Energy Consumptions of Display Cabinets in Supermarket

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ENERGY CONSUMPTIONS OF DISPLAY CABINETS IN SUPERMARKET

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ABSTRACT

The refrigeration activity represents between 35% and 60% of the electrical consumption in a supermarket and the energy needs for positive temperature application are mainly due to the open vertical cabinets. The Standard ISO23953 defines precisely a way to measure the refrigeration duty (HER) of the refrigerated cabinets in laboratory conditions. Unfortunately, the laboratory cannot reproduce the thermal stratification of the store, so the HER has to be corrected by a coefficient of reduction. Tests on in 2 stores showed that the class 3 was representative to size the cooling pack but a coefficient of reduction between 0.8 and 0.9 could be applied for open vertical cabinets. To calculate the average energy consumption, a new coefficient was introduced to take into account the climatic variation inside the supermarket. This coefficient was determined as the ratio between the enthalpy of the humid air in store and the enthalpy of the reference value.

1. INTRODUCTION

Energetic diagnosis of supermarkets and hypermarkets showed that the commercial refrigeration activity represented between 35% (PERIFEM, 2010) and 60% (ADEME Picardie, 2001) of the electrical consumption of a store. The energy needs for the cold application are due to the Refrigerated Display Cabinets installed in the store. Therefore it is essential to better know the cabinet performances, first to select the best product and to be able to calculate its energy consumption and secondly to be able to design properly the cooling pack – refrigeration system type and the right size – in order to minimize the cost investment.
An International Standard (ISO 23953, 2005) clearly describes a way to test the Refrigeration Display Cabinets (RDC) and it measures their consumption in a "reference condition". This strict method gives some reproducibility among all laboratories and it delivers comparable data from manufacturers. But in order to have reliable values and not "commercial data" we highly recommend considering data only controlled by an external organization or an independent laboratory. A good database could be found at the European organization Eurovent Certification.
Unfortunately the real life in store could be different from the ambient conditions defined by the ISO 23953. How different they are and what are the impacts as regard as energy consumption? This study is trying to answer this question as simple as possible through the analysis of results performed in 2 stores. The analysis concerned open vertical cabinets owing to their high sensitivity to their environment and also because they are the most used in supermarkets.

2. DESCRIPTION OF THE ISO23953 TESTS

First, some explanations about the ISO 23953 tests in order to understand the differences between the ISO test method and the store.
The cabinet is installed in the middle of a test room with minimum dimension X, Y, A, C (figure 1). The temperature, the humidity are controlled in the test room and a horizontal airflow simulate draught. The velocity of this airflow is fixed between 0.1m/s and 0.2m/s. In store, the hot air stays at the top the cold air is at the floor level, so the air circulation inside the store is mainly horizontal. The test room and the store have a similar dynamic air flow around the cabinets. Some exceptions could appear with some air-conditioning systems located on at the top but they can be local and they would affect the cabinet environment only locally.
Regarding the temperature and the humidity some ambient classes were defined (table 1) in order to standardize as much as possible the ambient conditions of the tests. Today, most of the tests are performed in class 3 (25°C/60%RH) to evaluate the performances of the Refrigerated Display Cabinets (RDC). It is a

request from our European customers and 25°C, 60%RH corresponds to a maximum climate situation inside the store during the hot season. With the class 3, the RDC must guarantee the food temperature and the associated cooling pack is selected according to its potential RDC energy need.

