Experimental characterization and modelling of refrigeration of pork carcasses during transport in field conditions

Mouna Merai, Steven Duret, Evelyne Derens-Bertheau, Alain Leroux, D. Flick, Onrawee Laguerre

Manuscript ID: 179
DOI: 10.18462/iir.icr.2019.0179

Experimental characterization and modelling of refrigeration of pork carcasses during transport in field conditions

Mouna MERAI[a,c], Steven DURET[a], Evelyne DERENS[a], Alain LEROUX[b], Denis FLICK[c], Onrawee LAGUERRE[a]

[a]Irstea, UR GPAN, Refrigeration Process Engineering Research Unit, 1 rue Pierre-Gilles de Gennes, 92761 Antony, France, onrawee.laguerre @irstea.fr

[b]IFIP, Institut du Porc, La Motte au Vicomte B.P. 35104, 35651 Le Rheu Cedex, France, alain.leroux@ifip.asso.fr

[c]UMR Ingénierie Procédés Aliments, AgroParisTech, INRA, Université Paris-Saclay, 91300 Massy, France, denis.flick@agroparistech.fr

ABSTRACT

Measurements of air and product temperatures were conducted at different positions in a semitrailer loaded by 480 warm half carcasses of pork (core temperature ~ 14°C, surface temperature ~ 7°C). The refrigerating curves of 8 instrumented half carcasses during the transport shows that the core temperature decreases significantly reaching the recommended value of 7°C almost everywhere after 9h whereas the product surface temperature decreases slightly (~ 5°C after 9h). A simplified model base on an analytical solution was proposed to predict the surface, core and average temperature changes during transport. The convective heat transfer coefficient of 7.7 $W.m^{-2}.K^{-1}$ was used in the modelling. This value represents the average value of the measurement in a reduced scale of refrigerated vehicle loaded by reduced scale of carcasses model. The refrigerating capacity was estimated for different loading ratios of warm carcasses in semitrailer. It was shown that the studied semitrailer has enough capacity to evacuate the heat whatever the percentage of warm carcasses.
Keywords: Transport, Warm Carcass, Temperature Prediction, Refrigerating Capacity

1. INTRODUCTION

To prevent quality loss, since 1964 in the European Union, pork carcasses must be chilled immediately after the post-mortem inspection and kept at a constant core temperature below 7°C until consumption. Because of the improvement in hygiene in the meat sector, slaughterhouses are now requesting derogations in order to be allowed to load warm carcasses (core temperature of 15°C) into refrigerated trucks under the condition that the surface temperature is below 7°C. This work was carried out with the following objectives:

- To present field data on the transport of pork carcasses in a refrigerated vehicle.
- To evaluate the heat load of the warm carcasses, thus, the capacity of the refrigerating system.

Transport of a food product in a refrigerated trailer is a specific process because of the high heterogeneity of air temperature and velocity (Merai et al 2018; Merai et al, 2019). Non-uniform air distribution inside the trailer was identified as the main problem in refrigerated transport (James, 1996). Lower product temperature is often observed at the front of the vehicle, while higher temperatures are observed at the rear close to the doors (Moureh and Flick, 2005). The potential position of high temperature can be influenced by the trailer design, the carcass arrangement and the loading density. Thus, knowledge of the airflow and the heat transfer at different positions is essential in order to enable the identification warm zones (areas of low air velocities and low convective heat transfer coefficients). During transport, conduction occurs within the carcass, while convection and water evaporation take place at the air-product interface. These phenomena, which vary with time, depend on the air characteristics (temperature, velocity and humidity). Several studies have been undertaken in order to characterize the airflow distribution inside chilled rooms by experimental and modelling approaches (Mirade and Picgirard, 2001; Mirade 2007). These studies have made it possible to develop solutions enabling control of the chilling parameters and to minimize product weight loss. However, experimental studies in field are rare because of the difficulty of implementation.

