Gas-Filled Panels for Building Applications: A State-of-the-Art Review

Ruben Baetens [a,b], Bjørn Petter Jelle [a,c,*], Arild Gustavsen [d] and Steinar Grynning [a]

[a] Department of Materials and Structures, SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway.

[b] Department of Civil Engineering, Catholic University of Leuven (KUL), B-3001 Heverlee, Belgium.

[c] Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.

[d] Department of Architectural Design, History and Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.

* Corresponding author: bjorn.petter.jelle@sintef.no, tel. +47 73 593377, fax +47 73 593380.

Abstract

With their thermal conductivity down to 10 mW/(mK), gas-filled panels (GFPs) are regarded as possible high performance thermal insulating solutions for building applications. However, thermal conductivities of respectively 46 and 40 mW/(mK) have so far been achieved for prototype air-filled and argon-filled panels, values slightly higher than currently traditional building insulation materials. Compared to other high performance thermal insulation materials and solutions, e.g. vacuum insulation panels (VIPs), the future of GFPs may therefore be questioned. Nevertheless, the application of a low-conductive gas and reflective barriers may have a potential in the development of new high performance thermal insulation materials. Within this work, a state-of-the-art review is given on the knowledge of GFPs for building applications today.

Keywords: Gas-filled panel, GFP, High performance thermal insulation material, Building application, State-of-the-art, Review.

Contents

1. Introduction

Since the European Union decided to reduce their greenhouse gas emission by accepting the Kyoto-protocol of the UNFCCC - United Nations Framework Convention on Climatic Change in 1997, many serious steps have been taken. A promise was made that emissions 8 % lower as the levels in 1990 would be reached in 2008-2012 and levels 20 % lower in 2020 (United Nations 1998).

In 1999, the total energy consumption in Europe was 1 780 million tons of oil equivalent, for which 35 % was used in the residential and commercial sector. It became clear that reducing the heat losses of buildings or in general the total energy consumption of buildings can have a major impact on the total greenhouse gas emissions in Europe. Traditional insulation materials were and are being used in thicker or multiple layers which resulted in more complex building details, an adverse net-to-gross floor area and possible heavier load bearing constructions. But simultaneously, a second strategy won interest. It became clear that *air as an insulator had reached his limit* (Thorsell 2006) and that there was a need to research and develop high performance thermal insulation materials and solutions.

Gas-filled panels (GFPs), as shown in Fig.1., are one of these new promising high performance thermal insulating solutions for building applications. Gas-filled panels are experimental and only limited commercial products are available so far (Coldpack 2009, Fi-Foil 2009). Most of the work carried out on GFPs in available literature is performed by Griffith and co-workers at Lawrence Berkeley National Laboratory (LBNL), e.g. Arasteh et al. 1990, Griffith et al. 1993, Koomey et al. 1994 and Walker & Guillot 2003, which is also depicted in the references of this review. In fact, some of the references cover refrigerator applications (Kruck & Cur 1990, Griffth & Arasteh 1995, Griffith et al. 1995b) and do not actually cover GFPs as applied in the building envelope.

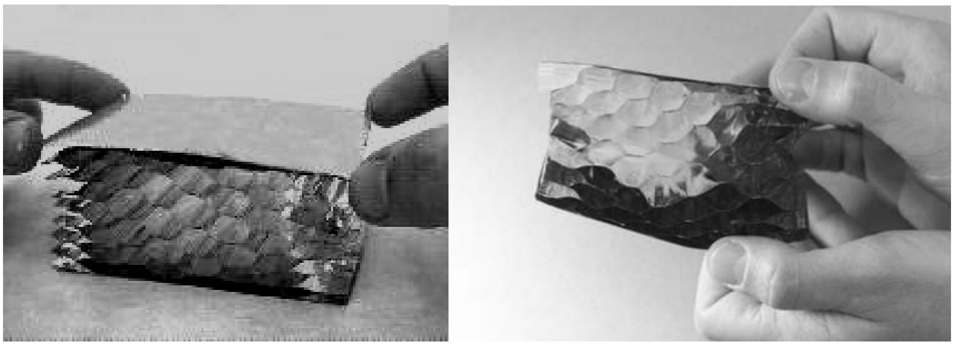

Fig.1. View on the barrier foil and the baffle structure inside a gas-filled insulation panel (LBNL 2008).

