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Enhanced Net Vapor Generation Modeling for Boiling Steam–Water Flow in Narrow Rectangular Channels †

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Abstract

Accurate net vapor generation prediction in narrow rectangular channels is crucial for advanced thermal systems. This study evaluates 17 existing net vapor generation (NVG) correlations against experimental data for boiling steam–water flow in such geometries. Most show poor performance. A new NVG correlation is developed based on the unique characteristics of narrow rectangular channels. The proposed correlation predicts the thermodynamic equilibrium quality at the NVG point with a mean relative error of 0.294 (120 data points), providing a critical input for void fraction determination downstream of the NVG point.

Keywords: thermal hydraulics; boiling; steam–water two-phase flow; Net Vapor Generation (NVG); drift-flux model

1. Introduction

Narrow rectangular channels are critical components in advanced thermal systems, such as compact heat exchangers, plate-type fuel reactors, spallation neutron source targets, and high-power electronics cooling, due to their superior heat transfer performance derived from a large fluid-wall contact area within a compact volume. Flow boiling is often employed to further enhance heat removal in these confined geometries. However, compared to conventional channels (e.g., circular tubes or rod bundles), the narrow rectangular shape profoundly alters bubble dynamics, flow pattern transitions, and void fraction distribution. These differences directly impact thermal–hydraulic performance, system stability, and safety margins. Therefore, accurate prediction of void fraction in boiling steam–water two-phase flow within vertical narrow rectangular channels is essential for reliable design and safety analysis of associated industrial and energy systems.

The drift-flux model by Zuber and Findlay [1] is widely used for void fraction prediction:

$$< \alpha > = \frac{< j_g >}{C_0\left(< j_f > + < j_g >\right) + \ll v_{gj} \gg}, \quad (1)$$

where $<\alpha>$, $<j_f>$, $<j_g>$, C_0 and $\ll v_{gj} \gg$ denote the void fraction, the superficial liquid velocity, the superficial gas velocity, the distribution parameter, and the drift velocity, respectively. The mathematical symbols of <> and «» represent the area-averaged quantity and the void fraction weighted mean quantity, respectively. For boiling flows:

$$< j_f > = \frac{G(1 - x)}{\rho_f} \text{ and } < j_g > = \frac{Gx}{\rho_g}, \quad (2)$$

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where G, ρ_f, ρ_g, and x are the mass flux, the liquid density, the gas density, and the flow quality, respectively. A major challenge is subcooled boiling non-equilibrium: the actual quality x differs from thermodynamic equilibrium quality:

$$x_e = \frac{i_z - i_{fs}}{i_{fg}}, \tag{3}$$

At the net vapor generation (NVG) point, vapor begins to contribute significantly to void fraction. The Saha and Zuber model [2] relates x to xe downstream of NVG:

$$x = \frac{x_e - x_{e,NVG}\exp\left(\frac{x_e}{x_{e,NVG}} - 1\right)}{1 - x_{e,NVG}\exp\left(\frac{x_e}{x_{e,NVG}} - 1\right)}, \tag{4}$$

Thus, the $x_{e,NVG}$ is a key input for Equation (2). However, most existing $x_{e,NVG}$ correlations were developed using data from conventional geometries (e.g., circular tubes) with little validation against narrow rectangular channel data. Some recent models rely on small or mixed datasets (e.g., air–water instead of steam–water). New experimental data now enable systematic evaluation. This study aims to develop an accurate $x_{e,NVG}$ prediction model for vertical narrow rectangular channels. A dedicated database is compiled to evaluate 17 existing correlations and then develop a new one.

