The impact of convective vapour transport on the hygrothermal risk of the internal insulation of post-war lightweight prefab housing

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Abstract

Interior insulation is being applied in dwellings constructed with the ‘Airey’ system, a post-war prefab construction system which has recently been gaining heritage significance recognition. It’s well-known that applying internal insulation in historic buildings may result in interstitial condensation, surface condensation, mould growth and decay. A review of literature on hygrothermal performance assessment of internal insulation of historic buildings is presented. The results show a strong focus on buildings constructed with solid masonry walls; an evaluation of construction types similar to the Airey system remains absent. The methods that have commonly been applied – being a 1D or 2D simulation of the envelope, focusing on vapour transport through diffusion - were developed to address the hygrothermal behaviour of solid masonry walls. These may not be suitable to identify hygrothermal risks in the Airey system, which is lightweight and has many air cavities. A method for hygrothermal performance assessment that is tailored to these specific characteristics of the Airey system is proposed, combining a whole building HAM-model with a coupled 3D heat transfer model of the construction details. The calibration of the HAM-model to on-site measurements demonstrates the importance of modelling convective vapour transport, specifically as it relates to air leakage through the vapour barrier. The results highlight the importance of accounting for convection in hygrothermal assessments and indicate that simulating a vapour barrier as being installed with perfect airtightness may lead to unrealistic outcomes. Moreover, the results demonstrate the need to further develop the understanding of hygrothermal risks associated with applying internal insulation to non-solid walls, and to adapt the methodology of hygrothermal performance assessments in order to do so.

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1. Introduction

1.1. The Airey-system

In the Netherlands, as well as in many other European countries, there was a large demand for housing after the Second World War. Approximately a quarter of the Dutch pre-war housing stock was either destroyed or severely damaged [1], and new construction was halted during the war [2]. However, both a shortage of the most commonly used building materials (i.e. brick and wood), and a shortage of trained construction workers, hindered the reconstruction efforts [3]. In order to overcome these issues and meet the demand for housing, in 1944, the Dutch government established a foundation1 with the aim of stimulating the development of non-traditional construction systems [2]. The task of this foundation was to vet the proposals sent in by sponsors, principally by individual building firms, and ultimately to designate a limited number of innovative construction systems to officially adopt in the Dutch housing program.

In order to speed up the developments, in 1947 the government introduced the Airey system2, a foreign industrialized building system, to the Dutch market [2]. The Airey system was the most popular of the pre-cast concrete systems in England [4], from which 26,000 dwellings were built [5]. In the Netherlands, 9,975 dwellings were built in the so-called Nemavo-Airey system [6] (see Fig. 1). The Airey system consists of pre-cast reinforced concrete posts and small concrete panels, which are small enough to be handled by two people [4,7]. The storey-height reinforced concrete posts are positioned at 62.5 cm centre-to-centre, and are connected

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2 Called ‘Stichting Ratiobouw’ (transl: ‘Foundation Reasoned-Construction’)

https://doi.org/10.1016/j.enbuild.2019.109418
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at floor height by a steel edge beam (see Figs. 2 and 3). This beam supports the floor structure, which consists of steel lattice girders. The concrete cladding panels are 37.5 cm high, 62.5 cm wide and 4 cm thick. The panels are laid without mortar and are attached to the concrete posts with copper wire. The inner wall consists of non-load-bearing pumice concrete blocks. The Airey system could be easily erected by unskilled labour, without the need for scaffolding, a crane, or other special equipment [2,4].

In recent years, the heritage significance of the Airey system is increasingly being recognized. This recognition is underlined by multiple neighbourhoods and complexes constructed with the Airey system recently being assigned monument status. To meet thermal comfort and energy savings requirements while recognizing heritage values, internal thermal insulation is being applied in Airey-buildings. It is well-known that applying internal insulation in historic buildings may result in interstitial condensation, surface condensation due to thermal bridging, and ultimately, mould growth and decay [8–11]. Due to the unique characteristics of the Airey system, standard solutions may not be applicable. The research aim is to conduct a hygrothermal performance assessment of the internal insulation of Airey-dwellings, as such an assessment remains absent in literature. The research will evaluate a proposed refurbishment design of 141 dwellings constructed with the Airey system in Amsterdam (see Fig. 1). The buildings currently do not have an official heritage status but are positioned in a neighbourhood that is a designated conservation area. Moreover, the refurbishment of the buildings was planned as a result of demolition plans being cancelled due to protests from residents and heritage groups. Therefore, the decision was made to apply internal insulation in order to preserve the exterior appearance of these Airey buildings.

As mentioned, the inner wall of the Airey system consists of non-load-bearing pumice concrete blocks. This provided the opportunity to remove this non-bearing part of the structure and replace it with interior insulation (see Figs. 2 and 3). The insulation ma-

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3 Dutch translation: drijfsteen. Lightweight concrete blocks with a density of 600-900 kg/m³
4 In 2010, the neighbourhood 'Frankendael/Jeruzalem' in Amsterdam was the first post-war neighbourhood to be assigned national monument status; in 2016, the large scale complex titled 'Sloterhof' in Amsterdam, was assigned national monument status; in 2015, the Jericho/Jeruzalem neighbourhood in Amersfoort was assigned municipal monument status; and lastly, a neighbourhood in Meppel was assigned provincial monument status.
5 Two layers of internal insulation were applied. Firstly, a 90 mm layer of light rock wool (ca. 35 kg/m²) [12] was applied in between the concrete columns in the
erals are vapour open (µ ~ 1.0). At the warm side of the insulation, a vapour barrier (PE-foil) was installed, on top of which gypsum board was applied as an interior finish. On the floor of the apartments, a gypsum fibre-based floor element containing 20 mm mineral wool was applied. The ceilings were hung from the steel lattice girders using a metal stud profile, on which firstly, a vapour barrier was applied; and secondly, gypsum boards were applied as a ceiling. Subsequently, glass wool insulation was blown into the cavities of the first and second floor (mainly for reasons related to acoustics). Lastly, the roof was insulated from the top⁶ (see a coupled publication on the dataset [15] for more details on material properties).

The first steps of this research are presented in this paper: Firstly, to both develop and position this hygrothermal performance assessment, this paper presents a review of the literature on hygrothermal performance assessment of internal insulation of historic buildings. Subsequently, this review is related to the Airey system, and a method for hygrothermal performance assessment that is tailored to the specific characteristics of the Airey system is proposed. Lastly, this model will be calibrated using on-site measurements conducted in three test-dwellings. An additional publication [16] reports on the results of the hygrothermal assessment, in order to provide insight into the hygric and thermal challenges involved when applying internal insulation in dwellings constructed with the Airey system. The outcomes may also be useful when evaluating other industrialized building systems: for example, the Cornish Unit system, which is closely akin to the Airey system [4], of which 30,000 were built in the United Kingdom [5].

