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TECHNICAL AND ECONOMICAL EVALUATION OF VACUUM INSULATED PANELS FOR A EUROPEAN FREEZER

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Abstract: Vacuum insulated panels (VIP) is an emerging technology that may constitute an alternative to rigid polyurethane (RPU) foam as insulation in refrigerators and freezers. The "skin effect" caused by the aluminum layer in the envelope complicates the evaluation of the global thermal resistance. This article present a new method of VIP characterization. Values of the global thermal resistance obtained are used in a dynamic simulation tool ENEREF® to perform predictive calculations. Direct experimental measurements permitted to validate calculations. Finally, a life cycle cost analysis is performed and payback period of the technical option is calculated.

Nomenclature

k	Thermal conductivity , W/m.K	A	Area, m^2
P,W	Electrical power, heat flux, W	ΔT	Temperature difference, K
e	Thickness, m	G	Specific heat loss coefficient, $W/m^3.K$

1. STATE OF ART

The Montreal Protocol phased out CFCs refrigerants. R-11 (CCL_3F) being used as an expanding gas in the rigid polyurethane foams (PUR) is replaced by alternative fluids such as R-141b, cyclopentane and CO_2. As a consequence, when using cyclopentane, the thermal resistance of PUR foams is reduced by about 33%. In parallel, international and particularly U.S. and European efforts [1] are focused on the reduction of appliance energy consumptions. The contradiction between lower thermal resistance of insulation and lower energy consumption of refrigerating appliances pushed the insulation manufacturers to find alternative solutions such as VIP.

2. VIP STRUCTURE

Vacuum panels are composed of three main components: a core material, an envelop and a getter. Many materials can be used as a core material in VIP such as open cell polyurethane, expanded polystyrene (XPS), silica powder, perlite... therefore, for technico-economical considerations, the open cell PU and the XPS are the most usual [2].

The internal absolute pressure of a VIP is about 50 Pa abs. The thermal resistance of the panel is directly related to this pressure level; i.e. for open cell PU, at a pressure of 10 Pa abs the thermal conductivity in the center of the panel is about 6 mW/m.K, that increases to 25 mW/m.K when the pressure reaches 1000 Pa abs [3]. The envelop and getter roles are to maintain this pressure during the panel lifetime.

The getter is a chemical adsorbent composed of barium and lithium alloy that adsorbs nitrogen in large quantities. Additions of calcium and cobalt oxides permit the adsorption of humidity, hydrogen, R-141b...

The envelop is a multilayer polymer (*figure 1*). The first layer is in nylon that stops water molecules. The polyethylene teraphtalate (PET) and aluminum layer prevent the passage of smaller molecules, and finally, the polyethylene (PE) layer permits the welding [4]. This envelop guarantees the leak tightness. Therefore, the aluminum layer creates a "skin effect", which is the heat transfer along the envelop.

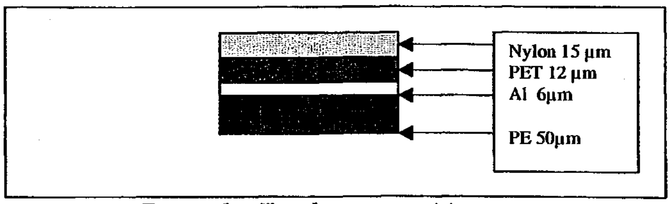

Figure 1 – Envelop composition

Considering the high thermal resistance of the panel in the normal direction, the heat transferred through the aluminum layer is not negligible and the equivalent thermal resistance is dimension dependent.

3. VIP CHARACTERIZATION

3.1. Standard Methods For Thermal Conductivity Characterization

The standard methods of thermal conductivity characterization are described in ISO 8301 and 8302 [5] and called respectively the "heat flow meter apparatus method" and "the guarded hot plate". Both methods are not convenient for the VIP characterization because of the apparatus size constraint. Only small specimen can be measured. Because of the "skin effect", the VIP characterization shall be performed in real dimensions.

The "guarded hot box" method described in ASTM [6] is used in general to characterize building assemblies. The method uses a measurement cell in which the temperature is maintained and a test cell where a thermal flux is generated. The tested material constitutes the partition wall between the two cells. As it is described, this method cannot be used to characterize super insulation since the estimated heat loss through the test cell walls are not negligible compared to the heat flow going through the VIP. An adaptation of the method is necessary to permit the exact measurement of the VIP equivalent thermal resistance.

