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浙江大学制冷与低温研究所
Institute of Refrigeration and Cryogenics, Zhejiang University

Improved Heat Transfer Prediction Methods in Channels for Natural Gas Liquefaction

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Motivation

Heat Exchanger in Natural Gas Liquefaction

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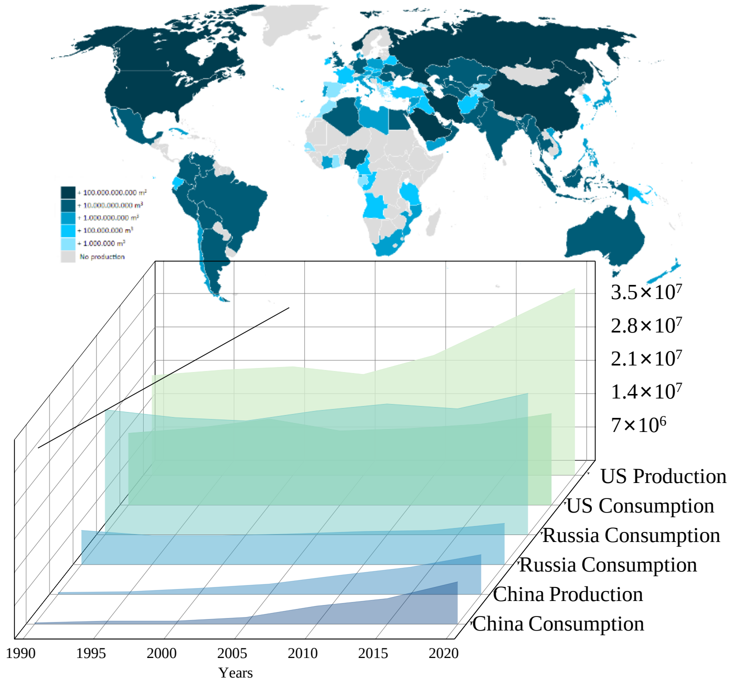
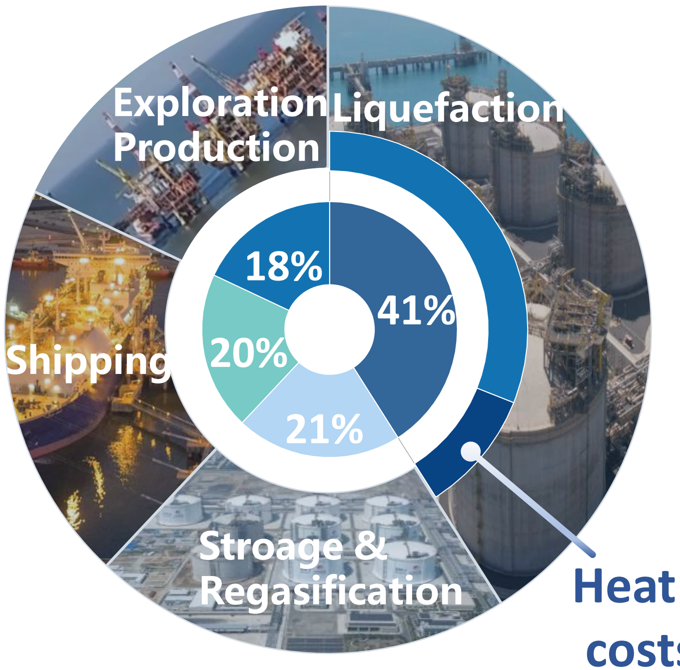
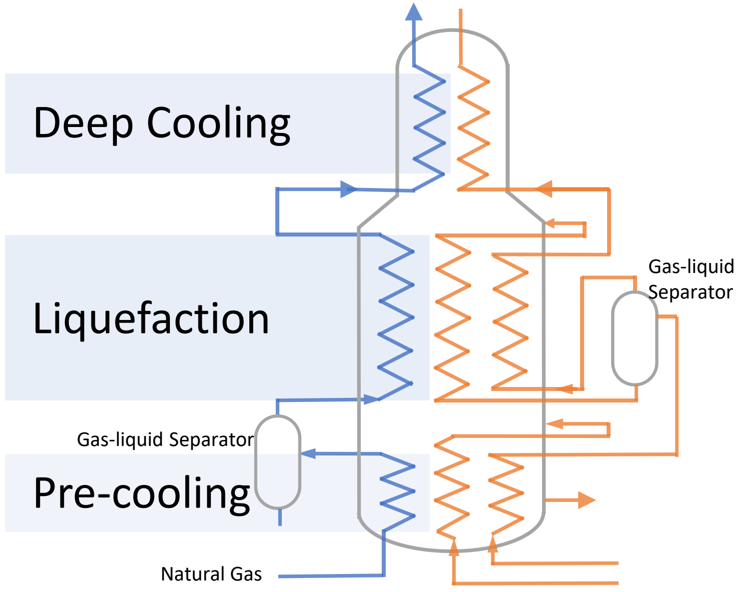
- **Liquified natural gas** is preferred method to achieve high energy density storage and long-distance transportation.
- **Heat exchangers(HEX)** as key equipment cost over 10% in natural gas liquefaction units and involve **multi-component condensation**. There is an urgent need for an **accurate heat transfer prediction method** in HEX design considering economic costs, efficiency and safety.



