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ScienceDirect
Journal of Food Engineering 85 (2008) 547–560
JOURNAL OF FOOD ENGINEERING
www.elsevier.com/locate/jfoodeng

Experimental study of air flow by natural convection in a closed cavity: Application in a domestic refrigerator

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Received 23 February 2007; received in revised form 20 August 2007; accepted 20 August 2007
Available online 12 September 2007

Abstract

An experiment was carried out using a refrigerator model in which heat is transferred by natural convection. This transfer takes place between a cold vertical wall and the other walls, which are exposed to heat losses. The air velocity measurements were undertaken using particle image velocimetry (PIV). Circular airflow was observed in the cavity: air flows downward along the cold wall and upward along the other walls. The maximum air velocity (0.2 m/s) was observed near the bottom of the cold wall. Non-stationary airflow with recirculation was observed along the horizontal bottom wall of the cavity. Airflow is very weak (<0.04 m/s) at the central zone and it is quasi-stagnant at the top. The velocity profile in the boundary layers of the empty refrigerator model was also investigated. The influence of temperature and surface area of the cold wall on air velocity were studied. It was found that the influence of the cold wall temperature on the air velocity is more significant than the surface area.

In order to study the effect of obstacles on velocity profiles, the refrigerator model was filled with four blocks of hollow spheres. The air velocity in the case of filled refrigerator was compared with the results of the empty one. The air velocity is lower almost everywhere in the filled refrigerator model. The presence of the blocks seems to homogenise the air velocity.

Keywords: Natural convection; Closed cavity; PIV; Air velocity profile; Domestic refrigerator

1. Introduction

Domestic refrigerator is an appliance widely used in industrialized countries. There are approximately 1 billion domestic refrigerators worldwide (IIR, 2002). The demand in 2004 in the world was 71.44 million units (11.2 million in China, 10.7 million in USA, 4.43 in Japan, 3.36 in India, 3.14 in Brazil, ..., JARN, 2005). In developing countries, the production is rising steadily: +30% of total production in 2000 (Billiard, 2005). In France, there are 1.7 refrigerators per household (AFF, 2001). Three types of domestic refrigerators are available in the market: static, brewed and no-frost. The static type (Fig. 1a) is widely used in Europe. In this case, heat is transferred principally by natural convection and airflow is due to variations in air density. These variations are essentially related to the temperature gradients: hot air is lighter than cold air. The cold air in contact with the evaporator (cold wall) flows downward. The air in contact with the other walls (warm walls) flows upward. Due to the principle of heat transfer, temperature heterogeneity is often observed in this type of refrigerator. The position of the evaporator (horizontal/vertical, top/bottom of the compartment) determines the location of cold and warm zones. The brewed type is a static refrigerator equipped with a fan (Fig. 1b). It promotes air circulation and the temperature decreases rapidly after door opening. Air temperature is more homogeneous in this case than in the static type but the energy consumption is higher due to the fan. In a

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doi:10.1016/j.jfoodeng.2007.08.023

Nomenclature

g	acceleration due to gravity (9.81 m/s^2)
K	permeability of the porous media (m^2)
H	height of cold wall or height of cavity (m)
M	enlargement factor (ratio between real dimension and image)
Ra	Rayleigh number
Ra_p	Rayleigh number of porous media
Ra_c	critical Rayleigh number
t	time (s)
T_{amb}	external ambient temperature (°C or K)
T_c	cold wall temperature (°C or K)
T_f	internal air temperature (°C or K)
ΔT	temperature difference between the cold and warm walls (°C or K)
u^*	dimensionless air velocity
u_y	velocity in the height direction of the refrigerator model (m/s)
u_z	velocity in the width direction of the refrigerator model (m/s)
u	velocity magnitude (m/s) $u = \sqrt{u_y^2 + u_z^2}$
X	distance of smoke particle displacement (m)

Greek symbols

α	thermal diffusivity of air (m^2/s)
α_p	thermal diffusivity of the porous media (m^2/s)
β	thermal expansion coefficient (K^{-1})
ν	kinematic viscosity (m^2/s)
δ	thickness of boundary layer (m)
δt	time interval between a pair of images (s)

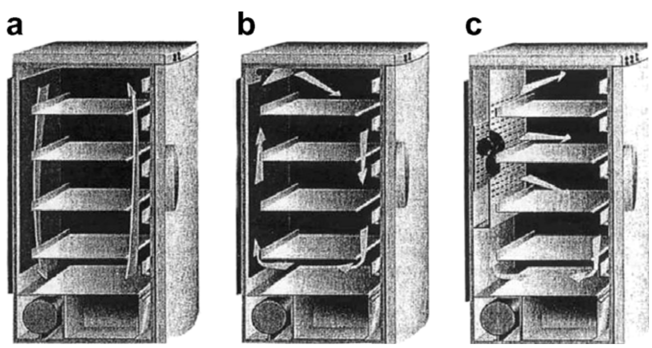

Fig. 1. Three types of refrigerator: (a) static, (b) brewed and (c) no-frost (Roussille, 2002).

no-frost refrigerator (Fig. 1c), a fan (embedded in the back wall) pushes air to flow over the evaporator before entering into the refrigerating compartment. Air temperature is more homogeneous compared to the two other refrigerator types. Disadvantages of no-frost type are noise, energy consumption, drying on food surface and high price.

Only the static refrigerator was studied in the present work in which a strong coupling between air velocity and temperature is observed. Temperature distribution in a refrigerator model was already presented (Laguerre, Ben Amara, & Flick, 2005). To complete this previous work, the air velocity field is now presented. Knowledge of air temperature and velocity profiles in a refrigerator is important for food quality control. Design of refrigerator can be modified or recommendations can be given to consumers, so that perishable food products are placed in low-temperature and well ventilated positions. Food products should also not disturb the boundary layer close to the evaporator wall. Indeed, obstacles in this location would reduce the heat transfer between cold wall and air and product could freeze.

The objective of this work is to generate experimental data on air velocity distribution in a static domestic refrigerator. This study allows gaining better insight into the mechanism of airflow by natural convection. Also, the data obtained can be used to compare with the modelling results. To achieve this objective, an experiment was carried out using a transparent refrigerator model, which makes it possible to visualize and measure the airflow by PIV (particle image velocimetry). This refrigerator model allows observing the same phenomena as those in a domestic refrigerator but with better-controlled boundary conditions and simpler geometry.

The influence of the following operating conditions on the air velocity was studied:

- cold wall temperature (parameter related to thermostat setting),
- dimension of cold wall (parameter related to design of evaporator),
- product loading. Comparison of the results obtained for empty and loaded refrigerator makes it possible to determine the influence of obstacles on airflow in the refrigerator.

2. Literature review

2.1. Air flow in domestic refrigerators

Several experimental studies were carried out on empty and loaded refrigerators (James & Evans, 1992; Masjuki et al., 2001). The objective was to analyze the effects of several parameters on the temperature in the refrigerating compartment (thermostat setting, frequency of door openings, filled volume, temperature and humidity of ambient air). However, few studies were carried out on airflow measurement due to the complexity of measurement techniques compared to the ones of temperature. Airflow measurement in a freezer compartment under real operating conditions was carried out by Lacerda, Melo, Barbosa, and