Drying Rate Calculations and Energy Modelling of Thermocill™

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This study is conducted by the ManchesterCFD Group in the Department of Mechanical, Aerospace and Civil Engineering (MACE), the University of Manchester. The work is commissioned by KSR Consultancy NW limited.

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1 Thermocill^{TM}

KSR Consultancy NW Limited has commissioned this study to conduct two series of analysis and calculations on the performance of one of their products, *Thermocill^{TM}* (hereafter, 'Thermocill').

Thermocill is an energy saving product that is designed for installation under the window board and above the radiator in a room. It is made from recycled plastic materials and can be retrofitted to existing homes as well as new builds.

In its operation, the product tends to direct the natural convection from the radiator to create a wall of warm air immediately in front of the internal side of the glazed window. It intends to prevent heat loss and cold air entering the room.

Due to its modular and telescopic nature, Thermocill can be installed in a wide range of window reveals and the amount of hot air being directed towards the glazing unit can be adjusted by adjusting its depth.

2 Aims and Objectives

The aim of this report is to conduct an independent study to assess the performance of the latest design of Thermocill in terms of the following:

1) Reducing condensation around the window frame/reveal.
2) Reducing energy consumption and/or CO_2 footprint in a typical dwelling in the UK.

Some of the calculations in this study will be based on the experimental data obtained from Salford Energy House 2.0 conducted by the University of Salford in 2019 and published in June 2020 [1].

3 Part A: Condensation

3.1 Vapour Pressure

When air holds the maximum possible amount of vapour, the vapour exerts what is called the 'saturation vapour pressure'. The 'vapour pressure' is the pressure exerted by a vapour which is in thermodynamic equilibrium with its condensed phases (liquid) in a closed system at a given temperature. The higher the temperature, the larger number of molecules having enough energy to escape from the liquid or solid, which leads to higher vapour pressure values.

The vapour pressure exerted by water or by a surface containing water rises very rapidly with increasing temperature. Therefore, by knowing the vapour pressure of water in two different temperatures, the rate of drying can be estimated. To illustrate the effect of temperature on the drying rate, it can be estimated that for example, for a piece of wood having a surface moisture content of 16% and a core moisture content of 40%, the vapour pressure gradient across the wood at a temperature of 50°C (Vp=12.3 kPa) is four times greater than that at 20°C (Vp=2.3 kPa). There are further advantages in the use of high temperatures in that the capacity of air for holding water vapour, and hence its drying potential increases rapidly with temperature and the amount of air which has to be exhausted is reduced [1].

Figure 1 illustrates the variation of vapour pressure for water in terms of temperature. As shown, the vapour pressure increases almost exponentially with temperature.

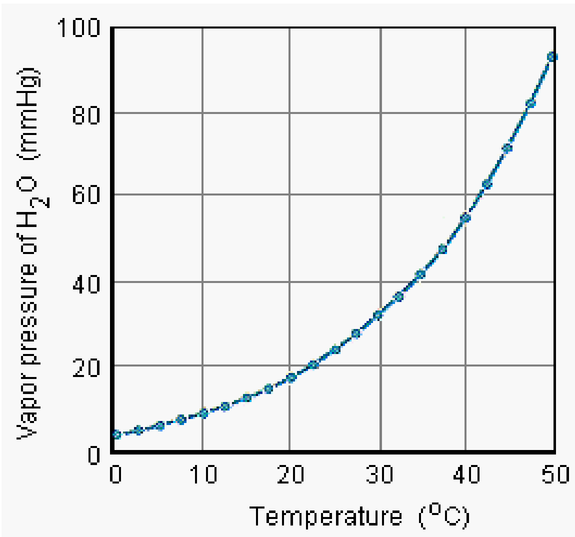


Figure 1: Vapour pressure in terms of temperature for water (taken from [2])

There are currently several different formulas and techniques through which one could calculate the vapour pressure of water. The most well-known and established one is the Antoine equation. The Antoine equation is derived from the Clausius-Clapeyron relation. It is a semi-empirical formula describing the relationship between vapour pressure and temperature. In the Antoine formula [3]:

$$\textit{Vapour pressure} = 10^{[A - (B / (C + \textit{temperature}))]} \qquad \text{(Eqn. 1)}$$

where the temperature is expressed in degrees Celsius and the vapour pressure is in mmHg. The constant parameters for water are given as: *A = 8.07131, B = 1730.63, C = 233.426.*

3.2 Condensation and Evaporation

Condensation occurs when warm air collides with cold surfaces, or when there is too much humidity in your home and creates water, water which collects as droplets on a cold surface when humid air is in contact with it. This is particularly common in winter when the warm air inside the house condenses on the cold windows. When warm, moist air comes into contact with a surface that is at a lower temperature, the warm air is unable to retain the same amount of moisture as it did and the water is released into the colder surface, causing condensation to form, quickly followed by mould, which is naturally undesirable in occupied spaces.

According to the World Health Organisation (WHO), occupants of damp or mouldy buildings are at significantly higher risk of experiencing health problems such as respiratory symptoms, respiratory infections, allergic rhinitis and asthma [4, 5].

In order to remove moisture and condensation from an open surface (such as the window frame and glazing), the molecules of water should diffuse through the gas phase away from the surface. The rate of evaporation or the speed with which this occurs depends on the vapour pressure of the liquid, which as established previously is exponentially proportionate to temperature (see Figure 1).

Therefore, in order to assess the effect of Thermocill on the moisture around the windows, we would need to compare the temperature for the cases of with/without Thermocill and relate those to the vapour pressure.

3.3 Effects of Thermocill on Temperature and Vapour Pressure

The produced water as a result of condensation is usually gathered in the bottom parts of windows due to gravity. Mould is naturally formed in areas with the highest amount of moisture. Therefore, the temperature in the lower regions/panes of the window is considered the most likely location prone to moisture, damp and mould formation.

As established by the data from the Energy House, Thermocill has shown to modify the temperature distribution, both in the room and particularly near the glazing unit. In this section, the temperatures obtained by a steady-state Computational Fluid Dynamics (CFD) simulations are used which have been conducted on Thermocill based on the Salford House configuration. Figure 2 shows several points near the glazing unit and its frame. Point 1-1 is considered as the most in terms of condensation as it is positioned near where it is most prone to the formation of maximum condensation and mould.

