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Review of spray cooling – Part 2: High temperature boiling regimes and quenching applications

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ABSTRACT

This paper is the second part of a comprehensive two-part review of spray cooling. The first part addressed the mechanisms and predictive tools associated with the relatively low-temperature single-phase liquid cooling and nucleate boiling regimes, as well as critical heat flux (CHF). The present part is focused on the relatively high-temperature transition boiling and film boiling regimes, and the Leidenfrost point. Discussed are dominant mechanisms, data trends, and predictive correlations and models. This information is especially important to the quenching of metal alloy parts from high initial temperature during heat treating. It is shown how correlations for the different spray cooling regimes and transition points can be implemented into boundary conditions for heat diffusion models to predict the temperature-time (quench) curve everywhere within the quenched part. It is also shown how the quench curve can be combined with the alloy's transformation kinetics to predict mechanical properties. By properly configuring the sprays used to quench complex-shaped parts, it is also possible to greatly enhance the mechanical properties while minimizing residual stresses.

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Nomenclature

A	area defined along heated surface
A'	area defined along spherical surface centered at nozzle orifice
C_i	empirical coefficient
c_p	specific heat at constant pressure
C_t	critical time during quench
D	diameter of cylinder; inner diameter of tube
d	droplet diameter
d_{30}	volume mean droplet diameter
d_{32}	Sauter mean droplet diameter
G	mass flux
H	nozzle-to-surface distance; hardness
h_{fg}	latent heat of vaporization
k_i	constants in critical time relations
N^{+}	droplet number density
n_i	number of droplets with diameter d_i in sample
Nu	Nusselt number
P	pressure
ΔP	pressure rise
Pr	Prandtl number
Q	volumetric flow rate
Q''	local volumetric flux
q''	surface heat flux
$\overline{Q}''$	mean volumetric flux on surface
Q''_{dense}	volumetric flux corresponding to dense spray
R	universal gas constant
r	r coordinate
Re	Reynolds number
T	temperature
t	time
ΔT_{CHF}	surface-to-fluid temperature difference at CHF, $T_{w,CHF} - T_f$
ΔT_f	$T_w - T_f$
ΔT_{sat}	surface superheat, $T_w - T_{sat}$
ΔT_{sub}	liquid subcooling, $T_{sat} - T_f$
T_w^*	dimensionless surface temperature
u	droplet velocity
u_m	mean droplet velocity
u_{sound}	speed of sound in liquid
We	Weber number
x	x coordinate
x_i	number of droplets with diameter d_i
z	z coordinate

Greek symbols

β	angle in volumetric flux model
γ	angle in volumetric flux model
η	evaporation efficiency
θ	spray angle
μ	viscosity
ρ	density
σ	surface tension; yield strength
τ	quench factor
φ	half-angle of unit cell

Subscripts

CHF	critical heat flux
$dense$	dense spray
DFM	departure from film boiling
f	liquid
FW	film wetting regime
g	vapor
L	Leidenfrost temperature
max	maximum
MIN	minimum or Leidenfrost point
min	minimum
NB	nucleate boiling
s	spray
sat	saturation
sd	single droplet
ss	single droplet stream
sub	subcooling
TB	transition boiling
w	surface

1. Introduction

1.1. Spray cooling applications

1.1.1. Relatively high-flux, low temperature, steady-state cooling applications

As discussed in Part I of this study [1], there are two main types of applications of spray cooling. The first involves maintaining acceptable temperatures of heat-flux-controlled devices found in computers and data centers, X-ray medical devices, hybrid vehicle power electronics, heat exchangers for hydrogen storage, fusion reactor blankets, particle accelerator targets, magnetohydrodynamic (MHD) electrode walls, rocket nozzles, satellite and spacecraft electronics, laser and microwave directed energy weapons, advanced radars, turbine engines, and air-fuel heat exchangers in high-Mach aircraft [2]. Spray cooling in these applications is maintained mostly in the nucleate boiling regime safely below the critical heat flux (CHF) limit. The cooling is achieved in an appropriately configured spray chamber, which is incorporated into a closed two-phase flow loop. And, while both pressure and air-assist spray nozzles can tackle large heat loads, pressure nozzles are favored in most of these high-flux applications. These pressure nozzles employ only the momentum of the working liquid to achieve the droplet breakup, whereas air-assist nozzles require a secondary air stream to promote the breakup. Mixing air into the primary coolant greatly complicates flow loop operation, requiring specialized air separation equipment, and compromising both reliability and repeatability of cooling within the spray chamber.

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