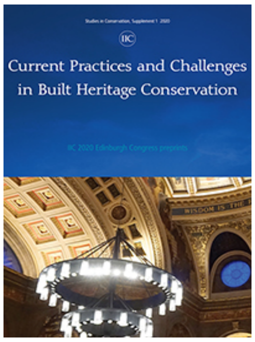

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ABSTRACT
Different environmental control types (background heating, electric and wet humidistatic heating, dehumidification and air-conditioning) have been assessed in more than 60 historic buildings. Performance in terms of climate and corrosion rates achieved, and energy consumption, were measured. An intensive series of trials compared dehumidification and humidistatic heating for stores. Damage to the wall surfaces and surface evaporation rates were measured. The impact of two types of evaporation rate equipment on surface temperatures and airflows was assessed. Humidistatic heating was found to generate a greater distribution in temperature and relative humidity across the room. It also caused increased surface damage rates in buildings with sulphate salts. The surface evaporation rates and energy used were lower for dehumidification.

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KEYWORDS
Environment; humidistatic heating; dehumidification; pollution; filtering; sustainability

Introduction

English Heritage cares for over 400 historic sites with more than 130 displaying or storing collections. Environmental control is frequently required. A range of methods have been used over the past three decades. Data has been collected on the performance of different environmental control types in 217 rooms in more than 60 historic buildings. Only rooms with a full year's calibrated data and fully functioning control systems were analysed. Control methods have included background heating, electric and wet humidistatic heating, dehumidification and air-conditioning. In the UK climate comfort heating cannot provide acceptable conditions for many materials without substantial humidification, which introduces other issues. Performance, in terms of climate and corrosion rates (considering external conditions) achieved, distribution in the rooms and energy cost were measured. Smart ventilation and underfloor heating were used in only one building each, so have not been included. Dehumidifiers were only used in stores. Each building is unique and whilst the large number of studies allows some general conclusions to be drawn, caution is required in transferring the results. Particular emphasis was put on buildings where the control method has changed, without significant alteration to the building's fabric or patterns of use. These instances allow a more direct comparison of performance.

Whilst many display rooms have too high an air exchange rate (AER) for dehumidifiers to work efficiently, their use in store rooms can be very effective. To assess this a comparison trial with conservation heating was undertaken. Very similar room dimensions in two buildings were used. Buildings with different moisture and ventilation regimes and soluble salts were selected.

Method

Assessment of performance of existing control

Air temperature (T) and relative humidity (RH) were measured in each room with a Rotronic Hygroclip based on radiotelemetry (Meaco) or logger (Hygrolog or Smartreader 002 or Humbug). All probes underwent annual three point RH calibration with National Accreditation of Measurement and Sampling (NAMAS) traceable salt pots. In several rooms multiple loggers were used to trace distributions, or the method developed by Camuffo with a probe was undertaken four times throughout the seasons (Camuffo 2019). Pollution, nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) were measured with Palmes diffusion tubes in 29 rooms across the seasons (Thickett, Chisholm, and Lankester 2013). The percentage of time within a reasonable RH band (40–65%) for a mixed collection was calculated. As this can be misleading, with significant damage done in even a small percentage of time outside the band, in some instances, damage functions were also calculated (Table 1).

To account for the different environments of the sites, the external data was used to calculate the same corrosion damage functions and internal to external ratios presented. Energy consumption was measured with stand-alone meters for plug-in units (background and electric humidistatic heating,

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Table 1. Damage functions used.

Damage function	Calculated from	Details	Threshold	Reference
Mould growth	T, RH	–	>1	Thickett, Lankester, and Pereira-Pardo (2014)
Dimensional change due to RH changes	RH	1 mm gesso on 5 mm oak board	>2%	Kupczak et al. (2018)
Corrosion rates of silver and copper	T, RH, [H_2S], [NO_2], [O_3], [SO_2]	-	Ratio to external value used	Thickett, Chisholm, and Lankester (2013)

dehumidifiers). The energy consumption in rooms housing collections was estimated from the total gas consumption for wet heating systems by measuring the surface temperature of all radiators in a building with Smartreader 2 loggers. Large-scale dehumidifiers and air-conditioning usage were metered separately from the rest of the building.