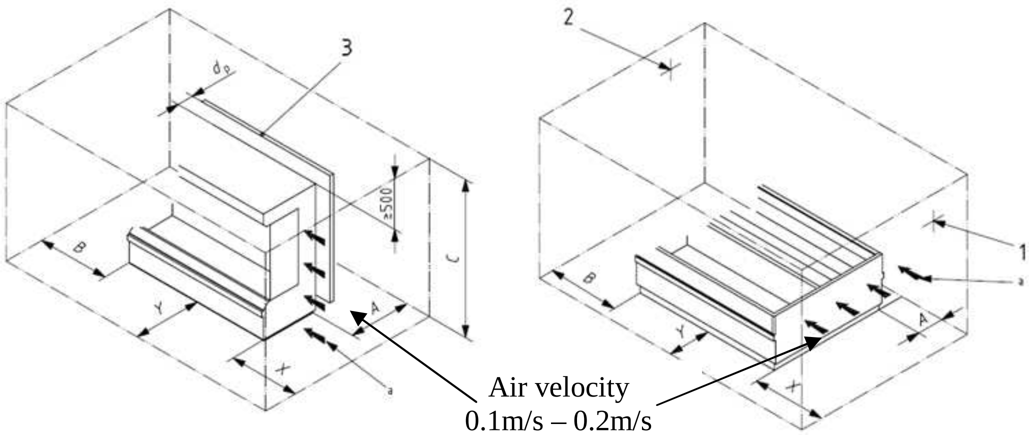

Figure 1: Cabinet location in a test room and air movement

Test room climate class	Dry bulb temperature °C	Relative humidity %	Dew point °C	Water vapour mass in dry air g/kg
0	20	50	9,3	7,3
1	16	80	12,6	9,1
2	22	65	15,2	10,8
3	25	60	16,7	12,0
4	30	55	20,0	14,8
6	27	70	21,1	15,8
5	40	40	23,9	18,8
7	35	75	30,0	27,3
8	23,9	55	14,3	10,2
NOTE Table 3 is sorted to the water vapour mass in dry air, which is one of the main points influencing the performance and the energy consumption of the cabinets. See also Annex D to compare lab and store conditions.				

Table 1: Climate classes (extraction from ISO 23953-2)

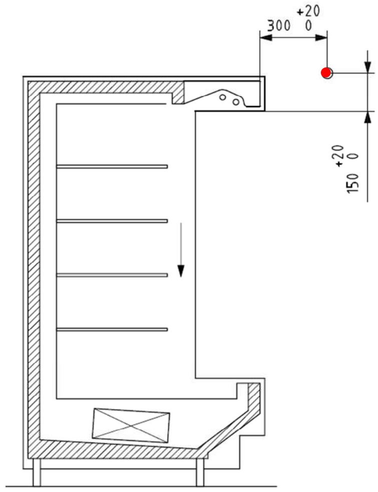

Figure 2: location of the ambient measuring points for a vertical cabinet (ISO23953-2, 2005).

The ambient measuring point is located at the top of the cabinet as described on the figure 2.

The temperature measurement in a store or in a test room can have the same reference. But there is a big gap between the store and the test room: the thermal stratification in the store. In the ISO 23953 test room, the temperature is 25°C bottom to top: all the temperature points at the surface outlet must not vary from the rated temperature by more 2°C (ISO 23953, 2005 - Paragraph 5.3.1.2). In the store when the temperature is 25°C at 2m high, at the floor level the temperature is about 15°C or less when the cabinets are face to face (NDOYE M.). **We think this thermal difference represents the most important deviation between the store and the ISO 23953 test room for which we cannot reproduce the stratification phenomena observed in the store.** May be there is also humidity stratification but we have no data reference.

And to complete the ISO 23953 description, the temperature performance is defined by M1, M2, … (table 2).

Class	Highest temperature, θ_{ah}, of warmest M-package less than or equal to (see Figure 25)	Lowest temperature, θ_{b}, of coldest M-package greater than or equal to (see Figure 25)	Lowest temperature, θ_{al}, of warmest M-package less than or equal to (see Figure 25)
	°C		
M1	+ 5	− 1	—
M2	+ 7	− 1	—
H1	+ 10	+ 1	—
H2	+ 10	− 1	—
S	Special classification		

Table 2: M-package temperature classes (extractions from ISO23953-2, 2005).

