuum Dewar, the high pressure nitrogen storage tank (high pressure LN_2), the test section, the evaporator, the sonic nozzle, the direct current (DC) power, and the data acquisition system;
- The vacuum Dewar is evacuated to 1×10^{-3} Pa by the two-stage-vacuum-pump and precooled to ~77 K by nitrogen forced convection;
- The mass flux and inlet pressure of the test section are controlled by adjusting the GN_2 pressure reducer, the diameter of the venturi tube, and the diameter of the supersonic nozzle.



(a) (b)

The picture (a) and the schematic drawing (b) of the cryogenic experimental system

Flow boiling experimental results

☐ The heat flux has a dramatic effect on the heat transfer coefficient. Three heat transfer trends were identified with increasing heat flux:

- At low heat flux, the heat transfer coefficient first increases and then decreases with the vapour quality;
- At intermediate heat flux, the heat transfer coefficient presents an inverted “U” shape;
- At high heat flux, the double valley shape was observed and the reason for this is that it corresponds to the partial dry-out in the intermittent flow and the annular flow.

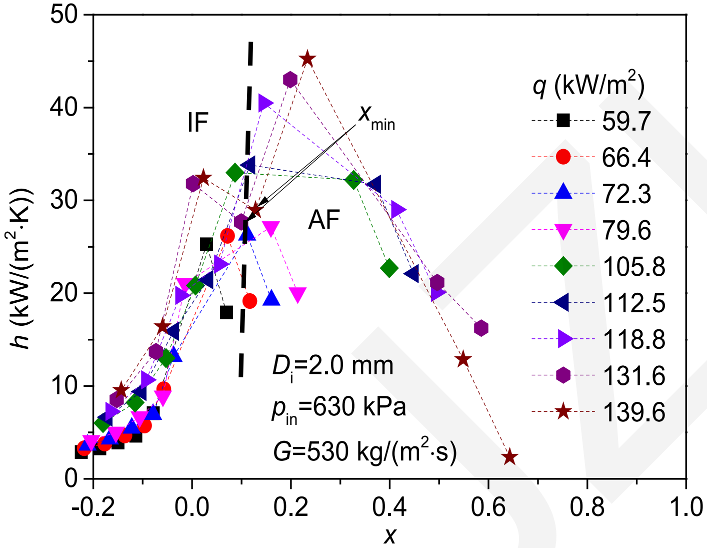


Fig. 1 Influence of heat flux on the heat transfer coefficient. D_i=2.0 mm, p_{in}=630 kPa, G=530 kg/(m²·s)

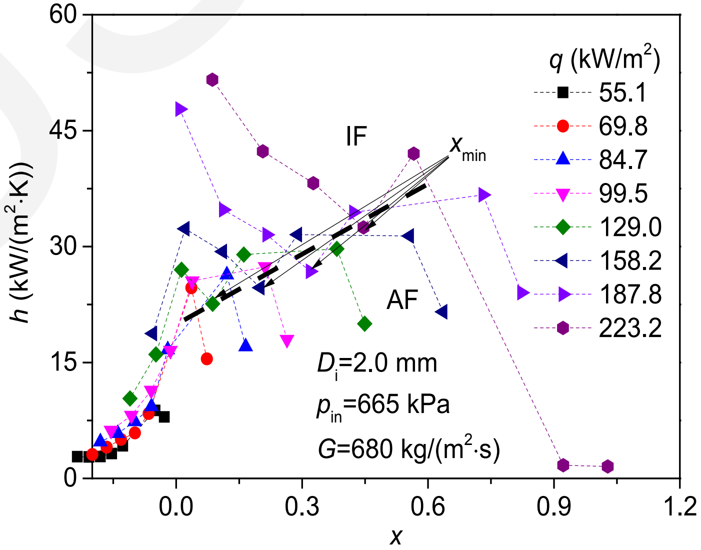


Fig. 2 Influence of heat flux on the heat transfer coefficient. D_i=2.0 mm, p_{in}=665 kPa, G=680 kg/(m²·s)

Flow boiling experimental results

☐ Within the limited mass flux conditions, the increase of mass flux suppresses the nucleate boiling contribution and decreases the heat transfer coefficient in annular flow：

- At low vapour quality (during intermittent flow), the increase of the mass flux suppresses the nucleate boiling;
- At high vapour quality (during annular flow), within the limited test conditions, the increase of mass flux increases the annular film thickness and decreases the heat transfer coefficient before dry-out occurs.

