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Energy Procedia 132 (2017) 454–459

Energy Procedia

www.elsevier.com/locate/procedia

11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

The thermal characteristics of roofs: policy, installation and performance

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Abstract

This paper investigates the in-situ performance of UK cold pitched roof structures through a case study dwelling of typical construction using site survey, and estimation of U-values through simple calculation and from measured heat flow data. Significant increases of U-values resulted from under- and un-insulated areas due to installation issues, whilst a higher than expected estimated thermal resistance of the roof space and structure was also noted, potentially associated with heat gains. Both issues are expected to be observed more widely in the stock and contribute to a performance gap for roof insulation.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: U-value; thermal resistance; roof; performance gap; in-situ

1. Introduction

Improving the thermal efficiency of the housing stock is central to many governments' policies to deliver the significant reductions in carbon emissions required to curtail global temperature rises [1]. For example, policies to realise the UK commitment to reduce carbon emissions by 80% from 1990 levels [2] identify improved thermal efficiency of dwellings as an important cost-effective measure [3]. It has been estimated that 87% of current UK buildings are still expected to be standing in 2050 [4], and consequently improvements in the performance of the existing stock are central to such policies. Certain types of retrofitted insulation have been identified as "*easy wins*"

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Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics
10.1016/j.egypro.2017.09.664

with "*all practicable cavity walls and lofts having been insulated by 2020*" [3]. However, the in situ performance of loft insulation in UK dwellings has not been extensively studied.

A significant performance gap between expected and actual energy use for energy efficiency interventions has been identified across a wide range of measures[5]. Recently, the performance gap associated with the thermal performance of walls has received considerable interest [6]. However, although loft insulation is one of the most common energy efficiency measures in the UK [7], there are few recent studies of its in situ performance.

This paper discusses the thermal performance of cold pitched roofs, which comprise approximately 80% of domestic roofs in the UK [8]. It identifies mechanisms that may lead to potentially systematic discrepancies between measured and expected U-values for dwellings.

1.1. The potential for a performance gap in roofs

Insulation of cold pitched roofs in the UK is typically rolled mineral wool quilt, installed between and across ceiling joists to meet target maximum U-values of 0.16 and 0.20 $Wm^{-2}K^{-1}$ for existing and new dwellings respectively [9], [10]. New dwellings typically exceed this as roof insulation is a cost effective measure to meet Target Fabric Energy Efficiency rates. Where loft insulation is retrofitted in existing dwellings, a total depth of 250 mm is usually fitted [9].

The thermal performance of loft insulation has been characterized in experiments using test cells, suggesting good agreement between literature U-values and those estimated from measurements in controlled environments [11]–[13]. Whilst increasing airflow over the insulation surface has been shown to result in decreasing performance, the experimental wind speeds were likely higher than those in typical loft spaces; therefore the effect of wind speed in situ is expected to be small [11], [12]. Studies on the impact of a 5% uninsulated area [11] and gaps between insulation rolls [14] suggest a significant effect on measured U-values: an increase of 57.5% for the former and approximately a factor of two in the latter. Both defects were found to have a higher measured impact than expected from simple calculation. However, these studies were carried out in purpose-built structures; the thermal performance of roofs in real UK dwellings has not been widely reported.

Differences between the expected and actual thermal performance of roofs may derive from issues associated with the materials, installation, usage factors and characterization of heat flow through the loft space. These defects can result in cold bridges that may be prone to condensation, and subsequent mould growth [15], such issues have been reported in UK and other Northern European countries and may lead to health impacts. Specific examples may include:

- gaps between insulation rolls [16];
- imperfections in coverage around service penetrations [17];
- practical challenges of finishing insulation around loft features, such as trusses and wall/roof junctions [17];
- reduced insulation thickness around the eaves to ensure adequate ventilation through soffit vents [17] or due to challenges of installation in a confined space, as discussed below;
- degradation of insulation materials due to age, dust/debris accumulation, water or damage from pests;
- thermal bridging and reduced insulation thickness under loft-boarding;
- reduced or missing insulation beneath water tanks and loft hatches [18].

Additionally, roof spaces are complex and challenging to represent in simple estimates of thermal performance or building simulation models. Ventilation from roof, eaves and wall vents depends on installation and specification, plus local wind speeds, whilst the flow of air and heat through partial-fill or unfilled cavity walls, partition walls and service penetrations is difficult to characterise and represent in models.

No recent studies have investigated the impact of installation in houses, degradation of materials and in use factors as outlined above. Results from one case study indicate good performance of loft insulation compared to literature estimates [19], but the loft conditions were not reported and required insulation levels have increased substantially in subsequent years. With the emphasis on improvement of the thermal performance of the stock to support the UK's decarbonisation strategy, there is a need to investigate the in-situ performance of cold pitched roofs.

