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SCIENCE DIRECT

International Dairy Journal 16 (2006) 920–930

INTERNATIONAL DAIRY JOURNAL

www.elsevier.com/locate/idairyj

Computational fluid dynamics prediction and validation of gas circulation in a cheese-ripening room

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Received 1 December 2004; accepted 26 August 2005

Abstract

This paper discusses the application of a computational fluid dynamics (CFD) approach to predicting air velocity patterns and circulation of an exogenous gas inside a pilot cheese-ripening room in 3 dimensions (3D). Comparison of numerical results with experimental data showed a fairly close agreement in the qualitative prediction and a few inaccuracies in the quantitative prediction of the air velocity patterns, with mean absolute differences of $0.12\,\mathrm{m\,s^{-1}}$ in half the volume of the ripening room and about $0.05\,\mathrm{m\,s^{-1}}$ inside the stacks filled with cheese models. A sensitive study revealed that using the standard $k-\varepsilon$ model for modelling the turbulence of the flow in combination with the first-order upwind differencing scheme offered a good compromise solution between accuracy of results and computation time, given the 3D mesh of 1.2 million cells created. Moreover, numerical calculations indicated that using the blowing duct for adding an exogenous gas seemed to provide a more efficient solution for levelling off the gas distribution throughout the whole volume of the room than an injection performed directly into the core of the stacks.

Keywords: CFD; Cheese; Ripening room; Air velocity; Gas circulation

1. Introduction

Computational fluid dynamics (CFD) solves fluid flow problems coupled with heat and mass transfers and turbulence phenomena in a given geometry by the use of a mesh where all the Navier–Stokes equations are solved across each mesh cell by means of an iterative procedure requiring specific algorithms. Due to the development of cheaper, more powerful computers and user-friendly commercial software packages, CFD techniques have been increasingly used in recent years in many areas of the food industry, as has been detailed in several reviews (Scott & Richardson, 1997; Xia & Sun, 2002). CFD techniques have been applied to industrial problems for predicting values for air velocities, composition of atmosphere and temperature fields inside food processing plants, including, for example, baking ovens (Verboven, Scheerlinck, De Baerdemaeker, & Nicolaï, 2000a, b; Mirade, Daudin, Ducept, Trystram, & Clément, 2004) and refrigerated rooms (Hoang, Verboven, De Baerdemaeker, & Nicolaï, 2000; Mirade, Kondjoyan, & Daudin, 2002; Foster, Barrett, James, & Swain, 2002). In addition to the above-mentioned industrial applications, nowadays one of the most important and advanced applications of CFD in food processing is spray drying, with calculations aiming at improving spray-dryer design and operation (Straatsma, Van Houwelingen, Steenbergen, & De Jong, 1999; Langrish & Fletcher, 2001; Ducept, Sionneau, & Vasseur, 2002).

Controlling airflow (air velocity, air change rate, and exchange with outside air) and climatic conditions (air temperature and relative humidity, gas concentration) inside cheese-ripening rooms is of paramount importance, because it determines both the efficiency and the homogeneity of cheese-ripening and weight losses. However, homogeneity in the distribution of climatic conditions is very hard to achieve at every single point of a ripening room. Consequently, industrial plants experience significant differences in the distribution of air temperature, velocity and relative humidity. For example, Pajonk (2001) reported differences greater than 10% in relative humidity inside an Emmental-ripening room, and attributed the

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0958-6946/$ - see front matter
doi:10.1016/j.idairyj.2005.08.007

