IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Novel methodology for diagnosis of causes associated with mould growth in dwellings

To cite this article: P Lopez-Arce *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 042025

Novel methodology for diagnosis of causes associated with mould growth in dwellings

P Lopez-Arce[1,2,*], H Altamirano-Medina[1], J Berry[2], D Rovas[1], F Sarce[3] and S Hodgson[2]

[1] Institute for Environmental Design and Engineering, University College London, UCL (UK),
[2] Property Care Association, PCA (UK), [3]Universidad Autónoma de Chile (Chile)
[*] p.lopez-arce@ucl.ac.uk

Abstract. Increased occupancy rates, inappropriate ventilation and intermittent heating regimes in dwellings can result in excessive atmospheric moisture levels, potentially leading to mould growth and lower indoor air quality. Identifying the causes associated to mould growth and taking correct remedial actions can be essential in reducing the prevalence of this problem. In practice it is often complex, even for experts, to accurately identify some of these causes and this can lead to costly and unnecessary interventions. Towards development of a novel systematic diagnostic procedure an extensive monitoring exercise has been undertaken involving collection of environmental data from dwellings with and without mould issues. The data has been analysed, considering building characteristics and occupancy's lifestyle features, with the objective to identify thresholds on measurable parameters that are indicative of mould growth risks. The proposed methodology links key parameters to identify factors that contribute to surface condensation and mould growth in buildings. This research presents a process towards environmental data collection, post-processing to compute and interpret pertinent environmental parameters, and displaying them in a clear and easy-to-interpret manner.
Keywords. Diagnosis, atmospheric moisture, root-cause analysis, mould growth, buildings

1. Introduction

High levels of indoor atmospheric moisture can lead to surface condensation and mould growth. Dampness and mould issues have been reported to affect between 15 and 30 % of European homes [1,2]. In the UK, mould growth has been associated with low indoor temperatures, high indoor humidity, and high occupancy density, with mould issues increasing in frequency over the last decades [3,4]. The combination of poor ventilation, irregular heating, poor thermal properties of external walls and high moisture generation (by breathing, showers, washing, cooking and drying clothes indoors, etc) have been shown to increase the risk of moisture-related problems including mould, condensation and dust mites. High levels of indoor moisture and dampness may give favourable conditions to microbial growth that can be harmful to occupant health [5,6]. The interest for healthier and moisture-balanced indoor environments has sparked an increased demand of finding effective methods to avoid inaccurate and expensive interventions or solving disrepair claim conflicts [7,8]. Identification of a robust diagnostic method based on scientific principles could support the interests of occupants, tenants, private or social homeowners (i.e. City Council, Housing Associations), insurance companies, surveyors or expert witnesses. Identifying ways to avoid moisture problems and mould growth in buildings has been the subject of many research studies. Still, in existing literature, measured data from real buildings in service are rather scarce [9]. Even though the need of developing accurate standardized protocols for assessing moisture problems in dwellings has been stated [10], an integrated methodology is still lacking.

The purpose of this study is to generate new insights and to propose a new methodology for easily determining the causes of mould growth. Dwellings with and without mould issues were environmentally monitored and key building characteristics and occupant lifestyle features collected and analysed. A moisture impact indicator is also proposed as a means of measuring the impact of key environmental parameters and supporting the identification of the most likely causes of mould growth.

2. Methodology

2.1. Selection of environmental parameters and critical thresholds as diagnosis indicators

The point of departure for this research was an extensive literature review of scientific publications, standards and regulatory guidance, to identify key environmental parameters and the corresponding critical thresholds proposed for the control and avoidance of surface condensation and mould growth in dwellings. Different critical thresholds, values or ranges were identified and then assessed through an environmental monitoring exercise in dwellings with and without mould issues (Table 1).

