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# Enhancement of Fluid-to-Fluid Scaling Criteria for Modeling Condensation in Horizontal Tubes Under Stratified Flow Conditions

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## 1. Introduction

Experimental investigations of high-pressure steam condensation heat transfer are limited due to technical requirements and construction costs of experimental facilities. Applying fluid-to-fluid scaling methods is a possible way to overcome those difficulties. Performing experiments with simulant fluid, Freon, for instance, allows testing at low pressure, low temperature and with low power requirements compared with the water-based prototype. Fluid-to-fluid scaling criteria for modeling high-pressure steam condensation have been developed [1]. It was shown that to guarantee the similarity between the prototype and the model, the liquid-to-vapor density ratio, the Froude number, and the vapor Reynolds number should be preserved. Preserving those three non-dimensional numbers allows quantities allows having control of the four degrees of freedom usually available during experimentation, the mass flux, temperature, pressure, and geometry.

By studying the condensation phenomena in horizontal tubes, the flow regimes are categorized into two main patterns, gravity dominated, and shear dominated [2]. The gravity dominated flow, or the stratified or the stratified-wavy flow, is characterized by a thick condensate layer flowing along the bottom of the tube, while a thin liquid film forms on the wall in the upper part. For this flow regime, the heat transfer coefficient is characterized to be dependent on the temperature difference between the flow and the tube inner wall. For the shear dominated flow, or the annular flow, which is characterized by the axial flow of the condensate along the channel. The forced convective condensation is the dominant heat transfer mode, and the heat transfer coefficient is characterized by the dependence on the mass flux and the flow quality.

In this paper, the improvement of the application of the developed scaling criteria [1] on the gravity dominated flow (the stratified flow) regime will be discussed.

## 2. Scaling Criteria Improvement

Based on the scaling criteria, the following relations should be satisfied.

$$\left(\frac{\rho_V}{\rho_L}\right)_P = \left(\frac{\rho_V}{\rho_L}\right)_M$$

$$\left(\frac{gD\rho_L^2}{G^2}\right)_P = \left(\frac{gD\rho_L^2}{G^2}\right)_M$$

$$\left(\frac{\mu_V}{DG}\right)_P = \left(\frac{\mu_V}{DG}\right)_M$$

Accordingly, the diameter and mass flux scaling factors have been defined as:

$$F_G = \frac{G_P}{G_M} = \left(\frac{\rho_{LP}^2}{\rho_{LM}^2}\frac{\mu_{VP}}{\mu_{VM}}\right)^{1/3}$$

$$F_D = \frac{D_P}{D_M} = \frac{\rho_{LM}^2}{\rho_{LP}^2}\left(\frac{\rho_{LP}^2}{\rho_{LM}^2}\frac{\mu_{VP}}{\mu_{VM}}\right)^{2/3}$$

And the scaling of the heat transfer coefficient is based on the Nusselt number,

$$\left(\frac{hD}{K}\right)_P = \left(\frac{hD}{K}\right)_M$$

All the terms will be defined in the nomenclature section of this paper.

However, when applying the scaling criteria for the stratified flow regime, an additional requirement should be added to address the temperature difference dependence of the heat transfer coefficient of this flow regime. Therefore, a heat flux additional criterion should be added to the previous requirements.

Two approaches, relate the prototype and the model, have been defined to develop the additional criterion, both of them will be derived, tested and the best, in terms of the similarity between the prototype and the model, will be chosen as the best approach for the heat flux similarity criterion.