2. EXPERIMENTAL CONDITIONS

2.1. Loaded semi-trailer

The studied refrigerated vehicle was a semi-trailer (length x width x height = 13.30 x 2.46 x 2.50 m), with an airflow rate at the discharge air outlet of 5000 $m^3.h^{-1}$ and a refrigerating capacity of 13 kW. According to the measured air temperature change with time, it was observed that the duration of compressor "on"/"off" cycles was 4 h, then, a defrosting duration of 20 min was undertaken during which the compressor was "off".
This semitrailer was equipped with 5 rails for product hanging, but only 4 rails were used in our study (rail 3 in the center was empty), as shown in Fig. 1a. There were 120 pork half-carcasses on each rail (total of 480 half-carcasses in the semi-trailer), with an average weight of 30.7 kg per half-carcass. Cold air was discharged at the top front area of the semi-trailer via an 11-metre long air distribution duct made of plastic with fine holes (Fig. 1b). Part of the cold air flows through the "porous" zones constituted by the half carcasses and exchanges heat with them, then, the air becomes warmer. The other part of air flows above the carcasses until it reaches the rear of the semi-trailer. The warm air then returns to the front to be cooled down by the refrigeration system.

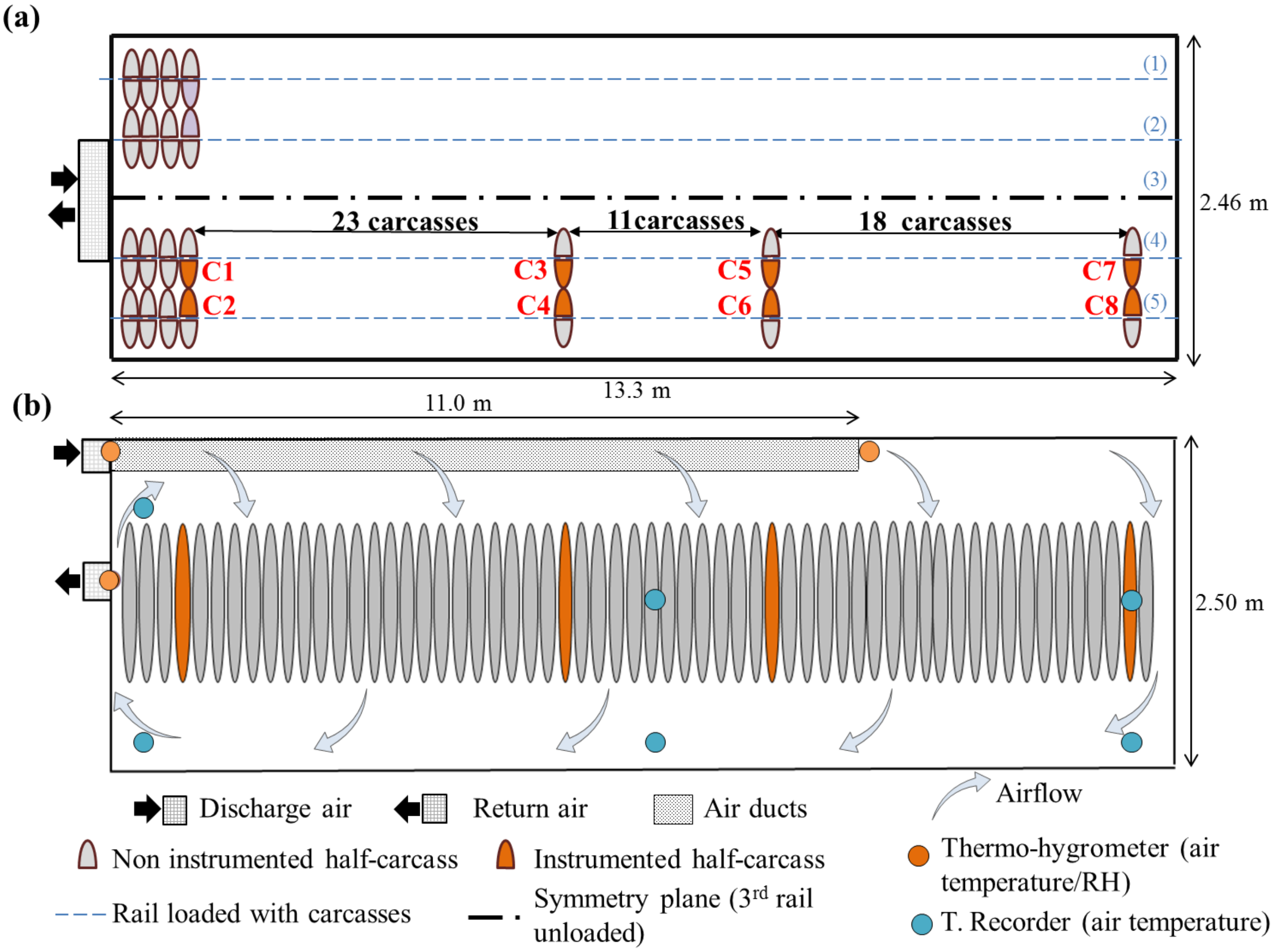

Figure 1: Positions of measurements in a semi-trailer loaded with pork carcasses (a) - Top view; (b) - Side view

2.2. Instrumentation