Table 1. Environmental parameters considered in the prevention of moisture associated problems

Environmental parameter	Symbol	Units	Critical Thresholds	Reference
Relative humidity	*RH*	%	45-80	[10, 11]
Temperature	*T*	°C	10-20	[12]
Vapour pressure excess	*VPE*	kPa	0.6-0.9	[13,14]
Water activity	a_w	-	0.65-0.9	[2,14, 15]
Temperature factor	*fRsi*	-	0.65-0.75	[11,16,17]

2.2. Data collection

2.2.1. Monitoring of indoor and outdoor environmental conditions

Fifty properties, including flats, bungalows, semi-detached, detached and terraced houses from different UK regions, were monitored during two consecutive heating seasons (i.e. two winters). The selection of buildings was based on the availability for taking measurements by surveyors (Property Care Association (PCA) members), UCL and PCA staff. Rooms (including bedrooms, living rooms, bathroom and kitchens) from dwellings affected with mould issues were monitored. External (*e*) and internal (*i*) air temperature (*T*), (Te_{air} and Ti_{air}), relative humidity (*RH*), and internal surface temperature ($Ti_{surface}$) were recorded every 30 min. for 2 and 4 weeks by means of *RH* and *T* environmental sensors (*Lascar EL-USB-2*). Internal sensors were placed at mid height, away from indoor external walls, air currents, heating sources and sun rays. Indoor surface temperatures were measured (using *Lascar EL-USB-TC-T-type* sensors) in wall surfaces largely affected by mould. For dwellings without visible mould, the sensor was placed in high-risk rooms and surfaces (i.e. high occupancy rooms close to high water vapour production rooms, e.g. bedrooms). The collected data was then used for the calculations of parameters such as temperature factor, $fRsi = (Ti_{surface} - Te_{air}) / (Ti_{air} - Te_{air})$, water activity, a_w= *Partial water vapour pressure* (P_v) / *Saturation vapour pressure* (P_{vsat}) = *RH (surface)/100 %,* and vapour pressure excess, *VPE*= differential vapour pressure (internal-external). The results were standardized for external reference conditions of 5ºC temperature and 80 % *RH* [13].

2.2.2. Social survey

An extensive survey was carried for each monitored dwelling. Information collected included: (i) history on the number and type of rooms affected by surface condensation and /or mould and location of these issues; (ii) Floor plans; (iii) information about building characteristics (e.g. age, typology, dwelling's size, orientation, building materials, type of walls and floors), glazing and provision of ventilation (e.g. trickle vents, doors under-cut, extraction fans, location, etc.) and heating system types. In addition, occupants were surveyed to capture lifestyle aspects regarding household activities and behaviours related to moisture generation (e.g. type of washing and drying cloths, presence and type of pets, etc.), occupancy density and home schedules. Ventilation and heating performance by the occupants were also inquired (e.g. frequency, way and location of forced and natural ventilation, opening windows and doors). Key characteristics were identified by investigating properties with and without mould problems. These were used to support the development and validation of the moisture impact indicator.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042025 doi:10.1088/1757-899X/609/4/042025

2.3. Moisture Impact Indicator

The various environmental parameters were processed, assessed and finally used to create a moisture impact indicator. This measures the impact of key parameters and helps in the identification of the most likely causes of mould growth reported in the studied properties. The indicator reports on the causes associated with mould growth in relation to the thermal quality of the building envelope, the ventilation and heating regimes, and the influence of people behaviour.

The impact indicator is based on the ratios calculated for each parameter analysed using the data monitored in the dwellings. These ratios refer to:

- The relationship between the values monitored and those that exceed the thresholds defined for each parameter.
- Weighted values that establish the severity and likelihood of the event. These consider the previously calculated ratios and place them in a scale that goes from high to medium and low.

3. Results and discussion

3.1. Environmental Monitoring data

The data obtained from the monitoring exercise shows distinct differences between dwellings with and without mould. Most of the environmental parameters recorded and calculated (Table 2) are closer or exceeding the values consider as critical in standards and guidance. The data obtained was used as a reference for the moisture impact indicator identified to help in the diagnosis of mould growth.

Table 2. Environmental parameters obtained in fifty UK dwellings

	$T_{surface}$ (°C)	a_w	*fRsi*	T_{indoor} (°C)	RH_{indoor} (%)	*VPE* (kPa)	*AMC* (g/m³)
Dwellings with mould							
MAX	19.8	1.0	0.8	23.4	82.1	1.0	12.2
MIN	10.2	0.7	0.4	13.7	54.3	0.2	6.9
Average	14.9±2.4	0.8±0.1	0.7±0.1	19.21±2.5	67.7±6.86	0.6±0.2	9.8±1.3
Dwellings without mould							
MAX	21.3	0.7	1.0	22.5	70.7	0.7	10.3
MIN	9.6	0.4	0.6	10.0	35.1	0.0	5.6
Average	16.7±2.8	0.6±0.1	0.8±0.1	18.7±2.9	56.5±8.7	0.3±0.2	8.0±1.1

