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# Eulerian multiphase analysis for heat transfer enhancement by $CO_2$ sublimation in slot jet impingement

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ABSTRACT

A new numerical method for carbon-dioxide ($CO_2$) slot jet impingement cooling with dry ice is proposed and its analysis predicts an improvement in heat transfer performance by sublimation. When the $CO_2$ passes through the tiny orifice gap or jet nozzle, it experiences the rapid temperature drop as well as pressure decrease by the Joule–Thomson effect. This temperature drop causes the formation of small $CO_2$ dry-ice particles in the jet flow. Besides the enhanced cooling performance by lowered bulk-jet temperature, the significantly improved heat transfer can be expected by the additional sublimation effect between the dry-ice particles and cooling target.

Computational analysis for solid–gas two-phase jet impingement flow was performed using a commercial CFD two-phase solver as a framework. Additional in-house code accounting for the sublimation effects is embedded into the solver. The effect of sublimation on heat transfer performance was investigated by the variance of flow rate or Reynolds number.

As a result, analysis of gas–solid jet considering sublimation predicts higher heat transfer coefficients than those without sublimation analysis, and sublimation maintains the temperature of the jet bulk flow for a longer time through the absorption of additional thermal energy. As the Reynolds number increases, the amount of sublimation increases and thus heat transfer enhancement is also accompanied. It can be confirmed that the heat transfer performance at the jet target surface edge weakened by the diffusion of the wall jet flow can be compensated by the dry ice sublimation. The sublimation model presented in the current study shows that the characteristics of the impinging jet cooling containing dry ice are effectively analyzed.



## 1. Introduction

An impinging jet is a flow in which a fluid accelerated through a nozzle or an orifice is projected onto a target surface. Such impinging jets can be used for a variety of engineering purposes, such as heating, cooling, drying or cleaning solid surfaces. This technique has been studied for decades in various heat transfer applications. Since high heat transfer rates can be obtained near the jet stagnation point, impinging jets are widely used in applications where tight area thermal management is required. Typical applications include processing glass or metal and cooling gas turbine or electronic components.

Impinging jets can be classified by the phase of the working fluid injected through the nozzle. Single-phase jets using gas or liquid phase fluids can be utilized using a simple pressurized equipment. Gas jets can be used for objects that are generally vulnerable to moisture, such as cooling of electronic components and drying of fabric surfaces. However, the liquid impinging jet can achieve a higher heat transfer enhancement effect than the gas jet due to the beneficial thermal properties of the working fluid. One drawback of liquid jets is the need for a recirculating closed-loop system for the recovery of working fluid.

The basic heat-transfer characteristics of a single round jet were documented by Jambunathan et al. (1992). Their work explained the effects of nozzle geometry and nozzle spacing (jet-to-target surface, h/D) and they concluded that the Nusselt number of the impinging jet was a function of the Reynolds number, the jet-to-target surface, and the Prandtl number. The characteristics of single and multiple jets were also well documented by Viskanta (1993), whose review work described the effects of nozzle spacing, geometric effects of the jet nozzle, adjacent jet flow interaction effects, and the effects of flame jets.

Numerous experimental and numerical studies of single-phase impinging jets have been performed and various methods to improve their heat transfer efficiency have been suggested.

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $c_p$ | specific heat, [J/kg-K] |
| $F$ | external force, [N] |
| $g$ | gravity, [N] |
| $h$ | nozzle spacing distance, [mm] |
| $HTC$ | surface heat transfer coefficient, [W/m²-K] |
| $i$ | total enthalpy, [J/kg] |
| $i_{ref}$ | reference enthalpy, [J/kg] |
| $i_s$ | sensible enthalpy, [J/kg] |
| $I$ | latent heat content, [J/kg] |
| $K_s$ | interphase momentum exchange coefficient, [kg/s] |
| $k$ | thermal conductivity, [W/m-K] |
| $L$ | latent heat of material, [J/kg] |
| $m$ | mass, [kg] |
| $\dot{m}$ | mass transfer between phases, [kg/s] |
| $p$ | pressure, [Pa] |
| $Q$ | heat transfer, [W] |
| $R$ | dimensionless interaction force between phases, [–] |
| $S$ | dimensionless source term, [–] |
| $T$ | temperature, [K] |
| $T_{avg}$ | average temperature, [K] |
| $T_c$ | sublimation temperature criteria, [K] |
| $T_{ref}$ | reference temperature, [K] |
| $T_{sat}$ | saturation temperature, [K] |
| $T_{wall}$ | wall(surface) temperature, [K] |
| $U$ | internal energy, [J] |
| $u$ | specific internal energy, [J/kg] |
| $v$ | velocity, [m/s] |
| $V$ | system volume, [m$^3$] |
| $w$ | nozzle width, [m] |

