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Comparison of empirical correlations and a two-equation predictive model for heat transfer to arbitrary arrays of single-phase impinging jets

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ABSTRACT

This paper presents a partial review of single-phase experiments & correlations for heat transfer to an array of impinging jets and compares their ability to be predicted by a two-equation numerical model for an arbitrary array of jets. It is found that the two-equation numerical model can predict the average Nusselt number with a mean absolute error of 15.8% over the following ranges: $Re < 10^5$, $0.054\ \text{mm} < d_n < 8\ \text{mm}$, $0.05\ \text{kg/m}^2\ \text{s} < \text{mass flux} < 7000\ \text{kg/m}^2\ \text{s}$, $0.25 < H/d_n < 30$, $1.8 < S/d_n < 330$, $1 < N < 397$, with test fluids including air, water, R134a, FC40, and FC77. Using the predictive model, optimization is then carried out and a correlation is found for optimum jet spacing for square heaters with regular rectangular jet arrays.

1. Introduction

Jet impingement has been studied extensively for its high heat transfer rates, which make it applicable to thermal management of turbine blades, combustors, metals processing, and power electronics. While jet impingement may be effective, there is currently no unified framework with which to design jet impingement cooling devices. Current numerical models, such as direct numerical simulation, and RANS modeling, along with turbulence models such as the κ–ϵ model, the κ–ω model, and the v^2f model have been summarized well by Zuckerman and Lior [1]. Such numerical models are used to get a detailed look at the three-dimensional structures in the flow, as well as fluid-surface interactions. Empirical correlations can also be used to solve for thermo- or hydrodynamic profiles (typically two-dimensional profiles), or heat transfer at a specific location such as a stagnation point. There are many different empirical correlations in the literature for specific cases, but these are generally limited to the design space from which they were derived.

From a design perspective, neither complex numerical techniques nor empirical correlations are well suited for predicting heat transfer to an arbitrary array of impinging jets. The best CFD model can predict heat transfer performance to within 30% [1] and takes considerable time to program and process; empirical correlations work well for bounding the performance of a given setup, assuming the proposed setup is similar to one from which the correlation was derived. These two approaches are not sufficient.

This paper describes the performance of the predictive model proposed by Lindeman et al. [2] and its ability to predict heat transfer to an arbitrary array of impinging jets; this includes the performance of impinging jets at high mass fluxes and micro-scale nozzles, such as Michna et al. [3], but also low mass fluxes and normalized nozzle spacings above 300, such as Yonehara and Ito [4]. Three of the most common arrangements for both normally impinging and oblique jet arrays are shown in Fig. 1. A single model that is able to predict heat transfer behavior from significantly different empirical correlations allows one to more accurately probe the design space for optimization of jet impingement devices.

Describing a predictive model meant to cover the entire domain of independent variables in jet impingement heat transfer would be of less value without the broad literature-based comparison presented here; however, this paper has no intention of presenting a full review of jet impingement literature. Jet impingement heat transfer is reviewed elsewhere by Webb and Ma [5], among others [6–8]. A comparison of the model presented by Lindeman et al. [2] with a broad array of correlations from literature follows in Section 5, but first, it is helpful to review the experimental parameters being evaluated to derive such correlations.

2. Experimental techniques in literature

In all experimental apparatuses for determining heat transfer to impinging jet arrays, there is an array of orifices, or extended nozzles, delivering fluid to a heated surface. A number of independent

