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Analytical study of the heat transfer coefficient of the impinging air jet during cold spraying

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ABSTRACT

A semi-empirical analytical model was developed to determine the convective heat transfer coefficient of an impinging air jet generated by a cold spraying nozzle. A low-pressure cold spraying unit was utilized to produce hot air jets that impinged upon a flat substrate surface. An infrared camera was used to measure the surface temperature of the substrate at different time intervals. A method involving Green's functions was employed to solve a transient two-dimensional heat conduction problem to obtain an expression for the temperature distribution within the substrate. By coupling the analytical results of temperature distribution and experimental surface temperature data, the radial variation of the non-dimensional heat transfer coefficient of the impinging air jets upon the substrate was estimated. The results showed that the maximum values of the heat transfer coefficient were present close to the stagnation point of the air jets. It was found that the heat transfer coefficient was independent of the time that the cold spray nozzle remained stationary over the substrate surface. It was found further that by increasing the stand-off distance of the nozzle, the radial variations of the heat transfer coefficient became negligible, compared to those for small stand-off distances. The close agreement between the experimental results and the predictions of the model suggested that the estimated heat transfer coefficient of the cold spray gas jet can be used to estimate the surface temperature of the substrate at any time.

1. Introduction

Cold-gas dynamic spraying is a coating process in which a supersonic gas flow is produced in order to accelerate un-melted metal or alloy powder particles. These un-melted particles are deposited with high impact forces on a substrate to form high quality coatings [1–3]. The high speed of the particles results in significant impingement forces, which leads to shear instabilities around the particles, which, in turn, cause plastic deformation of the colliding particles. Increasing the speed of the powder particles enhances the plastic deformation and as a result, the quality of the final coating [4–6]. To this end, it has been shown that higher gas pressure causes an increase in gas density, resulting in increased acceleration of the particles [7]. However, an alternative to increasing the speed of the gas and the particles is to preheat the propellant gas [7,8], especially when it is difficult or expensive to operate the cold spray system at high pressures. Increasing the gas temperature will increase the velocities of the gas and powder particles that exit the nozzle [7]. Schmidt et al. [8] also showed that increasing the propellant gas temperature from 300 to 900 °C at a pressure of 30 bars increased the speed of 25 μm copper particles from 490 to 620 m/s. In a parallel study, Fukumoto, et al. [9] observed that the particle deposition efficiency significantly improved with the increase in propellant gas temperature, which corresponded to heating of the particles while in flight. Therefore, in light of the desired high temperature and speed of the propellant gas, a notable amount of thermal energy is expected to be transferred from the impinging working fluid jet to the base substrate during operation of the cold spray system [10].

According to recent studies, the quality of the final coating, as well as the deposition efficiency of the particles, can be significantly affected by the substrate surface or particle/substrate interface heating during the cold spraying process [9–12]. Fukumoto et al. [9] showed that substrate heating is an effective method for improving the deposition efficiency of the cold-sprayed coatings, especially during the formation of the first layer of the coating. Legoux et al. [10] suggested that the optimum deposition efficiency can be expressed as a function of the ratio of the substrate impact temperature to the melting temperature of the powder particles. They experimentally determined that the optimum temperature ratio was in the range of 0.6–0.7. Moreover, Watanabe, et al. [11] investigated the effect of the surface temperature on the adhesion strength of cold-sprayed coatings. It was shown that higher substrate temperatures increased the adhesion strength of Cu coatings

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Nomenclature

b	thickness of the substrate (m)
C	arbitrary coefficient
D	cold spray nozzle diameter
f	function in Green's function equation (°C)
F	function in Green's function equation (°C)
Fo	Fourier number
G	Green's function (°C)
h	heat transfer coefficient (W/m^2-K)
J	Bessel function
k	thermal conductivity (W/m-K)
n	number of measurements
N	Norm of the differential equation
Nu	Nusselt number
r	radial coordinate
r'	radial dummy variable (m)
SD	standard deviation
t	time (s)
T	temperature (°C)
T_0	substrate initial temperature (°C)
U	arbitrary function
V	arbitrary function
z	axial coordinate
z'	axial dummy variable (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	eigenvalues in axial coordinate
Δ	uncertainty
δ	thickness of the substrate (m)
η	non-dimensional radius
θ	non-dimensional temperature
λ	eigenvalues in radial coordinate
τ	time dummy variable (s)
χ	precision coefficient
ψ	non-dimensional stand-off distance

Subscripts

AW	adiabatic wall
B	bias uncertainty
E	repeated experimental uncertainty
g	propellant gas
i	numerator in radial coordinate
j	numerator in axial coordinate
n	nozzle
s	substrate
∞	ambient

on A5083, Fe and Cu substrates. With knowledge of the significant role that substrate temperature plays on the quality of cold-sprayed coatings, it becomes important to study the gas-substrate heat exchange.

