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Thermal analysis of a wooden door system with integrated vacuum insulation panels

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Abstract

A wooden door leaf with two integrated vacuum insulation panels (VIPs) was investigated both experimentally and numerically. The main goal of this study was to determine the impact of damaged vacuum insulation panels on the thermal performance of the overall door system. Since the metal fittings act as thermal bridges in a highly insulating system, special attention was given to this effect. Comparison of the measured and calculated results reported here permit assessment of the feasibility of providing a reasonably accurate prediction of these thermal effects using the finite difference method. Additionally, an infrared imaging system was used to validate the computed temperature distribution on the surface. This investigation form part of the research programme ‘‘High Performance Thermal Insulation in Buildings and Building Systems’’ of the International Energy Agency (IEA).

Keywords: Door system; Fibreboard; Vacuum insulation panels (VIP)

1. Introduction

A new generation of highly insulating materials [1,2] called vacuum insulation panels (VIP) has been developed since the beginning of this millennium. These comprise a core material of fumed silica encased in a multi-component barrier film containing at least 90 nm of aluminium (Fig. 1; Type A). The core material is vacuum-packed to minimize heat transfer by convection [3], with an opacifier powder added to reduce heat transfer by radiation. The range of VIP products (Fig. 1) provided by different manufacturers employ various barrier envelope and sealing solutions. Given the vulnerability of these thin barrier envelopes, which are subjected to a pressure difference of about one atmosphere, VIPs require special protection during construction and over the entire building lifespan. Ideally, therefore, VIP units should be covered by a protective layer, as is the case for door systems with VIPs sandwiched between door facings. The present investigation set out to determine the impact of VIPs on the overall thermal behaviour of a door system for both intact and damaged cases. For this, hot box measurements and steady-state 3D calculations have been carried out and their results compared. Research conducted by the National Association of Home Builders (NAHB) in collaboration with the US industry [4] and aimed at accelerating the adoption of vacuum insulation technology in home construction, renovation and remodelling, reported on a number of VIP applications in residential schemes—specifically floor panels, exterior doors, garage doors, ceiling panels and attic access panels or insulated attic stairs. In the case of exterior doors, it was mentioned that the reduction of thermal bridges through the lock block area and metal fittings could be a requirement to be considered. This aspect was therefore specially examined in the present study. The fact that wooden door systems with integrated VIPs are already available on the Swiss market, chiefly for incorporation in low-energy houses, provided an additional incentive for this study. Further investigations dealing with the service life of VIPs have been published elsewhere [5].

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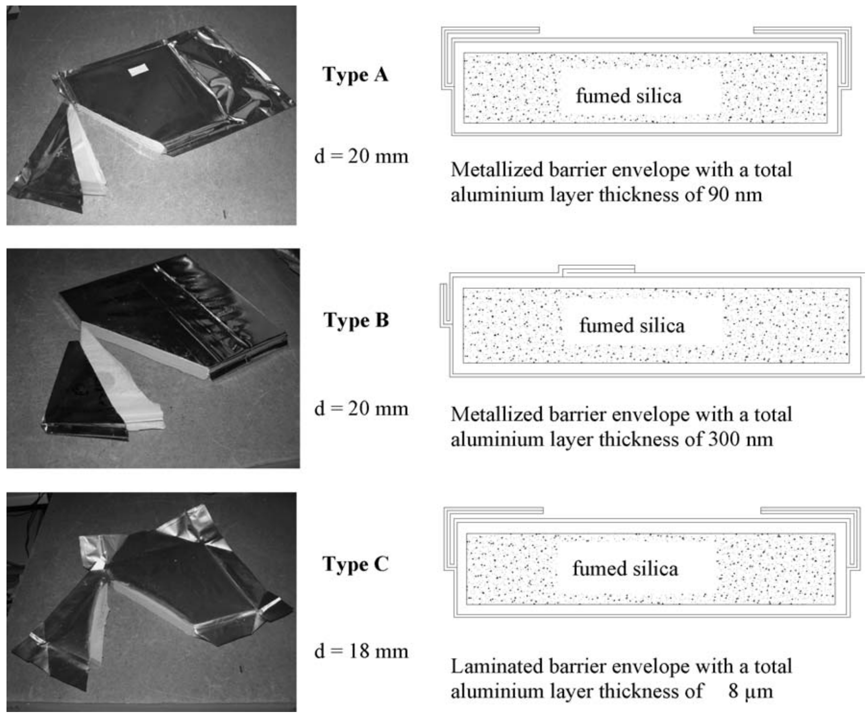


Fig. 1. Cross-section through corner of different VIP types with associated schematic sketch.