3.2. Adaptation Of "The Guarded Hot Box Method"

The test bench used for the VIP characterization consists of two identical cells in XPS separated by the tested panel (*figures 2a and 2b*). Each cell is equiped with an electrical heating device. The cell temperatures and the temperatures of the panel side surfaces are measured by PT100 resistive sensors.

The test is performed in two steps and the ambiance temperature is kept constant.

- A first step is needed to characterize the cell heat losses. Both cells are heated to have the same mean temperature on both surfaces of the tested panel. Since the separation wall is adiabatic, the heating power of each cell (P_{adiab}) corresponds to the cell heat loss.
- In the second step, one cell is removed and the remaining cell is heated up to the same temperature reached in the first step. In this case, the heating power (P_{spec}) is equal to the heat loss measured in the first step and to the heat flow passing through the tested panel.

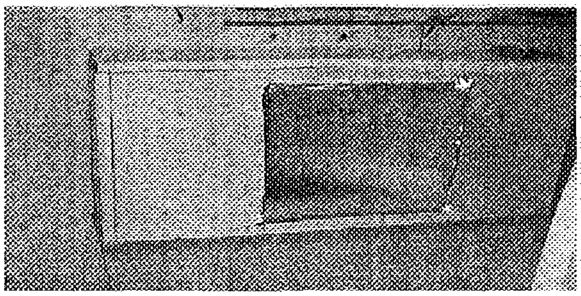

Figure 2a – Testing cell showing the VIP

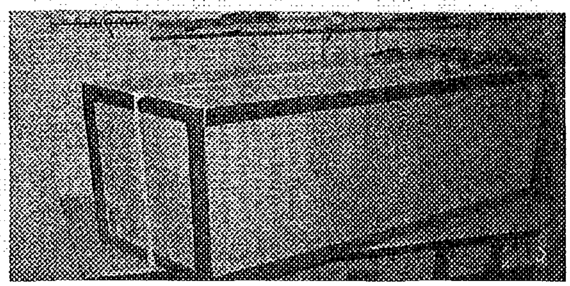

Figure 2b – Both cells closed

The difference between the two electrical powers measured in steps 1 and 2 is the heat flux that went through the tested panel. Both VIP side mean surface temperatures are measured and the geometric characteristics are known. The VIP equivalent thermal conductivity can be calculated using equation (1).

$$k = \frac{\left(P_{spec} - P_{adiab}\right)e}{A\,\Delta T} \qquad (1)$$

When the tested VIP does not fit exactly in between cells, a previously tested material is used as a frame, as shown in *figure 2a.* The heat flux (P_{frame}) passing through the frame can be calculated and equation (2) is used to calculate the VIP equivalent thermal conductivity.

$$k = \frac{\left(P_{spec} - P_{adiab} - P_{frame}\right)e}{A\,\Delta T} \qquad (2)$$

The novelty of the method consists in the measurement of the cell heat loss rather than trying to estimate or to calculate them; the first step permits this by keeping the separation wall adiabatic.

3.3. Results

The method is validated by measuring the thermal conductivity of a known material. A test is performed on RPU. Comparison between the given and measured values of the thermal conductivity is presented in the *table 1.*

Table 1 – Compared values of thermal conductivity.

Material	Measured thermal conductivity (mW/m.K)	Given thermal conductivity (mW/m.K)	Difference (%)
Usual PU	20	21	5

Measurements are performed on two types of VIP using different core material. The first is an open cell PU VIP and the second is using XPS. Temperature distribution on the VIP surface for both panels shows the existence of "the skin effect". On the VIP cold side, the lowest temperature is in the center and the highest one is located on the borders *(figure 3).*

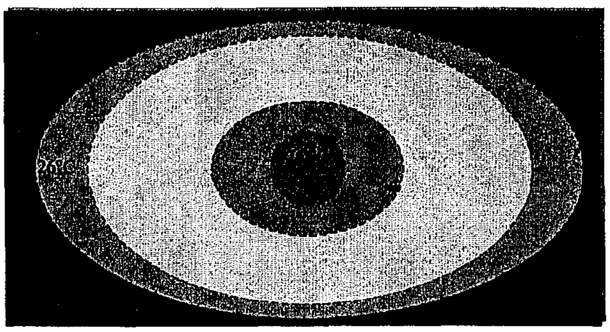

Figure 3 – Temperature distribution on the cold side of the VIP

The equivalent thermal conductivity of VIP panels and the conductivity in the center (the one measured in the center by the mean of a heat flow meter apparatus) are given in the *table 2.*

Table 2 – Equivalent thermal conductivity of the tested VIP

Core material	Dimensions (mm)	Equivalent thermal conductivity (mW/m.K)	Conductivity in the center (mW/m.K)
Open cell PU	450x450x20	12.7	9
XPS	450x450x20	9	5.5

4. EVALUATION OF VIP INTEGRATION IN A EUROPEAN UPRIGHT FREEZER

By using VIP in the insulation of a refrigerator/freezer, the energy consumption can be reduced without changing the thickness of walls. The freezer is the most advantageous model when using super insulation since the temperature difference is much higher than in a refrigerator.

