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Research Paper

Experimental and numerical studies for the air cooling of fresh cauliflowers

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HIGHLIGHTS

- The air-cooling of fresh cauliflowers is studied.
- A simple numerical model predicts the product temperatures and the water losses.
- The modelling approach takes into account the heterogeneities of the vegetable.
- The numeral results reveal a good agreement with the measurements.

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ABSTRACT

The fresh vegetable farm produce needs to be cooled after the harvest before the shipment and the sale. The cooling duration is very sensitive to several parameters: foodstuffs nature (size, weight, properties), harvest period, packaging shapes, climatic conditions … In this paper, experimental and numerical investigations focused on forced air-cooling and room cooling of fresh cauliflowers are presented. For this vegetable, the optimal storage conditions are 4–7 °C and 90–98% relative humidity. As cauliflower is a voluminous (15–20 cm diameter) and heavy vegetable (600 g to more than 2000 g), the cooling process lasts generally several hours (> 10 h) in the case of conventional room cooling. In order to apprehend the cooling kinetics of these products, some experiments carried out on a laboratory experimental set-up and on industrial site are presented. A 1D numerical model is firstly implemented to predict the temperature field and the mass loss of a single product. Several heat transfer mechanisms occur at the surface: convection, evaporation and long-wavelength infrared radiation. Based on in-situ experiments during which product temperature, air temperature and hygrometry were monitored, a second model is developed to simultaneously determine the temperature and the mass loss of several products placed in conventional room cooling. Comparisons between simulations and experiments show relevant results.

1. Introduction

The vegetables are perishable products whose metabolism activity continues after harvest. The purpose of cooling is to enhance the quality, safety and shelf life of foodstuffs by delaying the biological and chemical reactions induced into the produce. Thus, a rapid cooling of fresh vegetables is important to maintain quality by slowing down the rates of respiration and senescence [1]. Several methods are used in the food-processing industry, such as the natural or the forced-air cooling, the hydro-cooling and the vacuum cooling [2–4].

A literature survey reveals that many research works took an interest in this field for improving the understanding of physical phenomena and proposing some optimization ways through experimental and numerical approaches [5]. The studied products are very highly diversified, including fruit [6–9], vegetables [10,11] or meat [12,13]. For these last years, the computational fluid dynamics (CFD) based models have become more and more used for providing a precisely analysis of air flow around the produce or the impact of product interactions [6,14] and consequently for proposing new packages designs in order to improve the produce safety and the process efficiency [15–21]. These models provide a complete view of temperature fields (foods and air), relative humidity fields and air flow fields into stacked products. These tools allow to test various designs, various cooling scenarios and so, became a real decision aid for engineers to define the best fitted configuration to their process and products. Nevertheless, despite the calculation power of recent computers, the computation times of these complete models are quite long, up to several tens of minutes or even several hours. Therefore, making them inappropriate for an on-line optimization procedure aiming at the reduction of energy consumption and cooling duration as function of, climatic conditions,

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Nomenclature

Normal

$\dot{q}$	mass transfer rate, kg m^{-2} s^{-1}
h_c	convective heat transfer coefficient, W m^{-2} K^{-1}
h_m	mass transfer coefficient, m s^{-1}
h_{rad}	radiative heat transfer coefficient, W m^{-2} K^{-1}
X	moisture content, kg kg^{-1}
A	section, m^2
c	specific capacity, J kg^{-1} K^{-1}
HR	relative humidity
L	latent heat, J kg^{-1}
M	molar mass, g mol^{-1}
m	mass, kg
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
S	surface, m^2
T	temperature, K
t	time, s
V	volume, m^3
v	velocity, m s^{-1}

Greek letters

Δx	space discretization, m
ε	air fraction
λ	thermal conductivity, W m^{-1} K
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
τ	time constant, s

Subscripts

l	liquid
a	air
dry	dry
exch	exchange
i	sub-zone indice
j	layer indice
sat	saturation
t	total
v	vapour
wet	wet

Superscripts

^{o}	intrinsic
ini	initial
off	ventilation off

occupancy rates of the storage room, harvest temperatures, by acting on adequate commands (blown air temperature, blown air humidity, air flow rate).

Then, the purpose of this paper is to present a modelling approach for simulating the cooling of packed and stacked horticultural produce in a vented storage room (Fig. 1).

This model based on heat and mass conservation equations has to provide a satisfactory prediction of thermal fields (product and air), air humidity fields and product mass losses as a function of the product location into the storage room. The studied products are cauliflowers which major part of the production is exported and moreover marketed fresh, making cooling operations indispensable. Usually, six to eight cauliflowers, depending on the size, are positioned in perforated crates and about fifty crates compose one storage pallet. The pallets are next placed during several hours in a cooling room in order to reach the optimal storage conditions: temperatures range between 4 °C and 7 °C, and relative air humidity between 90% and 98% [22].

One part of the originality of this study is tied to the nature of the product (cauliflower), which is a heterogeneous vegetable having large size and mass including significant volumes of air. This particular morphology needs to be taken into account through the modelling approach.

In the second section, discussions about the material properties are firstly carried out. Then, the sub-model describing the thermal behaviour of a single cauliflower is confronted to the data acquired on the experimental set-up. A sensitivity analysis is also performed on this model. Once completed, the main model, which call the previous sub-model, is evaluated. The simulated data for the air and products domains (temperature and hygrometry) are confronted to measurements made on a real industrial site.

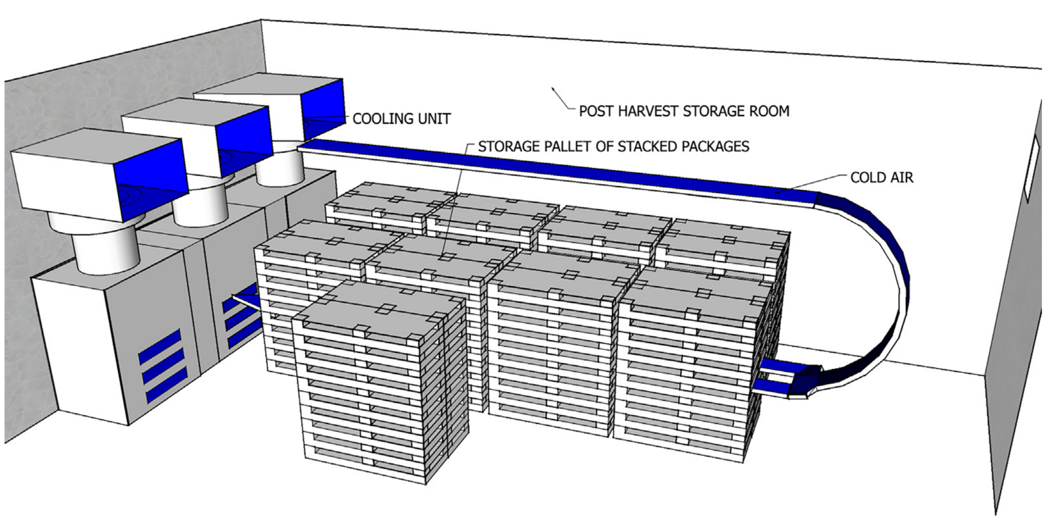

Fig. 1. Post-harvest storage room.