Advances in Thermal Insulation of Extruded Polystyrene Foams

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SUMMARY

Since their discovery in the early 40's extruded polystyrene foams (XPS) have been produced with various organic and inorganic blowing agents, and are now widely used as thermal insulators in building and construction. Blowing agent regulations have forced foam suppliers to look for new polymer - blowing agent - additive combinations. These must deliver high performance insulation, but must not compromise on high mechanical strength, foam integrity, and moisture resistance.

This paper focuses on the thermal resistance of XPS blown with zero-ODP blowing agent (hydrofluorocarbon HFC-134a) and with carbon dioxide. IR-blockers such as carbon black and graphite reduce the thermal conductivity of CO_2 blown XPS between 1 and 3×10^{-3} W/m.K depending on the concentration of IR-attenuators. Properties of a new XPS product using CO_2 with IR blockers are presented. This product is CE certified and fulfills the requirements of the European XPS product standard DIN EN 13164.

1. INTRODUCTION

The consumption of energy in residential and tertiary buildings accounts for more than 40% of the European energy consumption on a monetary basis, and more than 20% of total European CO_2 emissions. Buildings built during

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1940-1975 have the highest consumption of energy (heating, ventilation and cooling HVAC), typically 250 kWh/m^2/yr or more [1].

Improvements in energy efficiency [1] would lead to:

- Reduction of carbon dioxide emissions: in EU, the savings could be up to 460 MM tons/yr, which is more than EU's Kyoto commitment
- Significant cost saving: it is estimated to be >200 Billion Euros per year in EU at a barrel price of $70. With the current barrel price of > $100, the impact could be >250 Billion Euros a year
- Improvement in Energy Efficiency in buildings can lead to a creation/ preservation of 530,000 full time jobs for the entire period of the renovation cycle of 30 years

There are several ways to reduce the greenhouse gas emissions, and the most effective solution is the improvement of the building insulation [2]. Indeed, Enkvist et al. have compared all options to reduce the greenhouse emission and the two most effective ways are improvement of building insulation and fuel efficiency in commercial vehicles. These measures applied to roof and wall insulation can cut this energy use in half and save the EU the equivalent of 3.3 million barrels of oil per day [1].

These initiatives have been incorporated in the European "Energy Performance of Buildings Directive" (EPBD). The objective of the EPBD is to promote the improvement of the energy performance of buildings taking into account outdoor climatic and local conditions as well as indoor climate requirements and cost-effectiveness. The initial measures were initiated in 2002 and were implemented in the EU in January 2006. They were recently amended in May 2010 [3] (EPBD-2) with a more demanding building energy performance and a more aggressive time line [3].

New buildings or major renovations have to comply with the minimum energy requirement as set by the new EPBD-2 and the need for a better insulating material is obvious. Furthermore, as the lifetime of the building in Europe can be 50 years or more, it is desirable to have an insulator offering both excellent performance and durability.

There is quite a large range of thermal insulation materials, ranging from inorganic to organic, especially cellular plastics, offering the insulating performance from 0.020 W/m.K (like barrier polyurethane/ polyisocyanurate PUR/PIR foams) up to 0.045 W/m.K (loose mineral wool or cellulose fibers).

Among these insulating products, extruded polystyrene foam (XPS) specifically meets both the insulating performance and durability requirement. Using a depressurized foaming process, the foam presents a perfect regular closed cell structure, high mechanical properties, outstanding creep resistance, and no dust. It is non-friable, non corrosive, and offers very good resistance to water vapor and condensation. The long-term performance and its durability have been documented in a large number of reports from EU institutes such as CSTB and FIW. Some foam samples were taken from a roof, built in 1978, and after 24 years of service. The foam thermal conductivity was very good and showed no deviation from its long-term design value (0.028 W/m.K). Analysis of the foam showed no absorption of water nor deterioration of mechanical properties or creep resistance [4].

Extruded polystyrene foam is different compared to expandable polystyrene foam (EPS) in which the beads are thermally fused and typically exhibit an interstitial space in which the water vapour can condense and affect thermal insulating performance. Today, XPS has an important market share of the insulation of the buildings (more than 200 million m^2 in Europe) and is expected to enjoy higher growth thanks to its long-term performance and durability.

Historically, XPS was produced with insulating blowing agents chlorofluorocarbons (CFC) and hydrochlorofluoro-carbons (HCFC) and presented very good long-term insulating performance [5]. Due to their Ozone Depletion Potential (ODP), these gases were regulated by the Montreal protocol, and were completely phased out in developed countries. In Europe, CFC and HCFC have been banned from use since 1996 and 2001 respectively, and in North America, HCFC phase out was completed in January 2010.

Replacement of CFC and HCFC by CO_2, CO_2/ethanol (EtOH) or HFC-152a as primary blowing agents has resulted in a deterioration of thermal performance. The thermal conductivity of XPS, increased from its historical range of 0.026-0.028 W/m.K to 0.034 W/m.K, and even as high as 0.040 W/m.K as indicated in some commercial brochures.

These blowing agent changes have lead to a need for an improved thermal insulating performing XPS, that can be easily used or applied in buildings without having issues with water absorption, friability, corrosion. They have to comply with the zero ODP, low GWP requirements and building fire regulations, and also have the necessary mechanical properties and long-term durability.

