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- Page VI, lines 5-7:

  Alessandro Bortolin, Paolo Bison, Gianluca Cadelano, Giovanni Ferrarini, Lei Lei and Xavier Maldague *Mapping the heat flux of an insulated small container by infrared thermography*

  READS:

  Alessandro Bortolin, Paolo Bison, Gianluca Cadelano, Giovanni Ferrarini, Stefano Rossi, Lei Lei and Xavier Maldague *A Thermographic Approach to the Heat Flux Measurement of Insulated Containers*

- The following 4 pages present the correction and should be considered to replace the previously published, erroneous version of the paper by Alessandro Bortolin, Paolo Bison, Gianluca Cadelano, Giovanni Ferrarini, Stefano Rossi, Lei Lei and Xavier Maldague entitled *A Thermographic Approach to the Heat Flux Measurement of Insulated Containers* appearing at pages 45-48 of the proceedings.

We apologise to the authors for these mistakes.

A THERMOGRAPHIC APPROACH TO THE HEAT FLUX MEASUREMENT OF INSULATED CONTAINERS

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The overall thermal transmittance of a small insulated container has been measured according to the ATP (Agreement for Transport of Perishables foodstuffs) standard testing procedure. During the test a thermographic apparatus has been used to map the temperature of the external walls of the container and to identify possible defects and thermal bridges. Moreover a heat flux meter was positioned on different surfaces of the container in order to assess the convective heat transfer coefficient in the different directions. The thermographic images have been processed with the application of homography. With the knowledge of the convective heat transfer coefficient it has been possible to create temperature and heat flux maps of the observed walls. The heat flux exchanged between the container and the environment calculated with the alternative procedure has been compared with the results of the thermal transmittance value measured according to the ATP test. Finally, an IR camera was mounted on a pan-tilt head and automatically driven by a suitable software to map the temperature of the inner walls of the insulated box on a refrigerated vehicle.

Introduction

Nowadays the correct transport of perishable foodstuffs in the refrigerated vehicles, especially for dairy products, meat, and frozen foods, is going with the necessity of energy saving due to the ever increasing cost of energy. So it is essential that the refrigerated vehicles are equipped with a suitable thermal insulation in order to save energy, maintaining at the same time an appropriate conservation of the foodstuffs [1].
The ATP, whose complete denomination is "Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage" [2], is an international agreement about the means to be used for the perishable foodstuffs transport, in force since 1976. The ATP standard test is a procedure that measures the insulating performance of containers with a global approach; however the surface temperature distribution could be uneven. This is due to the presence of local defects in the structure of the equipment, such as thermal bridges, air leakages, and zones of anomalous aging, that could not be detected separately by the ATP procedure. In those cases the thermographic technique could be particularly helpful, as it is known to be a reliable asset in the field of non destructive thermal testing and evaluation [3]. All the structural defects mentioned above lead to a variation of the heat flux and temperature on the surface of the equipment. Therefore the local heat flux map of the equipment by Infrared thermography could give a straightforward visualization of the structure, and also a local evaluation of the U –value [4].

A simplified heat transfer model

In the standard testing procedure the heat is flowing from the inside of the equipment (small container) under test to the outside (test chamber). Therefore, an air heating device is placed inside the small container. After reaching the steady state conditions, the heater delivers a power *W* in order to maintain a constant air temperature T_i inside the box. As the temperature outside the container is lower than the internal one, heat flows from the inside to the outside of the box where a constant air temperature T_e is maintained.

The heat transfer mechanisms are convection from the inside air to the internal wall, conduction through the wall, and convection from the outer wall to the outside air as shown in Figure 1. A simplified heat transfer model based on a one – dimensional network of thermal resistances is then proposed for steady state conditions.

Under these conditions the heat flux could be assumed as one – dimensional and h_e and h_i are respectively the external and internal heat exchange coefficients. T_{we} and T_{wi} are the average temperature of the internal and external walls, while λ is the thermal conductivity of the wall and *l* its thickness. The main thermal resistance of Figure 1 is in the middle and represents the sum of the individual thermal resistances given by the different layers of the sandwich panel. The container under analysis has three layers: two external skins made by polyester-fiberglass and a core made by high density polyurethane foam.