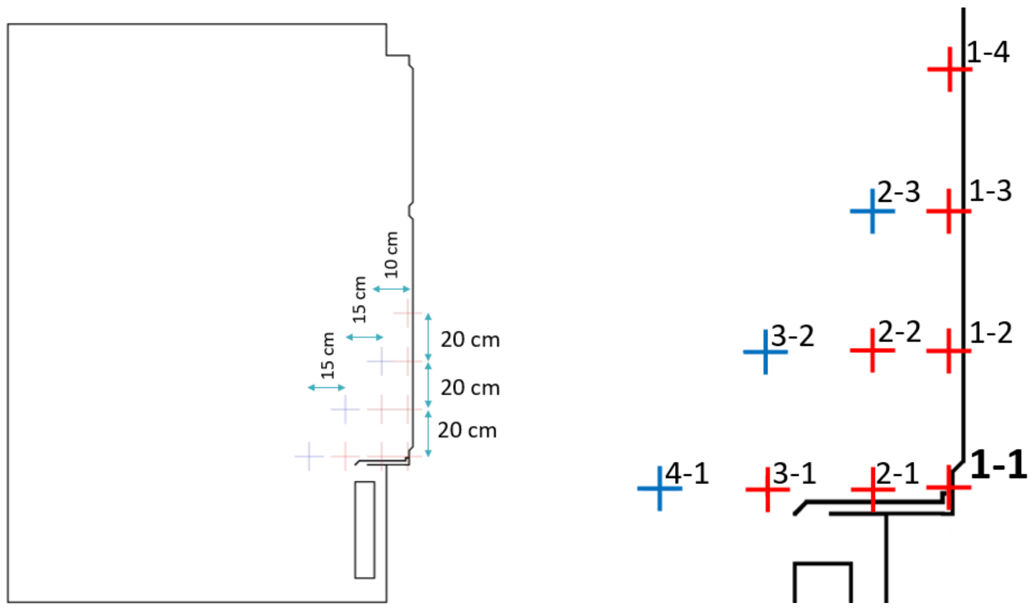
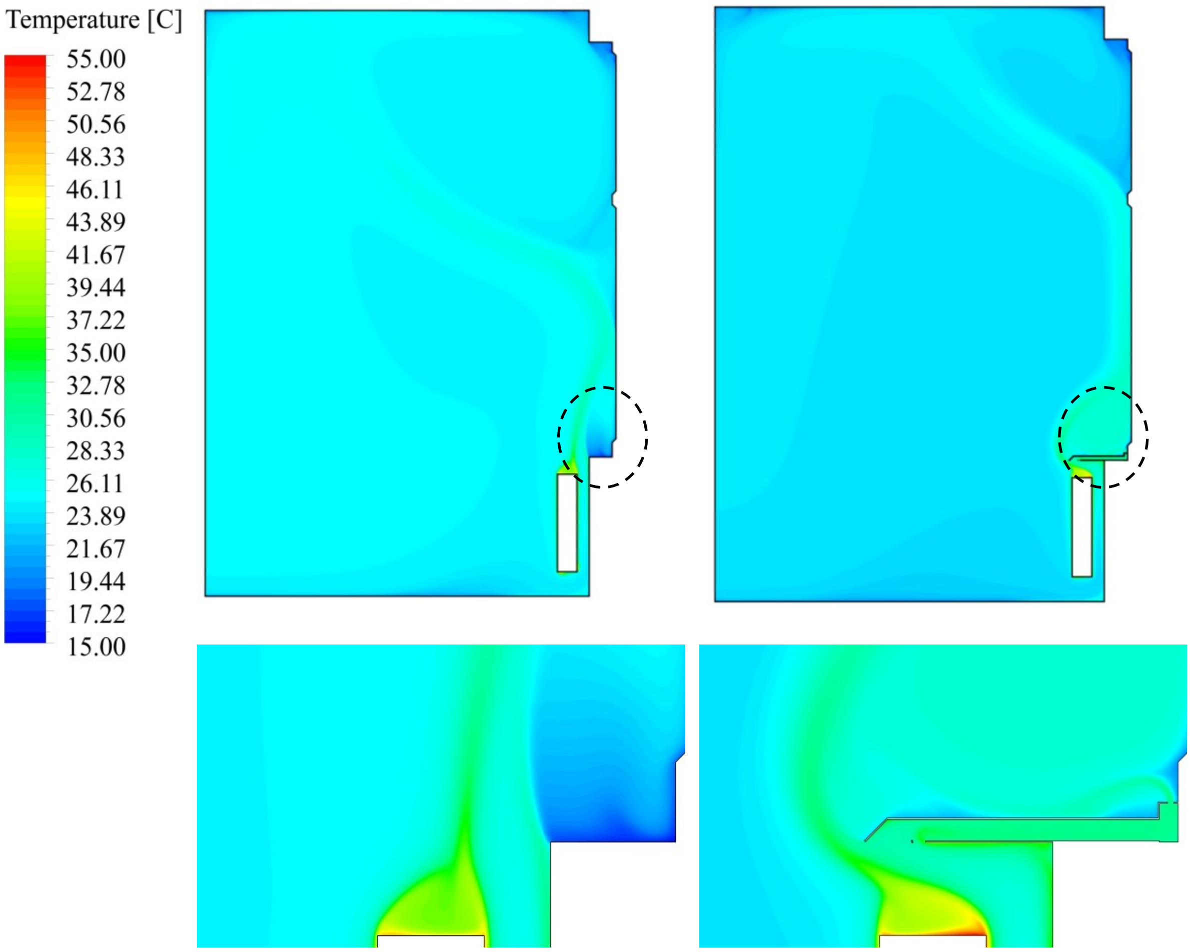


Figure 2: The temperature measurement points in the CFD results.

Figure 3 shows the temperature contours for the computational domain as well as the near-window regions for the cases of with/without Thermocill. As can be seen, the temperature in the near-wall region for the case with Thermocill is much higher than that for the case of no-Thermocill. The temperature is in the range of 19-24°C in the case of no-Thermocill, while as a result of installing Thermocill, the temperature has risen to 26-32°C due to the diversion of hot rising air from the radiator towards the glazing unit by Thermocill.

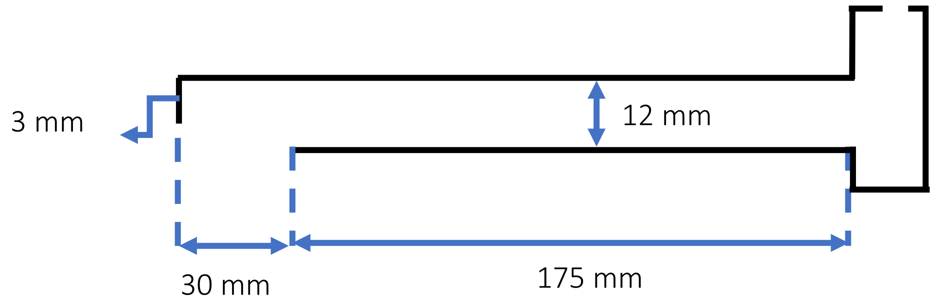


(a) Without Thermocill (b) With Optimised Thermocill

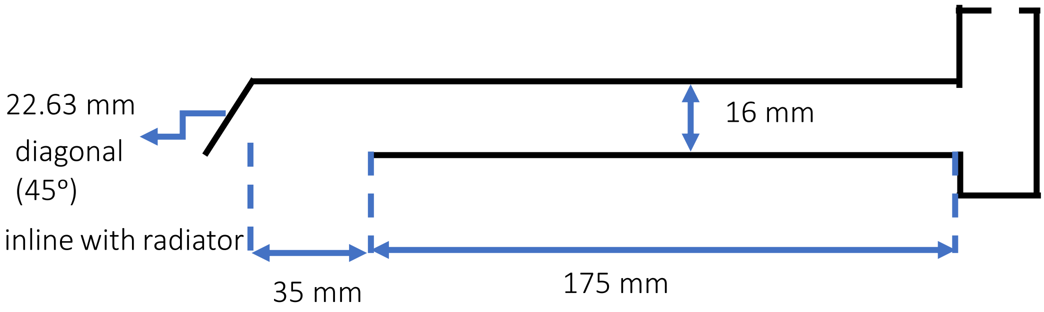
Figure 3: The contour plots of temperature distribution for the cases of (a) No Thermocill and (b) With optimised Thermocill, obtained by CFD.

