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Modelling hygrothermal performance of roof and floor structures with an energy-efficient constant output heating

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Abstract

In order to improve the energy efficiency of summer cottages in Finland, the effects of a constant output heating in unoccupied cottages are studied. The idea is to apply a minimum amount of energy in order to avoid moisture-related damages on structures and movables.
The modelling results of most commonly applied roof and floor structures in Finnish summer cottages show that heating is not always necessary, but in some cases, depending on structure's materials, ventilation and vapour barrier, the hygrothermal performance may need heating so that the indoor temperature is kept at 3–5°C above the outdoor temperature.

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Keywords: Summer cottages, constant output heating, modelling, roof and floor structures

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1. Introduction

A growing volume of research demonstrates the benefits of adopting energy-efficient or zoned heating, ventilation, and air conditioning (HVACs), with engineers concluding that substantial energy savings can be achieved through these systems [1, 2, 3, 4, 5]. Nowadays there are approximately 500,000 summer cottages in Finland and the amount will increase in the future. Also, the quality of building service systems of summer cottages has increased, i.e. almost two thirds of the cottages are connected to the power grid, and more often new summer cottages are fitted for a year-round use. Summer cottages are often heated in order to maintain living comfort for the next visit, and to ensure that the building will not be deteriorated [6].

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If a summer cottage is heated it is usually equipped with a conventional electric heating, keeping the indoor temperature at a specified level. Usually the temperatures are kept between the values 5 and 15°C, even if the cottage is not used or used very rarely during the heating period (from early autumn to spring). Keeping the indoor temperature relatively high, also during the times the house is not used, needs a lot of energy.

Favourable indoor conditions for movables and envelope structures can be achieved with a lower energy consumption than the conventional heating causes. Moisture related damages, like mould growth and moisture condensation on the surfaces, are depending mainly on the relative humidity of the indoor air. In summer cottage conditions (in the Nordic countries) a few degrees increase in temperature can decrease the relative humidity up to 10–15 %. The studied constant output heating keeps the indoor temperature only a few Celsius degrees above the level where it would be without any heating. At the same time this means that the indoor temperature is kept a few degrees above the outdoor temperature. During the coldest periods the indoor temperature can be very low, even below zero centigrade, which sets demands e.g. for the water systems, and means that it takes longer time to get the indoor temperature on a comfort level for living in the beginning of a visit [7].

The energy consumption of constant output heating is clearly lower than the energy consumption of conventional heating. The constant output heating needs an electric input of 5–15 W per floor square meter. The input varies depending on ventilation and the properties of house, like the heat resistance and air-tightness of building envelope.

In addition to low indoor temperatures, one reason for doing calculations was the moisture content of indoor air. Due to the minor use and the absence of humans and their activities in the summer cottages the average moisture content of indoor air is much lower than that in full-time residential buildings. Also, the indoor air cannot contain much moisture due to low indoor temperatures in summer cottages. The moisture buffering capacity of inner surfaces and movables also affects the situation.

The field measurements in summer cottages have demonstrated that the average moisture content of indoor air is mainly lower than the average moisture content of outdoor air, which opposes to the usual situation in full-time residential houses in Finnish climatic conditions. Even though the conditions differ, the structures in summer cottages and in full-time residential buildings are alike [7].

2. Calculation modelling

2.1. Software and calculation principles

One-dimensional software (Wufi Pro) was applied for the calculations. One hour time interval was applied in the calculations. The chosen one-year calculation conditions were applied after each other for the whole three-year calculation time.

A method for timber-framed external walls [8] was applied in the study. The method is based on a hypothesis that in case of properly functioning ventilation gap, rainfall and solar radiation have only a minor effect to the conditions of timber-framed external wall structures, and thus could be excluded from the calculations. Excluding rainfall and solar radiation eases the selection of the reference year for calculations, because then the suitable reference year can be determined on the basis of measured temperature and relative humidity values. Also, as the conditions of ventilation gap can be applied as outdoor air conditions, the ventilation gap and its external layers (cladding) are also excluded from the calculations.

2.2. Studied structures

Calculations were performed with the most common roof and floor structures of Finnish summer cottages. Studied structures were ventilated roof structure and floor structure with a poorly ventilated crawl space. Two types of porous insulation material and four types of vapour barrier were applied in the calculations. Measured values from the earlier studies were applied as material properties. Mineral wool and cellulose insulation (materials D1 and D4 in [9] and [8], respectively) were applied as thermal insulation and bitumen paper, two types of plastic-coated paper, or plastic foil (materials C7, C9, C10 or C11, respectively) were applied as a vapour barrier. The roof structures were modelled either without a sheathing, or with a glass wool fibreboard or a bitumen paper sheathing (materials A3 or B5, respectively). Wooden fibreboard (material A13) was modelled as a sheathing material in all of the studied floor structures (table 1).