1.2. The hygrothermal risk of internal insulation

In historical buildings, thermal insulation is mostly positioned at the inside of the building envelope, as the exterior appearance is often protected due to heritage significance considerations [10,17,18]. Applying internal insulation and improving the airtightness of the building envelope results in both greatly reducing the temperature of the historic envelope during winter [10,11] as well as higher levels of indoor humidity [5]. This reduces the drying potential of the envelope, and when indoor air enters the structure, this may lead to high humidity levels and interstitial condensation on the former interior surface [8–11]. This can lead to structural damage and mould growth. The World Health Organisation classifies mould growth as a potential health hazard, and strongly urges dampness and mould-problems to be prevented (and remediated when they occur) [19]. Therefore, when applying internal insulation in historic buildings, an evaluation of the possible hygrothermal risks is indispensable, both to protect the historic structure, as well as to prevent health hazards.

Although multiple publications review a small number of hygrothermal assessments and provide an overview of the issues related to the hygrothermal risk of internal insulation (e.g. [11,20]), no comprehensive or systematic review could be found on hygrothermal performance assessments of the internal insulation of existing buildings. Therefore, a literature review on this – still rather limited – body of literature was conducted. In Scopus, the search terms – 'hygrothermal' and 'insulation' – and – 'interior' or 'internal' – currently⁷ results in 95 journal, and 84 conference papers. Of these papers, only 39 journal papers and 20 conference papers report on a hygrothermal performance assessment of applying internal insulation to an exterior envelope of an existing building (the other 115 papers were excluded for a variety of reasons, see online supplementary material). The number of publications has grown rapidly during the last few years, with more than 80% of publications being published since 2013 (see Fig. 4). Most journal papers are published in Energy and Buildings (9), Building and Environment (9), and the Journal of Building Physics (5). The conference papers are mostly published in Energy Procedia. Considering these 59 remaining papers, the review focussed on:

1. Methods used in the data collection
2. Location and climate of the assessment
3. Composition of the existing exterior wall
4. Types of insulation systems and innovative insulation materials used
5. Methods and results of the risk assessment

Generally, three types of data collection are used for the hygrothermal performance assessment, on-site measurements (36%), laboratory measurements (27%) and hygrothermal simulations (80%). More than a third of the papers (41%), conducted both a hygrothermal simulation as well as either on-site measurements or laboratory measurements, which are generally conducted to calibrate and validate the simulation model. Quite a few publications indicate that the simulation models have a better correlation to temperature measurements than to humidity measurements (e.g. [17,21–25]). A standard means of evaluating whether the simulation model has achieved an adequate fit to the measurements was lacking. As a result, the calibration is often simply stated as being ‘good enough’, mostly by showing a graph comparing the measured and simulated data.⁸ Most papers that conducted a hygrothermal simulation (47), either used WUFI (36%) or Delphin (34%) software to conduct mostly 1D (66%) and/or 2D (40%) simulations. These simulations in WUFI and Delphin largely consist of a dynamic coupled heat and moisture transfer simulation, which focusses on vapour transport through diffusion. Vapour transport through convection is outside the scope of such simulations. Only 15% of the papers mention the word convection or air leak beyond stating it is not included. Only 2 papers conducted a 3D simulation [23,29], one of which being the only paper that included convection in the simulation [29]. In addition, one paper concluded that convection was occurring and consequently omitted the vapour barrier and adjusted the diffusion resistance of materials to be vapour open to achieve the best correlation to the on-site measurements [31].

Most papers (54 out of 59), conduct the hygrothermal risk assessment for a specific location – albeit on the location itself through on-site measurements, or mimicking the climate of the location in laboratory experiments or simulations. As some papers include multiple cases on different locations, a total of 65 cases were analysed. The literature is mostly focussed on cases in Europe, with only 9 cases focussing on other locations, being the United States [2], Canada, South Korea [5] and Japan. In Europe, the countries where the most cases were conducted are Germany (8), Switzerland (8), Czech Republic (7), Denmark (5) and Estonia (5). The Köppen-Geiger climate classification system [32] was used to analyse the types of climates that are included in the literature (see Fig. 5). 86% of the cases are located in climates in which the second letter is an ‘F’, which indicates that these climates have high levels of humidity all year round. More than three-quarter of the

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⁶ Either without providing any data to support this (e.g. [26]), or simply by showing a graph comparing the measured and simulated data. However, the period for comparison is often very short, which does not allow the evaluation of different climatic conditions (e.g. [27]), or very long period, which does not provide a sufficient level of detail in the charts (e.g. [28])

⁷ As searched on 20-08-2018
case studies (76%) is situated either in a ‘temperate continental / humid continental climate’ (Dfb – 51%), a ‘temperate oceanic climate’ (Cfb – 14%), or a mix of both previously mentioned climates (Dfb/Cfb – 11%).

Concerning the type of exterior walls assessed in the literature, there is a very strong focus on solid masonry walls (71%), consisting mostly of brick or stone. Out of the 42 papers that focus on solid masonry walls, 13 specifically assess the risk associated with the wooden beam ends that are often embedded in such walls. Other construction types are only covered by 1–5 papers (see Table 1), which indicates a lack of understanding related to these types of constructions. If a specific wall structure has only been assessed in a few papers, there may not be a sufficient range of climates, assessment methods, and/or insulation systems and materials, to draw reliable conclusions on the risks associated with applying internal insulation.

Interior insulation systems are either vapour tight or vapour open. A vapour tight system is often referred to as a ‘traditional’ or ‘conventional’ system [41], and includes a vapour barrier to avoid interstitial condensation. However, as these systems are also known to prevent the wall from drying out towards the interior climate, vapour open solutions are recently being promoted [46]. Capillary active insulation materials are a specific kind of vapour open insulation system with the purpose of absorbing liquid water that has accumulated on the interface of the former interior surface and the insulation (either caused by driving rain or by interstitial condensation), and transporting it inward toward the room [41]. Of all papers that include a hygrothermal simulation, 49% consider capillary active insulation materials without a vapour barrier (of which 39% also evaluate the use of a traditional insulation system with vapour barrier), 25.5% consider only vapour tight systems, and 25.5% consider vapour open systems without...
the use of a capillary active insulation material (of which 17% also consider vapour tight systems). In addition, six papers assess the application of a smart vapour barrier. A smart vapour barrier has a humidity-dependent vapour diffusion resistance [81], which is aimed at functioning as a vapour retarder during colder months, while allowing vapour to dry out towards the interior during warmer months [44]. Lastly, in addition to capillary active insulation materials, 24% of the papers consider one or more innovative insulation materials, such as aerogel (15%), hydrophobic insulation materials (19%), vacuum insulation panels (5%), and insulating renders (5%).

