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ENB 4780 1–9
ARTICLE IN PRESS
Energy and Buildings xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Energy and Buildings
journal homepage: www.elsevier.com/locate/enbuild

Energetic, environmental and economic analysis of climatic separation by means of air curtains in cold storage rooms

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ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form 9 January 2014
Accepted 11 January 2014

Keywords:
Cold storage room
Climate separation
Air curtain
Energy efficiency
CO_2 environmental impact
Economic analysis

ABSTRACT

Generally, doorways are the part of a cold storage rooms where maximum energy gains and losses occur. The main purpose of this research is to achieve a more efficient energy control for these areas. To do this, a comprehensive study of a climate separation system with highly efficient air curtains has been conducted. Not only the energy consumption has been analyzed but also the carbon dioxide emissions to the atmosphere, as well as the cost effectiveness of different alternatives. The results of the study, from the viewpoint of energy performance and amortization period, show that using high efficiency air curtains as a climate separation is a cleaner and cheaper solution than other commonly used systems. It reduces heat gains and losses through the door of the storage room by 80% compared with a physical separation solution. The simplicity of the installation makes these systems feasible not only in new buildings, but also in buildings under construction or refurbishment.

1. Introduction

One of the main reasons for the high energy consumption in cold storage rooms is the considerable thermal load caused by air infiltration through the doors while they remain open due to the circulation of vehicles loading goods from or into the room [1,2].

A common solution is to solve the separation by means of a door that, manually or automatically, remains open for the shortest time in order to allow the transit of goods through the opening. Under such circumstances every door opening, no matter how short, means an escape of cold air from the storage room to the surroundings. This load has to be matched by the evaporator which is oversized in order to maintain indoors temperature within certain limits [3]. Furthermore, draughts and unwanted air currents can be a constant feature when the door opens automatically, affecting hygrothermal comfort [4,5].

The situation is worsened when the doors do not close tightly due to the ice build-up on their frames. In such cases, the thermal load can even exceed the cooling capacity of the chiller, and for that reason the desired temperature is rarely achieved, although the air conditioning system is constantly running at full power [6].

The problem has been usually solved by means of a vestibule with double sliding door which, as simultaneous opening of both doors is precluded, cuts down heat infiltration into the storage room. However, this solution slows down the loading and unloading processes, making it impractical for large cold storage warehouses with high freight vehicles traffic [7].

Transparent PVC strips curtains are also widely used as separators, but they are generally considered as unsafe, not particularly efficient, unhygienic and requiring much maintenance [8].

An effective solution to reduce infiltration through openings is to incorporate a physical climate separation through air curtains. It consist in a fan, generally placed over the access door of the room, which blows down an air jet that creates a barrier to the heat transfer from the outside and the cold escape from the inside. This is an option that is more and more prevailing over traditional systems. In addition, modern development of highly efficient air curtains makes this system an alternative to be seriously considered when energy saving and CO_2 emission reduction are imposed by regulations [9].

The purpose of this work is to carry out an energetic, environmental and economic analysis on the use of high efficiency air curtains as climate separators in the entrances to cold storage warehouses with high freight vehicles traffic. To do this, the performance of a refrigeration equipment has been analyzed under three different scenarios, depending on the selected climate separator: physical separator (door), conventional air curtains and highly efficient air curtains system.

2. Materials and method

The great temperature and humidity differences between the outdoor air and room air conditions produces an effect of high pressure that makes heavier cold air escape through the lower parts of

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http://dx.doi.org/10.1016/j.enbuild.2014.01.026

Nomenclature

t	dry bulb air temperature (°C) dry
T	bulb air temperature (K)
c	air specific heat (kJ/kg K)
h	door height (m)
d	jet width (m)
z	vertical position (m)
S	door area (m^2)
Q	air flow through the door (m^3/s)
g	gravitational acceleration (m/s^2)
w	air humidity ratio ($g_{vapour}/kg_{dry\ air}$)
Φ_S	sensible heat flow rate (W) latent
Φ_L	heat flow rate (W)
ρ	air density (kg/m^3)
U	jet air velocity (m/s)
I	jet discharge momentum flux per length (N/m)
L	water latent heat of vaporization (J/g)

Subscripts

i	inside
o	outside
n	neutral
0	normal conditions

the opening, and forces lighter warm air infiltration through the top of the opening.

This natural convection effect [10] can be noticed by means of a thermographic camera if a white panel is placed perpendicular to the access door (Fig. 1). When the door of the cold storage room is