Table 1 provides the calculated temperature obtained by CFD and associated vapour pressure using the Antoine equation for the following three cases: (a) No Thermocill, (b) With Original Thermocill Design, and (c) with Optimised Thermocill Design. The percentage of differences compared with the 'No Thermocill' case is also included for both the temperature and vapour pressure.

Figure 4 shows the geometrical differences between cases (b) and (c), which are mainly in terms of improved inlet design (incorporating a 45° lip) and increased channel height (by 33%).



(a)



(b)

Figure 4: The schematic of the (a) original Thermocill design and (b) optimised Thermocill design, along with based dimensions.

Table 1: The temperature and calculated vapour pressure for different cases at Point 1-1 of Figure 2.

Case	**Temperature**		**Vapour Pressure**	
	Value (°C)	Percentage difference %	Value (kPa)	Percentage difference %
(a) No Thermocill	20.2	-	2.36	-
(b) With Thermocill (Original Design)	25.6	26.6	3.27	38.6
(c) With Thermocill (Optimised Design)	31.2	54.7	4.54	92.4

As can be seen in Table 1, the drying rate shown in terms of vapour pressure for case (c) (i.e. With Optimised Thermocill Design) is 92.4% higher than that for the case without Thermocill. In other words, the drying rate of moisture/condensation from the bottom region of the window can potentially be doubled when Thermocill with the optimised design is installed. The original Thermocill design could also improve the drying rate by nearly 40%.

In addition, a prior CFD work conducted on both the original and optimised designs have found that the latter will improve the flow rate through the channel and the temperature around the window frame by 47% and 22%, respectively.

3.4 Limitations and Future Work

In this part of the study, the temperatures used to work out the vapour pressure of water in standard conditions are based on CFD simulations. While CFD is a very well-established numerical technique with numerous validation tests against experimental data [6-8] [xxx], it may include some degree of numerical inaccuracies compared to physical testing, although in this particular case, due to simplicity of the geometry and physics, it is not considered to be a major concern. Also, since the CFD simulations have been carried out in a 2D configuration, the potential spanwise flow and heat transfer effects have not been accounted for.

The velocity of the air is another factor that affects the drying rate i.e. higher velocity results in a higher drying rate through forced convection [9]. However, the effect of the air velocity on the drying rate in most cases is less significant compared to temperature [10].

In addition to the temperature and velocity of the air, the material of the wet object/surface could also be important [11], however, this has not been accounted for here either, as the vast majority of windows are made of uPVC and/or aluminium frames.

4 Part B: Energy Modelling

4.1 EnergyPlus™

EnergyPlus™ is a powerful open-source whole building energy simulation software that engineers, architects, and researchers commonly use to model both energy consumption including heating, cooling, ventilation, lighting and plug and process loads as well as water usage [12]. In 1996, a US federal agency began developing a new building energy simulation tool, EnergyPlus, building on development experience with two existing programs: DOE-2 and BLAST [13]. EnergyPlus includes a number of innovative simulation features such as variable time steps, user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation and input and output data structures tailored to facilitate third party module and interface development [2]. Other planned simulation capabilities include multizone airflow, and electric power and solar thermal and photovoltaic simulation [3].

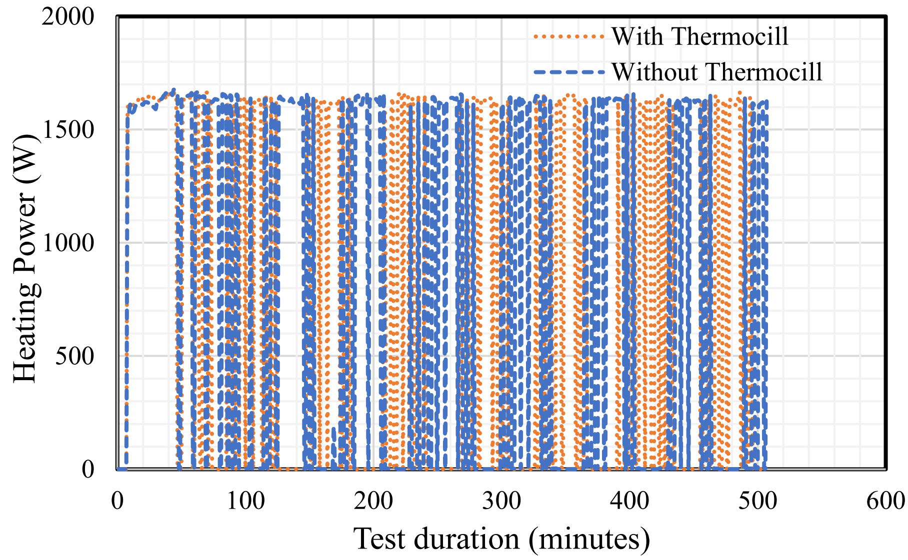
EnergyPlus has been used previously in various studies to estimate building energy performance [14-16]. Some of the advantages of EnergyPlus are given as follows [12]:

- Integrated, simultaneous solution of thermal zone conditions and HVAC system
- Heat balance-based solution of radiant and convective effects
- Sub-hourly, user-definable time steps for interaction between thermal zones and the environment
- Combined heat and mass transfer model that accounts for air movement between zones.
- Advanced fenestration models including controllable window blinds, electrochromic glazing, and layer-by-layer heat balances that calculate solar energy absorbed by window panes.
- Illuminance and glare calculations
- Component-based HVAC that supports both standard and novel system configurations.
- A large number of built-in HVAC and lighting control strategies and an extensible runtime scripting system for user-defined control.
- Functional Mockup Interface import and export for co-simulation with other engines.
- Standard summary and detailed output reports

