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Evaluation of Various Correlations for Direct-Contact Heat Transfer in Dispersed Flow Film Boiling Using the DRACCAR Code

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ABSTRACT

Following the core uncovering after a hypothetical loss of primary coolant accident (LOCA), a flow of steam with dispersed droplets forms downstream of the quench front. This flow is crucial for cooling nuclear fuel rods that are not in direct contact with water, representing a typical Dispersed Flow Film Boiling (DFFB) scenario. Depending on accident severity, fuel rod deformation may partially block subchannels, diverting steam towards less deformed areas and potentially impacting cooling. As a result, characterizing heat transfer under such conditions is essential to enhance the nuclear reactor safety during accidents like LOCA. The COLIBRI experimental loop was designed to assess the heat flux released by steam/droplet flow in intact and deformed fuel rod subchannels. Experimental results obtained with this facility helped evaluate various correlations for direct-contact heat transfer calculations in DFFB within the DRACCAR code. In this article, the DRACCAR code is used to compare different correlations for heat transfer due to droplet impacts onto the wall calculation. This comparison was made on four COLIBRI experiments, involving two different droplet mass flow rates (5 kg/h and 11.5 kg/h) and two levels of subchannel deformation (intact and 90% blocked).

KEYWORDS

LOCA, Thermal-hydraulics, Direct-contact heat transfer, Two-phase flow, Dispersed flow film boiling

1.0 INTRODUCTION

Following a hypothetical primary coolant loss accident, the reactor's safety systems will intervene by injecting water to cool the core. Despite the reactor being shut down, the core houses fissile elements that continue to generate residual heat, known as residual power, which must be removed from the reactor core to prevent the core melt down. Once water reaches the high-temperature fuel assemblies, a flow of steam and droplets is formed downstream of the quench front, commonly referred to as DFFB for Dispersed Flow Film Boiling. This flow is crucial as it cools parts of the fuel assemblies not yet in contact with liquid water. Therefore, understanding the physical heat transfer phenomena in this flow with the assemblies is crucial for nuclear safety.

However, this flow is intrinsically complex, as since droplets and steam are not in thermal or dynamic equilibrium. Additionally, there can be droplet fragmentation or coalescence, along with a non-uniform distribution of droplet sizes and velocities in the flow. Also, depending on the severity of the accident, fuel

rods may deform, creating partially blocked zones for the coolant flow. This phenomenon, in turn, causes steam to deviate towards the less deformed zones of the fuel assembly due to differences in pressure losses, a phenomenon known as steam redistribution in assemblies having partially blocked zones (Figure 1).

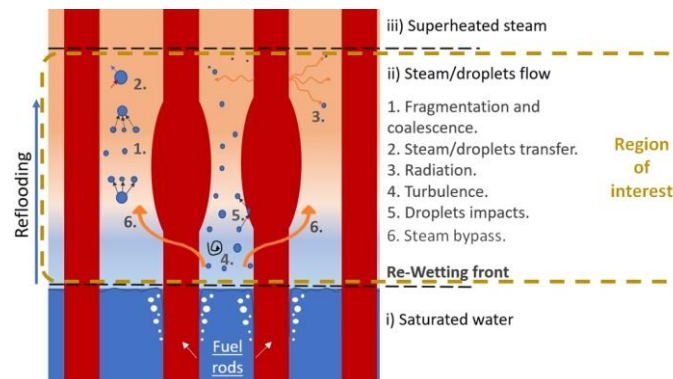


Figure 1. Heat and mass transfer phenomena in LOCA.

To enhance the understanding of nuclear assembly cooling after a LOCA, the IRSN developed the experimental facility COLIBRI (COoLing of Blockage Region Inside a PWR Reactor) [5]. This experimental bench aims to characterize the heat extraction by the DFFB on the scale of a subchannel, allowing for a detailed DFFB characterization using non-intrusive techniques such as Laser Induced fluorescence (LIF) and Phase Doppler Anemometry (PDA) for temperature and both size-velocity droplet measurements respectively. Additionally, COLIBRI enables the characterization of heat extracted from the tube by the two-phase flow in various geometric and thermohydraulic configurations, simulating different degrees of deformation of the fuel assemblies.

COLIBRI aims to provide crucial experimental data for validating the DRACCAR code (Deformation and Reflooding of a Fuel Assembly during a Cooling Accident), developed by IRSN to simulate fuel assembly behavior following a hypothetical Loss of Coolant Accident (LOCA). DRACCAR comprehensively models the dynamic evolution of rod geometry during the accident, considering various configurations of blocked sub-channels and encompassing phenomena such as 3D thermal conduction, thermal exchanges, cladding creep deformation, fuel relocation, oxidation, hydriding, mechanical interaction of deformed rods, and feedback on fluid passage sections [6]. DRACCAR is coupled to either CATHARE3 or CESAR for fluid thermal and hydraulic calculations. The code realistically captures the three-dimensional thermal-mechanical behavior of fuel rods, evaluating blockage degree caused by deformations and their impact on cooling, accounting for both mechanical and thermal interactions. The completion of COLIBRI experiments plays a vital role in enhancing the validation of DRACCAR, ensuring its reliability in simulating post-LOCA scenarios.

The comparison between DRACCAR and the first experimental campaign of COLIBRI revealed that DRACCAR accurately estimated the heat flux extracted by the internal flow [7]; however, a discrepancy was observed in DRACCAR's calculation when the volumetric fraction of droplets was more significant. This difference is likely attributed to DRACCAR's use of the Berenson correlation [8] for calculating wall/fluid heat transfer, which is not very suitable for DFFB. Therefore, in the second experimental campaign of COLIBRI, we significantly increase the injected mass flow of droplets and the steam injection temperature. Consequently, this upgrade increased sensitivity to detect the potential influence of droplets on heat transfer, especially due to their impacts on the wall and their role in steam/wall convection [8].

The calculation of heat flow from droplet impacts in film boiling occurs in two steps: calculating the energy transferred by a droplet impact and combining it with the calculation of the droplets' impact flux on the

wall. To enhance DRACCAR's accuracy in estimating heat flow between droplets and the wall, this article compares two correlations for calculating energy transfer during a droplet impact: Breitenbach et al.'s correlation [1] and Lelong et al.'s correlation [2]. Additionally, two correlations for calculating the droplet mass flux impacting the wall were evaluated: Hewitt and Govan's correlation [3] and Okawa and Kataoka's correlation [4]. These DRACCAR simulations were compared with four COLIBRI experiments, involving two droplet mass flows (5kg/h and 11 kg/h) and two subchannel configurations (intact and 90% blocked). The analyzed blockage ratio (τ_b) corresponds to the percentage reduction in the coolant flow area after the deformation of the fuel rods ($\tau_b = 1 - S_b/S_0$), where S_0 and S_b are the cross-sectional areas of the subchannel before and after the deformation (blockage) of the nuclear rods, respectively.

2.0 EXPERIMENTAL BENCH: COLIBRI

Figure 2a illustrates the schematic view of the COLIBRI experimental setup. The test section is divided into three key components: I. a segment dedicated to developing the steam flow with dispersed droplets through the independent injection of droplets at saturation and superheated steam. Notably, a T-type connector has been incorporated to deviate a part of the steam flow before it enters the test tube, specifically for experiments requiring this setup (as depicted in Fig.2b), II. A movable tube serving as a representative of a fuel subchannel, heated through the Joule effect, and III. A system designed for managing superheated steam with dispersed droplets. Positioned between each of the outlined sections is a Quartz window, allowing measurements of droplet distribution and velocity by PDA technique. Additionally, an infrared camera captures the transient temperature of wall of the test tube (as indicated in section II of the figure).