2. Gas-filled panels

Gas-filled panels (GFPs) consist of a barrier envelope and a gas between reflective layers (a baffle). The gas can be air or a heavier gas to decrease thermal advection and conduction. A low-emissivity barrier envelope is used to enclose the gas and to decrease the heat transfer due to radiation, while a low-emissivity baffle structure is included to decrease inner gas convection and radiation. As a result, both flexible and stiff GFPs are possible.

2.1. The gas

The thermal conduction through the gas is the most important heat transfer mechanism in a GFP. High performance GFPs use gases which have a lower thermal conductivity than air, or air itself [see Table 1]. Two general rules can be expressed to explain a lower thermal conductivity of a GFP: *(i)* A gas with a higher molecular weight will have a lower thermal conductivity, while *(ii)* mono-atomic (i.e. a noble) gases will have a minor thermal conductivity compared to polyatomic gases with the same molecular weight. The reason for this second rule is an extra factor of energy transfer for polyatomic gases due to possible rotation and vibration of the polyatomic gas molecules.

The heat flux through a gas will not equal its still-gas thermal conductivity. Possible convection of the gas and the conditions of the gas-containing volume have to be considered to come to the effective thermal conductivity of the gas.

However, not only the thermal conductivity of the gas is of importance for applications in GFPs: The gases should not be one of the greenhouse gases, i.e. gases in the atmosphere which absorb and emit radiation in the infrared spectrum such as CO_2, CH_4, N_2O and O_3, they should be stable and the production of the gases should be relatively environmental friendly. The gases may not condense at temperatures within the ambient temperature range, they may not be toxic and not be flammable. Potential gases are expressed in Table 1with their ideal still-gas thermal conductivity, i.e. their potential minimum thermal conductivity when applied in GFPs, and an approximated gas cost (Griffith & Arasteh 1992). Most attention is paid to the potential of GFPs with the inert noble gases argon (Ar), krypton (Kr) and xenon (Xe) as gas-fill because these gases can be extracted from the atmosphere and as consequence have a global warming potential (GWP) of zero.

Table 1**.** Ideal still-gas thermal conductivity at 25°C of gases, i.e. their potential thermal conductivity applied in GFPs and cost estimates of the gases (Griffith & Arasteh 1992).

	Air	Ar	CO_2	N_2O	CF_4	SF_6	CFC-12[1]	HFC-134a[2]	HCFC-22[3]	Kr	Xe

[1] The use of chlorofluorocarbon CFC-12 and of CFCs in general is forbidden since 1996 because of their negative effect on the earth's ozone layer. It is estimated that CFC-12 has a global warming potential (GWP) of 8 500 (compared to CO_2) over a time span of 20 years.

[2] Hydrofluorocarbon HFC-134a is the preferred alternative to CFC-12 for refrigerants. However, HFC-134a has a GWP estimated at 3 400 over a time span of 20 years whereby the use of it is under increased international supervision.

[3] Hydrochlorofluorocarbon HCFC-22 has an ozone depletion potential (ODP) of 0.11 meaning that it only destroys 11 % compared to the common CFC-12, but it has still a GWP estimated at 1 800 over a time span of 20 years whereby it is phased out in 2004 under the Clean Air Act.

Ideal still-gas λ_g, mW/(mK)	26.2	17.8	16.6	16.2	16.0	14.0	9.4	14.0	11.0	9.4	5.6
Approximated gas cost, \$/m³	0	1.27	4.24	10.6	170	63.5	42.4	170	16.9	50 8	9 500

2.2. The structure of GFPs: 'Barriers' and 'Baffles'

Gas-filled panels are made of two types of polymer films: *(i)* Metallized films are used in a tied assembly called 'the baffle' which produces a cellular structure in the panel whereby convection and radiation is suppressed, while *(ii)* a low-diffusive gas-barrier foil is used in a hermetic envelope that maintains the panels inner gas-fill [see Fig.1]. Depending on the type of foils used for the structure, these panels can be made both stiff or flexible insulation panels. As result of this structure, the total panel will have a thermal conductivity close to the still-gas thermal conductivity of the fill.