2. Experimental set-up

The thermal transmittance measurements were carried out using guarded hot box apparatus complying with international standard ISO 12567-1 [6]. The overall opening of the apparatus was 2.680 m (width) × 3.080 m (height) and the centrally positioned metering area was 2.003 m (width) × 2.504 m (height). The metering zone was surrounded by a guard zone held at a stable temperature. The door system was incorporated in a surround panel made of an insulation material of known thermal properties and was fully encompassed by the metering area on the warm side. As the door dimensions (1.126 m × 2.000 m) were not identical to those of the metering area, allowance had to be made for the heat flow component through the surround panel (Fig. 2) when analyzing the results. As prescribed by the standard, a set of six calibrations was performed prior to the main measurement to determine the thermal resistance of the surround panel, the total surface resistance and the convective fractions on either side [6].

3. Specimen

The investigations were performed on a highly insulated exterior door system (Fig. 3) for low-energy buildings. The frame was made of oak with a rebate and gasket (weather stripping). The door leaf (Fig. 4) comprised a timber leaf frame reinforced on both left and right hand side by a block of multi-layer fibreboard. The door leaf infill was made of two VIP units (Type A) with a fibreboard on either side. A composite facing comprising two identical plywood panels with a total thickness of 6.5 mm with core 0.4 mm aluminium sheet covers frame and infill on either side of the door leaf. The aluminium sheets are necessary to minimize bending of the leaf. For the present study, measurements and calculations were carried out for four different configurations of a single specimen:

(a) complete door system including fittings, handle, lock, etc.;
(b) overall door system as in (a) but without any metal parts;
(c) overall door system as in (a) but with upper VIP damaged;
(d) overall door system as in (a) but with both VIPs damaged.

While the door leaf was unhung twice to remove all fittings and metal parts, the doorframe remained untouched in the surround panel, thus allowing any potential additional errors produced by mounting and handling operations to be ruled out. To damage the VIPs, a 1.8 mm diameter 30 mm deep hole was drilled into each.

4. Visualization by infrared thermography

After each measurement the warm side of the hot box (guard zone including metering box) was moved aside while the specimen remained connected to the cold side under unchanged conditions (2 °C) so as to maintain a temperature difference of approximately 20 K. The infrared images