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Nomenclature

A	Magnitude coefficient in the Goldstein and Franchett [23] correlation
A_h	heater area
$A_{r(i)}$	area ratio where (i) is replaced by the first letter of the primary author's last name
B	exponential coefficient in the Goldstein and Franchett [23] correlation
C	exponential coefficient in the Goldstein and Franchett [23] correlation
d_n	jet diameter
H	submerged height
h_{final}	heat transfer coefficient after superposition
iso	assumption of an isothermal impingement surface
k	thermal conductivity
L	axial distance between orifice and impingement surface
L_e	length of unit cell per arrayed nozzle in the Womac et al. [17] correlation
L_h	side length of square heater used in the Womac et al. [17] correlation
L_n	length of nozzle/orifice
L^*	characteristic length in the Womac et al. [17] correlation
M	jet interaction scaling factor used in Eq. (2)
m	exponent on r/d_n term in Eq. (1).
m_R	S/d_n exponent in Eq. (20)
N	number of nozzles in nozzle array
n_R	H/d_n exponent in Eq. (20)
Nu_{d_n}	Nusselt number based on jet diameter, $= \frac{hd_n}{k}$
p_1	heat transfer coefficient profile based on one central jet
p_{final}	heat transfer coefficient profile of entire array after superposition and accounting for interaction effects
p_H	heat transfer coefficient profile of the maximum of all values transferred from p_1
p_L	heat transfer coefficient profile consisting of secondary maximum values transferred from p_1
Pr	Prandtl number
px	pixel. The discretization process generates squares of side lengths Δx defined by the resolution
r	Radial distance from local maximum of heat transfer coefficient in plane polar coordinates
r_s	radial distance from center of circular array to specific jet
Res	resolution
Re_{d_n}	Reynolds number based on jet diameter, $= \frac{\rho v d_n}{\mu}$
S	Jet spacing for regular hexagonal jet array. In terms of S_{col} and S_{row}, set $S_{col} = S$, then $S_{row} = 2S_{col}/\sqrt{3}$
S_{col}	spacing between jets from left-to-right (streamwise direction for oblique impingement)
S_{row}	spacing between jets from top-to-bottom (cross-stream direction for oblique impingement)
T_{inlet}	inlet fluid temperature
T_s	impingement surface temperature
uhf	assumption of a uniform heat flux impingement surface
v	velocity of jet exiting from orifice/nozzle
μ	viscosity
ρ	density
Φ	angle in plane polar coordinate system
θ	angle of impingement measured from impingement surface to jet. Units of radians in Eq. (1))
θ_S	arc length between adjacent jets in circular array

variables have been identified as important to the heat transfer to impinging jets – namely, the Reynolds number, here it will be based on the nozzle/orifice diameter, Re_{d_n}; the normalized jet-to-jet spacing, S/d_n; the minimum distance between orifice plate and impingement surface normalized by the jet diameter, H/d_n; and the mass flux. To use an empirically based correlation to predict heat transfer, these independent parameters must match the experiment from which the correlation was derived; however, Fig. 2 shows how this is not always a simple task. For instance, if one is interested in widely spaced jets at $S/d_n = 30$, none of the correlations presented in this paper will be applicable for sub-millimeter diameter jets or arrays containing greater than nine jets. Michna et al. [3] provide heat transfer results to jets of diameters less than 100 μm, however there is no correlation available for predicting heat transfer for a reduced mass flux on the order of that used by Garimella and Schroeder [9]. This underscores the benefits of a predictive model capable of predicting heat transfer for arbitrary independent variables.

Overall, the correlations being compared in this paper studied Reynolds numbers ranging from 43 to 10^5, centered near 8000. The plot of mass flux looks scattered, but this is mostly due to fluid choice. Those studies that used air typically had a mass flux below 10 kg/m^2 s, while those that used water or refrigerants were typically above 10 kg/m^2 s; Michna et al. [3], Browne et al. [10] had the highest mass flux, above 1000 kg/m^2 s, using a 1 mm^2 heater with sub-millimeter diameter jets. The number of jets in a given array ranged from minimum of 4 to a maximum of 397 with diameters ranging from 0.054 mm to 8 mm. Not all studies varied the number of jets, hence their representation as a horizontal line in Fig. 2. Spacing of the jets was fairly consistent across experiments: H/d_n was between 0.25 and 30; S/d_n was between 1.8 and 330.

The remainder of this section will describe the experimental designs used to achieve jet impingement heat transfer correlations, and is followed by a description of their findings in Section 3.

2.1. Jet nozzle and orifice layout

There are three nozzle arrangements being compared in this paper: regular rectangular, regular hexagonal, and circular. These arrangements can be seen in Fig. 1 where S_{row} and S_{col} represent the row and column spacings, respectively; d_n is the nozzle diameter; S is the jet-to-jet spacing assuming regular spacing; θ_S is the arc length between jets for a circular array; and r_s is the radial distance from the center of the circular array to the specific circle of jets. Most of the correlations [3,4,9,11–17] being compared with in this paper use rectangular arrays. Browne et al. [10], Michna et al. [3], and Pan and Webb [14] use regular hexagonal arrays, while Fabbri et al. [18] use circular arrays.

Standard machining techniques are assumed to have been used by the majority of studies, unless otherwise mentioned. A few studies made use of specialized manufacturing methods such as Browne et al. [10] and Michna et al. [3] who used MEMS processing techniques to etch their devices, Robinson and Schnitzler [15] used 3D printed orifice plates of regular rectangular arrays, while Fabbri et al. [18] used a method of laser drilling orifices and found that the hole diameters were inconsistently conical in shape as opposed to cylindrical.