In more than half of the papers, either a risk (37%) or potential risk (19%) was identified. These risks were related to high humidity or moisture content levels (32%), mould growth (32%) and/or freeze/thawing (15%). Although the risk of mould growth was mentioned in 64% of the papers, only 24% conducted an assessment using a mould growth prediction model, and an additional 15% evaluated the risk for mould growth by setting a RH limit (e.g. RH <80%). Out of those papers where mould growth risk was assessed, 61% identified a risk, and 17% identified a potential risk. In 41% of the papers, no risk was identified, and in 3% no clear conclusion was drawn. However, of those papers that didn’t indicate a potential risk, 80% did not evaluate the risk for mould growth (58% didn’t even mention the word mould, and 69% didn’t mention it beyond the introduction).

There is no clear difference between those case studies where a potential risk was identified, and those where no risk was found. Therefore, it is not possible to identify (based on a sufficient number of papers) a type of insulation system or insulation material that results in less than half of the studied case studies indicating a potential risk. No significant difference was found between applying a ‘traditional’ vapour tight insulation system and applying a capillary active insulation system. In addition, the application of a smart vapour barrier did not reduce hygrothermal risks being identified. The fact that the majority of studies indicate a potential risk in all types of insulation systems and materials may lead to the conclusion that there is no scientific consensus on a general solution that can be applied in most instances.

1.3. Hygrothermal performance assessment tailored to the Airey system

In general, literature on hygrothermal assessments for other types of structures besides solid masonry is still very limited. Moreover, no literature was found in which a construction system similar to the Airey system was considered. In the climate in which the case study is located (temperate oceanic - Cfb), a total of 15 case studies have been assessed. All but one of these case studies consider existing walls made up of solid masonry. The one exception considers a 200-year old wood framework house. The Airey system clearly has very different characteristics than those cases studied in the same climate. A hygrothermal assessment of this kind of construction system remains absent from literature, while the main characteristics of these types of buildings – being: lightweight; many air cavities in the construction; and very leaky [82] – strongly warrant such an assessment to be conducted.

If the methodology that is most commonly used in literature were applied, this would probably not result in the identification of hygrothermal risks for two reasons. Firstly, as the Airey system has an air cavity which is ventilated with exterior air, driving rain reaching and accumulating at the interface of the existing wall and the insulation is not an issue in this type of construction. This was confirmed by the measurements, which show that periods of rainfall have no significant effect on the relative humidity of the wall cavity or roof/ceiling cavities (see a coupled publication of the dataset and additional graphs [15]). Secondly, as a vapour barrier is applied, which has a high vapour diffusion resistance (S > 20 m), a 1D or 2D model that simulates vapour transport by diffusion, would not result in high quantities of vapour from the interior climate entering the construction.

The interior insulation system as described, is a vapour tight insulation system. Two types of vapour transport need to be controlled in order to prevent hygrothermal risks: diffusion and convection. Firstly, diffusion is the transport of vapour through construction materials, driven by vapour pressure differences [10,11]. Secondly, convection takes place when vapour is transported by an airflow through leaks, driven by air pressure differences across the envelope [10,11]. In conventional, vapour tight insulation systems, convection generally plays a more significant role in the amount of vapour transport in the construction than diffusion [8,10,11]. Both types of vapour transport are prevented by applying a vapour barrier (e.g. PE-foil) on the warm side of the envelope. This barrier prevents diffusion due to its high diffusion resistance, while convection is prevented by installing the vapour barrier such that it is as airtight as possible [8,11].

Literature on hygrothermal performance acknowledges the importance of the consideration of imperfections of the vapour barrier in hygrothermal simulations [9]. As Wegener and Bednar [29] state: ‘an absolutely airtight layer (without leakage) ... does not occur in building practice’. It has been well-known for a very long time that small holes in vapour barriers can result in a significant increase of vapour transport [83]. Kölsch et al. performed laboratory tests on the leakage occurring per metre in adhesive tape, and concluded that leakage will always occur, and moreover, that a single tiny imperfection – introducing vapour transport by convection – increases the permeability by a factor of 100 [84]. In addition, Seiffert [85] found that a 0.014% perforation of aluminium foil will increase the vapour transport – due to introducing vapour transport by convection – by 100-fold. Moreover, when 0.22% of the surface is perforated, a 4,000-fold increase follows. The ASHRAE Fundamentals Handbook provides an estimation of the effective air leakage areas in a ceiling being 1.8 cm²/m² (0.018%), but this does not take into account the presence of an installed vapour barrier [83].

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Review hygrothermal risk of internal insulation: Types of existing wall structures.</th>
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<tbody>
<tr>
<td>Type</td>
<td># Papers</td>
</tr>
<tr>
<td>Solid</td>
<td>Masonry (brick/stone) 42</td>
</tr>
<tr>
<td></td>
<td>+ with focus on wooden beam ends 13</td>
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<tr>
<td></td>
<td>Solid concrete 5</td>
</tr>
<tr>
<td></td>
<td>Hollow masonry bricks 1</td>
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<tr>
<td></td>
<td>Hollow concrete bricks 1</td>
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<tr>
<td>Cavity</td>
<td>Masonry 3</td>
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<tr>
<td></td>
<td>Masonry + concrete 2</td>
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<tr>
<td></td>
<td>Hollow concrete bricks 1</td>
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<tr>
<td>Wood</td>
<td>Logs 2</td>
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<td></td>
<td>Skeleton 2</td>
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The type of construction assessed in this case, is especially sensitive to air leakages because of multiple reasons: Firstly, especially in lightweight building components, it’s acknowledged that even state-of-the-art airtight constructions are not completely free from faults [8,86]. Secondly, it is well-known that good airtightness is much easier to achieve in new construction than in the refurbishment of existing buildings, as it is often impossible to achieve a continuous layer through all building components in existing buildings [11,83]. Thirdly, air leakages in ceilings require additional attention, because ceilings are often penetrated by installations, and because the stack effect is recognised as being a critical parameter for the hygrothermal behaviour of a construction [87]. In practice, moisture infiltration due to vapour convection can never be avoided completely [86], and condensation problems may occur as a result of air leakage through unintended gaps and perforations [8,86]. It’s acknowledged that a hygrothermal performance assessment should either account for air transfer [8], or provide a ‘drying reserve’, which has become an established moisture control design principle [86].

