Passivhaus: The Architectural Typology of Low Energy Housing

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Abstract: The growing number of Passivhaus buildings in the UK suggests an increasing acceptance of the low energy design methodology. Post occupancy evaluation shows that the energy use in Passivhaus homes are generally very low, and that running costs are considerably less than standard housing. However, the move to adopt Passivhaus Planning Package (PHPP) as a mandatory standard has been resisted in many areas with a belief that the benefits are outweighed by the limitations imposed on architectural design when using PHPP. Case study analysis of 42 Passivhaus homes has been conducted to examine the architectural typologies that are generated from the use of PHPP in the UK. This research explores the impact of the Passivhaus design approach on orientation, fenestration, size and spatial relationships of the buildings and determines the impact that it has on architectural design. Qualitative research with the occupants of these homes provides a further understanding of the lived experience of Passivhaus and how users adapt to the technical systems that are required to achieve Passivhaus certification. The case study analysis reveals connections between adaptations made in those living in a Passivhaus to achieve comfort, and questions how different this is to standard housing.

Keywords: Passivhaus, architectural design, adaptation, case study, overheating

Introduction

The beginning of the year 2003 saw a rapid growth in the number of Passivhaus projects around the world. It has been estimated that 30,000 Passivhaus buildings have been realised, with the majority being residential projects. The total number of Passivhaus projects in the UK is estimated to be around 400 units (94 projects), 380 of which were residential (at the time of March 2016). However, the move to adopt Passivhaus Planning Package (PHPP) as a mandatory standard has been resisted in many areas with a belief that the benefits are outweighed by the limitations imposed on architectural design when using PHPP. In this research, 42 Passivhaus homes have been surveyed in which 10 projects have been studied in detail to examine the architectural typologies that are generated from the use of PHPP in the UK. This paper explores the impact of the Passivhaus design approach on orientation, fenestration, size and spatial relationships of the buildings and determines the impact that it has on architectural design. Qualitative research with the occupants of these homes provides a further understanding of the lived experience of Passivhaus and how users adapt to the technical systems that are required to achieve Passivhaus certification. The case study analysis reveals connections between adaptations made in those living in a Passivhaus to achieve comfort, and questions how different this really is to standard housing.

Contextual background

The layout and arrangements of domestic space have been in a constant state of change with the development of technology. It was suggested by Wright (1964) that heating devices, including fireplaces, stoves and chimneys, have influenced social activities and space arrangement in domestic spaces. On the other hand, the mechanical service system has also been developed in line with advances in technology and the socially constructed idea of comfort. The result of this development suggests that a particular lifestyle is shaped by a combination of factors concerning technology, comfort and architecture.

Study on the post occupancy of Passivhaus began during the last decade in Sweden. According to Mlecnik (2012), a considerable amount of German-language research has been carried out regarding occupants' experience. The results showed that the majority of occupants living in Passivhaus expressed high levels of satisfaction in terms of comfort and energy saving. However, recent research has shown a significant risk of summer overheating in Passivhaus in the UK, with 72% of the surveyed Passivhaus households exceeding the benchmark (Tabatabaei S. et al, 2015). The same research also indicated the importance of household behaviour in the prevention of overheating. Since the current Passivhaus standard sets a fixed threshold temperature as the overheating benchmark (25 degrees for more than 10% of the total occupied hours) without consideration of external conditions or household characteristics (such as old age), the design method does not give an accurate prediction of summertime indoor temperature. Rojas's (2015) study of 18 Passivhaus suggested that most significantly exceed the Passivhaus certification criterion (i.e. 10% ≥25°C). The research also found that top-floor flats were much more vulnerable than those on other floors.

Research on Passivhaus tends to focus on energy performance, and very rarely focuses specifically on architectural design. A study focusing on the occupants of a house and their daily interactions with it may thus reveal a deeper connection between architectural design features and users of Passivhaus.

Sampling and data collection

42 new-build residential buildings occupied since 2011 have been selected to form the basic sampling pool. In examining the 42 projects together with previous literature, five basic categories have been established into which these projects can be grouped. The five categories are floor area, ownership, building type, construction type and bioclimatic region

Table 2. Comparison of the window-to-floor ratio of three case studies

Floor area (m^2)	No. of projects	Ownership	No. of projects	Building type	No. of projects	Construction type	No. of projects
<100	15	Privately owned	26	Detached house	24	Timber	26
100-200	19			Semi-detached	8	Masonry	12
200-300	6	Social rental	16	Mid-terrace	10	Mixed	4
>300	2						

Bioclimatic region	Scotland N	Scotland W	Scotland E	England E & NE	England W & Walse N	Midlands	East Anglia	England SW/Wales S	England SE/Central S
No. of projects	1	2	4	6	5	5	3	6	10

Of the 42 projects, more than half (24 projects) are single-family detached houses, a majority of which are privately owned. The remaining 18 projects are multi-family dwellings, of which six were developed privately. The treated floor area of the projects ranges from 52 m2 per household to 408 m2 per household. The majority of the projects have a floor area of around 130 m2. The two main structure systems are timber and masonry.
All 42 projects were contacted during the data collection period from March 2014 to October 2015. A total of ten projects (15 households) responded with an overall response rate of 23.8%. Among the ten cases, the seven single-family projects are all detached, privately developed houses. Their areas range from 151 m2 (House ST) to 219 m2 (House SA). The three multi-family projects (including DO, SL from the social rental sector and a cohousing project LA) appear to have relatively smaller floor areas ranging from 65 m2 (House LA 2bedroom) to 102 m2 (House DO 3bedroom). The multi-family dwellings are either semi-detached houses (Houses DO and SL) or mid-terrace houses (House LA). The ten projects are located across the UK, as shown in the following figure.

Figure 1. Location map of the studied cases

Quantitative analysis

In the Passivhaus design guide, several design features are highlighted as being the most important in terms of their effect on the performance of the Passivhaus. These are orientation and shading; building form and form factor; U-value; and airtightness. Those factors became the focus of the quantitative analysis. The design recommendations for a Passivhaus include a focus on achieving the standard's energy performance. In comparison, the studied cases exhibit similar properties in the U-value of external envelope and airtightness. The main differences occur in their form factors and orientation.

Orientation and shading

In the PHPP, the climatic data used to calculate thermal performance is based on 22 climatic regions across the UK, as specified by the BRE. It also makes adjustments for altitude (-0.6 degree for every 100 m increase in altitude). Aside from guidance in the PHPP, a Passivhaus design guide – the BRE Passive House Primer – has also been widely used for building practitioners aiming to achieve the Passivhaus standard. It is recommended in the BRE Passive House Primer that the orientation of a building should aim to maximise its solar gain, which means the main façade is oriented within 30 degrees south. A poor orientation can increase annual heating demand by 30% to 40% (McLeod et al.).

A majority of the projects (6 houses) are oriented due south. The remainder, with the exception of the SL and SA projects, are oriented within 30 degrees south. The SL project in East Lothian and the SA project in Durham face 57.7 degrees and 46.6 degrees southwest respectively. Very few of the projects have any natural shading from vegetation or adjacent buildings. Cases FO and TO have moderate shading to the west side, and the SL project is heavily shaded from natural sources to its southwest side. Case LA has heavy shading for a low-angle solar path (winter shading) from vegetation on the other side of the river. It can also be observed that every project has adopted other shading strategies such as a roof overhang, deep window reveal, brise-soleil, balcony, canopy and external/internal blinds or curtains. The design to maximise solar gain has evidentially been influenced by the requirement specified in the Passivhaus design guide. One exception can be seen in the SL project. This unit containing four flats is not only designed to reside outside the boundary of recommended orientation, but the site is also heavily shaded on the southwest side.

Form factor

Building form and form factor have been used to optimise the floor area, the footprint of the building, the plot ratio and other parameters. They have also been widely adopted to optimise the energy consumption of the building. Generally speaking, a smaller ratio of external envelope area to the volume of the building (A/V ratio) indicates a lower probability of heat loss and more efficient energy consumption. It has been recommended that 'a favourable compactness ratio is considered to be one where the A/V ratio ≤ $0.7m^2/m^3$' (McLeod et al.). This principle can be extended to indicate the complexity of building geometry. Because smaller buildings tend to have a higher A/V ratio, it has been recommended that small buildings be kept as simple and compact as possible, whereas larger buildings can have a slightly more complex shape.

This rule simplifies the certification procedure but also means that the performance of individual households varies. Using an estimation calculation tool developed by BRE, calculations have been carried out to examine the form factors of the studied cases. The calculations show that with the exception of the HI and HA projects, the studied cases have all achieved the benchmark of 3 for the form factor. In terms of the A/V ratio, the three multi-family projects, DO, LA and SL, achieved a ratio of no more than 0.70 m^2/m^3 (0.7, 0.58 and 0.6 respectively), whereas the single-family projects all scored slightly above the average A/V ratio, with the largest occurring in the ST and TO projects.

Qualitative analysis

Following the quantitative analysis of design factors, the correlational analysis below involves a cross-examination between the physical properties of each Passivhaus project and the corresponding interview data. The analysis has gathered the discomfort/problems highlighted in occupants' interviews in order to identify the design issues that contributed to those problems. For the purpose of this paper, one major issue concerning overheating is discussed.

In the interview, moderate or mild overheating was reported as a discomfort in almost all of the case studies in this research, including both the northernmost and southernmost projects. It can be observed that despite the geographical locations or bioclimatic regions of the building, certain design features of Passivhaus buildings make them more vulnerable to heat, resulting in the overheating issues seen in those projects. The analysis compared the interview data with the design features of each project. The results reveal the three main issues most likely to be contributing to the issue of overheating for eleven households in this research. These are glazing in relation to room size (W/F), the effectiveness of shading and design for natural ventilation.

Glazing in relation to room size (W/F)

In the PHPP, the criteria for checking overheating is specified as:
The frequency of overheating is the percentage of hours in a given year that the temperature exceeds 25 degree. For Passivhaus certification this must not exceed 10% of the year. (Lewis, 2014 p.58)

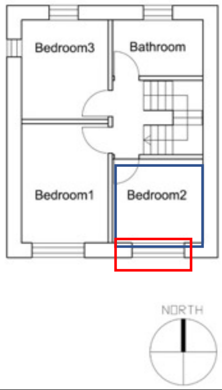
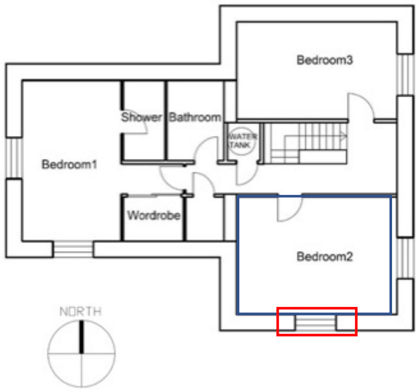
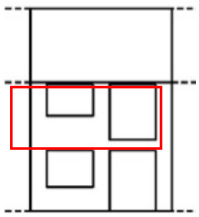
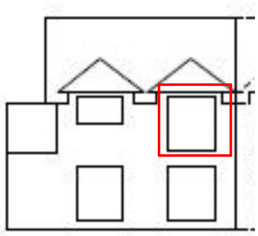
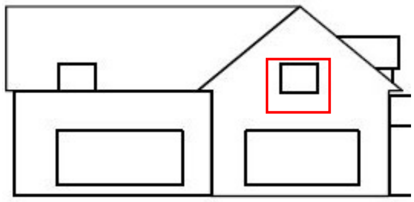
However, when calculating heat gains, the PHPP software distributes heat evenly across the whole building, hence it does not take into account the direct relationship between the size of the windows and the corresponding room size. The certification also means that the overall temperature of the building can remain below 25 degrees for the entire year, while a specific room (usually a small bedroom on the first floor with a large south-facing window) may potentially be above 25 degrees for more than ten per cent of the hours of the year. In this research, analysis was carried out specifically focusing on the window-to-floor ratio (W/F) for the smallest habitable room in each case. The following table (Table 2) shows a comparison with some extremes from the calculation.

All six occupants in the LA and DO projects reported overheating issues. The problem occurs especially in the bedrooms on the first floor. Calculation of the W/F revealed very high ratios of 0.51 and 0.4 respectively in comparison with a lower ratio of 0.21 in the TO project, where no overheating issue was reported. Each project has received its PHPP certification; however, it can be observed that the TO project has a more favourable W/F in each room, which prevents the problem of overheating. The LA and DO projects, in contrast, are more vulnerable to increased temperatures in the summer.

Effectiveness of shading

In addition to the size of the glazing, in most of the cases natural shading was designed to be just outside the site as a way of maximising the benefit of solar gain. The only building among the case studies to employ natural shading on the south side is the SL project. Not surprisingly, in the interview, the occupants suggested no discomfort/overheating problems in relation to the indoor environment during the summer. For the remainder of the case studies, certain types of external shading were integrated into some of the projects during the design phase. Deep window reveals and roof overhangs were also used quite commonly in most of the case studies. The shading devices used also included internal blinds and/or curtains installed post occupancy in every case study for the purpose of adding both shading and privacy. The integration of various shading devices in each project appeared to be aimed at moderating and eliminating overheating issues; however, the actual observations revealed otherwise. In terms of effectively controlling overheating, the effectiveness of the shading devices employed is more important than simply having a variety installed.