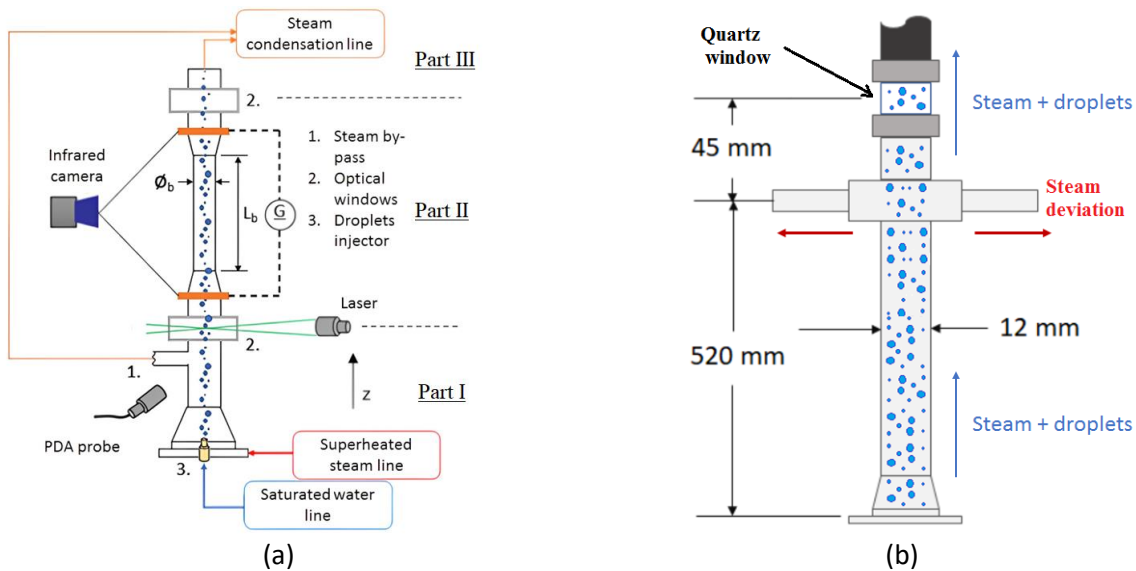


Figure 2. Diagram of a) the test section of COLIBRI and b) a detailed schema of Part I of COLIBRI [8].

To represent an unblocked subchannel, an intact tube of Inconel 625 with an internal diameter identical to the hydraulic diameter of a French reactor (PWR) subchannel ($D_h = 11.78$ mm) is used. For simulating a severely blocked tube (90% blockage), a Venturi-type geometry Inconel 625 tube was employed (Figure 3). This tube consists of two ends with an intact case diameter, followed by a conical section and a central (blocked) section with an internal diameter equal to the hydraulic diameter of partially blocked subchannels (3.72 mm).

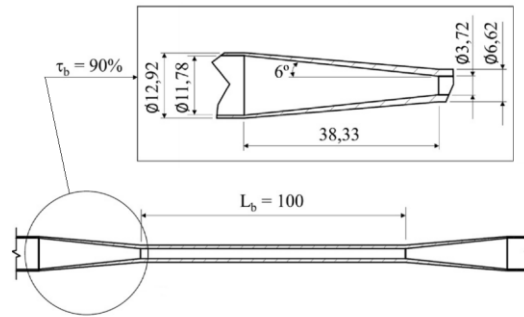


Figure 3. Detailed drawing of test tube (Part II in Fig. 2a) for the configuration of 90% blockage ratio [5].

The experimental setup allows for measurements of steam temperature, mass flow rates of steam and droplets at the inlet, and steam pressure at the inlet. These measurements are obtained using a type-K thermocouple, a Rosemount® flowmeter, and a Keller® pressure transmitter, respectively. The data is recorded during each experiment.

The primary goal of the experimental rig is to characterize the cooling of the tube representing a subchannel by a typical LOCA droplet and steam flow, along with a detailed characterization of the two-phase flow. To determine the heat flux, the transient temperature data from the infrared camera is utilized. By performing an energy balance on the tube wall, the internal heat flux extracted by the steam and droplet flow is obtained. The approximate error in the flux measurement in the film boiling region is 11.2% with a 95% confidence interval. Detailed information on the energy balance, experimental protocol, PDA system, and uncertainties of this experimental setup is described in Luna Valencia [8].

3.0 DRACCAR CODE

The DRACCAR code is a computational tool developed by IRSN to support the safety analysis of pressurized water reactors. The code is designed to simulate various types of loss-of-coolant accidents, including those affecting the reactor core (LOCA) and those leading to the uncovering of the fuel storage pool. DRACCAR realistically describes the 3D thermomechanical behavior of a fuel assembly during a LOCA, assessing the blockage rate due to deformed rods and their impact on cooling, considering both mechanical and thermal interactions between rods.

For COLIBRI test simulations, the thermomechanical and thermochemical models of the code are not activated as the COLIBRI geometry is fixed, and there is no oxidation phenomenon occurring in the tube. From a thermohydraulic perspective, DRACCAR employs the CESAR code for simulations. The coupling between the wall code and the thermohydraulic code is fully implicit and uses an advanced method to handle two-time steps, one relatively large for wall resolution and a smaller one for fluid resolution ensuring reasonable computation times.

3.1 Modeling of COLIBRI Test Tubes

DRACCAR can simulate 3D thermo-hydraulic phenomena inside a fuel assembly. The finest modeling scale from a thermo-hydraulic perspective is the subchannel, which means there is no radial velocity profile inside a subchannel. Therefore, for COLIBRI, DRACCAR utilizes a 1D mesh. The temperature evolution of the tube wall is estimated with DRACCAR. The discretization chosen for this wall consists of 5 nodes in thickness, 1 node azimuthally, and 33 nodes axially (Figure 4).

