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Using simplified models of cold chain equipment to assess the influence of operating conditions and equipment design on cold chain performance

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ABSTRACT

This numerical study presents the influence of input variables (ambient and thermostat setting temperatures) and equipment parameters (dimension, airflow rate, insulation) on the load temperatures. Simplified thermal models based on a zonal approach for domestic refrigerators, refrigerated vehicles and refrigerated display cabinets were used. The ranges of input variables and parameters, observed in practice, were presented. These ranges were obtained from laboratory studies, expertise, constructor data and literature review. The main factors which influence the load temperature in domestic refrigerators, refrigerated vehicles and display cabinets were reported. This information can be useful for cold chain management.

Utilisation de modèles simplifiés d'équipements de la chaîne du froid afin d'améliorer l'influence des conditions de fonctionnement et de la conception des équipements sur la performance de la chaîne du froid

Mots clés : Réfrigérateur domestique ; Véhicule frigorifique ; Meuble frigorifique de vente ; Température ; Charge

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Nomenclature

g	gravitational acceleration (m s^{-2})
H	door height (m)
Q	air infiltration rate ($m^3.s^{-1}$)
s	ratio of warm air density to cold air density (ρ_{out}/ρ_{in})
T_{ext}	external air temperature (°C)
T_{th}	thermostat setting temperature (°C)
T_1, T_2, T_3, T_4	load temperature at different positions in equipment (°C)
W	door width (m)
ρ_{out}	density of outside air ($kg.m^{-3}$)
ρ_{in}	density of inside air ($kg.m^{-3}$)

1. Introduction

The product time-temperature history in the cold chain from production until consumption is a determining factor in organoleptic and sanitary quality. Because of the concerns of industry and consumers, it is thus, necessary to control and maintain the appropriate temperature along the cold chain. Several surveys of temperature monitoring of food along the cold chain have shown temperature abuse in certain links, notably in display cabinets, transport by the consumer to the home and domestic refrigeration. A field study carried out in France (Cemagref and ANIA, 2004) showed that 7% of the products preserved in refrigerated display cabinets, 60% of the products transported by consumer after purchase and 40% of the products in domestic refrigerators, exhibited a temperature 2 °C higher than the recommended value.

A numerical approach notably by CFD simulation (Computational Fluid Dynamics) is often used to study heat/mass transfer and airflow in refrigerating equipment. It presents two main advantages; firstly, it enables the knowledge of local parameters such as temperature, humidity and velocity allowing the understanding of phenomena. Secondly, it enables the prediction of the influence of operating conditions and the equipment design without doing any experiments which are sometimes expensive or impossible to undertaken. However, this approach is difficult to apply in practice when considering the variability of a cold chain composed of varied equipment because of the calculation time. To avoid this problem and in order to predict the time-temperature history of a high number of products along the cold chain, it is necessary to develop simplified models.

Our team (Irstea-AgroParisTech) has developed simplified models of a domestic refrigerator (Laguerre and Flick, 2010), a refrigerated vehicle (Hoang et al., 2012a) and a display cabinet (Laguerre et al., 2012). These models are summarised in this paper while the ones for a cold room and a food production plant are in progression and will be presented in the future.

The simplified models of a display cabinet, transport by consumer from store to home and a domestic refrigerator were linked together enabling the prediction of product temperature evolution in the most sensible part of cold chain. These models were combined with stochastic models of the cold chain to take into account the variability of the operating conditions (Flick et al., 2012; Hoang et al., 2012b). To represent as well as possible the real cold chain conditions, a high number of simulations ($\geq 10^4$ simulations) were carried out to represent the time-temperature evolution of many product items. Models of quality and microbiological evolution can also be coupled with this approach enabling the cold chain evaluation. Due to our best knowledge, few studies were carried out using these approaches.

The present study focuses on the influence of the equipment design parameters, in conjunction with the operating conditions, on the variability of the temperature levels in domestic refrigerators, in refrigerated vehicles and in display cabinets. The data were obtained from our laboratory studies, our expertise, constructor data and literature review. They can be useful for research work and for industrial uses.

The first objective of this paper is to present the ranges of input variables and parameters observed in field. They are related to operating conditions (ambient temperature, thermostat setting) and to equipment design (dimension, air flow rate, insulation). The second objective is to carry out a numerical study to identify the input variables and parameters which have the most significant influence on the product temperatures. This information can be used, as a first attempt, to avoid product temperature abuse and to improve the cold chain management.

2. Literature review

2.1. Cold chain performance

Duret et al. (2014) proposed an approach combining deterministic (heat transfer) and stochastic (Monte Carlo) modelling to take into account the variability of the logistic chain (ambient temperature, thermostat setting temperature, product residence time in equipment etc.), product properties (aw, pH, nitrite content etc.) and microbial characteristics (initial contamination, physiological state etc.). A sensibility study carried out by these authors showed that the product time-temperature history is the factor which has the most impact on the final contamination of *Listeria monocytogenes* (at the consumption point). The performance of cold chain is, thus, really important to assure the product quality and safety.

The climatic change can have an influence on the performance of the cold equipment. Between 1900 and 2005, there has been a 0.45 °C rise in average world temperature (Carbon Disclosure Project, 2006). If climatic change results in important rise in average ambient temperatures this will impose higher heat loads on all systems in the cold-chain. From the microbiological point of view, a 2–4 °C rise in ambient temperatures leads to a similar rise in the temperature of chilled food (for constant refrigerating power) then food poisoning and spoilage would increase (James and James, 2010). Keeping food at current or lower temperatures will result in an increase in the energy used by food refrigeration systems. Sarhadian (2004) measured the average power consumed by refrigeration equipment in a catering establishment at different ambient temperatures. Increasing the ambient temperatures from 17 to 25 °C resulted in an 11% increase in average power consumed.