The temperature measurement is taken at the centre of M-packages (100mm×100mm×50mm) located at specific points on the cabinet shelves and described in the Standards. For example, the temperature performance of a RDC is classified 3M2 if all the M-Package temperatures on the shelves are between -1°C and +7°C with an ambient condition class 3 (25°C/60%RH).
For one performance temperature, the RDC has one energy performance identified by its electrical performance plus its refrigeration performance. The electrical performance is the power of the electrical components: fans, heaters, lighting, controllers. The electrical energy consumption does not depend on the ambient conditions and it represents less than 5% of the total consumption for an open vertical display cabinet. The refrigeration energy is measured by the Heat Extraction Rate (HER) plus the evaporating temperature. The Heat Extraction Rate is called $\Phi_{24\text{-deft}}$ in W (average without the defrost period) or Φ_{24} (average including the defrost period when Φ_{24}=0W). The organisation EUROVENT gives the value $\Phi_{24\text{-deft}}$ but for this study we can only reach the value Φ_{24} and so we can compare the different cases with Φ_{24}.
The evaporating temperature (T_{mrun} in °C) defines the cold point of the cabinet. The cooling pack must reach this evaporating temperature and it must deliver the HER needs in order to maintain the food temperature. The HER and the evaporating temperature are the values used to design the cooling pack. The evaporating temperature is usually a fixed value.
Especially for open vertical cabinets the Heat Extraction Rate is a value which depends on the ambient conditions, the temperature but also the humidity. In laboratory conditions (test room ISO 23953), we obtained excellent correlations between the value Φ_{24} and the enthalpy of the humid air (to see below figure 3 and 4, triangular dots). Therefore, in this study, we will make the hypothesis that the best parameter to characterize the ambient conditions – temperature and humidity – is the enthalpy of the humid air. We determined a linear correlation (equation 1):

$$\Phi_{24}\,\text{CLASS}\,x = \Phi_{24}\,\text{CLASS}\,3 \times \frac{\text{Enthalpy}\,\text{CLASS}\,x}{\text{Enthalpy}\,\text{CLASS}\,3} = \Phi_{24}\,\text{CLASS}\,3 \times K_{\text{AMBIENT}} \qquad (1)$$

With
- Φ_{24} CLASS x (W): Heat Extraction Rate in the ISO class x
- Φ_{24} CLASS 3 (W): Heat Extraction Rate in the ISO class 3
- Enthalpy CLASS x (kJ/kg): enthalpy of the humid air calculated with the temperature and humidity of the class x
- Enthalpy CLASS 3 (kJ/kg): enthalpy of the humid air calculated with the temperature (25°C) and humidity (60%RH) of the class 3.

Performances of RDC in Laboratory are well quantified; they are accurate and repetitive. What are the performances in store application?

3. FIELD TEST IN STORE

The objective was to measure the energy performance of vertical open cabinets in supermarkets. Two stores were selected; one located in Sainte Geneviève-des-Bois near Paris and another one in Urrugne in the South-western France. Cabinets were fitted with pressure probes (Bourdon-Sedeme, model E712), thermocouples (type T), humidity (E+E ELEKTRONIK, model EE21) and mass flow meter (Danfoss, Coriolis model MASS 2100). All the instruments were calibrated with its acquisition system (FLUKE, model Hydra) for the store in Urrugne. For the store in Sainte Geneviève-des-Bois, the instruments were calibrated but without the acquisition system (DANFOSS, model M2). The probes were been located to follow as much as possible the Standard ISO 23953 (paragraph 5.3.6.2.1, Figure 28) except the ambient probes which were aligned with the cabinets, the value 300mm (figure2) was set to approximately 0mm due to some store constraints.
The supermarket in Urrugne was a 5100m^2 and the instrumented cabinets represented 1 line of 6.25m (1×L2.5m + 1×L3.75m) set as shown on the pictures figure 3a. Food inside were pre-packed fishes and the request temperature performance was M2. During the field test period, the customer moved the application M2 to M1. The cabinets remained the same; just the evaporating temperature dropped from -6°C to -9°C.
The surface of the store in Sainte Geneviève-des-Bois was 8365m^2 and 1 line of 7.5m (1×L3.75m + 1×L3.75m) were instrumented (figure 3b). Cabinets were dedicated to stock meat, the request temperature was M2.

(a) (b)

Figure 3: Pictures of the cabinets installed in the 2 stores, (a) Urrugne, (b) Sainte Geneviève-des-Bois.

Technologies of these 2 lines of cabinets were different; the performances according the ISO 23953 are given in the table 3.

	Cabinets in Urrugne		Cabinets in Sainte Genevièves-des-Bois
Main characteristics	Open Vertical cabinet 2.0m high, chest depth 0.8m. Standard cabinet with shelves lighting. Total length = 6.25m		Open Vertical cabinet 2.2m high, chest depth 0.6m with a night blind. Total length = 7.5m
Evaporating temperature T_{mrun}	M1	M2	M2
	-9°C	-6°C	-2°C
Heat Extraction Rate Φ_{24} for 1 cabinet L=3.75m	5645W	5645W	6030W 3245W with night blind

Table 3: Energy cabinet performances installed in the 2 stores

The analysis period for Urrugne started in July 2008 and ended in August 2009.
The analysis period for Sainte Geneviève-des-Bois started in December 2008 and ended in June 2009.

4. AMBIENT CONDITIONS IN STORE

First results analyses were the ambient conditions in the 2 supermarkets with the objective to check if the class 3 was the right class to test and to display the cabinet performances. Because the performances of the cabinets depend on the temperature and the humidity in the store, these values were transformed in 1 value using the enthalpy. Towards 1 month, the enthalpy in the store was calculated at each time and it was ranked in 4 categories:

- Enthalpy inferior to Class 1: Enth < Class 1
- Enthalpy between Class 1 and Class 2: Class 1 < Enth < Class 2
- Enthalpy between Class 2 and Class 3: Class 2 < Enth < Class 3
- Enthalpy superior to Class 3: Class 3 < Enth

using the table 4:

	Class 1	Class 2	Class 3
Temperature / Humidity	16°C/ 80%	22°C / 65%	25°C / 60%
Enthalpy	39.2 kJ/kg	49.7 kJ/kg	55.8kJ/kg

Table 4: Enthalpy value for the ambient classes 1, 2 and 3

For example, now in my office the temperature is approximately 21°C and the humidity 55%RH. The calculated enthalpy for this condition is 42.8kJ/kg, so I am in the category “Class 1 < Enth < Class 2”. For the 2 stores, the percentage of the time in each enthalpy categories were calculated for each month and the values are given in the table 5 and table 6.

Enthalpy class	Enth < Class 1	Class 1< Enth <Class 2	Class 2< Enth <Class 3	Class 3 < Enth
July 2008	17.0%	82.3%	0.7%	0.0%
August 2008	13.8%	85.2%	1.0%	0.0%
September 2008	43.6%	56.3%	0.1%	0.0%
October 2008	69.9%	38.1%	0.0%	0.0%
November 2008	96.6%	3.5%	0.0%	0.0%
December 2008	100%	0.0%	0.0%	0.0%
January 2009	100%	0.0%	0.0%	0.0%
March 2009	99.9%	0.1%	0.0%	0.0%
April 2009	97.8%	2.2%	0.0%	0.0%
May 2009	69.8%	30.2%	0.0%	0.0%
June 2009	24.4%	74.4%	1.2%	0.0%
July 2009	9.7%	86.5%	3.8%	0.0%
August 2009	4.4%	81.3%	13.9%	0.4%
FULL PERIOD	57.45%	41.55%	1.59%	0.03%

Table 5: Monthly repartition of the enthalpy further the ambient classes for the supermarket in Urrugne

Enthalpy class	Enth < Class 1	Class 1< Enth <Class 2	Class 2< Enth <Class 3	Class 3 < Enth
December 2008	100%	0.0%	0.0%	0.0%
January 2009	99.9%	0.1%	0.0%	0.0%
February 2009	99.9%	0.1%	0.0%	0.0%
March 2009	99.9%	0.1%	0.0%	0.0%
April 2009	98.5%	1.5%	0.0%	0.0%
May 2009	88.5%	10.0%	1.1%	0.4%
June 2009	86.0%	12.7%	1.2%	0.1%
FULL PERIOD	96.10%	5.50%	0.33%	0.07%

Table 6: Monthly repartition of the enthalpy further the ambient classes for the supermarket at Sainte Geneviève-des-Bois

Most of the time the enthalpy in the stores was inferior to the class 2 but a non-significant percentage of time, the ambient conditions appeared between the class 2 and the class 3: 13.9% in August 2009 in Urrugne, it represented 103h. So to be safe for the food temperature it was essential that the cabinet was able to maintain the right temperature till the class 3. Also the cooling pack had to be designed with the refrigeration performance obtained in class 3 to be able to power the right energy need. A low percentage (0.4% = 3h) showed a higher enthalpy than class 3. If a cabinet and a cooling were strictly designed just for the class 3, the cabinet should not be able to maintain the right food temperature during these 3 hours. Hopefully "technical margins" were taken into account. **The design of the cabinet and the selection of the cooling pack system must be based on the ambient condition class 3 (25°C/60%RH).**

Furthermore the cabinets generally ran in conditions lower than the class 2 and in average around the class 1 in Urrugne and less than class 1 in Sainte Geneviève-des-Bois. So, to calculate the energy consumption of the cabinet, the refrigeration energy Φ_{24} found in class 3 would have to be reduced by a coefficient close to 0.7 using the equation (1) if the class 1 was selected as an average ambient condition.

5. ENERGY CONSUMPTION OF THE DISPLAY CABINET IN STORE

The average Heat Extraction Rate Φ_{24} was calculated during the opening days and for a period corresponding to the opening hours of the 2 supermarkets. The average enthalpy was calculated on the same period and for each opening day we correlated it to the average HER Φ_{24}. Urrugne's results are presented on the graph figure 4:

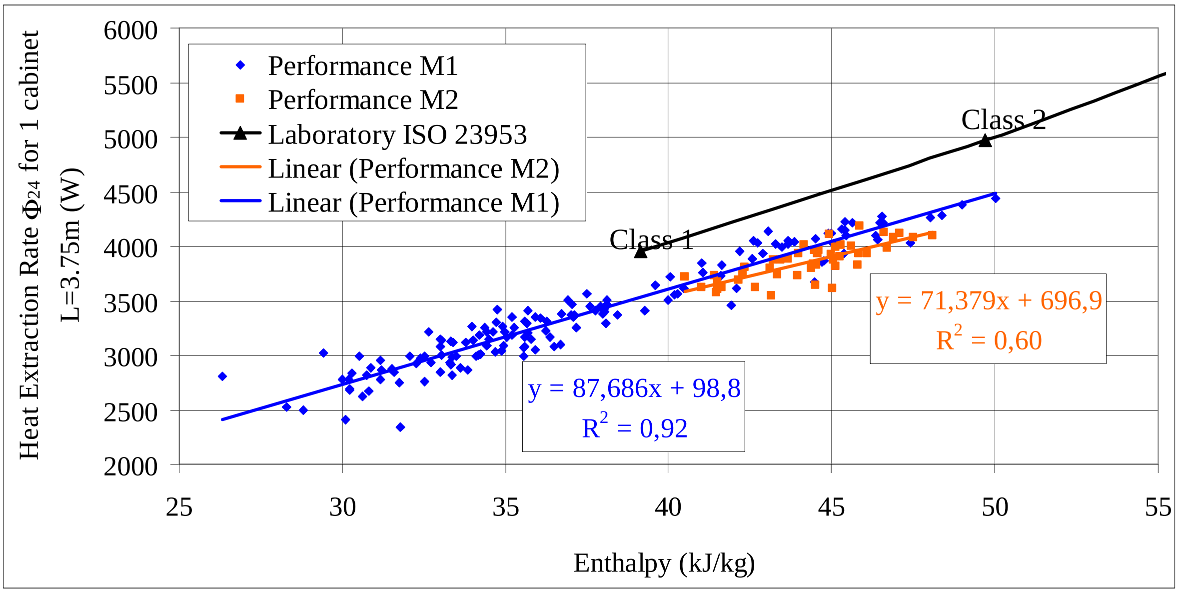

Figure 4: Urrugne's supermarket evolution of the Heat Extraction rate Φ_{24} with the enthalpy of the humid air

Φ_{24} as a function of enthalpy showed acceptable correlation even if discrepancies were observed with no explanations: we did not have the story of all the events (maintenance…) which happened in the store.
The cabinet Manager in the store changed the application temperature during the test period, the cabinets were designed to be able to move from 3M2 performance (square dot on the curves) to 3M1 performance (diamond dots). This was consisted in decreasing the evaporating temperature from -6°C to -9°C in average. Moving from 3M2 to 3M1, Φ_{24} increased by 5% only. In laboratory conditions (ISO 23953), we measured a 2.5% increase of $\Phi_{24\text{-deft}}$ moving from 3M2 to 3M1 (to see Eurovent Certification database). However, the cooling pack in the store would have to absorb this 5% plus the decrease of the evaporating temperature, 3K in average. We did not measure the electrical consumption of the cooling pack but we could estimate it: usually we consider a 3% increase of electrical consumption for each 1K of decreasing the evaporating temperature. The electrical energy consumption of the cooling pack would increase by approximately +14% (+3%/1K T_{mrun} + 5% from the cabinets).
But the most important observation was the high deviation between the laboratory ISO 23953 tests (black curve) and the results found in the store for identical enthalpy. There was clearly an offset between the ISO 23953 test and the store.

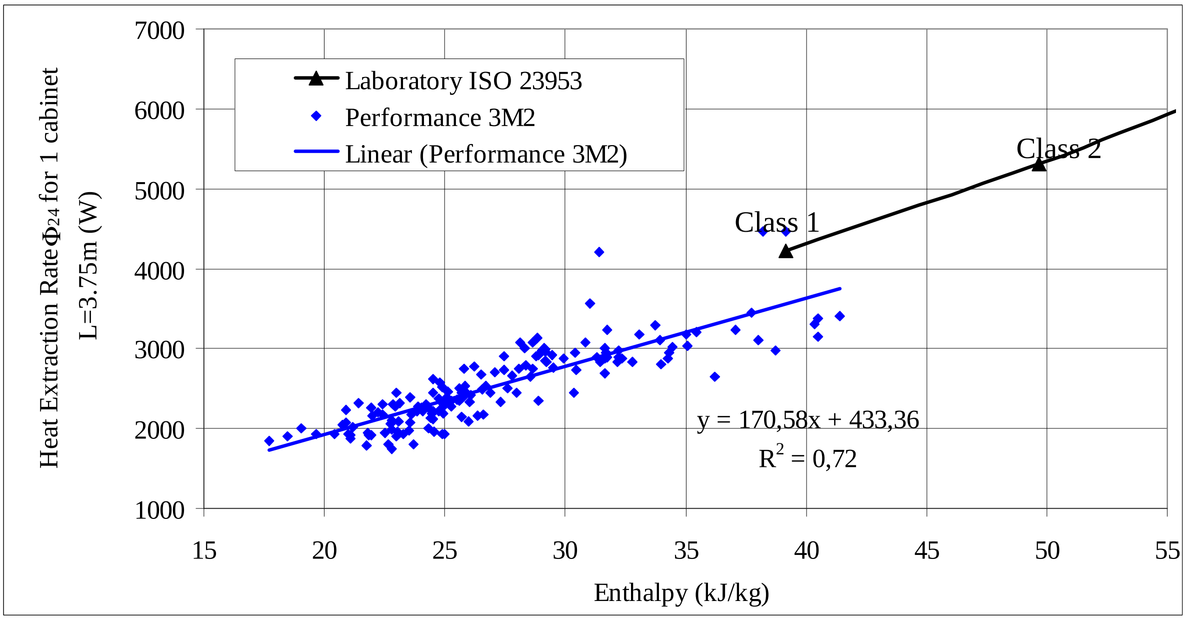

Figure 5: Supermarket Sainte Geneviève-des-Bois : evolution of the Heat Extraction rate Φ_{24} with the enthalpy of the humid air.

The same phenomenon was confirmed for the Sainte Geneviève-des-Bois' store (figure 5). Even if the open vertical cabinets were different from the ones put in Urrugne, we noticed that the average Φ_{24} in the store was lower than the ISO 23953 HER Φ_{24}.

One hypothesis to explain the difference is explained in the paragraph 2: the thermal stratification can not be reproduced in the test room, so when the probe measure 25°C in a store at 2.2m high, at the floor level, the temperature is below 15°C. In the laboratory, the temperature at the outlet of the airflow is regular and equal to 25°C. This assumption is based on the temperature stratification difference but it could also be linked to the humidity stratification. In the ISO test room the humidity is controlled and constant at the outlet. In the store, the humidity figures are unknown.

Back to the selection of the cooling pack based on class 3, for the same ambient condition in store we should design the cooling pack with a lower value than the Φ_{24} found according to the ISO23953. If we accept to extrapolate the results to class 3 with a linear curve, we could determine the coefficient of reduction (table 7): 0.83 for the 3M2 performance and 0.88 for the 3M1 performance. We can call it K_{STORE}. With all the experimental uncertainties, the same coefficient 0.83 is found for 2 different stores and for 2 different types of open vertical cabinets. It seems this coefficient is a function of the temperature application.

	Cabinets at Urrugne		Cabinets at Sainte Genevièves-des-Bois
Evaporating temperature T_{mrun}	M1	M2	M2
	-9°C	-6°C	-2°C
Heat Extraction Rate Φ_{24} for 1 cabinet L=3.75m **ISO 23953 application - CLASS 3**	5645W	5645W	6030W
Heat Extraction Rate Φ_{24} for 1 cabinet L=3.75m - Extrapolated **Store application - CLASS 3**	4993W	4681W	4976W
Coefficient of reduction to select the cooling pack $\mathbf{K_{STORE}}$	0.88	0.83	0.83

Table 7: Coefficient to apply on Φ_{24} to calculate the energy in store application from the laboratory ISO 23953 tests.

To assess the average Heat Extraction Rate Φ_{24} for the test period, we propose to use the equation (1). We applied the coefficient $K_{AMBIENT}$ to the Φ_{24} in store application (Class 3) found in the table 7. The results are in the table 8 and they are compared with the Φ_{24} average measurements in the 2 stores. The estimation based on the equation (1) and the average measurements were lined up ±5%. To notice that $K_{AMBIENT} = 0.49$ for the Sainte Geneviève-des-Bois's store, so it is important to not to confuse between Φ_{24} obtained in Laboratory condition ISO23953 and the average Φ_{24} in store for a long period

$$\Phi_{24\ \text{STORE CONDITIONS}} = K_{AMBIENT} \times K_{STORE} \times \Phi_{24\ \text{ISO 23953}}$$

		Urrugne		Sainte Genevièves-des-Bois
Evaporating temperature T_{mrun}		M1	M2	M2
		-9°C	-6°C	-2°C
Heat Extraction Rate Φ_{24} for 1 cabinet L=3.75m - Extrapolated **Store application - CLASS 3**		4993W	4681W	4976W
Average for the complete test period	Temperature	20.1°C	22.5°C	17.0°C
	Humidity	45.01%RH	49.7%RH	32.9%RH
	Enthalpy	37.2 kJ/kg	44.2 kJ/kg	27.4 kJ/kg
	Heat Extraction Rate Φ_{24} for 1 cabinet L=3.75m	3360W	3854W	2563W
Average Heat Extraction Rate Φ_{24} for 1 cabinet L=3.75m using equation (1) **Store application – Average CLASS**		3329W	3708W	2443W
Deviation using equation (1)		1.0%	3.8%	4.8%

Table 8: Average Φ_{24} and $K_{AMBIENT}$ coefficient

Taking the example of the supermarket in Sainte Geneviève-des-Bois, the declared value (from the ISO 23953 test class 3) was Φ_{24} = 6030W for 1 cabinet L=3.75m length. The design of the cooling pack in store class 3 should be $\Phi_{24} \times K_{STORE}$ = 4976W for 1 cabinet.
This value would be different to calculate the energy consumption of the store, it would be based on the average HER during the 7 month of measurements. We found $\Phi_{24} \times K_{STORE} \times K_{AMBIENT}$ = 2563W only for the day period and the opening hours. During the night and when the store was closed, the average Φ_{24} = 1295W. These cabinets were fitted with a night blinds and so the value Φ_{24} was divided approximately by 2 (Eurovent Certification data) during the night period. Including all, the total average Φ_{24} = 1965W for 1 cabinet L=3.75m and this value is the base to define the energy consumption of 1 vertical display cabinet in Sainte Genevièves-des-Bois. In the store Sainte Genevièves-des-Bois the average energy consumption was approximately 33% of the declared value in laboratory ISO 23953.

6. CONCLUSIONS

The International Standard ISO 23953 explains very precisely the way to test the Refrigerated Display Cabinets. Ambient conditions and open vertical cabinet performances were measured in 2 stores, 1 located close to Paris (Sainte Geneviève-des-Bois) and 1 in the South-western (Urrugne). The ambient conditions measurements showed that the class 3 could be reached during a non-significant time. So it is essential to consider the class 3 as a reference test for the safety of the food stored inside the cabinets. Furthermore, in store application the Heat Extraction Rate (Φ_{24}) for the open display cabinet was different from the values measured in laboratory according the ISO 23953 tests. We determined a coefficient K_{STORE} between 0.83 and 0.89 for which $\Phi_{24\ STORE\ CLASS\ 3} = K_{STORE} \times \Phi_{24}$. The difference between the store and the laboratory ISO23953 is explained by the important thermal stratification in the store. The value $\Phi_{24\ STORE\ CLASS\ 3}$ could be used to design the right cooling pack system.
To estimate the average energy consumption, we have to take into account the average ambient conditions in the store: $\Phi_{24\ STORE\ CONDITIONS} = K_{AMBIENT} \times \Phi_{24\ STORE\ CLASS\ 3}$ with $K_{AMBIENT}$ the ratio between the average enthalpy of the store and the enthalpy in class 3.
At the end, we have to consider 3 Heat Extraction Rate values (plus the evaporating temperature) to characterise the energy of refrigeration for an open vertical display cabinet:

- ❄ Φ_{24} : reference value found in laboratory using the Standard ISO 23953 and in class 3 (25°C/60%RH)
- ❄ $\Phi_{24\ STORE\ CLASS\ 3}$: maximum value that could be found in store CLASS 3. This value could be used to design the cooling pack system
- ❄ $\Phi_{24\ STORE\ CONDITIONS}$: average value based on the real average ambient conditions in store. This value could be the reference to calculate the energy consumption in W/day.

Next steps of this study could be to consolidate the values found in these 2 stores with measurements in other different stores. For example, if the thermal stratification is the right assumption to explain the differences, it could be interesting to make analyses in small shops where the stratification is weak. The coefficients found in this study were valid for the open vertical display cabinets. Because a close cabinet should have less interaction with the ambient conditions, it should be necessary to assess the coefficients for all the cabinets with doors, positive or negative application.

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