*Greek*

| | |
|---|---|
| $\alpha$ | phase volume fraction, [–] |
| $\beta$ | sublimation rate fraction, [–] |
| $\Delta$ | time step size, [s] |
| $\mu$ | dynamic viscosity, [Pa-s] |
| $\mu_{JT}$ | Joule–Thomson coefficient, [K/MPa] |
| $\rho$ | density, [kg/m³] |
| $\tau$ | shear stress, [Pa] |

*Subscript*

| | |
|---|---|
| $g$ | gas phase |
| $i$ | constant enthalpy |
| $m$ | mass averaged value |
| $q$ | phase index |
| $s$ | solid particle phase |
| $w$ | nozzle characteristic length (width) |

Caggese et al. (2013) showed a change in the heat transfer enhancement of the confined jet with varying nozzle spacing. The flow recirculation caused by a confined jet affects the wall jet flow streams over the target surface and the heat transfer performance. Behnia et al. (1999) showed the differences in flow characteristics between confined and free jets.

Impinging gas jets are commonly used for cooling electrical devices and drying, and many related studies have been reported. Jeng et al. (2014) studied the cooling effect of an air jet on a heated rotating cylinder. In their study, the effect of nozzle to target length, target cylinder diameter, and cylinder rotation speed on the heat transfer performance was discussed. In addition, various studies have examined the effects of changes in nozzle geometry (Choo and Kim, 2010b) and the influence of the pumping power of the gas source (Choo and Kim, 2010a). A liquid jet requires a closed loop system to collect and recirculate exhausted coolant. Although liquid coolants incur additional costs, they are widely used in industry because of their high heat transfer efficiency. Water is often used as the coolant, especially in metal processing, for which intensive cooling is often needed.

A two-phase impinging jet can be divided into two cases: a phase change occurs in the working fluid and a case in which no phase change occurs in the working fluid. A two-phase jet without a phase change has a working fluid that is an immiscible mixture of different phases, such as gas-liquid or gas–solid. This type of jet provides higher heat-transfer rates than a single-phase jet as the additional phase interaction makes heat transfer more effective. Impinging jets with a phase change are often applied to a metal or glass process in which a phase change occurs due to thermal energy supplied to a single-phase coolant from the target surface. When the temperature of the target surface is higher than the boiling point, the liquid jet starts to boil and the latent heat consumption during boiling provides an additional cooling merit. Li et al. (2014) studied the mechanism of subcooled boiling of impinging jet and the relationship between impact velocity and the critical heat flux (CHF). According to their study, a liquid jet breaks the bubble layer and improves liquid-solid contact. Rau and Garimella (2013) studied a local two-phase confined-array impinging jet and showed that the spacing of the jet array affects the boiling phenomena and consequently influences the heat transfer coefficient. In their study, HFE-7100 was used as a coolant. As its boiling point is relatively lower than the boiling point of water, boiling may occur at low heat flux conditions and localized two-phase jets may be present.

A spray or mist/air jet is little different from the two-phase impinging jet mentioned above, and this technique is also widely used for cooling or quenching materials. A spray or mist/air jet may cause a phase change when the atomized liquid phase is sprayed from a special nozzle and hit the target surface. Thus, boiling occurs in many cases and numerous studies of enhanced heat transfer resulting from the phase change in a mist/air mixture spray have been conducted (Hall et al., 2011; Visaria and Mudawar, 2008; Avulapati and Venkata, 2013).

The gas with solid particles is called as particle-laden flow and this mixture can be used as a working fluid to improve heat transfer. Heat transfer enhancement is affected by the material properties of solid particle, the size of particle and the composition ratio of mixture. Similar to spray jets, heat transfer rate increases to some extent as the particle composition in the mixture changes. Research on particle-laden impinging jet with phase change is very rare due to the limited availability of working fluids. Carbon dioxide can be considered as a useful medium because there are not many types of sublimable substances. The theoretical review of the sublimation phenomenon, which is a phase change between solid and gas, and case studies on the applied application are shown in Chen and Zhang's review paper (Chen and Zhang, 2014).

Carbon dioxide has some advantages for impinging jet cooling process. First, carbon dioxide has a high Joule–Thomson coefficient. In the case of a gas jet, the source of the gas working fluid is generally in the form of a compressed gas in the vessel and the jet flow is generated by the pressure difference between this source and the environment. The pressurized gas expands over some steps and the state of gas is continuously changed during expansion. The final state of injected gas is affected by the condition of ambient, but it is obvious that the gas temperature should be changed during expansion. Especially the change of gas temperature in expansion process is related to Joule–Thomson coefficient. Due to the high Joule–Thomson coefficient of carbon dioxide, the temperature of injected carbon dioxide gas jet drops rapidly. Theoretically the temperature of carbon dioxide from highly pressurized source becomes lower than the sublimation temperature and solid carbon