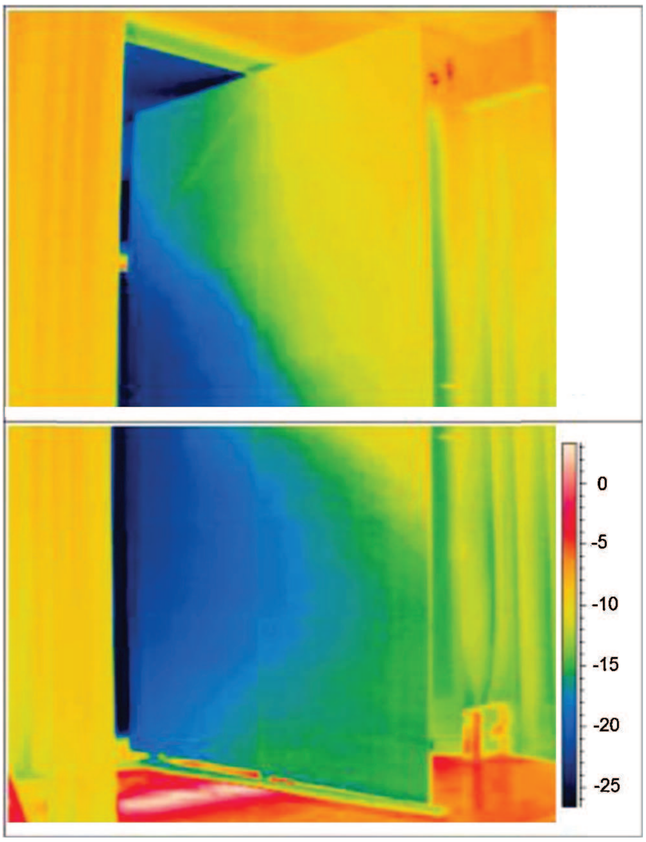

Fig. 1. Thermographic image taken during the opening of the door of a cold storage room.

Fig. 2. Ice effect outdoors (left) and indoors (right) of the cold storage room.

open, the warm air inflow at the top of the door and the cool air coming out of the room at the bottom can be easily observed.

The main effects of natural convection in cold storage rooms openings are:

(a) *Ice effect*. Warm air that enters the cold room has a high content of moisture. Upon contact with the cool indoor air, at very low temperatures, condensation occurs. It eventually results in ice build-up that remains attached to walls, ceilings, shelves, doors, i.e. every object placed in the room, even the refrigeration unit itself (Fig. 2).

This effect causes the following problems:

- Damage of the refrigeration unit, as well as deterioration of walls, storage shelves and doors, whether they are sliding (causing blockage and derailments) or plastic sheets (causing breakage and loss of transparency) [11].
- Loss of efficiency of the refrigeration unit of the cold storage room, as ice build-up in the evaporator considerably lowers its seasonal EER and makes the cycles of defrosting last longer.
- Increase in workplace accidents, caused by slippery walkways due to ice build up on the floor [12].
- Increased maintenance costs, since ice has to be periodically removed to prevent slipping.

(b) *Fog effect*. As a prelude to the formation of ice, water droplets and small ice crystals are formed due to sudden temperature change. This causes a lack of visibility in the traffic area which increases the chances of having accidents during loading and unloading operations (Fig. 3).

2.1. Experimental studies

This research has been carried out on an existing installation in an industrial warehouse for food packaging with high freight vehicles traffic.

The building is located in Valladolid (Spain), with a height above sea level of 740 m. The average outdoor air temperatures during winter (October to March inclusive) and summer (April to September inclusive) are 8 °C and 15 °C, respectively [13]. It has four cold storage rooms of different sizes and characteristics, each with an access door. Table 1 shows the dimensions both of the rooms and their access doors, the type of door and its opening period, and the indoor and outdoor weather conditions during the analyzed periods. The geometric measurements have been taken using Leica laser technology, Disto D5 model, and the temperature data with a Lufft precision thermohygrometer, Opus 10 model.

Please cite this article in press as: T. Gil-Lopez, et al., Energetic, environmental and economic analysis of climatic separation by means of air curtains in cold storage rooms, Energy Buildings (2014), http://dx.doi.org/10.1016/j.enbuild.2014.01.026

Fig. 3. Visibility reduction due to fog effect.

2.1.1. Temperature measurements

Carrying out a thermographic analysis, the effects of the climate separation in cold storage rooms using air curtains are clearly shown (Fig. 4).

In Fig. 5, the cross section of the door is marked with a dashed line. The left hand side picture shows the general air circulation, with warm air coming into the room through the upper part of the opening and an opposite direction cold air movement at the bottom, when no climate separation is used. In the right hand side picture, the air curtain acts as a barrier preventing cold air exfiltration.

Both images clearly show the effects of an air curtains climatic separation system that acts as an invisible thermal barrier preventing convection through the door to occur.

2.1.2. Case studies

In order to compare the highly efficient air curtain performance with conventional systems, it has been found necessary to carry out a thorough study on the energy performance, as well as the environmental and economic feasibility of the air curtains system. To do this, four cold storage rooms of the aforementioned building have been analyzed under three different conditions:

- Case study No. 1: With a physical separation (sliding door).
- Case study No. 2: With a conventional air curtain.
- Case study No. 3: With a highly efficient air curtain.

2.2. Calculation method

2.2.1. Energy losses

Through the permanent openings in building partitions air movement occurs. Its direction and velocity depends on the pressure difference between both sides of the partition. In the absence of mechanical ventilation systems, the pressure differential is due to the temperature difference between indoor and outdoor air (thermal draft). In case of external walls, effect due to wind pressure also has to be considered [14].

