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Investigating energy saving performance interdependencies with retrofit triple vacuum glazing for use in UK dwelling with solid walls

Saim Memon[1*]

1. School of Engineering, Science & Technology, North East Scotland College, Aberdeen, AB123LE, United Kingdom

Abstract: Space-heating loss through the windows of solid wall dwellings is one of the factors contributing to high energy consumption. Despite of significant achievements in the vacuum glazing science a practical benefit of retrofitting triple vacuum glazing to consumers in terms of energy saving is unclear, partly due to which it poses challenges in bringing vacuum glazing technology in the UK market for mass production. This research forms a part of novel contribution in vacuum glazing science presenting the refurbishment technology of an experimentally achievable thermal performance of triple vacuum glazing to existing UK solid wall dwelling by investigating inter-dependent performance of triple vacuum glazing on to the solid wall insulation, in comparison to triple air-filled glazing. Dynamic thermal modelling and steady state analyses were carried out. From the transient model simulations, an annual space-heating load input to an un-insulated solid wall house retrofitted with triple air-filled glazed windows and triple vacuum glazed windows were predicted to be 23883.6 kWh (84.92%) and 23320.5 kWh (84.47%). With a similar comparison but to an externally insulated solid walls, the heat load inputs were predicted to be 10995.7 kWh (72.18%) and 10309.1 kWh (70.63%). The steady-state heat loss calculations indicated the percentage of heat loss reduction, when replacing triple air-filled glazed windows to triple vacuum glazed windows, to be approximately 1.58% for un-insulated solid walls and 3.02% for an externally insulated solid walls. It was shown that retrofitting existing solid wall houses are essential for not only to reduce space-heating energy requirements but it also signifies clear advantages of retrofitting triple vacuum glazing's into a house. A more realistic approach have to be further explored when these result will be compared with the experimental results of space-heating performance when replacing triple air-filled glazed windows to triple vacuum glazed windows.

Key words: triple vacuum glazing, space-heating energy, solid wall dwelling, energy saving

1 Introduction

Demand side carbon reduction and energy efficiency of buildings are currently major concerns due to links with climate change and fuel poverty [1]. Indeed the current UK sustainable initiatives have already disenthralled the sustainable-business by providing long term energy saving opportunities to consumers [2]. Yet the total energy consumption in the UK has decreased by 3% in the industry sector and 1% in the transport sector but increased by 11% in the domestic sector and 3% in the service sector (includes agriculture) from 2011 to 2012 [3]. Natural gas consumption is dominant in providing space heating, water heating and cooking loads. The majority of total energy consumed in the domestic sector is due to space heating which accounted for 66% of total usage in 2012 [4]. Water heating, cooking and lighting and

[*] Corresponding author at: School of Engineering, Science & Technology, North East Scotland College, Aberdeen,AB123LE, United Kingdom. Tel.: +44 7735518528.
E-mail address: s.memon@nescol.ac.uk or memonsaim@gmail.com