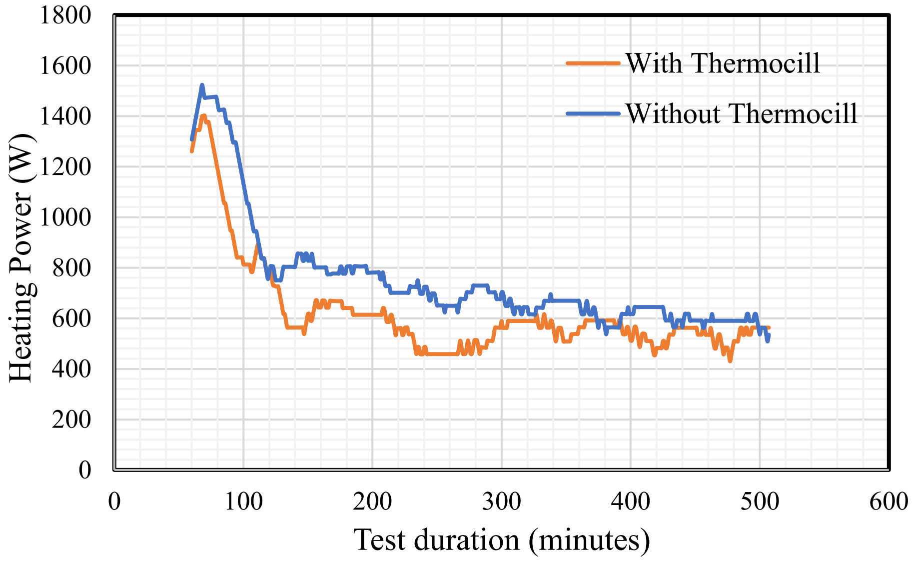
In this study, EnergyPlus is also used to calculate the energy performance of a typical semi-detached 3-bedroom house in the UK.

4.2 Experimental Data from Salford Energy House

Energy efficiency remains one of the goals of building retrofits and it is essential to compare the heating energy consumption by the various test scenarios. During the tests carried out in the Salford Energy House, both radiator’s power and energy consumption were recorded by the Building Management System (BMS) in the energy house. Figure 5(a) compares the heating power and Figure 5(b) displays the 60 minutes moving average power consumption over the test period for the cases of with/without Thermocill[1].



(a)



(b)

Figure 5: The variation of (a) heating power and (b) 60 minutes average heating power in terms of time for the case of with Thermocill compared with no Thermocill case

The moving average profile is consistent with the warm-up time profile for all the cases which is almost 60 minutes. It should be noted that the data covers the entire measurement period as the treatment for the steady-state condition in heat flux. Comparing the scenarios of with

[1] Note: The Thermocill design used by the Salford Energy House was based on the original design, shown in Figure 4(a).

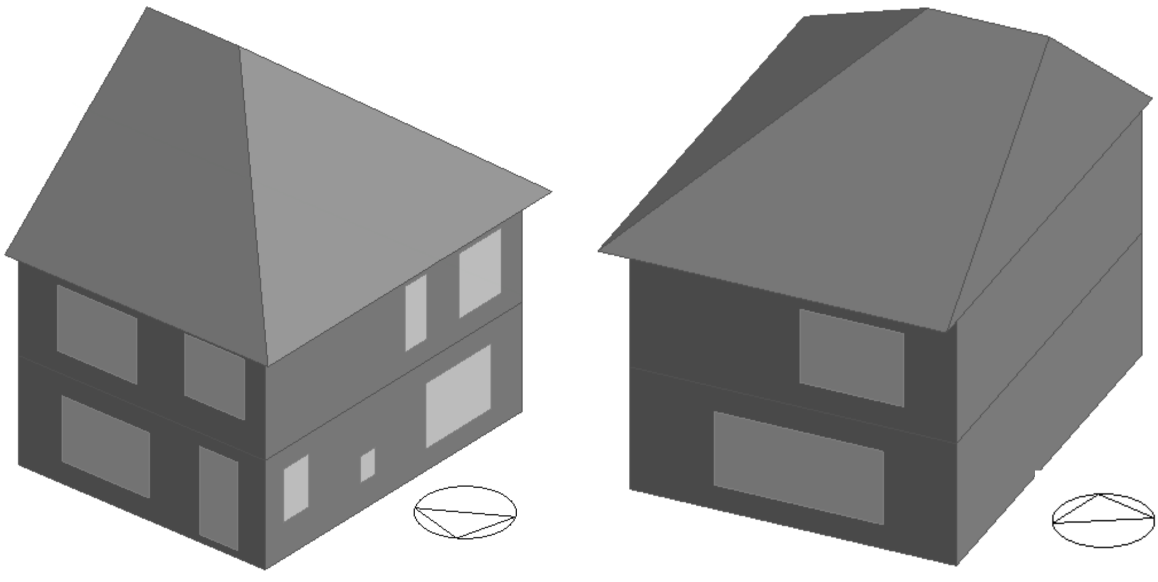
and without Thermocill, it was found that the moving average profile operates at a lower level during Thermocill operation than when not in use. The total energy consumption for the room with Thermocill is found to be 5.54 kWh, while it was 6.43 kWh for the system without Thermocill which means that the use of Thermocill saves approximately 16.1% of energy during the test period where the room's temperature and measured heat flux are constant showing steady-state condition inside the room.

The value of 16.1% saving in energy consumption gained from the experimental data conducted by Salford Energy House is subsequently used in the energy modelling presented in the next section.