Comparative stores trial

Air exchange rates were measured with carbon dioxide tracer gas (ISO 12569 2012). Moisture and soluble salt contents were measured by drilling, drying and ion chromatography (BS EN 16682 2017; BS EN 16455 2014; BS EN 16085 2012). Room details are given in Table 2.

One room (A) was controlled with a 2 kW Dimplex radiator switched with a Meaco CHH controller to 50% RH set point, the other (B) with a Munters MG50 dehumidifier with a Meaco LAE controller also set to 50% RH. Both controllers underwent calibration as before. Eight newly calibrated Rotronic hygroclip probes measured temperature and RH around each room. PVC guttering was placed along the bases of the walls to collect any salt or debris. A dust bug prototype unit was placed at the base of the wall to provide continuous monitoring during the trials. Precautions to exclude readings from deposited dust, as reported previously, were used (Thickett 2017). Evaporation rate was measured using two methods. Pairs of Shinea RH sensors were modified by coating all but the end 2 mm with a waterproof resin. The sensors were placed 2 mm and 25 mm from the wall, along with thermistors. The resistances were recorded with a CEM Datataker Logger and converted to RH with a custom calibration for each sensor. Five sets of probes ran continuously during each trial. The evaporation rate was calculated using the method derived by Watanabe (Watanabe and Osada 1991). Measurements of the near wall temperature, RH and air velocity were taken as before and with a Model WA-790 3-dimensional ultrasonic anemometer from Sonic Corporation Japan. This unit has very thin arms and produces no self-heating. The values were then used in a field laboratory emission cell (FLEC) unit with a FLEC Aircontrol pump to match the measured air parameters (Uhde, Borgschulte, and Salthammer 1998). The difference in absolute humidity from the inlet and outlet lines of the FLEC was used to estimate the evaporation rate. Ten measurements were taken over each room wall surface.

There are serious concerns with measurements interfering with air flows and evaporation rates over building surfaces. Surface temperatures were measured with a ThermoCam PM290 thermal camera in the trials and no differences were determined with adjacent areas of wall surface. Whilst the smallest available units have been used (Shinea sensors has dimensions 3 mm by 5 mm by 0.5 mm, thermistors 1 mm in diameter, 1 mm wire to

Table 2. Details, dimensions and measured parameters of the store rooms.

Room	Description	Height (m)	Width (m)	Depth (m)	AER (per hour)	Moisture content (%)	Chloride content (%)	Sulphate content (%)	Sodium content (%)	
Dov A	Stone and plaster walls, slate roof, concrete floors	3.0	2.6	3.3	0.13	2.1	0.08	0.01	0.11	Min
						4.1	0.30	0.04	0.36	LIR
						6.2	0.65	0.08	0.78	UIR
						9.1	0.80	0.12	0.96	Max
Dov B	Stone and plaster walls, slate roof, concrete floors	3.0	2.5	3.7	0.16	1.7	0.12	0.00	0.12	Min
						4.4	0.45	0.05	0.58	LIR
						6.2	0.89	0.12	1.04	UIR
						10.1	1.20	0.19	1.43	Max
Ft B A	Brick walls, under soil, concrete floors	3.5	10	15	0.32	3.3	0.02	0.04	0.11	Min
						5.4	0.11	0.31	0.76	LIR
						8.4	0.18	0.45	1.02	UIR
						9.5	0.21	0.67	1.52	Max
Ft B B	Brick walls, under soil, concrete floors	3.5	10	15	0.29	3.4	0.03	0.02	0.06	Min
						4.0	0.09	0.25	0.59	LIR
						4.8	0.15	0.44	1.05	UIR
						9.4	0.19	0.71	1.63	Max
Test	Stone and plaster walls, slate roof, concrete floors	2.8	4.1	3.2	0.22	4.3	Not determined			Min
						5.1				LIR
						9.1				UIR
						10.6				Max

Dov, Dover Castle; Ft B, Fort Brockhurst; Test room, similar sized room in a historic building. Min, minimum value, LIR, lower interquartile range, UIR, upper interquartile range, Max, maximum value.

support, WA-790 has the thinnest arms available), this impact was tested. Laser Doppler anemometry was undertaken in a non-listed but historic test room with similar characteristics to the rooms in Fort Brockhurst (Table 2). Measurements were taken for 60 minutes, the T/RH probes and anemometer assembly were then moved to within 2 mm of the wall with a remote positioning unit. Measurements continued for another 60 minutes.

Results

Assessment of performance of existing control

The performance of the rooms analysed is shown in Figures 1–3. The figures show the number of rooms falling into each performance band. The bands are percentage time between 40 and 65% RH, maximum strain calculated and mould risk index.

Wet humidistatic heating generated environments meeting the RH performance criteria between 63 and 96% of the time. Most of these generated maximum strain values considered acceptable by most authors (2%), see Figure 2, but seven rooms exceeded this value. The Image Permanence Institute (IPI) has reported a mould risk of 1 is acceptable. Most rooms have a lower index and risk, see Figure 3, but eight exceed that value, three of them quite significantly, and indeed mould has been reported in all but one of those eight rooms.

Electric humidistatic heating performed better, with all rooms meeting the RH criteria for over 80% of the time and many meeting it for over 95%. All bar one room were below 2% maximum strain and only three rooms exceed a mould risk index of 1.

Background heating performed worst, with a wide spread of numbers of rooms meeting the RH criteria, with several only meeting it for less than 60% of the time. The maximum strain and mould risk indices are correspondingly much higher. There are fewer rooms with background heating as it is generally used only at smaller sites.

Dehumidification performed extremely well, with all store rooms over 90% of the time for RH and very low risk maximum strains and mould risk indices. But these were all stores with limited public access and consequently, lower air exchange rates.

As expected, the air conditioned rooms performed very well. Surprisingly, several had RHs above 65% for some of the time. This was always in summer, and examination of the systems' initial specifications showed they had been mainly designed assuming an upper outside temperature of 23 or 26°C. When this was exceeded, the chilling water temperature was not sufficient to maintain 65% RH.

Equivalent carbon dioxide emission from energy consumption is shown in Table 3.

The wet humidistatic heating systems utilised natural gas or fuel oil. Overall, air-conditioning uses the most energy, followed by background heating, then humidistatic heating. Wet humidistatic heating may use slightly less energy than electric, but this may not be significant given the spread of the data. Dehumidification used the least energy. These figures are in general agreement with figures reported in other institutions (Ryhl-Svendsen et al. 2011; Larsen 2018).

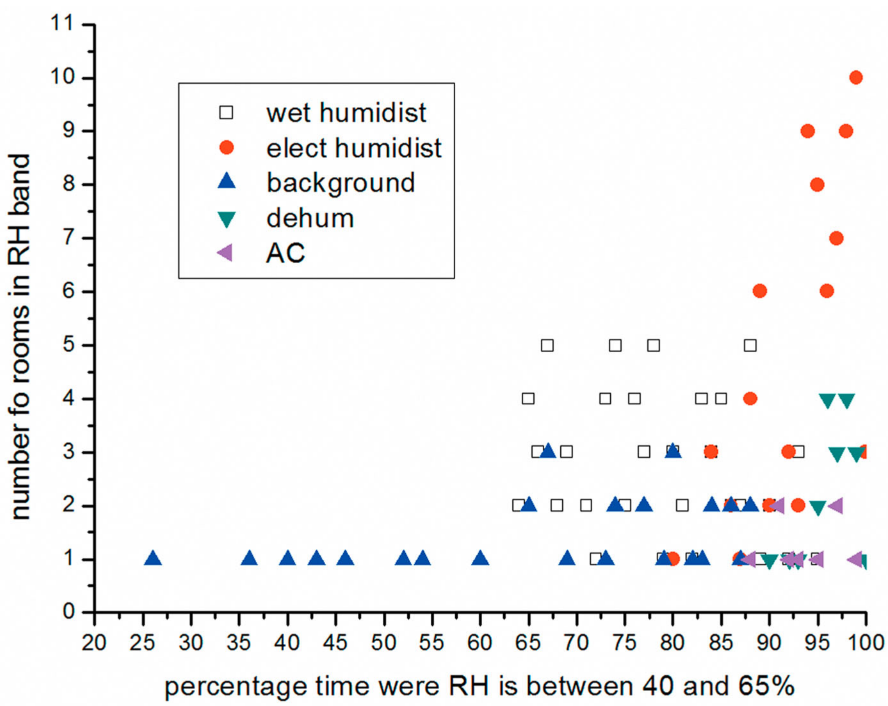

Figure 1. Percentage of time in 40–65% RH band for rooms with a variety of control methods.