Fig. 6 shows a cross section of a door, with the pressure distribution in the opening represented by means of vectors. Being h the height of the door, in the lower area cold air masses cause positive pressure (in blue) balanced by negative pressure (in red) in the upper part. In between, the neutral pressure level, whose height position, defined by z_n, is variable and depends on the wind pressure distribution along the building envelope. In the case of cold storage rooms, pressure difference between zones causes the exfiltration of cold air through the lower part of the opening, which is replaced by infiltration of outside warm air through its upper part.

The airflow through an opening due to thermal buoyancy has been studied by different authors. The classical simplified approach is based on the application of the continuity and Bernoulli equations before and after the opening [15]. A two-dimensional steady flow is considered, where air is studied as an incompressible and non-viscous fluid with constant density, and subjected exclusively to differential pressure gradients between both sides of the opening. Other important assumption made is to consider constant air temperature in the adjacent rooms [16]. In order to better fit with reality, experimental coefficients are introduced [3].

Table 1
Geometric characteristics and climatic conditions of the four storage cold rooms.

Cold storage room	1	2	3	4
Dimensions				
Width (m)	20.00	30.00	34.70	34.70
Length (m)	72.00	72.00	44.30	44.30
Height (m)	6.50	6.50	14.00	14.00
Area (m^2)	1440.00	2160.00	1540.00	1540.00
Volume (m^3)	9360.00	14,040.00	21,500.00	21,500.00

DOOR	1	2	3	4
Dimensions				
Width (m)	2.04	2.22	2.03	2.52
Height (m)	3.02	2.93	3.00	4.61
Area (m^2)	6.16	6.50	6.09	11.62
Type of opening	Sliding	Sliding	Sliding	Sliding
Opening frequency (min/h)	10	10	10	10

Period	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Indoor temperature – room (°C)	−25	−20	−25	−20	−25	−20	−25	−20
Outdoor temperature – surroundings (°C)	8	15	8	15	8	15	8	15
Indoor relative humidity – room (%)	95	95	95	95	95	95	95	95
Outdoor relative humidity – surroundings (%)	40	40	40	40	40	40	40	40

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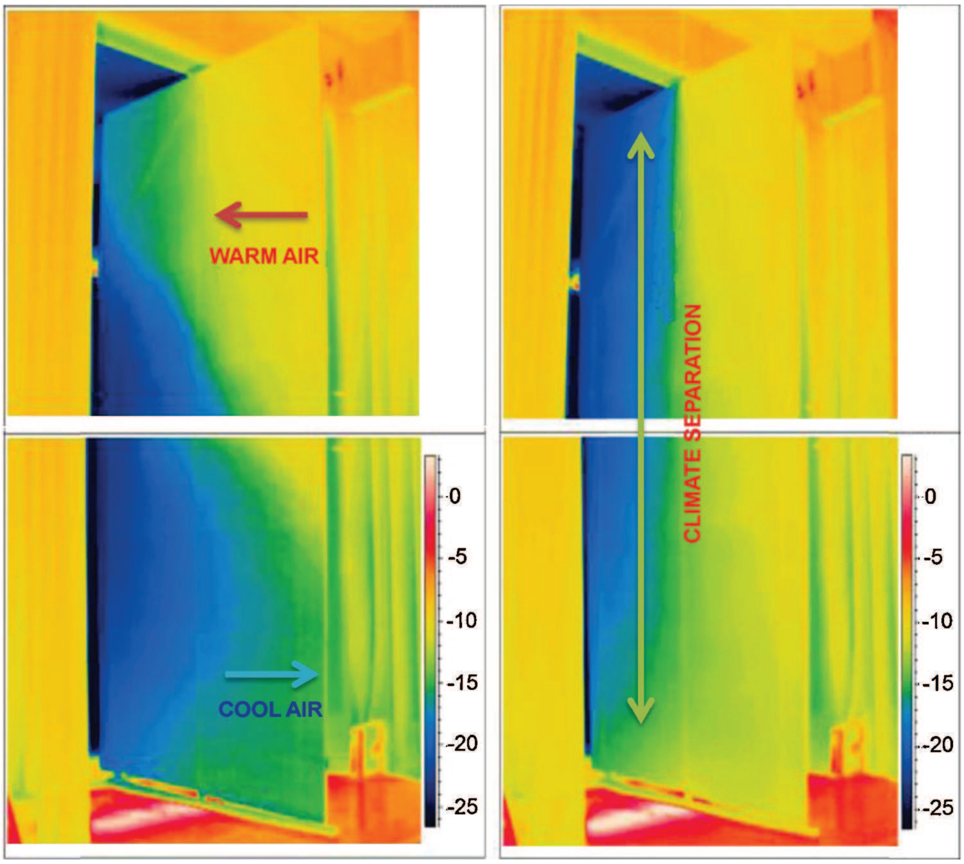

Fig. 4. Thermographic image of the entrance door of a cold storage room without climate separation (left hand side) and using an air curtains system (right hand side).

The air flow rate Q in m^3/s which enters through an opening h meters high and with a surface of S m^2 when there is a temperature difference $T_i - T_o$ between the inside air and the outside air can be obtained from Eq. (1).

$$S = \frac{Q}{g\rho_0 T_0((1/T_e)-(1/T_i))z^{1/n}} \tag{1}$$

where z is the neutral pressure level, that in the absence of wind corresponds to the centerline of the opening, and n is the flow exponent that indicates the degree of turbulence. A n value of 0.5 represents fully turbulent flow and 1.0 represents fully laminar flow. g stands for gravitational acceleration (m/s^2). ρ_0 and T_0 for air density and temperature at normal conditions, respectively.