Table 2 and Figure 1 show that water activity (a_w) values between 0.7 and 1.0 occur in rooms with mould, whereas dwellings without mould have all a_w values below 0.7. Values above 0.7 at a wall surface are appropriate for the development of most mould species [2,18]. In addition, dwellings with mould have *fRsi* values between 0.4 and 0.8, whereas in dwellings without mould, these values range between 0.6 and 1.0. The thermal quality of each building envelope element can be characterised by the temperature factor (fRsi) at the internal surface; values of 0.75 and higher are generally suggested for the avoidance of mould growth in UK dwellings [16]. Other parameters could reflect issues with the ventilation and heating regimes of a dwelling, such as *VPE* and indoor *T* and *RH*. Most dwellings with mould have *VPE* values above 0.6 kPa, whereas in non-mouldy dwellings these values are mostly below 0.6 kPa. An indoor environment is considered high in moisture when the *VPE* is > 0.6 kPa [13,14]. *RH* values range between 35 and 71 % in dwellings without mould. The values are higher, between 54 and 82 %, in dwellings with mould. Air moisture content (*AMC*) is also higher in mouldy dwellings. However, there are not large differences on indoor temperatures.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042025 doi:10.1088/1757-899X/609/4/042025

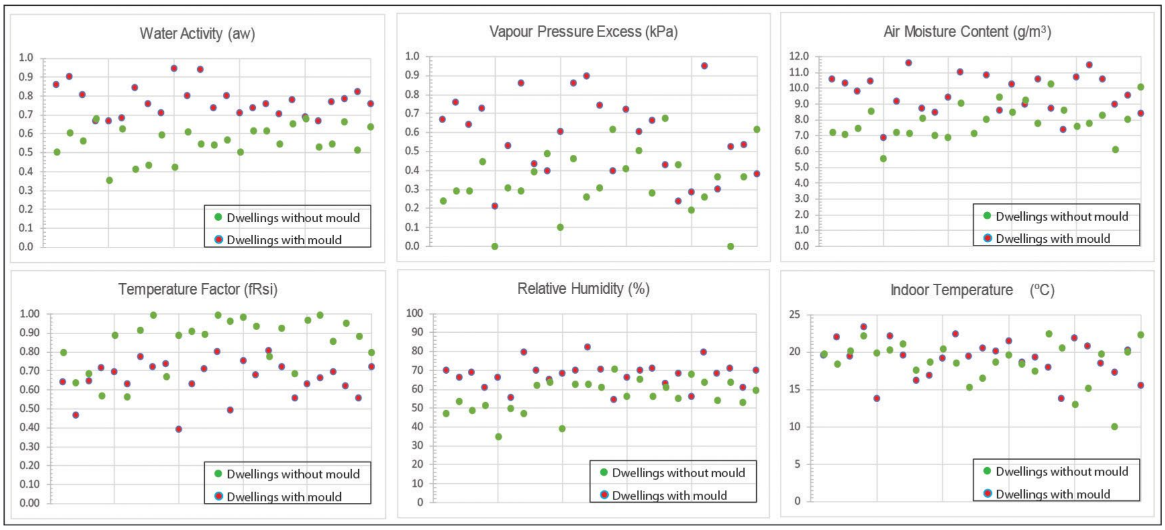

Figure.1. UK dwellings monitored with and without condensation and / or mould issues. Values presented are average for the different environmental parameters

3.2. Occupants' lifestyle and relation to building features

By investigating properties with and without surface condensation and mould problems, insights emerged on the influence of building characteristics and occupants' lifestyle as contributing factors to moisture excess problems (Table 3). These include features and materials of the dwellings, ventilation and heating regimes and people behaviour [19,20].

Table 3. Building and occupancy contributing factors and features for moisture related problems

Impact Factors	**Distinctive features**	**Common features**
Occupancy	Density, home schedules, pets	Drying cloths (indoors-airer)
Dwelling	Size, room (type and location), orientation, walls (solid, cavity)	Floors (solid, void)
Ventilation	Doors (open, closed), frequency, forced ventilation, location	Trickle vents, doors under-cut, natural ventilation (e.g. opening windows)
Heating	Not identified	Type (e.g. radiators electric or gas)

