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Performance comparison of ANN-based model and Empirical Correlation for Void Fraction Prediction of Subcooled Boiling Flow in Vertical Upward Channel

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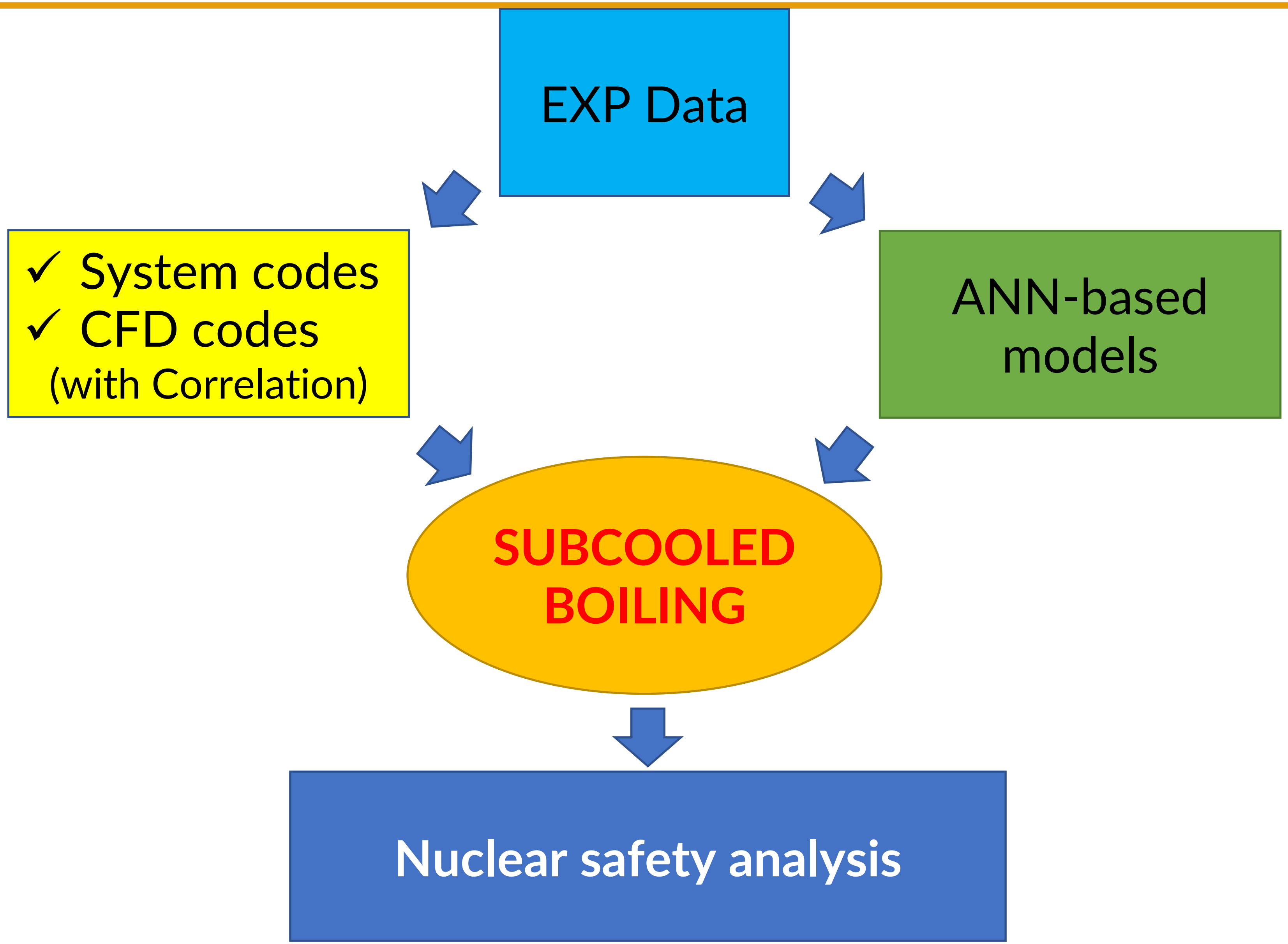
Contents