Once the air flow rate is obtained, the simplest expressions for calculating energy fluxes through openings are shown by Eqs. (2) and (3).

$$\Phi_S = Q \cdot (T_o - T_i) \cdot \rho_a \cdot c_a \tag{2}$$

$$\Phi_L = Q \cdot (w_o - w_i) \cdot \rho_a \cdot L \tag{3}$$

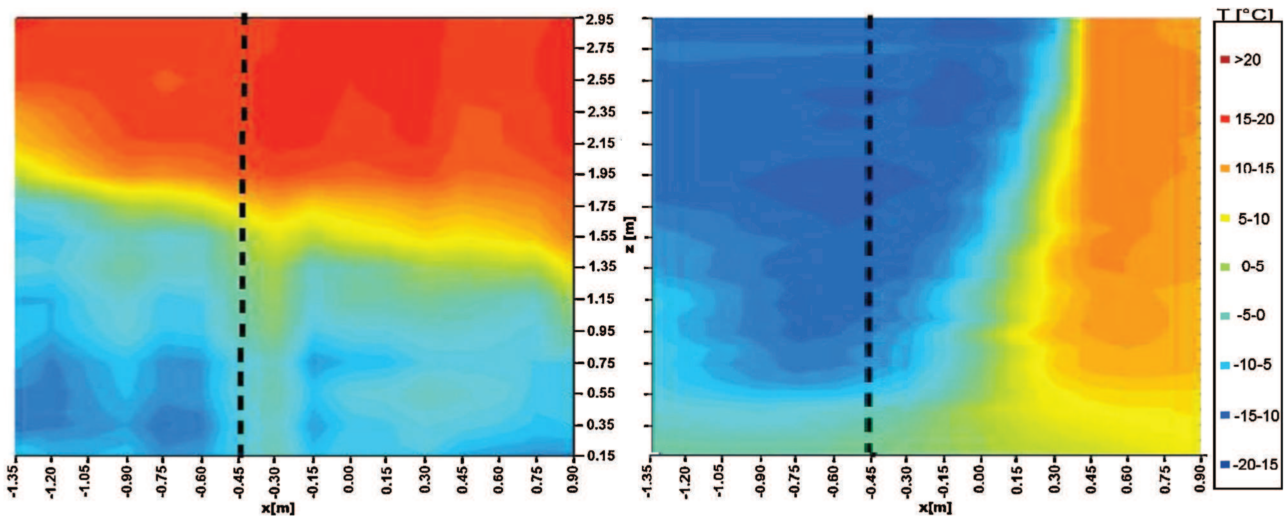

Fig. 5. Cross-section thermogram of the entrance door to a cold storage room. Left hand side: no climate separation. Right hand side: air curtain as climate separator.

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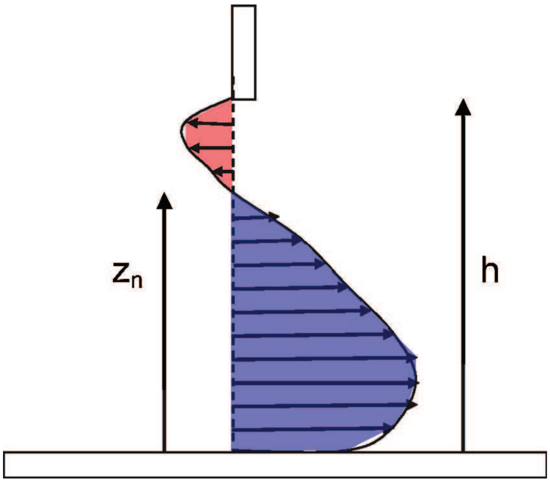

Fig. 6. Pressure distribution in an opening. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

where Φ_S and Φ_L are the sensible and latent losses (or gains), respectively, ρ_a is the air density, c_a the specific heat of air, w the humidity ratio (gv/kg of dry air). The subscripts o and i stand for outdoor and indoor, respectively.

These expressions assume the hypothesis discussed earlier in this section and consider no net air flow through the opening.

In the case of sensible heat flux, some authors have made slight corrections in order to account for the different air temperature gradients at both sides of the opening [17,18].

When experimental data are used, they are analyzed by means of correlations between dimensional parameters that includes thermal quantities as well as geometrical characteristics of the opening [16].

(a) Case study No. 1

In this research, energy loss has been calculated with Doorloss program, from Biddle climate solutions, whose calculation data and results have been validated through experimental tests [19,20].

The input values provided to the program are:

- Door dimensions (width and height in meters).
- Hygrothermal conditions for both warm and cold sides (temperature in °C and relative humidity in %).
- Ventilation conditions/infiltration (air flow rate in m^3/h).

And the output results returned by the program are:

- Energy fluxes (heat loss toward the cold side and vice versa in kWh).
- Air velocity in m/s.
- Neutral pressure level height in m.