appliances accounted for a further of 16%, 3% and 15% respectively. Due to an increase of gas consumption, specifically in the domestic sector, gas prices increased by 6.4% (including VAT) between second quarter (Q2) of 2012 and Q2 of 2013 [5]. The increase in fuel prices, specifically gas prices, is causing difficulties for domestic consumers to afford to heat their dwelling to standard comfort temperatures of between 17˚C and 19˚C during winter and summer seasons, respectively [6]. In the literature, the studies on active and passive measures have already been undertaken for the reduction of space heating load in the UK solid wall housing stock such as upgrading the efficiency of boilers, improving the internal or external wall insulations, proper airtightness whilst ensuring sufficient ventilation, and the replacement of existing single or double air-filled glazed windows to triple air-filled glazed windows [7-12]. The concept of triple vacuum glazing was introduced in 2006 [13]. This consists of three sheets of glass, a vacuum tight seal around the periphery of the three glass sheets, and two evacuated cavities at a pressure below 0.1 Pa to reduce heat transfer by gaseous conduction and convection to a negligible level. Radiative heat transfer can be reduced to a low level by using soft low-emittance coatings such as silver (Ag) on the surfaces of the glass sheets [14]. An array of stainless steel support pillars, typically 0.15mm high and 0.3mm diameter, maintain the separation of the three glass sheets[15]. The fabrication and predicted thermal performance of a new low temperature sealed triple vacuum glazing (i.e. 0.33 Wm-2K-1) is reported by Memon in [16]. This study predicts the performance of a modelled solid wall dwelling [17] by simulating the heat energy losses through the fabric of un-insulated and externally insulated solid wall dwelling with the use of achievable thermal performance of triple vacuum glazed windows and triple air-filled glazed windows. However, from their thermal transmittance values, the performance can be predicted; For example replacing standard triple air filled glazing, U value of 1.89 $Wm^{-2}K^{-1}$, with triple vacuum glazing, U value of approximately 0.33 $Wm^{-2}K^{-1}$, reduces the heat loss by more than five times [16]. A comprehensive contrasting survey of software for dynamic thermal modelling are reported in [18]. Significant data input to run precise simulations is immense, so is emphasis to perform and interpret the simulation results. In this paper a dynamic and steady state approaches were used, considering realistic scenario, in predicting the energy performance of un-insulated and externally insulated solid wall dwelling with an influence on total energy losses when retrofitting triple vacuum glazed and triple air filled glazed windows, which have not been reported before. Full details of the dynamic thermal simulation and energy modelling have been reported elsewhere [17] and are analysed here. This analysis will lead policy makers to a clear understanding of triple vacuum glazing's and achievable benefits to consumers in reducing the energy bills and gas consumption; therefore, lowering CO_2 emissions and avoiding the adverse impact of climate change. Note that, as the final retrofit measure is applied to annual space-heating loads. The results show the expected significant reduction in space-heating energy consumption as a result of replacing triple air-filled glazed windows to triple vacuum glazed windows. Note that measured thermal energy data is not yet available, since performance monitoring is still in progress and the model predictions will be compared with the experimental data.

2 Methodology

A number of thermal modelling software packages were studied for the precise calculation of detailed energy-performance tasks such as IES VE, ESP-r, Energy Plus, TRANSYS, IDA ICE. These are having certain characteristics and specific applications [18]. In this paper IES VE dynamic thermal simulation tool has been used mainly because; it allows modelling triple vacuum glazed windows, due to its narrow gap/vacuum space between the two glass sheets i.e. 0.13mm; enable detailed evaluation of building space-heating energy use, shading and solar penetration, natural ventilation and infiltration linked to occupancy, heating and ventilation profiles with the use of realistic weather data files, full simulation building design and methods of a three-dimensional dynamic thermal modelling have been published and reported in [17]. For the annual transmission heat losses through the envelope and ventilation heat losses, steady-state calculation methods have been applied.

The solid wall (un-insulated and externally insulated) detached house modelled was constructed using brick thick bond wall [19] and the building design is based on the likely construction of a 20th century solid wall dwelling. The detached solid wall house was considered to be located in the Heathrow area of London, UK. A certain element of refurbishment was incorporated in the modelled building design including loft insulation to 1995 building standards, details of the construction and the thermal properties for the modelled building are presented elsewhere [16]. The elemental U values of each element was simulated according to the method in the CIBSE Guide A [5] and comply with the BS EN ISO 6946 [20] standard. A dynamic thermal analysis undertaken was transient, to account for the thermal mass of the building fabric elements (wall, roof, ceiling, and floor), and a one-dimensional finite difference approach was used in predicting annual space-heating energy consumption. In order to determine transmission heat losses through the envelope and ventilation heat losses, a steady state analysis was carried out. In which all information about the geometry of windows, exterior walls (with and without external wall insulation), roof and floors were taken from the solid wall modelled dwelling, as detailed in [17]. In this analysis the indoor and outdoor temperature difference was assumed to be 10˚C. In the dynamic thermal simulations the indoor and outdoor temperature variations were taken into account and space-heating and solar gain analysis performed. The heat loss through internal partitions, internal ceilings/floor and internal doors were neglected, because the temperatures in different internal spaces were assumed to be the same. Thus, the total heat loss is the sum of transmission heat losses of the exterior envelope and air infiltration heat losses as expressed in Equ.1.