This article describes the advances in thermal insulation technology for XPS which will help to fulfill the thermal requirement as needed by EPBD-2 while using environmentally sustainable blowing agents.

2. EXPERIMENTAL DESCRIPTION

Styrofoam™ extruded polystyrene foam (XPS) is produced using Dow proprietary foaming technology. The base polystyrene resin employed has a base molecular weight ranging between 150 and 200 kg/mol.

The characteristics of key blowing agents used for XPS are described in **Table 1**.

Table 1. Characteristics of key blowing agents for XPS

Substance	Mw, g-mol	λ-value[a] W/m.K 10^{-3}	ODP	GWP	LEL, %
HCFC-142b	100.5	11.7	0.065	2310[b]	7.8 – 15.5
HFC-134a	102.0	13.5	0	1430[b]	NF
HFC-152a	66.1	12.6	0	124[b]	3.7 – 20
CO_2	44.0	16.5	0	1	NF
Ethanol	46.0	14.4	0	1	3.3 – 19
isobutane	58.1	16.6	0	4[b]	1.8 – 8.4
pentane	72.1	14.8	0	11[c]	1.4 – 7.8

(a): Values at 25°C, Matheson Gas Data book, 2001
(b): IPCC/TEAP-2006 report
(c): Polyurethane and Related Foams: Chemistry and Technology, K.Ashida, p.30, 2007

Inorganic additives such as carbon black and graphite can serve as attenuators to IR radiation thereby reducing thermal conductivity of XPS foam products. Characteristics of these additives are presented in **Table 2**.

Table 2. Characteristics of IR-attenuators

Type	Particle Size, nm	Surface Area, m^2/g
Thermal Black	250 - 300	7
Graphite Ultra Fine	3000 - 6000	20

Thermal conductivity is measured using a Fox LaserComp heat flow meter at an average temperature of 10°C. The long-term thermal conductivity is determined according to the standard EN-13164. It is an accelerated aging process applied for extruded polystyrene foams. It consists of slicing the foam product into several thin layers of 10mm and aging the thin layers for a period of 30 to 90 days, depending on the original thickness. After this accelerated aging period, the foams are stacked again and the thermal conductivity is determined. The measured λ value corresponds to an aging period of 25 years, according to the standard.

The fire retardancy test is also conducted for some products using the German B2 test method (DIN 4105) and the European Class-E method (EN-13164).

3. EFFECTS OF INSULATING GASES

As previously described [5], thermal conductivity of a cellular foam composes of four contributions factors:

Conduction through Solid phase - λ_s

Conduction through Gas phase - λ_g

Radiation energy transfer - λ_r

Convective heat transfer - λ_c

$$\lambda = \lambda_s + \lambda_g + \lambda_r + \lambda_c \qquad (1)$$

In the case of the extruded polystyrene foam where the cell size is small (<4 mm), the convection component of total thermal conductivity is negligible ($\lambda_c \sim 0$).

To reduce the conduction heat transfer, one can reduce the conduction through the solid or through the gas phase. For solid conduction, the lower the foam density, the lower the solid heat conduction. This solid heat transfer accounts for about 10% of the thermal conductivity in typical XPS foams.

Gas conduction accounts for about 60 to 70% of the thermal conductivity. When blowing XPS foam with CO_2 or CO_2/Ethanol (CO_2/EtOH), all these gases will diffuse out quickly and the air diffuses in. After a short curing time, all cells will contain only air and the thermal conductivity of air is 0.025 W/m.K at T_m=10°C.

One way to reduce the gas conductivity is to reduce the pore size to below the mean free path of air (70 nm), so that the air molecules will not collide with each other and consequently minimize kinetic energy and subsequent heat transfer (i.e., Knudsen effect). Conduction through the gas phase is thereby significantly reduced and in accordance with the following equation:

$$\lambda_g = \lambda_{g,o} \frac{(1-\phi_s)}{1+\beta \frac{T}{P_g D_{pore}}} \qquad (2)$$

where:

φ_s: solid fraction

β: Knudsen coefficient

P_g: gas pressure

D_{pore}: cell pore diameter

λ_g and $\lambda_{g,o}$: thermal conductivity of the gas mixture and at atmospheric pressure

There are many current research activities in industry and academia which aim to reduce the pore size of cellular plastics. When the pore size is smaller than 100 nm, for example like aerogel [6] or xerogel [7], a material with a thermal conductivity of about 0.022 – 0.025 W/m.K was obtained. The products usually have a high density (>150 kg/m^3) and the product is quite fragile, having a low resistance to compression. Their use in buildings is not yet developed, due to high cost and non-standard application techniques owing in part to its poor and/or atypical mechanical properties. This approach is still under development and does not appear to be commercially available within the next few years, except for niche applications.

Another route to improve the performance of thermal insulation is to use insulating blowing agents with sustainable environmental properties. The blowing agents should at a minimum be zero ODP. Furthermore, to qualify a blowing agent as insulating gas, the thermal conductivity of the gas should be as low as possible and its diffusion coefficient should be below 1×10^{-9} cm^2/sec in order to ensure the long-term XPS insulation performance over a period of 25 to 50 years.