Introduction



Introduction

- **Subcooled boiling flow have become challenging issues in safety analysis of water-cooled nuclear power reactors.**
- **Thermal-hydraulic system codes and *Computational Fluid Dynamic* (CFD) solvers are promising tools. However, it requires a lot of correlations with uncertainties of model parameter and model forms.**
- **The *Artificial Neural Network* (ANN) is a powerful machine learning tool.**
- **This study investigates the performance and applicability of the ANN-based model and the empirical correlations for void fraction prediction.**

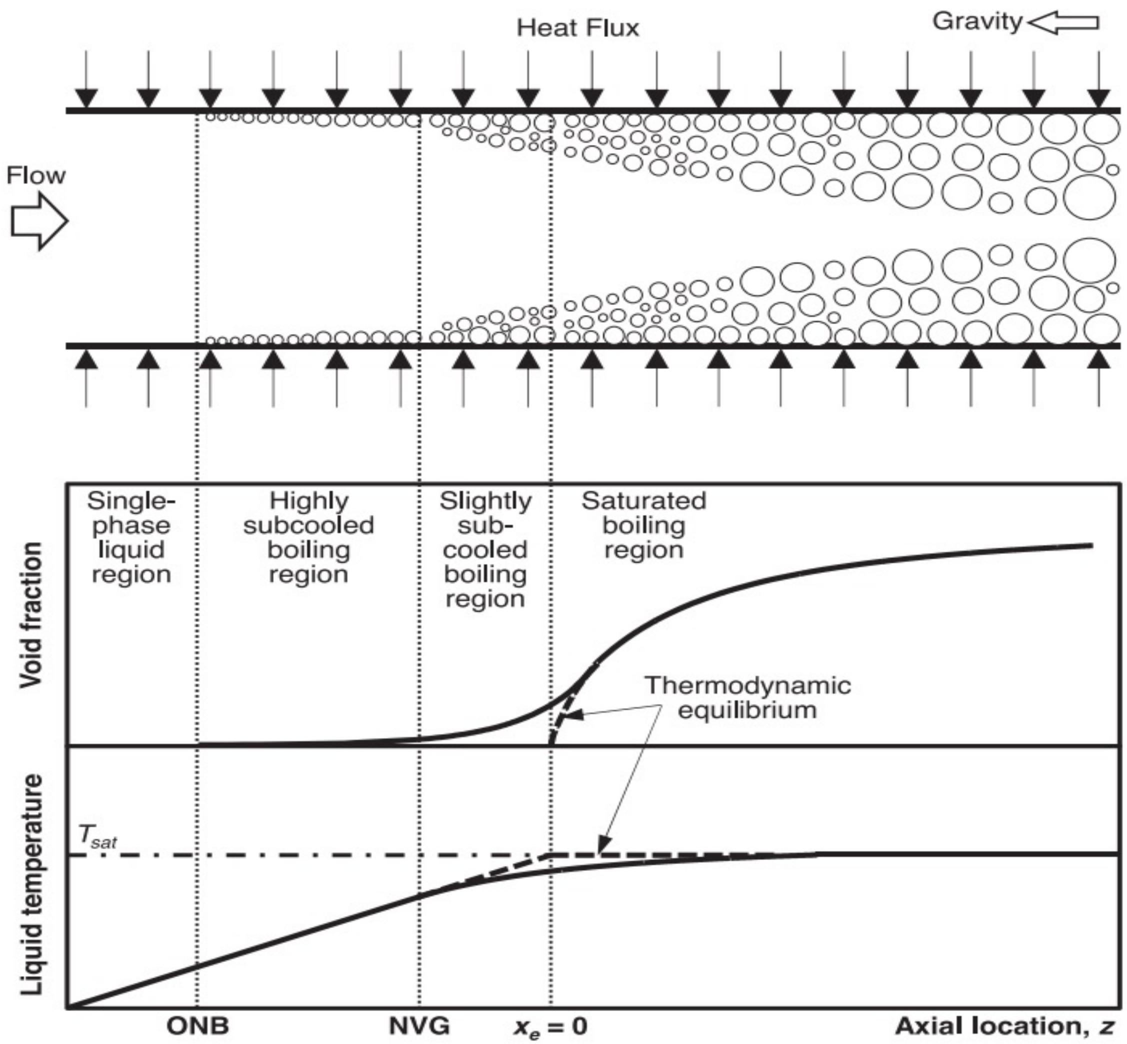
Introduction

- **Experiment data of void fraction axial-distribution performed by previous studies in vertical channels were used to assess the correctness accuracy of typical empirical correlations and the ANN-based model.**

Author(s)	D_h (mm)	L_{heated} (m)	q'' (kW/m^2)	G (kg/m^2-s)	$\Delta T_{sub,in}$ (K)	p_{in} (bar)