Fig. 7 shows the calculations for the cold storage room No. 1 door during warm season. Likewise, the program has been run for the winter period conditions and for the rest of the doors as well.

(b) Case studies No. 2 and No. 3

Air curtains have the function of neutralizing outside air infiltration through the doors, reducing up to 90% heating and cooling thermal demand [2]. Furthermore, they allow to control indoor environment regardless of external conditions.

To effectively carry out its function of climate separation, the curtains should maintain a proper discharge length whatever the external conditions of wind are. If the air curtain jet is too weak and the throw distance is short it does not prevent infiltrations. By contrast, excessive throw distance due to a strong jet can reduce efficiency by almost 50%. In this case, high velocity and turbulent flow make the air curtain partially mix with outside air [9,21,22].

The parameter that best characterizes the operation of a curtain is the jet discharge momentum flux per length, I_0 (N/m) that indicates the strength of the curtain (Eq. (4)).

$$I_0 = \rho_0 \cdot d_0 \cdot U_0^2 \quad (4)$$

being ρ_0 (kg/m^3) the air density, d_0 the outlet width (m) and U_0 the outlet velocity (m/s).

Modern air curtains vary the air flow driven maintaining a constant flow rate by adapting the geometry of the discharge outlet. By choosing a relatively large outlet width, it can be achieved an optimum momentum, as needed to reach the floor, but with low velocity that keeps the flow in laminar regime.

In this research, the selection of the air curtain model and the adequate supply air velocity and temperature was carried out with the program VCAP (Visual Air Curtain Program) [23]. Depending on

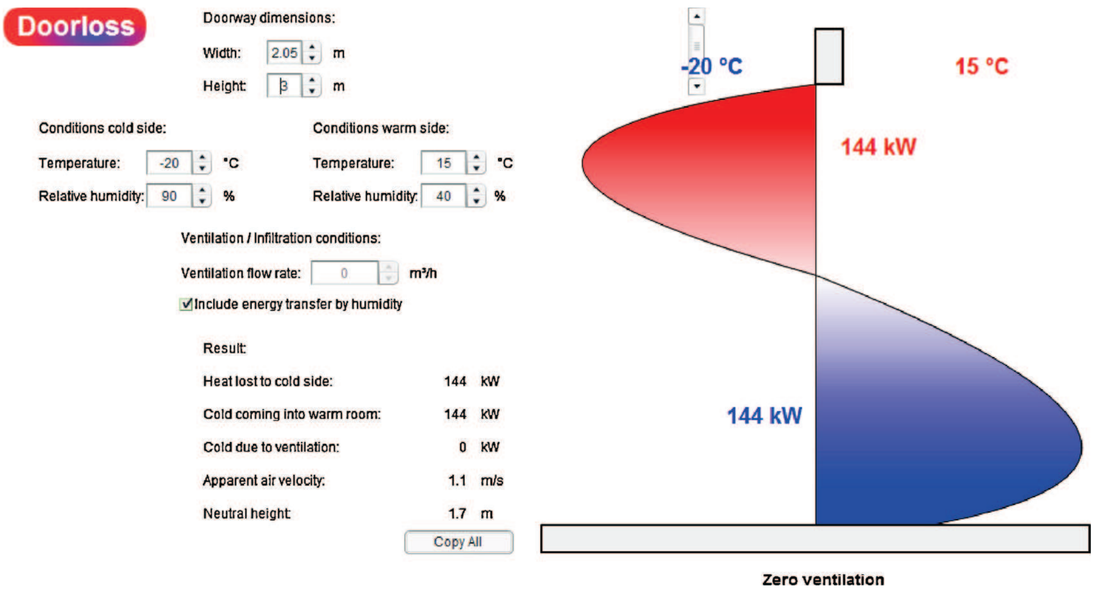

Fig. 7. Energy balance through door in cold storage room No. 1 during warm season.