Key properties of insulating and non insulating gases through polystyrene are shown in **Table 3**.

Table 3. Effective diffusion coefficient of key blowing agents through PS

Substance	Thermal Conductivity	Effective Diffusivity
	W/m.K 10^{-3}	10^{-10} cm^2/s
HCFC-142b	11.7	6.0
HFC-134a	13.5	8.5
HFC-152a	12.6	255
CO_2	16.5	40700
Ethanol (EtOH)	14.4	5260
isobutane (iC4)	16.6	5.7
iso-pentane (iC5)	14.8	34.1

Initially, the only gases in the cell are the blowing agents such as carbon dioxide and co-blowing agents. With aging, the blowing agent diffuses out of the foam while the air diffuses inwards into the foam. The gas diffusion follows Fick's second law as shown below:

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2} \qquad (3)$$

where:

C: gas concentration

t: aging time

D_{eff}: Effective diffusion coefficient

x: foam thickness

The lower the diffusion coefficient, the better the long-term insulation performance. HFC-134a, HCFC-142b and iC4 have similar diffusivity, while the HFC-152a diffuses out of the foam about 30 times faster, and EtOH, CO_2 diffuse at about 100 to 500 times faster respectively. The residual concentration can be computed from diffusion calculations, and **Figure 1** shows a graph that illustrates the respective half-life times (residual concentration is 50% of the initial feeding) for the considered blowing agents.

The graph applies for a very thin foam, 25 mm thickness. When increasing the thickness to 100 mm, the diffusion is reduced by a squared factor and

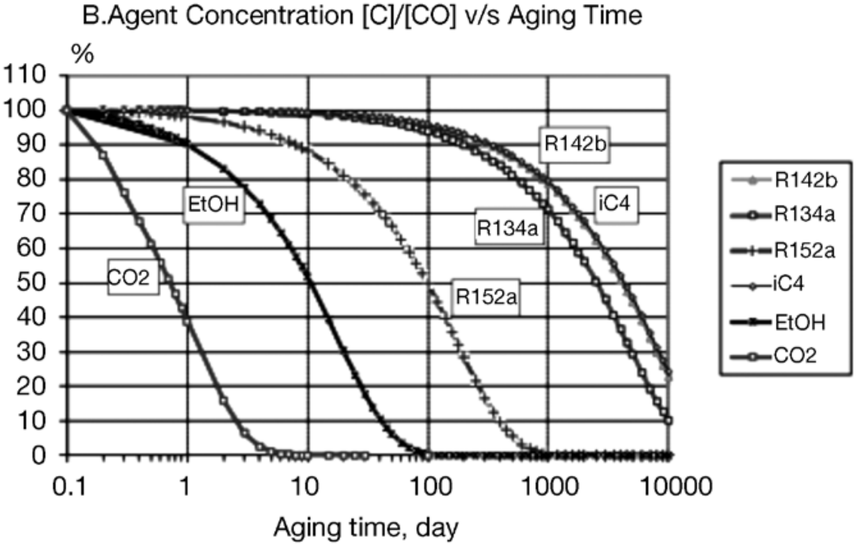

Figure 1. *Residual concentration as function of aging time (25 mm foam thickness)*

the half-life time of the insulating gases HFC-134a, HCFC-142b or iC4 can be increased from 25 years to more than 50 or 75 years.

The thermal conductivity of the gas phase depends on the concentration of insulating gases. The λ value of a blend of air and blowing agents can be calculated using the Wassijewa equation.

$$\lambda_g = \sum_{i=1}^{n} \left(\frac{x_i}{\sum_{j=1}^{n} x_j A_{ij}} \right) \cdot \lambda_i \tag{4}$$

x_i: mole fraction component i at time t

λ_i: thermal conductivity of gas i at mean temperature T

A_{ij}: interaction parameter

A_{ij} can be calculated with the Mason-Saxena equation. It can also be calculated with the Lindsay-Bromley equations using gas viscosity data. There is no noticeable difference between both methods. For the non polar gas mixture, the Mason-Saxena relation is recommended to be used.

In the case that the cell contains only air and insulating gases, like HFC-134a, the equation (4) can be expressed as:

$$\lambda_g = x_{134a}\lambda_{134a} + x_{air}\lambda_{air} \tag{5}$$

Figure 2 shows clearly the impact of concentration of insulating gas to the conduction through the gas phase.

Hydrocarbons (HC) like butane can also help to offer the long-term insulting performance, and low levels can be safely employed and still satisfy key XPS performance requirements. However, excessive concentrations of HC can create an additional risk for the customers during the application and use. When testing foams containing high amounts (>3 wt%) of butane and propane according to the German B2 fire test, the flame height reaches the maximum limit and the foams continue to burn significantly when a flame or a static discharge gets in contact with the foam. Consequently, it is desirable to use the insulating gases having zero or low flammability.

To meet the required long-term performance, one solution is to use HFC-134a with concentrations of at least 6% of the total feed, similar to the HCFC-142b used previously for making high performing insulating XPS foams.

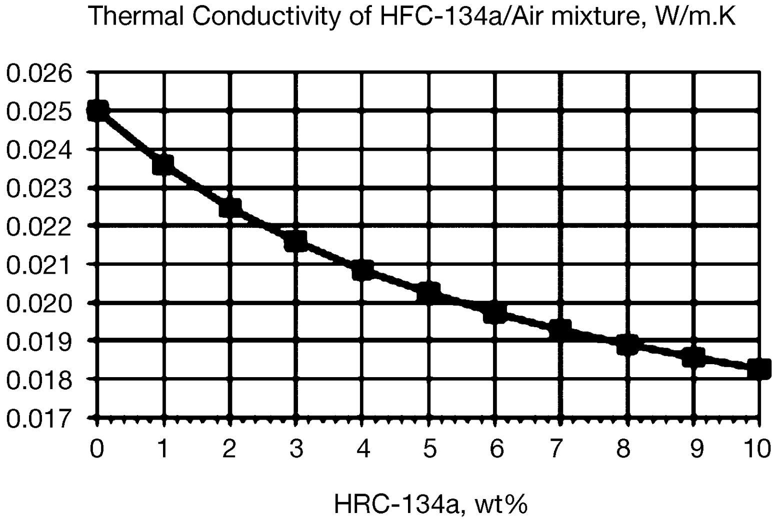

***Figure 2**. Thermal conductivity of gas mixture as function of HFC-134a%*

Not all XPS foaming technologies are capable of using high concentrations of HFC-134a. The Dow proprietary technology enables the use of relatively high amounts of HFC-134a, greater than 6 wt% and in some cases more than 8.5 wt% [8]. With this, the insulation performance of Dow Styrofoam-X is projected to be maintained, based on product thickness, for at least the next 50-75 years, which offers a significant reduction of energy consumption and greenhouse gas reduction if used as building insulation.

Figure 3 presents the long-term thermal insulation values obtained from accelerated aging technique, as defined by the EN-13164 standard. This technique offers an estimation of the performance equivalent to about 25 years aging. A majority of Styrofoam-X yields a thermal conductivity of less than 0.029 W/m.K which makes it an attractive thermal insulation material from a building-life cycle perspective.

Conventional foam processing technology based on tandem extrusion can also use HFC-134a for making XPS foam, however, the concentration is limited. It usually has to be used in combination with HFC-152a in order to achieve a reasonably low foam density. Data obtained during the period 2006-2010 showed that commercial XPS produced with HFC-134a/HFC-152a or HFC-152a also offer an improved insulating performance versus CO_2, although the long-term performance is not nearly as good as the ones produced at Dow, using high concentrations of HFC-134a.

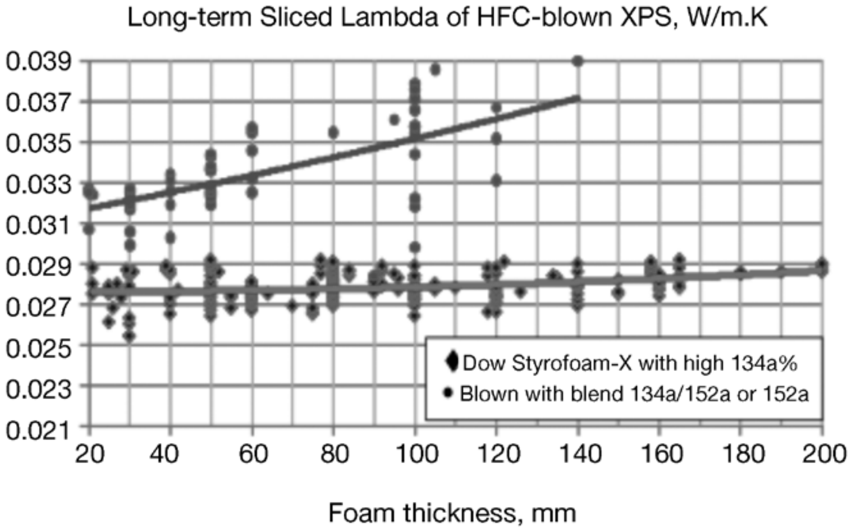

Figure 3. *Measured sliced λ-values obtained with HFC-134a and with 134a/152a or 152a*

An alternative approach is to modify the polystyrene matrix and to induce a certain polarity, such as PS-co-AN which enables the use of even higher concentrations of insulating HFC-134a [8]. This resulted in both short-term and long-term outstanding thermal performance, and approximates the λ-value of materials such as PUR foams or Phenolic products, as previously described in [8].

4. EFFECT OF IR-ATTENUATORS ON RADIATIVE HEAT TRANSFER

The radiative heat transfer takes approximately 20 to 30% of the thermal conductivity and it does not change with time. It is defined with the Rosseland approximation [9] as below:

$$\lambda_r = \frac{16\sigma_S T_m^3}{3\beta_R} \qquad (6)$$

σ_S: Stefan-Boltzmann constant, $\sigma_S = 57.6\times10^{-9}$ W/m²K⁴

β_R: Rosseland average extinction coefficient, depends on resin refractive index, mass distribution in the cell structure, porosity and foam thickness

T_m: mean temperature

The Rosseland average extinction coefficient can be calculated with the Placido equation [10], Glicksman et al. [11] or Campo-Arnáiz et al. [12] equations.