Ferrell (1964) [7]	11.84	2.44	230 – 682	134 – 1785	28 – 126	4 – 17
Rouhani (1966) [8]	13.00	1.09	600 – 1220	121 – 1445	6 – 150	9 – 50
Zeitoun (1994) [9]	12.70	0.30	207 – 705	139 – 412	12 – 31	1 – 1.7
Devkin (1998) [10]	10 – 12	0.4 – 1.5	132 – 2210	126 – 2123	4 – 171	11 – 150
Situ et al (2004) [11]	19.1	1.73	98 – 151	475 – 1181	8 – 13	1.26 – 1.36
Lee et al (2009) [12]	19.1	1.73	50 – 193	481 – 1939	8 – 15	1.32 – 1.48
SUBO (2010) [13,14]	25.52	3.1	364 – 568	1104 – 2129	17 – 30	1.8 – 2.0
Lee et al (2012) [15]	18.5	1.61	133 – 320	476 – 1061	12 – 21	1.15 – 1.6
Ozar et al (2013) [16]	19.1	2.8	109 – 241	445 – 1844	10 – 28	2.2 – 9.5
Brooks et al (2014) [17]	19.1	2.85	241 – 264	933 – 957	13 – 15	3.3 – 5.0
Overall	**11.84 – 25.52**	**0.3 – 3.1**	**50 – 2210**	**121 – 2129**	**4 – 171**	**1 - 150**

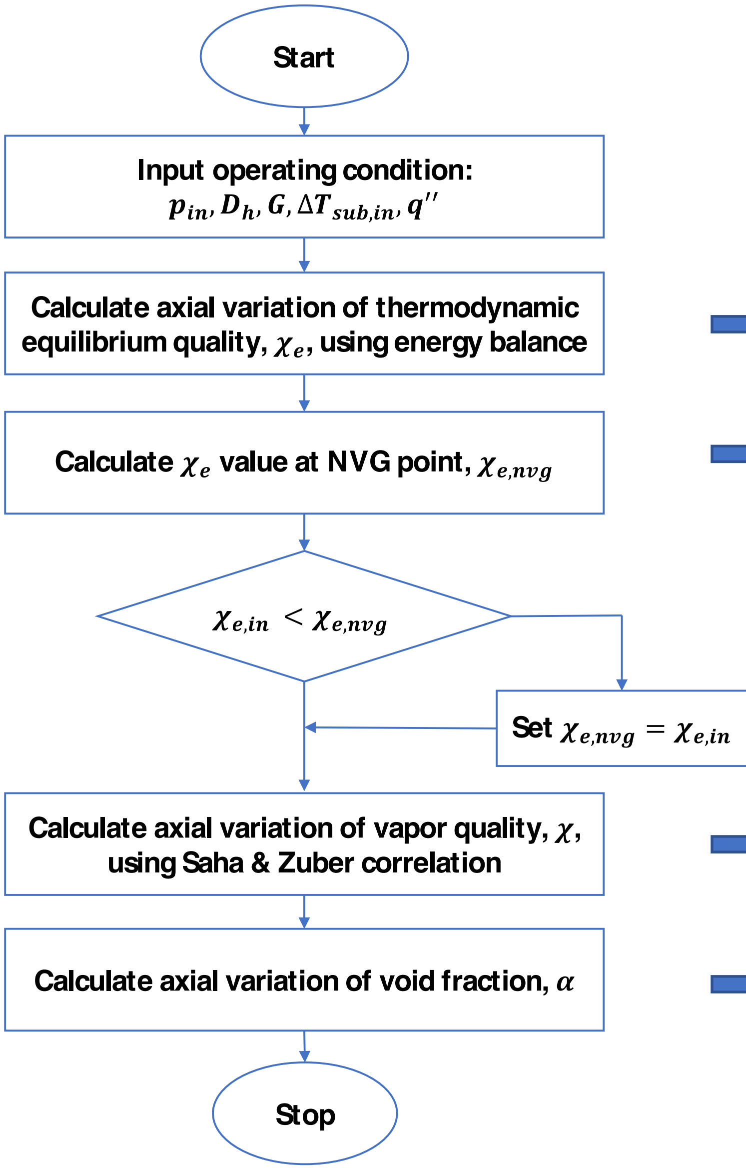
- Database including **308 cases** with a total of **2016 data points.**