2.2.1. The gas barrier

The barrier is a hermetically sealed enclosure to maintain the gas-fill and a critical component for the GFPs. The foil will have to act as an effective gas barrier in two directions: Moisture and air gases are driven into the panel, while the gas-fill is driven out of the panel. The quality of GFP barriers will be quantified by their gas transmission rate for which a distinction will be made for each type of gas because of the specific gas content of the panel. The most common gas transmission rates defined for GFPs are the O_2TR and N_2TR for air, the ArTR and the KrTR (m³/(day·atm)) reflecting to the respective gas types.

A gas loss of 0.1 $_{vol}$%/yr is acceptable for GFPs, which results in an acceptable air concentration of 2 % after 20 years, although longer lifetimes might be more appropriate for building insulation. The corresponding change of thermal conductivity can than be estimated based on the change of still-gas thermal conductivity, which is approximately the volume-weighted linear sum of the thermal conductivities of the gas mixture components.

Within this limitation, a variety of films and foil configurations are commercially available. A first group includes all foils for vacuum applications with very thin layers of aluminium such as in Vacuum Insulation Panels (VIPs). A second group is polymer barrier resins, including ethylene vinyl alcohol (EVOH), polyvinylidene chloride (PVdC) and polyvinyl alcohol (PVOH). EVOH is available with an ethylene content between 26 % and 48 % but a ethylene content as low as possible will be aimed at to achieve a greater gas barrier, however a low ethylene content will it make sensitive to moisture and difficult to fabricate. In general, multilayer films will be used to meet the demands: An EVOH-based film could have a structure nylon | adhesive | EVOH | adhesive | EVOH | adhesive | PE while a PVOH-based film may consist of PE | adhesive | PVdC | oriented PVOH | PVdC | adhesive | PE. This last film is reported to have an O_2TR of 10^{-9} m³/(day·atm) (Griffith & Arasteh 1992), which is 10 times better than required for GFPs. Also the EVOH foils achieve the required properties for applications in GFPs, but they have a much lower O_2TR compared to the PVA-based films.

Although, these values are very promising, nothing is known about the long-term applications of these films and several climate factors can age building materials and building components. These climate factors may be divided into ultraviolet, visible and near infrared solar radiation, ambient infrared heat radiation, temperature changes or freezing/thawing cycles, water (e.g. moisture, relative air humidity, rain and wind-driven rain), wind, erosion, pollutions, micro-organisms, oxygen and time determining the effect for all the previous mentioned factors to work (Jelle et al. 2008). The ageing factors on polymer degradation are divided in four main groups (Thorsell 2006): The chemical environment, thermal shocks, ultraviolet light and high energy radiation. However, the real effect of chemicals and radiation on GFPs is unknown. Some of these factors might also not be relevant for GFP entirely enclosed by other building materials within a wall assembly.

Furthermore, accelerated ageing of the envelope material by high temperatures and damaging by mechanical loads is worth mentioning. These mechanical loads can be a nail penetrating the envelope or a worker stepping on the GFPs on the construction site without any visible damage. A GFP is such a fragile material that one has to assume proper and careful handling at both the manufacturing and construction site. The best way to ensure safe handling would be to never allow the bare GFPs at the construction site but supplying them integrated into more durable building components (Thorsell 2006).

2.2.2. The baffle

The baffles are necessary to suppress convection and radiation. Compartmenting by constructing the baffle out of a solid material minimizes the convective heat transport of the gas. For this gas compartmentalizing, thin sheets are assembled in a three-dimensional form of multiple layers of cavities. The radiation heat transfer is decreased by using low-emissivity cavity surfaces, which are inexpensive and available as metallized thin polymer films. Most of them have an aluminium coating from vacuum techniques with a thickness between $5 \cdot 10^{-8}$ and $5 \cdot 10^{-9}$ m (Griffith & Arasteh 1992) and an emissivity of approximately 0.04.

