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Numerical investigation of solidification of single droplets with and without evaporation mechanism

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ABSTRACT

According to some experimental observations, water droplet with high initial temperature freezes faster than a cold one. There are some explanations to this problem such as subcooling, evaporation and radiation. In this work, solidification process of single droplets with and without the effect of evaporation is numerically investigated for three different drop diameters and initial temperatures. It seems that evaporation itself is able to explain why hot water freezes faster than cold water.

Enquête numérique portant sur la solidification de gouttelettes uniques avec et sans mécanisme d'évaporation

Mots clés : Effet Mpemba ; Évaporation ; Solidification ; MFN ; Transfert de masse

1. Introduction

The Mpemba effect has been a concerning debate for several years. A large number of papers have tried to interpret this phenomenon. This process was firstly seen by the ancient scientist, Aristotle, in 350 B.C. but the most famous observation belongs to a Tanzanian student, E. Mpemba in 1963 who placed two containers of water one at 35 °C and the other one at 100 °C in the cold box of a domestic refrigerator. He found that despite considering totally identical samples and similar external condition for both beakers, the initially hotter sample froze faster (Jeng, 2006). This effect has been named after him for his first observation in modern time.

Researchers have tried to give some interpretation to this problem. For example, considering the impact of supercooling,

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Nomenclature

C_{p1}	heat capacity of water $[kJ \cdot kg^{-1} \cdot K^{-1}]$
C_{p2}	heat capacity of air $[kJ \cdot kg^{-1} \cdot K^{-1}]$
C_{liquid}	heat capacity of liquid water $[kJ \cdot kg^{-1} \cdot K^{-1}]$
C_{solid}	heat capacity of solid water (ice) $[kJ \cdot kg^{-1} \cdot K^{-1}]$
C_D	drag coefficient of droplet
D_{AB}	diffusivity of water in air $[m^2 \cdot s^{-1}]$
$D_{Droplet}$	diameter of the sphere [m]
F_1	volumetric force due to Boussinesq assumption in liquid water $[N \cdot m^{-3}]$
F_2	volumetric force due to air density $[N \cdot m^{-3}]$
g	gravity acceleration $[m \cdot s^{-2}]$
h	heat transfer coefficient $[W \cdot m^{-2} \cdot K^{-1}]$
k_1	thermal conductivity of water $[W \cdot m^{-1} \cdot K^{-1}]$
k_2	thermal conductivity of air $[W \cdot m^{-1} \cdot K^{-1}]$
k_C	concentration-based mass transfer coefficient $[m \cdot s^{-1}]$
k_P	pressure-based mass transfer coefficient $[kg \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}]$
k_{liquid}	thermal conductivity of liquid water $[W \cdot m^{-1} \cdot K^{-1}]$
k_{solid}	thermal conductivity of solid water (ice) $[W \cdot m^{-1} \cdot K^{-1}]$
L	latent heat of solidification $[kJ \cdot kg^{-1}]$
p^{sat}	vapor pressure of water as a function of temperature [Pa]
p_0	partial pressure of water in surrounding air [Pa]
p_1	water pressure [Pa]
p_2	air pressure [Pa]
Pr	Prandtl number $= \mu_2 \cdot C_{p2}/k_2$
Re	Reynolds number $= \rho_2 \cdot u_2 \cdot D_{Droplet}/\mu_2$
r_0	initial radius of the droplet [mm]
Sc	Schmidt number $= \mu_2/(\rho_2 \cdot D_{AB})$
T_0	initial temperature of the droplet [K]
T_1	temperature of water [K]
T_2	temperature of surrounding air [K]
T_f	temperature of phase change in water [K]
ΔT	temperature interval near freezing point of water [K]
u_1	velocity of water in the droplet $[m \cdot s^{-1}]$
u_2	velocity of surrounding air $[m \cdot s^{-1}]$
v_n	normal velocity of droplet radius reduction due to evaporation from surface $[m \cdot s^{-1}]$
ρ_1	density of water $[kg \cdot m^{-3}]$
ρ_2	density of dry air $[kg \cdot m^{-3}]$
μ_1	dynamic viscosity of liquid water [Pa.s]
μ_2	dynamic viscosity of surrounding air [Pa.s]
λ	latent heat of evaporation $[kJ \cdot kg^{-1}]$

natural convection and evaporation are some suggested solutions. Auerbach (1995) suggested that initially warmer water supercools less than initially colder water. However, this cannot fully explain the Mpemba effect because we still need to explain why initially hot water supercools faster than the cold one. Vynnycky and Kimura (2015) investigated the effect of natural convection in a closed enclosure filled with water. They found that although natural convection could not explain the Mpemba effect by itself, other mechanisms might be responsible for this phenomenon. Kell (1968) and Vynnycky and Maeno (2012) introduced evaporation as a convincing reason for the Mpemba effect separately. Kell studied experimentally ice formation in a wooden pail and concluded that since considerable heat is not transferred through the sides of the pail, cooling is mostly by evaporation. The model by Vynnycky and Maeno consisted of two holes in a highly-isolated block filled with hot and cold water and surrounding stagnant cold air temperatures of 253 K and 263 K. They observed some considerable reduction in the height of water samples due to surface evaporation. In another paper, Vynnycky and Mitchell (2010) introduced a linear expression for mass transfer rate considering the difference of vapor pressure on the surface of water and water partial pressure in the air. However, they considered k, their mass transfer coefficient, as a constant value which did not vary with temperature.

Despite its challenging behavior, the Mpemba effect may have some economic benefits. For example, in producing artificial snow for ski resorts, reducing the required time to freeze each droplet can lead to a considerable time saving. Even though the Mpemba effect has been observed many times, few explanations have been presented about the reason behind this phenomenon. In the present work, we deal with a droplet solidification problem. We consider the effects of three heat transfer mechanisms on