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Evaluation of a chicory root cold store humidification system using computational fluid dynamics

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ABSTRACT

Humidification of chicory root cold stores helps in maintaining the quality and extending the postharvest storage time of chicory roots. Low evaporation rate of the sprayed droplets at such sub-zero temperatures (−2 °C to −1 °C) favours surface deposition that could have an adverse effect on the efficiency of the storage room. A three-dimensional computational fluid dynamics (CFD) model was developed and used to predict the storage room air velocity, temperature and humidity distributions, and fate of the water droplets that were sprayed for humidifying the storage room. The humidification system in a chicory root cold store was then optimized. The efficiency of the humidification system was affected by length of cold air deflector, stack height, number of nozzles and duration of humidification. Elongating the air deflector, reducing the stack height, reducing the number of nozzles and shortening the humidification time increased the amount of droplet evaporated and decreased the amount of droplet deposited on the stack. The following combinations of room design and operating parameters could clearly give the best performance of the humidification system: deflector length of 0.8 m, two nozzles with an interval humidification of 1.5 min on and 2 min off cycle and stack height of 3.4 m.

1. Introduction

Fruit and vegetable products are highly perishable that continue to respire and transpire water after harvest. For long term storage of these products, cold storage systems are commonly used. The cooling is usually performed by forcing cold air through the stored product. A low optimum storage temperature combined with a high relative humidity (RH) of the surrounding air can reduce the product moisture loss. Water loss during postharvest storage of fruits and vegetable products has an adverse effect on product quality and economic return (Henriod, 2006; Hertog et al., 2004; Paull, 1999; Sujau et al., 2005; Tu et al., 2000). However, an excessive RH level may encourage the development of moulds and rots and deposition of water droplet on products and room surfaces (Sujau et al., 2005; Tassou and Xiang, 1998).

Chicory roots are very susceptible to dehydration; this dehydration leads to lower yield and quality, higher percentage non-sprouting roots and longer forcing period (De Proft et al., 2000; Embrechts, 1989). For long storage (for about 9 months), chicory roots are usually stored at −2 °C to −1 °C with a RH of 95–100% (Hoang et al., 2003; Neefs et al., 2000; Seynnaeve et al., 2000). In order to achieve the required RH (minimum of 95%), humidifiers are usually installed.

The requirements for the humidification system are to produce a high RH with maximum droplet evaporation, minimum deposition of sprayed water droplet on the product and room surfaces, and minimum frost/condensation on the air cooling coils. However, fulfilling these requirements is very challenging; Fig. 1 shows the problem of ice accumulation over a stack of boxes with chicory roots. This accumulated ice can affect the cooling efficiency of the room by blocking the circulation of the cooling air. Such adverse effects can be minimized by optimizing the design and operation of the humidification system.

A number of previous studies demonstrated the applicability of CFD models for analyzing the flow inside and around cold storage systems (Chourasia and Goswami, 2007; Foster et al., 2002; Hoang et al., 2000, 2003, 2004; Nahor et al., 2005; Tassou and Xiang, 1998; Xu and Burfoot, 1999). None of these studies had modelled the humidification system. Recently, we developed a validated model that can predict the storage room air velocity, temperature and humidity distributions and fate of the water droplets that were sprayed from humidifying nozzles (Delele et al., 2009).

The aim of this paper is to apply the validated model of Delele et al. (2009) to evaluate a chicory root cold store humidification system. The study was used to analyse the effects of different cold store designs and humidification system operating parameters, and to recommend solutions that could improve the efficiency of the cold store and the humidification system. However, the recommendations were not based on a detailed optimization study of the