The first approach is based on the non-dimensionalization of the boundary conditions on the heated surface; the scaling factor is defined as:

$$F_q = \frac{q_m}{q_P} = \frac{K_{BM}D_P(T_B - T_C)_M}{K_{BP}D_M(T_B - T_C)_P}$$

The second approach is based on Nusselt film condensation. The stratified flow regime heat transfer coefficient dependence on temperature difference comes from the condensation on the upper wall of the tube, where the flow of condensate film from the top of the tube towards the bottom due to gravity. This film is considered laminar and usually heat transfer of this film is analyzed by the Nusselt film condensation. The Nusselt film heat transfer coefficient is defined as:

$$h = 0.655\left[\frac{\rho_L(\rho_L - \rho_v)gh_{LV}K_L^3}{\mu_L Dq}\right]^{1/3}$$

The heat flux scaling factor is developed by forming a relation between prototype and model. The scaling factor is defined as follow:

$$F_q = \frac{q_m}{q_P} = \frac{\mu_{LP}}{\mu_{LM}}\frac{D_M^2}{D_P^2}\frac{h_{LVM}}{h_{LVP}}\frac{\rho_{LM}}{\rho_{LP}}\frac{(\rho_L - \rho_v)_M}{(\rho_L - \rho_v)_P}$$

## 3. Criteria Validation

The scaling criteria, with the additional heat flux scaling criterion, have been validated by applying it to two different benchmark problems. The best approach, which fits the matching between the prototype and the model will be selected as the best approach for scaling the heat flux for condensation in horizontal tubes, at the stratified flow regime flow conditions.

The benchmark problems are defined in table 1 below.

Table 1: benchmark problems- prototype design

| | Fluid | P (MPa) | G (kg/m$^2$s) | D (mm) |
|---|---|---|---|---|
| 1 | water | 7.4 | 100 | 44.8 |
| 2 | water | 1.5 | 100 | 26.6 |

Based on the scaling criteria, the model design parameters are:

Table 2: benchmark problems- Model design

| | Fluid | P (MPa) | G (kg/m$^2$s) | D (mm) | Approach B | Approach B |
|---|---|---|---|---|---|---|
| | | | | | Fq | |
| 1 | R134a | 1.2 | 116 | 25.7 | 0.142 | 0.048 |
| 2 | R134a | 0.235 | 116 | 15.4 | 0.149 | 0.038 |

The heat transfer coefficients, the Nusselt number, stratification angle, and the stratified liquid thickness based on the Thome model [3] have been calculated over the quality range [0.1-0.9]. The results have been compared between the porotype and the models while considering the different approaches of calculating the heat flux. The results for the first benchmark problem is shown in the following figures.

