Journal of Food Engineering 190 (2016) 80–93

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Review

A review of the use and design of produce simulators for horticultural forced-air cooling studies

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
28 April 2016
Accepted 19 June 2016
Available online 21 June 2016

Keywords:
Produce
Simulator
Cooling
Design
Heat transfer

ABSTRACT

Forced air cooling studies are hindered by the practical difficulties and cost associated with pallet scale investigations. Produce simulators are a potential solution for overcoming some of these difficulties. Despite their common use in precooling research, there are a lack of design guidelines for such simulators in the literature which in some case has led to their inappropriate use. This review examines previous use of produce simulators in produce cooling studies in the context of transport phenomena theory. This allows constraints to be proposed which facilitate the design of produce simulators that can replicate transport phenomena in horticultural produce. These include the requirements of geometric and thermal property matching as well as the practical constraints imposed on produce simulators. It is suggested that future computational modelling work is well suited to the establishment of produce simulator design guidelines which incorporate complex effects such as the impact of variation in produce geometry on flow. The material engineering challenges posed by produce simulators are also discussed.

Contents

1. Introduction

The quality of horticultural produce progressively deteriorates post harvest due to continued physiological, biochemical, and microbiological processes (Verboven et al., 2006; Dehghannya et al., 2010). Immediate chilling of produce after harvest partially arrests these processes and is used to maintain quality and prolong storage (Castro et al., 2004). Such chilling is known as precooling and its optimisation is vitally important to the food industry (Brosnan and Sun, 2001), with up to 20% of all perishable foods

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http://dx.doi.org/10.1016/j.jfoodeng.2016.06.014
0260-8774/

Nomenclature

α	thermal diffusivity (m^2/s)
Bi	Biot number, hL/k
c	heat capacity (J/kg K)
E	activation energy of carbon dioxide respiration (J/mol)
V	evaporative heat loss as percentage of heat load
Fo	Fourier number, $\alpha t/L^2$ or $\alpha t/r_o^2$
h	convective heat transfer coefficient (W/m^2K)
ΔH_{vap}	latent heat of vaporisation (J/kg)
k	thermal conductivity (W/mK)
k_t	transpiration mass transfer coefficient (kg/kg s Pa or kg/m^2 s Pa)
k_{air}	air film mass transfer coefficient (kg/m^2 s Pa)
k_{skin}	skin mass transfer coefficient (kg/m^2 s Pa)
L	characteristic length, half the shortest dimension was used for produce (m)
M	percentage moisture loss from produce (%)
ρ	density (kg/m^3)
P	static pressure (Pa)
P_{air}	partial pressure of water in air (Pa)
P_{surf}	partial pressure of water at produce surface (Pa)
ϕ	volume fraction of filler material
q	heat of respiration (W/kg)
Q	heat of respiration as a percentage of heat load
R	the gas constant 8.314 (J/mol K)
r	radial distance from center (m)
r_o	radius (m)
r^*	dimensionless distance from centre (r/r_o)
T	temperature (K)
ΔT	change in temperature associated with a period of precooling (s)
t	time (s)
Δt	time period of precooling (s)
θ	temperature (°C)
u	flow velocity vector (m/s)
ν	kinematic viscosity (m^2/s)
Y	fraction of unaccomplished change in temperature, $(T-T_\infty)/(T_i-T_\infty)$
z	respiratory production rate of carbon dioxide (mL/kg hr)
z_o	respiratory pre-exponential for the production rate of carbon dioxide (mL/kg hr)

Subscripts

a	air
c	composite material
f	filler material
i	initial
m	matrix material
∞	Ambient
p	produce

being lost due to a lack of appropriate refrigeration (Defraeye et al., 2015a).

In order to slow spoilage processes it is desirable to cool produce as rapidly as possible, provided this does not cause chilling injury to the produce (Valente et al., 1996) and is done in a homogenous fashion. Non-uniform cooling results in under or over-cooling of produce in different locations, which leads to variation in product quality and associated product loss (Ferrua and Singh, 2009d; Dehghannya et al., 2010). Hence, minimisation of product loss can generally be achieved by cooling as rapidly and uniformly as possible. For forced air cooled systems, the rate and uniformity of cooling is ultimately determined by the flowrate, distribution and temperature of the air throughout the entire packaging structure (O'Sullivan et al., 2014).

One of the key parameters which effects airflow within horticultural packaging is the size and location of vents. Enhancement of cooling via design of vents is constrained by the requirement that the packaging be of sufficient strength to protect produce from damage during handling, transport and storage (Delele et al., 2008; Defraeye et al., 2015a). Though requirements of structural integrity have historically been prioritised over those which promote rapid and uniform cooling (Castro et al., 2004; Ferrua and Singh, 2009a), ventilated package design has still been the subject of a great deal of research as summarised in the review of Pathare et al. (2012). This review demonstrated that there is considerable variation in the design recommendations for ventilated packages made across various studies.

The lack of consensus in design recommendations is partly the result of the challenges associated with studies in this field which involve geometrically complex packaging systems and biologically variable produce. The experimental determination of airflow around individual products is difficult to achieve without disturbing the packaging arrangement itself (Dehghannya et al., 2010; O'Sullivan et al., 2014) and these difficulties have promoted the use and development of non-invasive flow measurement techniques in packaging studies (Ferrua and Singh, 2008; O'Sullivan et al., 2014).

Practical considerations of expense and time result from the fact that experiments are required to be on a full pallet scale and are subject to the seasonal availability of produce. This has limited the scope of many studies (Ferrua and Singh, 2008). Experimental replication of cooling studies is hindered by the biological nature of produce (Castro et al., 2004). Degradation of produce, for example, can change the heat transfer properties of produce during experimentation. Surface evaporation is a significant form of heat loss for some produce (Chuntranuluck et al., 1998a) and moisture loss from products may mean that this effect differs over time. To avoid such issues, replicate runs can be performed with fresh batches of produce, though this is costly, time consuming and subject to any biological variation in parameters such as shape and ripeness which will in turn lead to variability in replicate experiments.

These problems of experimental cost and time are magnified when considering designing packaging to ensure maintenance of temperature in transport systems such as refrigerated container ship holds. In these cases full containers may be required to conduct a useful experiment (e.g. Tanner and Amos, 2003; Defraeye et al., 2015b), resulting in considerable cost for a single replicate. Hence, cost becomes a limiting constraint when studying these systems (Tanner et al., 2002a; Ambaw et al., 2013).

The difficulties associated with experimentation have led many studies to focus on the alternative approach of developing mathematical models capable of predicting the flow fields and heat transfer within packaged commodities during forced air cooling (Ferrua and Singh, 2008). These mathematical approaches have been the subject of multiple reviews (Verboven et al., 2006; Dehghannya et al., 2010; Delele et al., 2010; Ambaw et al., 2013; Zhao et al., 2016). Earlier studies such as those of Talbot (1988) made the simplifying assumption that the packed structure was a