DYNAMIC BEHAVIOR OF THE INSULATED BOX IN REFRIGERATED TRUCKS

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EXPERIMENTAL ANALYSIS OF THE DYNAMIC BEHAVIOR OF THE INSULATED BOX IN REFRIGERATED TRUCKS

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Abstract

Refrigerated trucks are an essential step in the cold chain, since they are in charge of guaranteeing the delivery to the market of perishable freights in safe and high quality conditions. For a given truck, the average cooling demand depends on the external conditions and on the mission profile: ambient temperature, air velocity and vehicle velocity. In order to understand the dynamic load on the system and predict the peak cooling demand, the dynamic response of the insulated box is necessary.

This paper presents an experimental investigation to determine the time constant of the insulated boxes in refrigerated trucks; results are obtained by means of step input response test. Sensitivity to the main parameters of the box/truck is illustrated.

Data are acquired at ITC-CNR ATP test station located in Padova.

1. Introduction

Air conditioning system are widely used in modern society to transfer thermal energy from one physical location to another. In particular, refrigerated transport system are used to distribute chilled and frozen products through the world and thus more and more attention is paid to food transport refrigeration because of the increasing concerns on food safety and quality. Compared with stationary systems, transport refrigeration systems are required to perform reliably over a variety of operating conditions and to be energy efficient without compromising the temperature control of the product[1]. This paper analyzes the dynamic response of the insulated box of a refrigerated truck to a sudden change of the internal operating conditions. Being able to predict how the insulated box reacts to thermal input plays a crucial role in a correct design and sizing of the cooling unit of a refrigerated vehicle which has the role of maintaining an efficient temperature control with the minimum energy waste under the fluctuating external load.

2. Data Collection

Experimental data were acquired at ITC-CNR ATP test station in Padova. Test station's main dimensions can be seen in Figure1.

This test station is composed of two coupled rooms: the machine room where the cooling unit and the fan-group are located and the tunnel, under the machine room, where trucks reside during the test. Tests are carried out with the internal heating method according to ATP agreement [2]: this method prescribes to set a stable temperature difference between box indoor and outdoor air under a known thermal load.

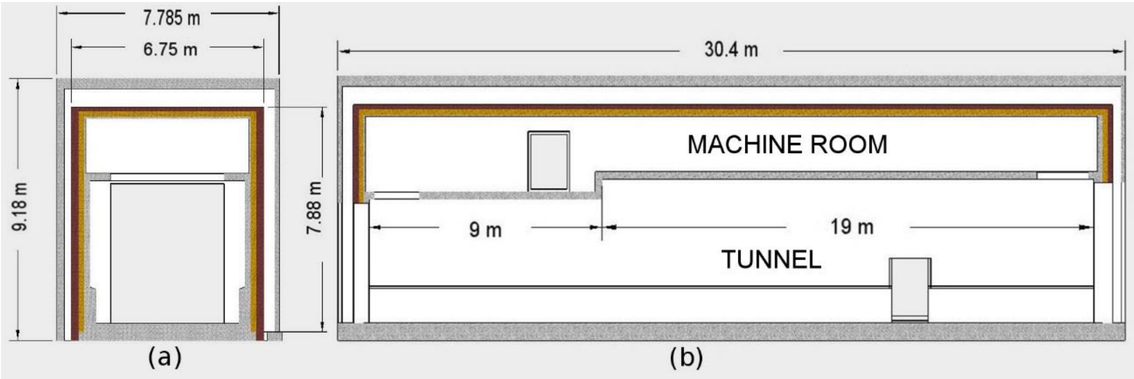

Figure 1: ATP test station (a) cross section (b) longitudinal section

The preferred testing method is based on imposing a controlled thermal load by electrical heating inside of the insulated box through the use of fan-heaters, thus also guaranteeing an internal air flow sufficient to move an air flow corresponding to 40 to 70 times the internal volume per hour, as prescribed by the ATP. As far as external conditions are related, the air velocity measured at 100 mm from the insulated box's walls is maintained between 1-2 m/s. The temperature constrains are defined in maintaining the temperature difference between the inside of the equipment and the insulated chamber in 25 °C ± 2 °C, while the mean temperature between inside and outside is 20 °C ± 0.5 °C, thus practically resulting in 7.5 °C out of the equipment and 32.5°C inside it. In order to satisfy these requests, the test station is equipped with a cooling unit having a nominal cooling capacity of 55.8 kW evaluated at the following conditions:

Working Fluid	R404A
$t_{evaporation}$ [°C]	-5
$t_{condensation}$ [°C]	35
$\Delta t_{sub\text{-}cooling}$ [K]	0
$\Delta t_{super\text{-}heating}$ [K]	20

The fan group is composed of 10 axial-fans each one having a nominal rating power 1.73 kW and providing the renewal air flow from the machine room to the tunnel during the test. The fan-heaters that heat up the air inside of the insulated box during the test are controlled with a PID system, which provides tension regulation so that, in standard test conditions, the stable test temperature, i.e. 32.5°C, is achieved. Within the purpose of evaluating the system response to heating power step variation, the test is conceived so that when, after 3 hours of steady state conditions the internal air is at its set point temperature of 32.5°C, an automatic system, developed with the software LabVIEW, perturbs the systems with a step change in the pilot-voltage of the fan-heaters and therefore to their heating, due being proportional to the supply voltage itself. The heating power during the steady state condition was used as reference and the step amplitude is set to 20% of this value.

3. Data Analysis

It's possible to calculate the value of the internal temperature in the new steady state conditions T''_i, after the step, since all the parameters in the formula are known:

$$T''_i = T_e + \frac{\dot{Q}''}{KS_m} \quad (1)$$

Where K is the overall heat transfer coefficient of the insulated box measured during the steady state before the step test, S_m is the mean exchanging surface of the insulated box calculated as the geometrical mean between the internal and external surfaces and Q'' is the heating power of the fan-heaters after the step input.

During the tests it has been observed that, for the insulated box of a truck, the transient region in which the system is responding dynamically can be in turn divided into 2 sub-zones: a first zone where the system responds rapidly to the increase of power, a zone where the system responds slowly (which also happened to be the dominant one in the long run). The rapid and the slow sub-zones are connected by a continuous trend. Since the slow response is the dominant one in terms of time, it was chosen as the one representative of the tests and thus every tested truck was associated with the insulated box's volume and its response's characteristic time. When the long run response is considered, the trend of the experimental process reaction curve can be approximated as a first order linear system response:

$$T_i(t) = T'_i + (T''_i - T'_i)(1 - e^{-\frac{t-\tau_D}{\tau}}) \quad (2)$$

Where τ is the response's characteristic time, τ_D is the time-delay and T'_i is the internal temperature in the steady state previous to the step test.

In order to fit the experimental data, a best-fit exponential curve was constructed using the equation (2). The best-fit process consists into the research of a value of τ and τ_D that minimize the error between the model's chosen function and the experimental data.

$$min\left\{\frac{\sum_{j=1}^{N_{data}}\left|T_{i,j} - T_{i,model,j}\right|}{N_{data}}\right\} \quad (3)$$