As is clearly visible in a 3D view of the construction (see Figs. 3 and 9), the characteristics of the Airey system make it practically impossible to model in a 1D or 2D simulation model. Moreover, as the vapour barrier is positioned alongside interior surfaces (see dotted line in Fig. 3), and the insulation materials are vapour open, it is the air positioned in the ceiling and roof air cavities that is most directly in contact with the critical evaluation points (being the roof-to-wall connection and floor-to-wall connection). Therefore, it is indispensable to assess the hygrothermal relations – and the extent to which air leakage is occurring – between the exterior climate, interior climate, and the air cavities of the construction.

2. Methodology

The proposed methodology consists of 3 phases: model validation, reference year simulation, and sensitivity analysis (see Fig. 6). This paper will elaborate on the first phase of the methodology, which focusses on the on-site measurements and the development and validation of the simulation models. An additional publication [16] presents the second and third phase of the evaluation, which covers the reference year simulation results and a sensitivity analysis. The first phase, the model validation phase, consists of four steps to construct both a reliable and validated Heat, Air and Moisture (HAM) model of the multi-zone building as well as a coupled 3D heat transfer model of the critical points of the construction. In order to achieve this, firstly, thermal imaging was conducted to assess the indoor surface temperatures and to identify possible thermal leaks in the façade. Secondly, critical points were identified and both temperature sensors and relative humidity sensors were placed at these points to conduct on-site measurements. As the building was not occupied during these measurements, the model calibration and validation were conducted on a non-occupied model. Thirdly, a multi-zone HAM building model was constructed in Matlab using HAMBase, which simulates the dynamic heat, air and moisture processes in the building, resulting in the hourly air temperature and relative humidity of the zones of the building. This model was validated using outdoor climate data and indoor measurements. Lastly, 3D dynamic heat transfer models of the critical points in the construction were constructed in COMSOL 5.2 [88](from this point referred to as the COMSOL model). The results of the HAM-model, being hourly relative humidity (RH) and temperature (T) data per zone of the building, provide the boundary conditions for the coupled COMSOL model, which in turn simulates the surface temperatures of the critical points of the construction. The COMSOL model was also validated using on-site measurements. This coupling of a HAM building model with a thermal model of the 3d construction detail has also been done by Antretter et al. [30].

2.1. On-Site measurements

The refurbishment design was applied to three ‘test-dwellings’. This meant that during the construction phase, temperature and relative humidity sensors could be placed both inside and outside of the envelope (further details regarding the sensors and exterior climate data can be found in a coupled publication of the dataset [15]). Although the on-site measurements were taken over the entire year, only the months March up to and including July were considered for the validation and calibration, as there was still ongoing construction activity in the dwellings up to January and the dwellings were used as office space from August. The calibration results for the months March through December did attain a similar fit, and are included in a coupled publication of the dataset [15]. Three parts of the construction were monitored and simulated (see Fig. 7): (1) the roof-to-wall detail; (2) the first-floor-to-wall detail; (3) the ground floor/wall detail. For the purpose of this paper, the results of part 1 are discussed, as in the final evaluation, a similar hygrothermal risk was found in part 1 and 2, and no significant hygrothermal risk was found in part 3. Fig. 7 shows the sensors that were positioned in this construction part.

2.2. HAM-model

A multi-zone building model was developed using HAMBase [89,90], a Heat, Air and Moisture modelling and simulation tool developed in the scientific programming environment MATLAB at Eindhoven University of Technology. The model was used to simulate the dynamic heat, air and moisture processes in the building, resulting in the hourly air temperature and relative air humidity of the multi-zone building. The physics of this model is extensively described by de Wit [80] and van Schijndel [89]. The airflow modelling considerations – related to interzonal flow, infiltration and stack effect – are extensively described and validated through multiple benchmarks in a report by Spruit and Bischoff [91]. A comparison of a range of HAM-models (including HAMBase) was...
conducted as part of IEA Annex 41 [92]. The main modelling considerations, material properties and infiltration rates can be found in a coupled publication and dataset [15].

For the evaluation of the part of the building that contains the roof-to-wall connection, a HAM-model was built of the apartment that covers the top floor. This model consists of three zones: zone 1, the indoor climate of the living spaces (living, kitchen, bathroom, hall, bedrooms); zone 2, the ceiling cavity in which the steel lattice beams are positioned; and zone 3, the roof cavity. The walls and floors to the adjacent apartments were simulated as being adiabatic (no heat or vapour transfer, no air flow exchange). Infiltration through the envelope was calculated according to NEN 8088 [93] and is included in all three zones. For the entire dwelling, the infiltration rate is 5.34 dm$^3$/s·Pa$^3$, which corresponds to 0.116 dm$^3$/m$^2$·s·Pa$^3$ per square metre of the building envelope (assuming $n = 0.65$). No infiltration was modelled through...
the roof. The apartment was modelled as a single zone, as it is a small apartment with lightweight internal walls. However, the internal walls, partition walls and floor were modelled for their contribution in thermal mass and moisture buffering capacity. The critical evaluation points are all positioned in the ceiling cavity in zone 2.

2.3. 3D dynamic heat transfer model

The construction details were modelled in Revit and subsequently imported into a 3D dynamic heat transfer model in COMSOL (see Fig. 9). As has already been illustrated in Figs. 2 and 3, the construction part is impossible to model in 1D or 2D. The results of the HAM-model (hourly RH and T per zone), in combination with the exterior climate data, provide the boundary conditions for the coupled COMSOL model, which in turn calculates the temperature of the critical points of the construction. Three evaluation points were selected: evaluation point Girder (positioned at the warm side of the insulation), and evaluation points Beam and Column (positioned at the cold side of the insulation (see Fig. 9). All three evaluation points are located adjacent to zone 2, the ceiling cavity. The vapour barrier is positioned in between two gypsum panels in the ceiling, in between zone 1 and zone 2. There is no vapour barrier within the ceiling cavity (zone 2), and the insulation is vapour open. This means that the vapour in the air of zone 2 can reach the surfaces of these points in the construction. Therefore, by combining the relative humidity data of the ceiling cavity with the surface temperatures of these 3 evaluation points – both in front of and behind the insulation – the relative humidity at these surfaces is calculated.

