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Heat transfer correlation for intermittent spray impingement: A dynamic approach

M.R.O. Panão*, A.L.N. Moreira

Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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A B S T R A C T

The work presented here investigates a new approach in the development of heat transfer empirical correlations for intermittent spray impingement, based on simultaneous measurements of the spray droplets characteristics and the surface thermal behavior. Conventionally, heat transfer correlations for spray impingement do not consider the temporal variations of droplets characteristics. However, in applications using intermittent sprays (internal combustion engines, cryogen spray cooling or microprocessor thermal management), the spray transient behavior suggests that heat transfer predictions may be improved using a dynamic approach. Additionally, the impact of multiple consecutive injections on a heated surface implies a certain degree of interaction, depending on the frequency of their intermittency. If the time between consecutive injections is shorten, the result is the formation of a liquid film which mitigates phase-change and privileges a single-phase heat transfer over a two-phase. This suggests that heat transfer correlations for spray impingement should take the spray unsteadiness and the multiple injections interaction degree into account. The dynamic approach here suggested presupposes the identification of systematic periods characterizing the spray dynamic behavior and, once identified, the development of a heat transfer correlation for each period. The analysis ends with a comparison between the dynamic heat transfer correlation with a correlation obtained using the conventional approach and a significant improvement in heat transfer predictions is achieved if the spray dynamic nature is considered.

1. Introduction

Spray cooling is recognized as a well known method for high heat flux removal. Recently, the application of an intermittent spray in thermal management systems has been proposed as a new technological concept for the enhancement of heat transfer, providing the system with an improved performance, as well as an active control over heat transfer mechanisms [1]. From another point of view, further enhancements in spray cooling technology have been suggested implying the active control of the spray characteristics using synthetic-jets [2]. This emphasizes a current trend in the development of efficient spray cooling systems by introducing a 'control' component in the system's design. This opens the research question of what is the relation between the ability to control the heat transfer process and the mechanisms which actually govern the process.

From the 'control' point of view, in intermittent spray cooling, Panão and Moreira [3] identified the 'duty cycle' as a parameter which expresses the interface between controlling the surface temperature and the physical mechanisms associated with spray impaction. The 'duty cycle' (DC) is defined as the percentage of the entire cycle time where fluid is injected, corresponding to the pulse duration (Δt_{inj}), and expressed as $DC = \Delta t_{inj} \times f_{inj}$. From the 'mechanisms governing heat transfer' point of view, some apparent contradictions can be found in the literature about what parameters actually govern heat transfer. For example, while Arcoumanis and Chang [4], Bernardin et al. [5] and Chen et al. [6] argued that droplet axial velocity plays a dominant role in governing local, time-resolved heat transfer, in Estes and Mudawar [7], and Rybicki and Mudawar [8] it is argued that volumetric flux is of much greater significance in characterizing spray heat transfer than drop velocity. In Sawyer et al. [9], Yao and Cox [10] and Cabrera and González [11] arguments are presented for the spray mass flux, and in Rini et al. [12] for the droplet number flux as the main parameters governing heat transfer. In Pikkula et al. [13] it is the Weber number ($\rho U_d^2 D_d/\sigma$), and in Chen and Hsu [14] it is the initial wall superheating degree ($T_w - T_b$) that is considered to be of primary importance for the heat flux removal in spray cooling. Therefore, there is still much uncertainty as to what are the actual parameters which mainly affect spray/wall heat transfer in general. Eventually,

* Corresponding author. Tel.: +351 218417851; fax: +351 218496156.
E-mail address: mpanao@dem.ist.utl.pt (M.R.O. Panão).