Some key distinctive and common characteristics have been found between dwellings with and without mould. Distinctive features of mouldy-dwellings mostly relate to the dwelling size (smaller), room type (e.g. bedrooms), orientation (e.g. North facing), and schedules (occupants being most of the day at home). The type of walls seems to be also a condition related to surface condensation and mould growth due to lower surface temperatures [14,16]. It was observed, that most solid wall dwellings had mould issues. Regarding ventilation patterns, occupants of non-mouldy dwellings allow better air circulation, hence avoiding high concentration of moisture in specific rooms (e.g. internal doors are kept open most of the time). One interesting observation was that mould issues were more prevalent in dwellings with pets. Occupants reported tending to keep doors closed to restrict pet (mostly dogs) movement, whilst at the same time reducing airflow. Most dwellings had intermittent ventilation systems (extraction fans) installed in bathrooms and kitchens. However, in many mouldy dwellings such type of forced ventilation was absent or not functional, which may have resulted in inadequate removal of excess moisture, as it has previously been reported by other authors [10].

3.3. Moisture impact indicator assigned to dwellings

After performing the analysis of the environmental monitoring data, a moisture impact indicator was derived to aggregate the impact of key environmental parameters of each dwelling (Figure 2). A category of high (H), medium (M) or low (L) was given to the obtained values according to the threshold considered in Table 1 and data from Table 2.

A dwelling with mould should be theoretically indoor moisture-unbalanced and should have internal conditions exceeding most of the thresholds defined. Whereas a dwelling without mould, one which is moisture-balanced, should show very few or not exceedances at all. As seen in Figure 2, dwellings with mould are in general unbalanced, showing high (H) exceedance in most of the parameters considered. On the contrary, dwellings without mould mostly have low (L) exceedance in relevant parameters.

Dwellings without Mould																											
Exceed	Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Exceed
L	a_w	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	L	L	L	L	L	L	
L	fRsi	L	H	H	H	L	H	L	L	H	L	L	L	L	L	L	L	H	L	H	L	L	L	L	L	H	
L	RH	L	L	L	L	L	L	L	L	L	L	M	L	M	M	L	H	M	L	L	H	H	L	H	L	L	Low
L	T indoor	L	M	L	L	L	L	L	M	L	L	L	H	M	L	L	L	M	L	L	H	H	L	H	L	L	Medium
L	VPE	L	L	L	M	L	L	L	M	L	L	M	L	M	M	M	L	L	H	M	L	L	L	L	L	M	High
Dwellings with Mould																											
Exceed	Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Exceed
H	a_w	H	H	H	L	L	L	H	H	M	H	H	H	M	H	H	H	H	M	H	L	L	H	L	H	M	Low
H	fRsi	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	L	H	H	H	L	H	L	H	H	Medium
H	RH	H	L	H	L	L	L	H	H	M	M	M	H	H	L	M	M	H	M	H	M	H	H	H	L	H	High
H	T indoor	L	L	L	L	H	L	L	H	H	L	L	L	L	L	L	L	L	M	H	L	L	L	H	L	H	
H	VPE	H	H	H	H	L	H	H	M	M	H	H	H	H	L	H	M	H	M	L	L	L	L	M	H	L	

Figure 2. Moisture impact indicator applied to the assessed dwellings

4. Conclusions

The following conclusions can be drawn from the study carried out and briefly summarised below:

- Ideally a dwelling in balance should have lower a_w, *RH* and *VPE* and higher *T* and *fRsi* values.
- The cause of mould growth may not be the result of just one parameter prompting the problem but a causal association between the different parameters. Mould growth could be an indication of an unbalanced dwelling, where a combination of parameters might be responsible for it.
- The higher the number of environmental parameters above or below certain thresholds could be indicative of an unbalanced house, therefore the higher the likelihood of mould development, being *aw* or *VPE* the most critical parameters. Values related to the thermal quality of the envelope (*fRsi*) can be less important if the other environmental parameters, related to surface moisture (*aw*) and air exchange (*VPE*), do not exceed their corresponding stablished thresholds.
- The lower the thermal quality of the dwelling's envelope (high *aw* and low *fRsi* values) and/or an inadequate forced or natural ventilation (high *VPE* values), the higher the likelihood of developing mould growth by an excess of moisture production.
- Inadequate ventilation has been found the main cause leading to mould growth in most of the studied dwellings. This is reflected by an excess of *VPE*, that in many cases is also combined by a poor quality of the dwelling envelope, reflected by a high a_w and low *fRsi*.
- Building characteristics such as size, room type, orientation, type of walls and occupancy behaviour and ventilation patterns (e.g. home schedules, closing or opening internal doors) supported the diagnosis.
- The proposed methodology based on data collection, post-processing by linking key surface and air environmental parameters together with critical thresholds and the interpretation of pertinent environmental parameters provides clear insights of the likely origin of mould growth.