In the previous work, it was demonstrated that for polystyrene foam, the optimum range of cell size is between 120 – 180 µm [13]. This optimum cell size reflects both the transmission and scattering properties through the polystyrene cell walls and struts. Smaller cell sizes will lead to a significant increase of the radiative conductivity, as material becomes more transparent to IR, in contrast to the previous models like the one established by Glicksman et al. [9]. Hemispherical reflectance and transmittance measurements were made and confirmed the results from the total thermal conductivity measurements [13] (**Figure 4**).

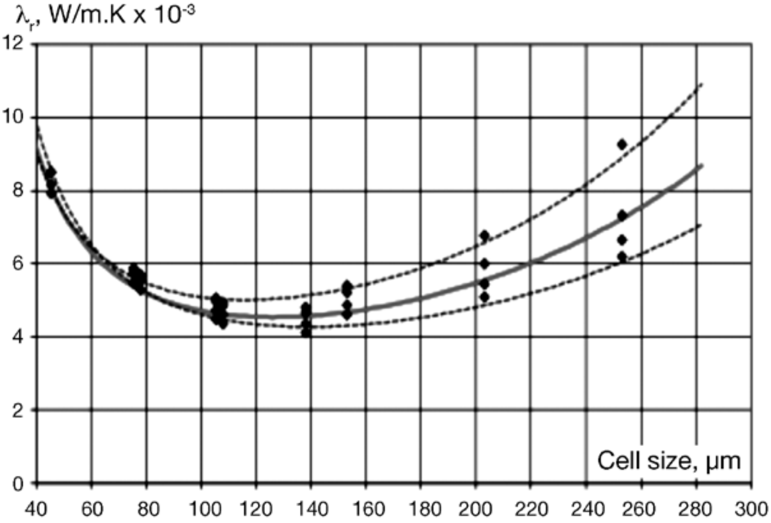

***Figure 4**. Optimum cell size for extruded polystyrene foam*

Another route to reduce radiative heat transfer is to increase the coefficient of extinction through addition of IR-attenuators.

Attempts to use materials such as carbon black and/or graphite are not new. In 1948, McIntyre, utilized TiO_2, Carbon Black and Aluminum powder to improve the thermal insulation performance of extruded polystyrene foam [14]. Aluminum and TiO_2 reduce the IR transmission by increasing reflection whereas carbon black and graphite reduce transmission due to scattering and absorption.

In this article, we present the development of the new insulating product, produced with CO_2 as a key blowing agent and containing various amounts of IR-attenuators, as indicated in **Table 2**.

Carbon black or Graphite was added into the formulation, at concentrations ranging between 0.5 and 10 wt%. Foams produced have a similar density, between 34 and 40 kg/m^3, and a cell size ranging from 300 μm to 100 μm. Higher IR-attenuator levels result in smaller cell size due to nucleation potentials. Addition of these IR-blockers helps to absorb/reflect IR and to increase the extinction coefficient of the foam, hence reduces λ_r.

Cell morphology can be seen in **Figures 5** to **7**, for the control foam, 5% carbon black and 3% graphite respectively.

The SEM pictures employ a material contrast imaging analysis technique. The white spots correspond to the brominated fire retardant used in the XPS process. The granular lines are the carbon black or graphite, and the optical microscopy confirms very good distribution of carbon black and graphite in the cell wall and the cell struts. Furthermore, the graphite with its platelet-shape is well aligned in the cell direction and generally completely encapsulated by the resin. This helps to enhance a higher reflection compared to the carbon black. However, the SEM picture in **Figure 7** shows some holes as open cell wall, due to lack of material during foam expansion. The % of open cell is increased with a high loading of graphite. This adversely affects both the conduction and radiative properties exhibited by the material.

The long-term thermal conductivity was measured and the variation in thermal conductivity as function of the IR-attenuators can be subsequently calculated.

The morphological factors such as cell size, polymer mass distribution in the cell and other additives could affect this radiative property. In order to fully evaluate the effect of IR-attenuator on radiative heat transfer, the conduction through solid and gas phases has to be considered.

