INTERNATIONAL JOURNAL OF REFRIGERATION 32 (2009) 220–234

available at www.sciencedirect.com

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

Air velocity characteristics within vented pallets loaded in a refrigerated vehicle with and without air ducts

J. Moureh[a,*], *S. Tapsoba*[a], *E. Derens*[a], *D. Flick*[b]

[a]*UMR Génie Industriel Alimentaire AgroParisTech, Cemagref, INRA, Génie des Procédés AN/Refrigerating Process Engineering Research Unit, Cemagref, BP 44, 92163 Antony Cedex, France*

[b]*UMR Génie Industriel Alimentaire AgroParisTech, Cemagref, INRA, AgroParisTech 16, rue Claude Bernard, 75231 Paris Cedex 05, France*

ARTICLE INFO

Article history:
Received 3 April 2007
Received in revised form 6 May 2008
Accepted 12 June 2008
Published online 26 June 2008

Keywords:
Refrigerated transport
Road transport
Pallet
Modelling
Computational fluid dynamics
Experiment
Flow
Air
Ventilation
Duct

ABSTRACT

During transport using refrigerated vehicles, this being a vital link in the cold chain, the maintaining of even temperature throughout the cargo is essential in order to preserve the quality, safety and shelf life of perishable food. Within the refrigerated container, the temperature level and its homogeneity are directly governed by airflow patterns. The design of the air-distribution system should allow these airflows to compensate heat fluxes exchanged through the insulated walls or generated by the products.

In this paper, a reduced-scale model and CFD predictions were used to investigate experimentally and numerically the airflow patterns within a typical refrigerated truck configuration loaded with vented pallets filled with spherical objects. The experiments were carried out using a laser Doppler velocimetry and thermal sphere-shaped probes located inside the pallets. The aim was to investigate air velocity characteristics above and within pallets. The performance of ventilation was characterized with and without supply air duct systems. Both configurations are extensively used in refrigerated transport. Full-scale measurements were also performed within a load of fruit during transport in a refrigerated truck in order to evaluate the temperature distribution under given operating conditions. The numerical modelling of airflow was performed using the computational fluid dynamics (CFD) fluent code and the Reynolds Stress Model (RSM) turbulence model. Numerical and experimental data make it possible to evaluate the air ventilation levels and their heterogeneity between the pallets. The numerical predictions show reasonable agreement with experimental data. The studied supply air duct system improves significantly the homogeneity of ventilation in the vehicle.

Caractéristiques de la vitesse de l'écoulement d'air à l'intérieur de palettes munies de ventilation chargées à bord d'un véhicule frigorifique avec ou sans gaines d'air

Mots clés : Transport frigorifique ; Transport routier ; Palette ; Modélisation ; Dynamique numérique des fluides ; Expérimentation ; Écoulement ; Air ; Ventilation ; Gaine

* Corresponding author. Tel.: +33 (0)1 40 96 60 88/61 21; fax: +33 (0)1 40 96 62 49.
E-mail address: jean.moureh@cemagref.fr (J. Moureh).

0140-7007/$ – see front matter © 2008 Elsevier Ltd and IIR. All rights reserved.
doi:10.1016/j.ijrefrig.2008.06.006

Nomenclature

C	pressure drop coefficient
D_H	hydraulic diameter of inlet duct (m)
d_p	sphere diameter (m)
H	enclosure height (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	turbulent kinetic energy, $(1/2)u_i^2$ (m^2 s^{-2})
L	enclosure length (m)
Nu	Nusselt number
p	static pressure (Pa)
Pw	heating power of the probes (W)
Re	Reynolds number
T	temperature (K)
U	time-averaged velocity (m s^{-1})
U_D	Darcy's velocity (m s^{-1})
u	velocity fluctuation (m s^{-1})
$\dot{V}_p$	flow rate within a pallet (m^3/s)
W	enclosure width (m)
x, y, z	space coordinates (m)

Greek symbols

Σ	pallet surface (m^2)
α, β, γ	empirical constants
δ_{ij}	Kronecker symbol
ε	turbulent dissipation rate (m^2 s^{-3})
λ	air conductivity (W m^{-1} K^{-1})
μ	laminar dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

o	relative to inlet boundary condition
outlet	relative to exhaust air (outlet of the vehicle)
$\perp$	normal
x, y, z	relative to coordinate system
ε	relative to turbulent dissipation rate

1. Introduction

This work is part of a research activity aimed at improving and optimizing air-distribution systems in refrigerated vehicles in order to decrease the temperature differences throughout the palletized cargos. This condition is essential in order to preserve the quality, safety and shelf life of perishable products and it thus allows better compliance with European standards concerning food safety.

Recent developments in the refrigerated transport sector have led to the expectation of air temperature tolerances of the order of ±2 °C in refrigerated truck containers. In such equipment, non-uniform cooling of perishable foodstuffs may cause considerable loss in product quality, making products unsuitable for sale. During the transport of fruit and vegetables, the product load is subjected to internal production of heat, moisture and chemical degradation due to respiration. If ventilation is insufficient, the temperature, moisture content and ethylene concentration increase and this causes several phenomena that harm the quality of the products, namely: premature ripening (caused by a high ethylene concentration), microbial development, drying, modification of flavour, change of colour and loss of firmness.

Given that about 3 million tons of fruit and vegetables per year are going through the cold chain in France, the correct temperature management during post-harvest treatment becomes indispensable, especially during refrigerated transport. Over the past few years, more attention had been paid to the increasing of the load volume in a given truck than to the optimisation of the air distribution. Truck-transported fruit and vegetables are usually packed in porous bins or wooden crates forming pallets, which are not subjected to any rules.

In the refrigerated enclosure, heat is transferred primarily by convection; therefore, the temperature and its homogeneity are directly governed by the patterns of airflow. Air renewal provided by these airflows should compensate for the heat fluxes exchanged through the insulated walls or generated by the products. This process is essential in order to decrease temperature differences throughout the cargo. The aim is to ensure that neither overcooling nor undercooling occurs in any localized areas. This, however, is particularly challenging given the length of the container ($L/H > 5$), the small air gaps between pallets, the compactness of the load, and the locations of both the air delivery and return on the same face of the refrigerated container.

2. Literature review

2.1. *Essential features of airflow behaviour and measurement techniques*

The aim of this section was to describe the essential aerodynamic features encountered in the studied configuration. These aspects play an important role in performing the numerical approach.

In a refrigerated vehicle enclosure, the air is supplied at relatively high velocities through a small inlet section located adjacent to or near the ceiling. Due to the adherence of the jet on this boundary by the Coanda effect, this design should allow the confined jet to expand while following the room wall surfaces and hence provide a high degree of ventilation throughout the entire enclosure.

The principal aerodynamic particularity of this configuration is the presence of inlet and suction sections on the same face since it is very practical to bring together all the refrigerating equipments at one side of the transport unit. This leads to a strong short-circuit between the two sections, implying high velocities in the front of the enclosure (Moureh et al., 2002; Finn and Brennan, 2003; Tapsoba et al., 2006). According to Finn and Brennan (2003), airflow patterns are subject to severe maldistributions with the majority of flow circulating in only the front quarter of a typical container. As a consequence, stagnant zones with poor ventilation can be observed in the rear part of the vehicle. In these zones, higher temperatures can occur locally within the load of product (Gögüs and Yavuzturk, 1974; Lenker et al., 1985;