The solid conduction due to the baffles is minimized by using solid conduction paths that are relatively long compared to the panel thickness. The geometry of the baffles can vary strongly, but hexagonal baffles are most interesting because they are easy to produce. The dimensions of the foil and the formed cavities are selected to minimize the gas convection in these cavities, to reduce the solid conduction and to minimize the economic cost. There is an optimal number of baffle layers (Griffith et al. 199a) to use in a GFP with its specific thickness, gas fill and temperature difference regarding the economic cost and the thermal performance.

3. Effective thermal conductivity of gas-filled panels

3.1. Analytical model

A simplified one-dimensional model for the effective thermal conductivity of gas-filled panels is proposed by calculating the heat flux through a gas-filled cavity in a one-layer baffle assembly subjected to a temperature difference (Griffith et al. 1993). The cavity and heat fluxes used for this model are schematized in Fig.2. The heat flux across the cavity is then calculated as

$$q_{2,3} = q_r + q_{cd} + q_g + q_{cv} \qquad [2.1]$$

See below for a definition of the various heat fluxes. The heat flux is driven by an overall temperature difference ΔT_{hc} between the two outer surfaces at T_{hot} and T_{cold}, a temperature difference ΔT_{23} across the baffle cavity between the two surfaces at T_2 and T_3 and a mean temperature T_{mean}. In the heat flux calculations, three different components are treated separately: The baffle layers, the gas and the core support foils between the baffle layers.

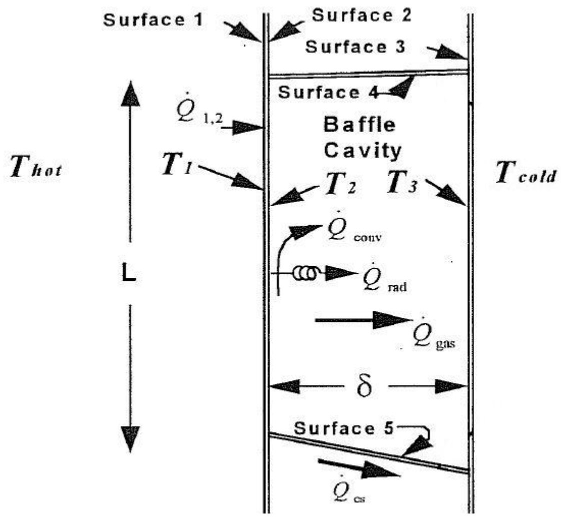

Fig.2. Cavity geometry for the heat flux calculation in the simplified model for the effective thermal conductivity of gas-filled panels (Griffith et al. 1993).

An assumption is made that both sides of the baffle have the same temperature, i.e. T_1 equals T_2. The radiative heat transfer across the cavity can be calculated with the Stefan-Boltzman law for two infinite planes, assuming that the support foils have no influence on the radiation (Griffith et al. 1993):

$$q_r = \frac{A_{cavity}\sigma}{\frac{1}{\varepsilon_2}+\frac{1}{\varepsilon_3}}\left[(T_3+\Delta T_{23})^4-(T_3)^4\right] \qquad [2.2]$$

where A_{cavity} is the product between the cavity length L and unit width, σ the Stefan-Boltzmann constant and ε_1, ε_2 the emissivities of the respective surfaces. However, for this equation, the cavity length L is assumed to be much greater than the characteristic cavity gap width δ, which is not valid for the prototype GFPs. Foils used for baffle constructions in GFPs have a typically emissivity of 0.04.

The heat flux through the gas is modelled as the sum of the heat flux due to conduction and the heat flux due to convection: The gas conduction can be derived from $\lambda_g A_{cs}\Delta T_{23}/\delta_{cs}$ with λ_g the still-gas thermal conductivity of the fill-gas, while an additional heat flux due to transport of gas in the cavity has to be included in the model, defined as an heat flux due to convection q_{cv}:

$$q_{cv} = q_g Nu \qquad [2.3]$$

where Nu is the dimensionless Nusselt number defining the ratio between convective heat transfer and conductive heat transfer q_g. Griffith et al. 1993 used this equation for Nu:

$$Nu = \left[0.825+\frac{0.387(\Pr Gr)^{1/6}}{\left(1+(0.492/\Pr)^{9/16}\right)^{8/27}}\right]^2\left(\frac{\log(L/\delta)+0.53}{1.35}\right) \qquad [2.4]$$