2.4. Validation & calibration indicators

As mentioned, in the literature review on hygrothermal assessment of internal insulation in existing buildings, there does not seem to be a standard means of evaluating whether a simulation model has achieved an adequate fit to the measurements. However, in the wider field of building simulation models, two statistical indices are widely used as a means to demonstrate the calibration accuracy of building simulation models in comparison to measurements: the mean bias error (MBE), and the cumulative variation of the root mean squared error (CVRMSE) [94]. The MBE (see Eq. (1)) serves as an indicator of the overall bias of the simulation model, as it reflects the mean difference between measured and simulated data points. However, as any positive difference compensates for negative differences (the cancellation effect), an additional measure of error is required. The CVRMSE (see Eq. (2)) determines how well the model fits the data by capturing the offsetting errors between the measured and simulated data.

\[
MBE(\%) = \frac{\sum_{i=1}^{N_p} (m_i - s_i)}{\sum_{i=1}^{N_p} (m_i)}
\]

(1)

\[
CVRMSE(\%) = \sqrt{\frac{\sum_{i=1}^{N_p} (m_i - s_i)^2 / N_p}{m}}
\]

(2)

Whereby:

- \(m_i\) = measured data points for each model instance ‘i’
- \(s_i\) = simulated data points for each model instance ‘i’
- \(N_p\) = number of data points at interval ‘p’ (i.e., \(N_{monthly} = 12\))
- \(N_{hourly} = 8760\)
- \(m\) = mean of the measured data points

A European standard for the calibration of building performance simulations is being developed by CEN Technical Committee 89. The validation of building energy simulation models is currently based on the compliance of a model with standard criteria for CVRMSE and MBE set out by ASHRAE Guideline 14 [95]. A model is considered ‘calibrated’ if it attains a 5% MBE and a 15% CVRMSE using monthly data, and a 10% MBE and a 30% CVRMSE using hourly data. This ASHRAE Guideline however, is meant to evaluate the calibration of energy performance models and is therefore not specifically developed for hygrothermal performance models. Nevertheless, the MBE and CVRMSE have been used to assess hygrothermal performance simulation models as well (see for example [96–99]). One of the papers included in the literature review adopted a similar kind of indicator, the root mean square deviation [77]. In addition to these two indices, another index (RN RMSE) was used which does not use the mean of the measured data in order to normalize the results. The use of this index did not significantly change the results (a full evaluation of all three indexes can be found in [15]).

2.5. Interzonal air leakage

Initially, there was no air leakage modelled between zone 1 and zone 2. However, it was observed that both during the design as well as during construction, there was no strong emphasis on the airtightness of the construction. Firstly, the design of the refurbishment was not particularly attentive to the airtightness of the vapour barrier, as it was positioned directly behind the gypsum ceiling panels, which were screwed onto a metal stud system. Naturally, this caused the vapour barrier to be punctured by these screws numerous times (see Fig. 2 in the online supplementary material). This type of construction is flagged in the ASHRAE Fundamentals Handbook[83], which warns against faults or leaks occurring at electrical boxes, plumbing penetrations, telephone and television wiring and other unsealed openings. Moreover, it warns against mechanical fasteners penetrating the vapour barrier. Secondly, it seemed that absolutely no attention was given during construction to the penetrations of the vapour barrier by ducts or PVC tubes (see Fig. 1 in the online supplementary material). A recent study [100] showed that even in new construction projects,
the attention to airtight workmanship is key in achieving good air-tightness, and that a ‘random’ selection of the mainstream construction market resulted in high leakage rates. According to these observations, air leakage between zone 1 and zone 2 was considered to be highly likely. This assumption was confirmed by the initial results. Therefore, subsequently, interzonal air leakage between the interior climate and the ceiling was added to the HAM-model. 

As a clear estimation of the air leakage rates between the interior climate and a ceiling cavity separated by gypsum panels and a vapour barrier could not be found in literature, other estimations were used to test which provided the best fit to the measurements. The handbook ‘AIVC Guide to Ventilation’ lists air leakage rates for parts of the construction, such as windows, doors, walls, floors and ceilings [101]. A literature review [102] on airtightness estimation concluded the AIVC database to be dominating when it comes to estimating component leakage rates. For plasterboard ceilings, the handbook lists 0.11 dm$^3$/m$^2$·s·Pa$^n$ with $n = 0.75$ as the median air leakage coefficient and 0.2 dm$^3$/m$^2$·s·Pa$^n$ with $n = 0.72$ as the upper quartile air leakage coefficient. For a timber panel with an air barrier, the handbook lists 0.066 dm$^3$/m$^2$·s·Pa$^n$ with $n = 0.78$ as the median air leakage coefficient. These estimates were used to model a pressure dependant airflow. In addition to this pressure dependant airflow, a constant interzonal airflow was modelled in order to see which provided the best fit to the measurements.

The air leakage between zone 1 and zone 2 (interior and ceiling) was simulated as:

- Constant interzonal airflow ($\beta_{12}$) between zone 1 and zone 2 (values tested: 0.00233; 0.0467; 0.0700; 0.0933; 0.1166; 0.1400; 0.1633 dm$^3$/m$^2$·s)
- Pressure-dependant air leakage ($C_{12}$) between zone 1 and zone 2 (values tested: 0.066; 0.11 and 0.20 dm$^3$/m$^2$·s·Pa$^n$) ([101])

The air leakage between zone 2 and 3 was estimated to be large, as these are only separated by some plywood boards, with many visible cracks and holes in this location. This was simulated in two ways:

- Constant airflow ($\beta_{23}$) of 0.279 dm$^3$/m$^2$·s between zone 2 and 3
- Pressure-dependant air leakage ($C_{23}$) of 0.52 dm$^3$/m$^2$·s·Pa$^n$ with $n = 0.67$ as the median air leakage coefficient. (timber panel with wall board [101])
- An overview of the air flows is presented in Fig. 10.

3. Results

3.1. Initial results

Both the 3D heat transfer model and the HAM-model were validated by means of a comparative analysis with the on-site measurements. The 3D heat transfer model attained a good fit (e.g. 1.54% MBE and 11.97% CVRMSE for evaluation point Beam). Graphs showing both the measured and simulated data are included in a coupled publication and dataset [15]. The HAM-model initially had a good fit in zone 1 (the interior climate), with the hourly temperature simulation scoring −1.57% MBE and 6.66% CVRMSE and the hourly relative humidity simulation scoring −1.99% MBE and 9.25% CVRMSE. Although zone 2 (roof cavity) had a good fit in terms of the temperature simulation (−4.92% MBE and 11.55% CVRMSE), the relative humidity simulation didn’t perform as well (10.90% MBE and 19.20% CVRMSE). Although the HAM-model did meet the set requirements at this point, and it is common to have a better correlation to temperature measurements than to humidity measurements (e.g. [17,21–25]), these results should be optimized, as specifically the relative humidity of zone 2 was considered to be crucial for the evaluation of the hygrothermal risk of the roof-to-wall construction part. Moreover, the MBE of the relative humidity of zone 2 shows a positive bias, which means that the simulated relative humidity was lower than the measured relative humidity. Therefore, accepting the model without further optimization would lead to an underestimation of the potential risk.