Table 1. Structures and material combinations listed from inside out.

Structure	Vapour barrier	Thermal insulation	Sheathing
Roof S1	Different types 1 mm*	Mineral wool 200 mm	-
Roof S2	Different types 1 mm*	Cellulose insulation 200 mm	-
Roof S3	Different types 1 mm*	Mineral wool 200 mm	Glass wool fibreboard 30 mm
Roof S4	Different types 1 mm*	Mineral wool 200 mm	Bitumen paper 1 mm
Floor S5	Different types 1 mm*	Mineral wool 200 mm	Wooden fibreboard 12 mm
Floor S6	Different types 1 mm*	Cellulose insulation 200 mm	Wooden fibreboard 12 mm

* *Bitumen paper (vapour diffusion resistance factor 187), plastic coated paper A (3880), plastic coated paper B (9640) and plastic foil (89000).*

2.3. Mold growth indexes and performance criteria of structures

The performance of structures was evaluated by using an updated calculation model for mould growth [10], which was based on the earlier model [11]. The model calculates mould index values on a range of 0 to 6, on the basis of given temperature and relative humidity values. Index 0 means that no mould growth exists on the surface of the examined material. Incipient mould growth, detectable only under a microscope indicates index 1 and 2 (less or more than 10% of the surface, respectively). Mould growth detectable with bare ranges from indexes 3 to 5. Index 6 means that the material surface is completely covered with mould.

The performance criterion of each structure was that the mould growth should not exceed either index 1 in the interior parts of the structure, or the index value was calculated on the basis of outdoor air conditions, anywhere in the structure. The most critical interfaces, the interior and the exterior surface of insulation layer, were chosen as the examination points. The exterior surface of insulation layer of structures without sheathing were not examined, as their conditions were almost the same as outdoor conditions. Pine sapwood was studied as a material for the timber-frame and mould indexes were calculated using one-hour time interval. Value 1 was applied as a mould regress factor.

2.4. Modelling conditions

The outdoor conditions in 2007–2008 of the town of Kankaanpää, Finland were chosen for the reference year. Very critical conditions for mould growth (maximum mould index of 3.6) and moisture condensation (the minimum average saturation deficit value in 30 days was 0.117 g/m^3) appeared in 2007/2008, as compared to 30 years climatic data in four different localities in Finland [8,7].

The research included also field measurements in selected Finnish summer cottages. Based on indoor and outdoor RH logger measurements both moisture excess, but mostly moisture deficit exist in case buildings during different times a year [7]. Therefore, both the cases with weekly minimal moisture deficit (-3 g/m^3) and moisture excess (+2 g/m^3) were separately modelled for roof structures.

An average moisture excess of 3 g/m^3 was found in an earlier study on poorly ventilated floor crawl spaces [12]. In case of floor structures both the weekly minimal moisture deficit (-3 g/m^3) and moisture excess in crawl spaces were accounted (+3 g/m^3); leading to an overall moisture deficit – 6 g/m3 in modelling conditions. Additional information on modelling conditions could be found on [7].

3. Results and discussion

3.1. Roof structures

Calculation results of roof structures in 64 variations are demonstrated in Fig. 1. The calculation results indicate that the mould indexes do not exceed the value 1 in the case of 3 g/m^3 moisture deficit in the indoor air. The indexes stay low because temperatures at the monitoring points are quite low also in heated houses (constant output heating; set up temperature difference of 3°C), and therefore relative humidities in the structures were too low for noticeable mould growth. Mould growth starts to regress at degrees below zero centigrade. Mould growth needs at least 80–

100% relative humidity at temperatures between 0 to 20°C [10]. The type of insulation material (mineral wool or cellulose insulation) does not have a significant effect on calculated hygrothermal performance of the roof structures.

