International Journal of Heat and Mass Transfer 118 (2018) 518–526

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Thermal assessment of sublimation cooling with dry-ice sprays

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ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 5 November 2017
Accepted 5 November 2017

Keywords:
Dry ice
Thermal management
Particle spray
Mold cooling

ABSTRACT

Spray cooling systems usually use liquids to extract large amounts of heat through phase-change vaporization processes. However, in several applications, cooling requirements are transient and an efficient thermal management implies a proper control of the liquid film deposited on the surface. This represents a challenge to the optimization of thermal management systems and raises the question if there are other approaches able to perform cooling without a liquid film. This is why the present work explores sublimation as the phase-change cooling process using dry ice (CO_2) particle sprays. By the Joule-Thomson effect through a sudden expansion, liquid carbon dioxide can be converted into dry ice particles. The experimental results obtained with dry ice sprays for transient cooling show how shorter injection durations (<0.5 s) produce more uniform decays in temperature distribution, while longer pulses (>0.5 s) lead to higher heterogeneities on the impact area with potential use for hotspot cooling. The cooling heat flux generated by spray impact produces a maximum around the aforementioned temporal threshold of 0.5 s, although the maximum performance is close to the 1 s injection duration. Finally, the order of magnitude of the measured spatial average energy removed from the surface is compatible with cooling requirements found, for example, in mold cooling processes. Therefore, this evidences its potential application as an additional thermal management strategy to reduce cycle times and improve the industrial production of molding parts.

1. Introduction

Industrial competition often depends on the ability to optimize its technological processes, reducing costs and the time spent in production cycles. In fact, reducing this time may represent a substantial increase in production and income for an industry. Several of these processes require an efficient cooling of surfaces, and one of the best strategies is spray cooling, which takes advantage of phase-change to remove large amounts of heat. Liquids are the most common coolants. However, if the amount of liquid injected does not fully vaporize, a liquid film forms on the surface, mitigating phase-change and, thus, affecting cooling performance.

Most spray cooling systems use liquid vaporization, and seldom consider sublimation. The heat transfer mechanism on the impact of solid dry-ice particles onto a heated surface is by forced convection to the high velocity two-phase flow including phase-change by sublimation upon the intermittent contact of CO_2 particles with the impinging heated surface. To the best of our knowledge, only *Linde* has developed a patented spot cooling system using CO_2 to resolve thermal management of local hotspots in molded parts [1]. However, the process operates in steady-state and may not apply to processes requiring short transient cooling.

One advantage of using sublimation as the phase-change thermal process associated with spray cooling is the absence of a liquid film, although a limitation would be the difficulty of having it in a closed circuit operating system. Therefore, its usefulness depends on the application. In the present work, the aim is to assess the thermal performance of transient sublimation spray cooling using dry ice, i.e. CO_2 particles formed through the Joule-Thomson expansion effect. Lin et al. [2] investigated the different patterns of dry-ice sprays formed by flash atomization depending on a normalized superheating degree. From the lowest values to values closer to unity, the pattern changes from a spray jet to a spray cone and, finally, a bowl shape spray made of a dense concentration of micro-particles leaving the expansion nozzle. This bowl shape pattern corresponds to the conditions in our experiments. However, after the release of liquid CO_2 through the expansion nozzle and formation of micro-particles, Liu et al. [3] show the effect of the diffuser in providing a boundary condition for particle-wall collisions resulting in agglomerate particles with larger sizes. It is only the combination of expansion nozzle and diffuser which allows the formation of CO_2 agglomerated particles (see also Reeder et al. [4], and Liu et al. [5]) used to perform cooling by sublimation.

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.015
0017-9310/

Nomenclature

A	surface impact area [m^2]
c_p	specific heat [J kg^{-1} K^{-1}]
D	diameter of nozzle exit [m]
E''	energy flux [J/m^2]
h	heat transfer coefficient [W m^{-2} K^{-1}]
h_{sg}	solid-gas latent heat [J/kg]
k	thermal conductivity [W m^{-1} K^{-1}]
L	nozzle-to-surface distance [m]
$\dot{m}$	mass flow rate [kg/s]
q''	surface heat flux [W/m^2]
r	radial location [m]
t	time instante [s]
T_c	coolant temperature [°C or K]
T_{ext}	extraction temperature of molded part [°C or K]
T_{inj}	temperature of material injected in a mold [°C or K]
T_m	mold average temperature [°C or K]
T_s	surface temperature [°C or K]
$T_{s,st}$	stabilized surface temperature [°C or K]
W	surface width of the square plate [m]