3.2. Results interzonal air leakage

The results of the calibration of the simulation to the measurements, being the corresponding MBE and CVR MSE values, are listed in Table 2. Additionally, Table 3 lists the improvement of these statistical indicators in relation to the base scenario of having no air leakage modelled. The improvement of the fit of the model by adding the air leakage was highly significant. The bias (MBE) of the model in predicting a lower relative humidity in the ceiling than measured, was greatly reduced. It is puzzling that the modelled constant airflow provides a better fit to the measurements than the pressure dependant airflow. Theoretically, a pressure dependant flow should be a more accurate way of modelling convective air transfer. However, this counterintuitive result may be due to the fact that the simulation of airflows caused by wind pressures and stack effects is ‘very inaccurate’, (see [90] for more details and explana-
Table 2
Model calibration in relation to air leakage rate from indoor climate (zone 1) to the ceiling cavity (zone 2).

<table>
<thead>
<tr>
<th>zone 1 - zone 2</th>
<th>n</th>
<th>CV RMSE</th>
<th>MBE</th>
<th>CV RMSE</th>
<th>MBE</th>
<th>CV RMSE</th>
<th>MBE</th>
<th>CV RMSE</th>
<th>MBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dm³/(m²·s)</td>
<td>-</td>
<td>6.66%</td>
<td>-1.57%</td>
<td>11.55%</td>
<td>-4.92%</td>
<td>9.25%</td>
<td>-1.99%</td>
<td>19.20%</td>
<td>10.90%</td>
</tr>
<tr>
<td>0.0233 dm³/(m²·s)</td>
<td>-</td>
<td>6.65%</td>
<td>-1.57%</td>
<td>11.53%</td>
<td>-4.99%</td>
<td>8.96%</td>
<td>-1.44%</td>
<td>14.47%</td>
<td>4.05%</td>
</tr>
<tr>
<td>0.0467 dm³/(m²·s)</td>
<td>-</td>
<td>6.64%</td>
<td>-1.56%</td>
<td>11.50%</td>
<td>-5.05%</td>
<td>8.93%</td>
<td>-1.29%</td>
<td>13.20%</td>
<td>2.32%</td>
</tr>
<tr>
<td>0.0700 dm³/(m²·s)</td>
<td>-</td>
<td>6.64%</td>
<td>-1.56%</td>
<td>11.48%</td>
<td>-5.12%</td>
<td>9.01%</td>
<td>-1.21%</td>
<td>12.47%</td>
<td>1.56%</td>
</tr>
<tr>
<td>0.0933 dm³/(m²·s)</td>
<td>-</td>
<td>6.83%</td>
<td>-1.55%</td>
<td>11.46%</td>
<td>-5.18%</td>
<td>9.13%</td>
<td>-1.15%</td>
<td>11.96%</td>
<td>1.14%</td>
</tr>
<tr>
<td>0.1166 dm³/(m²·s)</td>
<td>-</td>
<td>6.83%</td>
<td>-1.55%</td>
<td>11.44%</td>
<td>-5.24%</td>
<td>9.26%</td>
<td>-1.12%</td>
<td>11.56%</td>
<td>0.88%</td>
</tr>
<tr>
<td>0.1400 dm³/(m²·s)</td>
<td>-</td>
<td>6.62%</td>
<td>-1.55%</td>
<td>11.42%</td>
<td>-5.30%</td>
<td>9.39%</td>
<td>-1.09%</td>
<td>11.24%</td>
<td>0.70%</td>
</tr>
<tr>
<td>0.1633 dm³/(m²·s)</td>
<td>-</td>
<td>6.62%</td>
<td>-1.54%</td>
<td>11.40%</td>
<td>-5.36%</td>
<td>9.52%</td>
<td>-1.06%</td>
<td>10.99%</td>
<td>0.58%</td>
</tr>
<tr>
<td>0.066 dm³/(m²·s·Pa)</td>
<td>0.78</td>
<td>6.65%</td>
<td>-1.56%</td>
<td>11.55%</td>
<td>-4.96%</td>
<td>9.21%</td>
<td>-1.92%</td>
<td>17.46%</td>
<td>7.95%</td>
</tr>
<tr>
<td>0.11 dm³/(m²·s·Pa)</td>
<td>0.75</td>
<td>6.65%</td>
<td>-1.56%</td>
<td>11.55%</td>
<td>-4.96%</td>
<td>9.21%</td>
<td>-1.91%</td>
<td>17.43%</td>
<td>7.87%</td>
</tr>
<tr>
<td>0.20 dm³/(m²·s·Pa)</td>
<td>0.72</td>
<td>6.65%</td>
<td>-1.56%</td>
<td>11.55%</td>
<td>-4.96%</td>
<td>9.21%</td>
<td>-1.91%</td>
<td>17.41%</td>
<td>7.84%</td>
</tr>
<tr>
<td>0.066 dm³/(m²·s·Pa)</td>
<td>0.78</td>
<td>6.74%</td>
<td>-1.87%</td>
<td>11.05%</td>
<td>-5.72%</td>
<td>9.25%</td>
<td>-1.76%</td>
<td>16.00%</td>
<td>5.06%</td>
</tr>
<tr>
<td>0.11 dm³/(m²·s·Pa)</td>
<td>0.75</td>
<td>6.74%</td>
<td>-1.87%</td>
<td>11.05%</td>
<td>-5.72%</td>
<td>9.25%</td>
<td>-1.76%</td>
<td>15.94%</td>
<td>4.96%</td>
</tr>
<tr>
<td>0.20 dm³/(m²·s·Pa)</td>
<td>0.72</td>
<td>6.74%</td>
<td>-1.66%</td>
<td>11.05%</td>
<td>-5.72%</td>
<td>9.24%</td>
<td>-1.76%</td>
<td>15.91%</td>
<td>4.90%</td>
</tr>
</tbody>
</table>

* = zone 2 – zone 3, $\beta_{13} = 0.279$ dm³/(m²·s).
** = zone 2 – zone 3, $C_{2,3} = 0.52$ dm³/(m²·s·Pa) with $n = 0.67$
Colour scale: CV RMSE: 0% = green, 15% = white, 30% = red; MBE: 0% = green, 5% = white, 10% = red.