4.3 Energy Modelling of a 3-Bedroom Semi-Detached House

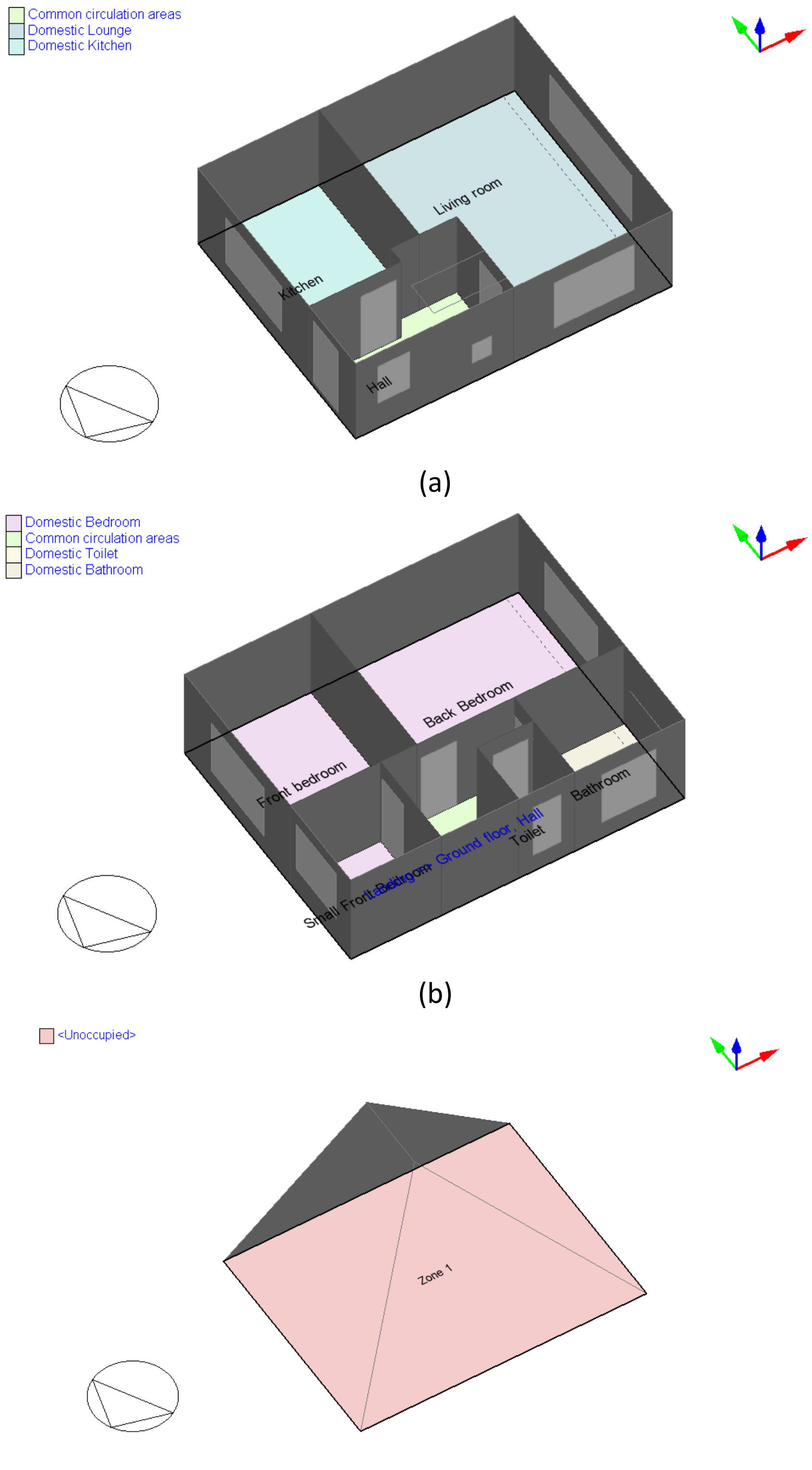
4.3.1 Introduction

A 3-bedroom semi-detached house, as the most common house in the UK, is considered in this study in order to analyse the energy consumption using EnergyPlus software.



(a) (b)

Figure 6: The schematic of the studied semi-detached 3-bedroom house. The wall with no windows in (b) represents the shared wall with the adjacent semi-detached house.



(c)

Figure 7: The sketch of different floor plans (a) ground floor, (b) first floor, (c) roof space

Figure 6 displays the two different views of the notional house modelled in this study. Since the experimental evaluation was performed by the Salford Energy House (based in Manchester), in the energy modelled performed here, the house is assumed to be located in the Northwest of England. Therefore, the weather station located in Aughton (in the Borough of West Lancashire) is selected in the EnergyPlus with the data obtained from ASHRAE International Weather for Energy Calculation (IWEC) database. The IWEC files are derived from up to 18 years of hourly weather data originally archived at the National Climatic Data Centre. The weather station provides data for the purpose of wind, solar and weather conditions.

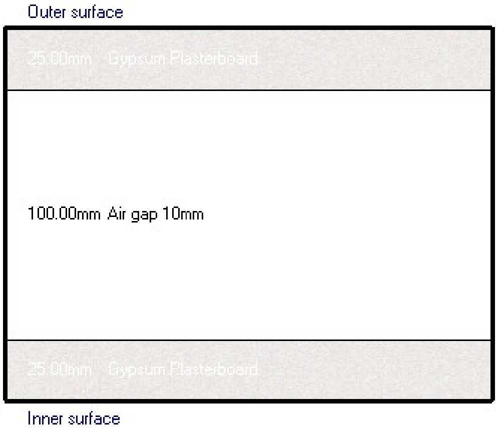
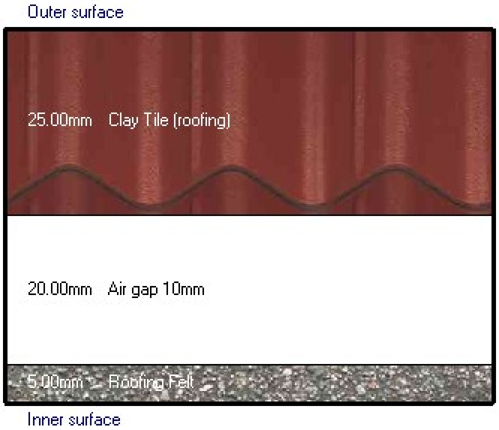
The building has two floors where the occupied and unoccupied area of the building are 86.1 m^2 and 58.7 m^2, respectively. The occupied and unoccupied volumes of the building are 219.2 m^3 and 84.3 m^3, respectively. Figure 7 (a) displays the floorplan of the ground floor which consists of a kitchen, a hallway and a living room. Figure 7 (b) displays the floorplan for the first floor including 3 bedrooms, one toilet, one bathroom and a landing area connecting the first floor to the hallway on the ground floor. Figure 7 (c) also shows the unoccupied zone representing the loft space under the roof. Since the building is considered as a semi-detached house, the wall with no windows shown in Figure 6 is considered as the shared wall, assumed as an external adiabatic wall.

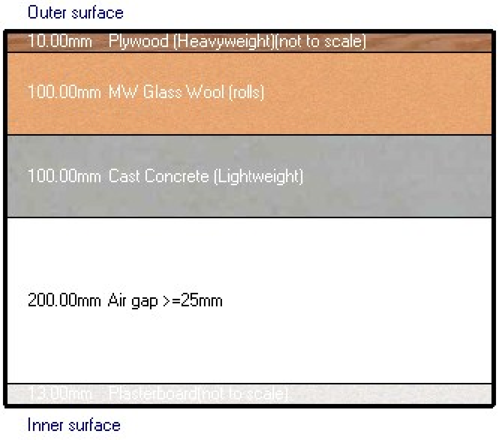
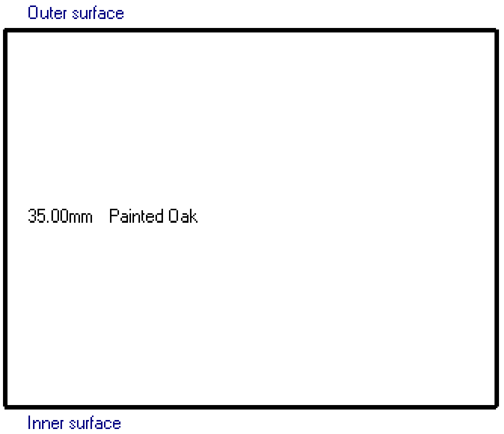
4.3.2 The Construction of the Building

The construction details employed in the studied building are selected from the typical reference database of the Enrgyplus and the library of Design builder and shown in Table 2.