4.1. Simulations of Different Integration Scenarios

A European upright freezer has been chosen for evaluation. A dynamic simulation software ENEREF® [7] (*figure 4*) is used to calculate the appliance dynamic behavior when adding VIP to the insulation. The reference is simulated and results are compared to the measured annual consumption measured and the specific cabinet heat loss (*table 3*).

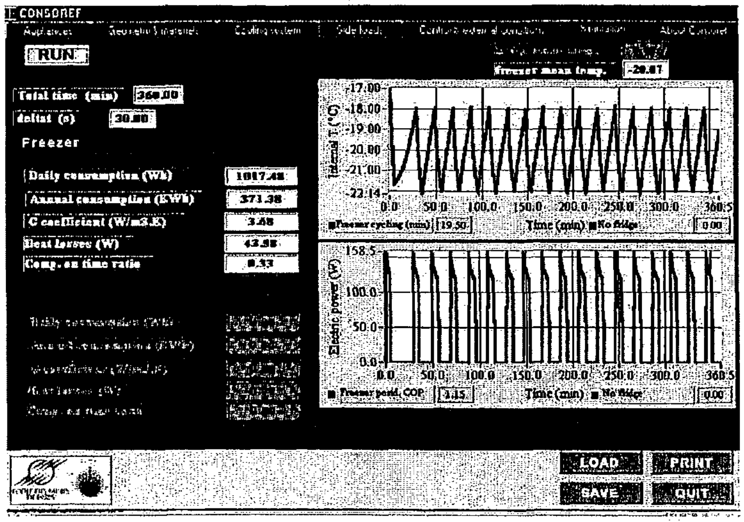

Figure 4 - ENEREF® output screen.

Table 3 – Reference simulation.

	Measured	Calculated	Difference
Energy consumption (kWh/an)	535	502	6 %
G ($W/m^3.K$)	4.73	4.82	2 %

Differences are acceptable and the simulation is validated for the reference. The modification of the reference permits to estimate the VIP integration impact in one wall or more. The appliance used can integrate VIP in the door, the top and partially in the side walls because of the compressor niche. In order to maintain the mechanical rigidity of the cabinet, the VIP does not occupy all the wall thickness; the use of 60% of the thickness is a good compromise. Two walls cannot be easily modified: the back wall because of the condenser, and the bottom because of the appliance weight.

Different combinations of modifications are simulated and the results are presented in *table 4.*

Table 4 – Simulation results for different scenarios of integration.

Scenario	G ($W/m^3.K$)	COP	Energy saving (%)
Reference	4.82	1.08	-
Door only	4.5	1.1	8
Side walls only	4.25	1.1	13
Side walls and top	3.92	1.13	21
Side walls, top & door	3.68	1.15	26

Table 4 indicates that the energy saving potential of the VIP option is significant. This gain cannot be calculated using a steady state simulation of heat loss because of the strong dynamic behavior of the cycle coefficient of performance (COP). The mean COP of the cycle decreases with the compressor running time. The energy saving due to the heat loss reduction is amplified by the compressor running time reduction thus the mean cycle COP increases.

4.2 Demonstrator Realization And Experimental Results

The predictive calculations presented promising energy savings. The realization of a demonstrator permitted to confirm the results. For this purpose, the VIP location is cut out in the walls of the reference upright freezer (*figures 5a & 5b).*

