International Journal of Thermal Sciences 111 (2017) 450–462

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Study of the water evaporation rate on stainless steel plate in controlled conditions

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ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form
7 September 2016
Accepted 24 September 2016

Keywords:
Water
Evaporation droplet
Humidity
Temperature
Air velocity

ABSTRACT

The evaporation of water droplets is involved in many applications: fire extinction, building and greenhouse. On the equipment of a food plant (mostly made of stainless steel), bacterial contamination can cause the deterioration of food quality and safety. To avoid this problem, cleaning by water and subsequent drying are often performed. Water stagnation, however, is observed at certain positions if the ambient conditions during the drying process are not well-controlled. The water evaporation rate depends on the room conditions (temperature, velocity, humidity). It is thus necessary to understand the evaporation mechanism of water droplets on solid surfaces and the influence of the room conditions on the evaporation rate. Experiments were performed in a wind tunnel, in which the air velocity, temperature and relative humidity were controlled. Water droplets were deposited onto a stainless steel plate (15 cm × 15 cm × 0.1 cm). This plate, placed in a work zone, was exposed to several air velocities (0.5 m s^{-1} to 2.0 m s^{-1}), relative humidities (50%–85%) and temperatures (4 °C–20 °C). The evolution of the wet surface on the plate was observed using a camera, and the evolution of the water weight was determined using a digital balance. The influence of the initial percentage of wet surface on the water evaporation rate was studied at various ambient conditions. It was observed that the air relative humidity is the factor that has the greatest influence on the evaporation rate.

1. Introduction

The evaporation of water droplets is involved in many applications. In a closed display cabinet, condensation and evaporation on the glass door are often observed [1]. For fire extinction, the cooling of solid surfaces can be performed thanks to the evaporation of water droplets [2,3], as well as the enhancement of heat exchanges [4,5]. For fruit and vegetable humidification, the use of small water droplets accelerates the product temperature decrease because of water evaporation from the product [6,7,8,9]. Heat and moisture transfer is a determining factor of the food product cooling rate [10,11] and heating rate [12]. Humidity control (evaporation, condensation) has a significant impact on the well-being of humans indoors [13].

In a food plant, after production, cleaning by water is often practiced, which leads to high humidity in the air and to the presence of water droplets on walls (e.g., equipment and floor). These conditions are favourable for microbial growth, such as *Listeria Monocytogenes*, a serious foodborne pathogen [14]. Equipment that is mostly made of stainless steel can be contaminated, causing a threat to food quality and safety [15]. Several studies have shown the presence of *Listeria* in production plants and along the food chain [16,17]. These authors investigated food factories and found the presence of *Listeria* inside the production room (on the evaporators, floors, drains, food-contact surfaces…). The influence of temperature, humidity and air-blowing velocity on the contamination was noted. Despite the cleaning, which requires large amounts of water and chemical substances that remain, microbial contamination was observed. They concluded that dry conditions and the restriction of food residues contribute to the control of these microorganisms. The presence of water must be eliminated by drying, especially right after cleaning, to limit contamination; thus, the evaporation phenomenon of a liquid deposited onto a solid surface has to be well-understood.

The main objective of this work is to study the influence of the following factors on the water evaporation rate: ambient

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.09.030
1290-0729/

Nomenclature

C_{sat}	Concentration of saturated water vapour kg m^{-3}
C_{wa}	Concentration of water vapour in air kg m^{-3}
e	Plate thickness m
h	Heat transfer coefficient W m^{-2} K^{-1}
k	Mass transfer coefficient m s^{-1}
l	Half distance between two drops m
$\dot{m}$	Evaporation rate kg s^{-1}
$\dot{q}$	Mean value of measured heat flux W m^{-2}
RH	Relative humidity %
S	Total surface of the plate m^2
T	Temperature °C
v	Air velocity m s^{-1}
α_{diff}	Thermal diffusivity m^2 s^{-1}
β	Wet surface over total surface Dimensionless
ε	Emissivity Dimensionless
Φ	Heat flux density W m^{-2}
λ	Thermal conductivity W m^{-1} K^{-1}
ΔH_v	Heat of water evaporation J kg^{-1}

Subscripts

a	air
d	dry zone of plate
i	initial
pl	plate
w	wet zone of plate
wb	wet-bulb

conditions (relative humidity, temperature, velocity) and percentage of wet surface. A correlation for the evaporation rate as a function of these parameters is proposed.

