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Heat transfer and flow characteristics of air-assisted impinging water jets

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ABSTRACT

The heat transfer performance of circular, air-assisted liquid water jets is experimentally observed over a wide range of physical parameters, including nozzle tube diameter and surface tension. Dimensional analysis is used to identify the parameters of importance. A new correlation of the local Nusselt number is suggested along with a separate correlation of the average Nusselt number for several values of r/D. The new correlations allow for prediction of heat transfer performance over a much broader range of conditions than previously available. Trends in both local and averaged heat transfer are discussed, including the effect of the liquid Weber number which has not been included in any previous analysis. The maximum stagnation point Nusselt number enhancement was 2.6 times the liquid only value. The maximum enhancement of the averaged Nusselt number (at a radius of five tube diameters) was 1.8 times the liquid only value. A clear trend of decreasing averaged heat transfer with increasing liquid Weber number is observed. Flow visualization of the two-phase flow patterns and water splatter are used to explain the observed heat transfer trends. The two-phase flow pattern affects the heat transfer in the region near the stagnation point, but does not affect the radial flow region. An experiment to quantitatively evaluate water splatter was also conducted. Water splatter is shown to correlate well with both gas Reynolds number and liquid Weber number, and has a significant effect on heat transfer outside the impingement region. Finally, optimal operating points for $D = 4$ mm and 8 mm jets, in terms of the dimensionless pumping power requirement, are observed for several values of r/D.

1. Introduction

Liquid impinging jets are used in cooling systems due to their high heat transfer capability. They have been used in diverse applications including quenching of steel plates during the manufacturing process, direct liquid cooling of microelectronic components, and cooling of X-ray and laser equipment. A number of methods to enhance the heat transfer of liquid impinging jets have been investigated in the past, including nozzle geometry control [1], jet pulsation [2,3], and use of nanofluids [4]. Most of these methods have resulted in moderate to large improvements in performance, but some can be difficult or expensive to implement.

Injection of air into a liquid jet flow before it exits the nozzle, forming an air-assisted impinging jet, can provide a large heat transfer enhancement. Exiting liquid-only jet systems can be easily modified to produce air-assisted jets through the addition of some inexpensive equipment including an air compressor, a flow rate controller, and supply tubing. The performance of an air-assisted liquid impinging jet can be quickly changed by controlling the air injection rate. However, application of this method to an industrial process requires knowledge of the performance characteristics over a wide range of parameters and an ability to predict performance within that range. Although some research in this area has been performed, the current level of knowledge is not sufficient for confident application of this method to industrial processes.

Serizawa et al. [5] were the first to investigate air-assisted liquid jets. They used a 4 mm tube type nozzle and mixed air and water well upstream of the nozzle exit. Liquid-only Reynolds numbers in the range $25{,}000 \leqslant Re_L \leqslant 125{,}000$ were studied. The stagnation point Nusselt number was observed to increase by as much as two times the water-only value at a given Re_L. Heat transfer enhancements were attributed to high turbulence levels and to acceleration of the liquid phase by the injected air.

Chang et al. [6] studied heat transfer due to a 4 mm circular submerged two-phase jet, where the working two-phase fluid was R-113 and its vapor (produced by heating the working fluid) at qualities up to 0.31. Liquid-only Reynolds numbers between $15{,}000 \leqslant Re_L \leqslant 31{,}000$ were studied. Heat transfer was observed to increase by a factor of 1.4 relative to a single-phase jet at a

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Nomenclature

A	averaging area [m^2]
C_P	heat capacity [J/kg-°C]
D	nozzle tube diameter [m]
H	nozzle-to-target spacing [m]
h	heat transfer coefficient [W/m^2-°C] $(q''/(T_r - T_{jet}))$
$\bar{h}$	area-average heat transfer coefficient [W/m^2-°C] $\left(q''/\overline{(T_r - T_{jet})}\right)$
j	superficial velocity [m/s]
k	thermal conductivity [W/m-°C]
m	mass [kg]
Nu	Nusselt number [-] (hD/k_L)
$\overline{\text{Nu}}$	area-average Nusselt number [-] $(\bar{h}D/k_L)$
PP	pumping power [W] $(Q_{\text{tot}}\Delta P)$
PP^*	dimensionless pumping power [-] $\left(PP/\left(\nu^2\mu L/D^2\right)\right)$
Pr_L	Prandtl number [-] $(C_{P_L}\mu_L/k_L)$
q''	heat flux [W/m^2]
r	radial distance from stagnation point [m]
R	radius [m]
Re	Reynolds number [-] $(\rho jD/\sigma)$
T	temperature [°C]
We	Weber number [-] $\left(\rho j^2 D/\sigma\right)$

α	cross-sectional average void fraction [-] $(A_G/A_L + A_G)$
β	void fraction [-] $(Q_G/(Q_L + Q_G))$
ΔP	pressure drop [Pa]
μ	dynamic viscosity [Pa-s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

0	stagnation point ($r = 0$)
film	water which flows as film over target
G	gas (air)
jet	value in pre-impingement jet
L	liquid (water)
r	local value at impingement surface
ped	pedestal
gap	gap between pedestal and splatter pool
SP	single-phase (liquid water only)
TP	two-phase (air/liquid water)

mixture quality of 0.11. Enhancements were attributed to increases in both mixture velocity and turbulence.