This study shows that using easily acquired environmental data taken from occupied buildings, the causes of moisture imbalance and mould growth can accurately being determined. Using knowledge of critical thresholds to evaluate the impact of key environmental parameters, the cause, likelihood, severity of imbalance can be precisely calculated and direct the most appropriate and effective rectification strategies.

Acknowledgements

This research has been supported by a Grant funded by the Technology Strategy Board and Engineering & Physical Sciences Research Council (Innovate UK) and The Property Care Association (PCA) through a Knowledge Transfer Partnership (KTP) project (KTP010485) between University College London (UCL) and PCA.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042025 doi:10.1088/1757-899X/609/4/042025

References

[1] Bonnefoy XR, Braubach M, Moissonnier B, Monolbaev K and Röbbel N 2003 Housing and health in Europe: preliminary results of Pan-European study *Am J Public Health* **93** 1559-63

[2] Adan OC and Samson RA 2011 Fundamentals of mold growth in indoor environments and strategies for healthy living *Springer Science & Business Media*

[3] Woolliscroft M 1997 'PH-97-8-3. Residential ventilation in the United Kingdom: An overview' in *ASHRAE Transactions: Symposia* **103** (1) 706–16

[4] Government DfCaL 2015 English Housing Survey - Headline Report 2015-16 London

[5] Bornehag CG, Sundell J, Bonini S, Custovic A, Malmberg P, Skerfving S, Sigsgaard T, Verhoeff A 2004 Dampness in buildings as a risk factor for health effects *Indoor Air* **14** 243–57

[6] Mendell MJ, Macher JM and Kumagai K 2018 Measured moisture in buildings and adverse health effects: A review *Indoor Air* **28** 488–99

[7] Rose WB and Francisco PW 2004 Field Evaluation of the Moisture Balance Technique to Characterize Indoor Wetness In: Proceeding of Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes IX conference, Florida

[8] Altamirano-Medina H, Davies M, Ridley I, Mumovic D and Oreszczyn T 2009 Guidelines to Avoid Mould Growth in Buildings *Advances in Building Energy Research* **3** 1,221-235

[9] Vinha J, Salminen M, Salminen K, Kalamees T, Kurnitski J and Kiviste M 2018 Internal moisture excess of residential buildings in Finland *J Build Phys* **42** (3) 239-58

[10] Tsongas G 2009 Case Studies of Moisture Problems in Residences In Moisture Control in Buildings The Key Factor in Mold Prevention *ASTM-MNL18-2nd*

[11] Dedesko S and Siegel JA 2015 Moisture parameters and fungal communities associated with gypsum drywall in buildings *Microbiome* **3** (71)

[12] Azevedo JA, Chapman L and Muller CL 2015 Critique and suggested modifications of the degree days methodology to enable long-term electricity consumption assessments: a case study in Birmingham, UK *Meteorol Appl* **22** 789–96

[13] Oreszczyn T, Ridley I, Hong S and Wilkinson P 2006 'Mould and winter indoor relative humidity in low income households in England' *Indoor Built Environ* **15** (2) 125–35

[14] BS5250:2011 + A1:2016 Code of practice for control of condensation in buildings

[15] Hens H 1992 IEA: Annex 14: Condensation and Energy *J Therm Insul* **15** 261-73

[16] BS13788:2012 Hygrothermal performance of building components and building elements Internal surface temperature to avoid critical surface humidity and interstitial condensation

[17] Kalamees T 2006 Critical values for the temperature factor to assess thermal bridges. Proc. Estonian Acad. Sci. Eng **12** (3-1) 218–29

[18] Flannigan B and Miller JD 2011 Microbial growth in indoor environments In: Microorganisms in Home and Indoor Work Environments: Diversity, Health Impacts, Investigations and Control. 57-107.

[19] Madgwick D and Wood H 2016 The problem of clothes drying in new homes in the UK *Structural Survey* **34** (4/5) 320-30

[20] Moller EB and Hansen EJP 2017 Moisture supply in Danish single-family houses – the influence of occupant behavior and type of room *Energy Procedia* **132** 141-46