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Review Article

Thermal performance indicators for refrigerated road vehicles

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Abstract

An experimental evaluation of insulation effectiveness, pull-down times and effectiveness of a mechanical refrigeration unit was performed on five refrigerated panel vans. Additionally, a mapping of temperature variability in the cargo space was carried out during a simulated journey encompassing several door openings. The temperature variability measured in the vans was neither correlated to the effectiveness of the insulation nor the time required to achieve complete cooling of the cargo space. These criteria are common thermal performance indicators used to evaluate refrigerated vehicles in international standards. The efficiency of insulation was correlated to the pull-down times, presenting the possibility of calculating the former as a function of the latter. The temperature variability was correlated with the time required for the unit to recover temperature control after a door opening and the difference between the maximum and minimum temperatures reached during a door opening cycle.

Keywords: Refrigerated transport; Road transport; Experiment; Measurement; Efficiency; Insulation; Temperature; Regulation

Indicateurs de performance thermique pour les véhicules frigorifiques routiers

Mots clés : Transport frigorifique ; Transport routier ; Expérimentation ; Mesure ; Efficacité ; Isolation ; Température ; Régulation

1. Introduction

Thermal performance standards serve as benchmarking instruments to compare refrigerated transport systems and to ensure that these systems provide a minimum level of operating effectiveness. Insulated and refrigerated sea, rail and road freight containers must comply with the international standard ISO 1496-2 [1]. In Europe, the specifications for refrigerated vehicles are covered by the International Agreement for the Transport of Perishables (ATP), which has the status of a standard [2]. The Australian Standard 4982-2003 for refrigerated vehicles [3] defines testing specifications and procedures to evaluate the thermal performance of refrigerated equipment, used to transport perishable goods by road. The equipment covered by the standard includes insulated trailer, truck and van bodies (single or multi-compartment) fitted with any form of refrigeration.

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Nomenclature

A_{do}	amplitude of mean temperature during the door opening cycle (°C)
C_p, C_{pk}	process capability indices for normal processes
C_p^{WSD}, C_{pk}^{WSD}	weighted process capability indices for non-normal processes
D_x	parameter of Eq. (6)
I	parameter of Eq. (6)
K_{value}	overall heat transfer coefficient (W m^{-2} K)
LSL	lower temperature specification limit (°C)
n	sample size
P_x	probability in Eq. (7)
Q	electrical power dissipated inside the body by the heaters and fans (W)
Q_h	total heat load during the final 4-h period in the refrigeration capacity test (W)
S_m	mean surface area of the body (m^2)
T_{ms}	arithmetic mean of skin temperature (°C)
$t_{pull\text{-}down}$	pull-down time (h)
$t_{recovery}$	recovery time (h)
USL	upper temperature specification limit (°C)
X_i	data values, observations

Greek letters

$\hat{\mu}$	mean temperature (°C)
$\hat{\sigma}$	sample standard deviation

Subscripts

o	outside, external
i	inside, internal

Key thermal tests described in AS 4982-2003 and relevant to refrigeration plants already fitted to the unit are:

(a) Insulation efficiency (heat leakage) test by the inner heating method: this test determines the effectiveness of the insulated body, measured as a K_{value}, by means of creating a temperature differential of no less than 20 °C between the cargo space and the external environment. The method includes measurement of at least 12 temperatures encompassing the corners, sidewalls, ceiling and floor of the vehicle.
(b) Performance tests of the refrigeration system: this test evaluates the ability of the truck to maintain the set-point temperature within the cargo space during 8 h of uninterrupted operation. The vehicle is tested for a further 4 h with an additional heat load. The AS 4982-2003 specifies an ambient external temperature of 38 °C for this test.
(c) In-service (pull-down) test: this assessment measures the time required to cool down the empty truck to the classification temperature.

The evaluation of vehicles following AS 4982-2003 and similar standards rely on temperature measurements in selected locations throughout the tested body; however, these locations usually reflect the dynamics of the layers adjacent to the walls of the van, rather than the thermal behaviour of the cargo space. Furthermore, most regulations do not test vehicles under realistic logistics scenarios. For example, vehicles carrying out home delivery operations will have at least three deliveries (i.e. three door openings) per hour [4]. Frequent door openings can lead to increased evaporator frosting, resulting in a reduction of the evaporator's performance and an increase in the need of defrosts, particularly in humid weather conditions. The effect of these variables on temperature control in refrigerated vehicles is of concern to the logistics providers, who identify temperature control as a parameter directly linked to food safety regulations. However, the relationship between temperature variability and key thermal performance indicators, such as insulation efficiency, is far less understood.

An experimental K_{value} reflects: (a) the properties of the van's insulation; (b) the van's design; and (c) the van's manufacturing process. Regarding (a), the properties of the insulation depend on the age of the vehicle and this aspect has been thoroughly investigated elsewhere [5,6]. Nevertheless, the effect of the design and manufacture variables on the effectiveness of insulated bodies has been less studied. A refrigerated body may be insulated with a high-quality, low conductivity material, but a poor design and/or a defective foaming can lead to significant thermal bridges (e.g. structural pockets, air gaps, metallic latches, structural ribs, hinges, rivets or screws). These losses and their effect on the K_{value} of an insulated body cannot be predicted theoretically, unless the model used also considers the existence of thermal bridges (e.g. dimensions and location) in that particular body. Current computational methods used to calculate a K_{value} (e.g. [7]) need to be refined in order to account for these design and manufacturing variables.

This paper presents the results of thermal performance tests carried out on five refrigerated vans, following the methodology described in the AS 4982-2003. Additionally, a detailed mapping of temperature variability in the cargo space of each van was carried out during a simulated 8-h delivery schedule.

2. Methodology

Tests were carried out in Food Science Australia's controlled-environment shipping-container test facility.