The dominant mode of energy exchange between the compressed gas working fluid and the substrate during cold spraying is expected to be convective heat transfer. Therefore, estimation of the convective heat transfer coefficient between the under-expanded gas jet and the base substrate is necessary to determine the heat transfer rate and the temperature distribution within the substrate. In this regard, several numerical and experimental investigations have been conducted to quantify the heat transfer coefficient of impinging air jets in a wide variety of applications and geometries [12–15]. In an early work, Donaldson and Snedeker [12] studied the behavior of free jets and the effect of the jet flow pattern on the heat transfer coefficient during impingement on a flat substrate. The measurements were obtained over a wide range of Reynolds numbers (1×10^4 to 2×10^5) and nozzle-to-substrate distances (1.96–58.7 nozzle diameter). It was observed that for small nozzle-to-substrate distances, due to the pressure difference within an assumed ring surrounding the stagnation point of the impinging jet, an inward radial flow occurred toward the stagnation point. Rahimi et al. [13] employed the results of the aforementioned study to estimate the heat transfer coefficient of an impinging air jet at different nozzle pressure ratios and nozzle-to-substrate distances. It was suggested that the Nusslet number of an under-expanded air jet should be presented as a function of Mach number, the pressure ratio, as well as the Reynolds number and nozzle-to-substrate distance. Ramanujachari et al. [14] used a simplified lumped heat transfer model coupled with a set of experiments to obtain the approximate heat flux over the substrate. It was observed that the Nusselt number of the impinging jet was influenced by the mixing of the air jet at higher nozzle-to-substrate distances. In a parallel study, Limaye, et al. [15] employed the so-called experimental thin metal foil technique to estimate the heat transfer coefficient of an impinging air jet on a heated substrate. It was found that by increasing the Mach number of the jet, which was measured at the nozzle exit, the heat transfer rate between the air jet and the substrate increased for all nozzle-to-substrate distances. Sagot et al. [16], Afroz and Sharif [17], and Singh et al. [18] combined the results of the experiments with numerical computational fluid dynamics (CFD) modelling and commercial codes to study the heat transfer of the impinging air in various applications and geometries. In a recent numerical investigation, Zhou, et al. [19] adopted the V2F turbulent model to analyze the impingement heat transfer rate at high temperature differences. It was suggested that the Nusselt number was independent of the temperature differences between the substrate surface and the air jet, and could be calculated from the correlation equation that was developed for small temperature differences between the air jet and the substrate.

Along with these numerical and experimental investigations on the heat transfer of impinging air jets, specific studies have shed light on the gas-substrate heat exchange during cold-gas dynamic spraying. Ryabinin et al. [20] coupled the results of a finite difference code with experimental data to estimate the Nusselt number of an impinging hot air jet originating from a cold spray unit. In a complementary work, McDonald, et al. [21] employed the Nusselt number obtained by Ryabinin et al. [20] to investigate the effect of substrate thickness, substrate properties, and the motion of the cold spray nozzle on the temperature distribution of the substrate. It was suggested that the non-dimensional Peclét number played a major role in determination of the substrate temperature distribution during axial motion of the nozzle. Preliminary work by Mahdavi and McDonald [22] has been conducted to evaluate the heat transfer coefficient of a cold-sprayed impinging air jet on a substrate. It was reported that the radial distribution of the Nusselt number of the impinging jet upon the substrate may range from 100 to 300. While these studies have focused on numerical and experimental investigation of heat transfer during jet impingement, the development of detailed analytical and mathematical models that are capable of predicting the Nusselt number and heat transfer coefficient *a priori* before experimentation is still lacking.

The objectives of the current study were to: (1) develop a transient two-dimensional heat conduction model of the transient temperature distribution within the substrate under impinging cold spray air jets, (2) develop a semi-empirical analytical model to