



Article title: The causes of air movement in hidden indoor micro-environments: measurements in historic bookshelves

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Keywords: Air movement, Historic buildings, Preventive conservation, Micro-environment, Mould, Built environment

Covering letter

This research article is part of a wider research project assessing the use of air movement as a preventive measure for mould growth. Environmental control in historic buildings is a challenge because of the nature of the buildings, which can be draughty and not well insulated. As a consequence, controlling moisture and temperature levels in more secluded spaces (e.g. room corners, behind furniture and in books in bookshelves) is a difficult task and it is in these spaces that mould tends to develop. Another challenge faced by institutions such as the National Trust (UK) is building sustainable conservation strategies, including being more energy efficient and reducing energy consumption.

In this study, we have investigated what causes air movement in spaces behind books in historic bookshelves. The aim was to understand the role of air passages in shelves and which mechanisms are involved in causing the air movement measured. The results show that both natural convection (caused by differences in temperature and also known for stack effect) and forced convection (caused by drafts in the room due to opening doors or people movements) cause air movement in these spaces. It also showed that while in some cases, one mechanism prevails, both may be present in most cases. It was also possible to predict the air movement caused by natural convection using a simple mathematical model that considers the temperatures in the bookshelf and the room.

We believe the conclusions can be generalised to other types of buildings holding collections in bookshelves and that air movement should be further explored to prevent damage caused by mould in historic collections. Including it in preventive conservation strategies could reduce the pressure on existing environmental control systems and be used to control moisture and temperature levels locally.

The causes of air movement in hidden indoor micro-environments: measurements in historic bookshelves

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Abstract

The use of ventilation holes in small micro-environments has been proposed as a mechanism to improve the environmental conditions of moisture and temperature within bookshelves. The National Trust, for example, has used these mechanisms to encourage air movement behind books as a possible strategy to reduce the risk of mould growth. It is believed that including ventilation holes as a passive design solution to promote airflow within micro-environments could prevent decay from occurring in archives of historic buildings. This paper investigates the mechanisms that cause airflow behind bookshelves using field measurements in three National Trust historical libraries. The measurements indicate that small but measurable velocities, up to 4 cm/s, can be generated passively behind bookshelves. Air movement in such confined micro-environments is caused by a combination of natural convection, caused by temperature differences between the interior and the exterior of the bookshelf (stack effect), and forced convection due to drafts in the surrounding environment. While in some cases one mechanism prevailed, both mechanisms may be present simultaneously in most cases. Finally, this paper proposes that air movement as a result of the stack effect in these micro-environments can be predicted with a simple mathematical model, which offers a good fit with the experimental data in the cases where temperature differences promote air motion.

Keywords: Air movement; Historic buildings; Preventive conservation; Micro-environment; Mould

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1. Introduction

Environments with higher relative humidity are a big challenge for conservation in historic buildings as they may promote the decay of building fabric and collections (Florian, 1997; Valentín *et al.*, 1998). High humidity provides suitable conditions for mould development, especially in micro-environments that can occur in hidden areas of rooms, such as corners and/or behind furniture. Higher relative humidity and low temperatures have been found behind bookshelves in historic buildings, increasing the risk of biodeterioration of books. It is believed that increasing air motion in shelves using ventilation holes can eliminate these conditions, which is a strategy being tested by the National Trust (Curteis, 2016). Such holes can have different geometries and can be put into horizontal shelves, behind the books or into the vertical backboard of the bookshelf.

It is well-known that natural convection caused by temperature differences can promote buildings ventilation (Letan, Dubovsky and Ziskind, 2003). This air movement mechanism has been studied extensively, but usually in geometries far larger than the micro-environments found at the back of bookshelves. Examples of spaces similar to the one studied in this paper are the ventilation cavities in walls (Rodrigues *et al.*, 2000), air movement within double-glazed windows (Dalal, Naylor and Roeleveld, 2009), or air movement in the space behind paintings and walls in museums (Ferrer *et al.*, 2020). These studies have shown that mathematical modelling can successfully predict the dynamic environmental conditions of these spaces. However, micro-environmental simulations are usually compared with measurements of temperature or humidity, rather than measurements of air motion. This paper presents an alternative approach to this analysis, providing direct measurements of air velocity taken within and outside the micro-environments of interest.