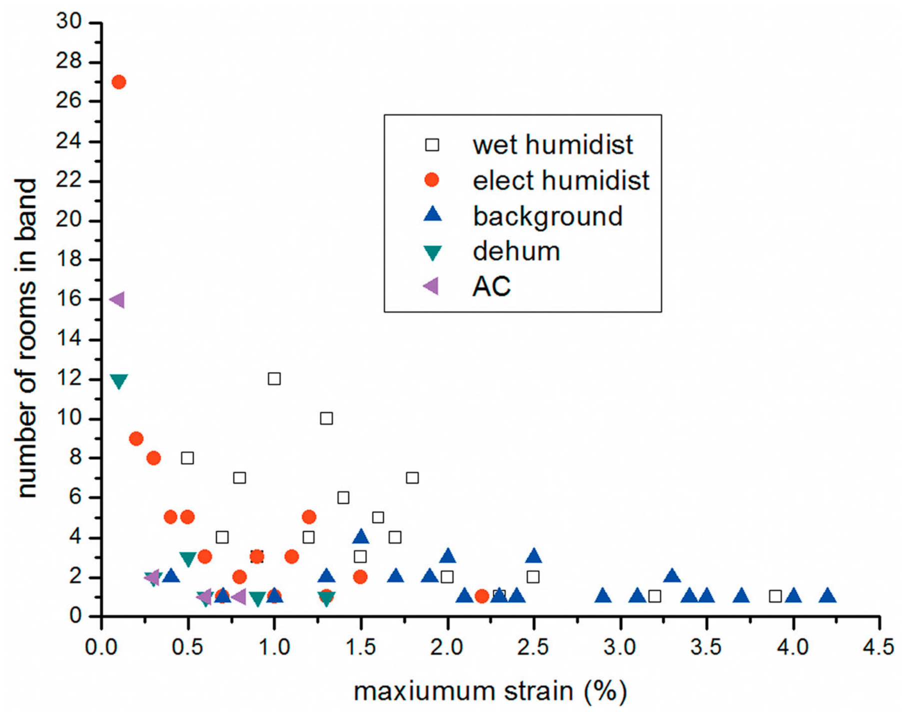

Figure 2. Maximum strain calculated from RH data for rooms with a variety of control methods.