$$\Pr = \frac{\mu_g c_g}{\lambda_g} \text{ and } Gr = \frac{g\beta^* \Delta T_{23}\delta^3}{\nu^2} \text{ with } \beta^* = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T_g}\right)_{p_g} \quad [2.5]$$

where L the cavity length as for free convection from a vertical plate, Pr the Prandtl number defining the ratio between the kinematic viscosity and the thermal diffusivity on a vertical plate (modified in Eq.2.4 with the logarithmic for the increased heat flux due to convection), where the Grasshof number Gr defines the ratio between buoyancy and the kinematic viscosity for a gap width δ and a characteristic length and where μ_g (sPa) is the viscosity of the fill-gas, c_g the specific heat of the fill-gas, g the standard gravity, β^* (K^{-1}) the volumetric thermal expansion coefficient, ν (m^2/s) the kinematic viscosity and for which subscript p_g stands for a constant gas pressure. The notion that convection is suppressed in cavities with a gap-width smaller than certain thresholds depending on the gas is not supported in the model for the heat flux through GFPs. Infrared pictures of prototype GFPs (Griffith et al. 1993) show that convection will even appear in gap widths of 6 mm.

The heat flux due to solid conduction via the core support foils between the baffle layers is calculated as $\lambda_{cs}A_{cs}\Delta T_{23}/\delta_{cs}$ in the proposed model, where λ_{cs} is the thermal conductivity of the core support foils, A_{cs} the conduction surface and δ_{cs} the length of the core support.

Here, it becomes clear that the model proposed by Griffith et al. (1993), which is the only analytical model on the effective thermal conductivity found in literature, is a very simplified model. Two remarks can be made: Firstly, the physical model as proposed in Fig.2 is very simplified compared to effective current baffle structure as shown in Fig.1. Secondly, the prediction of the heat transfer due to conduction of the solid foils and due to radiation is too simplified for an accurate prediction of the overall thermal performance of the GFP. When heat transport through gas conduction is suppressed by a low conductivity gas and by the baffle structure, radiation and solid conduction become more important factors of heat conduction in the GFPs. As a result, the simplifications made for the solid conduction and radiation will mean a low accuracy of the model: By comparing the results of the model with experimental results (Griffith et al. 1993), a precision less than 10 % is noticed for the model.

More accurate models can be used for the radiation and convection heat transfer within GFPs, in order to achieve more realistic and better results. Computational Fluid Dynamic (CFD) simulations are also possible to get more accurate predictions of the effective thermal conductivity of the panels.

3.2. The effective thermal conductivity

As can be concluded from the analytical model of Griffith et al. (1993), the effective thermal conductivity (as well as the manufacturing cost) of GFPs will depend on the number of cavities, on the baffle thickness, on the thermal conductivity of the foil material and on the gas type. The influences of these parameters on the effective thermal conductivity are expressed in Fig.3 based on the calculation model. Also adapting the emissivity of the inner surfaces influences the effective thermal conductivity: Calculations in the same paper show that using cavity emissivities of 0.04 instead of the typical 0.9 of an opaque surface can decrease the effective thermal conductivity up to 35 % for air-filled GFPs and up to 65 % for krypton-filled GFPs.

Heat-flow meter apparatus measurements on prototype GFPs (Griffith et al. 1993, 1995a) and numerical simulations with THERM (Griffith et al. 1995a) show an effective apparent (optimized) thermal conductivity of 28 mW/(mK) for air-filled panels, 20 mW/(mK) for argon-filled panels and 12 mW/(mK) for krypton-filled panels. These measurements were carried out at a mean temperature of 23.9 ± 0.5°C and with a temperature difference of approximately 22.2°C. However, it must be noted that for lower temperatures, a reduced thermal conductivity will be noticed due to a lower thermal conductivity of the gas-fill on lower temperatures which is strongly dependent on the temperature.

It was shown that the gas fill, the baffle material, the amount of baffles and the barrier material determinate the effective thermal conductivity of GFPs, but the same factors also determine the marginal cost of the manufacturing. A model on this marginal cost is given by Griffith et al. (1993). The costs used in the model are very simplified and are only meant to provide information on optimizing the design of the GFPs. Two analysis are made: *(i)* a study is made of the sensitivity of the costs on the barrier component and *(ii)* an analysis is made for the complete panel assuming one single type of barrier envelope. The results of the model were presented as cost per unit of thermal resistance per square meter ($m^2K\$/(W/m^2)$).