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Nomenclature

c_p	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Ca	capillary number
D	droplet diameter (μm)
DC	duty cycle $= \Delta t_{\mathrm{inj}} f_{\mathrm{inj}}^{-1} \times 100\%$ (%)
f	frequency (Hz)
h_c	heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
h_{fg}	latent heat of evaporation ($\mathrm{J\,kg^{-1}}$)
Ja	Jakob number
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
L_w	plate thickness (mm)
La	Laplace number
Nu	Nusselt number
p	pressure (bar)
Pr	Prandtl number
$\dot{q}''$	heat flux ($\mathrm{W\,m^{-2}}$)
$\dot{q}''_{d,n}$	number flux of droplets ($\#\,\mathrm{m^{-2}\,s^{-1}}$)
r_{disc}	disc radius (mm)
r_{tc}	thermocouple radius (mm)
Re	Reynolds number
T	temperature (°C)
t	time (s)
U	droplet axial velocity ($\mathrm{m\,s^{-1}}$)
We	Weber number
Z	axial distance (mm)

Greek letters

β	thermal effusivity ($\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$)
χ	evaporated mass fraction
δr	interaction radius of multiple drop impacts
Δt	time interval (ms)
ΔT	temperature difference (°C)
λ	Dimensionless number flux
Λ	average liquid film thickness (μm)
μ	dynamic viscosity ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
θ	top to bottom surface temperature difference
ρ	specific mass ($\mathrm{kg\,m^{-3}}$)
σ	surface tension (N m)
ξ	$= L_w \beta k_w^{-1}$ ($\mathrm{s^{1/2}}$)

Subscripts

b	boiling point
c	convection
er	electric resistance
f	fluid
imp	impingement
inj	injection
w	wall
wb	wall to boiling

Abbreviations

LFS	leading front of the spray
PDA	Phase Doppler Interferometry
SS	steady spray
ST	spray tail

all these parameters are simultaneously present and interrelated, and depending on the experimental or operating conditions, one of them governs heat transfer, while others may govern less. Nevertheless, this usually ends in the lack of universality of any derived empirical correlation, which can only be resolved through incremental improvements. Moreover, to accurately model the energy exchanges in spray cooling, it is important to understand the main effects underlying the interaction between the impinging spray characteristics and the heat flux removed from the impinging heated surface, which is the context of the work presented here.

In cases where the heat flux removal is transient, such as in intermittent spray cooling, the interaction between the impinging spray and the heat removal is affected by the spray dynamic behavior along each injection cycle, and by the interaction between consecutive injections. Therefore, it is also worth questioning about the role of the spray dynamics in governing heat transfer phenomena, which requires simultaneous measurements of the spray characteristics and the heat transferred in the cooling process [15].

This work uses such simultaneous measurements to investigate a novel approach in the development of heat transfer correlations for spray impingement, based on the spray dynamic behavior. The paper is structured as follows. After briefly reviewing what has been the conventional approach in the development of heat transfer empirical correlations in Section 2, an experimental setup and the diagnostic techniques used in the characterization of spray impingement heat transfer are described in Section 3. Section 4 analyzes the simultaneous measurements of the spray droplets characteristics and the resulting heat transfer upon their impaction. The results in this section suggest that devising heat transfer correlations with intermittent sprays should be approached from a dynamic point of view. The section ends with a physical interpretation and comparison with a heat transfer correlation derived from the same data, however, using a conventional approach. Finally, Section 5 contains some concluding remarks.

2. Review on the development of heat transfer correlations for spray cooling

This section briefly reviews the empirical correlations found in the literature for spray impingement heat transfer and advances a physical interpretation of their outcome. The elementary way of establishing a spray/wall heat transfer correlation is through dimensional analysis. The simplest form of an arbitrary function in dimensional analysis, for developing a spray/wall heat transfer correlation, was used in the modeling scheme of Eckhause and Reitz [16] as

$$f(h_c, \rho, k, \mu, c_p, \Lambda) = 0 \tag{1}$$

The assumptions behind equation (1) depart from a boundary layer flow analogy applied to a single drop impact which floods the wall, forms a thin liquid film of average thickness Λ, thus, the heat transfer is correlated with this liquid film. Considering the 6 parameters in (1) and 4 independent dimensions (kg, m, s, K), two dimensionless groups are determined: i) the Nusselt number, $\mathrm{Nu} = h_c\Lambda/k$; ii) and the Prandtl number, $\mathrm{Pr} = \mu c_p/k$. The final correlation is written as

$$Nu = aPr^b \tag{2}$$

which in Eckhause and Reitz [16] assume the values $a = 3.32$ and $b = 0.333$, for a wetting regime. The fact that $b > 0$ denotes the positive influence of drop impact velocity – determinant to the velocity boundary layer – over the thermal boundary layer developed in the liquid film. In the non-wetting case, particularly in the