Predictive method using empirical correlations



Schematic of Void Fraction evolution in Subcooled flow boiling (*Cai et al, 2021*)

Predictive method using empirical correlations



In this study

$$\chi_e = \frac{h - h_{f,sat}}{h_{fg}} = \frac{\frac{4q''z}{GD_h} + h_{in} - h_{f,sat}}{h_{fg}}$$

- ✓ *Saha & Zuber (1974)*
- ✓ *Ha et al (2020)*

$$\chi = \frac{\chi_e - \chi_{e,nvg}\exp(\chi_e/\chi_{e,nvg} - 1)}{1 - \chi_{e,nvg}\exp(\chi_e/\chi_{e,nvg} - 1)}$$

- ✓ Homogeneous model
- ✓ Slip ratio model (*Ahmad, 1970; Cai et al, 2021*)
- ✓ Drift flux model (*Dix, 1971*)

Corelations of NVG point

- **NVG point: the location where there is a high probability of bubble leaving the wall, leading to an increase in significant of void fraction parameter.**
- *Saha & Zuber (1974)*

$$\chi_{e,nvg} = \begin{cases} -0.0022\dfrac{q''c_{pf}D_h}{h_{fg}k_f}, Pe < 70000 \\ -153.85\dfrac{q''}{h_{fg}G} \quad , Pe \geq 70000 \end{cases}, \qquad Pe = \frac{G.D_h.c_{pf}}{k_f}$$

- *Ha et al (2020)*

$$\chi_{e.nvg} = \begin{cases} -\dfrac{q''c_{pf}D_h}{h_{fg}k_f}\left[0.0901 - 0.0893\exp\left(-\dfrac{158}{Pe}\right)\right], u^* \leq 1.3 \\ -\dfrac{q''c_{pf}D_h}{h_{fg}k_f}\dfrac{Re^{-0.77}Pr^{-1.35}}{0.0959} \quad , u^* > 1.3 \end{cases}$$

$$u^* = \frac{G}{1.53\rho_f}\left[\frac{\rho_f^2}{g\sigma(\rho_f - \rho_g)}\right]^{0.25}$$

Correlations of Void Fraction

- **Homogenerous flow model:**

$$\alpha_H = \frac{1}{1 + \frac{1-\chi}{\chi}\frac{\rho_g}{\rho_f}}$$

- **Slip ratio model:**

✓ *Ahmad (1970)*

$$\alpha = \frac{1}{1 + \frac{1-\chi}{\chi}\left(\frac{GD_h}{\mu_f}\right)^{-0.016}\left(\frac{\rho_g}{\rho_f}\right)^{0.795}}$$