Most interesting is the result of the second analysis on the complete panel as plotted in Fig. 4. The results show that a strong optimization can be performed on GFPs by adapting the number of cavities to minimize the specific cost. Note in Fig.3 that increasing the number of cavities has a major effect on the effective thermal conductivity of the insulation panels, but also strongly influences the marginal costs. A table with the optimum number of cavities can be made, resulting in an economical optimum effective thermal conductivity of GFPs (see Table 2).

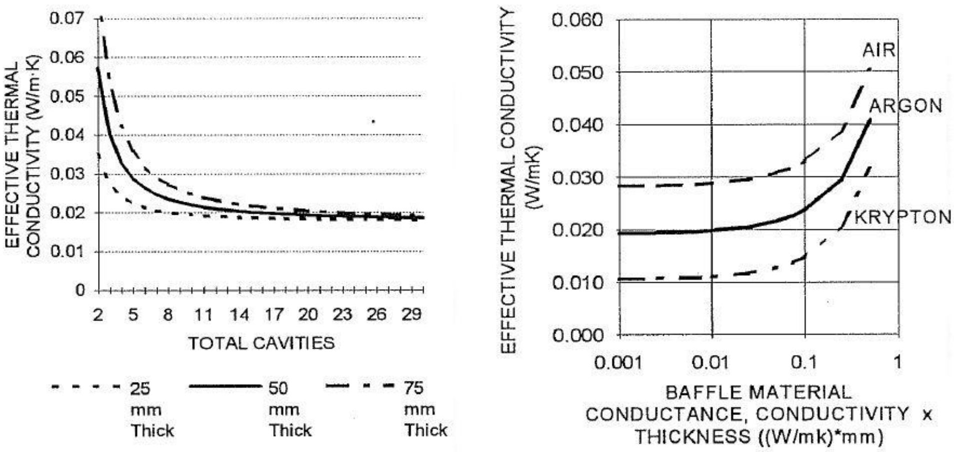

Fig.3. [left] Effective thermal conductivity λ_{eff} (W/(mK)) of an Argon-filled GFP as function of the number of cavities and the thickness of the baffles. A cavity length of 50 mm and a 0.0178 mm thick core support foil is assumed with a thermal conductivity of 0.36 W/(mK) and an emissivity of 0.04 and 0.25 (Griffith et al. 1993). [right] Effective thermal conductivity λ_{eff} (W/(mK)) of GFPs as function of the number of the foil type. A characteristic cavity length of 50 mm is assumed, 50 mm thick with a total of 15 cavities and with an emissivity of 0.04 for every cavity surfaces (Griffith et al. 1993).

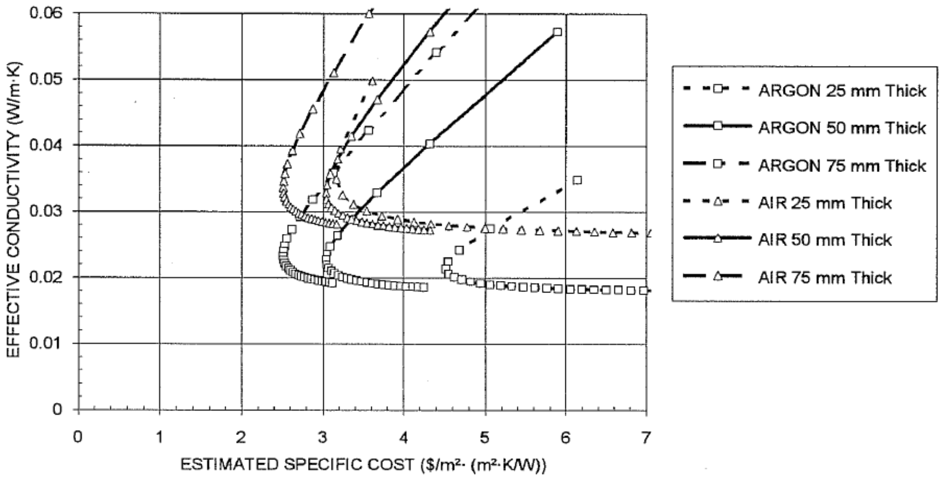

Fig. 4. Effective thermal conductivity of air-filled and argon-filled insulation panels versus the estimated cost for flexible GFPs of 25, 50 and 75 mm (Griffith et al. 1993).