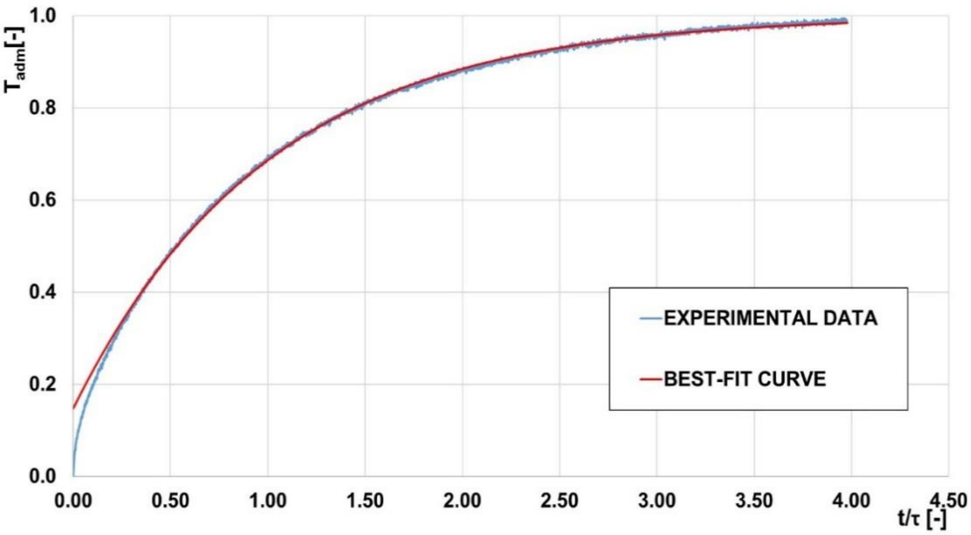

Figure 2: Step response evolution and best-fit curve in non-dimensional terms

In Figure 2, the temperature's trend is expressed in non-dimensional terms and T_{adm} is defined as:

$$T_{adm}(t) = \frac{T_{i,best-fit}(t) - T_i'}{T''_i - T_i'} \qquad (4)$$

4. Results

A total of 38 experimental tests took place: Figure3 provides a representation of the characteristic time collected in these tests, function of the insulated box's volume. The figure also supplies a distribution frequency representation which displays that the most frequent value of the characteristic time can be found between 7-9 h.

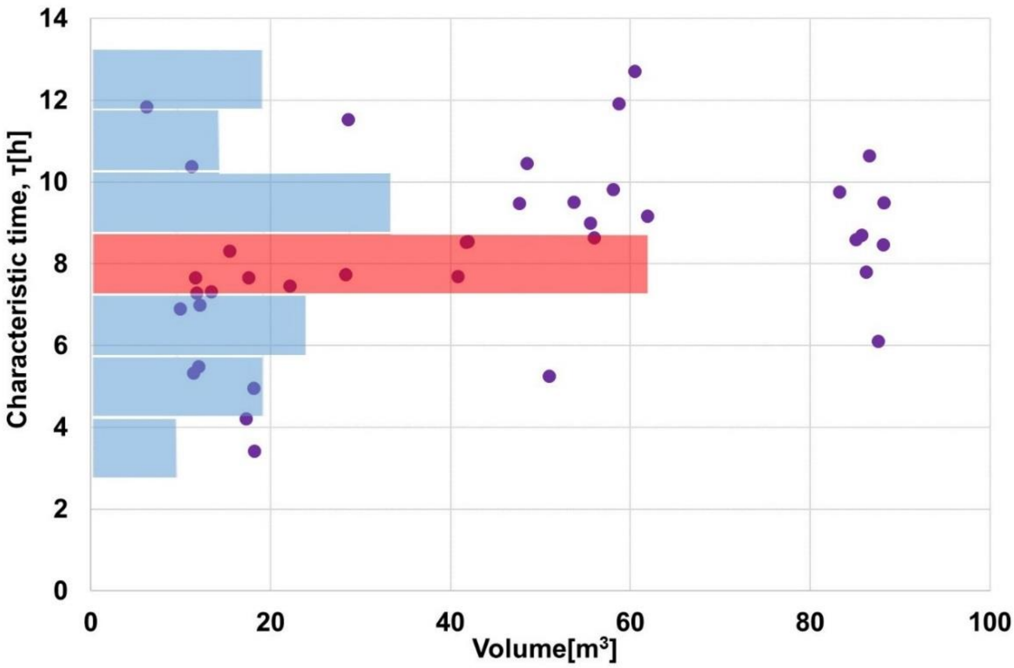

Figure 3: Plot of the characteristic time function of the insulated box's volume and distribution frequency

It is possible to classify the type of trucks in three mayor classes depending on the size of the insulated box: small vehicle for volumes of the insulated box between 5-30 m^3, medium vehicle for volumes between 40-65 m^3 and large vehicle for volumes between 80-90 m^3.