✓ *Cai et al (2021)*

$$\alpha = \frac{1}{1 + \frac{1-\chi}{\chi}\left(\frac{\rho_g}{\rho_f}\right)^{0.7988}}$$

- **Drift-flux model:**

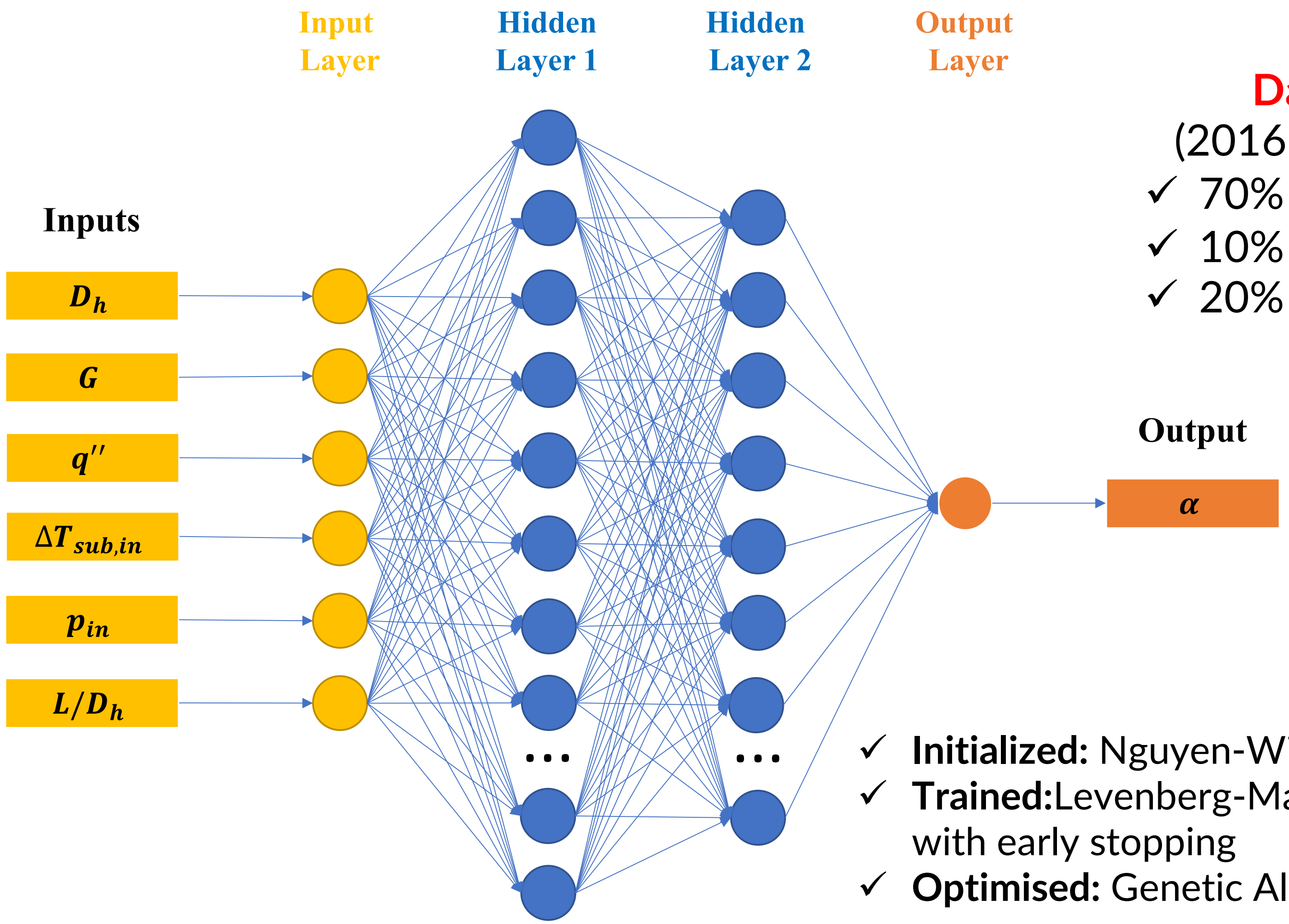
✓ *Dix (1971)*

$$\alpha = \frac{\chi}{C\left[\chi + \frac{\rho_g}{\rho_f}(1-\chi)\right] + \frac{\rho_g u_{gj}}{G}}$$