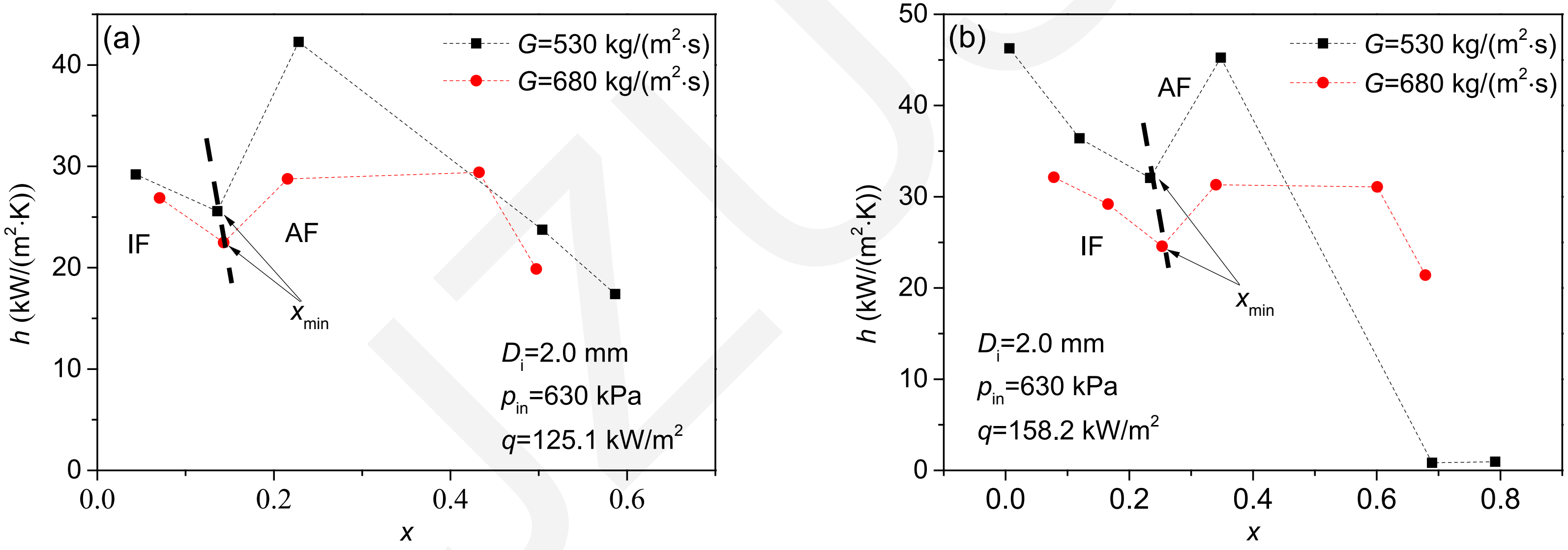


Fig. 3 Influence of mass flux on the heat transfer coefficient:
(a) q=125.1 kW/m^2; (b) q=158.2 kW/m^2. D_i=2.0 mm, p_{in}=630 kPa

Flow boiling experimental results

☐ The increasing inlet pressure increases the heat transfer coefficient over a wide range of vapour quality until the inception of partial dry-out.

- ➢ For higher inlet pressures, the lower surface tension and lower latent heat of evaporation enhance the nucleate boiling;
- ➢ The increase of inlet pressure leads to the earlier occurrence of the partial dry-out, with the reason for this related to the unsteady liquid film with a lower surface tension under high inlet pressure.