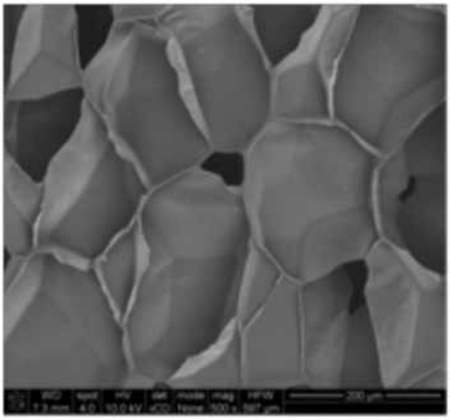

***Figure 5**. Cell morphology of control XPS*

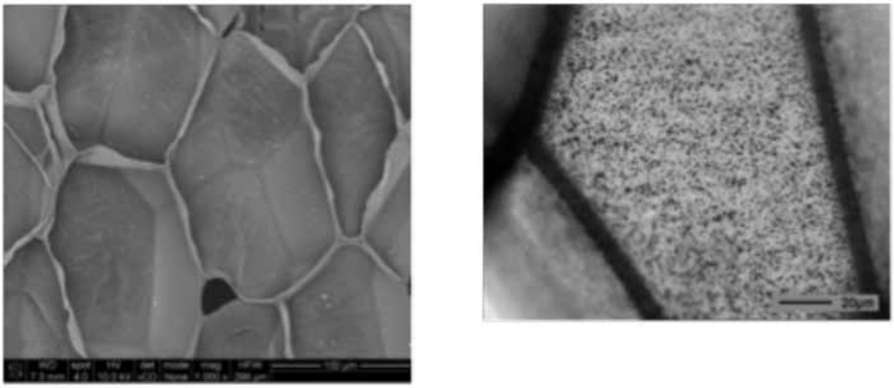

***Figure 6**. Cell morphology of XPS containing 5% thermal black (SEM and Optical Microscopy)*

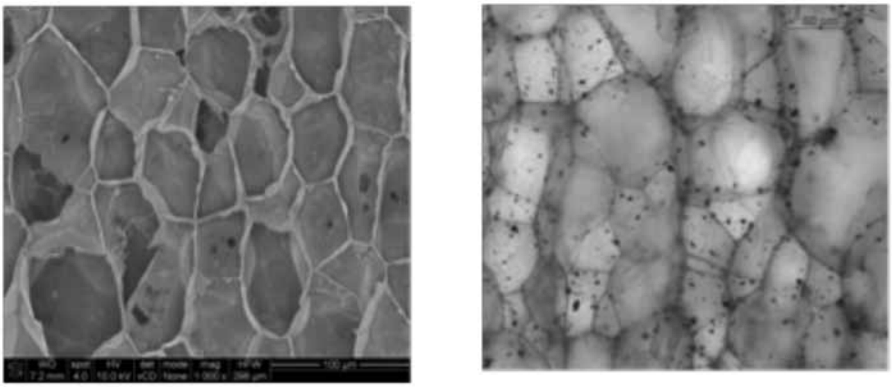

***Figure 7**. Cell morphology of XPS containing 3% graphite (SEM and Optical Microscopy)*

The heat transfer from solid conduction (λ_s) can be calculated with the equations below:

$$\lambda_s = \phi_s \left(\frac{1}{3} f_{strut} + \frac{2}{3} f_{face} \right) \lambda_P \qquad (7)$$

In the case that the majority of polymer resides in the face like extruded polystyrene foam, the above equation can be assimilated as:

$$\lambda_s = \left(\frac{2}{3} \frac{\rho_f}{\rho_p} \right) \lambda_P \qquad (8)$$

where:

ρ_f and ρ_p : density of foam and of polymer

Φ_s: solid fraction in the foam (ρ_f/ρ_p)

f_{strut} and f_{face}: fraction of polymer in the strut and in the face respectively

λ_P: thermal conductivity of polymer, function of temperature

In the case of significant cellular anisotropy, the impact of distribution of polymer in one direction could influence the solid conduction, and for this, a modification of equation (8) is needed.

The thermal conductivity of polystyrene [15] can be calculated using the equation below:

$$\lambda_P = 0.147 + 0.000124 \cdot (T - 273.15) \ \text{(W/m.K)} \qquad (9)$$

The intrinsic thermal conductivity of carbon black and graphite are very high and their high concentration can affect the thermal conductivity of the blend. It can be computed using the inverse mixing rule [16] as below:

$$\frac{1}{\lambda} = \frac{f_1}{\lambda_1} + \frac{f_2}{\lambda_2} \qquad (10)$$

where: f_1 and f_2 are volume fraction of polymer and additive respectively.

The density of polystyrene is about 1.05 g/cm³, while density of carbon black and graphite is 1.6-3.5 g/cm³. The thermal conductivity of carbon black (thermal black or furnace black) is between 15.6-27.7 W/m.K and the one of Graphite fine structure is 117.6 W/m.K [17].

Addition of 1 to 10% by weight of carbon black or graphite respectively will increase the thermal conductivity of the solid blend from 0.144 W/m.K. to 0.154 W/m.K. This value is small but does affect the overall performance of the product.

Subtracting the solid and gas conduction, one can estimate the change in radiative heat transfer function of carbon black and graphite. The results are presented in **Figure 8**. Graphite offers a slightly better IR attenuation, due to its multiple functions of absorption and reflection, however thermal carbon black is also shown to be effective, as addition of 5% of carbon black helps to reduce the radiative conductivity by more than 2.5 mW/m.K.

Certain elements of the technologies discussed herein have been scaled up to production for making the new XPS XENERGY™ grade that contains IR-attenuators. The foaming process technology employs supercritical CO_2

and small amount of other co-blowing agents. Foams with a thickness from 30 to 120 mm were produced and the long-term thermal conductivity was measured. As can be seen in **Figure 9**, most data yielded a thermal conductivity ≤ 0.030 W/m.K, which represents an improvement of more than 20% versus conventional XPS blown with CO_2 or CO_2/EtOH.