$$C = \frac{\chi\rho_f}{\chi\rho_f + (1-\chi)\rho_g}\left[1 + \frac{(1-\chi)\rho_g}{\chi\rho_f}\right]^b ; b = \left(\frac{\rho_f}{\rho_g}\right)^{0.1} ; u_{gj} = 2.9\left[\frac{g\sigma(\rho_f - \rho_g)}{\rho_f^2}\right]^{0.25}$$

Predictive method using ANN-based

Structure of ANN-based model with multilayer feedforward net



Database

(2016 data points)

- ✓ 70% for training
- ✓ 10% for validation
- ✓ 20% for testing

- ✓ **Initialized:** Nguyen-Widrow method
- ✓ **Trained:**Levenberg-Marquardt algorithm with early stopping
- ✓ **Optimised:** Genetic Algorithm

Results and Discussion

Predicted results are compared with experiment data through

- **Mean Absolute Error (MAE):**

$$MAE = \frac{1}{n}\sum_{i}\left|\alpha_{i,pred} - \alpha_{i,exp}\right|$$

- **Coefficient of Determination (R):**

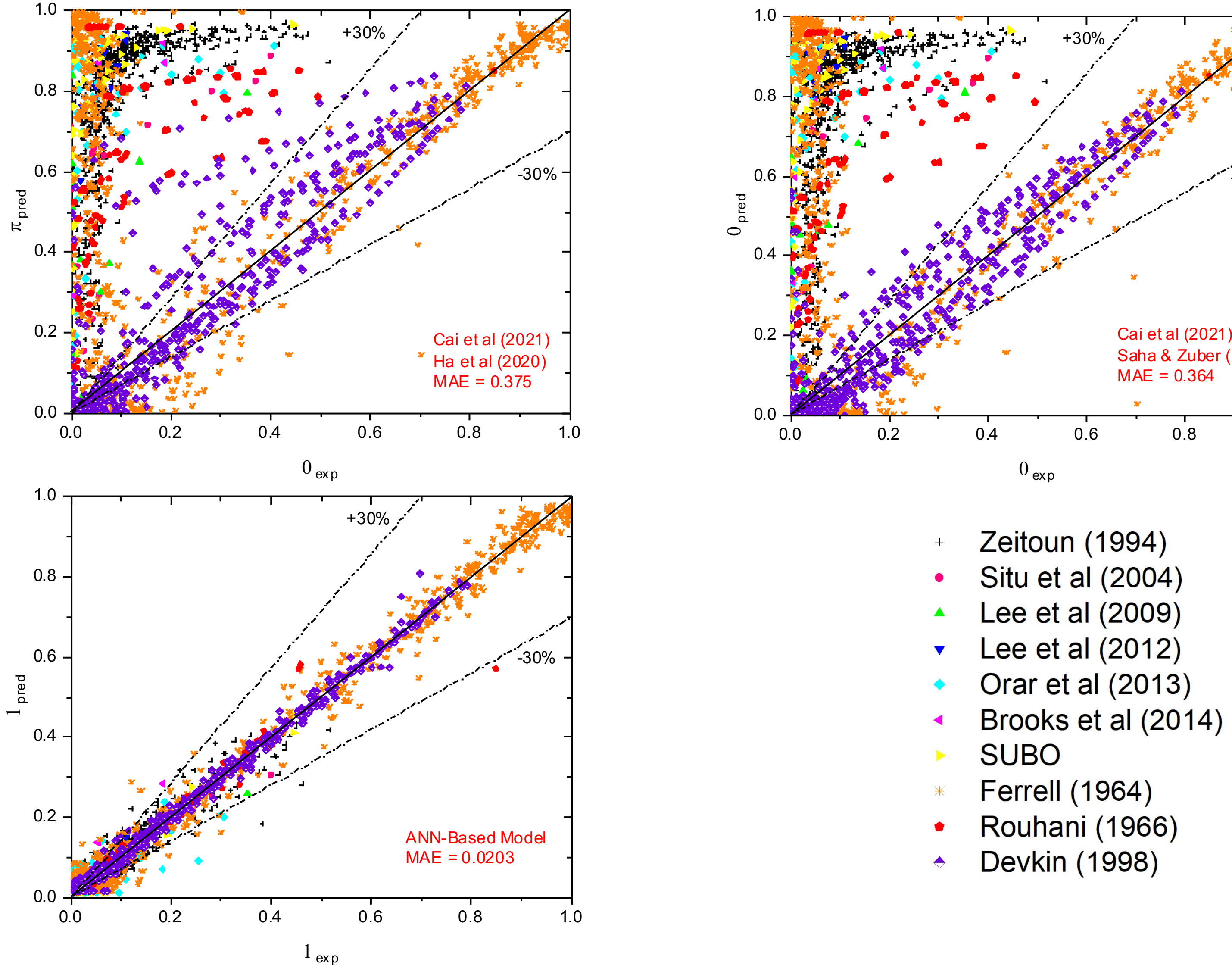
$$R = 1 - \frac{\sum_i \left(\alpha_{i,pred} - \alpha_{i,exp}\right)^2}{\sum_i \left(\alpha_{i,exp} - \alpha_{mean}\right)^2}$$

Results and Discussion

Mean absolute errors of 8 empirical correlation models and ANN-based model against experimental data

Author(s) $\chi_{e,nvg}$	Author(s) α	Overall MAE	Ferrell 1964	Rouhani 1966	Zeitoun 1994	Devkin 1998	Situ 2004	Lee 2009	SUBO 2010	Lee 2012	Ozar 2013	Brooks 2014
Saha&Zuber	HM	0.473	0.394	0.497	0.737	0.134	0.526	0.433	0.712	0.879	0.725	0.770
Saha&Zuber	Ahmad	0.375	0.312	0.523	0.605	0.078	0.317	0.240	0.569	0.763	0.600	0.625
Saha&Zuber	Dix	0.369	0.316	0.507	0.593	0.057	0.339	0.266	0.600	0.800	0.612	0.650
Saha&Zuber	Cai	0.364	0.309	0.494	0.589	0.071	0.293	0.218	0.545	0.742	0.576	0.598
Ha	HM	0.485	0.385	0.626	0.769	0.155	0.548	0.473	0.697	0.869	0.725	0.759
Ha	Ahmad	0.387	0.299	0.527	0.639	0.097	0.357	0.274	0.558	0.741	0.599	0.613
Ha	Dix	0.380	0.302	0512	0.628	0.075	0.387	0.303	0.589	0.779	0.612	0.636
Ha	Cai	0.375	0.295	0.499	0.623	0.087	0.337	0.251	0.535	0.719	0.574	0.585
ANN-based model		**0.020**	**0.027**	**0.013**	**0.020**	**0.012**	**0.016**	**0.021**	**0.017**	**0.019**	**0.034**	**0.036**

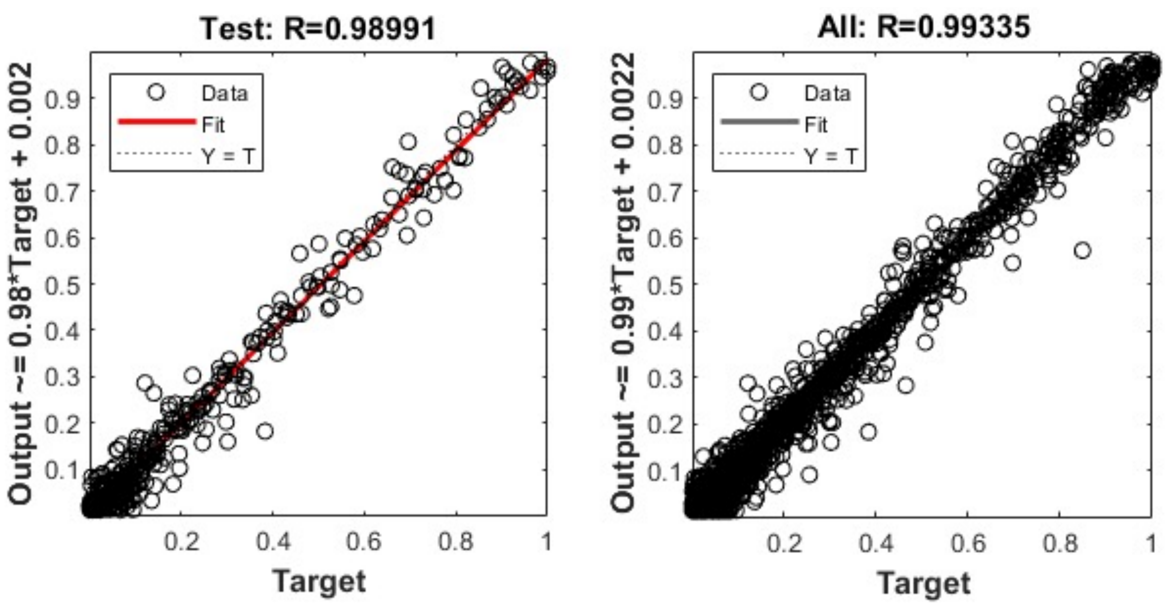
Results and Discussion

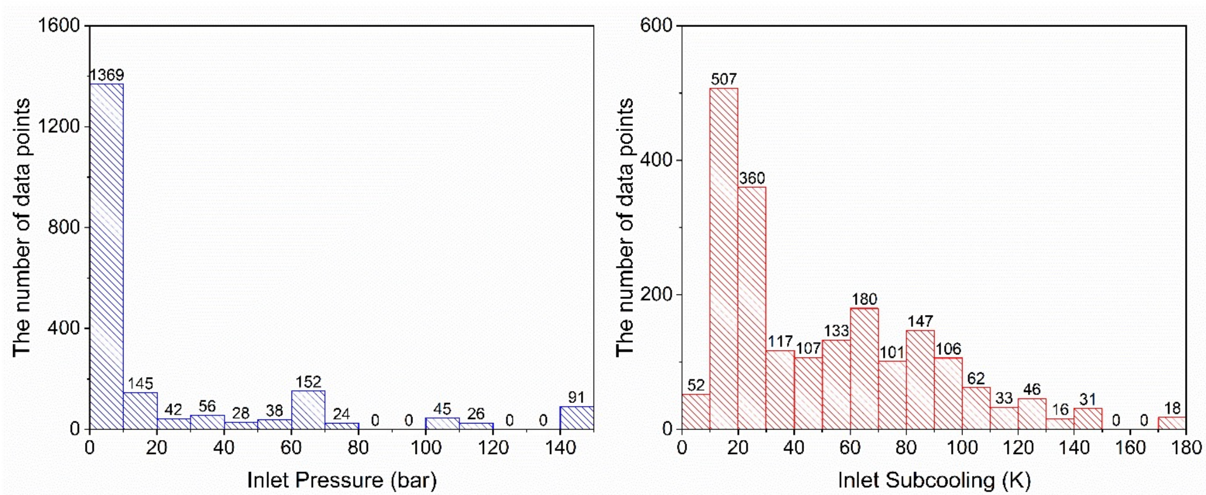


Comparison of experimental data with predicted results

Results and Discussion

ANN-based model





Work Efficiently in the low pressure range (1-10 bar) and inlet subcooling range 10-30 K

Conclusions

- **Investigation different empirical correlations to predict void fraction of subcooled boiling flow.**
- **Proposes the data-driven model based on ANN, which provides better predictive performance the empirical correlations.**
- **This study is the first step to build the ANN-based model to replace mathematical models implemented in CFD codes.**

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