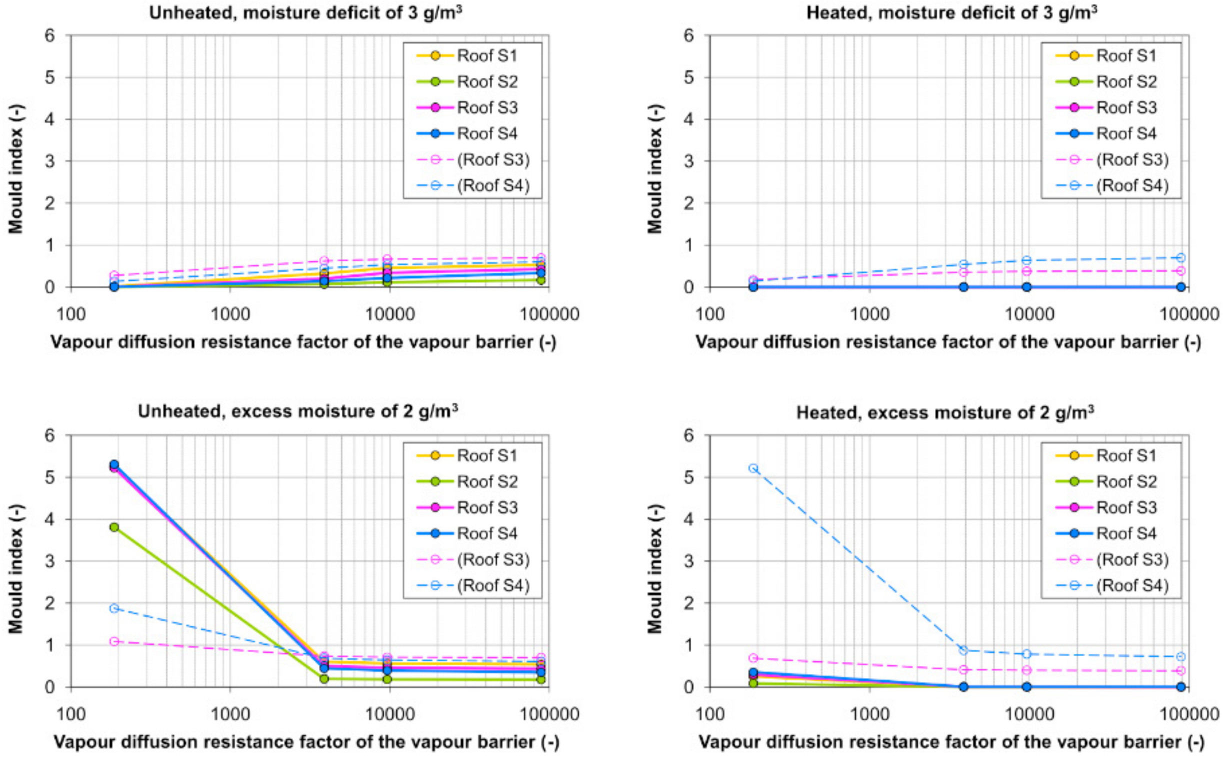

Fig. 1. The calculation results of roof structures. Each dot represents the maximum mould index during the three-year-calculation period. Solid and dashed line refers to the monitoring point at the interior and exterior surface of the insulation layer, respectively. The indoor temperature in heated building is constantly 3°C higher than in unheated building.

Fig. 1 shows that even minor heating improved the performance of roof structures. More dominant trend was found in vapour barriers with lower vapour diffusion resistance. The general performance of the studied roof structures was acceptable both in unheated and heated summer cottages.

It should be taken into account that the calculated results in case of 2 g/m^3 moisture excess in the indoor air, are not corresponding to the actual conditions in summer cottages. The 2 g/m^3 excess moisture in unheated (or in low-heated) cottage means that the relative humidity in the indoor air is close to 100% RH (very critical) for long time periods. Only a large moisture source (production) could create and maintain the continuous moisture excess of 2 g/m^3. Mostly moisture deficit was noticed in the field measurements of unused summer cottages, with the measured relative humidities below 80% RH [7].

3.2. Floor structures

Calculation results of floor structures in 23 variations are shown is Fig. 2. The results show that the hygrothermal performance of floor structures, with a poorly ventilated crawl space is substantially more critical than the performance of roof structures. Mould indexes are very high, especially with a tight vapour barrier. Constant output heating with set up temperature difference of 3°C reduces the mould index (growth risk) at the inner surface of cellulose-insulated floor structures (all variations in S6). However, it was not enough when mineral wool insulated floor structure with high vapour diffusion resistance vapour barrier (floor S5) was applied. Based on the floor calculations it could be stated that a summer cottage with a poorly ventilated crawl space should be heated. In order to determine sufficient amount of constant output heating the calculations with floor structure with most critical mould index values (floor

S5 with the plastic foil vapour barrier) at set up temperatures differences of 3, 4 and 5°C were compared (Fig. 3).