$$\phi_T = \phi_{tranmission} + \phi_{infiltration} \quad (1)$$

The total transmission heat loss $\phi_{tranmission}$ was calculated by summing the heat loss through the windows, exterior doors, exterior walls, roof and ground, as expressed in Equ.2 and 3.

$$\phi_{tranmission} = \phi_{window} + \phi_{exterior\ doors} + \phi_{exterior\ walls} + \phi_{roof} + \phi_{ground} \quad (2)$$

$$\phi_{tranmission} = \sum(F_{tc} \times U \times A) \times (10)\ \text{W} \quad (3)$$

The temperature correlation factor (F_{tc}) enables using the same temperature difference (10˚C) to be used for parts of the envelope exposed to different environmental conditions. This factor was set to 1.0 for the exterior walls and roof and to 0.6 for the ground floor [21].

ϕ_{window} is the heat loss through the window. This was calculated by considering the number of windows modelled (i.e. 10), the area of windows modelled and their respective frame areas comprising 26.91%, 31.62% and 42.85% of the total window area, the type of window (in specific to this paper triple air-filled glazed and triple vacuum glazed are discussed) and their respective total U values including frame areas. The net U-value of window (including the effect of the frame) is calculated by taking an average of the En-ISO centre-of-pane and frame U-values weighted according to their percentage contribution to the area of the window (BS 10077-2, 2003), construction and design parameters are detailed in [17]. Thus the Equ.3 is expressed as,

$$\phi_{window} = [7.686 \times U_{26.92\%} + 0.24 \times U_{42.85\%} + 0.651 \times U_{31.61\%}] \times [10℃] \quad (4)$$

The total heat losses through triple air-filled glazed and triple vacuum glazed windows in the modelled solid wall detached house were calculated to be 164.84 W and 75.38 W respectively. There are four external doors being modelled in a solid wall detached house that give a total area of 8.41m^2, using Equ. 3, the total heat loss through the exterior doors, $\phi_{exterior\ doors}$, was calculated to be 215.3 W. The total exterior wall area of the modelled house is 169.25m^2. Using Equ. 3, the total heat loss through the exterior insulated walls, $\phi_{exterior\ walls}$, was calculated to be 881.45 W. The total heat loss through exterior un-insulated walls was calculated to be 3588.1 W. The total roof area of the modelled detached house is 71.91m^2. Using Equ 3, the total heat loss through the roof was calculated to be 165.39 W. The total ground area is 205.53m^2. Using Equ. 3, considering the temperature correction factor to 0.6, the total heat loss through ground area of the modelled house was calculated to be 776.89 W. The ventilation heat loss can be calculated using Equ. 5 [21]. The overall volume of the model, i.e. 402.33 m^3, and designed air exchange rate i.e. 0.5 ach are required using the specific heat capacity of air 0.34 W h^{-1}m^{-3} and the mean temperature difference of 10˚C, the heat loss through ventilation was calculated to be 683.96 W.

$$\phi_{infiltration} = (0.34 \times air\ exchange\ rate \times volume) \times 10℃ \quad (4)$$

3 Results and discussion

Spontaneous design input variables and instantaneous calculations are substantial for the performance assessment of triple vacuum glazed windows, in comparison to triple air-filled glazed windows, in a scenario when un-insulated and externally insulated solid walls were used. In particular to the performance assessment in realistic scenarios when the solid wall insulations influence the heat loss through the fabric plays a very important role in predicting the benefits of triple vacuum glazed windows. In this paper the performance of modelled solid wall is analysed with two types of glazing systems (triple vacuum glazing and triple air-filled glazing) in two scenarios of the solid wall insulation (un-insulated solid wall and externally insulated solid wall). In the first case scenario, from the transient model simulations, an annual space-heating load input to an un-insulated solid wall house retrofitted with triple air-filled glazed windows and triple vacuum glazed windows were calculated to be 23883.6 kWh (84.92%) and 23320.5 kWh (84.47%) respectively as shown in Fig. 1 and 2. In this case the performance of the low-heat loss glazings is not ostentatious mainly due to the occurrence of large percentage of the heat loss through exterior walls. For example, in the heat flow diagrams shown in Fig. 1 and 2, with the steady-state heat loss calculations on this model the percentage of heat loss reduction when replacing triple air-filled glazed windows to triple vacuum glazed windows is approximately 1.58%. In this context, the investment on to the commercialisation of triple vacuum glazings will not bring significant cost benefits to consumers. The heat loss due to air infiltration can be reduced by improving the insulation and reducing air leakage through the building envelope. It is also pertinent to mention here, in general, the cost, stability of vacuum, ageing and degradation of vacuum glazings are also the current challenges or hindrances in leading this technology at the manufacturing level in the UK. Even when the solid walls are partially insulated the cost-benefit would not be at a convincible level unless if the solid walls are well insulated to a U value of minimum 0.52 $Wm^{-2}K^{-1}$, as per building regulations, then the benefits to consumers can be taken into account as detailed in the second case scenario.