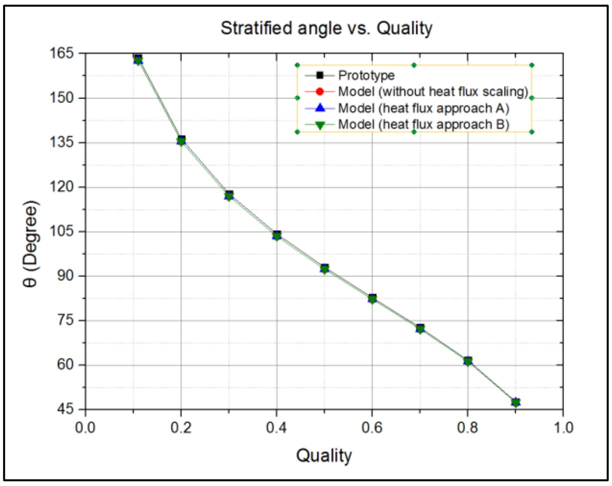

Fig 2.a

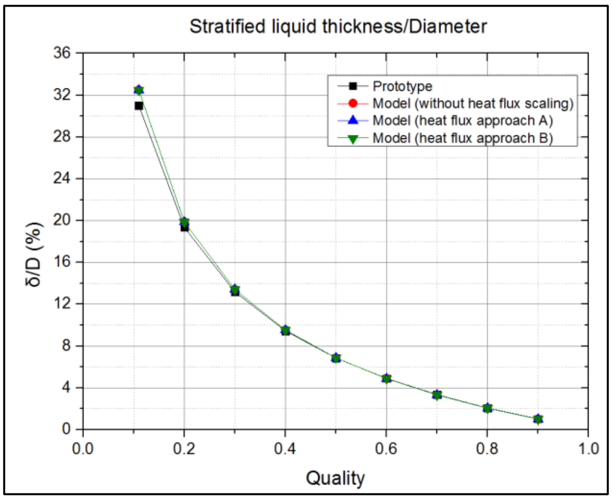

Fig 2.b

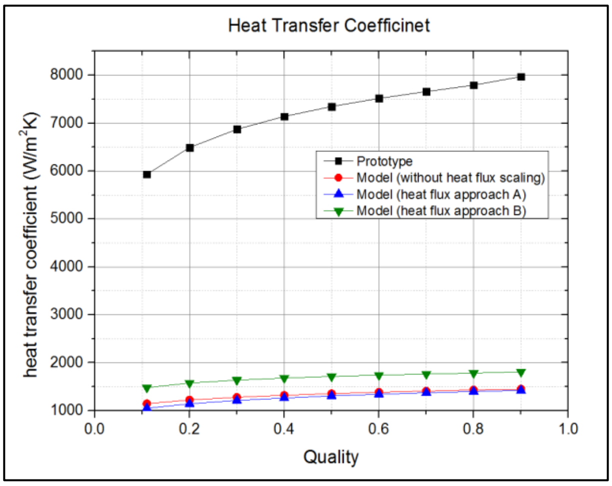

Fig 2.c

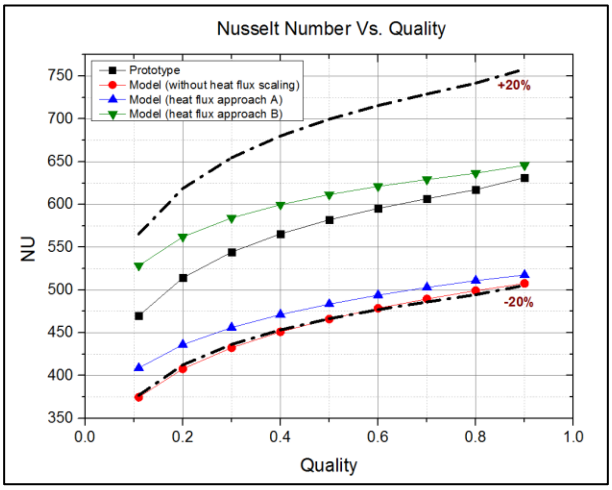

Fig 2.d

Fig. 2 (a-d) Scaling criteria validation for benchmark problem 1.

For the second benchmark problem:

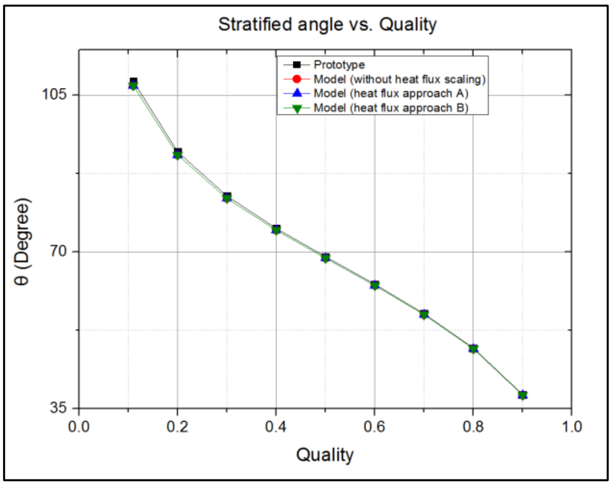

Fig 3.a

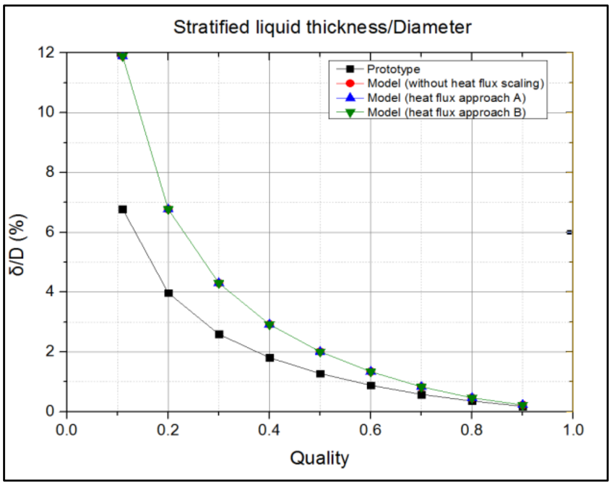

Fig 3.b

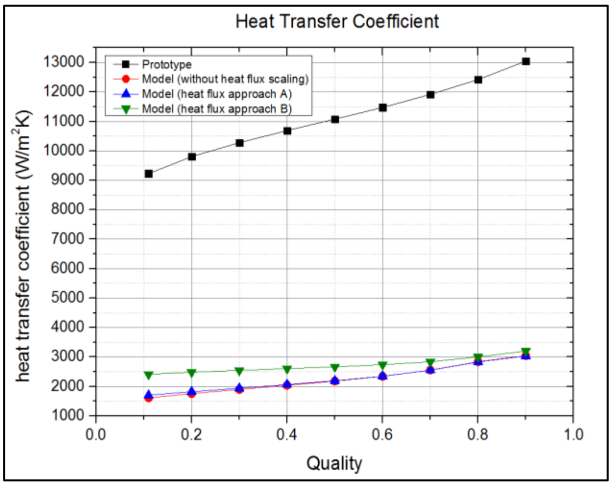

Fig 3.c

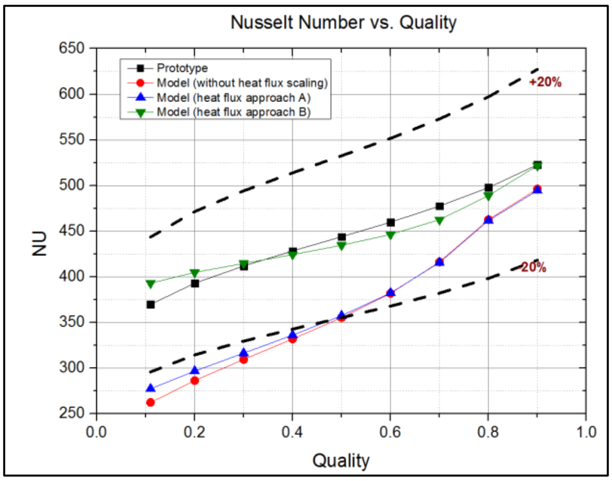

Fig 3.d

Fig. 3 (a-d) Scaling criteria validation for benchmark problem 2.

## 3. Conclusions

In this paper, the case of the stratified flow regime conditions in condensation in horizontal tubes has been studied, and a new heat flux scaling criteria have been added to the developed scaling criteria[1]. It was shown that approach B of the heat flux scaling criterion had shown better matching between the prototypes and the models in terms of the Nusselt number. A further study will be conducted which include more benchmark problems and experimental data for the scaling criteria validation.

## Nomenclature

D: tube diameter
G: mass flux
g: gravity acceleration
P: prototype
k: thermal conductivity
h: local heat transfer coefficient
M: model
V: vapor phase
L: liquid phase
q: heat flux
ρ: density
μ: viscosity

## REFERENCES

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[2] M.K. Dobson, J.C. Chato, condensation in smooth horizontal tubes, J. Heat Transfer Trans. ASME (1983) 193-213.

[3] J.R. Thome et al., Condensation in horizontal tubes, Part2: new heat transfer model based on flow regimes. International Journal of Heat and Mass Transfer 46 (2003) 3349-3363.