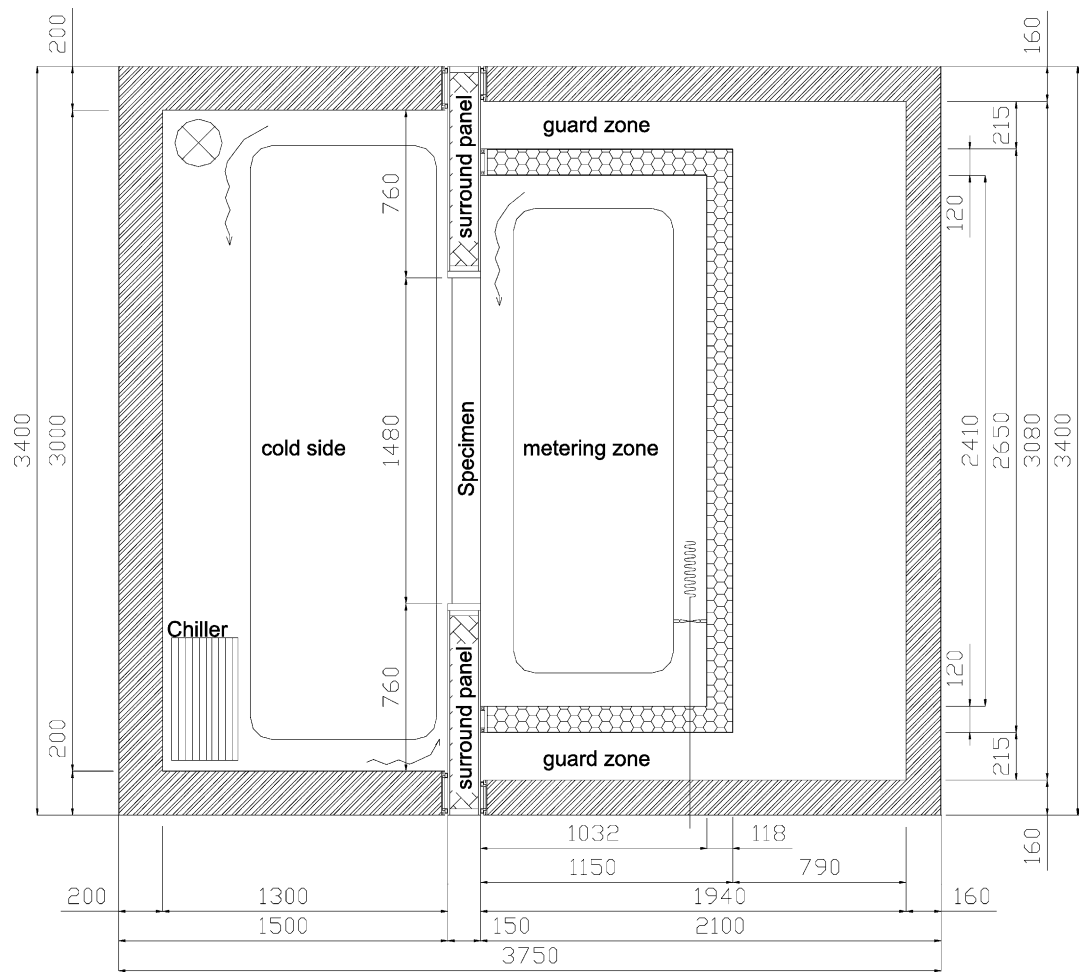


Fig. 2. Schematic vertical cross-section of guarded hot box apparatus.

produced therefore showed conditions similar to those prevailing during a hot box test. These IR pictures reveal the surface temperature distribution on the warm side of the specimen and enable comparison with the surface temperature distribution obtained from numerical analysis. Additionally, IR imaging was used to check air tightness at the junction between specimen and surround panel and the integrity of the vacuum in the VIPs, as both of these factors are likely to leave an imprint on temperature distribution. The IR camera with integrated Stirling cooler was mounted on a tripod, positioned in front of the hot box and automatically took an IR image every 15 min during a 15-h period.

5. Numerical analysis

Numerical analysis was carried out for all four configurations using the TRISCO program [7], which calculates the three-dimensional steady-state heat transfer in objects described in a rectangular grid using the energy balance technique. The most challenging task of this analysis was to develop a simplified yet adequate model, as the thinnest layers contained in the specimen had a thickness of 30 nm with a very high thermal conductivity of 230 W/m K embedded in materials with a fairly low conductivity of 0.07 W/m K (Table 1). These abrupt changes in size and thermal conductivity were accommodated by various simplifications such as combining three (30 nm) aluminium layers into a single 90 nm layer. The same approach was adopted for the substrate layers of the barrier envelope. The area of the joint around each of the two VIPs was handled using a special simplified model [8]. Even so, the modelling ended with a total of about 1.5 million nodes which made it impossible to check the accuracy of the results due to the grid size required by standard EN ISO 10211-1 [9]. As will be shown later, comparison with the infrared images confirmed the quality of the grid size. The thermal conductivities of the materials used in the model, as shown in Table 1, are based on either measured [8] or tabulated values [10]. The boundary conditions (environmental temperatures and heat transfer coefficients) used for the numerical analysis correspond to the values of the measurement (Table 2). Reduced surface coefficients were used in all calculations concerning the overall door system where applicable according to the appropriate standard [11].