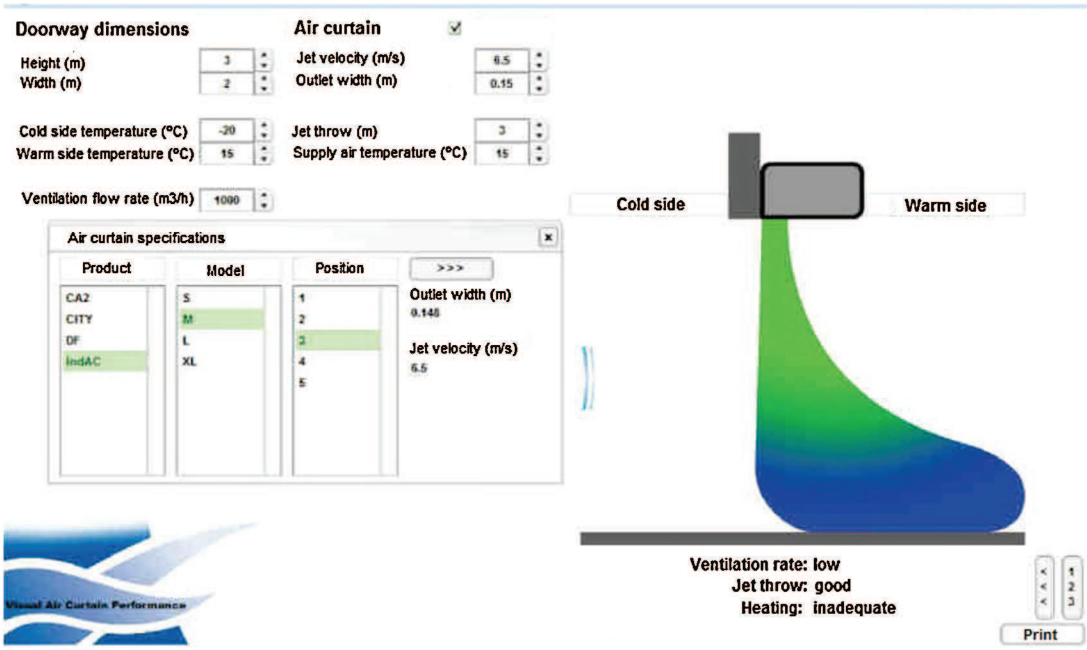

Fig. 8. Door No. 1 calculations during warm season.

the dimensions of the door and the hygrothermal conditions at both sides of the opening, the program provides the jet velocity and the supply air temperature needed to reduce the natural convection.

The input values provided to the program in this case are:

- Door dimensions (width and height in meters).
- Hygrothermal conditions for both warm and cold sides (temperature in °C and relative humidity in %).
- Ventilation conditions/infiltration (air flow rate in m^3/h).

And the output results returned by the program are:

- Supply air jet characteristics (velocity in m/s, discharge length and width in m).
- Air temperature (in °C).
- Level of ventilation and supply air penetration achieved (inadequate, low or good).

Fig. 8 shows the input data and the results for cold storage room No. 1 under summer conditions. The program has also been run for winter period, and likewise applied to the other three cold storage rooms.

For the existing door dimensions, a 100 m^3/h air flow rate is sufficient to provide optimal climate separation between the cold room and the adjacent front hall. This is achieved with a jet velocity of 6.5 m/s if the jet is blown at 20 °C, the air temperature of the surroundings.

In this case, there is no need to heat the supply air. With the only functioning of fans, climate separation is obtained, thereby reducing the operating costs of the air curtains system.

A summary of the technical characteristics of the Biddle air curtains selected for case studies No. 2 and No. 3 is shown in Table 2. In case No. 2, ST2 model units are chosen for doors 1, 2 and 3, while for the door 4 is necessary to install EP2 model units (Mars Air Systems). For the study case No. 3 INDAC model units, M Series (that stand for medium capacity, especially suitable for doors with a height under 4 m) are installed for doors 1, 2 and 3, while for door No. 4, INDAC model units, series L (high capacity series, especially suitable for doors with a height over 4 m) are required. In all cases, air curtains must be placed in series of two units in order to cover the total width of the door, since the standard length of the curtains is 150 cm. The fan units will be placed in the top compartment of the door, so that they blow a downwards jet to create an air barrier in the opening.

2.2.2. CO_2 emissions

Primary energy is the essential energy indicator to determine the net energy balance of a building (when heat production involves different energy vectors), or to compare the energy performance of different technical systems [24]. As such is considered by European official methodology of calculation, and has been accordingly

Table 2
Technical characteristics of the selected air curtains.

Case study	2			3				
Model	ST2/EP2			INDAC M/INDAC L				
Width (m)	1.5/1.5			1.5/1.5				
Electrical supply (V/ph/Hz)	400/3/50			400/3/50				
Max. current (A)	1.56/4.3			1.56/4.1				
Max. consumption (per phase) (A)	69.8/78.9			67.8/77.3				
Max. power motors (kW)	0.84/2.64			0.81/2.52				
Max. power consumption (kW)	54.4/65.8			46.8/62.8				
Speed (position)	1	2	3	1	2	3	4	5
Fan power consumption (W)	236/582	412/1014	556/1329	252/624	352/817	424/1023	496/1244	558/1427
Air flow rate (m^3/h)	2160/3590	4570/6540	6840/11,200	2750/4120	4160/6160	5230/8320	5790/10,100	7410/13,700

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Table 3
Annual energy losses for different climatic separation solutions.

Case study	Energy losses (kWh)						Energy losses (kWh/year)					
	1 Without climate separation		2 Conventional climate separation		3 High efficiency climate separation		1 Without climate separation		2 Conventional climate separation		3 High efficiency climate separation	
Period	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Room 1/Door 1	288	260	173	156	58	52	180,000	150,000	108,000	89,900	35,900	30,000
Room 2/Door 2	300	254	180	152	60	51	187,000	146,000	112,000	87,800	37,400	29,300
Room 3/Door 3	288	260	173	156	58	52	179,700	150,000	108,000	89,900	35,900	30,000
Room 4/Door 4	666	602	400	361	133	120	416,000	347,000	249,000	208,000	83,100	69,400
Total	1540	1380	925	826	308	275	962,700	793,000	577,000	475,600	192,300	158,700
							1,755,700		1,052,600		351,000	

incorporated into rating procedures for energy building performance of different member countries, including Spain [25].

