INTERNATIONAL JOURNAL OF REFRIGERATION 34 (2011) 2007–2017

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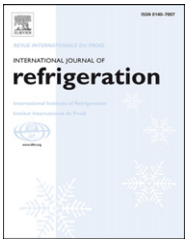

INTERNATIONAL JOURNAL OF

refrigeration

# Freezing mechanism of supercooled water droplet impinging on metal surfaces

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ARTICLE INFO

*Article history:*
Received 20 January 2011
Received in revised form
2 July 2011
Accepted 6 July 2011
Available online 12 July 2011

*Keywords:*
Supercooling
Water
Droplet
Freezing
Ice
Morphology

ABSTRACT

Ice accretion on power lines is a random natural phenomenon and may seriously harm to the safety of power network. However, the mechanism of the freezing process of supercooled water droplet impacting on wires is still not fully understood. In this study, an experimental investigation on the freezing mechanism of the supercooled water droplet impinging on cold metal surfaces was performed. The morphological characters and the dynamics of a single supercooled droplet collide on the cylindrical metal surfaces had been revealed with high-speed photographing. The experimental data for the surfaces of stainless steel, copper and aluminum, on which the supercooled droplets impinging with speeds of 2.3 m s$^{-1}$ and 4.3 m s$^{-1}$ had been plotted. The phenomena of instantaneous and non-instantaneous freezing of the supercooled impinging droplet were identified and the conditional boundaries for these two kinds of freezing were found statistically.

# Mécanisme de congélation des gouttelettes d'eau surrefroidies impactant sur des surfaces métalliques

*Mots clés* : Surrefroidissement ; Eau ; Gouttelette ; Congélation ; Glace ; Morphologie

## 1. Introduction

Ice accretion on power lines, which is a random natural phenomenon, has done a great harm to the safety of power network. Due to existence of an inversion atmospheric layer in winter precipitation climate, the rain drops or snow flaks in the air could become supercooled water droplets which impinge on the surfaces of wires where temperature is close or below 0 °C. The supercooled water collected on the wire can form an accretion of glaze ice. This kind of ice accretion phenomenon has been recognized and studied for many years. Makkonen and Lozowski (2008) elaborated the model of icing and those early studies of ice accretion problems and had developed a numerical modeling for prediction of the rate of icing on power network and equipments. Kollar et al. (2005) presented a theoretical model of a two-phase air/dispersed

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doi:10.1016/j.ijrefrig.2011.07.001

**Nomenclature**

| | |
|---|---|
| $C_d$ | drag coefficient |
| $c_p$ | specific heat capacity (J (kg K)$^{-1}$) |
| $d$ | diameter of droplet (mm) |
| $d_s$ | droplet spread diameter on impinging surface (mm) |
| $g$ | gravity (m s$^{-2}$) |
| $h$ | heat transfer coefficient (W (m$^2$ K)$^{-1}$) |
| $h_m$ | mass transfer coefficient (m s$^{-1}$) |
| $K$ | mass diffusivity of water vapor in air (m$^2$ s$^{-1}$) |
| $k$ | heat conductivity of air (W (m$^2$ K)$^{-1}$) |
| $M_a$ | molecular weight of air |
| $M_w$ | molecular weight of water |
| $m$ | mass (kg) |
| $P_a$ | air stream pressure (kPa) |
| $P_{sat}$ | saturation vapor pressure of water (kPa) |
| Pr | Prandtl number |
| Re | Reynolds number |
| Sc | Schmidt number |
| $T$ | water droplet temperature (K) |
| $T_0$ | droplet temperature at outlet of pinhole (K) |
| $T_a$ | airflow temperature (K) |
| $T_i$ | supercooled droplet temperature at impact moment (K) |
| $T_w$ | metal surface temperature (K) |
| $t$ | time (s) |
| $t_m$ | droplet displacement time (s) |
| $u$ | droplet falling speed (m s$^{-1}$) |
| $u_i$ | droplet impact speed (m s$^{-1}$) |
| $V$ | airflow velocity (m s$^{-1}$) |
| *Greek* | |
| $\lambda$ | latent heat of water vaporization (J kg$^{-1}$) |
| $\nu$ | kinetic viscosity of air (m$^2$ s$^{-1}$) |
| $\rho_a$ | density of air (kg m$^{-3}$) |
| $\rho_w$ | density of water (kg m$^{-3}$) |