2. Assessment of Existing Representative $x_{e,NVG}$ Correlations

2.1. Collected Experimental Data on $x_{e,NVG}$

A dedicated experimental database for $x_{e,NVG}$ is compiled for boiling steam–water flow in vertical narrow rectangular channels (gap < 6.35 mm, aspect ratio > 2). The data, spanning 1957–2024, include 120 points from six studies (Egen et al. [3], Maurer [4], Costa (No.1 and 2) [5], Martin [6], Wang et al. [7], Yang and Xiong [8]). The parameter ranges are: pressure 0.174–14.2 MPa, heat flux 0.0641–4.20 MW/m^2, mass flux 151–7500 kg/(m^2·s), gap 2.00–3.60 mm, width 25.4–70.0 mm, and hydraulic diameter 3.80–6.58 mm. The measurement uncertainty of $x_{e,NVG}$ is consistently reported as 20%.

2.2. Existing Representative $x_{e,NVG}$ Correlations

Representative correlations fall into three mechanistic groups: (1) bubble departure (Bowring [9], Levy [10]), (2) bubble ejection (Dix [11]), and (3) thermal/hydrodynamic (Griffith et al. [12], Thom et al. [13], Saha and Zuber [2], Ünal [14], Sekoguchi et al. [15], Kataoka et al. [16], Kalitvianski [17], Sun et al. [18], SRL (Chung et al.) [19], Wang et al. [7], Ha et al. [20], Lee and Jeong [21], Wisudhaputra et al. [22], Jeong et al. [23]).

2.3. Prediction Performance of Reviewed Correlations

Performance is evaluated using the mean relative error (MRE, m_{rel}). An MRE below 0.4 indicates good prediction. As shown in Figure 1, most correlations perform poorly for narrow rectangular channels. Saha and Zuber gives an MRE of 0.506; its Peclet transition criterion (70,000) does not suit these geometries. Thom (0.858), Sekoguchi (1.10), Bowring (0.539), Levy (0.459), and Dix (0.787) show high errors due to mechanistic inconsistencies or lack of validation.

Four thermal/hydrodynamic correlations show relatively better performance: Sun et al. [18] (MRE 0.339), Griffith et al. [12] (0.347), Ünal [14] (0.374), and Jeong et al. [23] (0.401). However, none maintain MRE < 0.4 across all individual datasets. For example, Sun et al. [18] gives 0.647 for Maurer [4] and 0.435 for Wang et al. [7]; Griffith et al. [12] gives 0.429 and 0.481; Ünal [14] gives 0.568, 0.537, and 0.404; and Jeong et al. [23] gives 0.585, 0.625, and 0.432. As none were specifically developed for narrow rectangular channels,

consistent reliability is lacking. These results clearly demonstrate the need for a new dedicated correlation for narrow rectangular channels.