A literature review of a liquid evaporating on a solid surface is carried out for better understanding of this phenomenon.

Evaporation of a liquid is a phenomenon that occurs in many industrial operations (refrigeration, spray cooling, drying processes…). Because evaporation is endothermic, the evaporation rate is influenced by the heat transfer in the liquid phase and at the liquid/vapour interface [18,19]. The heat transfer during evaporation is mainly driven by the temperature gradient, while the mass transfer, by the concentration gradient [20,21]. In the case of forced convection, air velocity and turbulence also influence the evaporation process [22,23,24]. These studies showed the influence of the neighbouring environment on evaporation. The initial deposition of the droplets on the solid surface is another parameter that has an impact on the evaporation rate. This deposition depends on different parameters, such as the droplet size and the droplet impact velocity [25] during water pulverization. When a liquid is carefully placed on a surface of a given solid, it remains as a drop with the formation of a contact angle between the liquid and solid phases. The magnitude of the contact angle depends on the physical characteristics of both the liquid and the solid phases [26,27]. For a given drop volume, a higher value of the contact angle produces a thicker drop with a smaller base radius. The contact angle plays, therefore, an important role in the rate of evaporation of the drop. Birdi et al. [26] reported that the rate of evaporation is linearly proportional to the radius of the liquid-solid interface. According to Beysens [28] and Croce et al. (2005) [29], the evaporation of a droplet may be distinguished into 2 periods. During the first period, the base area of the droplet is constant while the contact angle decreases until the receding value is reached: the evaporation rate is almost constant. During the second period, the contact angle is constant: the wet area decreases, which modifies the evaporation rate. Therefore, the change in the evaporation rate when the water surface varies has to be considered. Hsu et al. (2015) [30] investigated experimentally water droplets on hydrophilic, hydrophobic and mixed wettability surfaces. The measurement of the contact angle and volume evolution was undertaken over the evaporation time. The results revealed that surface wettability plays a critical role not only in vapour bubble formation but also in evaporation rate.

2. Materials and methods

Experiments were carried out in a wind tunnel, in which velocity, temperature and relative humidity of the air were controlled. In the work zone of this wind tunnel, a stainless steel plate wetted by water was exposed to several air conditions. The water mass and the wet surface evolutions were examined.

2.1. Description of the wind tunnel

The experimental device consists of a wind tunnel (length x height x width = 64 cm × 19 cm × 19 cm, Fig. 1) made of PVC, except the upper wall, which is made of Plexiglas. This device is located in a test room where temperature and relative humidity can be controlled. In the work zone, a stainless steel plate (15 cm × 15 cm × 0.1 cm) is placed on a balance. Underneath this plate, extruded polystyrene (4 cm thickness) is used as thermal insulation. In this way, the result interpretation is facilitated because the exchange with air is undertaken only between the upper surface of the stainless steel and the air. This plate, wetted by water (procedure explained in Section 2.2), was exposed to different ambient conditions: air temperature (4.2 °C–19.6 °C), relative humidity (51%–85%) and air velocity (0.45–2.0 m s^{-1}). During the experiments, the air and plate temperatures, the air velocity, the relative humidity in the tunnel, the water weight and the wet surface on the stainless steel plate were measured.

2.2. Parameters measurement

Water droplets of 0.1 mL (30 droplets, 60 droplets, 100 droplets, using a pipette), puddles and a film were deposited onto the stainless steel plate (Fig. 2). Moreover, another experiment was carried out with smaller droplets: 60 droplets of 0.05 mL. The water weight on the plate was recorded every 5 s using an electronic balance (Sartorius, 3410028, ±0.001 g precision) connected to a data-logger (Agilent 34970A). Measurement was carried out until all the water was evaporated.

The air temperature inside the wind tunnel and the plate temperature were measured using calibrated T-type thermocouples (1 mm diameter, ±0.1 °C precision) during the evaporation. One thermocouple was put in the wind tunnel to measure the air temperature and 4 thermocouples were put underneath the plate (between the stainless steel and polystyrene plates).

The air relative humidity was measured using a capacitive humidity sensor TESTO 174H (±3% precision).

The air velocity in the wind tunnel was varied from 0.45 to 2.0 m s^{-1} using a variable frequency drive. To stabilize, as much as possible, the air inside the wind tunnel, ventilation was operated in aspiration mode. Moreover, a honeycomb (tubes of 3 mm in