Table 2. Optimum number of cavities with their effective thermal conductivity, based on the lowest marginal cost of the fabrication of the gas-filled panels (Griffith et al. 1993).

		Air	Argon	Krypton	
	gas cost	0.00 \$/l	0.002 \$/l	0.30 \$/l	0.50 \$/l
25 mm GFP	optimum cavities	4	6	12	13
	λ_e (W/(mK))	0.0350	0.0213	0.0106	0.0103
	cost (\$/m²)	2.26	5.30	12.22	21.54
50 mm GFP	optimum cavities	6	9	20	24
	λ_e (W/(mK))	0.0380	0.0226	0.0106	0.0104
	cost (\$/m²)	3.02	6.70	26.81	39.46

3.3. Effective thermal performance of applied GFPs in constructions

Measurements and simulations on the thermal performance of applied GFPs are done for building construction applications (Griffith et al. 1995a, Yarbrough et al. 2007) and for other applications in refrigerators, as duct insulation and as insulation for cryogenic vessels (Griffith et al. 1995b, Walker & Guillot 2003, Mills & Zeller 2008). Only the test results on GFPs as building insulation will be discussed.

GFPs in wood-frame walls are studied (Griffith et al. 1995a) based on numerical simulations with THERM. The study compares the thermal values of argon-filled panels insulated cavities and mineral wool insulated cavities between studs. The simulations show that argon-filled panels could offer a possibility to achieve higher thermal performances of building envelopes: The simulation show improvements of 50 up to 100 % compared to the classic mineral wool insulated cavities. However, it consists here only of a simplified THERM analysis with simplified thermal behaviour of the GFPs and nothing is so far known on the hygric behaviour and service life of GFPs in such applications.

Compared to Griffith et al. (1995a), more significance may be given to the study by Yarbrough et al. (2007) see Fig.5. Here, some tests are designed to test GFPs as a radiant barrier in attics on full-scale. Three comparative tests were performed in the Large-Scale Climate Simulator at *Oak Ridge National Laboratory* (Tennessee, USA) at both winter and summer climatic conditions: One attic insulation system with conventional fibreglass in the attic floor, a second system with air-filled panels and radiant barrier on top of the fibreglass and at last a third system with argon-filled panels and radiant barrier on top of the fibreglass in the attic floor. Such large-scale tests are necessary because three factors will contribute to the thermal performance of the system: *(i)* the thermal resistance of the GFP improves the thermal performance, *(ii)* the reduction of heat flux due to the attic radiant barrier has his influence and *(iii)* the change in the operating temperature of the attic floor influences the overall thermal performance.

The used GFPs in the tests had a thermal conductivity of 46 mW/(mK) for the air-filled panels and 40 mW/(mK) at 23.9°C for argon-filled panels. The small difference between both values is due to a higher content of solid material in the argon-filled panels, partly compensating the higher thermal performance of the argon-fill. The average thermal resistance of the entire air volume of the attic was 0.22 m²K/W under winter conditions and an average of 0.31 m²K/W under summer conditions for measurements that included simulated solar input.

Fig.5. The tested attic construction [left] with only the fibreglass batts between wooden beams and without roof shelter and [right] a view in the attic construction when the GFPs with the attic radiant barrier are installed (Yarbrough et al. 2007).