Considering these three groups, a volume-average value of the characteristic time can be estimated:

$\bar{\tau}_{small-vehicle}[h]$	7.32
$\bar{\tau}_{medium-vehicle}[h]$	9.40
$\bar{\tau}_{large-vehicle}[h]$	8.68

The high dispersion of data around the mean value can be ascribed to different reasons: different type of trucks were tested, belonging to different builder and thus assembled with different logic. Not only the layers composing the insulated box could be different but the cooling unit and the purpose of the truck as well, leading to a different wear of the insulated box. Considering that the wear of the insulated box could also play a major role, this wear itself can be accelerated by the eventual damaging trucks are exposed during a mission due to being a road vehicle. A major number of experimental data is crucial to a proper further investigation.

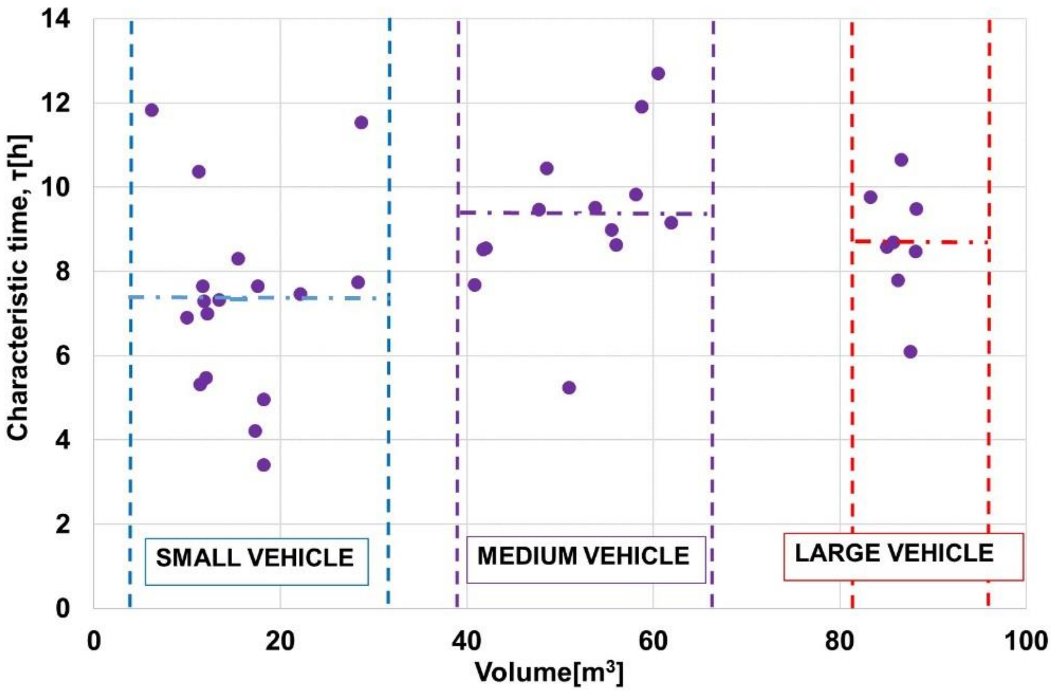

Figure 4: Plot of the characteristic time function of the insulated box's volume and dispersion around the mean value

5. Conclusions and Future Work

The objective of this article is to presents the study of the dynamic response of the insulated box of a refrigerated truck by means of step test. The purpose of this study is to value the time needed to the system to reach a new operating condition and, due the response being approximatively referable to the one given from a first order linear system, this time can be evaluated with the characteristic time. The study was extended to different type of trucks classified in 3 major classes: small vehicle, medium vehicle and large vehicle depending on the volume of the insulated box and for each class was possible to estimate a mean characteristic time based on the collected data. Future work will involve a collection of more experimental data for each class so that a better statistical analysis can be performed.

The knowledge of the mean characteristic time is crucial for the simulation of a refrigerated truck and the evaluation of the efficiency of its cooling unit during a typical mission.

References

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[2] United Nations economic commission for Europe (2015), *Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage*, Annex 1(pp.15-19)