Table 2: Details of the construction in the notional building.

Unit	Name	Image	U-value (W/m^{2}K)
External walls	Wall - Typical reference - Medium weight		1.491

Internal partitions / external adiabatic wall	Lightweight 2 x 25mm gypsum plasterboard with 100mm cavity		1.639
External roof	Pitched roof - Uninsulated - Lightweight		2.93
Ground floor	Combined ground floor - Typical reference - Medium weight		0.314
Internal floor	100mm concrete slab		2.929

Semi-exposed ceiling	Combined semi-exposed roof - Typical reference - Medium weight		0.312
Door	Wooden door		2.823

The windows for the building are selected from EnergyPlus database according to:

Table 3: Details of the glazing units used in the notional building.

Unit	Name	Number of layers	Outermost pane	Window gas	Innermost pane	U-value (W/m^2K)
External windows	Reference Glazing	2	Generic PYR B CLEAR 3MM	Air 12 mm	Generic CLEAR 3MM	1.973

The windows do not have any shading and airflow control. They have a free aperture on the left with 5% opening area. The windows cover 30% of the walls including windows. Note that windows frame occupied 20% of the windows area based on the EnergyPlus reference made from uPVC with a U-value of 3.476 W/m^2K with 20mm in thickness.

4.3.3 The Activity inside the Building

Normal activity related to a domestic building is considered. Generic summer and winter clothing are considered for the clothing of the people in the building. Other activities for the room including the occupancy, equipment and metabolic are considered as follows based on UK NCT[2] dataset for residential spaces:

Table 4: Details of the people activity inside the notional building.

Unit	Occupancy density (people/m^2)	Activity	Equipment (W/m^2)	Lighting (lux)
Bedrooms	0.0229	Bedroom (dwelling)	3.58	100
Bathroom	0.0187	Light work	1.67	150
Toilet	0.0243	Standing/walking	1.61	100
Hallway	0.0196	Light manual work	2.16	100
Kitchen	0.0237	Work involving walking etc	30.28	300
Living room	0.0188	Eating/drinking	3.90	150

It should be noted that:

- The radiation fraction of 0.2 is considered for the equipment considering dwelling domestic equipment based on residential spaces database.
- The metabolic rate per person is defined based on the activity according to the CIBSE[3] source in the category of Miscellaneous occupational.
- For the lighting, the power density of 15 W/m^2 is considered based on the defined schedule of people activity in different rooms.

4.3.4 HVAC System and DHW

The selected Heating, Ventilation and Air Conditioning (HVAC) system for heating the building is radiator using water (central heating with water) based on BRE[4] source in the category of UK NCM[5] and SBEM[6]. The radiator heating system uses natural gas with the Coefficient of Performance (CoP) of 0.853 worked based on Domestic common areas for heating according to the BRE for residential spaces [17].

Domestic Hot Water (DHW) is also considered for the building with the same type as the HVAC

[2] National Calculation Methodology (NCM)
[3] Chartered Institution of Building Services Engineers (CIBSE)
[4]Building Research Establishment (BRE) is the world's leading building science centre that provides unique energy advisory services to government and major public and private sector clients worldwide. These range from strategic and commercial support, and carbon and energy management programmes, to regulatory and policy guidance [17] BRE, SBEM: simplified Building Energy Model https://www.bre.co.uk/page.jsp?id=706, 2013..
[5] UK's National Calculation Methodology [1] M. Oladokun, R. Fitton, Energy House 2.0 Thermocill Research Report, University of Salford, Salford, 2020.
[6] Simplified Building Energy Model (SBEM) [17] BRE, SBEM: simplified Building Energy Model https://www.bre.co.uk/page.jsp?id=706.

system (hot water boiler worked with Natural gas) using a similar schedule based on EnergyPlus for different types of rooms. The amount of consumption rate is selected based on the type of the room. The delivery temperature and main supply temperature are considered 80°C and 10°C, respectively. The DHW CoP is taken as 0.708.

Natural ventilation is also considered as 5 ACH (Air Changes per Hour) using a similar schedule based on the UK NCM.

The heating setpoint and set back temperatures are considered 21°C and 16°C, respectively, and the cooling setpoint and set back temperatures are set to 25°C according to ASHRAE standard for thermal comfort condition.

4.4 Results and Discussion

4.4.1 Energy Consumption/CO_2 Emission in the House without Thermocill

In order to calculate the potential energy savings by installing Thermocill inside a house, the entire house needs to be modelled using EnergyPlus without accounting for the installation of Thermocill.

Table 5 presents the yearly amount of heating including the heating load of space heating and DHW as well as electricity including the equipment and lighting.

Table 5: Yearly energy consumption in kWh for a 3-bedroom semi-detached house modelled in the study.

Heating (kWh)		Electricity (kWh)	
Heating load [kWh]	**DHW [kWh]**	**Interior equipment**	**Lighting**
8484.3	1819.43	1500.3	2915.08
10303.73		4415.11	

The results in Table 5 can also be expressed in terms of the total amount of gas and electricity, as well as the CO_2 emissions which are presented in Table 6. Note that the amount of gas is calculated based on the CoP of the boiler using natural gas which is taken as CoP = 0.853 for the space heating system and 0.708 for the hot water system based on the UK SBEM and NCM library in the BRE source.

To provide some context to the values in Table 6, it is worth noting that according to a survey conducted in 2017, the gas consumption for UK properties built after 1999 had a mean of

11,100 kWh, while for new builds with the first year of consumption, the mean gas consumption was 9,300 kWh.

Table 6: Yearly gas and electricity consumption as well as CO_2 emission for a 3-bedroom semi-detached house modelled in the study.

Gas [kWh]	Electricity [kWh]	CO_2 emissions [kg]
12516.24	4415.11	4996.5

According to the UK Power, the average national electricity price per kWh is 14.37p (ranging from 13.86p to 15.60p by region). Gas unit prices are much lower. On average, the gas price is between 2.9p/kWh to 4.4p/kWh. Some companies also charge a standing charge for both gas and electricity ranging from 10p-80p/day. The average gas price of 4.17p per kWh with the standing charge of £93.39 is considered in this study. Therefore, the electricity and gas bill for the studied house in a year can be estimated according to Table 7.

Table 7: Yearly gas and electricity bill for a 3-bedroom semi-detached house modelled in the study. All figures are excluding VAT.

Gas bill [£][1]	Electricity bill [£][2]	Total bill (£)[3]
521.9	634.5	1307.59
[1] Unit gas price = 4.17 per kWh [2] Unit electricity price = 14.37p per kWh [3] Standing charge = £93.39p		

Thermocill affects the required heating load of the room for space heating. Therefore, the required energy consumption by the HVAC system is affected using Thermocill inside the room. Table 8 presents the area and volume of the rooms as well as other characteristics of the rooms. Note that according to the ASHRAE standards, the maximum percentage of windows in a wall is 40%. In this project, almost 30% of the walls are assigned for a window.