As starting insulation, 89 mm fibreglass was used between the wooden beams, resulting in a winter thermal resistance of 2.20 m²K/W and a summer thermal resistance of 1.90 m²K/W, resulting in an increase in thermal conductivity of the mineral wool with increasing temperature. For the test, first a layer of air-filled panels with a thickness of 46 mm was added on top of the fibreglass and second, a layer of argon-filled panels with a thickness of 41 mm was added. The result of this improvement can be noticed in Table 3. The conclusions made in the study can be summarized as follows: The installation of the GFPs on top of the fibreglass layer resulted in a drop of the operating temperature of the fibreglass batts in the summer simulations, resulting in an increase of thermal resistance of 0.1 m²K/W of the fibreglass batts. The thermal resistance of the attic air space above the GFPs increased with an average of 1.06 m²K/W for summer conditions. The overall increase of thermal resistance of the attic was determined at 2.17 m²K/W for the simulated summer conditions and 0.88 m²K/W for the simulated winter conditions (see Table 3).

However, two remarks must be made here: *(i)* the retrieved improvements due to the GFPs are remarkably high, having in mind the rather poor achieved thermal conductivities of 40 mW/(mK) or higher and *(ii)* no difference is found in the results between the air-filled and argon-filled panels. The reason for both remarks may be found in the first fibreglass-insulated model to which one compares the performances of the GFP-insulated attic: The model for the attic is not airtight whereas GFPs and hereby also the GFP-insulated attics are. The largest thermal improvements are achieved by eliminating air convection through the attic and by the temperature drop due to the GFP radiation barrier instead of the thermal performance of the gas itself, which might explain simultaneously that no difference is noticed in the results retrieved for the air-filled and argon-filled panels. Having this in mind, the true value of gas-filled insulation panels for the building sector may be questioned because more economic solutions could produce the same effect.

Table 3. Thermal resistances R (m^2K/W) of the attic before and after the improvements with air-filled and argon-filled panels (Yarbrough et al. 2007).

		summer conditions R (m^2K/W)	**winter conditions** R (m^2K/W)
Fibreglass between beams	88.9 mm	1.90	2.20
with air-filled panel on top	+ 45.7 mm	4.37	3.33
with argon-filled panel on top	+ 40.6 mm	4.35	3.36

4. Other high performance thermal building insulating materials and solutions

Other state-of-the-art thermal insulation solutions do exist. In principle close to GFPs is the technology of vacuum insulated panels (VIPs) (Baetens et al. 2010), studied extensively at IEA/ECBCS Annex 32 (Binz et al. 2005, Heinemann et al. 2005, Simmler et al. 2005) among others.

Compared to GFPs, VIPs apply a vacuum instead of a low-conductive gas to obtain high performance thermal insulating properties. However, to prevent collapsing under atmospheric pressure, a core material has to be added in the envelope, i.e. most common fumed silica. Commercial VIPs achieve an overall thermal conductivity down to 3.5 mW/(mK), which is far better than the achieved values for GFPs, but a value of 8 mW/(mK) is mostly used including thermal bridging due to the metallized envelope and ageing due to air and moisture intake. VIPs share its most important disadvantage with GFPs: Damaging the envelope brings back the thermal conductivity to that of the core material, i.e. 20 mW/(mK), still far better than traditional thermal insulation materials.

Fumed silica achieves it low thermal conductivity because of the Knudsen effect, describing the strong reduction of the gaseous conductivity if the mean free path of air is larger than the characteristic pore size of the material. The principle is used in VIPs by applying a vacuum (and as such increasing the mean free path of air), but at the same time also provides a low thermal conductivity at atmospheric pressure due the maximum pore size of 300 nm of fumed silica.

Even more, aerogels (Zeng et al. 1994) achieve an even lower thermal conductivity of 13 mW/(mK) because its characteristic pore size between 10 and 100 nm and is regarded as one of the most promising new high performance thermal insulating materials for building applications.

5. Conclusions

Theoretical values of 35, 21 and 10 mW/(mK) have been retrieved for air-filled, argon-filled and krypton-filled panels, respectively. However, thermal conductivities of 46 and 40 mW/(mK) have been achieved for prototype air-filled and argon-filled panels, respectively, i.e. values slightly higher than currently traditional building insulation materials.

As a result, although a commercial product for building applications has recently been brought on the market, the true value of gas-filled panels as high performance thermal insulation material for building applications may be questioned. The other high performance thermal insulation materials and solutions mentioned in this work seem more promising.

Nevertheless, it may be concluded that the application of a low-conductive gas may have a potential in the development of new high performance thermal insulating materials.

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