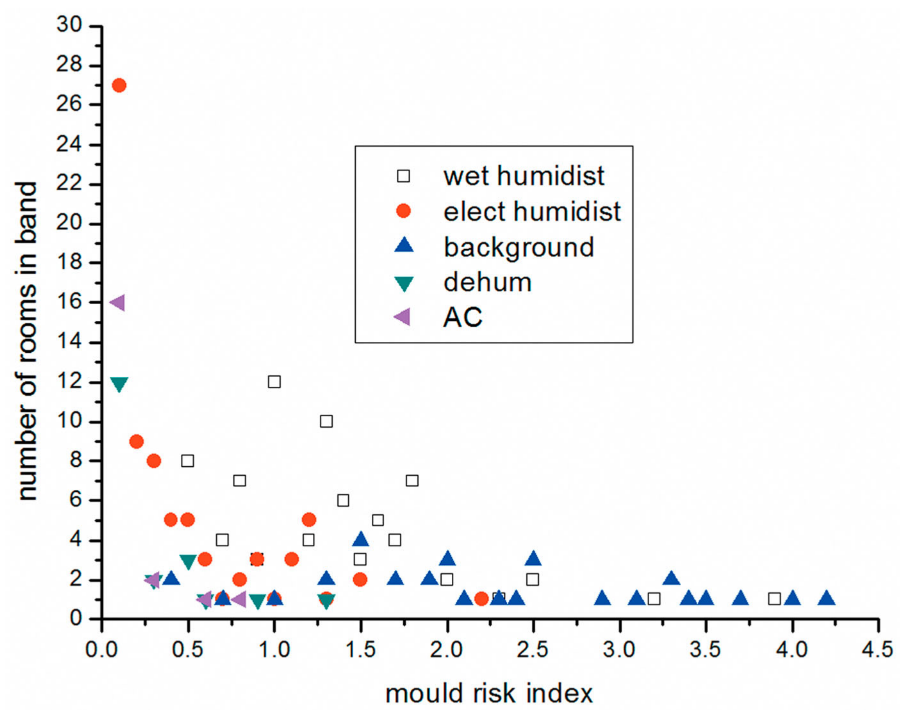

Figure 3. Mould risk index for rooms with a variety of control methods.

Table 3. Equivalent carbon dioxide emission from energy consumption.

	Energy consumption kW/m^3/year: eq CO_2 kg/m^3/year			
	Minimum	Lower quartile	Upper quartile	Maximum
Background heating	2.275: 0.644	3.412: 0.966	4.553: 1.288	5.525: 1.564
Wet humidistatic heating	1.072: 0.219	2.177: 0.49	3.607: 1.028	3.997: 1.139
Electric humidistatic heating	1.355: 0.383	2.225: 0.63	3.841: 1.087	4.207: 1.191
Dehumidifier	0.656: 0.186	0.975: 0.276	1.307: 0.370	2.657: 0.752
Air-conditioning	6.573: 1.860	7.475: 2.115	8.775: 2.483	10.07: 2.850

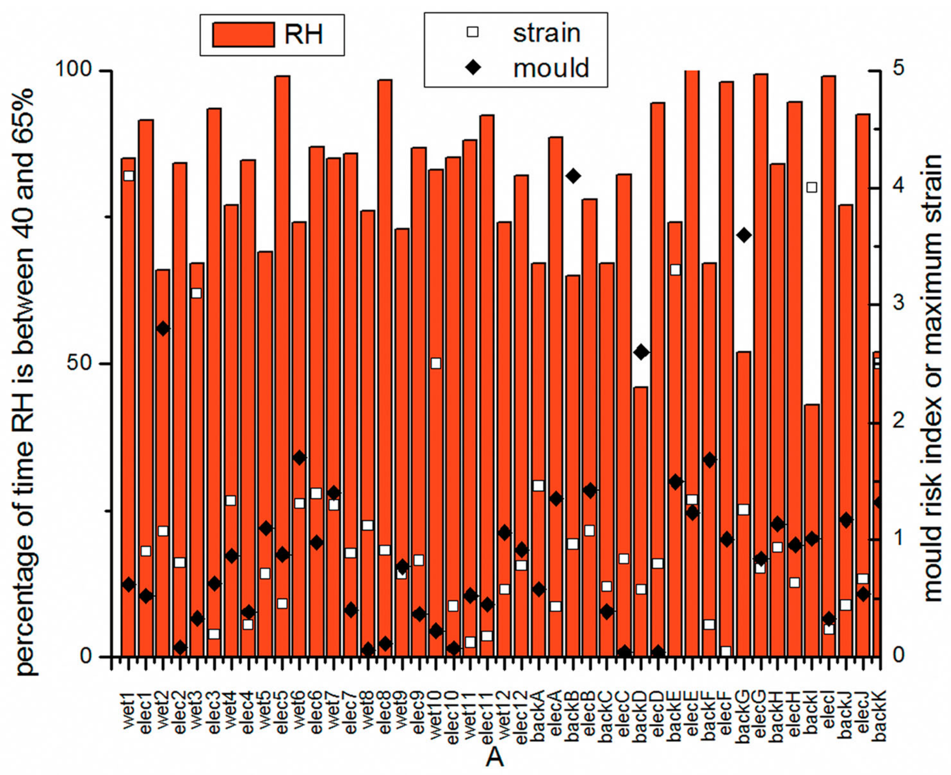

Figure 4. Measurements for rooms where control method was changed.