Considering a symmetry plan in the semitrailer, a half of the semi-trailer was instrumented and the other half was not instrumented (Figure 1a). Eight half-carcasses located at 4 distances from the cold air discharge outlet were instrumented. The average weight of the instrumented carcasses is 30.6 ± 1.7 kg and the thermo-physical properties of pork are shown in Table 1. On each instrumented carcass, rigid thermocouples (Testo 171-4, T-type, precision ± 0.2°C) were inserted to a depth of 12 cm under the ham surface and 6 cm under the shoulder surface. To measure the product surface temperature, temperature recorders (trade name thermo-buttons Progesplus, 22L type, precision ± 0.5°C) were pasted on the ham and shoulder surfaces. To measure the air temperature and relative humidity near the product, thermo-hygrometers (Testo 174H, ± 0.5°C, precision ± 3% RH) were located at about 5 cm from the ham and the shoulder surfaces.
Data were recorded every minute over 9 h (total transport duration). The water content in the air (kg water/kg dry air) was calculated using a humid air diagram (Beysens, 1995).

Table 1. Thermophysical properties of pork

Property	Value	Reference
Equivalent radius, R_{eq} (m)	0.1	$R_{eq} = 0.005(12.93 + 0.24W)$ W = Weight of half-carcass (kg) Daudin and Kuitche, 1996
Density, ρ ($kg.m^{-3}$)	1072	Harkouss et al., 2018
Thermal conductivity, k ($W.m^{-1}K^{-1}$)	0.45	Kondjoyan et al., 2013
Thermal capacity, Cp ($J.kg^{-1}.K^{-1}$)	3200	Kondjoyan et al., 2013
Thermal diffusivity, $\boldsymbol{\alpha} = \frac{\mathbf{k}}{\boldsymbol{\rho}\mathbf{C_p}}$ ($m^2.s^{-1}$)	1.31 x 10^{-7}	