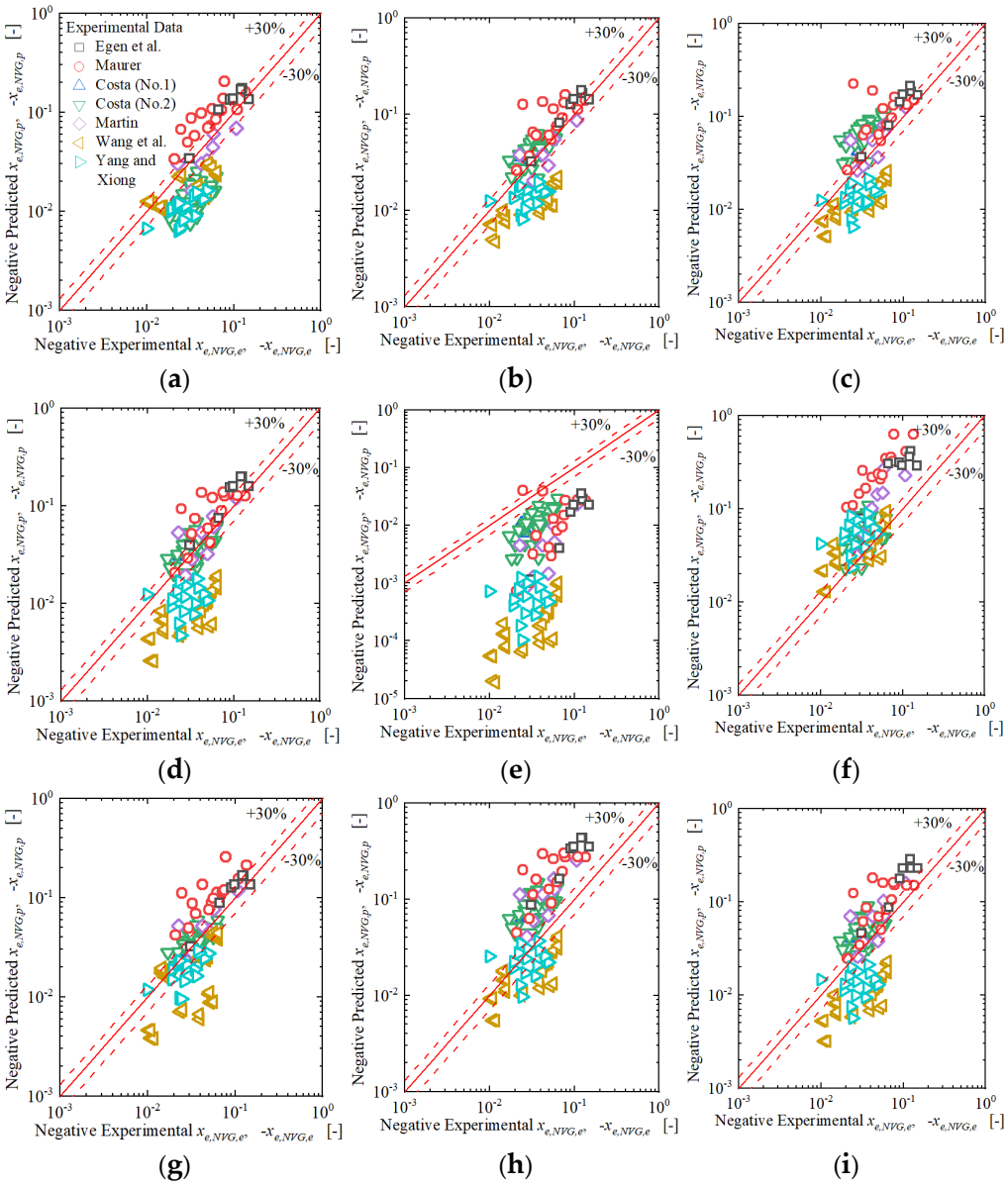


Figure 1. Evaluation of $x_{e,NVG}$ correlations with experimental data. (**a**) Egen et al. [3], Maurer [4], Costa (No.1 and 2) [5], Martin [6], Wang et al. [7], Yang and Xiong [8], Bowring [9]. (**b**) Levy [10]. (**c**) Dix [11]. (**d**) Saha and Zuber [2]. (**e**) Kataoka et al. [16]. (**f**) Kalitvianski [17]. (**g**) Ha et al. [20]. (**h**) Wang et al. [7]. (**i**) Lee and Jeong [21].

3. Development and Evaluation of a New $x_{e,NVG}$ Correlation

To improve prediction accuracy for narrow rectangular channels, a new $x_{e,NVG}$ correlation is developed by modifying the best-performing existing model (Sun et al. [18]), which is based on the thermal/hydrodynamic mechanism. The modification accounts for unique thermal–hydraulic features of narrow rectangular channels.