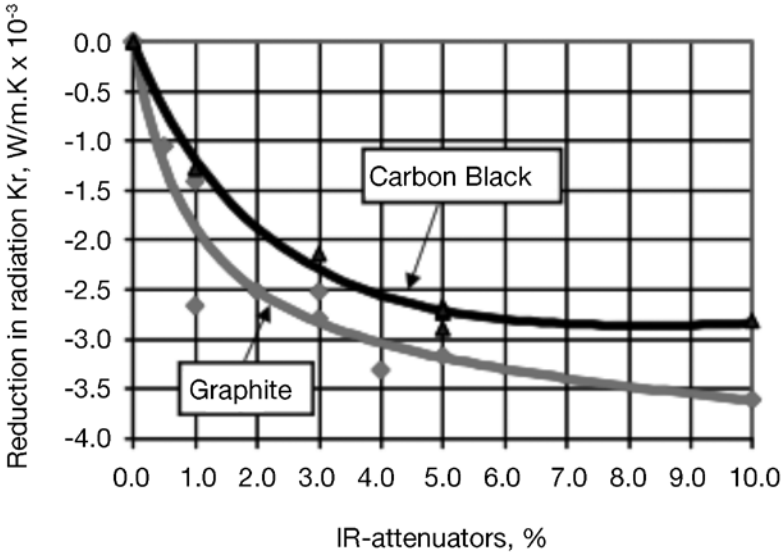

***Figure 8**. Effect of IR attenuators on Kr*

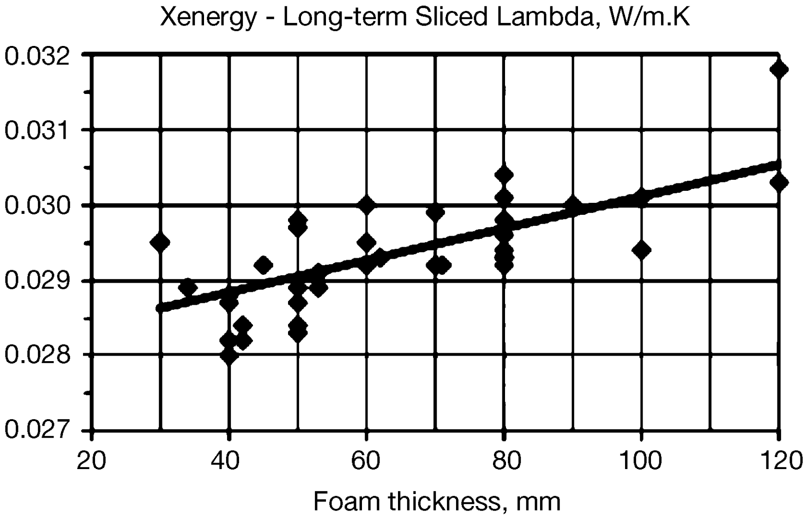

***Figure 9**. Long-term thermal conductivity of XENERGY™ products*

5. LARGE SCALE APPLICATIONS

This new Dow CO2-based XPS grade containing IR attenuators is sold in Europe under the trade name of XENERGY™ [18]. The product is CE certified and fulfills the requirements of the European XPS product standard DIN EN 13164. All properties relevant for the targeted applications must be met as described in DIN 4108-10. **Table 4** is listing the key properties of XENERGY™.

Table 4. Properties of XENERGY™ products

Property	Class. acc. to DIN EN 13164	XENERGY[a]	unit
Thermal conductivity			
60 mm	λ D	0.031	W/m.K
80 mm	λ D	0.031	W/m.K
100 mm	λ D	0.032	W/m.K
120 mm	λ D	0.032	W/m.K
Compressive strength DIN EN 826	CS(10\Y)300	≥ 300	kPa
Compressive creep DIN EN 1606	CC(2/1.5/50) 110	110	kPa
Water pick-up after diffusion DIN EN 12088	WD(V)3	60 mm: ≤ 2.7 120 mm: ≤ 1.3	Vol-%
Water pick-up after freeze/thaw DIN EN 12091	FT2	≤ 1.0	Vol-%
Fire resistance	E	Euro class E	
[a]: *Product with extrusion skin*			

Perimeter insulation of basement walls and floors requires high mechanical resistance and low water pick-up to assure its performance over the entire life span of buildings in a moist environment. Water pick-up after diffusion and freeze-thaw cycling must be measured according to DIN EN 12091.

Figure 10 describes the test in principle. After loading up the sample with water vapor in the diffusion chamber, the product is subjected to 300 freeze/thaw cycles. The additional water pick-up is less than 1 vol% [19].

Basement insulation today requires a U-value of 0.30 W/(m^2.K) to meet the current EnEV2009. With the improved XPS this is achieved with 100 mm insulation thickness, compared to 120 mm of CO_2 blown XPS. This represents a 17% reduction in material for this example, which is a significant contribution towards improved sustainability. It is anticipated that by year 2020 all new buildings in Europe must fulfill an even higher demanding quasi zero energy standard. The application of 2 layers of 100 mm of the newly developed XPS results in a U-value of 0.15 W/(m^2.K) that would meet such a standard. **Figure 11** shows application of XPS foam board on a basement wall.