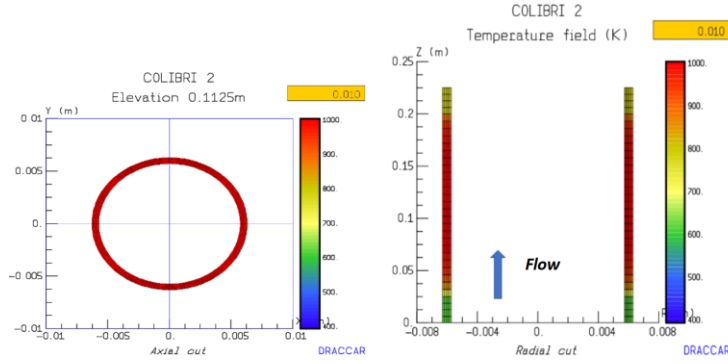


Figure 4. COLIBRI mesh diagram made for DRACCAR [8].

3.2 DRACCAR thermal module

DRACCAR solves the heat equation in the walls, considering heat transfer through conduction (3D), radiation between walls and with the fluid, and convection. The heat transfer by conduction between mesh faces is explained by the thermal resistance associated with the mesh structure. Radiative heat transfer considers radiation between wall surfaces and the interaction between radiation and steam. Convective heat transfer is determined by different models for various flow configurations expected during a LOCA (Liquid Convection, Nucleate Boiling, Film Boiling, etc.). Table 1 summarizes the correlations used by DRACCAR in film boiling regime. In film boiling, it is considered that part of the extracted heat goes to the droplets through a vapor layer that separates them (wall to droplets heat transfer) and another part to the superheated vapor (wall to vapor convection).

Table 1. Correlations used by DRACCAR to calculate wall-to-fluid heat transfer in the film boiling regime [6].

Description	Equation
Radiation	Two-dimensionnal Hottel's crossed string method [9], applied to determine the view factors to solve: $\Phi_{i \rightarrow j} = \sigma \overline{S}_i \overline{S}_j (T_i^4 - T_j^4)$, where σ is the Stefan-Boltzmann constant and $\overline{S}_i \overline{S}_j$ is the total surface area for radiation exchange.
Steam/wall convection [10] [11]	$Nu = \max[0.0083 \cdot Re_s^{0.877} Pr_s^{0.611}, 0.0210 \cdot Re_s^{0.8} Pr_s^{0.5}]$
Wall to droplets heat transfer [12]	Berenson transfer coefficient: $h_{film} = 0.425 \left[\frac{k_s^3 g^{3/2} \rho_s (\rho_d - \rho_s)^{3/2} D_h}{2\pi \mu_s \sigma^{1/2} (T_w - T_{sat})} \right]^{1/4}$

3.3 CESAR thermo-hydraulic code

CESAR, the thermo-hydraulic code used in DRACCAR, employs a two-fluid model with 6 balance equations for mass, energy, and momentum conservation. It calculates key fluid characteristics, including pressure, void fraction, phase temperatures, and velocities. Notably, it does not account for a polydisperse

droplet distribution, instead characterizing droplets by void fraction, liquid velocity, and average diameter (d_{10}). The equations of balance are summarized in Table 2.

Table 2. Conservation equations of CESAR [6] from Ishii average equations [13].

Description	Equation
Phase k mass conservation	$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \vec{V}_k) = \Gamma_k$
Phase k momentum conservation	$\alpha_k \rho_k \left(\frac{\partial \vec{V}_k}{\partial t} + \vec{V}_k \cdot \nabla \vec{V}_k \right) = -\alpha_k \nabla P + (P_i - P) \nabla \alpha_k + (-1^k) \vec{\tau}_i + \vec{\tau}_{kw} + \alpha_k \rho_k \vec{g}$
Phase k energy balance	$\begin{aligned} \frac{\partial}{\partial t} \left[\alpha_k \rho_k \left(H_k + \frac{V_k^2}{2} \right) \right] + \nabla \cdot \left(\alpha_k \rho_k \vec{V}_k \left(H_k + \frac{V_k^2}{2} \right) \right) \\ = (-1^k) \Gamma_k \left(H_k + \frac{W_i^2}{2} \right) + q_{ki} + q_{kw} - \alpha_k \frac{\partial P}{\partial t} + \alpha_k \rho_k \vec{V}_k \vec{g} \end{aligned}$

With Γ_k representing the volumetric production rate of phase k due to the phase change resulting from various thermal exchanges between steam and liquid. The variables P , P_i , $\vec{\tau}_i$, and $\vec{\tau}_{kw}$ denote the common pressure of both phases, interfacial pressure, interfacial friction per unit volume (changes sign depending on the phase k), and wall friction per unit volume respectively. Finally, H_k represents the enthalpy of phase k , q_{ki} and q_{kw} are the volumetric energy exchanges between phase k and the interface and between phase k and the wall respectively. W_i is the velocity of the interface.