Natural gas production and consumption



Heat exchanger costs over 10%



Database Establishment

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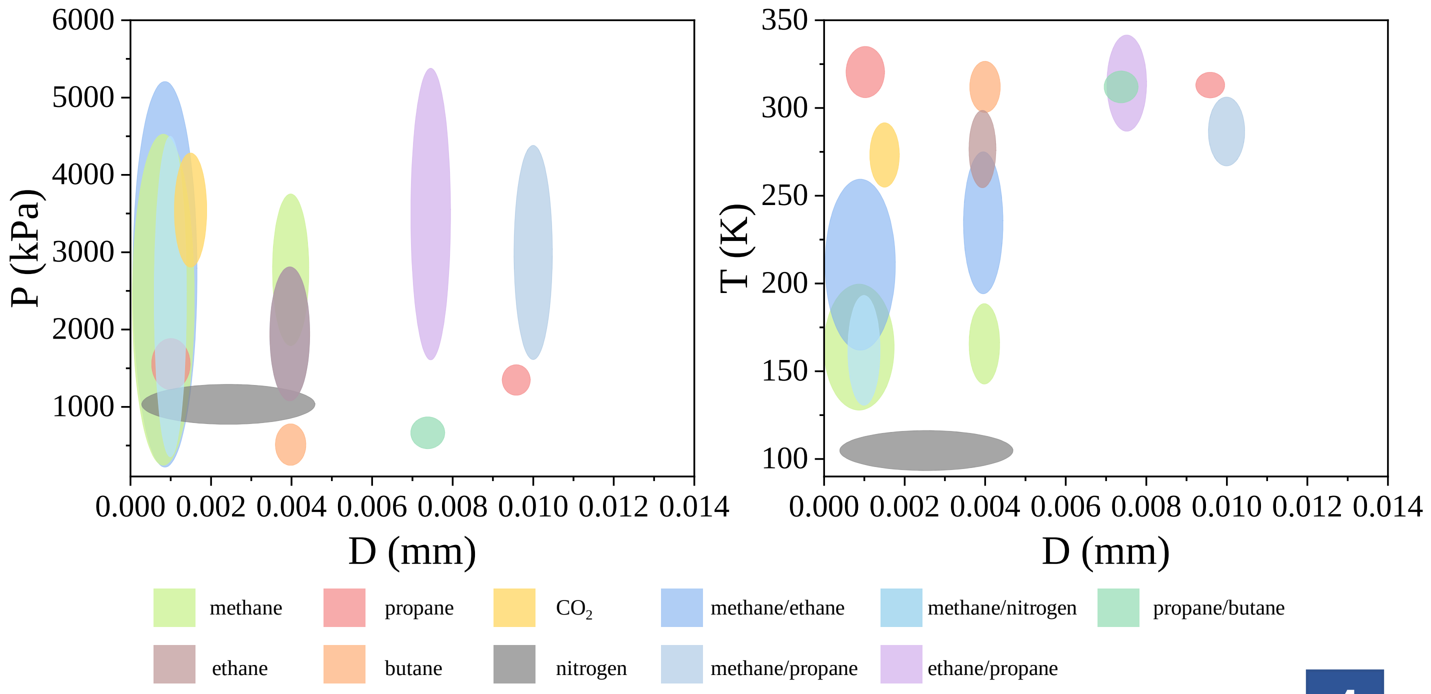
- Establish a condensation heat transfer database that includes **pure fluids** such as methane, ethane, propane, butane, carbon dioxide, and nitrogen, as well as **mixtures containing non-condensable gases** like methane/ethane, methane/nitrogen, ethane/propane, and propane/ butane.
- It comprises **1499 data points**, covering a temperature range of **105K to 330K.**

Authors	fluids	Test Channels	D_h (mm)	G (kg/m²s)
Agra et al	Butane	circular, single, copper, horizontal	4	76-118
Davide et al.	Propane	circular, single, copper, horizontal	0.96	100-800
Heo et al.	CO_2	rectangular, multi, horizontal	1.5	400-1000
Liu et al.	Propane	circular, rectangular, single, horizontal	9.52	200-500
Macdonald et al.	Ethane/propane	circular, single, copper, horizontal	7.5	150
Marak	Methane, methane/ethane, methane/nitrogen	circular, single, stainless, vertical	0.25 - 1	140-1372
Qi	Nitrogen	circular, single, copper, horizontal	1 - 4	8.2-262
Wen et al.	Propane/butane	circular, multi, copper, horizontal	7.38	205-320
Yu et al.	Methane/propane	circular, single, copper, helical	10	200-400
Zhuang et al.	Methane	circular, single, copper, horizontal	4	99-253
Zhuang et al.	Methane/ethane, ethane	circular, single, copper, horizontal	4	99-255



Conventional Correlations Comparison

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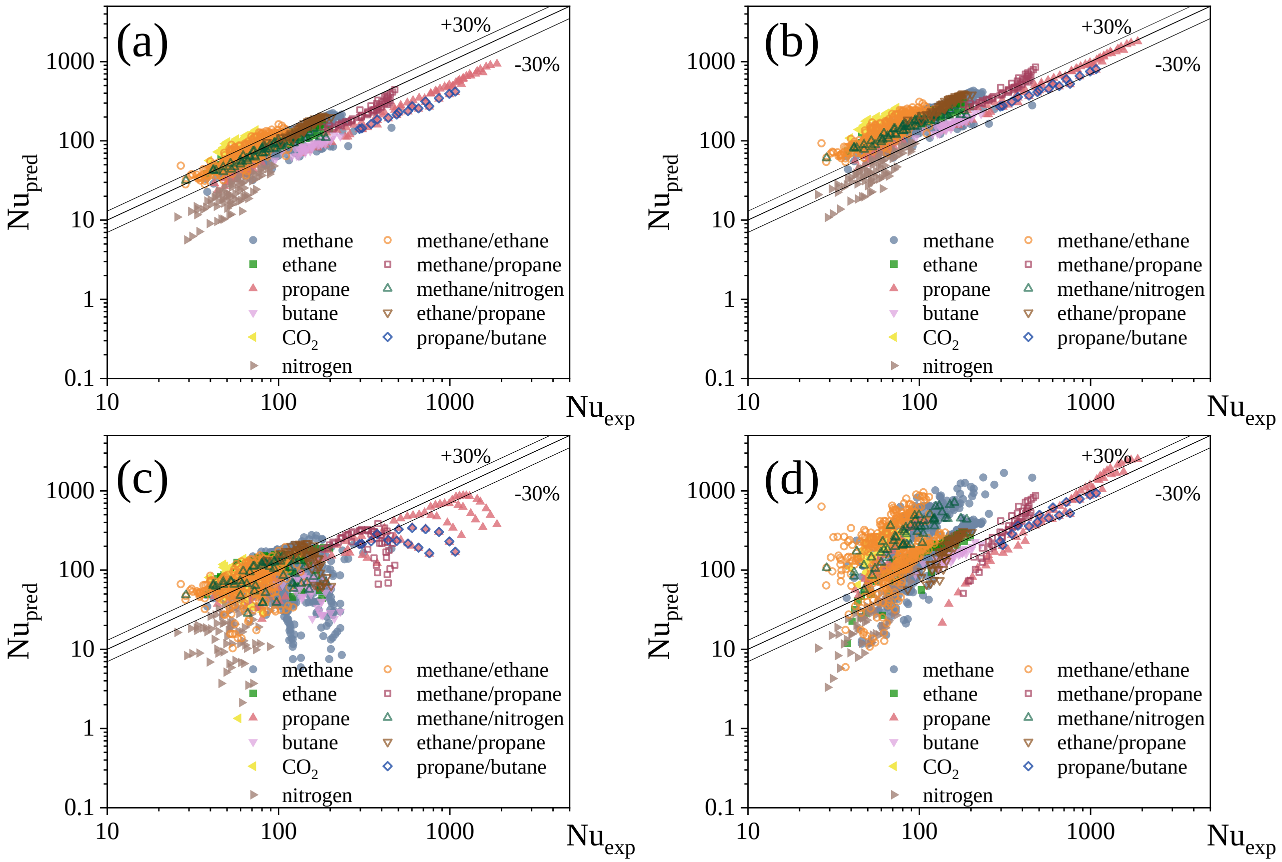
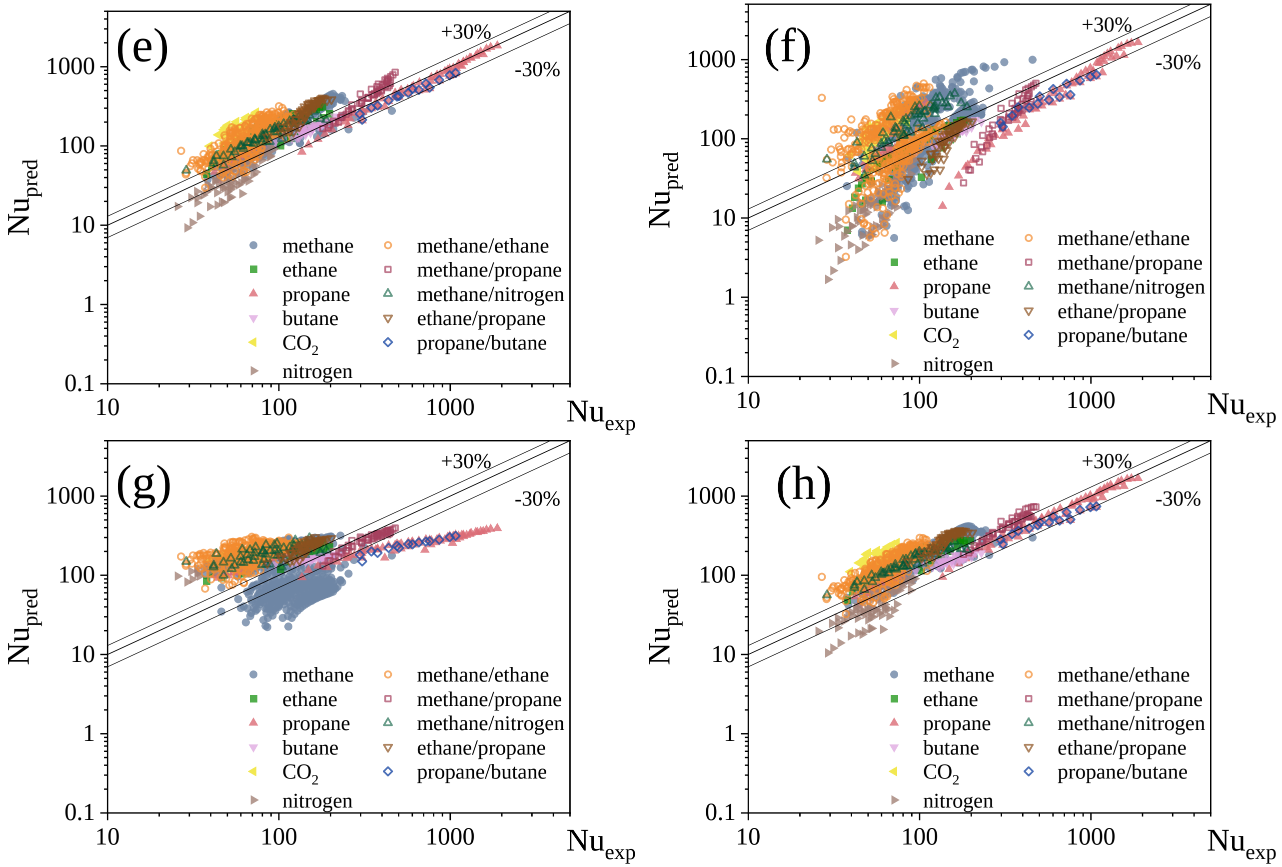
Authors	Correlation	MAD	MRD
(a) Akers and Rosson	$\mathrm{Nu} = 0.026\mathrm{Pr_f}^{1/3}\{G[(1-x)+x(\frac{\rho_f}{\rho_g})^{0.5}]\frac{D_h}{\mu_f}\}^{0.8}$	23.0%	-4.4 %
(b) Cavallini and Zecchin	$\mathrm{Nu} = 0.05\mathrm{Re_f}^{0.8}\mathrm{Pr_f}^{0.33}[1+\left(\frac{\rho_f}{\rho_g}\right)^{0.5}(\frac{x}{1-x})]^{0.8}$	87.2%	83.4%
(c) Shah	$\mathrm{Nu} = 0.023\mathrm{Re_{fo}}^{0.8}\mathrm{Pr_f}^{0.4}\left[(1-x)^{0.8}+\frac{3.8x^{0.76}(1-x)^{0.94}}{P_R^{0.38}}\right]$	43.1%	-5.1%
(d) Haraguchi	$\mathrm{Nu} = 0.0152(1+0.6\mathrm{Pr_f}^{0.8})\frac{\phi_g}{X_{tt}}\mathrm{Re_f}^{0.77}$	151.3%	136.8%