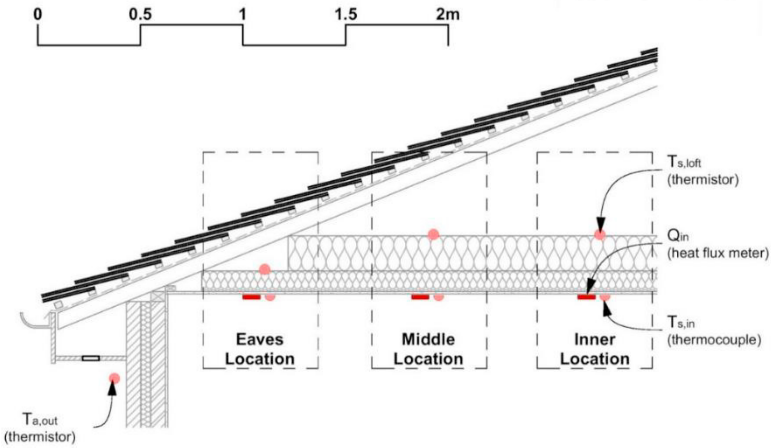

Figure 1: Schematic illustrating sensor locations for this case study, and diminished insulation near the eaves due to space restrictions.

2. Method

This paper reports the case study results from a 1970s detached home in East Anglia, UK. The dwelling is of masonry cavity wall construction, with a duo-pitched cold roof. In 2014 the property was retrofitted with top-up mineral fibre loft insulation to a total thickness of 270 mm in accordance with UK Building Regulations [9].

Following a site survey, including the measurement of key features and thermography, a bedroom ceiling was instrumented with Hukseflux heat flux sensors and thermistors (see Figure 1). Thermal paste was used to ensure good thermal contact and sensors were fixed with tape which did not cover the sensing element of the heat flux plates. Data was collected from February to June 2015 using Eltek Squirrel 450/850 Series data loggers.

Data was analysed to determine the U-value at each location using the average method [20]. Results from a two-week period, between 20/3/2015 08:00 and 03/04/2015 08:00, are presented here. The estimates from the in-situ measurements are compared to standard calculation of the expected thermal properties of the roof, and points on it, following standard methods [21].

3. Results and discussion

3.1. Site survey

A site survey revealed the loft space to be in generally good condition, with no apparent structural issues, infestation or damage. However, as shown in Figure 1, in most locations top-up insulation was not present within approximately 600 mm of the eaves, within which no insulation was present within 300 mm of the eaves. The former accounted for approximately 9% of the total ceiling area, and 19% of the total area was uninsulated, as indicated by Table 1.

Reduced insulation near the eaves, shown in Figure 2(a), is likely a common defect in existing and new dwellings, given the restricted access to this part of the roof (which impedes installation and quality monitoring) and the need to maintain an air gap for ventilation. This is further illustrated in the thermal image of Figure 3(a), taken in a different case study building with a cold pitched roof, which shows a clear cold bridge near the eaves, which may be liable to condensation and mould growth.

A second, potentially common defect with ceiling insulation arises from the fact that, in the UK, an uninsulated space is often left below the cold water tank to prevent freezing in winter; this is illustrated in Figure 2(b). However, while necessary, this measure constitutes a significant cold bridge that may make it difficult or impossible to meet Building Regulations [9] requirements for maximum roof U-values using typical depths of insulation. Instead, the

Figure 2: a) insulation missing above ceiling near eaves b) lack of insulation beneath cold water tank.

cold water tank should be brought within the thermal envelope of the dwelling by ensuring the jacket around the tank forms a continuous layer and overlaps the insulation at ceiling level [22].

Table 1: Site survey data indicating the features and their area that lead to reduced thermal insulation between the ceiling and loft void.

Type of defect	Description	Area (m^2)	Area (% of total)
Uninsulated area	Around water tank	2.8	7
	Eaves (assuming 300mm width on each side)	4.2	9
	Chimney	0.4	1
	Beside loft hatch	0.3	1
Total – Uninsulated area		8.2	19
Under-insulated area	Eaves (assuming 300mm width on each side)	4.2	9
Total – Under-insulated area		4.2	9
TOTAL – Combined affected area		12.4	28

3.2. Calculated U-values from literature material properties

Literature values for the thermal properties of building materials and standard methodology [21] were used to determine the U-value of the case study roof, excluding thermal bridging at the junctions between building elements. Assuming full coverage of insulation apart from the loft hatch and a 300 mm wide band of reduced insulation at the eaves to facilitate ventilation, the whole roof U-value is 0.17 $Wm^{-2}K^{-1}$, just outside the 0.16 $Wm^{-2}K^{-1}$ limit required by UK Building Regulations [9]. However, accounting for the observations in the site survey, the whole roof U-value increases to 0.59 $Wm^{-2}K^{-1}$, well outside the required performance. This increase in U-value is primarily associated with the large uninsulated areas under the cold water tank and around the edge of the roof.