At the NVG point, vapor generation on the heated wall is balanced by bubble condensation in the subcooled bulk flow. The wall heat flux is expressed as

$$q'' = G_s i_{fg} + \frac{G_s}{\rho_g}\rho_f c_p\left(t_s - t_{f,NVG}\right), \quad (5)$$

Over a differential length, heat used for vapor generation ($dQ_{g,NVG}$) and heat released by condensation ($dQ_{c,NVG}$) are:

$$dQ_{g,NVG} = G_s i_{fg} P_h dz = \frac{q'' i_{fg} P_h dz}{i_{fg} + c_p\left(\rho_f/\rho_g\right)\left(t_s - t_{f,NVG}\right)}, \tag{6}$$

$$dQ_{c,NVG} = a_{i,NVG} h_{i,NVG} (t_s - t_{f,NVG}) A_F dz, \tag{7}$$

From heat balance ($dQ_{c,NVG} = dQ_{g,NVG}$), and assuming $t_{f,NVG} \approx t_{NVG}$, the subcooling at NVG is:

$$t_s - t_{NVG} = \frac{\sqrt{1 + 16\left(\rho_f/\rho_g\right)\left(q'' c_p / a_{i,NVG} h_{i,NVG} D_h i_{fg}\right)} - 1}{2\left(\rho_f/\rho_g\right)\left(c_p/i_{fg}\right)}, \tag{8}$$

Thus,

$$x_{e,NVG} = \frac{1 - \sqrt{1 + 16\left(\rho_f/\rho_g\right)\left(q'' c_p / a_{i,NVG} h_{i,NVG} D_h i_{fg}\right)}}{2\left(\rho_f/\rho_g\right)}, \tag{9}$$

Two unknown interfacial parameters must be modeled.

(1) Interfacial area concentration at NVG ($a_{i,NVG}$): Assuming spherical bubbles in a square arrangement on the heated surface:

$$a_{i,NVG} = \frac{C_1}{D_h}, \tag{10}$$

(2) Interfacial heat transfer coefficient at NVG ($h_{i,NVG}$): For narrow rectangular channels, the Nusselt number depends on Reynolds, Prandtl, density ratio, and channel geometry (gap s, width w):

$$Nu = \frac{h_i D_B}{\lambda_f} = C_2 Re^{C_3} Pr^{C_4} \left(\rho_g/\rho_f\right)^{C_5} (s/w)^{C_6}, \tag{11}$$

Substituting yields:

$$h_i = C_8 \frac{\lambda_f}{D'_B} \left(\frac{\rho_f D'_B}{\mu_f} \left(\frac{\sigma g \left(\rho_f - \rho_g\right)}{\rho_f^2} \right)^{0.25} \right)^{C_3} Pr^{C_4} \left(\rho_g/\rho_f\right)^{C_5} (s/w)^{C_6} = C_8 h'_i, \tag{12}$$

Finally, the new correlation is:

$$x_{e,NVG} = \frac{1 - \sqrt{1 + C_9\left(\rho_f/\rho_g\right)\left(q'' c_p / h'_i i_{fg}\right)}}{2\left(\rho_f/\rho_g\right)}, \tag{13}$$

Five adjustment factors (C_3, C_4, C_5, C_6, C_9) are calibrated using the 120-point database. The recommended values are 0.252, −0.382, 0.526, 0.360, and 0.101, respectively. Figure 2 compares the predicted values with measured data, showing good agreement and no obvious systematic deviation. The overall mean relative error (MRE) reaches 0.294 across all 120 points. It is worth noting that, since the empirical coefficients in the new correlation are derived from fitting to experimental data, its applicability should be strictly confined to the range of experimental conditions covered in Section 2.1.