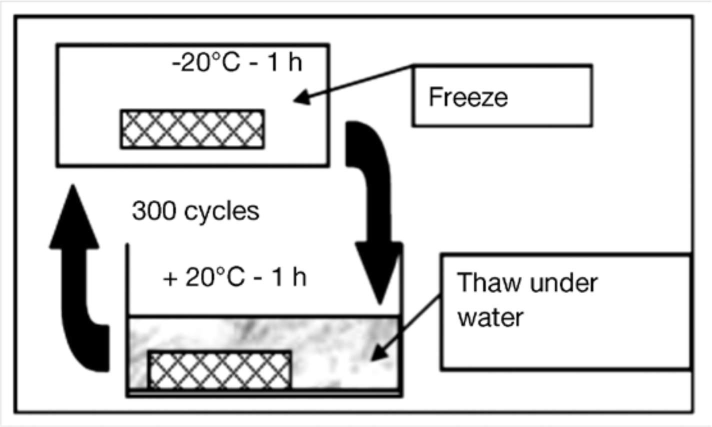

Figure 10. *Freeze-thaw-cycle phases according to EN 12091*

Figure 11. *Application of XPS insulation boards on a basement wall*

6. CONCLUSIONS

Thermal conductivity of extruded polystyrene foams can be significantly improved, by the optimization of cell gas conduction and/or by the reduction of radiative heat transfer. This improvement must not adversely affect other critical properties of XPS such as mechanical properties, water resistance, creep performance, fire retardancy compliance and durability.

The use of high concentrations of low or non-flammable insulating blowing agent is required to ensure the long-term performance of extruded polystyrene foams. The zero ODP HFC-134a yield the best thermal performance compared to other insulating substances. Blends of HFC-134a and HFC-152a cannot achieve the low lambda values demonstrated in products blown with HFC-134a such as Styrofoam-X™.

Addition of IR-attenuators offers a sustainable improvement of thermal insulation for non-HFC foams. Graphite is demonstrated to be slightly better than carbon black, although both materials enable a reduction of 1 to 3 $\times 10^{-3}$ W/m.K, depending on the concentration of the additive employed. Short and long-term physical properties of CO_2-blown extruded polystyrene foams containing IR-attenuators are fulfilling the requirements for low energy or passive houses.

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REFERENCES

1. *Energy Efficiency, Climate Change and Insulation*, Source: Eurima.org

2. Per-Anders Enkvist, Tomas Nauclér, and Jerker Rosander, "*A cost curve for greenhouse gas reduction, A cost curve for greenhouse gas reduction*", McKinsey Study, Feb 2007.

3. Directive 2010/31/EU, European Parliament of the Council, "*Energy performance of buildings*", 19 May 2010.

4. C. Gueret, P. Dussaux, and W. Georges, CSTB Report HO 02-025, April 10, 2002.

5. C. Vo and A. Paquet, "An Evaluation of the Thermal Conductivity of Extruded Polystyrene Foam Blown with HFC-134a or HCFC-142b", ***J. Cel. Plas***, **40**, (May 2004) 205-228,

6. R.W. Pekala, C.T. Alviso, X. Lu, J. Gross, and J. Fricke, "New organic aerogels based upon a phenolic-furfural reaction", *J. Non-Cryst. Solids*, **188**, (1995) 34-40.

7. A. Rigacci, J.C. Maréchal, M. Repoux, M. Moreno, and P. Achard, "Preparation of polyurethane-based aerogels and xerogels for thermal superinsulation", *J. Non-Cryst. Solids*, **350**, (2004) 372–378.

8. S. Costeux, C. Vo, and L. Hood, "Long term performance of Insulating Foams", *Foams 2010 SPE Conference*, Seattle, Sept-2010

9. L.R. Glicksman, M.A. Schuetz, and M. Sinofsky, "Radiation heat transfer in foam insulation", *Int. J. Heat Mass Transfer*, **30(1) (**1987) 187–197.

10. E. Placido and M.C. Arduini-Schuster and J. Kuhn, " Thermal properties predictive model for insulating foams", *Infrared Physics and Technology*, **46** (2005) 219-231.

11. L.R. Glicksman and M. Mozgowiee and M. Torpey, "Radiation heat transfer in foam insulation", *Proceedings of the Ninth International Heat Transfer Conference*, Jerusalem, pages 379-384, 1990.

12. R.A. Campo-Arnáiz and M.A. Rodríguez-Pérez and B. Calvo and J.A. de Saja, "Extinction coefficient of polyolefin foams", *J. of Pol Sci Part B: Polymer Physics*, **43** (2005) 1608-1617.

13. A. Kaemmerlen, C. Vo, F. Asllanaj, G. Jeandel, and D. Baillis, " Radiative properties of extruded polystyrene foams: Predictive model and experimental results", *Journal of Quantitative Spectroscopy & Radiative Transfer*, **111** (2010) 865–877.

14. O.R. McIntire and R.N. Kennedy, "Styrofoam for Low Temperature Insulation", *Chemical Engineering Process*, **44** (1948) 727-730.

15. E. Moore, Styrene polymers, *Encyclopedia of Polymer Science and Engineering*, **16** (1989) 113.

16. H. Lobo and C. Cohen, "Measurement of Thermal Conductivity of Polymer Melts by the Line-Source Method", *Polym. Eng. Sci*., **30(2)** (1990) 65-70.

17. Handbook of Tables for Applied Engineering Services, 2nd edition, page 180

18. XENERGY Data, http://www.dowxenergy.eu/eu/deu/de/

19. F. Bunge and H. Merkel, " Polystyrol-Extruderschaum mit verbesserten wärmetechnischenEigenschaften – Entwicklung,Prüfung und Anwendung", *Bauphysik*, 67–72, February 2011.