3. EXPERIMENTAL RESULTS OF TEMPERATURE CHANGES DURING TRANSPORT

The temperatures of the half-carcasses and air near the carcasses (5 cm from the product surface) decreased gradually during transport. The example of the half-carcass located at the center of the semi-trailer (C3) is presented in Fig. 2a. During transport, the core temperature decreased by about 6.5°C both for ham and shoulder (from 13.8°C to 7.4°C for ham and 13.4°C to 6.8°C for shoulder). The surface temperature decreased by about 2.9°C both for ham and shoulder (from 6.8°C to 4.0°C for ham and 8.4°C to 5.4°C for shoulder). The air temperature decreased by 1.3°C near the ham (5.0°C to 3.7°C), whereas it decreased by 4.1°C near the shoulder (from 7.7°C to 3.6°C). The air temperature near the shoulder was much higher than that near the ham at the beginning of the transport because at this position (bottom), the air was previously warmed up when flowing around the carcasses while the air surrounding the ham (top), was blown from the discharge air (Fig. 1b).
The surface and core temperatures of ham and shoulder of the eight instrumented carcasses at the beginning (t = 0 h) and at the end of transport (t = 9 h) are shown in Fig. 2b and 2c respectively. The surface temperatures of certain carcass cannot be presented because the temperature recorders were removed from the surface during the transport. At the beginning (t = 0 h), the surface temperature ranged from 5.0°C (C4) to 8.0°C (C6), the core temperature ranged from 8.8°C (C7) to 14.0°C (C5) The lower core temperature of the carcasses C7 compared with those at other positions can be explained by several reasons: (1) this carcass may have spent a longer period in the cold room of slaughterhouse (2) the carcass was thinner than the other carcasses and (3) the position of the probe was not exactly in the core. At the end of transport (t = 9 h), the surface temperatures were in all parts of the vehicle lower than 7°C, which complies with the recommended value. The core temperatures ranged from 4.7 to 8.0°C, even if some core temperatures were still above 7°C after 9h of transport, it still complies with the derogation which concerns the surface temperature.