4.0 Heat Transfer correlations

4.1 Droplet Impacts on the Wall

For this analysis, it was decided to assess the heat transfer between the wall and droplets in DFFB as the heat transfer extracted from the droplets during their impact on the wall. This impact is characterized by the instantaneous generation of a vapor layer that separates the droplet from the high-temperature wall. Similarly, droplets bounce without fragmentation during their impact because the impact velocity is generally small ($We < 10$). For this heat transfer estimation, the following equation is employed:

$$\Phi_{imp} = \frac{6\dot{m}_{dep}E_{1d}}{\rho_d \pi d^3} \quad (1)$$

This implies that the energy extracted by the impact of a droplet (E_{1d}) and the mass flux rate of droplets impacting the wall (\dot{m}_{dep}) must be estimated. Table 3 summarizes the correlations used for the estimation of the energy extracted during the impact of a droplet.

Lelong et al. [2] used the model proposed by Biance et al. [14] for calculating the variation in droplet diameter during impact ($R_s(t)$) on a horizontal wall. Since our study focuses on the interaction of a droplet in a vertical tube, it has been decided to replace the gravity acceleration g with the impact acceleration on the $R_s(t)$ equation, using the following expression as an approximation:

$$a_{imp} = \frac{2u_{imp}}{t_R} \quad (2)$$

Table 3. Energy of single droplet correlations in DFFB.

Description	Equation
Lelong et al. [2] Gradeck et al. [13]	$E_{1d} = \pi \left[\frac{8}{9} (Nuk_s (T_w - T_{sat}) r_d)^3 \frac{\rho_s \rho_d (h_{fg} + Cp(T_{sat} - T_d)) [a_n]}{\mu_s} \right]^{1/4} \int_0^{t_R} r_d(t) dt + \epsilon_w \sigma_B (T_w^4 - T_d^4) \pi \int_0^{t_R} r_d^2(t) dt$ <p>With:</p> $R_s(t) = (2r_g^3)^{1/2} \left(\frac{g}{w_0^2} e^{-\lambda t} \left[\cos(w_1 t) - \frac{w_0}{w_1} (2\pi r_t + r_g) \sin(w_1 t) \right] - \frac{g}{w_0^2} + d_g \right)^{-0.5}$ $\lambda = 0.1 \mu_g d_g Re^{0.8} m_d^{-1}, w_0 = \sqrt{\frac{4}{5 m_d} \sigma \pi (0.92 We + 1.25)},$ $w_1 = \sqrt{w_0^2 - \lambda^2}, r_g = \frac{\lambda}{w_0}, r_t = u_{imp} w_0 / (2\pi g)$
Breitenbach et al. [1]	$E_{1d} = \frac{4.63 D_0^{5/2} G e_w (T_w - T_{sat})}{u_{imp}^{1/2} (K + 2G)}, \quad K = \sqrt{(B - G)^2 + \frac{4G}{\sqrt{\pi}}} - B - G$ $G = \frac{\sqrt{\pi} \lambda_s \rho_d h_{fg}}{2(T_w - T_{sat}) e_w^2}, \quad B = \frac{\sqrt{5} (T_{sat} - T_d) e_f}{\sqrt{\pi} 2(T_w - T_{sat}) e_w}$

The impact velocity is calculated as:

$$u_{imp} = \frac{\dot{m}_{dep}}{\rho_d \alpha_d} \quad (3)$$

Finally, for the estimation of the droplet flow extracted from the wall, a comparison was made between the correlations for annular flow proposed by Hewitt and Govan [3] and Okawa and Kataoka [4], correlations summarized in Table 4.

Table 4. Correlations for droplets deposition calculation.