In the second case scenario, from the transient model simulations, an annual space-heating load input to an externally insulated solid wall house retrofitted with triple air-filled glazed windows and triple vacuum glazed windows were calculated to be 10995.7 kWh (72.18%) and 10309.1 kWh (70.63%) respectively, as shown in Fig. 3 and 4. In this case the performance of the low-heat loss glazings is exaggerated mainly due to the reduction in the percentage of heat loss through exterior walls. The steady-state heat loss calculations show the percentage of heat loss reduction when replacing triple air-filled glazed windows to triple vacuum glazed windows approximately to 3.02%, as shown in the heat flow diagrams in Fig. 3 and 4. It is predicted from these analyses that retrofitting existing solid wall houses is important for the reduction of space-heating energy requirement. A significant energy saving was predicted when triple vacuum glazed windows were retrofitted into the house with external solid wall insulation. An approach used can apprehend the complex inter-dependencies between the solid wall insulation and the performance of triple vacuum glazing. A more realistic approach have to be further explored when these result will be compared with the experimental results of space-heating performance when replacing triple air-filled glazed windows to triple vacuum glazed windows. In these simulations the experimentally achievable thermal performance of triple vacuum glazing (as detailed in Memon, 2013) was used and its thermal performance can also further be improved in future.

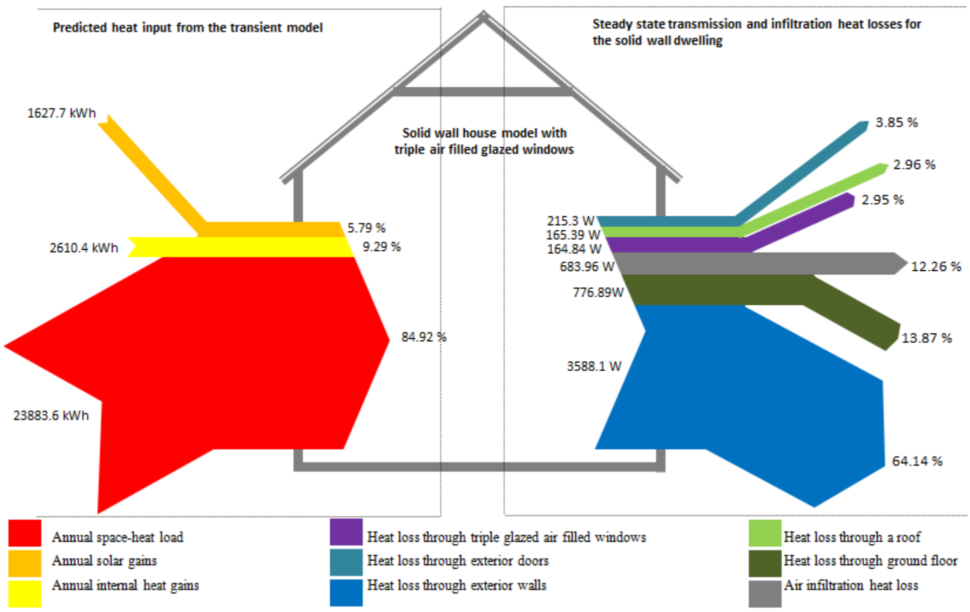

Figure 1: Heat flow diagram a solid wall (without external wall insulation) house with triple glazed air filled windows. Simulated heat input from a dynamic model and steady state transmission heat losses through the envelope and by air infiltration.