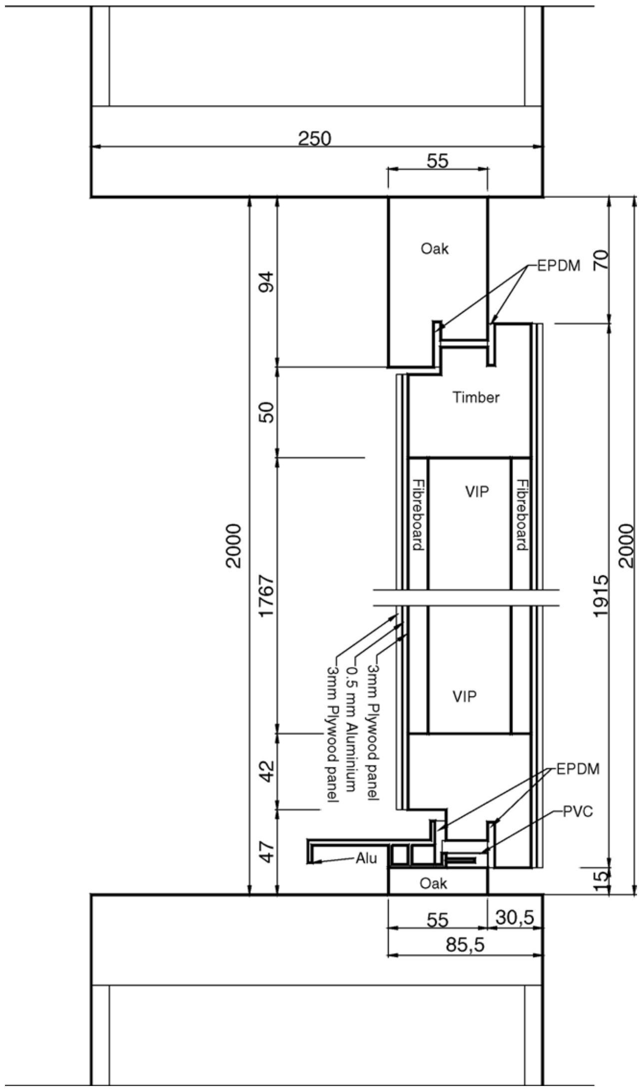


Fig. 3. Vertical cross-section through the door system with surrounding panel.

Table 1
Thermal conductivities of used materials

Material	Thermal conductivity (W/m K)
Frame wood (oak; 700 kg/m^3)	0.18[a]
Multi-layer fibreboard (610 kg/m^3)	0.14[a]
Fibreboard (250 kg/m^3)	0.07[a]
Plywood panel (410 kg/m^3)	0.13[a]
Timber (590 kg/m^3)	0.13[a]
EPDM (gasket)	0.25[a]
PVC	0.17[a]
Synthetic material mix	0.23
Aluminium	160[a]
Aluminium foil	230
Stainless steel	17[a]
Steel	50[a]
Polyethylene (low-density)	0.32
VIP core material undamaged	0.0042
VIP core material damaged	0.019

[a] Values given in [10].

6. Results and discussion

Measurement and computational results (heat fluxes) are summarized in Table 3. It is immediately noticeable that the calculation results (column 4) always exceed the measurement results (column 3)—in compliance with the general principle that calculated results should be on the safe side. Nonetheless, given the acceptable degree of concordance between measurement and computational results, prediction by means of finite difference calculations may be assumed to achieve reasonable accuracy. This concordance was visualized by means of a comparison between an IR image of the measurements and the computed surface temperature distribution (Figs. 5–6). The gradation of the surface temperatures corresponds well although the computed image is symmetrically whereas the IR image is not. It needs to be like this because the convection in the metering zone of the hot box flows from top to bottom (Fig. 2) and therefore produces a surface temperature gradient. The calculation, in contrast, has no asymmetrical component. Furthermore it seems to be possible that the core material of the lower VIP has a higher thermal conductivity than assumed. But this assumption could not be verified. The attempt to obtain a visual representation of the local imprint of damaged VIPs (cases (c) and (d)) by means of IR imaging failed due to the blurring of the surface temperature distribution by the thin aluminium sheet (very high thermal conductivity) of the facing plywood panels: the only minor differences revealed by the coloured IR images are completely indiscernible in the black-and-white picture.