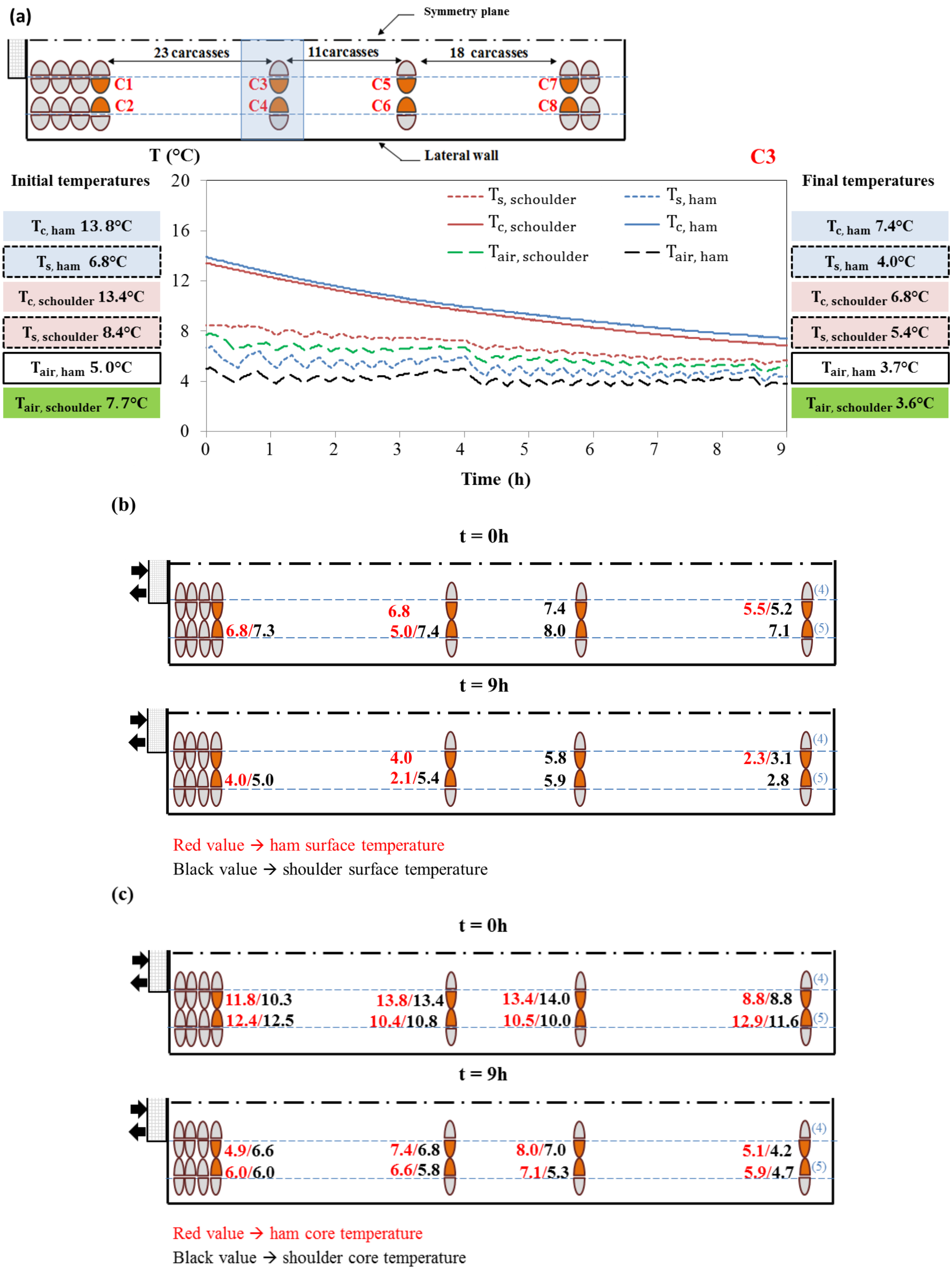

Figure 2: (a) - Product and air temperature changes during transport (9 h) of the carcass C3; (b) - Product surface temperature (c) - Product core temperature at the beginning (t=0) and at the end (t=9h) of transport

4. ESTIMATION OF HEAT LOAD OF WARM CARCASSES

Considering a carcass as a semi-infinite cylinder, the average temperature change can be represented as follows (Carslow and Jaeger, 1959):

$$T_{av}^{*} = 4Bi \sum_{n=1}^{\infty} e^{-\beta_n^2 Fo} \frac{J_1(\beta_n)}{\beta_n(\beta_n^2 + Bi^2) J_0(\beta_n)} \qquad \text{Eq.(1)}$$

For simplification purposes, only the first term is considered:

$$T_{av}^{*} \cong 4Bi.\, e^{-\beta_1^2 Fo} \frac{J_1(\beta_1)}{\beta_1(\beta_1^2 + Bi^2) J_0(\beta_1)} \text{with } Fo = \frac{\alpha t}{R_{eq}^2} \qquad \text{Eq.(2)}$$

Equation 2 was used to calculate the average carcass temperature changes in the cold room of a slaughterhouse and in the semi-trailer in the following manner.

Semitrailer can be loaded with both warm (T_c=15°C and T_s=7°C according to the derogation) and cold (T_c=7°C and T_s=7°C according to the regulation) carcasses. In both cases, it is assumed that after slaughtering, the carcasses (initial temperature T_0 = 40°C) are cooled down in the cold room of a slaughterhouse and in the semi-trailer with the same air temperature T_a of 2.5°C and with the same heat transfer coefficient h of 7.7 $W.m^{-2}.K^{-1}$ (average value measured in a reduced scale semitrailer loaded by reduced scale carcass model, Merai et al. (2019). Carcasses benefiting a derogation leave the cold room of the slaughterhouse after the duration t_D at which the core temperature reaches $T_{c,D}$ = 15°C while the carcasses under regulation stay in the cold room for a duration t_R corresponding to a core temperature $T_{c,R}$ of 7°C (Fig. 3a).

Both types of carcasses are then loaded at the same time into a semi-trailer. The evolution of the core and average temperatures of warm and cold carcasses during transport in a semi-trailer with are shown in Fig. 3b.

