Journal of Food Engineering 143 (2014) 90–101

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Review

Airflow measurement techniques for the improvement of forced-air cooling, refrigeration and drying operations

Justin O'Sullivan [a,*], Maria Ferrua [b], Richard Love [a], Pieter Verboven [c], Bart Nicolaï [c], Andrew East [a]

[a] Centre for Postharvest and Refrigeration Research, Massey University, Private Bag 11-222, Palmerston North 4442, New Zealand
[b] Riddet Institute, Massey University, Private Bag 11-222, Palmerston North 4442, New Zealand
[c] BIOSYST-MeBioS, University of Leuven, Willem de Croylaan 42, Heverlee, Belgium

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 6 June 2014
Accepted 29 June 2014
Available online 8 July 2014

Keywords:
Numerical model validation
Experimental
Laser doppler anemometry
Particle image velocimetry
Thermal anemometry
Flow visualisation

ABSTRACT

Flowrate and distribution of air is a critical design factor in the cooling, refrigeration and drying of horticultural food products. These operations rely on a constant supply of air distributed throughout bulk arrangements of the produce. Local distribution of the air is critical to optimising the design and efficiency of these processes. Identification of the key parameters affecting the airflow distribution has been done either experimentally (using intrusive point-wise or bulk measurement techniques) or numerically. The detailed information provided by the use of computational fluid dynamic models has facilitated unique opportunities to investigate alternative system designs, without the need for expensive and time consuming experiments. This study provides a review of the techniques available to measure airflow (thermal and rotatory vane anemometry, pressure differential devices, tracer gases, LDA and PIV). Their advantages and disadvantages (accuracy, resolution, application range, cost, and ease of use) as well as their application in the validation of numerical models are reviewed. The novel and scientifically based design guidelines developed by a better understanding of the airflow behaviour within the system for each of the operations under study are also presented.

Contents

* Corresponding author. Tel.: +64 6 350 4336; fax +64 6 350 5657.
E-mail address: j.osullivan@massey.ac.nz (J. O'Sullivan).

http://dx.doi.org/10.1016/j.jfoodeng.2014.06.041
0260-8774/

1. Introduction

Common cooling and drying operations of food are typically based on the heat exchange between a food product and a constant supply of airflow through the system (Ghisalberti and Kondjoyan, 1999). For the cooling, refrigeration and drying of food the flowrate, distribution and temperature of the airflow throughout the entire packaging structure ultimately determines the rate, uniformity and efficiency of these processes. As uniform temperatures are desired in all three operations any operating and/or design feature capable of affecting the local distribution of the airflow behaviour within the system will have a profound effect on the performance of these processes.

In forced-air cooling, the size and location of the openings of the ventilated packages have been found to have a particular effect on the rate and uniformity of the process (Defraeye et al., 2013, 2014; Delele et al., 2008; Ferrua and Singh, 2009a; van der Sman, 2002; Vigneault et al., 2006). Ventilated packaging should be designed to provide uniform airflow distribution. However, uniform cooling does not always go hand in hand with higher cooling rates, and package design is a determining factor (Defraeye et al., 2014). The vents or openings determine how much air can come in contact with the product, how it is distributed inside the package, and what the air velocity magnitude is. Hence, cooling heterogeneity within packages is often a result of uneven airflow distribution (Dehghannya et al., 2008, 2011, 2012). A comprehensive review by Pathare et al. (2012) gives the recommended vent areas for a wide range of ventilated packages for horticultural produce.

In refrigerated rooms pallet stacking patterns can result in an uneven airflow distribution. When pallets are stacked high and closely packed together those centrally located and at the rear of the room (away from the evaporator fans) will receive smaller volumetric flows of refrigerated air compared to the pallets at the front of the room (adjacent to the evaporator fans). These local differences in flowrate throughout the room cause differences in the air temperature, with warm spots developing depending on pallet location (Verboven et al., 2003). Similarly, for refrigerated transport vehicles, pallet compactness can lead to high airflow resistances and uneven airflow distribution, with the formation of stagnant zones with higher air temperatures in the rear of the vehicle (Smale et al., 2006).

Typically, in forced-convection drying, warm, dry air exits an inlet and is distributed under a bed of horticultural produce. This air tends to follow a streamline flow and if not redirected will be distributed along the centre and towards the back of system, with regions not in the main pathway receiving smaller volumetric airflows, resulting in a non-uniform final moisture content (Nagle et al., 2010). When using impinging hot air jets for drying, the location and direction of the jet can affect the rates of heat and mass transfer spatially along the product width, as a higher percentage of the airflow is directed to one section of the product (Marcroft et al., 1999).

To improve the performance of these food operations a detailed understanding of how different design parameters and operating conditions affect the airflow behaviour within the systems is essential. This information has been traditionally obtained by measuring the local distribution of the airflow within the system using a wide range of experimental techniques. In addition, experimental information collected on the behaviour of the airflow has been also recently used for the validation of numerical models of the process (Smale et al., 2006). Beginning in the 1990s engineering simulation tools, such as Computational Fluid Dynamics (CFD), have become increasingly used in the analysis of cooling and drying processes within the food industry. Relevant examples are given in Wang and Sun (2003). Advanced CFD tools can predict complex airflow patterns in food operation systems in a level of detail difficult to achieve experimentally, facilitating a better and more fundamental understanding of the effect of the design and operating conditions on the efficiency of the process.

This study reviews not only the airflow measurement techniques currently employed to characterise airflow behaviour in forced-air cooling, refrigerated and drying applications but also their application in developing a better understanding and design of these processes.

2. Airflow measurement techniques

2.1. Direct airflow measurement

Direct flow measurement techniques are generally devices placed in the flow field which measure point-values in a system. They are widely used due to their robustness, ease of use and competitive price compared to non-invasive image analysis. These techniques include thermal anemometry, vane anemometry and differential pressure flowmeters.

2.1.1. Thermal anemometers

Thermal anemometers consist of a small, electronically heated sensor, initially kept at a constant temperature above that of the fluid flow temperature. Once the sensor is placed in the flow field it experiences a certain amount of cooling. As the electrical resistance of the sensor is dependent upon its temperature, a relationship can be obtained between the flow speed and the voltage output from the sensor.

Thermal anemometers can be operated to maintain a constant temperature or constant current through the sensor. In the case of constant temperature anemometers, the sensor's resistance is constant and the required voltage (or current) to maintain the temperature is measured. Conversely, for constant current anemometers the applied current is held constant and the sensor's voltage drop (or electrical resistance) is measured (Fingerson and Freymuth, 1996). The air velocity can then be inferred from the power required to maintain the temperature or current of the sensor. The sensor placed in the fluid flow is a wire for hot-wire anemometers and a film in the case of hot-film anemometers.

Thermal anemometers can be made at a relatively low cost and when thin wires are used a high sampling frequency can be used (up to 10^5 Hz). Limitations of thermal anemometers include the requirement for regular calibration, which often involves the