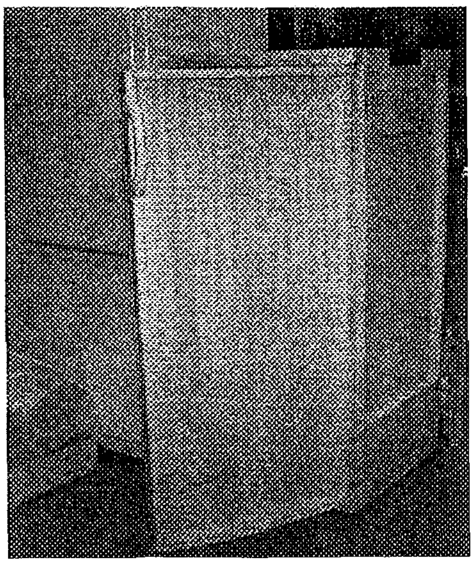

Figure 5a –VIP location

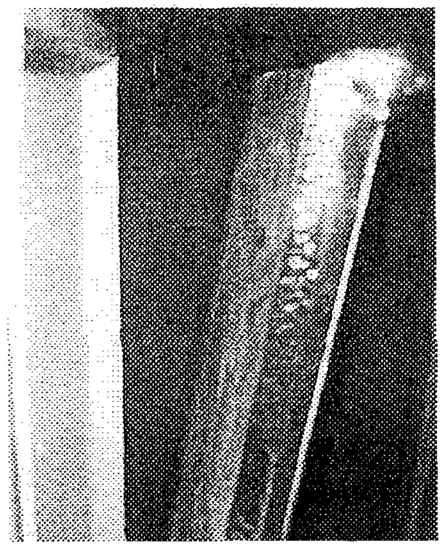

Figure 5b – Integration of VIP in a side wall

Three different integration scenarios are tested using the modified demonstrator. Test results compared to the calculations are presented in *table 5.*

Table 5 – Experimental results for three scenarios of integration.

Scenario	Measured energy saving (%)	Calculated energy saving (%)
VIP in the door	6.8 %	8 %
Door and top	8.3 %	10.3%
Door, top & one side wall	14%	-

The first and the second results are very close to calculations. The difference observed may be caused by the bad contact between the VIP and the residual RPU. This will not happen if the RPU is foamed with the VIP installed. The last scenario could not be simulated because the actual version of ENEREF® does not permit non symmetric side walls.

Validation of the first two tests allows to generalize the simulation results. The energy saving calculated is technically possible.

4.3 Life Cycle Cost Analysis

An economical evaluation of the VIP is performed in this section. The main difficulty consists in the evaluation of the over cost. Two approaches are available.

For both approaches, assumptions are as follows.

- Appliance lifetime: 15 years,
- Discount rate: 5% and
- Electricity price: 0.55 FF/kWh (which is the price in France).

The first approach is proposed by AHAM [8]. It considers a material over cost of 15$/m^2 and an investment over cost of 10$/unit. The life cycle cost analysis based on this approach is performed and results are given in *table 6.*

Table 6 – Life cycle cost analysis (first approach).

Description	Purchase price	Purchase price diff.	Energy consumption	Energy saving	Life cycle cost	Payback period
	FF	FF	kWh/an	(%)	FF	(Year)
Reference	3000	0	502	0	5866	0
Door	3136	136	462	8	5774	7,6
Side walls	3162	162	439	13	5667	5,45
Door and top	3232	232	398	21	5504	4,65
Door, top &side walls	3259	259	371	26	5377	4,06

With this approach, the payback period is acceptable and the VIP option seems to be viable.

The second approach is more conservative. It is proposed by CECED to be used in the European project SAVE II. The proposition is to increase the manufacturing cost with an additional value of 15$/m^2 for the use of VIP. When applying the usual margins, this over cost becomes 45$/m^2 added to the purchase price. The calculations corresponding to this assumption are given in *table 7.*

Table 7 – Life cycle cost analysis (second approach).

Description	Purchase price	Purchase price diff.	Energy consumption	Energy saving	Life cycle cost	Payback period
	FF	FF	kWh/an	(%)	FF	(Year)
Reference	3000	0	502	0	5866	0
Door	3216	216	462	8	5853	13.83
Side walls	3302	302	439	13	5808	11.73
Door and top	3518	518	398	21	5790	12.36
Door, top &side walls	3596	596	371	26	5714	10.94

By using this assumption, the payback periods have doubled. This assumption allows to judge that the VIP option is not viable.

5. CONCLUSION

In this paper, the new method presented to characterize thermal resistance of VIP allows to have real data to be used in predictive calculations. These data are used to evaluate VIP technology in a European freezer. The calculated energy savings are significant (about 26%) for a coverage of 4 walls. With appropriate design a higher coverage may be possible and thus more energy savings.

Two opposite economical approaches are used to calculate the payback period. The two assumptions can lead to contradictory conclusions. The first approach considers the VIP option as viable but the second rejects it. The VIP technology allows to reduce energy consumption without changing the appliance geometry, which is a real advantage compared to options like increasing wall thickness.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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