The rate of heat flow to be evacuated from the carcass ($\dot{Q}$) can be estimated as follows:

$$\dot{Q} = -Cp\left(m_{tot.R}\frac{dT_{av.R}}{dt} + m_{tot.D}\frac{dT_{av.D}}{dt}\right) = Cp(T_o - T_a)\left(m_{tot.R}\frac{dT_{av.R}^{*}}{dt} + m_{tot.D}\frac{dT_{av.D}^{*}}{dt}\right)$$

$$= Cp(T_o - T_a)4Bi\frac{J_1(\beta_1)\beta_1^2\alpha/R_{eq}^2}{\beta_1(\beta_1^2 + Bi^2)J_0(\beta_1)}\left(m_{tot.R}.\, e^{-\frac{\beta_1^2\alpha(t+t_R)}{R_{eq}^2}} + m_{tot.D}.\, e^{-\frac{\beta_1^2\alpha(t+t_R)}{R_{eq}^2}}\right)$$

This heat flow is maximal at the beginning of transport (t = 0 h) and can be estimated as follows:

$$\dot{Q} = Cp(T_o - T_a)4Bi\frac{J_1(\beta_1)\beta_1^2\alpha/R_{eq}^2}{\beta_1(\beta_1^2 + Bi^2)J_0(\beta_1)}\left(m_{tot.R}.\, e^{-\frac{\beta_1^2\alpha t_R}{R_{eq}^2}} + m_{tot.D}.\, e^{-\frac{\beta_1^2\alpha t_D}{R_{eq}^2}}\right) \qquad \text{Eq.(3)}$$

The terms in Eq. 3 involving t_R ($e^{-\frac{\beta_1^2\alpha t_R}{R_{eq}^2}}$) and t_D ($e^{-\frac{\beta_1^2\alpha t_D}{R_{eq}^2}}$) can be obtained by using eq. 4 and 5 since the values of $T_{c,R}$, $T_{c,D}$, T_0 and T_a are known:

$$T_{c,R}^{*}(t_R) = \frac{T_{c,R} - T_a}{T_0 - T_a} = 2Bi\frac{1}{(\beta_1^2 + Bi^2)J_0(\beta_1)}e^{-\frac{\beta_1^2\alpha t_R}{R_{eq}^2}} \qquad \text{Eq.(4)}$$

$$T_{c,D}^{*}(t_D) = \frac{T_{c,D} - T_a}{T_0 - T_a} = 2Bi\frac{1}{(\beta_1^2 + Bi^2)J_0(\beta_1)}e^{-\frac{\beta_1^2\alpha t_D}{R_{eq}^2}} \qquad \text{Eq.(5)}$$

Considering that a semi-trailer (with an air temperature Ta = 2.5°C) is loaded with different percentages of half-carcasses benefiting from a derogation (core temperature $T_{c,D}$ = 15°C) and regulated carcasses (core temperature $T_{c,R}$ = 7°C). For a total number of half-carcasses of 480 (35 kg/carcass, the mass of half-carcasses generally observed in practice), the heat flow to be evacuated ($\dot{Q}$) at the beginning of the transport (t = 0) should be less than the refrigerating capacity of the semi-trailer required to cool down all of the half-carcasses is presented in Table 2. When all the half-carcasses benefiting from derogation are loaded into the semi-trailer (100%), the refrigerating capacity should be about 10 kW.

Table 2. Estimated refrigerating capacity ($\dot{Q}$) of the semi-trailer (ambient temperature T_a = 2.5°C) required to cool down 480 half-carcasses (35 kg/carcass) at the time of loading (t = 0h) with different ratios of half-carcasses benefiting from a derogation (core temperature Tc = 15°C) and regulated half-carcasses (core temperature Tc = 7°C).