It is calculated by multiplying the energy supplied to the system by a factor greater than unity. If, however, the carbon emission is preferred as indicator, a second conversion factor has to be applied.

According to it, the method used to evaluate the carbon emission due to the energy source is:

- Annual energy consumption of the primary fuel used by the tech-nical system (refrigerator and fans) = Annual energy needed by the technical system (refrigerator and fans) × Coefficient for the primary energy used.
- Amount of carbon emitted = Annual energy consumption of primary fuel × Carbon conversion factor.

The conversion coefficients used in this work are those used by the official program for energy rating process in Spain, CALENER [26].

2.2.3. Economic survey

As it is usual when calculating the amortization of facilities of this type, a 10 years period has been analyzed. In the economic study, it has been taken into account the cost of energy (affected by annual inflation), the installation cost of the climate separation facility and the maintenance costs.

Economic indicators are those commonly used in economic studies for capital investments recovery [27].

Fuel costs have been estimated with an annual estimated increase of 3.47%. In order to obtain reliable data, the time required to recoup the cost of the facility was taken into account, as well as the calculations made by the electricity companies, so as to be able to calculate the bills.

With respect to the installation costs of the climatic separation for case studies No. 2 and No. 3, it has been considered both equipment cost as well as the necessary installation for its operation. Regarding maintenance costs, in the case study No. 1, it has been included the cost of removing the ice from the perimeter of the door (which causes derailments and blockage) and from the surface of the evaporator (which reduces its performance). In cases No. 2 and No. 3, the periodic reviews and adjustments of the air curtains system have been considered instead.

3. Results and discussion

3.1. Energy consumption analysis

(a) Energy losses

Table 3 shows the energy loss for each of the three studied cases (no climate separation, conventional air curtains and highly efficient air curtains). The energy loss through the door is to be delivered by the refrigeration unit to keep the temperature of the cold storage room within acceptable limits.

From the table, it can be deduced that keeping a cold storage room door open during loading and unloading process means a high energy loss. This energy loss (due to the leakage of cold air which is replaced by warm air from the surroundings) causes an increase of the air temperature of the room that has to be neutralized by the evaporator of the refrigeration system. This energy loss is greatly reduced when efficient climate separation technologies are used.

The annual energy loss is obtained by multiplying the values obtained by the total hours of operation of the system, in summer as well as in winter.

The installation of high efficiency air curtains (case study No. 3) reduces heat losses by approximately 80% compared to a cold storage room without climate separation. Moreover, in the case of case studies No. 2 and No. 3, this solution increases the safety at work, for it not only prevents the ice built up, avoiding falls due to slippery floors, but also prevents fog formation in front of the openings, which improves the visibility of the operator during the loading and unloading processes.

(b) Energy consumption of fans

Case studies No. 2 and No. 3 require the operation of fans to ver-tically discharge an air jet powerful enough to reach the floor. The electrical power consumed by the fan is a function of the supplied air flow rate. Highly efficient curtains are equipped with a flow rec-tifier that maintain the jet convergent and rectilinear, allowing to vary the thickness of the jet, instead of controlling the velocity of discharge, as most systems do. Thus, the supplied air flow rate is fixed for each fan position and the equipment adapts its velocity of discharge by a variation of the outlet geometry, according to the external conditions. It allows greater efficiency compared to con-ventional curtain. The necessary air flow rate in each case has been obtained by means of VCAP program. Multiplying the power of the fans (two per door) by the total hours of operation, annual energy consumption is obtained (Table 4).

(c) Energy balance

Table 5 compares the annual energy consumption for each of the studied solutions.

Table 4
Annual energy consumption of fans.

Case study	Fans energy consumption (kWh/year)		
	1 Without climate separation	2 Conventional climate separation	3 High efficiency climate separation
Room 1/Door 1	0	1340	1020
Room 2/Door 2	0	1340	1020
Room 3/Door 3	0	1340	1020
Room 4/Door 4	0	3430	2460
Total	0	7450	5520

Table 5
Annual energy consumption comparison.

Case study	Energy balance		
	1 Without climate separation	2 Conventional climate separation	3 High efficiency climate separation
Refrigeration unit consumption (kWh/year)	1,750,000	1,053,000	351,000
Fans consumption (kWh/year)	0	7440	5510
Total (kWh/year)	1,750,000	1,060,440	356,510
Energy consumption per unit volume (kWh/year m^3)	26.40	16.00	5.37
Energy consumption per unit of room floor (kWh/year m^2)	263	159	53
Annual savings (kWh)	–	694,000	1,398,000
Annual specific savings (kWh/m^3)	–	10.50	21.00
Annual savings (%)	–	39.60	79.70

As the analysis has been carried out for storage rooms with different dimensions, it seems necessary to obtain consumption per unit of floor area and per unit volume, so that they can be compared with data from other research works.

As it is shown in Table 5, the annual energy savings obtained by installing a conventional air curtain (case study No. 2) instead of a sliding door (case study No. 1) reaches 39.60%. The savings double to 79.70% when a highly efficient air curtain is installed.