Figure 4 shows measurements for rooms with a variety of control methods. In three properties some rooms moved from wet humidistatic to electric humidistatic heating (labelled 1–12), or from background heating to electric humidistatic heating (labelled A–K). All these rooms showed an increase in the percentage time between 40 and 65% RH. The vast majority showed a decrease in both maximum strain and mould risk index, some of the decreases were very large. Three rooms showed an increase in mould risk

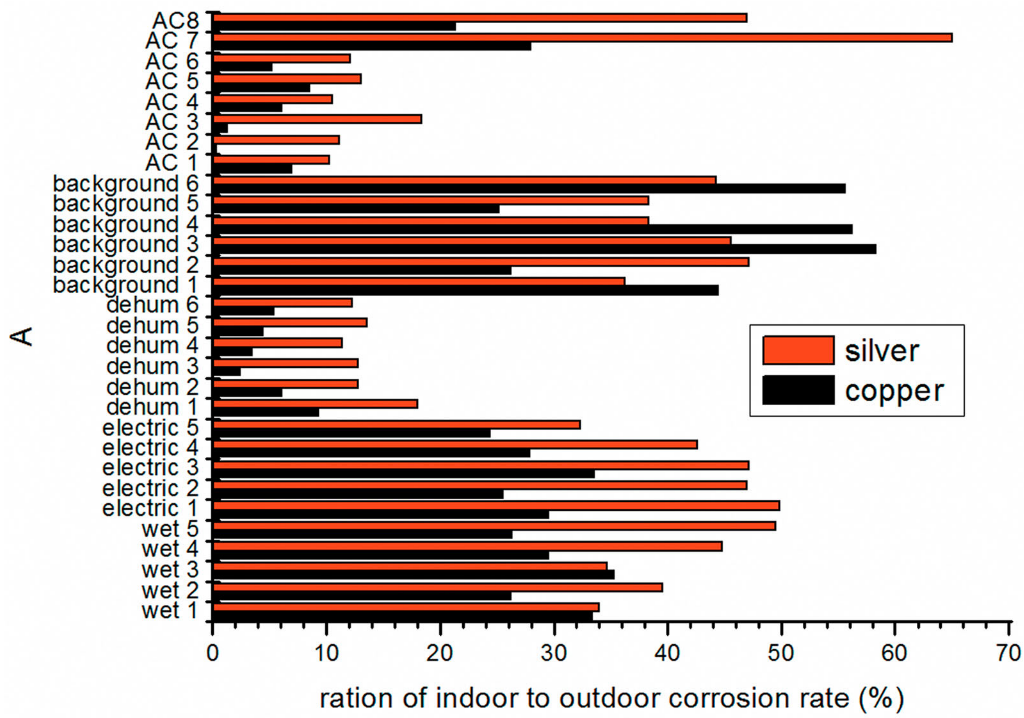

Figure 5. Ratio of indoor/outdoor corrosion rates for copper and silver in rooms with a variety of control methods.

Table 4. Summary of the comparative stores trial results.

Room	Control	Percentage time, 40–65%	Mass loss (g)	Largest variation in T	Largest variation in RH	Energy Use (kW/m^3/year)	Evaporation rate, Watanabe method (mg/m^2/s)	Evaporation rate, FLEC (mg/m^2/s)	
Dover	HH	87.2	0.9	3	8	2.74	0.21	0.23	Min
		90.1					0.74	0.89	LIR
		94.2					1.23	1.43	UIR
		96.4					2.68	2.46	Max
Dover	DH	96.3	0.8	1	2	0.99	0.01	0.11	Min
		98.7					0.25	0.31	LIR
		99,6					0.41	0.51	UIR
		100.0					2.31	0.82	Max
Fort Brockhurst	HH	75.6	7.3	3	10	3.12	0.21	0.34	Min
		80.1					0.82	1.03	LIR
		85.3					1.54	1.98	UIR
		87.5					5.31	3.45	Max
Fort Brockhurst	DH	96.4	1.2	1	3	1.21	0.04	0.12	Min
		98.3					0.25	0.45	LIR
		99.2					0.76	0.89	UIR
		100.0					1.85	1.94	Max

HH, humidistatic heating; DH, dehumidifer.

index: wet3, wet8 and backA. The increases in wet3 and wet8 are small and still below the reported threshold value of 1. The increase in backA is higher and moves to above that threshold. This emphasizes the fact that in some instances the percent time within a safe band can be misleading in terms of object risk. These values compare two consecutive years. Monitoring in three rooms without any heating showing quite large increases in the mould risk indexes in the second year with the electric humidistatic heating installed in the rooms reported. Several rooms showed small increases in maximum strain, including wet12, backC, backD and backJ, but were all still well below 2%, so the risk is negligible.