Fig. 11. Measured (m) and simulated (s) RH of the ceiling; simulated with (green) and without (red) interzonal airflow, during the entire calibration period (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

According to the simulated model with an interzonal airflow of 0.0933 dm³/(m²·s), the average pressure difference between the interior and the ceiling is approximately 0.66 Pa during the 3 months that were used to calibrate the model, which would correspond to a pressure dependant airflow of 0.1274 dm³/(m²·s·Pa). This falls in the range of pressure dependant flows that were tested. This estimated air leakage rate of 0.0933 dm³/(m²·s) thus corresponds well to the air leakage rates as estimated by the AIVC Guide to Ventilation and provides a very significant improvement of the fit of the simulation. Therefore, this leakage rate was used for the initial assessment. Fig. 11 compares the measurements (black) to the simulation model with (green) and without (red) an interzonal airflow. When adding an interzonal airflow to the model of 0.0933 dm³/(m²·s), the CVRMSE and the MBE of the relative humidity of zone 2 (ceiling) improve by approximately 38% and 90% respectively. Figs. 12–14 present a more detailed overview of the relative humidity, temperature and vapour pressure of the ceiling cavity, comparing the outcomes of the measurements (black) to the simulation model with (green) and without (red) an interzonal airflow. The introduction of interzonal airflow barely influences the temperature of the ceiling. Although the ceiling temperature attained a good fit, the peak loads during the day could be
Table 3
Percentage improvement of the simulation model in relation to having no air leakage simulated.

<table>
<thead>
<tr>
<th>zone 1 - zone 2</th>
<th>n</th>
<th>T in</th>
<th>T ceiling</th>
<th>RH in</th>
<th>RH ceiling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>RMSE</td>
<td>MBE</td>
<td>CV</td>
</tr>
<tr>
<td>0 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>0.0233 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.09%</td>
<td>0.27%</td>
<td>0.22%</td>
</tr>
<tr>
<td>0.0467 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.19%</td>
<td>0.52%</td>
<td>0.43%</td>
</tr>
<tr>
<td>0.0700 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.27%</td>
<td>0.77%</td>
<td>0.64%</td>
</tr>
<tr>
<td>0.0933 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.36%</td>
<td>1.02%</td>
<td>0.83%</td>
</tr>
<tr>
<td>0.1166 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.44%</td>
<td>1.26%</td>
<td>1.01%</td>
</tr>
<tr>
<td>0.1400 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.52%</td>
<td>1.49%</td>
<td>1.18%</td>
</tr>
<tr>
<td>0.1633 dm³/(m²·s)</td>
<td>-</td>
<td>*</td>
<td>0.60%</td>
<td>1.72%</td>
<td>1.34%</td>
</tr>
<tr>
<td>0.066 dm³/(m²·s·Pa)</td>
<td>0.78</td>
<td>*</td>
<td>0.10%</td>
<td>0.65%</td>
<td>0.03%</td>
</tr>
<tr>
<td>0.11 dm³/(m²·s·Pa)</td>
<td>0.75</td>
<td>*</td>
<td>0.10%</td>
<td>0.67%</td>
<td>0.03%</td>
</tr>
<tr>
<td>0.20 dm³/(m²·s·Pa)</td>
<td>0.72</td>
<td>*</td>
<td>0.10%</td>
<td>0.67%</td>
<td>0.03%</td>
</tr>
<tr>
<td>0.066 dm³/(m²·s·Pa)</td>
<td>0.78</td>
<td>** -1.27%</td>
<td>-6.10%</td>
<td>4.38%</td>
<td>-16.16%</td>
</tr>
<tr>
<td>0.11 dm³/(m²·s·Pa)</td>
<td>0.75</td>
<td>** -1.26%</td>
<td>-6.05%</td>
<td>4.38%</td>
<td>-16.18%</td>
</tr>
<tr>
<td>0.20 dm³/(m²·s·Pa)</td>
<td>0.72</td>
<td>** -1.26%</td>
<td>-6.03%</td>
<td>4.38%</td>
<td>-16.19%</td>
</tr>
</tbody>
</table>

* = zone 2 – zone 3, $\beta_{2,3} = 0.279$ dm³/(m²·s).
** = zone 2 – zone 3, $C_{2,3} = 0.52$ dm³/(m²·s·Pa) with $n = 0.67$

Colour scale: −100% = red, 0% = white, 100% = green.

Fig. 12. Measured (m) and simulated (s) RH of the ceiling; simulated with (green) and without (red) interzonal airflow, during 31 days of the calibration period (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Fig. 13. Measured (m) and simulated (s) T of the ceiling; simulated with (green) and without (red) interzonal airflow, during 31 days of the calibration period (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).
further optimized. Concerning the vapour pressure in the ceiling, the simulation without interzonal airflow almost continuously predicts a lower vapour pressure than the measurements. The simulation with interzonal airflow achieves a better calibration, but does predict a higher vapour pressure than measured during those peak loads where the ceiling temperature is higher. Adding this interzonal airflow does not affect the temperature in zone 1 (the interior), neither does it significantly affect the relative humidity of zone 1 (more graphs comparing measured and simulated data are included in [15], as well as access to all data presented in this paper). The final fit of the model is excellent, with MBE and CVRMSE values of: Interior temperature, MBE = −1.55% and CVRMSE 6.63%; Interior relative humidity, MBE = −1.15% and CVRMSE 9.13%; Ceiling temperature, MBE = −5.18% and CVRMSE 11.46%; Ceiling relative humidity, MBE 1.14% and CVRMSE 11.96%.

An additional publication [16] reports on the results of the initial hygrothermal performance assessment, using the model as described in this paper. Additionally, a sensitivity analysis will be conducted, in which the air leakage rates will be further examined to assess the effect on the hygrothermal performance. Firstly, a strongly reduced interzonal airflow will be modelled; and secondly, a pressure dependant air leakage coefficient based on airtightness standards will be modelled. This will provide more insight into the impact both that the amount of air leakage as well as the simulation method of air leakage have on the final outcomes of the hygrothermal risk assessment.

4. Conclusion

Based on the results from the literature review, it can be concluded that there is a lack of research on the hygrothermal risks of applying interior insulation to constructions that are not solid masonry walls. It can be expected that the initial focus of research in this area is focused on solid masonry walls, as this is the most common construction type for very old buildings in Europe. However, as younger heritage (e.g. modernist architecture) is increasingly being recognized as being of significance, interior insulation is being applied in other types of constructions as well. There is a clear lack of understanding of the risks involved in applying insulation in these types of constructions.