Description	Equation
Hewitt and Govan [3]	$\dot{m}_{dep} = \min \left[0.18, 0.083 \left(\frac{\rho_s}{\bar{C}} \right)^{0.65} \right] \bar{C} \left(\frac{\sigma}{\rho_s D_h} \right)^{0.5}$
Okawa and Kataoka [4]	$\dot{m}_{dep} = \min \left[0.19 \left(\frac{\rho_s}{\bar{C}} \right)^{0.2}, 0.105 \left(\frac{\rho_s}{\bar{C}} \right)^{0.8} \right] \bar{C} \left(\frac{\sigma}{\rho_s D_h} \right)^{0.5}$

As mentioned, the DRACCAR code does not consider the polydispersity of the droplets. Therefore, for this analysis, it was decided to fix a single diameter for the droplets in each experiment, corresponding to the experimentally obtained average Sauter diameter (d_{32}) in COLIBRI. Additionally, the effect of diameter

variation due to evaporation is neglected. Likewise, for each simulation, the DRACCAR code initializes with the wall temperature from COLIBRI at first time step and uses the same steam mass flow recorded during each experiment. Pressure and droplet mass flow variations are insignificant during the experiments, so a fixed value is used throughout the simulation, corresponding to the experimentally obtained value.

4.2 Steam to wall convection

Luna Valencia found that the Gnielinski [15] and Petukhov [16] correlations adequately describe the heat convection transfer between single-phase steam flow in COLIBRI and the high-temperature wall [8]. In the present analysis, it was decided to change the correlation used by DRACCAR (Table 1) to calculate steam-to-wall convection to the Gnielinski correlation [15], validated in COLIBRI. Additionally, the term used by TRACE [17] was added to account for the enhancement in heat convection transfer between steam and the wall:

$$Nu_{sw} = Nu. \min \left[5, \left(1 + 25 \frac{\alpha_d \rho_s g \Delta \rho D_h^3}{\mu_v^2 Re_s^2} \right)^{0.5} \right] \quad (4)$$

In equation 4, the Nusselt number is calculated with Gnielinski correlation [15].

4.3 Steam to droplets convection and radiation

In this analysis, the correlation used to calculate radiation between the wall, droplets, and steam was not modified. This is because the temperature range in COLIBRI is low, making thermal radiation insignificantly influential in the calculations. Similarly, the model used by DRACCAR to calculate convective heat transfer between the steam and droplets was not altered. This is because a change in the correlation would not be sensitive in the calculation. Previous analysis indicate that this heat transfer mechanism contributes less than 20% to droplet evaporation [8].

5.0 Results and discussion

Table 5 provides an overview of the experimental parameters employed in each test. The recorded values encompass the mass flow rates of droplets (\overline{m}_d) and steam (\overline{m}_s), measured upstream of the test section, in addition to the steam pressure (p_s). These values are averaged from the data measured during each specific experiment. The presented bypass measurement signifies the percentage of steam mass flow deviated before entering the test tube, and it is assumed to closely correlate with the blockage ratio. Within the table, both the total injected steam flow into the test section and the fraction of steam mass flow entering the test tube after deviation are detailed. The determination of the deviated steam rate relies on the experimental outcomes observed by Oliveira et al. [18], confirming a proportional relationship with the blockage ratio ($\tau_b = 1 - S_b/S_0$), estimated at approximately 90% in this instance.

Table 5. Thermal-hydraulics parameters of COLIBRI experiments

Exp.	τ_b	\overline{m}_s	\overline{m}_d	Bypass	$\overline{m}_{s,i}$	\overline{p}_s	$T_{s,i}$
B0-L	0%	3.9 kg/h	5.1 kg/h	0%	3.9 kg/h	1.3 bar	363 °C
B0-H		3.3 kg/h	11.5 kg/h		3.3 kg/h	1.5 bar	292 °C
B90-L	90%	3.9 kg/h	5.7 kg/h	92%	0.31 kg/h	1.3 bar	313 °C
B90-H		3.8 kg/h	11.5 kg/h	86%	0.49 kg/h	1.3 bar	317 °C

The results were compared based on the mean heat flux extracted by the flow in the central 60 mm of each tube as a function of the wall temperature obtained from the COLIBRI experiments and calculated by the DRACCAR code. Similarly, only the results in DFFB were compared; thus, only this region of cooling is shown and compared. Figure 5 shows the film boiling region in a typical figure of mean internal heat flux.