Adaptation to European Directive 2010/31/EU on the energy performance of buildings, that is near to come into force, considers the renovation of existing buildings as an opportunity to reduce both energy consumption and carbon dioxide emissions, set for their technical systems demanding requirements in respect of their overall energy performance and encourages when undergoing major renovation the consideration of high efficiency alternative systems in so far as this is technically, functionally and economically feasible [28]. In the case of refurbishment of cold storage rooms as the studied in this paper, it is observed that highly efficient climate separation significantly reduces the energy consumption per unit of floor area of the (from 264 to 53.40 kWh/m^2 year). Although the installation of air curtains has a major impact in energy consumption reduction, it does not prevent from the need of additional measures to reduce energy consumption in order to achieve EU Directive target of transforming existing buildings into Nearly Zero Energy Buildings.

3.2. CO_2 emissions analysis

The energy consumption of the refrigeration system when access to cold storage chambers is made via sliding doors means an annual amount of carbon dioxide emissions per unit volume of 7.39 kg CO_2/year m^3 (Table 6). If conventional and highly efficient air curtains are used for the climatic separation in access doors, this emission is reduced to 4.47 kg CO_2/year m^3 and 1.50 kg CO_2/year m^3, respectively. That is, 60.50% and 20.30% lower than in the initial case. Consequently, for the analyzed building, installing a high efficiency air curtain system for climate separation reduces the amount of carbon dioxide annually emitted in 392 Mg.

Table 7
Annual cost.

Case study	Annual cost per unit volume (€/m^3)		
	1 Without climate separation	2 Conventional climate separation	3 High efficiency climate separation
Fuel operating costs	1.03	0.62	0.21
Installation costs	0.00	1.81	2.41
Maintenance costs	0.02	0.01	0.01

Table 8
Annual savings and pay-off period comparison.

Case study	Savings evolution per unit volume (€/m^3)		
	1 Without climate separation	2 Conventional climate separation	3 High efficiency climate separation
Annual cost	1.03	0.62	0.21
Annual savings	–	0.41	0.82
5 years savings	–	0.47	0.94
10 years savings	–	0.55	1.11
Pay-off period	–	5th year	3rd year

3.3. Economic survey

Table 7 shows the annual cost per unit volume in the three cases studied. It has been differentiated between energy, installation and maintenance during operation costs.

Table 8 compares the annual cost savings for three alternatives to the problem of climate separation in cold storage rooms. When choosing a conventional air curtain (as it has been done in case study No. 2) instead of a physical separator (case study No. 1), the estimated annual savings per unit volume are 0.41 €/m^3 (which means a total savings of 27,000 € in the building refurbishment). In the case of a high efficiency air curtain (case study No. 3) the annual savings per unit volume amounts to 0.82 €/m^3 (54,400 € considering the four installed doors). Moreover, the table shows

Table 6
CO_2 annual emissions.

Case study	Carbon dioxide emissions		
	1 Without climate separation	2 Conventional climate separation	3 High efficiency climate separation
Total consumption (kWh/year)	1,755,000	1,060,000	356,000
Amount of CO_2 emitted (kg CO_2/year)	491,000	297,000	99,800
Amount of CO_2 emitted per unit volume (kg CO_2/year m^3)	7.39	4.47	1.50
Amount of CO_2 emitted per unit of room floor (kg CO_2/year m^2)	73.60	44.50	15.00
Annual savings (kg CO_2)	–	194,000	392,000
Specific annual savings (kg CO_2/m^3)	–	2.93	5.89

Please cite this article in press as: T. Gil-Lopez, et al., Energetic, environmental and economic analysis of climatic separation by means of air curtains in cold storage rooms, Energy Buildings (2014), http://dx.doi.org/10.1016/j.enbuild.2014.01.026

the pay-off period for case studies No. 2 and No. 3, when compared to the sliding door present solution. The shortness of the pay-off period is mainly due to the energy savings in the refrigeration units, free from having to match the additional load caused by cold air exfiltration through doors.

4. Conclusions

Installation of high efficiency climate separators in cold storage rooms as an alternative to traditional solutions reduces heat exchange through doors, prevents ice and fog effects that can lead to an increase in accidents at work and optimize the functioning of refrigeration units. Furthermore, since it means the elimination of any physical barrier, the use air curtains for climatic separation is specially suitable in cases of high freight vehicles traffic.

For the studied case, an industrial building with four large cold storage rooms and high freight traffic during loading and unloading periods, the energy consumption of the refrigeration system is reduced by 39.60% when conventional air curtains replaces the existing sliding doors, and by a 79.70% if the air curtains are of the high efficiency type. The simplicity of the installation makes these systems appropriate, not only for new buildings but specially for buildings under construction or renovation, when most of the solutions for increasing energy efficiency are unfeasible due to technical difficulties.

The proposed solution for climate separation not only reduces energy consumption but also carbon dioxide emissions (by a 60.50% or 20.30%, depending on the model to be highly efficient or conventional) and, consequently, improves the building rating qualification. According to the economic survey that has been carried out, the installation of conventional and high efficiency air curtains can be amortized in 5 and 3 years, respectively.

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Please cite this article in press as: T. Gil-Lopez, et al., Energetic, environmental and economic analysis of climatic separation by means of air curtains in cold storage rooms, Energy Buildings (2014), http://dx.doi.org/10.1016/j.enbuild.2014.01.026