

# Validation of Two-Phase Flow Boiling Heat Transfer Correlations and Application to Steam Generator Design

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## 1. Introduction

Helical steam generators have recently attracted attention due to their large surface-area-to-volume ratio, relative to traditional straight tubes. The helical structure induces secondary flows, in which centrifugal forces influence flow and heat transfer.

A wide range of empirical and semi-empirical correlations have been developed to model convective boiling heat transfer in helical heat exchangers. However, these correlations exhibit acceptable accuracy only within the specific experimental conditions for which they were derived. When these correlations are applied outside the ranges of data used for the development, these correlations often exhibit significant deviations, which is natural and understandable. However, the issue is when the correlation is used in the safety analysis code, and the valid ranges cannot be always checked during the analysis.

The present study aims to evaluate several two-phase flow heat transfer correlations under operating conditions of a Gen-IV reactor. High-Temperature Gas Reactor's (HTGR) secondary side conditions are used: high pressure, high mass flow rate, and high heat flux. Based on this assessment, a steam generator design is proposed to ensure that operating conditions remain within the validated range of correlation accuracy. Unfortunately, due to the valid range of correlation is low heat flux case, the designed steam generator has low heat flux. It is noted that this is not due to the intrinsic limitation of the helical steam generator; rather it is the current limit of available data that can be used for developing the correlation.

## 2. Correlation Validation

Correlation performance was assessed against the experimental results of Chang et al. [1], who investigated flow boiling heat transfer of water in a helical tube under high-pressure condition.

### 2.1 Evaluated Correlations

Five correlations were evaluated. Yang's correlation, a modification of Chen's well-known two-phase flow boiling model for straight tubes, and Chang's correlation, derived from his own helically coiled tube experiments, were tested [2].

The other three correlations were Moradkhani's [3], Kim's [4] and Fang's [5]. These correlations are different from others as they were developed using machine-learning techniques trained on large experimental datasets collected from previous studies. These models attempted to develop a correlation with minimum error across diverse conditions, since experimental data on boiling flow in helical tube for high pressure conditions are limited.

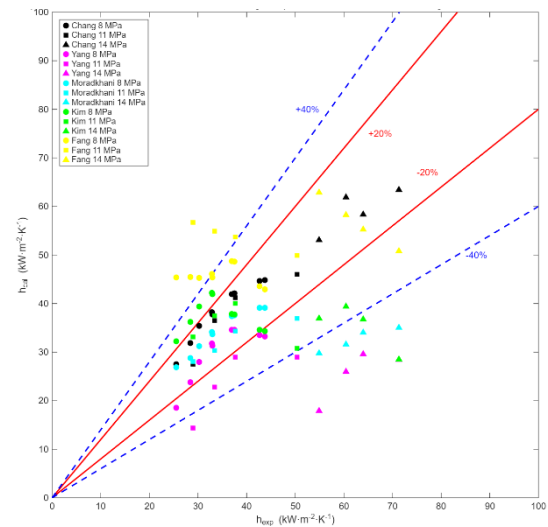


Figure 1. Various Correlations vs. Chang's experimental results at  $G = 500 \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$  and  $Q = 100 \text{ kW}\cdot\text{m}^{-2}$

As shown in Fig. 1, Yang's correlation accurately predicts the heat transfer coefficient (HTC) at 8 MPa but underestimates values at 11 MPa and 14 MPa. Chang's correlation demonstrates good agreement with his experimental values across all pressures at the

given conditions. Moradkhani's model underpredicts at 14 MPa, while Kim's tends to overpredict at lower pressures and underpredict at higher pressures. Fang's consistently overestimates HTC at 8 and 11 MPa. In summary, Chang's correlation seems to be the best for representing the two-phase heat transfer at given mass flux and heat flux.

Table 1 compares  $R^2$ -values of correlations to experimental data for varying pressures.  $R^2$ -values were derived from following calculation:

$$R^2 = 1 - \frac{\sum (h_{tp,exp} - h_{tp,cal})^2}{\sum (h_{tp,exp} - \bar{h}_{tp,exp})^2}$$

Table 1. Evaluation of the correlations to experimental data using  $R^2$ -value

| Correlation | Pressure | $R^2$ -value |
|-------------|----------|--------------|
| Chang       | 8 MPa    | 0.5258       |
|             | 11 MPa   | 0.8332       |
|             | 14 MPa   | 0.3045       |
| Yang        | 8 MPa    | 0.0619       |
|             | 11 MPa   | -2.3402      |
|             | 14 MPa   | -34.4383     |
| Moradkhani  | 8 MPa    | 0.8741       |
|             | 11 MPa   | 0.2142       |
|             | 14 MPa   | -24.9736     |
| Kim         | 8 MPa    | -0.6719      |
|             | 11 MPa   | -0.6564      |
|             | 14 MPa   | -22.5534     |
| Fang        | 8 MPa    | -3.9027      |
|             | 11 MPa   | -4.8208      |
|             | 14 MPa   | -2.9887      |