- The existing correlations show **low prediction accuracy** primarily evaluated by MAD and MRD.
  - **Akers and Rosson correlation** has a relatively high accuracy, with a **MAD of 23%**.
  - The Cavallini and Zecchin correlation shows a predictive distribution that aligns better with the experimental values.

Conventional Correlations Comparison

Authors	Correlation	MAD	MRD
(e) Dobson and Chato	$Nu = 0.023Re_f^{0.8}Pr_f^{0.4}\left(1+\frac{2.22}{X_{tt}^{0.89}}\right)$	73.4%	68.4%
(f) Bohdal	$Nu = 25.084Re_f^{0.258}Pr_f^{-0.495}P_R^{-0.288}\left(\frac{x}{1-x}\right)^{0.266}$	138.1%	86.4%
(g) Huang	$Nu = 0.0152\left(-0.33+0.83Pr_f^{0.8}\right)\frac{\phi_g}{X_{tt}}Re_f^{0.77}$	74.7%	34.2%
(h) Jung	$Nu = 0.023[1+\frac{2.22}{X_{tt}^{0.89}}]Re_f^{0.8}Pr_l^{0.4}$	82.2%	76.2%



- Predicted trends of Dobson-Chato and Jung correlations are consistent with experimental values but **overestimate the heat transfer coefficients of mixtures**.
- Perfect prediction line of Bohadl correlation is higher than experimental points while that of Huang correlation is lower.

Machine Learning Model Performance

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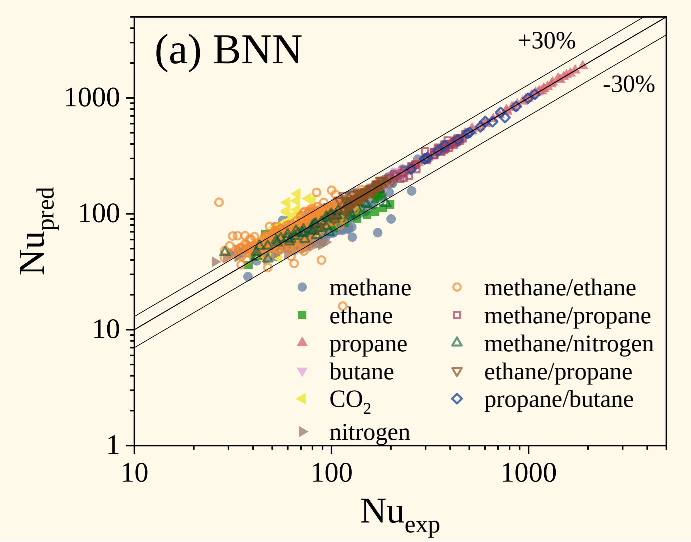
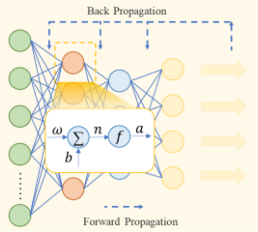
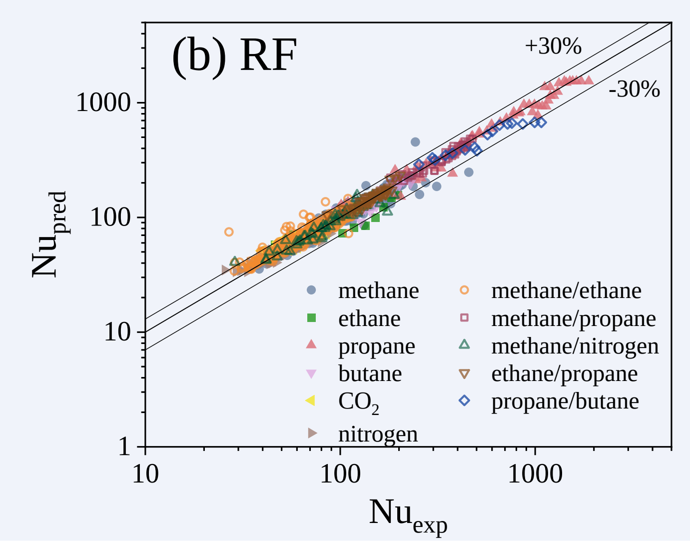
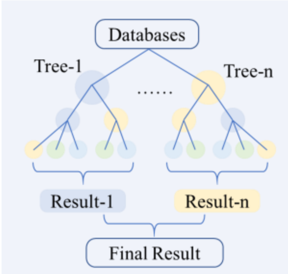
- Backpropagation neural network (BNN) and random forest (RF) show **accurate prediction performance** with multiple-input with MADs of **11.61%** and **4.43%**.
- **Re, Bd, Ga, and We$_g$** show strong linear correlations with the heat transfer values by calculating Pearson correlation coefficients (PCCs).