3.3. U-values estimated from in situ measurements

The thermal resistance of the roof was estimated firstly from the interior to the loft void (thermal resistance of the ceiling only), and secondly from the interior to the outdoors (including the thermal resistance of the loft space). These

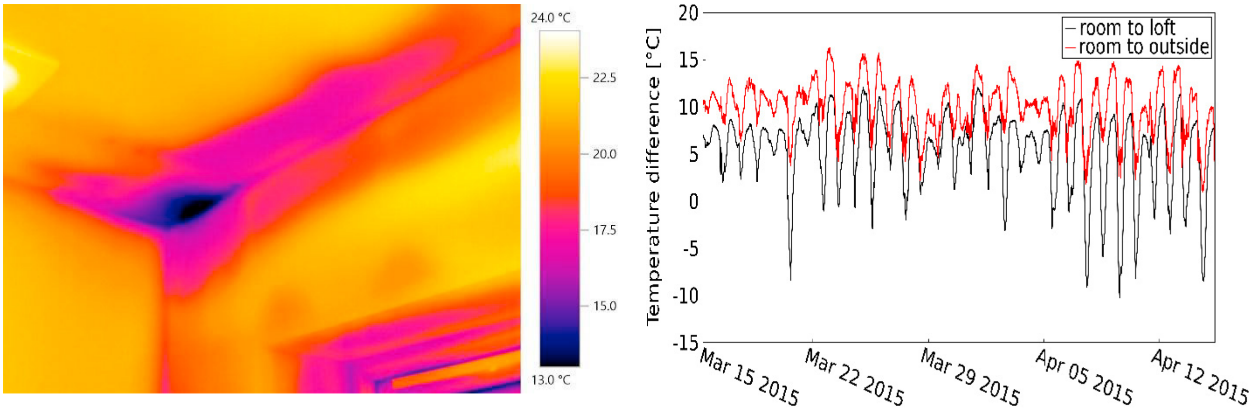

Figure 3: (a) Thermal image illustrating the impact of missing insulation at the eaves of a cold pitched roof (from a different case study to that reported in the rest of this work). (b) room, loft void and outside temperatures recorded during this study

results were converted to U-values, Table 2, which exhibit two notable deviations from literature-based U-values: the impact of the loft space on estimates is larger and the U-value at the eaves location is higher than expected.

Table 2: U-values estimated at the three measurement locations from in-situ measurements and calculation based on literature properties of materials. In-situ U-values are estimated with the average method and agree within error margins to those calculated using a dynamic method based on electrical analogy combined with Bayesian analysis, presented elsewhere [23].

U-values ($Wm^{-2}K^{-1}$)	Eaves	Middle	Inner
In-situ indoor to outdoor	0.56 ± 0.08	0.14 ± 0.02	0.11 ± 0.02
In situ indoor to loft void	0.95 ± 0.13	0.20 ± 0.03	0.16 ± 0.02
Calculated from material properties indoor to outdoor	0.37	0.14	0.14
Calculated from material properties indoor to loft void	0.38	0.14	0.14

The assumed thermal resistance of the loft void and cold roof structure is 0.2 m^2KW^{-1} [21]. However, assuming that standard surface resistances apply, values derived from in-situ measurements are 0.8, 2.2 and 2.9 m^2KW^{-1} for the eaves, middle and inner locations respectively. Whilst these values are subject to significant uncertainty, it is likely that the thermal resistance of the loft is significantly higher than standard assumptions. Figure 3(b) shows room, loft and outside temperatures during the monitoring campaign, indicating that, contrary to expectations, the loft void temperature is consistently significantly higher than outside temperatures. This may be due to low ventilation rates, solar gains or air leakage from other construction elements, e.g. warm air from inside the dwelling entering around service penetrations. Such heat gains into the loft are not represented by the analysis model for in-situ measurements or by the simple calculation of U-values and are therefore represented as thermal resistance here. Whilst accounting for such effects in models is complex, the reduced heat loss due to additional insulation on the ceiling surface will be partly offset by failing to account for these gains, contributing to the performance gap.

There is a significant increase in U-value (Table 2) from in-situ measurements near the eaves compared to that using literature values and calculation [21]. The mechanism requires further investigation, but may be associated with greater air movement around or within the insulation (e.g. associated with poor contact between the plasterboard ceiling and insulation, leading to losses in excess of that assumed in the correction due to air gaps method [21]).

4. Conclusions

This paper reports the results from investigating the thermal performance of a cold pitched roof in a case study dwelling of typical UK construction, through site survey, calculation of U-values based on material properties and in situ monitoring. A significantly higher U-value was calculated based on literature material properties and site survey than that assuming a nominal fitting to the required standard [9]. This is associated with larger than expected uninsulated and under-insulated areas possibly associated with access difficulties, and the interpretation of appropriate insulation around a cold water tank. Such issues are likely to be present more widely in the UK stock due to installation guidance and practice, contributing to a performance gap associated with loft insulation.

Results from in-situ measurements highlight a larger than expected estimated thermal resistance of the loft void and roof structure, which may be associated with ventilation and heat gains. If present more widely in the stock, as expected, this would lead to a systematic decrease in energy savings associated with fitting additional loft insulation in existing dwellings, contributing to the performance gap.

Acknowledgements

This research was made possible by support from the EPSRC Centre for Doctoral Training in Energy Demand (LoLo), grant numbers EP/L01517X/1 and EP/H009612/1, and the RCUK Centre for Energy Epidemiology (CEE), grant number EP/K011839/1.

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