## 2.2 Chang's correlation under different conditions

HTR-PM is an exemplary HTGR that is operating in China, and according to conditions reported in the previous research [6], its estimated pressure, mass flux rate and heat flux are approximately 13.24 MPa, 650  $\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$  and 100~1,000  $\text{kW}\cdot\text{m}^{-2}$ . Chang's correlation was compared to experimental results at higher mass flux and heat flux in order to see if his model stays accurate at such conditions.

Fig. 2 displays that as mass flux and heat flux increases, the correlation tends to underestimate HTC. When mass flux is at 1,500  $\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ , the HTC is below 40% error band regardless of heat flux. When mass flux is at 1,000  $\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ , higher pressure and heat flux shows high deviation below 40% error band. At lower pressure and heat flux, the correlation seems to predict HTC within 40% error band.

The correlation analysis indicates that significant prediction uncertainties arise under conditions of high

heat flux and mass flux, particularly at high pressures. In order to mitigate such discrepancies, this study is limiting the design of a steam generator that intentionally operates at low heat flux condition to guarantee the validity of the design.

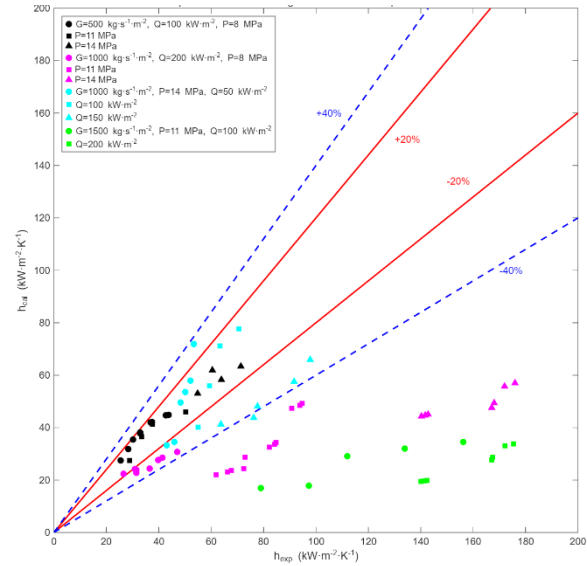


Figure 2. Chang's correlation vs. his experimental results at varying  $G$ ,  $Q$ , and  $P$

## 3. Steam Generator Design for HTGR

The HTR-PM model [6] is taken as the reference plant. The same structural concept was adopted, consisting of 19 steam generator cassettes, each containing 35 helically coiled tubes.

### 3.1 Adjusted Parameters

To limit the operating mass flux and heat flux within the valid range of the utilized correlation, geometric and thermal parameters were modified. Heat flux and mass flux are defined as:

$$Q = \frac{q}{A_s}, \quad G = \frac{\dot{m}}{A}$$

where  $q$  is the heat transfer rate (W),  $A_s$  is the effective heat transfer surface area ( $\text{m}^2$ ),  $\dot{m}$  is the mass flow rate ( $\text{kg/s}$ ), and  $A$  is the flow cross-sectional area ( $\text{m}^2$ ).

Expanding the tube's outer and inner diameter,  $d_{o,i}$ , increases both flow area and heat transfer surface area, decreasing local values of heat flux and mass flux. To accommodate the enlarged tube diameters, shell side parameters were enlarged also. Since several correlations include the parameter  $\frac{d}{D}$ , where  $D$  is the helical coil diameter,  $D$  was proportionally increased to preserve the ratio and ensure correlation applicability.

Geometric modification alone is likely insufficient,

given that heat flux of HTGR reaches up to  $1,000 \text{ kW}\cdot\text{m}^{-2}$ . Thus, the driving temperature difference,  $T_{pri} - T_{sec}$ , was reduced to further limit heat flux. To maintain total reactor power output of  $250 \text{ MW}_{th}$ , the mass flow rate was correspondingly adjusted.