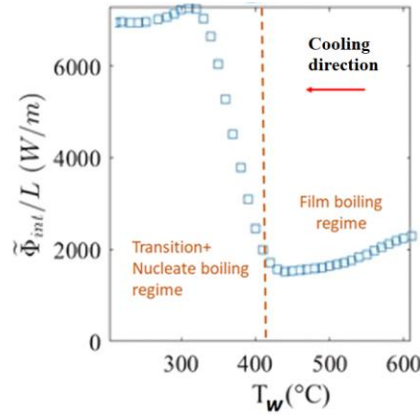
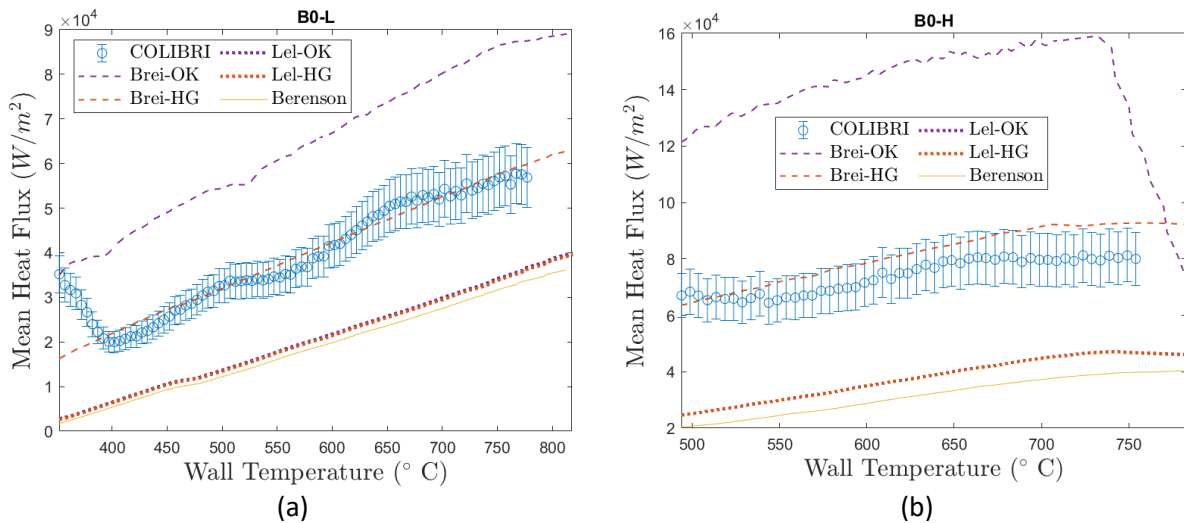


Figure 5. Film boiling region of experimental results.

Figure 6 depicts the comparison of the calculated internal heat flow using different correlations in DRACCAR and the experimental results from COLIBRI for various experiments. As evident, in general, DRACCAR simulations correctly estimate only experiments without deviation (B0-L and B0-H) using the Breitenbach et al. correlation [1] and the Hewitt et Govan correlation [3], while they overestimate correlations with steam deviation (B90-L and B90-H). Similarly, DRACCAR simulations underestimate the flow obtained by COLIBRI when using the Lelong et al. correlation [2] and Berenson correlation [12] in all cases. Similarly, a significant difference in the result is observed when using the Breitenbach correlation [1] for calculating the energy transferred during droplet impact and the two correlations analyzed for estimating the droplet flux impacting the wall. This difference is not evident when using the Lelong et al. correlation [2]. This is because the Breitenbach correlation is more sensitive to the droplet impact velocity, which is calculated from the droplet flux impacting the wall.