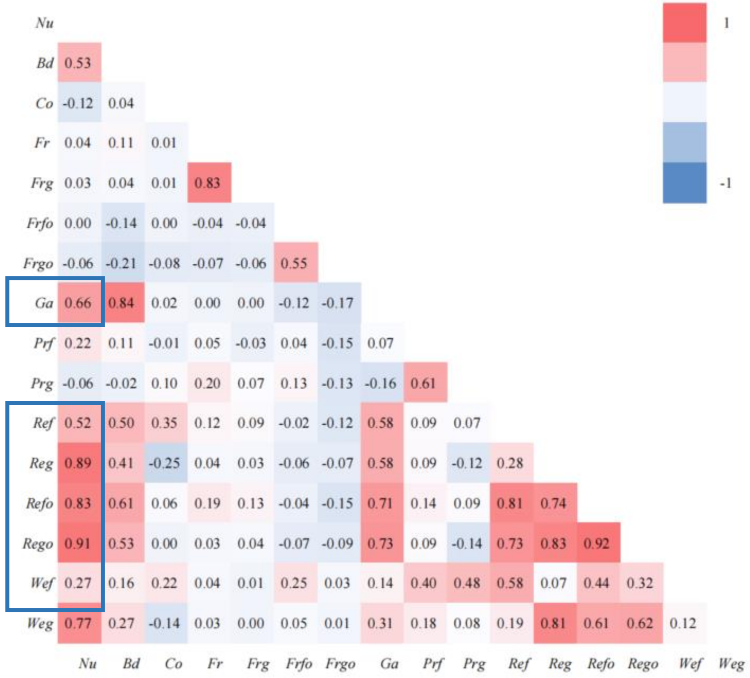
Input Parameters		Model	MAD	MRD	R^2
Few Input	Bd, Pr_f, Re_f, Fr_f	BNN	45.90%	23.86%	0.5709
		RF	29.63%	12.94%	0.6387
Multiple Input	Bd, Co, Fr_f, Fr_g, Fr_{fo}, Fr_{go}, Ga, Pr_f, Pr_g, Re_f, Re_g, Re_{fo}, Re_{go}, We_f, We_g	**BNN**	**11.61%**	**2.53%**	**0.9919**
		RF	**4.43%**	**1.11%**	**0.9947**