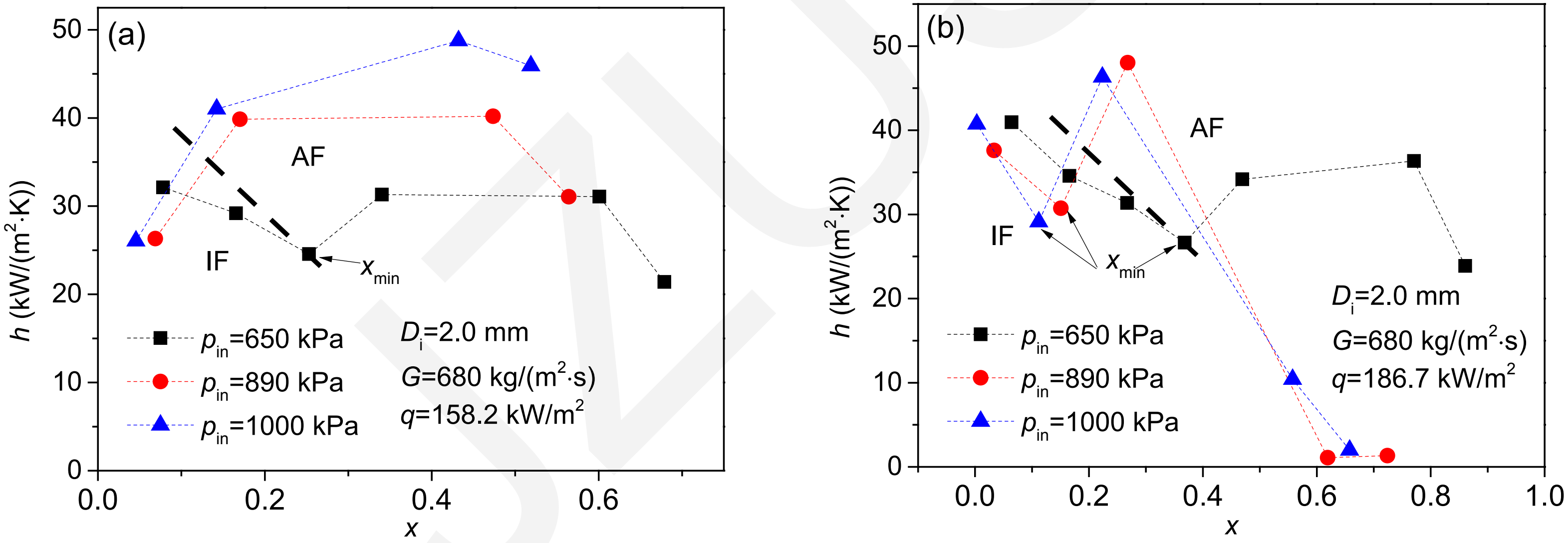


Fig. 4 Influence of inlet pressure on the heat transfer coefficient:
(a) q=158.2 kW/m^2; (b) q=186.7 kW/m^2. D_i= 2.0 mm, G=680 kg/(m^2·s)

Flow boiling experimental results

☐ It was found that the Klimenko and Tran correlations have better prediction accuracies among the six selected correlations.