Table 2. Comparison of the window-to-floor ratio of three case studies

Plan			
	LA1 first floor	DO1 first floor	TO first floor
Elevation			
	LA1 bedroom 1	DO1 bedroom 2	TO bedroom 2
W/F	**0.51**	**0.4**	**0.14**

For instance, in the PL project, as the occupants did not understand the function of the shading, they never used it to control overheating. On the other hand, in the HA project, it was suggested by the occupants that the brise-soleil installed was effective in shading most of the summer sun. However, it was insufficient to provide enough shading to control the sunshine at a lower angle in the late afternoon. Thus, the external shading in each of these three projects does not effectively serve its design intention.

Meanwhile, internal shading devices such as blinds or curtains have been adopted in all projects. The effectiveness of these devices for controlling indoor temperature was proved to depend largely on the proper installation of the shading as well as on the behaviour of the occupants. It was observed that the design details of window blinds can play an important role in supporting the occupants' behavioural adaptation to control overheating. Two examples are selected from the case studies as shown below. In most of the case studies, classic 'tilt and turn' windows are used as openable windows. This type of window features two methods of inverted opening. Both opening methods are difficult to use in conjunction with a traditional installation of curtains, and they are even more difficult to use with blinds. This means that natural ventilation cannot be achieved at the same time as shading. This can be a particular problem for Passivhaus in the UK as shading is needed from the low-angle sun during long summer days, while cool air is also needed in the mornings and evenings for ventilation. The window detail in the SL project has further restricted the options in the way that the tilted roof prevents the installation of a curtain rail. However, a more considerate design in the HA project has achieved a better integration of shading and natural ventilation. The design has attached the blinds directly onto the 'tilt and turn' window frame, so that a tilted opening is not disrupted by the drawn blinds.

Figure 2. Comparison of blind arrangement in SL project (left) and HA project (right)

Therefore, it can be observed that the control of overheating using shading devices depends to a great extent on the environmental conditions and also on the occupants' behaviour. The effectiveness of either external or internal shading needs to be considered in the design phase in relation to the prevailing weather conditions, window detail and the occupancy.

Cross and stack ventilation

Natural ventilation using windows on both sides of the house is regarded by all occupants to be the most effective way to control overheating and the most preferred way to ventilate. However, it is worth repeating that in order to sufficiently control overheating by natural ventilation, cross ventilation needs to be designed in conjunction with proper control activities practised by the occupants. In this research, several cases can be listed as examples of such a design feature, including cases CR, FO and HA, as well as the DO project. The overheating problems in these projects were resolved through effective ventilation, with the support of fair cross ventilation and, wherever possible, stack ventilation design and an active adaptation of behaviour in controlling the windows.

Taking CR project for example, in order to control overheating, an observable behavioural adaptation, a newly developed routine of combining natural ventilation, shading and mechanical ventilation was performed:

> *[…] In the summer we do open the windows in an intelligent way so early in the morning we open north facing windows on the ground floor, let the cool air come in and walk its way upstairs. So we pull blinds down to keep away the mid-day summer sun out when necessary, we also use the MVHR system to do night time purging. […] From about mid night through to 6 am, […] by the morning the house is quite cool. (interview with CR occupant)*

Concluding remarks

The rigour and care that were put into the research design have ensured the results of this research are valid. However, it is important to acknowledge that the existence of a number of limitations during the research design process may have prevented it from achieving more significant findings. Firstly, in terms of the qualitative nature of this research, no environmental measurement was taken to indicate temperature, air velocity, humidity and accurate energy consumption. This decision was made at the beginning of this research in order to set a clear focus for the experiential data, at the same time to avoid causing any inconvenience to or violating the privacy of the occupants. The data collected have proved to be representative of the occupants' experiences and can be correlated to other quantitative measures (such as building parameters and energy consumption) for the purpose of drawing conclusions. However, the results may have benefitted from further comparison and analysis if environmental measures had been taken at the time of the interview.

Secondly, the significance of this study is limited by the response rate for the chosen sample. In this research, ten projects have been studied. However, the range of project types has given a good sample of the PH community and is fairly representative. It can be stated that a wider study would have enabled a broader testing or a further theoretical saturation of the codes, but would not have revealed any additional categories. While emphasising the rigorous methodological approach of this research, it is also important to acknowledge that the conclusions drawn from cross-case analysis with the interview data and a comparison of the cases remain context based. In addressing comfort issues in design, this paper confirms the risk of overheating in certain Passivhaus in line with previous studies conducted in the UK. The result from this study suggests certain connections between the design recommendations of Passivhaus and the risk of overheating, especially for south-facing houses/flats with smaller area and a more compact form. However, the study also reveals the various behavioural adaptations performed by the occupants, which, if supported by appropriate architectural design, can be exercised effectively to control overheating and to achieve comfort.

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