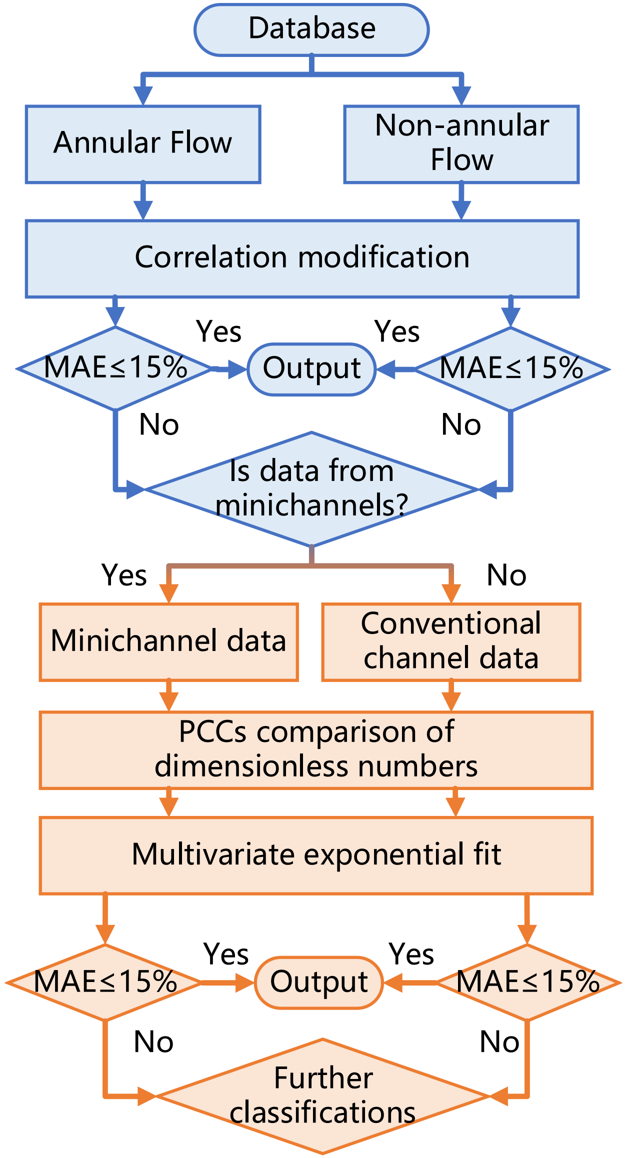


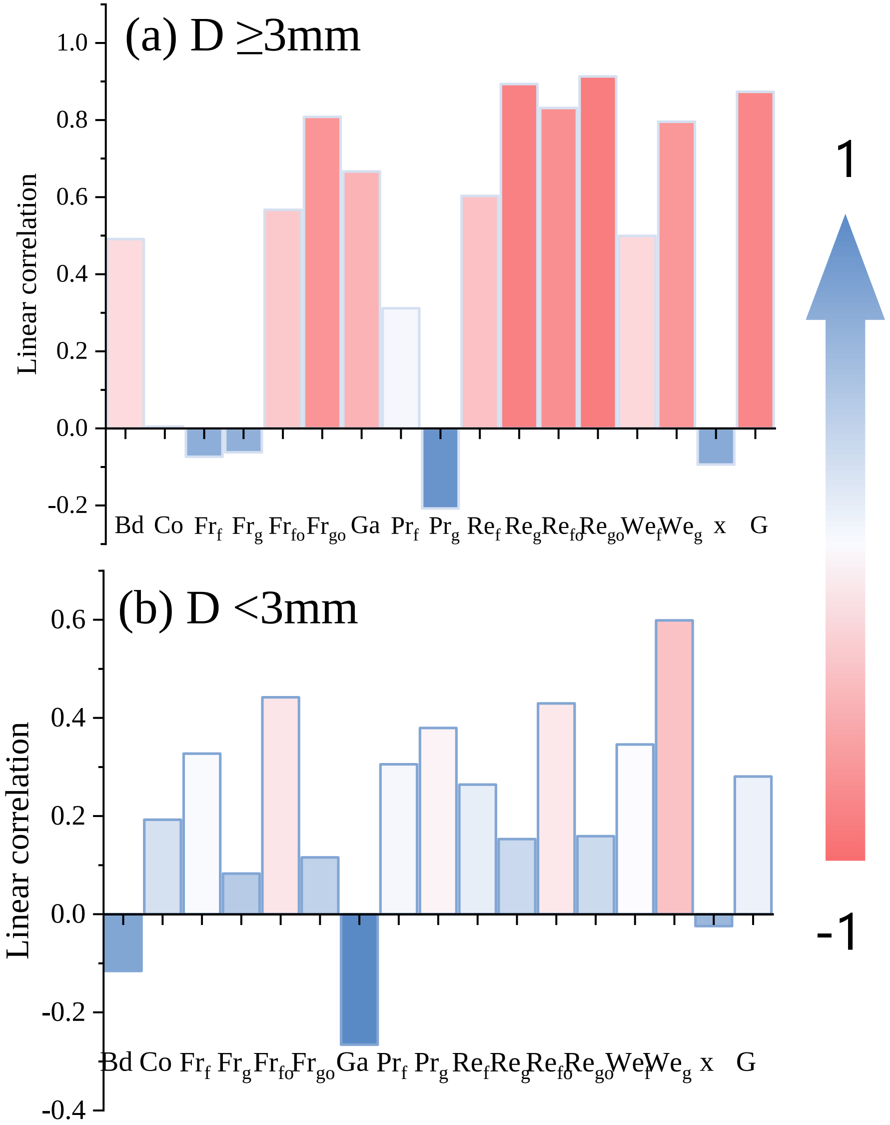




Heatmap of PCCs between input and output

Database Classification and Parameters Analysis



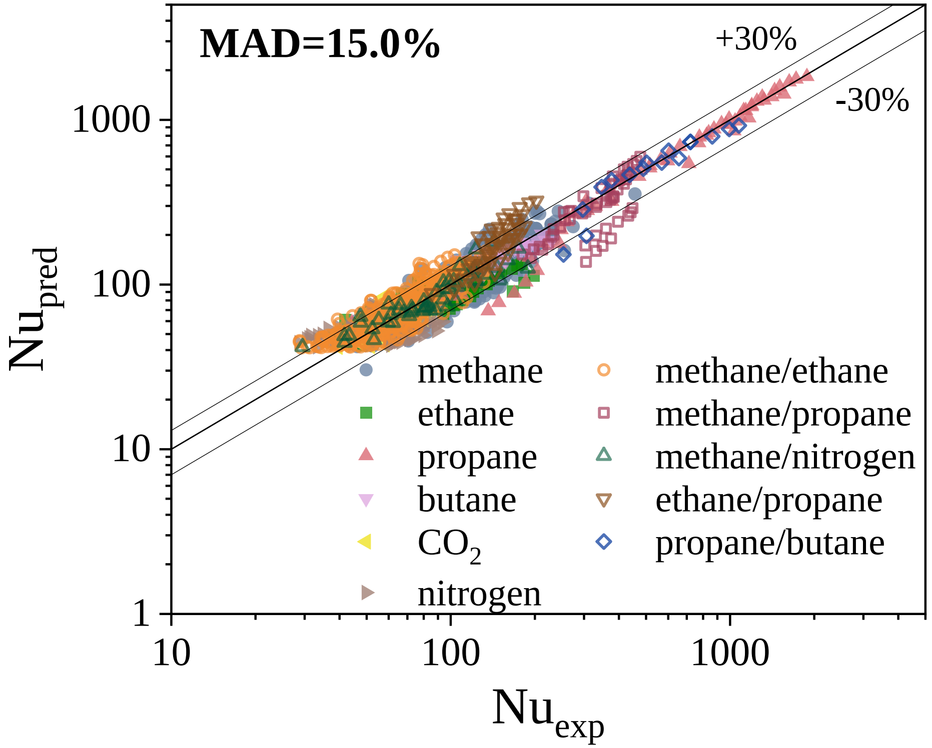


Linear correlations of factors

- Database is initially divided into **annular and non-annular** based on flow pattern division.
- Further classifications divide annular flow region into **conventional (D ≥ 3mm) and mini channels (D<3mm)**.
- Compute and select **strong linear correlation factors** as variable.

Modified Correlation Performance

Region		Correlation
Annular flow	$\mathrm{We}^* \geq 18.91\mathrm{X}^{0.33}$, $D \geq 3\mathrm{mm}$	$\mathrm{Nu} = 9.3371\mathrm{We}_{\mathrm{g}}^{0.8877}\mathrm{Fr}_{\mathrm{fo}}^{0.1733}\mathrm{Re}_{\mathrm{fo}}^{0.06716}\mathrm{Pr}_{\mathrm{g}}^{-0.3947}\mathrm{Fr}_{\mathrm{f}}^{0.3045}G^{-1.0845} + 53.64$
	$\mathrm{We}^* \geq 18.91\mathrm{X}^{0.33}$, $D < 3\mathrm{mm}$	$\mathrm{Nu} = 0.011\mathrm{Re}_{\mathrm{go}}^{1.9747}\mathrm{Re}_{\mathrm{g}}^{-0.517}G^{-1.5668}\mathrm{Re}_{\mathrm{fo}}^{-0.3113}\mathrm{Fr}_{\mathrm{f}}^{0.1037}\mathrm{We}_{\mathrm{g}}^{0.5} - 5.47$
Non-annular flow	$\mathrm{We}^* < 18.91\mathrm{X}^{0.33}$	$\mathrm{Nu} = 2.884 \times 10^{-7}\mathrm{Pr}_{\mathrm{f}}^{1.4948}G^{1.7399}[(1-x) + x(\frac{\rho_f}{\rho_g})^{0.5}]^{2.6752}(\frac{D}{\mu_f})^{1.813} + 41.18$



- Based on Akers and Rosson correlation and **high-PCC factors**, correct coefficients and indices.
- The MAD of correlations is raised to **15.0%** with a **over 34% improvement** over Akers and Rosson correlation in heat transfer prediction for condensation flow in-channel.

Conclusions

- A consolidated database of **1499 data points** is established, covering a **wide range of operating conditions**.
- **BNN** and **RF** models for heat transfer prediction are built and **show high accuracy** with MADs of 11.6% and 4.4% respectively.
- A **new correlation** has been proposed with **MAD of 15.0%**, achieving an effective **improvement of 34.8%** compared to the Akers and Rosson correlation.

THANK YOU