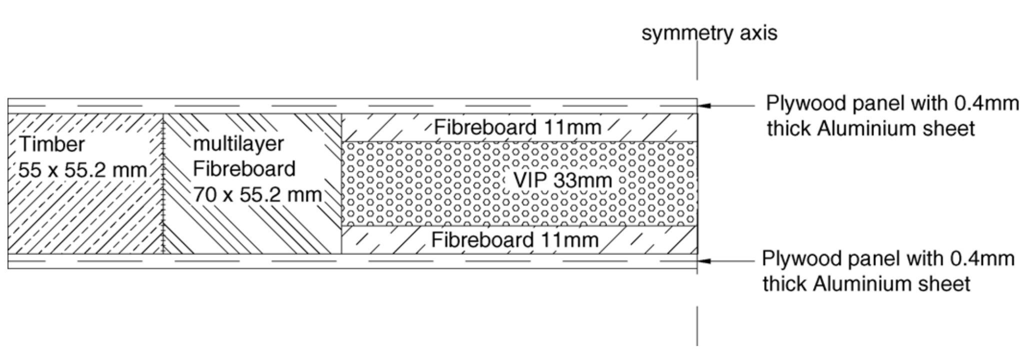


Fig. 4. Vertical cross-section through half of door leaf (left and right hand sides are symmetrical).

Table 2
Boundary conditions for both measurement and calculation

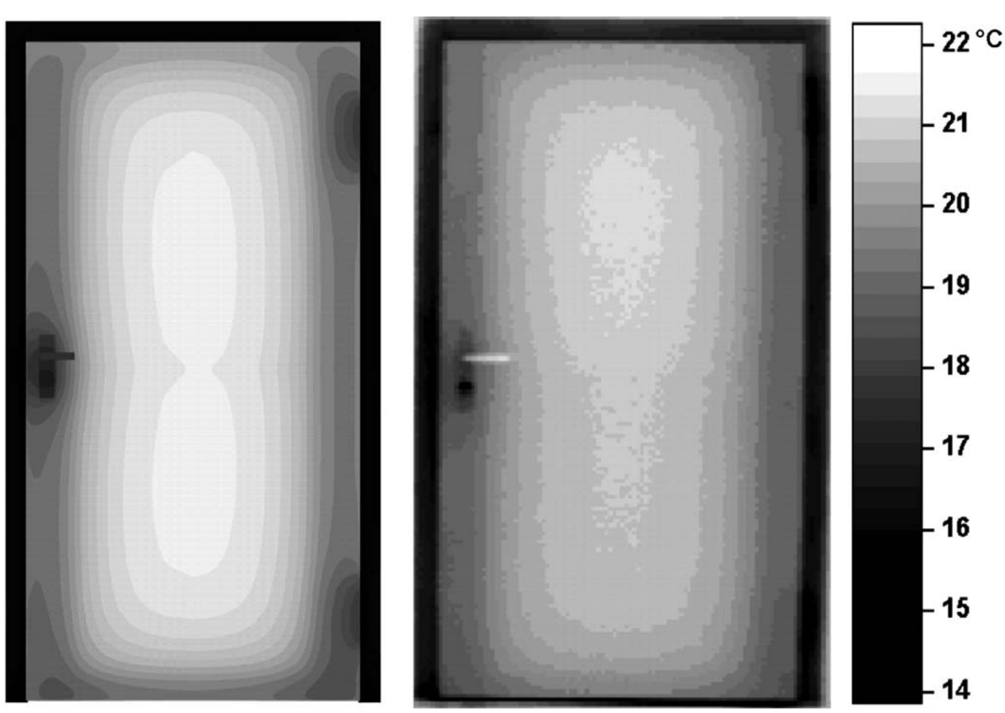
Case	Specimen description	Cold side		Warm side	
		θ_{ne} (°C)	h_e (W/m^2 K)	θ_{ni} (°C)	h_i (W/m^2 K)
(a)	Complete door system including fittings, handle, lock, etc.	2.04	22.5	21.80	7.9
(b)	Overall door system as in (a) but without any metal parts	2.03	22.5	21.81	7.9
(c)	Overall door system as in (a) but with upper VIP damaged	2.12	22.5	21.77	7.9
(d)	Overall door system as in (a) but with both VIPs damaged	2.02	22.5	21.77	7.9

Table 3
Results of measured and calculated total heat fluxes

Case	Specimen description	Measurement (W)	Calculation (W)
(a)	Complete door system including fittings, handle, lock, etc.	40.54	43.71
(b)	Overall door system as in (a) but without any metal parts	38.10	40.09
(c)	Overall door system as in (a) but with upper VIP damaged	44.00	46.91
(d)	Overall door system as in (a) but with both VIPs damaged	46.19	50.62