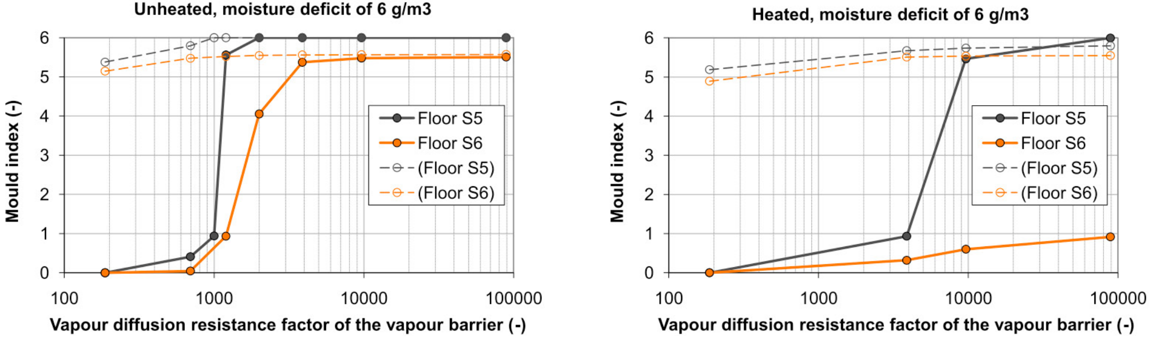

Fig. 2. The calculation results of floor structures. Each dot represents the maximum mould index during the three-year-calculation period. Solid and dashed line refers to the monitoring point at the interior and exterior surface of the insulation layer, respectively. The set up temperature difference is 3°C.

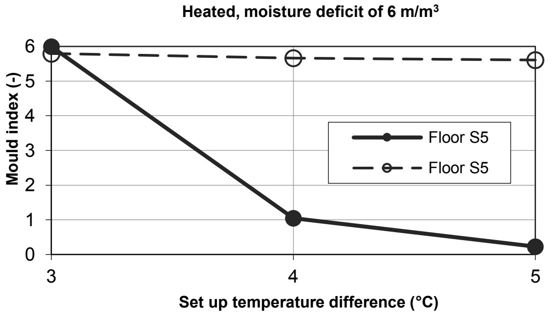

Fig. 3. The calculation results of floor structure S5 at set up temperature differences 3, 4 and 5°C. Each dot represents the maximum mould index during the three-year-calculation period. Solid and dashed line refers to the monitoring point at the interior and exterior surface of the insulation layer, respectively.

Modelling results indicated that increasing the amount of constant output heating (set up temperature differences of 4 and 5°C) reduces also the risk for mould growth. The maximum mould index on the interior surface of insulation layer of the floor structure S5 with a set up temperature of 4°C was slightly above the value 1. With a set up temperature of 5°C the value was close to 0, and so this was a sufficient temperature difference between indoor and outdoor air.

Mould indexes at the interface of insulation layer and sheathing were very high with every calculated set-up temperature differences (3, 4 and 5°C). This might be a result of very critical conditions in the crawl space chosen for the study.

3.3. Uncertainty factors

Several uncertainty factors related to the simplification of calculation, calculation conditions, and to the limits of the software appeared during the study. The software was not able to take into account the heat or moisture transfer by convection. The timber frames of the structures could not be modelled due to one-dimensional calculation model. Lower temperatures and higher relative humidities at timber frames due to higher heat conductivity of timber. Therefore, slightly higher mould indexes would have occurred at the timber frames compared to the presented results.

Chosen calculation conditions were partly too critical. Constant moisture excess of 2 g/m^3 in indoor was overestimated. The conditions of crawl space were consciously chosen to correspond to very critical conditions, and therefore calculation conditions were on a secure side. Excluding rain fall and different types of radiation had also an effect especially on the result of roof structures. Another factor, related to the software, was that the convection could have not been taken into account. This could have affected essentially to the results as porous materials were applied as an insulation. Several structural defects and faults of different degree were noticed during the field measurement to the actual summer cottages, which however could not be accounted in the modelling-based research.

4. Conclusions

All of the studied roof and floor structures fulfilled the requirements of present Finnish building codes. The results of current study have demonstrated that usually the floor structure determines the amount of heating in a summer cottage. The floor with a poorly ventilated crawl space demonstrated the most critical hygrothermal performance. In case of floor structure with very diffusion resistant vapour barrier (e.g. plastic film or plastic coated paper), the temperature difference of constant output heating should be at least 5°C. In case of floor structure with diffusion permeable vapour barrier (e.g. bitumen paper or air barrier paper) the temperature difference of 3°C should be sufficient. Floor covering and finishing has also to be taken into account as those may create a vapour tight layer. Regardless of used vapour barrier material, the air/vapour barrier must be sealed airtightly, so that the mould spores (and other impurities) could not drift from the crawl space to the building.

The temperature difference of constant output heating of 3°C is sufficient with ventilated roof structures irrespective of structure's vapour barrier.

Further studies are needed in order to specify the adequacy of the presented heating demands. Reference field measurements on the conditions at the ventilation gap of roof and in well and poorly ventilated crawl space in part-time summer cottages are highly anticipated. Additional comparison studies of different type of common wall structures of summer-cottages are necessary in order to apply the constant output heating more widely.

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