observed damages on crust formation to these differences. In an 81 m^3 ripening room filled with 10 cm diameter cheese models, Mirade, Rougier et al. (2004) measured air velocities ranging from less than 0.05–0.40 $m\,s^{-1}$ inside the stacks and showed that heat and water transfer coefficients tripled when air velocity was increased from 0 to 0.45 $m\,s^{-1}$ around plaster casts of cylinders 100 mm in diameter and 40 mm high. Falconer (1993) also highlighted significant heterogeneity in air velocity distribution in two cheese cooling stores, with air velocities ranging from 0.1 to over 2.5 $m\,s^{-1}$, and, therefore, differences in the cooling of the cheeses. The heterogeneity in climatic conditions existing in cheese-ripening rooms means that cheesemakers have to regularly move cheeses to achieve even water losses and an even appearance in the cheese surfaces. Nevertheless, only a few studies on this very real problem can be found in the literature because most of these studies are confidential. Even the books dealing with cheese-ripening processes (Eck, 1990; Mahaut, Jeantet, & Brulé, 2000) do not give accurate information on the relationship between ventilation, indoor atmosphere and cheese quality; the authors only recommend a homogeneous atmosphere with low air circulation around the cheeses (air velocity not exceeding about 0.1 $m\,s^{-1}$) and a "high enough" airflow rate in the room. Indeed, the role played by ventilation is complex and remains poorly quantified. Ventilation allows heat and humidity produced by the cheeses to be evacuated and also determines both weight losses and the gas concentrations (CO_2, O_2, NH_3) in the atmosphere surrounding the cheeses, which itself influences cheese ripening. For example, during the manufacturing of the Camembert cheese, the presence of ammonia and oxygen in the atmosphere of the ripening room makes it easier to reduce acidity on the surface of the cheese (Vassal & Gripon, 1984) and for the *Penicillia* to grow (Roger, Desobry, & Hardy, 1998), respectively. Furthermore, the presence of carbon dioxide in the indoor atmosphere would increase the opening of the curd of hard cheeses as Emmental, Gruyere and Comté by stimulating propionic acid fermentation (Mahaut et al., 2000).

The results presented in this paper stem from a research programme aiming at building instrumentation for controlling gas concentrations in the atmosphere of ripening chambers. The development of a system based on high-performance sensors coupled with information on airflow patterns would give ripening chamber operators greater flexibility in both controlling and adjusting the composition of the atmosphere, which would contribute to improving the consistency and the quality of the cheese-making process. This paper is restricted to presenting the CFD prediction of air circulation in a pilot cheese-ripening room of 81 m^3, the comparison of these numerical results with air velocity measurements, and the calculation of the circulation of an exogenous gas injected from points located either in the blowing duct or in the core of the cheese stacks. The geometry and operation of the pilot-ripening chamber were selected with the help of a plant designer as being representative of current standards in the industry.

2. Materials and methods

2.1. Description of the pilot-ripening room

The pilot-ripening room was 5.8 m long, 4.8 m wide and 2.9 m high, which gives an overall volume of 81 m^3. Inside this room, 6 rows of 7 stacks of 16 racks of 21 cans (i.e. a total of 14,112 cans) were installed to obtain a filling pattern representing current industrial practice (Fig. 1). Free space according to the height between two consecutive racks was 10 cm. As our interest in this study was the airflow inside the room and not the heat and water transport stemming from the interaction between the cheeses and their surroundings, we replaced cheeses by empty cans 10 cm in diameter and 4.4 cm high, i.e. inert objects presenting the same resistance against air circulation.

An air conditioning system comprising of two fans and two batteries and installed in a space located above the ceiling of the pilot-ripening room controlled the temperature and flow rate of the air blown into the room. The airflow rate was determined from the measurement of the pressure difference between two points of a diaphragm located in the duct supplying air to the blower duct made of textile material and placed in the chamber.

Inside the pilot-ripening room, the ventilation system was designed to mimic a common industrial configuration, namely an air conditioning system placed at the end of the room, extracting air in its lower part and blowing the conditioned air through a duct in its upper part. This system was composed of a 340 mm blowing duct made of textile material and a 315 mm suction duct (Fig. 1). The blowing duct running along the ceiling at half-width in the room was fitted on each side with several hundred holes 6 mm in diameter and divided into 3 rows. After being blown into the room, the air was extracted at 35 cm from the ground by means of a suction duct placed against a vertical wall at half-width in the room (Fig. 1). The suction duct was connected to the space located above the ceiling of the pilot ripening room in which the fans were installed. The full airflow rate blown into the room was 1600 $m^3\,h^{-1}$, i.e. an air change rate of 20 volumes h^{-1}, which corresponds to normal industrial practice.

2.2. Air velocity measurements

In the free spaces of the pilot ripening chamber, i.e. between the rows of the stacked racks and above the stacks, we applied a fast method set up at the laboratory and described in Mirade and Daudin (1998), using a specially built system (Fig. 1) to support and automatically move the measurement devices at a slow and fairly constant velocity. The measurement devices were multi-directional hot-film-type anemometers (model 8465, TSI,