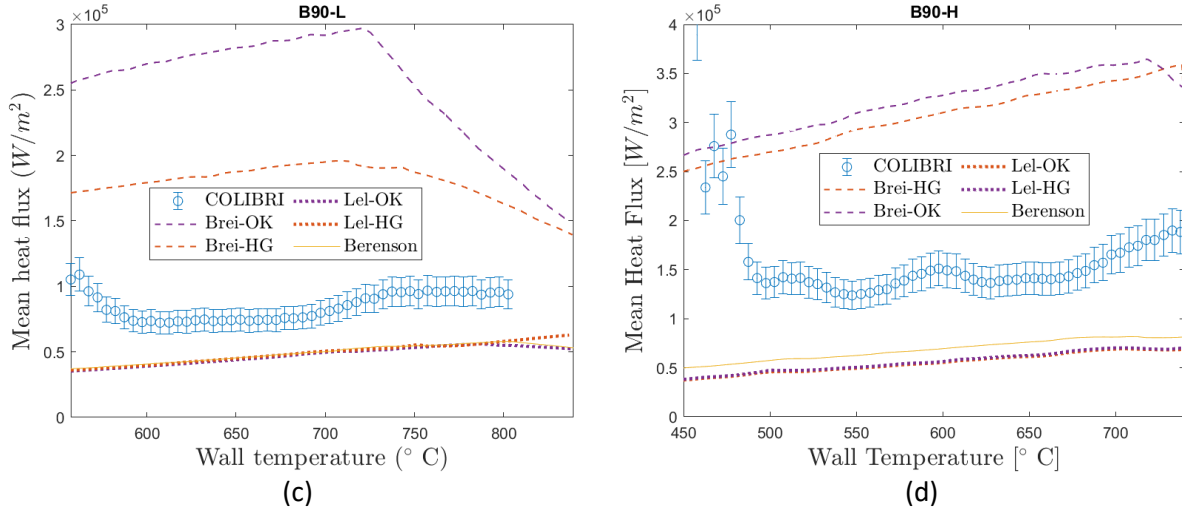


Figure 6. Simulation and experimental results comparisons of a) B0-L, b) B0-H, c) B90-L and d) B90-H (the legends correspond to the following correlations: Brei for Breitenbach et al., Lel for Lelong et al., OK for Okawa and Kataoka, and HG for Hewitt and Govan.).

Table 6 summarizes the average error between various DRACCAR simulations and the experimental results from COLIBRI in the film boiling regime. As evidenced in the preceding figures, DRACCAR using the Berenson correlation [12] does not yield satisfactory results in estimating the internal flow extracted by the steam and droplet mixture. Similarly, the table confirms that DRACCAR simulations perform well when utilizing the Breitenbach correlation [1] combined with Hewitt et Govan [3], but only for experiments without deviation. In cases where there is steam deviation, the DRACCAR results with the analyzed correlations are not accurate. This can be explained by the fact that two correlations obtained for annular flow were used to calculate the droplet flow rate impacting the wall. This regime differs from film boiling because in annular flow, there is a liquid layer separating the steam and dispersed droplet flow from the wall. Consequently, possible interactions that droplets may have when near a high-temperature wall are ignored. Unfortunately, there are no correlations applicable to the studied regime. One option proposed by Meholic [19] is to perform a force balance on the droplet near the wall to determine whether the droplet has sufficient inertia to impact the high-temperature wall or not. However, it is a challenging model to adapt for a 1D code.

Table 6. Mean error between DRACCAR simulations and COLIBRI experimental results.

Experience	Breitenbach et al.		Lelong et al.		Berenson
	Okawa and Kataoka	Hewitt and Govan	Okawa and Kataoka	Hewitt and Govan	
B0-L	67.2%	4.4%	49.9%	50.6%	54.6%
B0-H	95.5%	9.4%	48.6%	48.7%	57.3%
B90-L	228.4%	125.1%	41.5%	40.6%	39.9%
B90-H	127%	115%	60%	59.5%	51%

6.0 Conclusions

A comparison of different correlations for estimating the energy transferred by droplet impact in DFFB was conducted using the DRACCAR code and experimental results from COLIBRI. The selected COLIBRI experiments involved two different droplet mass flows and two blockage ratios (0% and 90%), evaluating the influence of steam deviation, as might occur in a LOCA. The results showed that the correlation of Breitenbach et al. [1] used with the Hewitt and Govan correlation [3] obtained the lowest error in comparison with experimental data in cases without steam deviation. In cases of deviation, DRACCAR calculations with this correlation combination overestimated the transferred energy, likely due to the increased droplet concentration in the blocked region. On the other hand, the DRACCAR code with the Lelong et al. [2] correlation underestimated the internal heat flux in all evaluated experiments, regardless of which correlation was used for calculating the wall-impacting droplet flux.

Similarly, a considerable influence of the correlation used for calculating the wall-impacting droplet mass flux is evident when using the Breitenbach correlation [1]. When the Okawa and Kataoka correlation [4] is used with Breitenbach correlation [1], the internal heat flux is considerably overestimated. However, this phenomenon is not evident when using the Lelong et al. correlation [2], where the change in correlation for droplet mass flux has little effect on the final calculation. This is probably because the Breitenbach's correlation [8] is more sensitive to changes in the droplet impact velocity.

No combination of correlations provided satisfactory results when the simulation was conducted in cases with steam deviation and a decrease in diameter due to partial sub-channel blockage simulation. This could be linked to the fact that the correlations used for calculating the wall-impacting droplet flux are not valid in these cases. It is essential to note that these correlations were obtained for an annular flow, where there is the presence of a liquid film on the wall. Consequently, they do not consider the influence of the interaction between droplets and the high-temperature wall. An analysis of droplet forces is planned in a future study.

7.0 References

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