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Maximum heat flux in relation to quenching of a high temperature surface with liquid jet impingement

Aloke Kumar Mozumder, Masanori Monde *, Peter Lloyd Woodfield, Md. Ashraful Islam

Department of Mechanical Engineering, Saga University, 1 Honjo-machi, Saga 840-8502, Japan

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Abstract

Experimental investigation has been conducted for quenching of hot cylindrical blocks made of copper, brass and steel with initial block temperature 250–400 °C by a subcooled water jet of diameter of 2 mm. The subcooling was from 5 to 80 K and the jet velocity was from 3 to 15 m/s. After impingement, the jet stagnates for a certain period of time in a small region near the centre and then the wetting front starts moving outwards. During this movement, when the surface temperature at the wetting front drops to 120–200 °C, the surface heat flux reaches its maximum value due to forced convection nucleation boiling. The maximum heat flux is a strong function of the position on the hot surface, jet velocity, block material properties and jet subcooling. A new correlation for maximum heat flux is proposed.

Keywords: Quenching; Wetting front; Inverse solution; Impinging jet; Boiling curve

1. Introduction

Jet impingement quenching is used widely in industry. At present, mainly two interest groups are dealing with the research and development of jet quenching. One group is interested to use the knowledge of quenching for controlling the mechanical and metallurgical properties of industrial products. They also use this knowledge for controlling high temperature in manufacturing industries. The other interest group uses jet impingement quench cooling to prevent overheating. For the purpose of emergency core cooling of nuclear reactor, water jets are impinged on the hot fuel element and the heat flux is the vital parameter at that time. Impinging jet cooling is also in use for removal of heat from electronic chips.

Quenching can be defined as a heat transfer process in which extremely rapid cooling results from bringing a high temperature solid into sudden contact with a lower temperature fluid. Studies of jet impingement quenching have been performed by a number of researchers [1–4] who gave attention to heat flux, temperature, and the flow field by flow visualization. Some other researchers [5,6] have focused on the phenomena that occurred during quenching of a hot surface.

Knowledge of the maximum heat flux and its position is of great importance since the maximum heat flux usually corresponds to the maximum temperature gradient in the solid and therefore the largest thermal stress. In addition the maximum cooling rate is directly connected to the maximum heat flux. Thus to be able to predict and ultimately control the maximum heat flux during quenching is a key goal for boiling research.

In the present article we have decided to use the term 'maximum heat flux' rather than 'critical heat flux' (CHF) since there may be a difference between the critical heat flux appearing in steady-state experiments and the maximum heat flux arising in quench cooling experiments. There is a wealth of literature relating to steady-state critical heat flux [7] but in contrast relatively fewer

* Corresponding author. Tel.: +81 952 28 8608; fax: +81 952 28 8587.
E-mail addresses: 03ts11@edu.cc.saga-u.ac.jp (A.K. Mozumder), monde@me.saga-u.ac.jp (M. Monde), peter@me.saga-u.ac.jp (P.L. Woodfield), ashraful@me.saga-u.ac.jp (M.A. Islam).

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Nomenclature

a	thermal diffusivity (m^2/s)
c	specific heat (kJ/kg K)
d	diameter of liquid jet (mm)
D	diameter of heated surface (mm)
h_{fg}	latent heat of evaporation (J/kg)
Ja	Jacob number $= (\rho_l/\rho_g)(c_l \Delta T_{sub}/h_{fg})$
q_c	critical heat flux of subcooled liquid jet (MW/m^2)
q_{co}	critical heat flux of saturated liquid jet (MW/m^2)
q_{max}	maximum heat flux (MW/m^2)
q_w	surface heat flux (MW/m^2)
r	position in the radial direction of the block (mm)
r_q	radial position at q_{max} (mm)
t	time (counted from the impingment of jet) (s)
T	measured temperature (°C)
T_b	block initial temperature (°C)
T_{liq}	liquid temperature (°C)
T_{sat}	saturated temperature of liquid (°C)
T_w	surface temperature (°C)
u	jet velocity (m/s)

Greek symbols

ΔT_{sub}	liquid subcooling (K)
λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

g	gas (vapor)
l	liquid
s	solid

publications are available for insight into maximum heat flux during transient quenching [8–16].

Barnea and Elias [9] conducted experiments and performed a theoretical study of flow and heat transfer regimes during quenching of a heated vertical channel. They observed that the quench front was in the transition-boiling region, which stretched between the dry and wet segments of the surface. Dua and Tien [10] performed an experimental study on rewetting of a copper tube by a falling film of liquid nitrogen. They observed that the maximum heat flux in rewetting occurred at the location of the wet front and its magnitude was comparable to the average of the maximum and the minimum heat fluxes of nucleate and film pool boiling.

Filipovic et al. [11] performed transient boiling experiments using a large preheated test specimen exposed to a water wall jet on its top surface. They reported that during much of the quenching process, conditions on the test surface were characterized by propagation of a quench front in the direction of flow along the surface. Heat transfer occurred by nucleate boiling or single-phase convection upstream of the front, while film boiling existed in a precursory region downstream of the front. The front itself was at the leading edge of a transition-boiling zone, which was approximately coincident with location of maximum heat flux. They also found that the location of the maximum heat flux on the surface moved downstream with increasing time and its value decreased with time. Kumagai and Suzuki [12] also conducted a transient cooling experiment of a hot metal slab but with an impinging plane jet. They observed that local surface temperature fell rapidly when the temperature at that point reached the temperature corresponding to the high heat flux region of transition boiling.

Hall et al. [13] performed an experimental study of boiling heat transfer during quenching of a cylindrical copper disk by a subcooled, circular, free-surface water jet. Their study reveals that quenching measurements encompass three distinct boiling regimes; nucleate boiling in the impingement zone, the upper limit of nucleate boiling (maximum heat flux for the entire surface) and transition boiling which is characterized by minimum film boiling heat flux and the temperatures for the radial flow region. They correlated the radial distributions of maximum heat flux data with relations developed by others researchers from steady-state experiments for radial flow region.

Hammad et al. [14] conducted experiments for investigating the heat transfer characteristics and wetting front during quenching of a high temperature cylindrical block by water jet at atmospheric pressure. Ochi et al. [16] also experimentally investigated transient heat transfer using circular water jet impingement. Their test piece was a flat plate. They observed that heat flux at the stagnation point (in the central region) was higher than those at further radial positions. In the stagnation region the heat flux increases with water subcooling and with jet velocity divided by the nozzle diameter. Their observation revealed that the velocity of the rewetting front increases with nozzle diameter, jet velocity and water subcooling.

In quenching experiments on large test pieces a phenomenon termed ‘wetting front’ [14], ‘quench front’ [9] or ‘wet-front’ [10] has been observed. It is a little difficult to unambiguously define what the ‘wetting front’ is. The wetting front phenomenon should not be thought of as a single point or line but the entire transition boiling region should be understood to be a part of the wetting front. However, for convenience of discussion, in the present article the wetting front is defined as follows. In all of our experiments, a black region at the outer zone of the moving liquid was