water spray flow in an icing wind tunnel. Naterer (2003) modeled the processes of rime ice, transition and combined rime/glaze ice conditions and solved the heat conduction equation simultaneously with mass balance in the ice and unfrozen water layers including incoming droplets. Tabakova and Feuillebois (2004) modeled the solidification and subsequent cooling of a supercooled droplet lying on a cold solid substrate after impact, in which it was assumed that solidification occurs for a given fixed droplet shape. Myers and Hammond (1999) and Myers and Charpin (2004) presented a theoretical model for ice growth due to supercooled fluid droplets impacting on a subzero substrate and was valid only for “thin” water layers. These studies are valuable for solving some aspects on the problem of ice accretion, but cannot completely reflect the real process of the supercooled droplet impact. Schaub Jr (1996) had indicated that there was not one model validated by comparing with real data of icing at the present time.

Because of the randomness of ice accretion on wires and the difficulties in simulation of real natural conditions, there are only a few of the experimental investigations on freezing mechanism of supercooled droplet impacting wires. Prodi et al. (1986) studied the morphological and physical properties of ice deposits accreted on fixed and rotating cylinders in a wind tunnel for various temperature, liquid water content and air speed. Fumoto et al. (1999) carried out an experimental study on the critical heat flux of ice accretion along a horizontal wire immersed in a cold air stream with water spray. Lu et al. (2000) undertook a more extensive experimental investigation on fixed, unheated conductor sections by using an outdoor freezing rain simulator at University of Manitoba. Personne and Gayet (1988) performed experiments on both the accreted ice formation and the Joule-effect anti-icing around the rotating wires under gravitational and aerodynamic forces in an instrumented wind tunnel operating in natural condition. However, microscopic process mechanism of the impinging supercooled droplet freezing on the surface of wires is so far not fully understood and further experimental investigations are needed.

In view of the shortage of laboratory data on the mechanism of the impinging supercooled droplet freezing on the surface of wires and the destitute knowledge of investigation, we performed an experiment on freezing mechanism of supercooled water droplets impinging on cylindrical metal surfaces. The test was carried out by high-speed photographing a single supercooled water droplet under well-controlled experimental conditions. The main purposes are to improve the understanding of the glaze ice accretion mechanism with clear views of the process phenomena and reliable experimental data, and to lay the groundwork for developing the more effective theoretical models.

## 2. Experimental method

Fig. 1 illustrates the experimental apparatus. The main components were the water droplet generator, a test surface on which supercooled water droplet landed, a wind tunnel, the high-speed photography equipments, the temperature measurement instruments and a cold climate chamber. The water droplet generator consists of a 0.5 mm inner diameter by 20 mm long needle and a 9 mm diameter by 28 mm long red copper cylinder which was machined as a syringe in shape. It was weld to a 6.8 mm diameter by 4 m long copper pipe that was connected to the water tap. Droplets were formed by increasing the water pressure, forcing water through the needle which was mounted on the syringe. The needle was protected from air current by an aluminum tube (12 mm outer diameter and 9 mm inner diameter). The space between the needle and the aluminum tube was filled with thermal grease to strengthen the heat conduction. The water droplet generator and the copper pipe were heated by two layers of wire heaters, which were controlled by three controllers to maintain them above freezing temperature.

The supercooled droplet was to land on three different metal tube surfaces, stainless steel, aluminum and red copper, which were 36 mm diameter by 290 mm long, and polished with 600 grit emery clothes. Filled with magnesium