Cases (a) and (b) in Table 2 showed the impact of the metal parts on thermal behaviour to have been overestimated in the calculation. This is mainly because the metal parts in the calculation were modelled with perfect thermal contact to the other components, i.e. too conservative. For example, ideal contact was assumed between the pin and integrated aluminium sheets on either side of the door leaf. In reality, as the pin is fitted through a cylindrical hole (Fig. 7), the thermal bridge exists only in the calculation, but not in the actual measurements. The results are also converted to overall U-values of the door system U_D (Table 4), which is the standard quantity for building elements in real applications. Comparison of the measured results for cases (a)–(d) (Table 3) allows the following conclusions to be drawn:

- The impact of the metal fittings is about 6.4% (cases (a) and (b)).
- A single damaged VIP reduces the thermal performance of the overall door system by 8.5% (cases (a) and (c)).
- In the case of two damaged VIPs, the thermal performance is reduced by about 14% (cases (a) and (d)).



Figs. 5–6. Calculated isothermal image (left) and IR picture (26.04.2004; 14:48) of door system (right) for case (a).

Table 4
Results of measured and calculated total U_D-values

Case	Specimen description	Measurement (W/m^2 K)	Calculation (W/m^2 K)
(a)	Complete door system including fittings, handle, lock, etc.	0.91 ± 0.05	0.98
(b)	Overall door system as in (a) but without any metal parts	0.85 ± 0.04	0.90
(c)	Overall door system as in (a) but with upper VIP damaged	0.99 ± 0.05	1.06
(d)	Overall door system as in (a) but with both VIPs damaged	1.03 ± 0.05	1.13
(e)	Overall door system as in (a) but with conventional insulation (fibreboard with λ = 0.07 W/m K) instead of VIPs	–	1.31

Table 5
Results of calculated U-values for door leaf only

Case	Specimen description	Calculation (W/m^2 K)
(f)	Complete door leaf only with both VIPs undamaged	0.58
(g)	Complete door leaf only, but with upper VIP damaged	0.67
(h)	Complete door leaf only, but with both VIPs damaged	0.77
(i)	Complete door leaf only, but with commonly used insulation instead of VIPs	1.08

It should be kept in mind that the reduced thermal performance relates to the overall door system, i.e. frame, door leaf and mounting. More substantial changes (of 16 and 33%) may be observed for the U-value of the door leaf alone (Table 5) computed with the associated boundary conditions for the overall door system. The method of mounting the door system in the hot box (front-mounted frame fixed in the reveal of the surround panel), likewise simulated in the calculations, represents the worst case in that it maximizes the doorframe area and hence the impact of the U-value of the unprotected doorframe on the overall door system. Were the frame to be side-mounted (planted) on the wall, this would reduce the area of the unprotected frame and improve the thermal resistance of the overall door system. The thermal performance of the frame, with its U-value of about 2.1 W/m^2 K and an area fraction of around 20%, seems to offer considerable scope for improvement given that the U-value of the door leaf alone with undamaged VIPs is about 0.58 W/m^2 K. The resulting substantial temperature difference of 4 K between frame and door leaf is clearly observable in Figs. 5–6.

Fig. 7. Cylindrical hole accommodating the pin in door leaf facing after removing doorplate.

7. Conclusions

The safest and most promising applications of VIPs involve their use behind a protective layer, e.g. integrated in a door leaf in an exterior door system. In this case, the main advantage consists in vastly increasing insulation performance without changing the overall door thickness. Achievement of the same U-value for the door leaf alone using conventional insulation instead of integrated VIPs would require an insulation thickness of about 194 mm compared to the 33 mm needed for VIPs. Even with one damaged or at worst two damaged VIPs, the door leaf still exhibits a U-value far superior to present-day equivalents incorporating standard insulation. Furthermore, the doorframe is clearly shown to substantially reduce the impact of the VIPs, whether damaged or undamaged. Hence, possible ways of enhancing the performance of the incorporated VIPs include the use of a side-mounted frame fixed to the wall or a thermal optimization of the frame system. In the present study, the use of VIPs attained a 25% improvement for the overall door system in terms of energy consumption, while a maximum reduction of about 50% appears achievable where the performance of the overall door system is not compromised by the frame. The comparison between measurement and calculations, visualized by means of the infrared images, reveals a high degree of concordance and provides encouragement for the continued use of computational methods.

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