Table 8: Dimensions for different parts of the notional house as well as the windows.

Zone Summary		Area [m^2]	Volume [m^3]	Window Glass Area [m^2]	Opening Area [m^2]	Windows Height [m]	Windows width [m]
Roof	zone-1-roof	58.7	84.27	0	0	0	0
First floor	small front bedroom	3.67	9.18	1.91	2.14	1.5	1.43
	toilet	1.69	4.22	0.82	0.99	1.5	0.66
	bathroom	4.59	11.48	1.73	1.95	1.5	1.3
	front bedroom	10.81	27.02	2.74	3.01	1.5	2.01
	back bedroom	18.48	46.19	2.72	2.99	1.5	1.99
Ground floor	hallway	9.4	27.53	1.02	1.25	-	-
	kitchen	11.79	29.47	3.03	3.32	1.5	2.21
	living room	25.66	64.15	7.24	7.88	1.5	5.25

Table 9: Breakdown of heating load for different parts of the house and various effective parameters such as people, equipment and lightings.

	HVAC Zone Eq & Other Sensible Air Heating [kWh]	People Sensible Heat Addition [kWh]	Lights Sensible Heat Addition [kWh]	Equipment Sensible Heat Addition [kWh]	Window Heat Addition [kWh]	Interzone Air Transfer Heat Addition [kWh]	Infiltration Heat Addition [kWh]	Opaque Surface Conduction and Other Heat Addition [kWh]	Window Heat Removal [kWh]	Interzone Air Transfer Heat Removal [kWh]	Infiltration Heat Removal [kWh]	Opaque Surface Conduction and Other Heat Removal [kWh]
First floor: Small front bedroom	767.9	21.0	76.4	37.0	238.2	38.2	0.0	0.0	-216.9	-7.2	-206.8	-747.7
First floor: Toilet	283.5	6.5	73.9	7.5	145.2	40.8	0.0	0.0	-104.5	-5.2	-102.7	-345.1
First floor: Bathroom	687.6	9.4	176.1	14.0	316.9	71.6	0.0	0.0	-197.4	-6.9	-262.8	-808.5
First floor: Front bedroom	1179.8	59.8	224.9	109.1	349.4	0.0	0.0	0.0	-327.2	0.0	-624.5	-971.4
First floor: Back bedroom	1337.1	101.6	384.4	186.5	928.4	174.4	0.0	0.0	-328.0	-30.7	-1128.5	-1625.1
Ground floor: Hallway	2392.0	48.4	544.3	123.5	205.2	81.4	0.0	0.0	-128.0	-516.7	-678.8	-2071.2
Ground floor: Livingroom	1108.2	74.3	983.4	353.5	2299.6	198.6	0.0	0.0	-826.3	-73.3	-1626.4	-2491.7
Ground floor: Kitchen	728.2	32.3	451.8	668.9	429.9	76.3	0.0	0.1	-350.2	-53.2	-727.4	-1256.6
Roof space: Zone1	0.0	0.0	0.0	0.0	0.0	0.0	76.7	375.2	0.0	0.0	-451.9	0.0
Total Facility	**8484.3**	**353.3**	**2915.1**	**1500.0**	**4912.7**	**681.3**	**76.8**	**375.3**	**-2478.4**	**-693.3**	**-5809.8**	**-10317.3**

Table 9 presents the breakdown of the heating load for different rooms within the notional building as well as different heating loads related to various effective parameters such as people, equipment and lightings.

4.4.2 Energy Consumption/CO_2 Emission in the House with Thermocill

As was alluded to earlier, Thermocill can be installed in any room where the radiator is placed under the window. In order to capture the realistic effect of Thermocill being installed in the simulated house, Thermocill is assumed to be installed only in the bedrooms and the living room, as indicated in Table 10.

Table 10: List of rooms and spaces where Thermocill is assumed to be installed in the simulated house.

Zone		Thermocill Installed
Roof	zone-1-roof	×
First floor	small front bedroom	✓
	toilet	×
	bathroom	×
	front bedroom	✓
	back bedroom	✓
Ground floor	hallway	×
	kitchen	×
	living room	✓

In this section, in order to account for the effect of including Thermocill in the house, we make use of some of the experimental data obtained from Salford Energy House (specifically those presented in Figure 5).

While there are several different scenarios that one could consider, in this study, we have obtained the result for two different scenarios, discussed below.

- **Scenario 1: Heating Provided by All Sources**

In this scenario, the software accounts for the effects of lighting, equipment, people, natural ventilation, etc on the total heating load required in the house. This is equivalent to the house being fully occupied throughout the year. Therefore, in this scenario, lower heating energy should be provided by the heating system in order to achieve the required thermal comfort condition in the house (i.e. 21°C). For example, as presented in Table 9, the presence of people living in the house leads to approximately 353.3 kWh heating load and the lighting produces 2915.1 kWh thermal load, which otherwise should be provided by the central heating system.

In this scenario, the heating load for the entire house is first calculated (breakdown for each space is presented in Table 11, where, as expected, the numbers are consistent with those presented in Table 9).

Table 11: Breakdown of heating load for different parts of the house for Scenario 1.

Zone Summary		**HVAC Zone Eq & Other Sensible Air Heating [kWh]**
Roof	zone-1-roof	0
First floor	small front bedroom	767.9
	toilet	283.5
	bathroom	687.6
	front bedroom	1179.8
	back bedroom	1337.1
Ground floor	hallway	2392.0
	living room	1108.2
	kitchen	728.2
Total Heating Load [kWh]		8484.3
Heating (gas) [kWh] (= Total Heating Load/CoP)		9946.4

Subsequently, the heating load required for the rooms where Thermocill has been installed in are calculated and the energy saving features of Thermocill (original design) found by Salford Energy House will be used to work out the potential savings.

Table 12: Calculated savings in energy and CO_2 emission for Scenario 1.

Heating load for all rooms with Thermocill [kWh]	**Heating (gas demand) [kWh] = Heating load/CoP**	**Energy saving (kWh)**	**Energy saving in space heating (%)[1]**	**Energy saving (£)[2]**	**CO_2 emission saving [kg][3]**
4392.99	5150.05	710.71	7.15	31.12	147.83

[1] Calculated based on energy saving (710.71 kWh) as percentage of the space heating (gas) in kWh for the whole house (9946.42 kWh).

[2] Includes Value Added Tax (VAT) at 5% but excludes any daily standing charge.

[3] Calculated based on the calculated energy saving (710.71 kWh) and CO_2 emission factor for natural gas which is equal to 208 grCO2e/kWh according to Energyplus data set based on data from EPA [18].