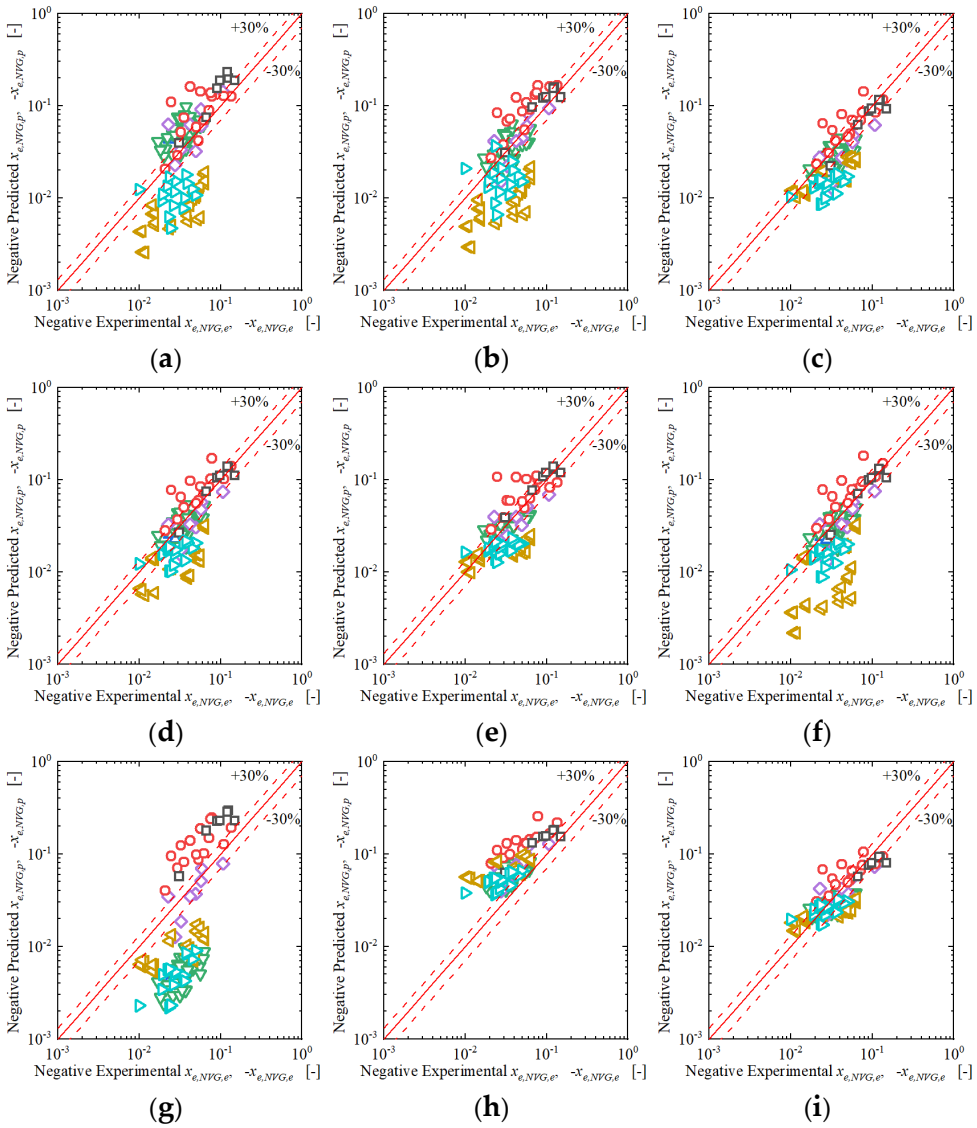


Figure 2. Evaluation of $x_{e,NVG}$ correlations with experimental data (continued). (**a**) SRL [19]. (**b**) Wisudhaputra et al. [22]. (**c**) Griffith et al. [12]. (**d**) Ünal [14]. (**e**) Sun et al. [18]. (**f**) Jeong et al. [23]. (**g**) Thom et al. [13]. (**h**) Sekoguchi et al. [15]. (**i**) Newly proposed.

4. Conclusions

This study developed a new $x_{e,NVG}$ correlation for boiling steam–water flow in vertical narrow rectangular channels. Evaluation of 17 existing correlations against a dedicated 120-point database revealed that most, including widely used models, exhibit poor predictive performance (MRE > 0.4). Only a few thermal/hydrodynamic-based correlations showed moderate capability, but with inconsistent accuracy. The proposed correlation refines the heat balance and achieves a mean relative error of 0.294.

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