Percentage of half-carcasses benefiting from a derogation	Weight of half-carcasses benefiting from a derogation (kg)	Weight of regulated half-carcasses (kg)	$\dot{Q}$ (W)
0	0	16.800	3.544
20	3360	13.440	4.804
40	6720	10,080	6.064
60	10.080	6.720	7.324
80	13.440	3.360	8.584
100	16.800	0	9.844

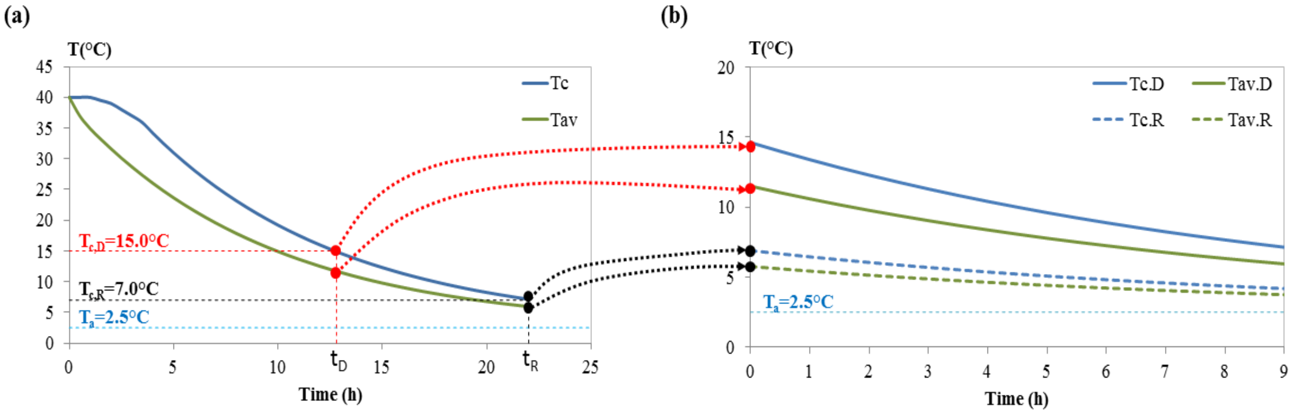

Figure 3: Carcass core and average temperature changes during refrigeration: (a)-in a cold room of a slaughterhouse; and (b)-in a semi-trailer (Dotted lines show the corresponding temperatures of carcasses transferred from a cold room to a semitrailer)

It should be borne in mind that heat loss also occurs through the walls of the semi-trailer, and these losses are higher in summer (when the external ambient temperature is 30°C) than in winter (when the external ambient temperature is 5°C). Considering a heat transmission K = 0.44 $Wm^{-2}K^{-1}$ (average value of 97 semi-trailers tested by Cemafroid, personal communication), the estimation of the heat losses in summer through the walls is as follows:

$$\dot{Q} = K.A\,(T_{ext} - T_{int}) = 0.44 \text{ x } 144.3 \text{ x}(30 - 2.5) = 1745 \text{ W} \quad \text{Eq.(6)}$$

A = surface area of the semi-trailer = 144.3 m^2 (length x width x height =13.3 x 2.46 x 2.5 m)

The total required refrigerating capacity of a semi-trailer loaded with warm carcasses and taking into account heat loss through the semi-trailer walls can therefore reach about 12 kW.

The refrigerating capacity of the studied semi-trailer was 13 kW, and thus it can be considered that the cooling capacity of the semi-trailer was sufficiently high to cool a load of up to 100% of half-carcasses benefiting from derogation. According to the information of semitrailer refrigerating system, the refrigerating capacity can vary from 12.0 to 18.5 kW (Carrier, https://www.carrier.com/truck-trailer/fr/fr/products/eu-truck-trailer/trailer/).