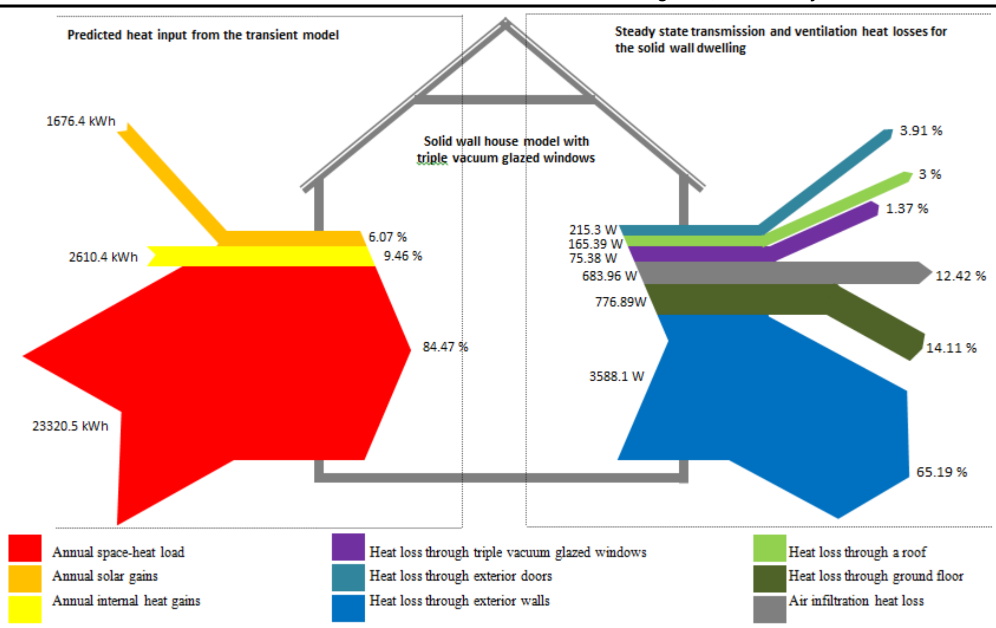

Figure 2: Heat flow diagram of a solid wall (without external wall insulation) house with triple vacuum glazed windows. Simulated heat input from a dynamic model and steady state transmission heat losses through the envelope and by air infiltration.

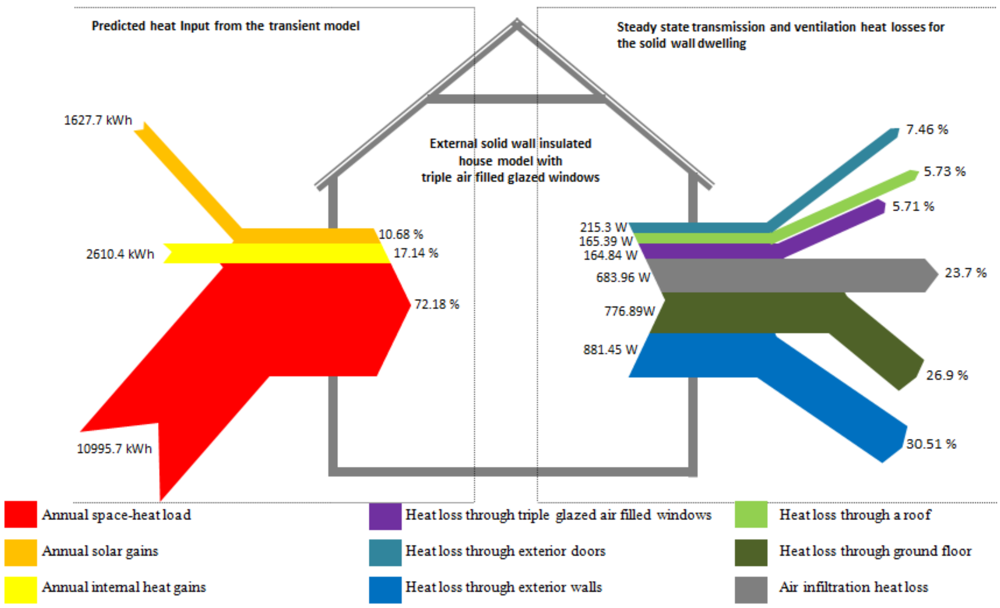

Figure 3: Heat flow diagram for an external solid wall insulated house with triple glazed air filled windows. Simulated heat input from a dynamic model and steady state transmission heat losses through the envelope and by air infiltration.