Greek symbols

β	thermal effusivity [J m^{-2} K^{-1} s$^{-1/2}$]
δ	Plate's thickness [m]
δt	acquisition time interval [s]
Δt	injection duration [s]
η	cooling efficiency [%]
θ	temperature difference $T_s(t) - T_s(0)$ [°C or K]
ρ	density [kg/m^3]
ϕ	spray dispersion angle [°]

Acronyms

CT	cooling time in a molding cycle [s]

Sublimation spray cooling has mainly two stages. Stage 1 occurs through process a-b, as shown in Fig. 1, with an isenthalpic expansion of the liquid CO_2 leading to a thermodynamic state (b) where there is a two-phase mixture of solid and gas. The cooling occurs in stage 2 with an isobaric process from thermodynamic states b to c, removing large amounts of heat from the surface by convection with phase-change.

In most applications using dry ice sprays, the purpose is to perform a surface cleaning due to CO_2 solvent properties [6]. Only a few studies consider the thermal effects of its impact on a surface, and even less their application to develop thermal management systems. For low flow rates (0.236–1.18 l/s), Kim and Lee [7] characterized the heat transfer coefficient in steady-state conditions, measuring values between 1 and 3.5 kW m^{-2} K^{-1}. For the highest value of h, the stagnation temperature varied between 0 °C and 16 °C depending on the impingement distance. In fact, increasing the distance between 5 and 20 times the diameter at nozzle exit ($D = 1$ mm) led to a non-linear decrease of h by 40%. The authors conclude that dry ice particles are an advantage in CO_2 jet cooling, making it a better suited system for cooling applications. However, there are applications where CO_2 particle sprays have a short time frame to cool a heated surface, meaning it is operating in highly transient conditions. However, the analysis of the corresponding transient thermal behavior is still lacking in the literature, therefore, it is a motivation for this work.

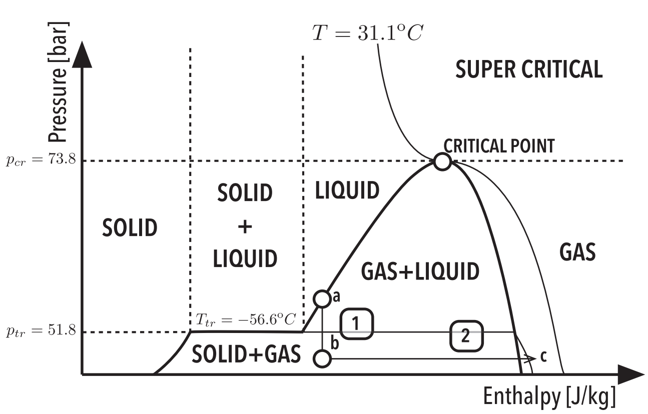

Fig. 1. CO_2 phase diagram. Process 1 corresponds to the expansion from points a to b producing a two-phase mixture of gas and CO_2 solid particles. Process 2 corresponds to the sublimation associated with surface cooling.

Using a mass flow rate of the order of $\sim 10^2$ g/s, the present investigation focuses on the transient heat transfer in sublimation spray cooling for several distances between the diffuser exit and the impinging heated surface. The experiments devised allow quantifying the cooling potential of dry ice particle sprays, assessing its potential application in the transient thermal management of molds exploring the short time frame available between releasing the molded part and closing the mold before starting another injection cycle by achieving a significant heat dissipation in the molding cavity surface.

After this introductory section, the following one describes the experimental setup and method used in this work. Section 3 explores the results in terms of the distribution and time evolution of temperature on the impinging surface, overall heat flux and heat transfer coefficient, ending with an analysis of the total energy removed by cooling and the corresponding thermal efficiency. The last section, besides drawing some concluding remarks, based on the outcome of this work, ends with prospects of ongoing and future research on sublimation spray cooling.

2. Experimental procedure

This section describes the experimental setup, the initial conditions associated with the injection of CO_2 onto the heated surface, and the measurement approach to quantify and analyze the thermal performance of transient sublimation spray cooling.

2.1. Experimental setup

The experimental setup comprises a 5 kg CO_2 fire extinguisher reservoir containing a liquid-'saturated gas' mixture. The pressure inside is kept by the vaporization of CO_2 at the liquid–gas interface. When the level of liquid CO_2 reaches the bottom end of the probe, the risk of having a mixture of gas and liquid inside the channel is higher. When this happens, the spray structure becomes solely made of micro-particles, without any formation of agglomerated particles. The atomizer corresponds to the assembly of an expansion nozzle (coupled to a valve) and a diffuser. Once the valve opens and the saturated liquid CO_2 suddenly expands into the atmosphere, assuming an isenthalpic process as depicted between