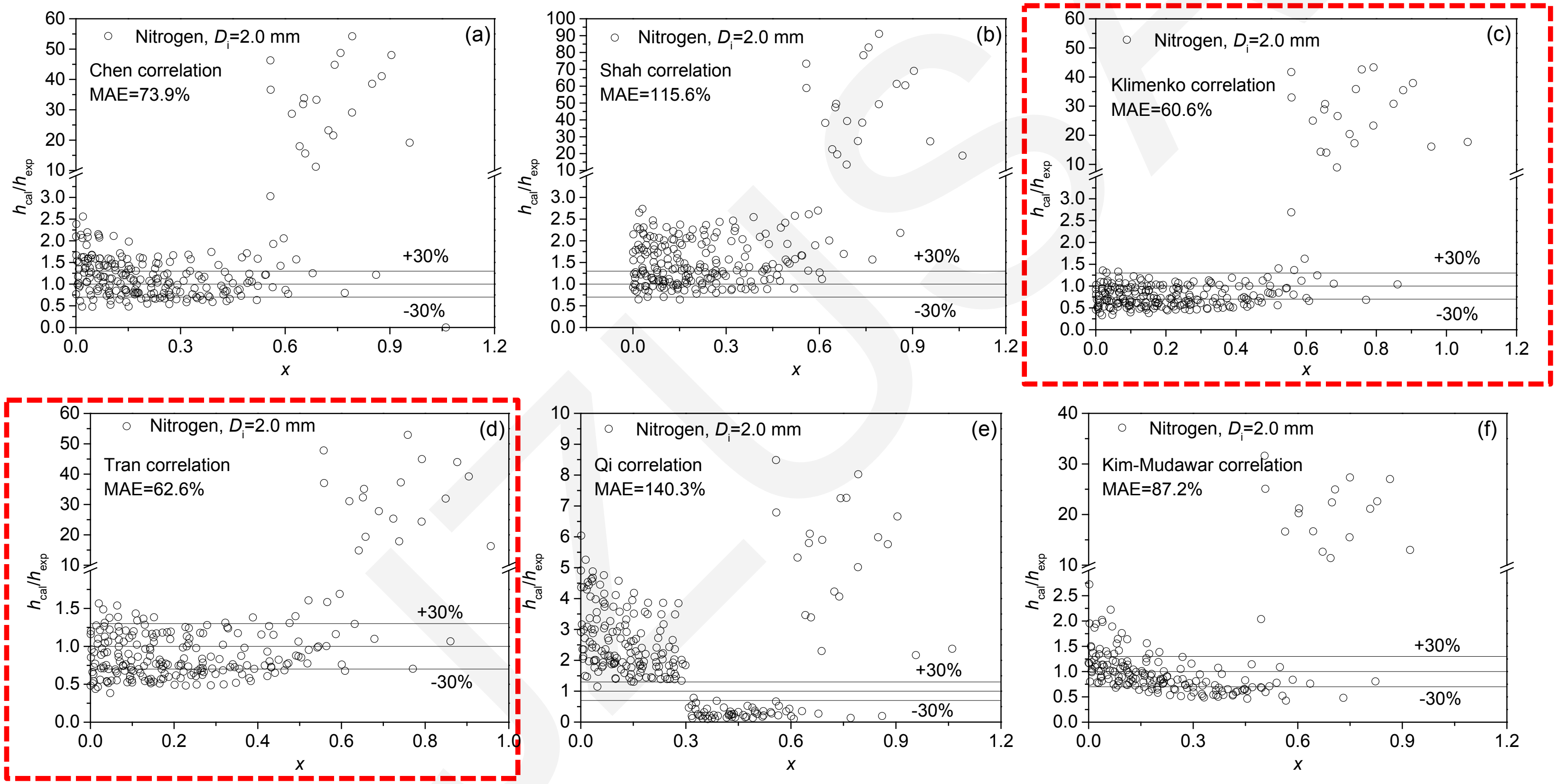
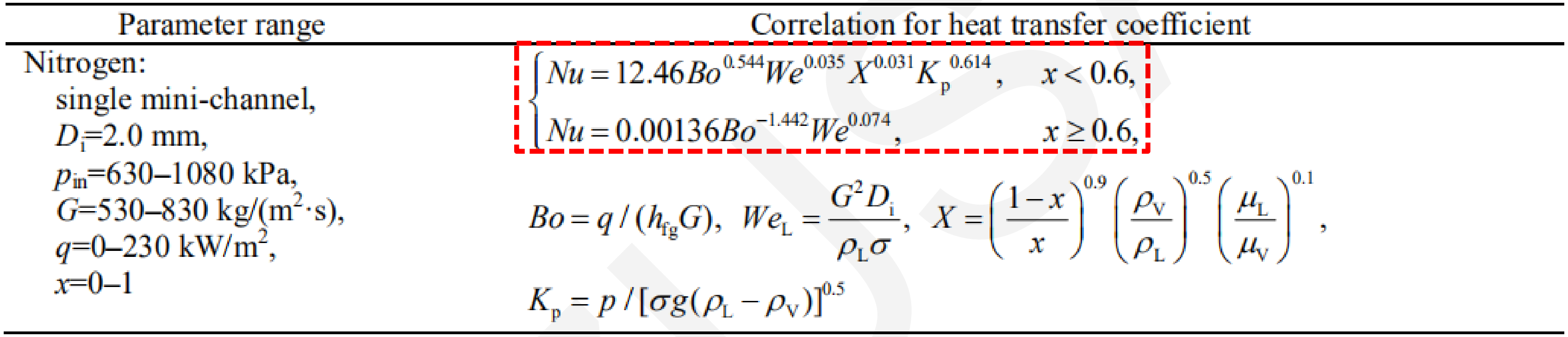


Fig. 5 Ratios of the calculated to experimental heat transfer coefficient versus vapour quality
(a) Chen; (b) Shah; (c) Klimenko; (d) Tran; (e) Qi; (f) Kim-Mudawar

Flow boiling experimental results

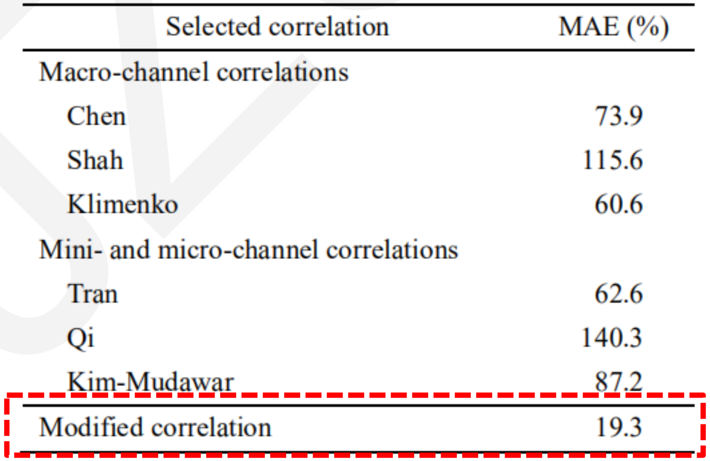
☐ A modified correlation (MAE=19.3%) was proposed on the basis of the Tran correlation considering both nucleate boiling and the partial dry-out heat transfer mechanism.

Table 3 Modified correlation for nitrogen flow boiling heat transfer



Parameter range	Correlation for heat transfer coefficient
Nitrogen: single mini-channel, D_i=2.0 mm, p_{in}=630–1080 kPa, G=530–830 kg/(m^2·s), q=0–230 kW/m^2, x=0–1	$\begin{cases} Nu=12.46Bo^{0.544}We^{0.035}X^{0.031}K_p^{0.614}, & x<0.6, \\ Nu=0.00136Bo^{-1.442}We^{0.074}, & x\ge 0.6, \end{cases}$ $Bo=q/(h_{fg}G),\ We_L=\frac{G^2D_i}{\rho_L\sigma},\ X=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_V}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_V}\right)^{0.1},$ $K_p=p/[\sigma g(\rho_L-\rho_V)]^{0.5}$

Table 4 Summary of MAEs of selected correlations and the modified correlation



Selected correlation	MAE (%)
Macro-channel correlations	
Chen	73.9
Shah	115.6
Klimenko	60.6
Mini- and micro-channel correlations	
Tran	62.6
Qi	140.3
Kim-Mudawar	87.2
Modified correlation	19.3

Conclusions

- The flow boiling heat transfer of nitrogen at high subcritical pressure in a single vertical mini-channel was experimentally investigated. The mechanism of flow boiling heat transfer of liquid nitrogen under high subcritical pressure in mini-channel is revealed, and the modified correaltion of flow boiling heat transfer under high pressure is proposed, which provides a basis for the modeling of subcritical regenerative cooling heat trasnfer calculation.
    - The heat flux has a dramatic effect on the heat transfer coefficient. Three heat transfer trends were identified with increasing heat flux.
    - Within the limited mass flux conditions, the increase of mass flux suppresses the nucleate boiling contribution to the heat transfer during intermittent flow. In annular flow, the increase of mass flux increases the annular film thickness and decreases the heat transfer coefficient before dry-out occurs.
    - The increasing inlet pressure increases the heat transfer coefficient over a wide range of vapour quality until the inception of partial dry-out. The lower surface tension and lower latent heat of evaporation enhance the nucleate boiling for higher inlet pressures. The increase of inlet pressure leads to the earlier occurrence of the partial dry-out, with the reason for this related to the unsteady liquid film with a lower surface tension under high inlet pressure.
    - It was found that the Klimenko and Tran correlations have better prediction accuracies among the six selected correlations. A modified correlation (MAE=19.3%) was proposed on the basis of the Tran correlation considering both nucleate boiling and the partial dry-out heat transfer mechanism.