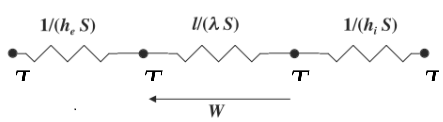

Fig. 1: One – dimensional model based on a thermal resistance network of the heat exchange through the small container.

Experimental setup

In order to verify the feasibility of the thermographic approach to the local quantitative evaluation of the heat transfer coefficient, a small insulated box (the roll container shown in Figure 2) was submitted to the standard test of the *K*-value according to the ATP. The idea is to measure the heat flux with a thermal flux meter in a reference zone of the outside surface of the roll container. Based on this measurement, it is possible to build a surface map of the heat flux as a linear relation of the temperature difference between the outside wall temperature and the air temperature.

The adopted technique to evaluate the global heat flux, being referred to the zone of the heat flux meter, is loosely influenced by this value.


Figure 2: Roll container and equipment utilized for the experimental tests: infrared camera, thermocouples, RTD, and heat flux meter.

The heat flux meter and the RTD probe are positioned:

- on the front vertical wall (in respect to the air stream);
- on the right vertical wall;
- on the back vertical wall.

The following hypotheses are assumed:

- the heat flux is one - dimensional;
- the convective coefficient values of the left and top surfaces are equal to the one calculated for the right surface;
- the wall temperature is supposed to be uniform, therefore the temperature value measured by a unique RTD probe is representative of the whole surface.

An ATP test is performed for each position of the heat flux meter. The temperature inside the roll container is equal to 32.5°C. In order to maintain the prescribed temperature difference between interior and exterior (ATP standard requires 25±2 K), the facility is maintained at a temperature of about 7° C by the air conditioning system. Once reached the steady state condition several thermal images of all the roll container walls (except the bottom one) have been acquired.

Experimental results

According to the scheme described in the previous section, it has been possible to calculate the convective heat transfer for each surface of the roll container h_e with the following equation:

$$h_e = \frac{q_r}{T_r - T_{out}} \qquad (1)$$

where:

- q_r is the heat flux across the roll container;
- T_r is the surface temperature measured;

Thermographic images allow to determine the local heat flux exchanged *q(x,y)* between the roll container and the external environment, from the measurement of the local surface temperature *T(x,y)*:

$$q(x,y) = q_r \frac{T(x,y) - T_{out}}{T_r - T_{out}} = \frac{q_r}{\Delta T_r} \Delta T_{x,y} + q_r = h_e \Delta T_{x,y} + q_r \qquad (2)$$

where $\Delta T_{x,y}=(T(x,y)-T_r)$ and $\Delta T_r=(T_r - T_{out})$.
As the thermographic measurement is aimed to quantify a heat flux, the geometric reconstruction of the images is of paramount importance. In this work the image processing was performed by Matlab algorithm based on homography. This technique allows to perform the image rectification and registration with the knowledge of few control points and to obtain the corrected heat flux mapping of each surfaces (Figure 3).
After the calculation of the heat flux of each surface by averaging the punctual thermal flux, the global heat flux between roll container and ambient is given by means of a weighted average of the thermal flux of each surface:

$$q_{glob} = \frac{\sum_i q_i S_i}{\sum_i S_i} \qquad (3)$$

where q_i are the heat flux and S_i are the values of the area of each surface. The average value of the heat flux of the three experimental tests is equal to 12.7 W m^{-2}, whereas a value of 13.5 W m^{-2} was obtained applying ATP standard.