### 3.2 Design Adjustments

Following adjustments were made:

Table 2. Parameters that were modified from reference HTR-PM model

| Parameter                    | Reference                            | Adjusted Value                       |
|------------------------------|--------------------------------------|--------------------------------------|
| $d_{o/i}$                    | 19/17 mm                             | 30/28 mm                             |
| $D_{avg}$                    | 165 mm                               | 350 mm                               |
| Shell Height                 | 8.6 m                                | 10 m                                 |
| $T_{Pri, in} - T_{Pri, out}$ | $750 - 250 \text{ }^{\circ}\text{C}$ | $750 - 350 \text{ }^{\circ}\text{C}$ |
| $T_{Sec, in} - T_{Sec, out}$ | $205 - 566 \text{ }^{\circ}\text{C}$ | $300 - 550 \text{ }^{\circ}\text{C}$ |
| $\dot{m}_{Pri/Sec}$          | 96/95 kg/s                           | 120.5/118 kg/s                       |

The diameters of tube and shell were increased, but thickness of the tube was not changed. Shell Height increased to 10 m to accommodate for the volumetric change. Temperature of both primary and secondary fluid were changed. Primary side (Helium) inlet temperature did not change, but outlet temperature increased by  $100^{\circ}\text{C}$ . Secondary side (water) inlet temperature increased to  $300^{\circ}\text{C}$ , close to saturation temperature of 14 MPa, while outlet temperature stayed relatively the same. Mass flow rate was increased to maintain  $250 \text{ MW}_{th}$  value. The above parameters yield  $G = 288.17 \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$  per tube.

### 3.3 Correlations used

Table 3. Heat Transfer and Pressure Drop Correlations used for Modeling LHF Heat Exchanger for HTGR

| Zone                                                     | Correlation   |
|----------------------------------------------------------|---------------|
| Single-phase liquid zone (shell side)                    | Žukauskas     |
| Single-phase liquid zone (tube side)                     | Schmidt       |
| Subcooled boiling zone                                   | Hardik        |
| Saturated boiling and forced convection evaporation zone | Chang         |
| Liquid deficiency zone                                   | Xiao          |
| Single-phase vapor zone (tube side)                      | Mori-Nakayama |
| Single-phase liquid zone (shell side)                    | Gilli         |
| Single-phase liquid & vapor zone                         | Ito           |
| Two-phase liquid zone                                    | Colombo       |

Table 3 lists heat transfer and pressure drop correlations used for designing the steam generator. Except for the two-phase boiling zone, the same correlations as in the previous research [6] were used. Liquid deficiency zone was unchanged, since Chang's experimental data did not provide sufficient measurements in this region. Chang's work successfully identifies temperature jump of wall temperature at quality of 0.93, but provides no data in regions between 0.93 to 1.0.

## 4. Results and Discussions

Using the adjusted parameters and correlations described in Section 3, the following profiles of thermal hydraulic parameters were obtained within the steam generator:

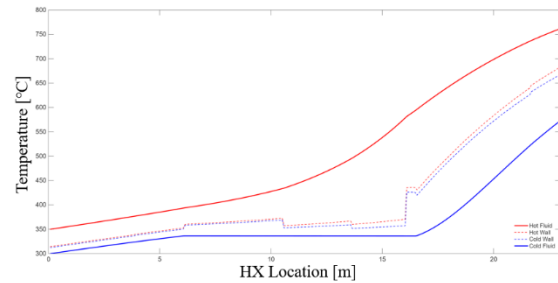


Figure 3. Temperature profile of primary, secondary fluids, and wall along tube length

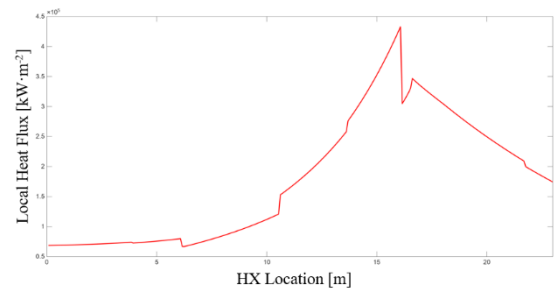


Figure 4. Local heat flux profile along tube length

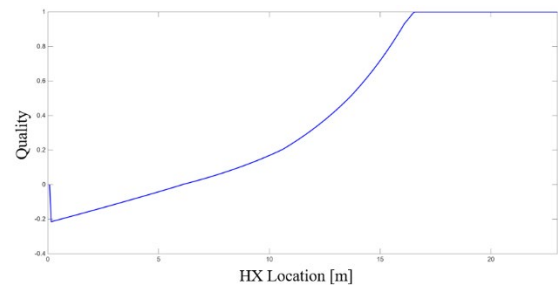


Figure 5. Quality profile along tube length

As shown in Fig. 3, the desired temperature range is achieved at a tube length of 22.5 m. There are a few notable variations in wall temperature that are observed. At ~6 m, there is slight jump in wall