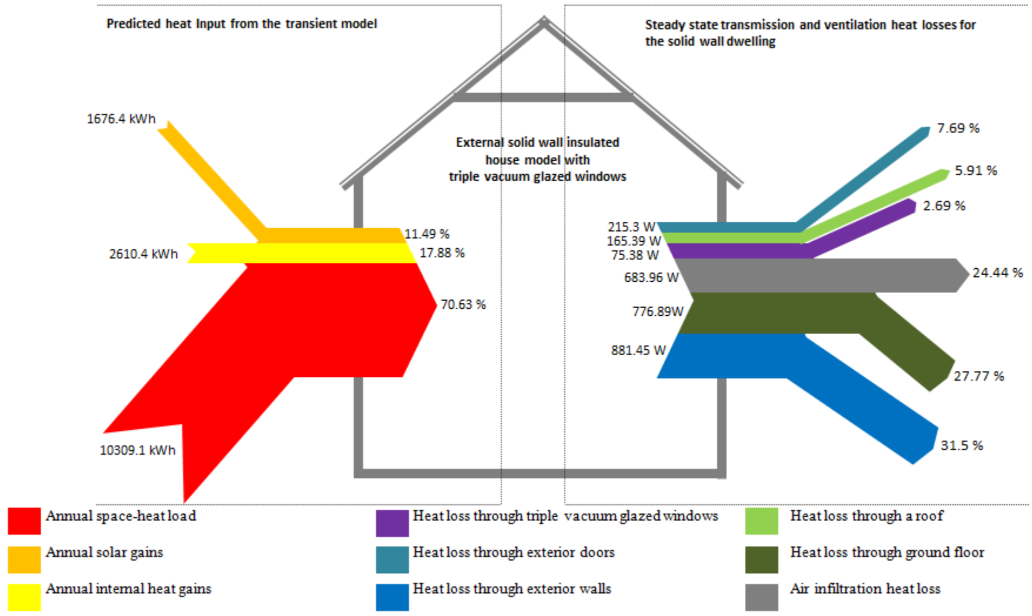

Figure 4: Heat flow diagram for an external solid wall insulated house with triple vacuum glazed windows. Simulated heat input from a dynamic model and steady state transmission heat losses through the envelope and by air infiltration.

4 Conclusions

One of the principal challenges of bringing vacuum glazing technology in the UK market for mass production is its energy cost saving to consumers. The importance of retrofitting triple vacuum glazed windows, in comparison to triple air-filled glazed windows, to a modelled solid wall (un-insulated and externally insulated) detached house was presented. In which the influence of achieving a better benefits of triple vacuum glazings was shown when the solid walls are insulated. In which the heat loss due to air infiltration was reduced by improving the insulation and reducing air leakage through the building envelope. From the transient model simulations, an annual space-heating load input to an un-insulated solid wall house retrofitted with triple air-filled glazed windows and triple vacuum glazed windows were predicted to be 23883.6 kWh (84.92%) and 23320.5 kWh (84.47%). With a similar comparison but to an externally insulated solid walls, the heat load inputs were predicted to be 10995.7 kWh (72.18%) and 10309.1 kWh (70.63%). The steady-state heat loss calculations indicated the percentage of heat loss reduction, when replacing triple air-filled glazed windows to triple vacuum glazed windows, to be approximately 1.58% for un-insulated solid walls and 3.02% for an externally insulated solid walls. A more realistic approach have to be further explored when these result will be compared with the experimental results of space-heating performance when replacing triple air-filled glazed windows to triple vacuum glazed windows. It was shown that retrofitting existing solid wall houses are essential for not only to reduce space-heating energy requirements but it also signifies clear advantages of retrofitting triple vacuum glazing's into a house.

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