Considering pollution, the ratio of calculated silver and copper corrosion rates to the outdoor conditions are shown in Figure 5. Generally, both air-conditioning and dehumidification perform well. Two of the air conditioned rooms did not have chemical filtration in the plant, and gave very high silver corrosion rates. Whilst heating would be expected to have little impact on pollution concentrations, it does affect RH, which strongly influences the copper corrosion rate. Silver is less affected by RH. When the external conditions were taken into account the three heating methods had similar calculated silver corrosion rates. Copper had a higher rate under background heating, which probably reflects the difficulty in maintaining the RH below 65%.

Comparative stores trial

Although significant disruption of air flow was observed near the ultrasonic transducers, and to a lesser extent around the support arms, the averaged air flows across the three acoustic paths were very similar to those measured in adjacent areas of the wall. In 93% of the measurements, the difference was less than 17%, the maximum difference was 34%. The much smaller T/RH sensors showed much less disruption of airflows and all values were within 19% of adjacent wall areas.

The summarised trial results are shown in Table 4.

Figures for the minimum, lower interquartile range, upper interquartile range, and maximum are given for percentage time that 40–65% RH was recorded by the 8sensors in each room and for the multiple evaporation rate measurements. They show that the humidistatic heating did not perform as well as dehumidification, mainly because of high RH values in the warm summer months when the upper temperature limit turned off the heater. Conservation heating also generated a much more variable environment across both spaces. The heater was against a wall and the racking down the centre of the room at Fort Brockhurst probably interfered with the heat flow, but such constrictions are common in stores. Dover had wall racking only, but a similar distribution of T and RH was observed. At Dover, where the salts are chloride-rich, there was little difference in impact between the two trial rooms. However, at Fort Brockhurst, with sulphate-rich salts, the humidistatic heating caused much larger losses from the walls. The salt efflorescence was mainly observed at the mortar surfaces and not at the brick surfaces. The water evaporation rates appeared higher with humidistatic heating than dehumidification. The two methods gave comparable results (within 35% on all measurements). Some caution is required interpreting these results due to the aforementioned impact of the measuring systems on the surface conditions. However, the trend is consistent and any perturbation is probably of similar magnitude.

The material losses were probably through salt efflorescence and not hydration of sodium sulphate at Fort Brockhurst, since the RH was never high enough to cause hydration from thenardite (Na_2SO_4) to mirabalite ($Na_2SO_4.10H_2O$). Calculations with the *Environmental Control of Salts* (ECOS) programme indicated mixing with chlorides lowers the sulphate hydration equilibrium RH line (there is a strong temperature dependence) (Price 2000). The observed lowering of this line in some stone objects may also be occurring here, moving the critical thresholds into the region of the room climates (Thickett 2017). The automated imaging system showed losses falling onto the imaging plate when the lowered transition line was crossed due to changes in T and RH in the rooms. Energy use was lower for dehumidification, as expected from the relatively low air exchange rates.

Conclusions

The measured data shows a marked improvement moving from background heating, to wet humidistatic to electric humidistatic heating in historic buildings. Dehumidification has been found to be very effective in storage situations. Older air-conditioning systems struggle with higher temperatures. Considering pollution ingress and metal corrosion rates, there seems little difference between the heating systems. Both dehumidification and air-conditioning perform very well, but an absence of chemical filtration on air-conditioning systems can very adversely affect silver and copper corrosion rates. Care needs to be taken extrapolating these results to other locations, especially in different climatic zones.

For storage, a comparative trial of humidistatic heating and dehumidification indicated that dehumidification had several advantages, producing a more even environment, less salt damage to historic fabric (when sulphate was present), lower water evaporation rates from walls, and used less energy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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