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# Falling film evaporation on enhanced tubes, part 2: Prediction methods and visualization

*Marcel Christians, John Richard Thome**

*Laboratory of Heat and Mass Transfer (LTCM), Ecole Polytechnique Fédérale de Lausanne, ME G1 465, Station 9, CH-1015 Lausanne, Switzerland*

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ABSTRACT

For falling film evaporation, the most important thermal design parameters that need to be predicted are the onset of dryout, after which a severe degradation in the evaporator performance is found, and the local heat transfer performance in fully wet and partially dry conditions. Presently, based on the new data and previous data presented in Part 1, new methods for prediction of (i) the nucleate pool boiling heat transfer coefficient, (ii) the onset of dryout and (iii), the bundle heat transfer performance for the enhanced boiling tubes tested at the LTCM laboratory have been developed. These methods minimize the amount of empirical constants required, resulting in only one tube-specific parameter for all three conditions for each enhanced tube. The results from the visualization studies performed are presented and discussed.



# Evaporation d'un film tombant sur des tubes améliorés, Partie 2 : méthodes de prévision et de visualisation

*Mots clés :* Evaporation ; Film tombant ; Ebullition libre ; Assèchement ; Amélioration ; Ebullition ; Ecoulement diphasique ; Visualisation

## 1. Introduction

Numerous attempts at generating empirical and semi-empirical methods for the design of falling film heat transfer equipment have been proposed in the literature. The methods that have been developed for use with different tubes and refrigerants have all generated multiple tube/refrigerant empirical constants which are difficult to keep track of; however, it is not a simple matter to obviate the use of such parameters. Furthermore, since the parameters are tube/

* *Corresponding author*. Tel.: +41 21 693 5981; fax: +41 21 693 5960.
E-mail address: john.thome@epfl.ch (J.R. Thome).

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**Nomenclature**

*Symbol*

| | |
|---|---|
| $A$ | area ($m^2$) |
| $A$ | empirical coefficient |
| $b_i$ | Roques (2007) constants |
| $c$ | empirical coefficient |
| $c_p$ | isobaric specific heat ($J\,kg^{-1}K^{-1}$) |
| $D$ | diameter (m) |
| $E$ | Two-phase enhancement factor |
| $f_{ps}$ | frames per second |
| $F$ | Wet area fraction |
| $G$ | gravitational acceleration ($m\ s^{-2}$) |
| $G_{t-s}$ | tube-specific factor |
| $H$ | heat transfer coefficient ($W\,m^{-2}\ K^{-1}$) |
| $K$ | thermal conductivity ($W\,m^{-1}K^{-1}$) |
| $K_{ff}$ | Falling film multiplier |
| $L$ | tube length (m) |
| $P$ | pressure (kPa) |
| $P$ | tube pitch (m) |
| $Q$ | heat flux ($W\,m^{-2}$) |
| $Re$ | Reynolds number ($4\Gamma\ \mu_l^{-1}$) |
| $S$ | Two-phase suppression factor |
| $T$ | temperature (°C) |

*Greek*

| | |
|---|---|
| $\Gamma$ | ref. overfeed per unit length ($kg\,m^{-1}s^{-1}$) |
| $P$ | density ($kg\,m^{-3}$) |
| $\sigma$ | surface tension ($N\,m^{-1}$) |
| $\mu$ | viscosity (Pa s) |

*Subscripts*

| | |
|---|---|
| *C* | convective |
| *Corr* | correlation |
| *Crit* | critical |
| *Dry* | dry |
| *Ff* | falling film |
| *L* | liquid |
| *O* | internal |
| *Onset* | liquid |
| *Pb* | pool boiling |
| *Pred* | outer |
| *Sat* | saturation |
| *Top* | top |
| *V* | vapor |
| *Wet* | wet |

*Superscripts*

| | |
|---|---|
| *b,d* | empirical exponents |

refrigerant specific, their application to other situations is not recommendable. Below is a brief overview of the previous methods proposed for this purpose.

A simple method of combined evaporation and nucleate boiling in liquid falling films on horizontal plain tubes was developed by Lorenz and Yung (1979). A single smooth horizontal tube was studied by ‘unwrapping’ it to form a vertical surface of length $L = \pi D/2$ and modeling the overall heat transfer coefficient as a superposition of the convective evaporation and nucleate boiling components. This model used the Rohsenow correlation, which requires the knowledge or specification of an empirical fluid-surface factor.

Two methods were developed by Chyu and Bergles (1987) for saturated falling film evaporation (without nucleate boiling) on smooth tubes. The only difference between their two methods was in the fully developed region. The first used the correlations developed by Chun and Seban (1971) for fully developed film evaporation on a vertical tube, while the second used a conduction solution based on Nusselt’s film condensation analysis. For both methods, the perimeter-averaged heat transfer coefficient was obtained from the heat transfer contributions from each of the flow regimes. However, these methods are not applicable when there is nucleate boiling in the film.

Fujita and Tsutsui (1998) performed R-11 falling film evaporation tests on a plain tube bundle, and based on a turbulent flow analysis they proposed a correlation which predicted their experimental data within ±20%.

Chien and Cheng (2006) proposed a new predictive model for smooth tubes including bubble nucleation for five different refrigerants. They developed a superposition model in which the nucleate boiling and the convective components are respectively weighted by a boiling suppression factor $S$ and a two-phase enhancement factor $E$. The $S$ -factor was correlated as a function of the Reynolds, Boiling and Weber numbers. The convective heat transfer coefficient $h_c$ was calculated using the Alhusseini et al. (1998) correlation. The Cooper (1984) correlation was utilized for the nucleate pool boiling heat transfer coefficient. This model predicted their plain tube database consisting of refrigerants R-11, R-123, R-134a, R-141b and R-22 within ±20% for plain tubes and ±33% for the Turbo-B tube.

Roques and Thome (2007a,b) proposed a correlation to predict the falling film multiplier $K_{ff} = h_{ff}/h_{pb}$ for R-134a as a function of the tube pitch $P$ and heat flux for various tubes (plain and enhanced tubes). In their method, the tube pitch $P$ was non-dimensionalized with the minimum tube pitch tested, $P_o = 22.25$ mm and the heat flux $q_o$ was reduced with the critical heat flux $q_{crit}$ from the correlation of Kutateladze (1948). The main limitation of this method is the estimation of the empirical constants $b_1$, $b_2$, $b_3$ and $b_4$ for each fluid/tube combination, which requires a large database of falling film evaporation measurements.

Ribatski and Thome (2007) developed a predictive method for plain tubes using R-134a to characterize both local dryout and non-dryout conditions. They defined an objective criterion to characterize the onset of dryout based on $K_{ff}$. The onset of dryout (i.e. the formation of dry patches) was detected in their database by the resulting drastic decrease of the heat transfer coefficient with decreasing film flow rate and a decrease in the average heat flux.

This selection criterion was used to segregate the data as either being under partial dryout or non-dryout conditions. In this new method for partial dryout, the heat transfer area was divided into wet and dry regions respectively governed by nucleate boiling and vapor natural convection heat transfer.