temperature, which jumps back down at ~11 m. This corresponds to transition from single-phase subcooled boiling flow to saturated boiling heat transfer and bubbly flow, where equilibrium quality goes above 0.0 (Fig. 5). The vapor nucleation initially reduces effective heat transfer, which increases wall temperature. As vapor generation intensifies, the bubble flow develops into slug flow where vapor moves towards the core. Bubble induced turbulence increases HTC and decreases wall temperature. These trends are consistent with the experimental observations of Chang [1], who reported wall temperature decrease near a quality of 0.2.

A second drop in wall temperature occurs when quality reaches 0.5 at ~13 m. This corresponds to transition from slug flow to annular flow, where HTC increases further due to enhanced two-phase turbulence.

At ~16 m, the quality reaches 0.93 and enters liquid deficiency zone. Wall temperature rises sharply due to dryout and HTC is reduced sharply. The local heat flux reaches  $431 \text{ kW}\cdot\text{m}^{-2}$  (Fig. 4). While this value still exceeds  $200 \text{ kW}\cdot\text{m}^{-2}$  reported in Chang's experiments, it remains significantly lower than  $1,000 \text{ kW}\cdot\text{m}^{-2}$  predicted under the original HTR-PM's configuration.

The significant enlargement of tube and shell diameter raises practical concerns regarding system compactness, a key attribute of Small Modular Reactors (SMR). Thus, new correlation that can cover higher mass flux and higher heat flux is necessary.

## 5. Conclusions & Further Works

This study evaluated several two-phase boiling heat transfer correlations under high-pressure conditions relevant to HTGR secondary systems and applied them to the design of steam generator.

Chang's correlation demonstrated the most consistent agreement with experimental data across pressures of 8-14 MPa, but it showed increasing deviations exceeding 40% when heat flux and mass flux increased, highlighting the limitations of applying correlations beyond their validated ranges.

To address this issue, a steam generator is newly designed within the valid range of the utilized correlation. The new model shows mass flux of  $228.17 \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$  and maximum heat flux of  $431 \text{ kW}\cdot\text{m}^{-2}$ , which are significantly lower than those of the reference HTR-PM configuration. Also, the resulting temperature profile along tube length matches the experimental results observed by Chang.

Future work will employ the parameters obtained from the steam generator to conduct density wave oscillation simulations and experiments. The goal is to

compare the dynamic stability of conventional water-cooled SMRs and HTGR systems.

## ACKNOWLEDGEMENT

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## REFERENCES

- [1] Chang, F., Liu, Y., Lou, J., Shang, Y., Hu, H., & Li, H. (2023). Experimental investigation on flow boiling heat transfer characteristics of water and circumferential wall temperature inhomogeneity in a helically coiled tube. *Chemical Engineering Science*, 272, 118592. <https://doi.org/10.1016/j.ces.2023.118592>
- [2] Yang, S. H., Kim, S. H., Chung, Y.-J., Park, H.-S., & Kim, K. K. (2008). Experimental validation of the Helical Steam Generator model in the TASS/SMR code. *Annals of Nuclear Energy*, 35(1), 49–59. <https://doi.org/10.1016/j.anucene.2007.06.004>
- [3] Moradkhani, M. A., Hosseini, S. H., & Karami, M. (2022). Forecasting of saturated boiling heat transfer inside smooth helically coiled tubes using conventional and machine learning techniques. *International Journal of Refrigeration*, 143, 78–93. <https://doi.org/10.1016/j.ijrefrig.2022.06.036>
- [4] Kim, M. G., Yun, B., & Jeong, J. J. (2024). Development of a new correlation for saturated flow boiling heat transfer in a helically coiled tube. *Nuclear Technology*, 211(1), 93–110. <https://doi.org/10.1080/00295450.2024.2319926>
- [5] Fang, X., He, Z., Wang, X., Qin, Y., & Fang, Y. (2025). New correlation of heat transfer coefficient for saturated flow boiling in smooth helically coiled tubes. *International Journal of Heat and Fluid Flow*, 113, 109778. <https://doi.org/10.1016/j.ijheatfluidflow.2025.109778>
- [6] Kim, H., Hwang, J., and Lee, J. (2025). Modeling Heat Transfer in Helically Coiled Steam Generators Using Different Correlations, 2025 KNS Spring Conference, Jungmun, Jeju, Republic of Korea.