As shown in Table 12, the total amount of heating load for the spaces equipped with Thermocill (i.e. 3 bedrooms and the living room) is 4392.99 kWh, which translates itself into

5150.05 kWh gas fuel. Considering 13.8% energy saving achieved from the experimental results of Salford Energy House, the amount of saving in energy and CO_2 emission for this scenario are presented in Table 12.

- **Scenario 2: Heating Provided only by HVAC System**

Table 13: Breakdown of heating load for different parts of the house for Scenario 2.

Zone Summary		HVAC Zone Eq & Other Sensible Air Heating [kWh]
Roof	zone-1-roof	0
First floor	small front bedroom	896.3
	toilet	352.8
	bathroom	838.8
	front bedroom	1503.8
	back bedroom	1793.4
Ground floor	hallway	3105.4
	living room	1790.8
	kitchen	1406.1
Total Heating Load [kWh]		**11687.5**
Heating (gas) [kWh] (= Total Heating Load/CoP)		**13701.7**

Once again using the potential energy saving achieved from the original design of Thermocill obtained by Salford Energy House and using the calculated heating load for this scenario, would enable one to calculate the potential savings in energy and CO_2, which are presented in Table 14.

Table 14: Calculated savings in energy and CO_2 emission for Scenario 2.

Heating load for all rooms with Thermocill [kWh]	Heating (gas) [kWh] = Heating load/CoP	Energy saving (kWh)	Energy saving in space heating (%)[1]	Energy saving (£)[2]	CO_2 emission saving [kg][3]
5984.39	7015.69	968.17	7.07	42.39	201.38

[1] *Calculated based on energy saving (968.17 kWh) as percentage of the space heating (gas) in kWh for the whole house (13701.7 kWh).*

[2] *Includes Value Added Tax (VAT) at 5% but excludes any daily standing charge.*

[3] *Calculated based on the calculated energy saving (968.17 kWh) and CO_2 emission factor for natural gas which is equal to 208 grCO2e/kWh according to Energyplus data set based on data from EPA [18].*

4.5 Limitations and Future Work

In Part B of this study, a 3-bedroom semi-detached house hypothetically located in the Northwest of England, UK was simulated for energy modelling purposes. This model has been chosen as it represents the most common type of dwelling in the UK. As was alluded to in the report, the notional house modelled here does not represent every single house that could benefit from installing Thermocill, since different houses could have very different thermal and energy performance due to their size, construction, fabric, windows sizes/types, layout, location, occupation, thermal comfort requirement etc. Therefore, the potential saving values presented in this study is merely a representative figure and could vary in different situations. As a future work, it is suggested to repeat the same analysis for other types of houses such as detached, terraced and flats with different sizes (number of bedrooms). The same analysis could also be applied to commercial properties (e.g. shops, warehouses, offices, etc) which in theory could benefit from installing Thermocill.

To address the above question about the effect of the house size on the potential benefits of Thermocill, it is worth highlighting that an important parameter in determining the amount of energy and CO_2 emission savings is the 'Total Useful Floor Area (TUFA) of spaces equipped with Thermocill' (i.e. 'TUFA-Thermocill') compared to the Total Useful Floor Area of the house (as defined by Part L of UK Building Regulations). In the notional house tested here, this ratio is 68%. Applying a simple extrapolation to the existing 3-bedroom notional house studied here, one can obtain an estimated energy and CO_2 emission savings which will directly be proportional to the ratio of TUFA-Thermocill to TUFA. For instance for a 4-bedroom semi-detached house with exactly the same specification to the notional house teste here, the energy and CO_2 emission savings will work out to be £40.59 and 192.82kg, respectively. This suggests a trend that the larger the TUFA, the larger the energy and CO_2 emission savings.

In addition, unlike CFD analysis where detailed fluid and heat transfer equations are solved, in thermal/energy modelling, it is not possible to directly assess the geometrical effects of internal features (i.e. Thermocill in this case). Therefore, in order to calculate the energy and CO_2 emission savings, using the experimental data taken from Salford Energy House was the only choice. While such data are scientifically reliable, they have been obtained for a single room with a window in a certain size and specification. Therefore, generalisation of such data could introduce some uncertainties in the results presented in this report. Furthermore, since the energy and CO_2 emission savings relied on the experimental data from Salford Energy House, the new design improvements introduced by the company which came after the completion of the field testing, has not been accounted for in Part B of the present study.

However, given the improvements in the flow and heat transfer observed from the CFD results, one could expect that the energy and CO_2 emission savings for the new optimised Thermocill design should be higher compared to the original design.

5 Summary

The present study consisted of two distinct parts. In Part A, the focus was on calculating the effects of Thermocill on condensation and moisture around the windows. In this part of the study, the original and optimised designs of Thermocill were compared against the case without Thermocill.

In Part B, energy modelling was conducted for a 3-bedroom semi-detached house in order to calculate the potential energy and CO_2 emission savings as a result of installing Thermocill in the bedrooms and the living room. This part of the study investigated 2 different scenarios based on how the thermal comfort level is achieved in the house throughout the year.

The main findings from Parts A and B of this study can be summarised as follows:

Part A (Drying Rate):

- Drying rate was calculated for both the original and optimised Thermocill designs, as the calculations rely on the latest computational simulation data and the latest configuration provided by the client.
- A prior computational simulation work conducted on both the original and optimised designs have found that the latter will improve the flow rate through the channel and the temperature around the window frame by 47% and 22%, respectively.
- The drying rate shown in terms of vapour pressure for the 'Optimised Thermocill Design' was found to be 92% higher than that for the case without Thermocill. In other words, the drying rate of moisture/condensation from the bottom region of the window (i.e. region most prone to the formation of mould) can potentially be doubled when the optimised Thermocill design is installed in the window reveal. The original Thermocill design was also found to improve the drying rate by 39%.

Part B (Energy Modelling):

- The energy modelling was conducted on the original Thermocill design (and does not take into account the significant improvements made to the latest Thermocill design), as the analysis in Part B directly rely on the experimental data from Salford Energy House which were conducted on the original Thermocill design.
- In the first scenario where the heat loading required to achieve a desirable thermal comfort (21ºC) came from all sources including the HVAC, lighting, equipment, people etc., the annual energy and CO_2 emission savings were found to be 7.15% (£31.12) and 147.83kg, respectively.
- In the second scenario where the HVAC system was solely responsible for achieving the desirable thermal comfort level in the house, the annual energy and CO_2 emission savings were found to be 7.07% (£42.39) and 201.38kg, respectively.
- Having applied an extrapolation to the 3-bedroom notional house studied here, the energy and CO_2 emission savings were found to increase with increasing the ratio of floor area of spaces equipped with Thermocill over the total occupied floor area. Therefore, savings are expected to increase for larger houses with more bedrooms and living areas (with the same or similar specification to the notional house tested here).
- The new design features of Thermocill are very likely to improve the energy and CO_2 emission savings reported here mainly due to higher rate of flow diversion (increased by 47%) towards the window (in agreement with what has been observed for the drying rate).

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