5. CONCLUSIONS

This study was carried out in order to acquire knowledge of the transport of pork carcasses under real conditions, and was designed to complement our previous studies on heat transfer and airflow on a laboratory scale under well-controlled conditions. This study demonstrated the heterogeneity of the surface and core temperatures of carcasses located at different positions in a semi-trailer. The experimental results (transport of half carcasses of average weight of 30.5 kg) demonstrated that the studied semi-trailer allowed product cooling during the transport of warm carcasses: the product surface temperature was lower than 7°C (recommended temperature) in all locations at the end of a transport period of 9 h. The average convective heat transfer coefficient identified from the experimental cooling curves of carcasses during transport (7.7 Wm-2K-1) is close to that measured in a laboratory. The numerical study on the transport of different ratios of warm and cold carcasses in the studied semi-trailer showed that the refrigerating capacity of the refrigeration system was sufficient to remove the heat from the carcasses. The results of this study can be used by industry and public authorities to support decision making related to the carcass initial temperatures during transportation.

ACKNOWLEDGEMENTS

This research work was carried out within the framework of a DIM ASTREA grant by the Regional Council of Ile-de-France, France. The authors would like to thank "IFIP" for the contact with the meat industry and Cemafroid (Private Organism of refrigerating vehicles test) for providing statistical data on the insulation of refrigerated vehicles in use.

NOMENCLATURE

A	Exchange surface area (m^2)	K	Coefficient of heat transmission of the semi-trailer ($W.m^{-2}.K^{-1}$)
Bi	Biot number $= \frac{hR_{eq}}{k}$	m	Product mass (kg)
Cp	Thermal capacity of pork ($J.kg^{-1}.K^{-1}$)	R_{eq}	Equivalent radius of carcass (m)
F_o	Fourier number $= \frac{\alpha t}{R_{eq}^2}$	T	Temperature (°C)
$\dot{Q}$	Rate of heat flow to be evacuated from the carcass (W)	T*	Dimensionless temperature $= \frac{T(t)-T_a}{T_0-T_a}$
h	Convective heat transfer coefficient ($W.m^{-2}.K^{-1}$)	t	Time (s)

Greek symbols

ρ	Density ($kg.m^{-3}$)	α	Thermal diffusivity ($m^2.s^{-1}$)

Subscript

a	Air	ext	External
av	Average	int	Internal
c	Core	0	Initial
D	Derogation	R	Regulation
		s	Surface

REFERENCES

Beysens, D., 1995. The formation of dew. Atmos. Res. 39, 215-237.

Daudin J.D., Kuitche A., 1996. Modelling of temperature and weight loss kinetics during meat chilling for time variable conditions using an analytical based method - III. Calculations versus measurements on pork carcass hindquarters. J. Food Engineering 29(1), 39-62.

Harkouss, R., Chevarin C., Daudin J.D., Sicard J., Mirade P.S., 2018. Development of a multi-physical finite element-based model that predicts water and salt transfers, proteolysis and water activity during the salting and post-salting stages of the dry-cured ham process. J. Food Engineering 218, 69-79.

James, S., 1996. The chill chain “from carcass to consumer”. Meat Science 43(1), 203-216.

Mirade, P.S., Picgirard, L., 2001. Assessment of airflow patterns inside six industrial beef carcass chillers. Int. J. Food Sci. Technol. 36, 463-475.

Kondjoyan, A., S. Oillic, S. Portanguen, J.B. Gros, 2013. Combined heat transfer and kinetic models to predict cooking loss during heat treatment of beef meat. Meat Science 95(2), 336-344.

Merai M., Flick D., Guillier L., Duret S., Laguerre O., 2018. Experimental characterization of airflow inside a refrigerated trailer loaded with carcasses. Int. J. Refrigeration 88, 337-34.

Merai M., Flick D., Guillier L., Duret S., Laguerre O., 2019. Experimental characterization of heat transfer inside a refrigerated trailer loaded with carcasses. Int. J. Refrigeration 99, 194-203.

Mirade, P.S., 2007. CFD modelling of indoor atmosphere and water exchange during the cheese ripening process. Da-Wen Sun (Ed.), Computational fluid dynamic in food processing, CRC Press, 697-726.

Moureh, J., Flick, D., 2005. Airflow characteristics within a slot-ventilated enclosure. Int. J. Heat and Fluid Flow 26, 12-24