Moreover, the methods that have commonly been applied for hygrothermal assessment – being a 1D or 2D simulation of the envelope, focussing on vapour and moisture transport through diffusion – may not be suitable to identify hygrothermal risks in these other types of structures. The Airey system for example, is a lightweight system and therefore has large air cavities in both walls, ceilings and roof. The vapour and moisture transport between the interior climate and these cavities can not be understood merely by evaluating the vapour transport through diffusion. In addition, the structure is very delicate and intricate, making it impossible to accurately represent in 1D or 2D simulations.

A method to evaluate the hygrothermal risks in the Airey system has been proposed, which relies on a whole building HAM model to simulate the different zones of the building, which is coupled to a 3D heat transfer model of the construction details. The first part of this methodology, constructing and validating these two simulation models, has demonstrated the importance of modelling convective vapour transport. The relative humidity of the ceiling cavity attained a significantly better fit to the measurements (CV RMSE improved by approximately 40% and MBE improved by approximately 90%) once convective vapour transport was added to the simulation. Moreover, the bias indicator (MBE) showed that not simulating convective vapour transport through air leakage would result in an underestimation of the hygrothermal risk. It is clear that the vapour barrier that was installed in these dwellings is perforated, and air leakage is taking place. An additional paper presents the sensitivity of this leakage in relation to the hygrothermal risk [16].

With one exception, the papers included in the literature review on hygrothermal assessment of interior insulation in existing buildings do not include convection in a hygrothermal performance simulation. Therefore, 95% of simulations (19 out of 20 papers) that include a vapour barrier assume the vapour barrier to be applied perfectly and do not consider any air leakage caused by unintended gaps or cracks in the vapour barrier. Even papers that specifically review methods to assess interstitial condensation completely neglect issues related to convection or leakage (e.g. [103]). While this research mainly relates to lightweight constructions, and this shouldn’t be conflated with issues related to the hygrothermal assessment of solid masonry walls, completely discounting the issue of convection when addressing the internal insulation of solid masonry walls can be dangerous, particularly when it concerns vapour tight insulation systems.

The importance of taking convection into account has been underlined by many authors (e.g. [8,10,11,83,86,104]). The hygrothermal evaluation in this paper is illustrative of this importance, as it shows that although the vapour barrier has been placed, it may have been punctured on countless of places. As has been pointed out in literature, even in case of perfect execution of the airtight layer, with connections sealed according to the rules of engineering, fractional leakages cannot be prevented. Therefore, it is recommended for all studies to not assume the effectiveness of the vapour barrier as if such flawlessness is the case. Just like having correction factors that correct for the application of insulation materials and other materials, such factors should apply to the air leakage rate of vapour barriers.
5. Discussion & recommendations for future research

Standards and evaluations of the airtightness of buildings are readily available and often studied, especially in relation to energy efficiency. However, this does not provide a specific estimation of the airtightness of a ceiling component. The air exchange between the indoor climate and the ceiling cavity is however, assumed to be critical in the evaluation of hygrothermal risks. The review has shown that aspects related to air leakage - and convective vapour transport in general - are rarely modelled in hygrothermal evaluations. Moreover, the airtightness of ceilings should be an area of concern, as the ceiling is one of the building components most sensitive to air leakage, since it is often penetrated by ducts, vents and tubes. The lack of research in this area, and it's crucial role in hygrothermal simulations, has previously been identified in literature (e.g. [8,102,104]).

The lack of attention that air leakage has received is also apparent in the policy and regulations related to hygrothermal risks. Even the ISO standard related to interstitial condensation [105] does not include convection and states, that 'if convection is negligible, the calculations will normally lead to designs well on the safe side'. It is widely acknowledged in literature (e.g. [8,10,11,83,86,104]) that convection is not negligible, but in fact is a crucial factor in modelling vapour transport. The assumption being made in this ISO standard – and in many of the papers included in the literature review – is therefore both uninformed as well as dangerous.

The lack of reported information on interzonal leakage is caused by two factors: (1) as leakages are accidental, their specific characteristics are unknown; (2) the difficulty and expense of such measurements [83]. This research underlines the need for future research in this area, in order to be able to accurately predict the air leakage of vapour barriers. This better understanding could result in better guidelines for the design of vapour barriers, which protect the vapour barrier from being punctured. Additionally, this could result in better application procedures, as poor craftsmanship on the construction site is still often cited as one of the main risk factors for air leakage. Moreover, this could result in this type of very commonly applied ceiling construction, with a vapour barrier that is positioned right behind the interior finish, being more widely acknowledged as being unsafe, as has already been flagged by others [79,83].

6. Limitations

The scope of the literature review is limited to papers using the term ‘hygrothermal’ in either the title, abstract or keywords. Future research could extend the review to include papers not mentioning this term, but instead mentioning mould growth, condensation, or other types of hygrothermal risks. However, an additional search was done specifically targeted to find hygrothermal assessments of ‘other structures’ (not being solid masonry walls) and this did not result in additional literature to be added. Therefore, it is assumed that no critical literature has been excluded, and that the selection is sufficient for the purpose of understanding the main aspects studied in relation to the hygrothermal performance of the internal insulation of existing buildings.

The methodology as proposed in this paper combines a whole building HAM-model with a 3D heat transfer model of components of the wall construction in order to evaluate the relative surface humidity of critical points in the construction. As a recommendation for future research, the moisture processes in the model of the wall component could be added to the simulation. This would allow for the evaluation of the amount of condensation occurring in the construction, and the associated drying out potential. This potential moisture accumulation in the construction may lead to a reduced performance of insulation materials (increased thermal conductivity), and can lead to the degradation of materials in the construction. However, the purpose of the methodology as proposed in this paper is to prevent hygrothermal risks and to flag them, therefore the aim is to identify the risk of condensation and mould growth occurring, which should be avoided altogether.

Lastly, for the whole building HAM-model, only the top floor apartment was modelled, and the adjacent apartments (including the apartments below) were assumed to be adiabatic, and that no air flow was taking place between them. As the dwellings’ airtightness was found to be lacking, this may also have been the case in relation to the lower apartments, which should be further explored. In addition, the air flow model inputs were based on estimated leakage coefficients and flows, not measured ones. To better understand the differences between models with constants and pressure dependant air flow it is important that future research performs measurements and verifies the air flow patterns and quantities.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work is supported by the Municipality of Amsterdam. The authors would like to thank: Firstly, Marco Larcher and Alexandra Troi for their valuable input in reviewing the work; Secondly, Dolf van Onna, a master’s student, for his work on the data collection and modelling as part of his graduation project.; and lastly, the housing corporation, architectural office, contractor and building physics consultancy firm associated with the refurbishment project of the Airy dwellings, both for providing access to the construction site, as well as for the sharing of information and data during the process.

Supplementary materials


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