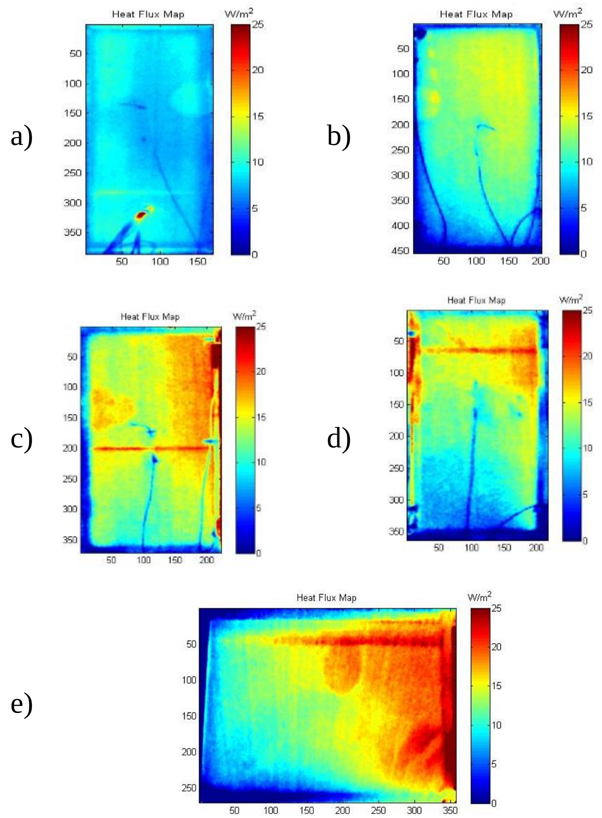

Figure 3: Heat flux map of each roll container surface (in respect to the air stream direction): a) front surface, b) back surface, c) right surface, d) left surface, e) top surface.

Application for an insulated vehicle

IR thermography was applied also to map the temperature of the inner walls of the insulated box on a refrigerated vehicle, similarly to what has been done for the roll-container.

Two assumptions were proposed in this test: 1) the heat exchange coefficients, inside (h_i) and outside (h_e) of the container are constant; 2) the heat diffusion is mainly 1D.

An IR camera was mounted on a pan-tilt head and automatically driven by a suitable software in order to scan a wall by taking images of neighboring fields of view (Figure 4). The angles of the Pan-Tilt camera are set as: for horizon, from 0° to 360° with a step of 20°; for vertical, from 0° to 180° with a step of 15°.

Figure 4: The inside of the truck used for the test with the experimental setup.

This equipment allows to collect several thermal images of the walls of the refrigerated vehicle. The acquisition is automatically managed by custom Labview software while the IR image processing is done in Matlab environment (Figure 5).

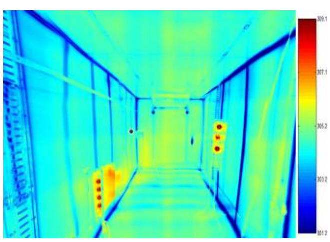

Figure 5: IR image of the internal surfaces of the refrigerated vehicle.

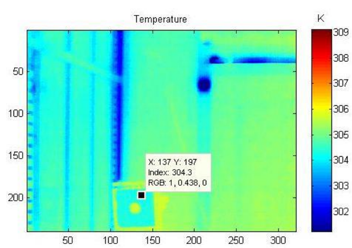

Figure 6: Target temperature from Thermography

A thermal calibration device was utilized in order to correct the error that affects the thermal camera. The temperature target shown in Fig. 6 represented the inside temperature of the refrigerated vehicle that was measured by a RTD probe attached to the device. The difference between the temperature measured by the thermal camera and the RTD probe indicated the offset value that was applied to all the temperature values from IR camera.

Conclusions

This work aims at mapping the heat flux exchanged between an insulated roll container and the external environment by means of infrared thermography. The measurement relies on a simplified thermal resistance model.

Three experimental tests according to ATP standard are performed positioning a heat flux meter and a RTD probe on three roll container surfaces that are differently impinged by the air stream. It allows to calculate the convective heat flux coefficient for each surface that is considered in the thermal model. A strong variation of the convective heat flux coefficients is observed for the different orientations.

The raw thermographic images are processed with a dedicated algorithm in order to create geometrically corrected maps, easing the calculations and enhancing the visualization of the results.

The value obtained with the infrared thermography technique is very close to the ATP testing result. The difference between the two measurements is around 6 %.

References

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