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Nomenclature

C_d	drag coefficient
C_p	specific heat, J kg^{-1} K^{-1}
d	diameter, m
$Co_{v,s}$	vapour concentration on the droplet surface, kmol m^{-3}
$Co_{v,\infty}$	vapour concentration in the bulk air, kmol m^{-3}
D	molecular diffusion coefficient, m^2 s^{-1}
F_i	additional forces, N
g	gravitational acceleration, m s^{-2}
h	static enthalpy, J kg^{-1}
h'	fluctuating static enthalpy, J kg^{-1}
K	Darcy permeability, m^2
L	latent heat of condensation vaporization, J kg^{-1}
m_d	mass of discrete droplet, kg
M_{wv}	molar mass of water vapour, kg kmol^{-1}
Nu	Nusselt number
p	pressure, Pa
p_{vd}	vapour pressure over water droplet surface, Pa
p_{vf}	vapour pressure over flat water surface, Pa
Q_{res}	heat of respiration, W m^{-3}
r	droplet radius, m
R	universal gas constant (8.314 J mol^{-1} K^{-1})
Re	Reynolds number
S_e	energy source term, J m^{-3} s^{-1}
S_m	mass source term, kg m^{-3} s^{-1}
S_u	momentum source term, kg m^{-2} s^{-2}
Sh	Sherwood number
t	time, s
t_w	wall thickness, m
T	temperature, K
T_o	reference temperature, K
u_i,u_j	mean velocity components in X, Y, and Z directions, m s^{-1}
u'_i, u'_j	fluctuating velocity components, m s^{-1}
u_s	superficial velocity, m s^{-1}
v_i	velocity, m s^{-1}
V_m	molar volume of water, m^3 mol^{-1}
x_i,x_j	Cartesian coordinates, m
Y_v	vapour mass fraction
Y'_v	fluctuating vapour mass fraction
β	Forchheimer drag coefficient, m^{-1}
δ_{ij}	kronecker delta
λ	molecular thermal conductivity, W m^{-1} K^{-1}
λ_{eff}	effective thermal conductivity of porous zone, W m^{-1} K^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
μ_t	turbulent viscosity, kg m^{-1} s^{-1}
σ	surface tension, N m^{-1}
ρ	density, kg m^{-3}
ϕ	porosity

Subscripts

a	continuous air phase
d	discrete droplet phase
p	product
i, j	Cartesian coordinate index

system, rather it focused only on some parameters that we expect could improve the system efficiency.

2. Materials and methods

2.1. Humidification system and cold storage room

This study was performed on a large chicory root cold store with a dimension of 13 m in length, 5.5 m in width and 4.2 m in height (Kampenhout, Belgium). The room is equipped with two cooling units that were located at the back of the room (Fig. 2). The cooling air is circulated using six fans (three fans for each cooling unit) with a diameter of 45 cm and total capacity of 25,200 m^3 h^{-1}. At the exit of the cooling unit, the air is deflected upward (22°) by using a 0.2 m length deflector. Six compressed air atomizer nozzles are positioned in front of the cooling units. The nozzles have a 30° spray angle. The capacity of each nozzle is 5 L h^{-1}. The water was purified using a wrapped propylene filter. The humidification system was originally set to a 10 min spraying time after every cooling cycle. The cooling cycle is determined by the storage room air setpoint temperature (−2 °C) and the temperature difference between the incoming refrigerant and the storage room setpoint (7 °C). The distance between the nozzles and the cooling unit and between the nozzles and the roof were 0.6 m and 0.3 m, respectively.

The room was filled with 102 chicory root bins with dimensions of 1 m width, 1.2 m depth and 1.2 m height; the height of the four top bins under the cooling unit was 1 m. The bins were stacked in 4 rows. Two rows contained nine bins in three levels and the third and fourth rows (the rows near to the door) contained eight bins in three levels. Gaps between the bins along the height and depth, between the bins along the width, and between bins and walls were 0.1 m, 0.16 m and 0.5 m, respectively.

2.2. Model description

A complete CFD model of a cool room, including product characteristics, stacking pattern, cooling unit and humidification was

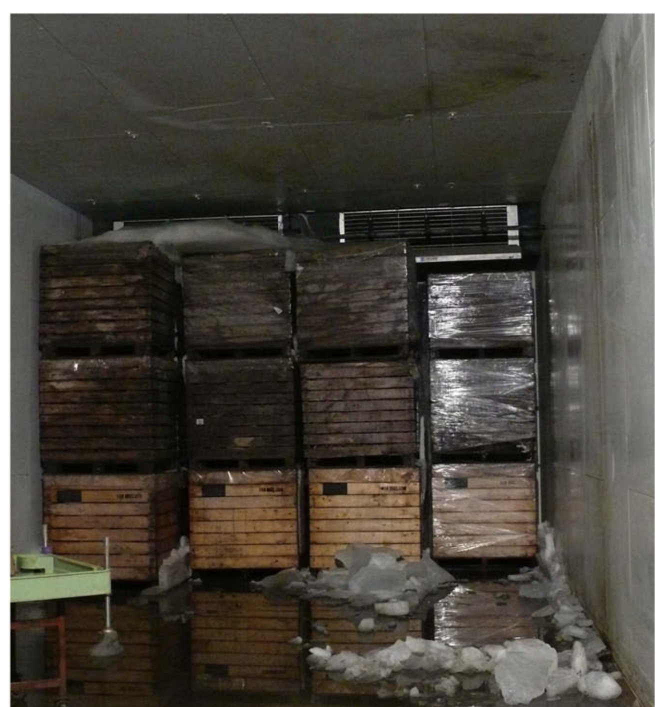

Fig. 1. Ice accumulation at different locations inside a loaded chicory root cold storage room with humidification system after a storage time of 9 months.