Zumbrunnen and Balasubramanian [7] observed the heat transfer due to a free-surface 5.08 mm planar water jet with air injected near the nozzle exit via capillary tubes. Liquid-only Reynolds numbers between $3700 \leqslant \text{Re}_L \leqslant 21{,}000$ and void fractions between $0.0 \leqslant \beta \leqslant 0.86$ were studied. Heat transfer was observed to increase by as much as 2.2 times the liquid-only value. Heat transfer enhancement was attributed to intermittency effects at low air injection rates, and to increased turbulent mixing and an accelerated air–water mixture at higher injection rates.

Hall et al. [8] observed transient single-phase and boiling heat transfer on an instrumented steel plate subject to a 5.1 mm diameter air-assisted water jet. The range of liquid-only Reynolds numbers was $11{,}300 \leqslant \text{Re}_L \leqslant 22{,}600$ and void fractions were between $0.0 \leqslant \beta \leqslant 0.4$. However, the full range of void fraction values were not examined at each liquid-only Reynolds number. At $\beta = 0.3$ and $\text{Re}_L = 17{,}000$ they observed a 2.2 times increase in the impingement point Nusselt number over the liquid-only Nusselt number. This observation was in disagreement with Zumbrunnen and Balasubramanian [7], who observed only a 1.3 times increase in the Nusselt number at $\beta = 0.3$ and $\text{Re}_L = 17{,}000$. Hall et al. attributed the disagreement to differences in the air injection methods which most likely caused differences in total fluid velocity.

Recently, Choo and Kim [9] observed the heat transfer effects of an air-assisted impinging jet using a 4 mm circular tube-type nozzle, where the air and water were mixed well upstream of the nozzle exit. Heat transfer characteristics were obtained under fixed flow rate and fixed pumping power conditions, and flow visualization was performed. Stagnation point heat transfer results for constant liquid flow rate cases showed increasing enhancement with the amount of injected air, up to 2 times the liquid only value at a void fraction of $\beta = 0.9$. The fixed pumping power case showed that $\beta = 0.1$–0.3 provided optimal heat transfer enhancement over the studied range of pumping power levels. Flow visualization showed that the optimal point corresponded to a bubbly flow regime within the pipe-type nozzle.

The work reviewed above has consistently shown that air-assisted jets can provide up to twice the heat transfer rates of liquid-only impinging jets. However, designing an air-assisted jet system using the available studies is difficult since the existing data and heat transfer correlations for circular jets are limited to $D = 4$ mm nozzles which lie within the transition region between macro-channel and micro-channel where the two-phase flow patterns are dependent on tube diameter. About half of the previous studies provided some sort of heat transfer correlation but these are inadequate for two reasons. First, the available correlations are for impingement point heat transfer only. While heat transfer prediction at this point is very important, the ability to predict heat transfer at radial points is also needed. Second, a very limited range of dimensional parameters were used. Specifically, a parameter containing the surface tension has not been included until now, with no specific reason given for its exclusion.

The present study investigates the heat transfer characteristics of circular air-assisted impinging jets using nozzle diameters from 3 mm to 10 mm, a much wider range of nozzle sizes than previously considered. Dimensional analysis is performed to identify the non-dimensional parameters which control heat transfer, and experiments are conducted to confirm their appropriateness. Surface tension, which was previously ignored, is included in the analysis because of its influence on two-phase flow patterns within the nozzle, especially as diameter is varied. The spatial resolution of temperature measurements is higher than previous studies, so that heat transfer curves can be accurately determined. New correlations of impingement point, local, and area-averaged Nusselt numbers are developed. Flow visualization and measurement of water splatter, a phenomenon which has not been considered in regard to air-assisted water jets until now, are performed to explain some previously unobserved heat transfer characteristics. Finally, the two-phase pumping power requirement and its relation to the stagnation point and area-averaged heat transfer, the latter of which has not been significantly explored, is investigated.

2. Problem definition

The local heat transfer coefficient for an air-assisted water impinging jet are assumed to depend on the following physical parameters: