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Performance Evaluation and Design Optimization of Refrigerated Display Cabinets Through Fluid Dynamic Analysis

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ABSTRACT

Computational fluid dynamic technique (CFD) plays today a key role in the design of refrigerated display cabinets. Many parameters affect the performance of such equipments: refrigeration circuit, products displayed, thermal insulation, air curtain circulation and external environment.
All these parameters have been considered in a CFD-2D modelling of two representative models in commercial refrigeration business: an open vertical multi-decks cabinet and an open horizontal serve-over cabinet.
Theoretical analysis and experimental data according ISO23953 have been compared with good results in term of reliability of calculation.
The results obtained show how the evaporator position and the design of air curtain affect the performance of the cabinets in terms of energy consumption and temperature prescriptions for displayed food.
Also the effect of Cold Aisle has been investigated through a CFD-3D modelling to evaluate the cold stratification phenomena and its effect on cabinet performance.

Key words: *Computational Fluid Dynamic, CFD, Refrigerated Display Cabinet, Cold Aisle*

1. INTRODUCTION

Open refrigerated display cabinets are widely used in retail food stores due to their unrestricted access to displayed goods. Unfortunately, the drawbacks of this kind of equipments are the large energy consumption necessary to maintain goods inside the temperature limits. To obtain an acceptable level of insulation from the external environment a cold air barrier is re-circulated inside the cabinets and through the evaporator. The efficiency of this air curtain insulation is poor due to the turbulence phenomena that lead to a mixing of the cold air curtain with the external air. As result, food refrigeration is responsible of about 50% of the total energy consumption. Considering the increasing cost of energy, a fundamental asset of modern refrigerated equipment is an improved design that minimizes the overall energy consumption.
The Computational Fluid Dynamic technique (CFD), combined to the traditional thermodynamic approach can give to technicians working in commercial refrigeration field a good tool to analyze the areas that have the more sensitive effect on the efficiency of the cabinets.
In details, two main parameters have been identified as mayor areas leading to a possible efficiency increase: the evaporator and its position inside the cabinet, and the design of the air duct inside the cabinet.
Two typical examples of open refrigerated cabinets have been considered in a CFD-2D model: an open vertical multidecks and a horizontal serve over. Several layout solutions have been investigated as regard the position of the evaporator and their effect on the cold air curtain. To evaluate the advantage of a solution respect to the others the two parameters defined are the temperature limits of the displayed goods and the refrigeration duty as described in ISO 23953 standard.
As s further step of this research, a CFD-3D model have been developed to evaluate the well-known “cold aisle” effect between two rows of multidecks cabinets. A solution to remove the cold stratification through fans placed on the top of the cabinets has been investigated also.

2. 2D MODELING STRATEGY

2.1 Definition of the system:

The energy balance of open display cabinets and the use of CFD as tool to investigate the performance of a display cabinet have been explained by other authors: Cortella *et al*. (2001), Evans *at al*. (2005).
The two systems investigated in this study are defined by the following pictures.

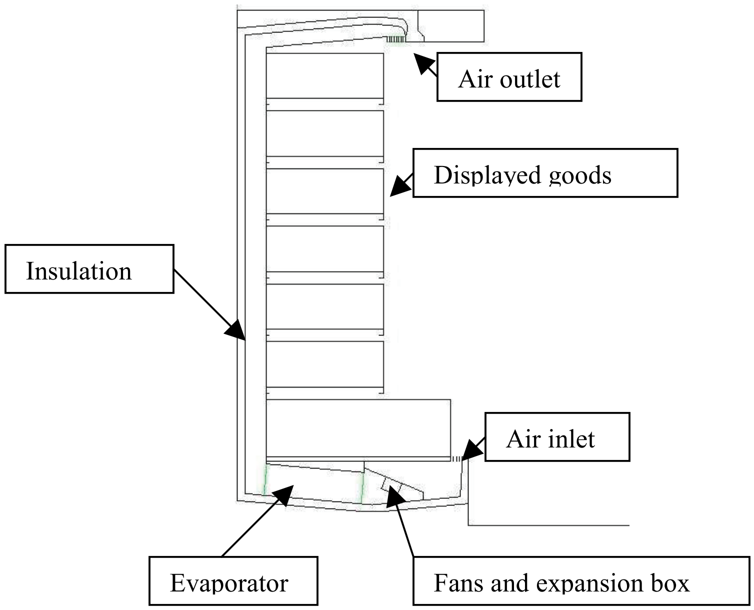

Figure 1: Main components of a multidecks cabinet

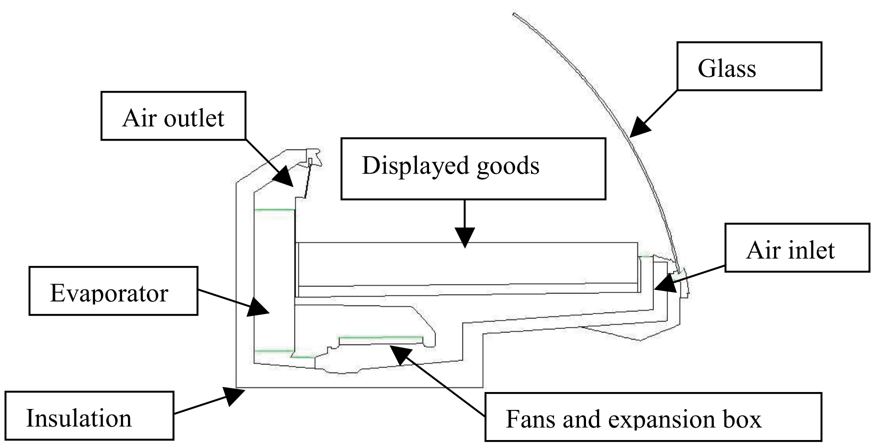

Figure 2: Main components of a serve over cabinet

2.1 Definition of the model:

As CFD source, Fluent 6.3.26 commercially available has been used. A stationary solver has been chosen, the turbulence model is standards k-ε and the radiation model is DO (Discrete Ordinate). No humid air has been considered.
The several boundary conditions have been defined as follow:

Domain the domain has been set up in order to reproduce the ISO 23953 climate class 3 conditions, i.e. air temperature at 25°C and wall velocity at 0,1m/s. In a 2D model the prescriptions for the airflow cannot be adopted, in the chosen model the airflow goes from the top to the lateral exit of the domain.
Fans: a simple Delta of pressure has been imposed. The correct value has been defined according the correct mass flow rate calculated with experimental values of velocity taken from experimental data.
Displayed goods: value of density, enthalpy and emissivity are taken from ISO 23953.
Evaporator: The evaporator is defined as a porous media exchanging power. Pressure drop air side, refrigeration duty and air outlet temperature have been taken by classic thermodynamic approach, using a private software tool dedicated to the calculation of geometric characteristics of a finned coil. The correct values have been calculated by an iterative procedure between CFD and Thermodynamic. The algorithm used is below reported:
Insulation: Insulation has been considered as solid media. Values of density and thermal conductivity have been taken by technical datasheet from polyurethane foam suppliers.

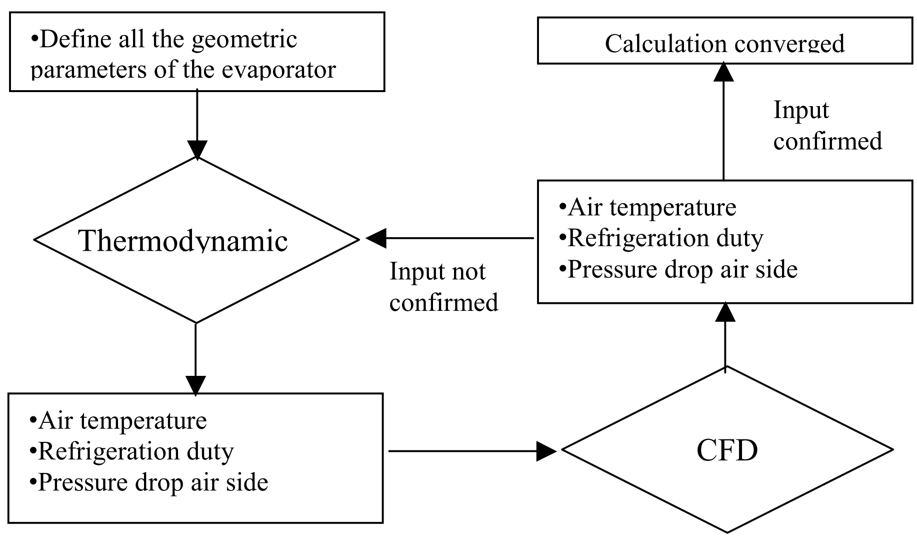

Figure 3: Convergence algorithm

2.1 Model validation

Once the model has been defined as above reported, results obtained have been compared with experimental data taken by test rooms at ISO 23953 standard condition climate class 3. The following table reports the deviations of the model:

Multidecks Cabinet			
	Exp. Data	CFD	Δ
P [kW]	4.57	3.95	-13.6 %
T_{Hot} [°C]	6,8	7.0	+ 0,2 °C
T_{Cold} [°C]	1.8	0.6	-1.1 °C
Serve Over Cabinet			
	Exp. Data	CFD	Δ
P [kW]	0.740	0.680	-8.1%
T_{Hot} [°C]	4.5	3.4	-1.1 °C
T_{Cold} [°C]	2.8	2.7	-0.1 °C

Table 1: comparison between experimental and calculated data

Where P is the refrigeration duty, T_{Hot} is the hottest temperature of the M-package and T_{Cold} is the coldest temperature of the M-package. According to the shown values, multidecks cabinets is rated according product temperature class M2 [-1:+7], typical of diary application, while serve over cabinet is rated according product temperature class M1 [-1:+5], typical of meat application, as reported in ISO 23953.
As regard refrigeration duty, Δ is the difference between experimental and calculated data, defined by:

$$\Delta = \frac{P_{CFD} - P_{EXP}}{P_{EXP}} * 100$$

Where P_{CFD} and P_{EXP} are the values taken respectively from simulations and experimental data
As regard temperatures, Δ is the geometric difference between experimental and calculated data, defined by:

$$\Delta = T_{CFD} - T_{EXP}$$

Where T_{CFD} and T_{EXP} are the values taken respectively from experimental data and simulations.
The shown values give a very good reliability in term of temperature, while significant differences are reported in term of refrigeration duty. This is due to the approximations introduced by the absence of humid air and to the impossibility to simulate defrosts time and consequent pull-down of the system. Anyway, once the corrective coefficients have been defined for the refrigeration duty, the same coefficients have been considered in all the other calculations, and the model, that has proven to be robust, has been compared with itself.
The following pictures show the temperature contours and the stream functions calculated for both cabinets:

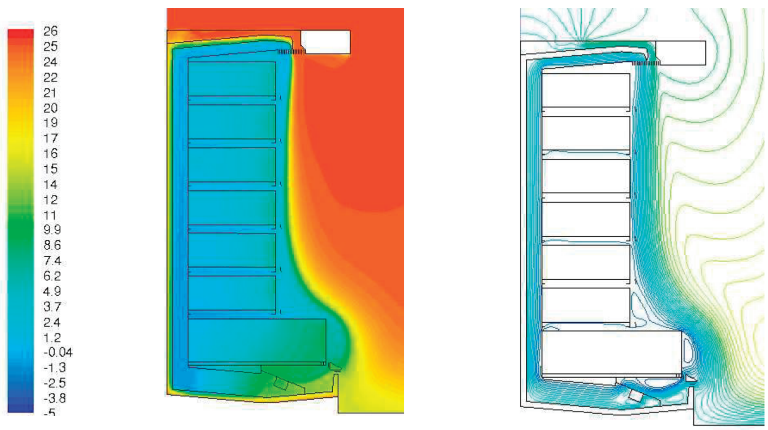

Figure 4: temperature contours and stream lines of multidecks cabinet

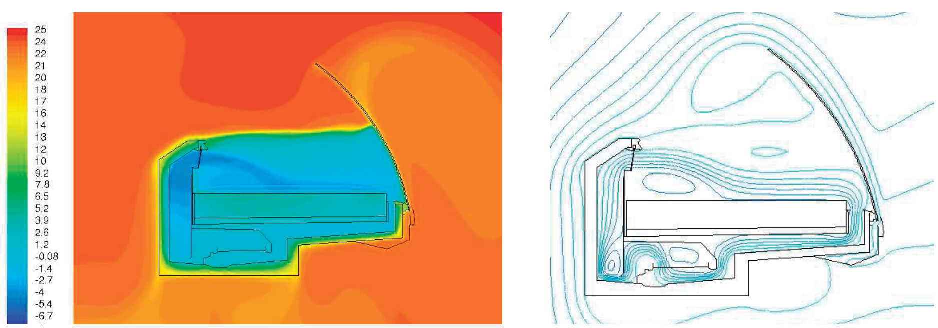

Figure 5: temperature contours and stream lines of serve over cabinet

3. EFFECT OF THE POSITION OF THE EVAPORATOR

3.1 Multidecks Cabinet

The system evaporator-fans-expansion box has been placed inside the back channel of the cabinet to verify the effect of this solution on the overall efficiency of the cabinet, and which design solutions must be introduced.
As a first attempt, all the other geometric parts of the cabinet have been kept as in the former case. The many thermodynamic conditions investigated never gave acceptable results due to the temperature of the displayed goods. As reported in refrigeration rating standard, M-packages must stay inside a temperature range with a maximum and a minimum: as example for M2 applications the temperature range is from –1 °C to +7 °C. The main problems encountered were the short distance from the evaporator to the displayed goods near the back panel, that leads to a

temperature below imposed inferior temperature limit, and the low cold air flow rate from the back panel, especially on the firs shelf. A temperature class 3M2 has not been reached.
As second attempt the cabinet has been modified significantly. A small panel of insulating material has been placed between the evaporator and the back panel. The overall air flow inside the cabinet has been modified: the upper part of the back panel has been closed in order to increase the mass flow on the first shelf, and, for the same reason, a deflector orthogonal to the main air flow has been introduced in the middle of the back panel.

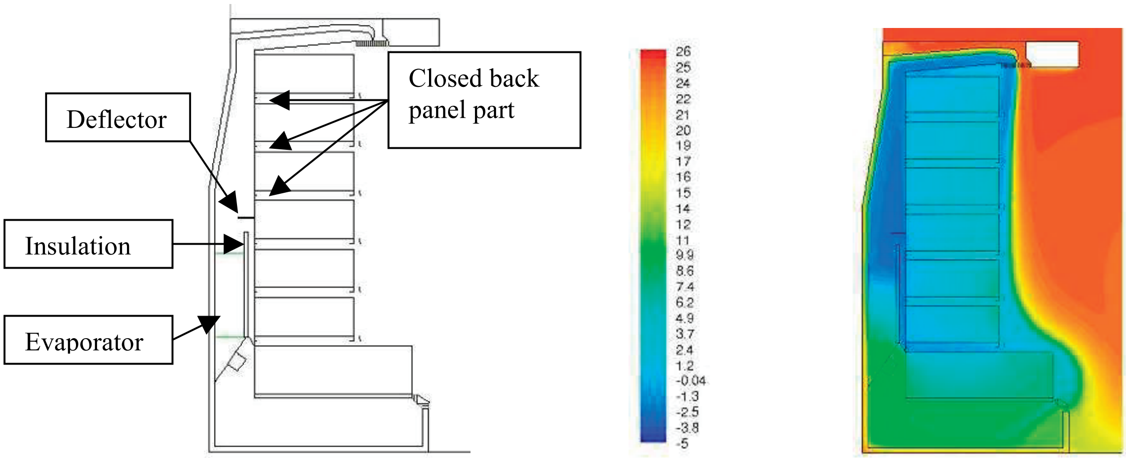

Figure 6: Geometric lay-out and temperature contours of multidecks cabinet

The modified multidecks cabinet can be considered very near to M2 class [-1;+7], but the simulations gave a worse overall efficiency than the former solution with the evaporator on the well.

	Evaporator on the well	**Evaporator on the back panel**	**Δ**
P [kW]	3.95	4.3	+8.1 %
T_{Hot} [°C]	7.0	7.6	+ 0,6 °C
T_{Cold} [°C]	0.6	0.3	-0.3 °C

Table 2: comparison between different layouts for multidecks cabinet

3.1 Serve Over Cabinet

The Serve Over Cabinet has been investigated with two different layouts. In the first one (case 1), the evaporator is placed in horizontal position in the well, in the second one (case 2) a different design of evaporator has been chosen. The evaporator has been placed according a layout that can be considered at half way between the vertical position and the horizontal position.
The geometric layouts of case 1 and temperature contours are reported in the following pictures:

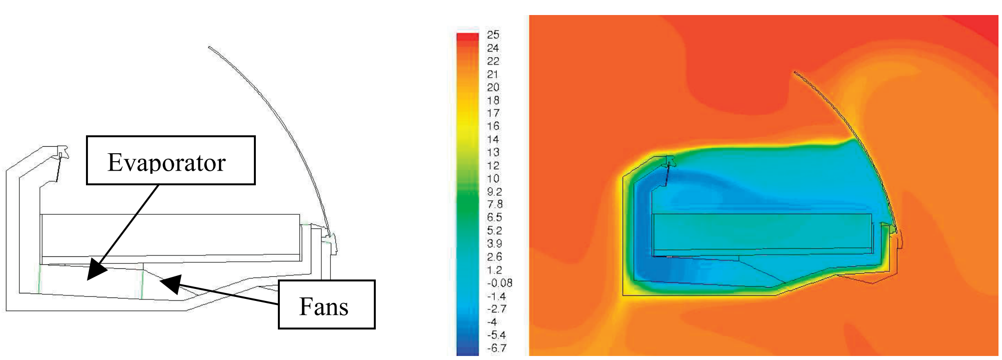

Figure 7: Geometric lay-out and temperature contours of Serve Over cabinet

The geometric layouts of case 1 and temperature contours are reported in the following pictures:

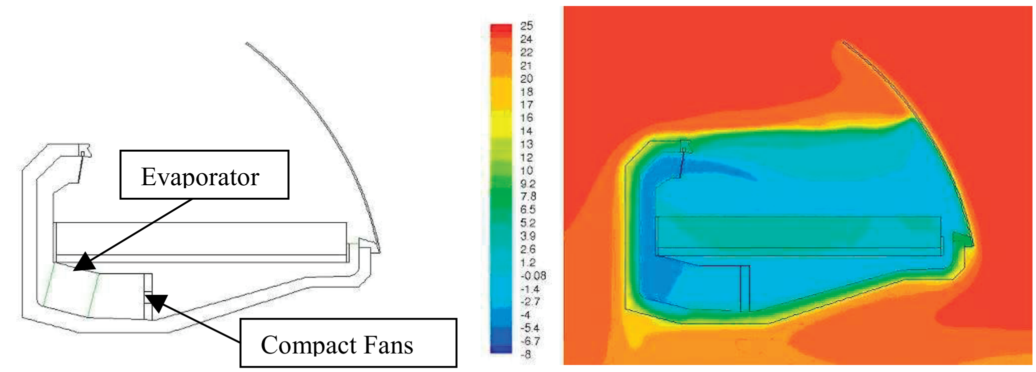

Figure 8: Geometric lay-out and temperature contours of Serve Over cabinet

The following tables reports the results obtained by calculations for the case 1 and 2 respectively, compared with the layout described in the paragraph 2 (Reference).

	Reference	**Case 1**	**Δ 1**	**Case 2**	**Δ 2**
P [kW]	0.680	0.680	0.0 %	0.613	-9.8 %
T_{Hot} [°C]	3.4	3.4	0,0 °C	3.4	0,0 °C
T_{Cold} [°C]	2.7	0.4	-2.3 °C	1.6	-1.1 °C

Table 3: comparison between Reference and Serve Over case 1 and case 2

The Case 1 solution didn't give appreciable advantages and class M1 [-1;+5] is respected.
The case 2 gave a good saving in term of refrigeration duty due to the chosen layout that offers a better air distribution inside the evaporator. Further, the compact dimension allows the use of compact fans and the air flow is in perfect counter current with the refrigerant flow rate.

4. 3D MODELING AND COLD AISLE PROBLEM INVESTIGATION

The cold aisle effect is a well-known problem in commercial refrigeration business. This effect occurs when two rows of open multidecks cabinet are installed in the shopping area and it is due to the unperfected isolation capability of the air curtain. This stratification effect leads to a not comfortable temperature for the shoppers.
As described by authors D'Agaro *et al*. (2005) and Tassou (2003), the best way to approach this problem is through a 3D-CFD model. The domain is defined by two 5 meters long rows of multidecks cabinet. The boundary conditions are the same as described in paragraph 2, but of course they are applied to surfaces and the set up is defined in order to create two symmetry plans and to adopt a symmetric calculation, with big savings in term of cells and computing time.

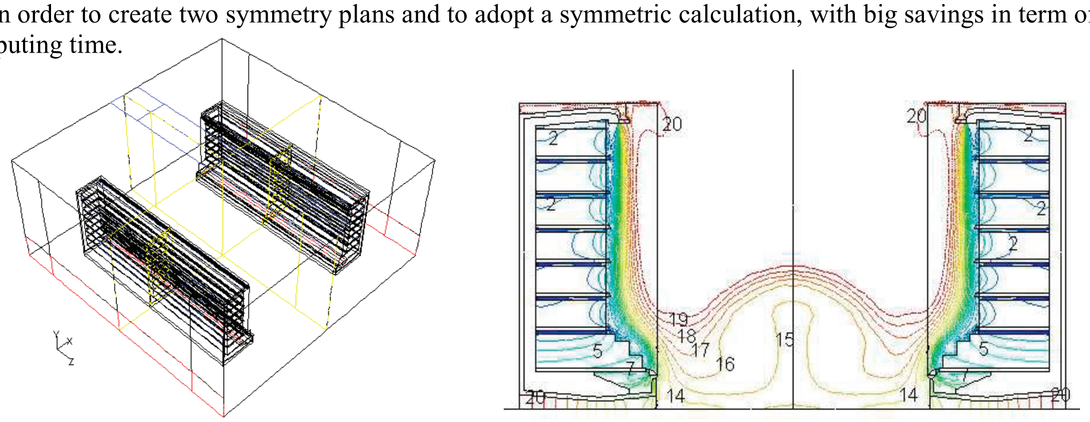

Figure 9: Domain definition and temperature lines of the cold aisle

In order to reduce this effect, without introducing heating kit that may have a negative effect on cabinet's performance, a simple solution is to install additional fans on the roof of the cabinet. The cold air from the aisle is aspired through the back of the cabinet and pushed on the top of the domain.

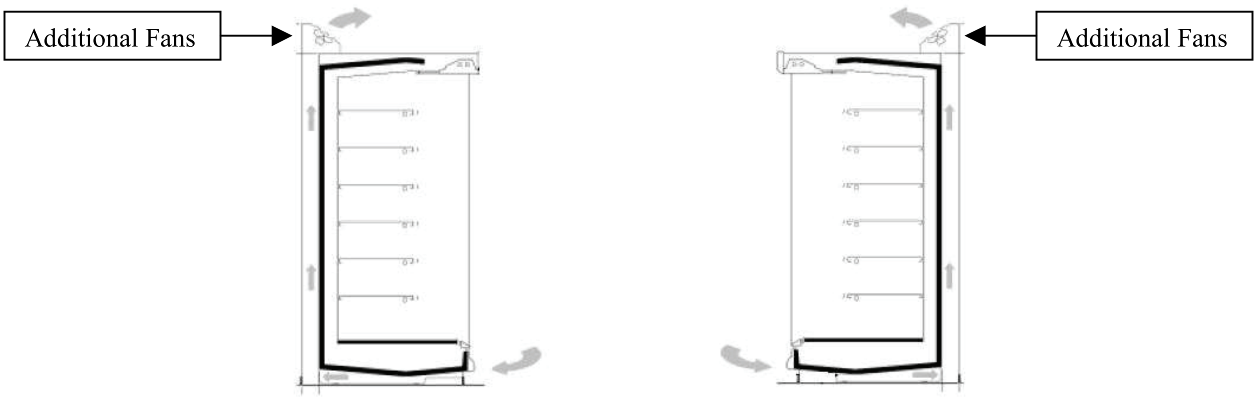

Figure 10: Recirculation of the cold aisle

The effect of the recirculation system has been compared with the same domain at the same conditions as the situation without recirculation. The good results obtained are shown in the following 2D temperature contours collected at a height of 0.5 meters from the floor.

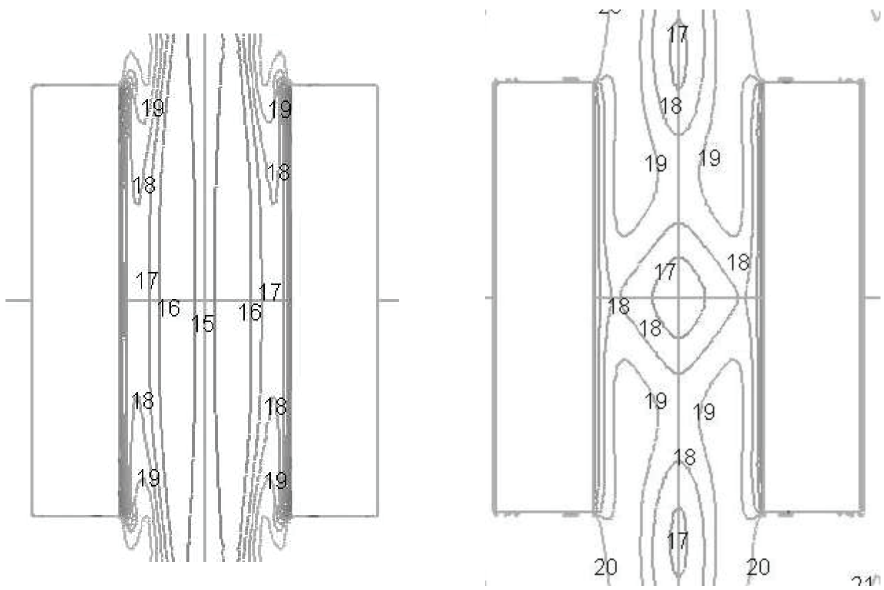

Figure 11: Temperature contours of the cold aisle without recirculation system and with recirculation system

The effect of the recirculation system leads to an average increase of temperature of 2 °C.

6. CONCLUSIONS

The use of CFD has been revealed as a very good tool for the design of refrigerated display cabinets. The main advantages are the possibility to verify different solutions without prototyping activities and with good savings in term of costs for developments and tests. An integrated analysis of the results obtained by CFD and experimental test data allow a better physical understanding of the problem.
The simulations carried on gave the following indications:

- For a multidecks open vertical cabinet the evaporator placed in the well allows an easier design and a good efficiency of the system in term of refrigeration duty and displayed goods temperature
- For a multidecks open vertical cabinet the evaporator placed on in the back panel gives a more complex design and some problems as regard the displayed goods temperature. The necessary refrigeration duty is higher.
- For a serve over cabinet the position of the evaporator in the well or in the back panel doesn't give appreciable differences.
- The design of a squared evaporator allows a better air circulation with a consistent saving in term of energy consumption. Compact fans can be easily adopted.
- The cold aisle discomfort in the shopping area can be easily reduced by the introduction of a simple recirculation kit. The temperature increase is about 2 °C.

NOMENCLATURE

P:	Refrigeration Duty	(kW)	**Subscripts**
T:	Temperature	(°C)	Hot: Hottest M-Package
			Cold: Coldest M-Package
			CFD: calculated
			EXP: Experimental data

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