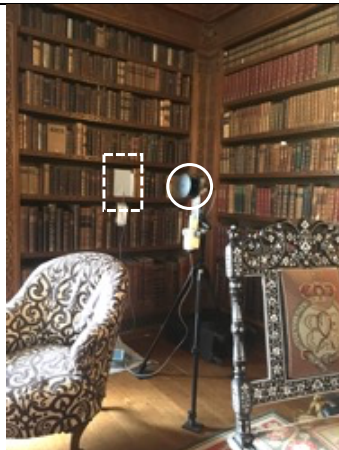


This study aimed to understand which physical mechanisms are responsible for the air movement within bookshelves. This study focused on historic bookshelves of three UK National Trust properties. The selection of properties was made based on different scenarios of mould development incidence; a relatively constant presence of mould (Charlecote Park), some previous mould development (Blickling Hall), no records of mould development (Ham House).

The environmental parameters in each property varied considerably; climate conditions, visiting patterns, the configuration of rooms and bookshelves, the orientation of rooms, etc. Therefore, the study aimed not to compare the three case studies but to use their diversity to better understand the context of air movement in such micro-environments.

2. Methodology

2.1 Monitoring locations

Table 1 - Bookshelves monitored and its context in the respective historic properties, with type of gaps in shelves and monitored periods.

| | Charlecote Park | Ham House | Blickling Hall |
|---|---|---|---|
| Location of studied room (red dot) (north points up) |  |  |  |
| Location | | | |
| View of the shelf with anemometers in the shelf (dashed line) and in the room (circled) |  |  |  |
| Position and dimensions of the shelf studied | 149 cm wide and 27 cm high. The shelf is at 118 cm from the floor. | 96 cm wide, 45 cm high and 27 cm deep. The shelf is at 114 cm from the floor. | 40 cm high and 77 cm from the floor. |
| Gap on the shelf | No gap. | Continuous. 1.5 cm wide. | Continuous gap. Approximately 3 cm wide. |
| Monitoring Times | Summer: 20/07/19 to 24/07/19 (Open to the public daily 11:30 to 16:00) Winter: 05-08/02/20 (closed to the public) and 16-20/02/20 (open to the public) | Summer: 04/07/19 to 08/07/19 (Open to the public daily 12:00 to 16:00) Winter: 24/01/20 to 28/01/20 (closed to the public) | Summer: 14 to 18/08/19 (open to the public daily 12:00 to 17:00) |
| Heating in the room | Yes (conservation heating: low level wet system heating plus electric radiators on local humidistats) | Yes (conservation heating controlled by building management system) | Yes (conservation heating: wet system heating plus electric radiators on local humidistats) |
| Bookshelf wall | External (Facing North) | Internal (Facing South-East) | Internal |
| Visitor Movement | Visitors enter the room but do not walk past the bookcase. | Visitors enter the room but do not walk past the bookcase. | Visitors enter the room and may walk in front of the bookcase. |

Charlecote Park (CP)

The Charlecote Park house is a Tudor mansion built in 1558. The library and the dining room, were added as a new extension to the Tudor mansion in the 1830s. The bookshelves in the library were built between 1835 and 1839 (English Heritage, 1999). The monitored bookshelf sits next to a window in the north external wall. A second window is located on the west wall. The library is part of the visitor route. Visitors enter the room from the hallway (east entrance) and walk parallel to the wall where the monitored bookshelf is located (north-facing). However, the bookshelf is set apart from the route as visitors circulate through the centre of the room, as can be seen in **Error! Reference source not found.A.** Visitors are directed to the west wall and exit the room through the south wall towards the adjacent room.

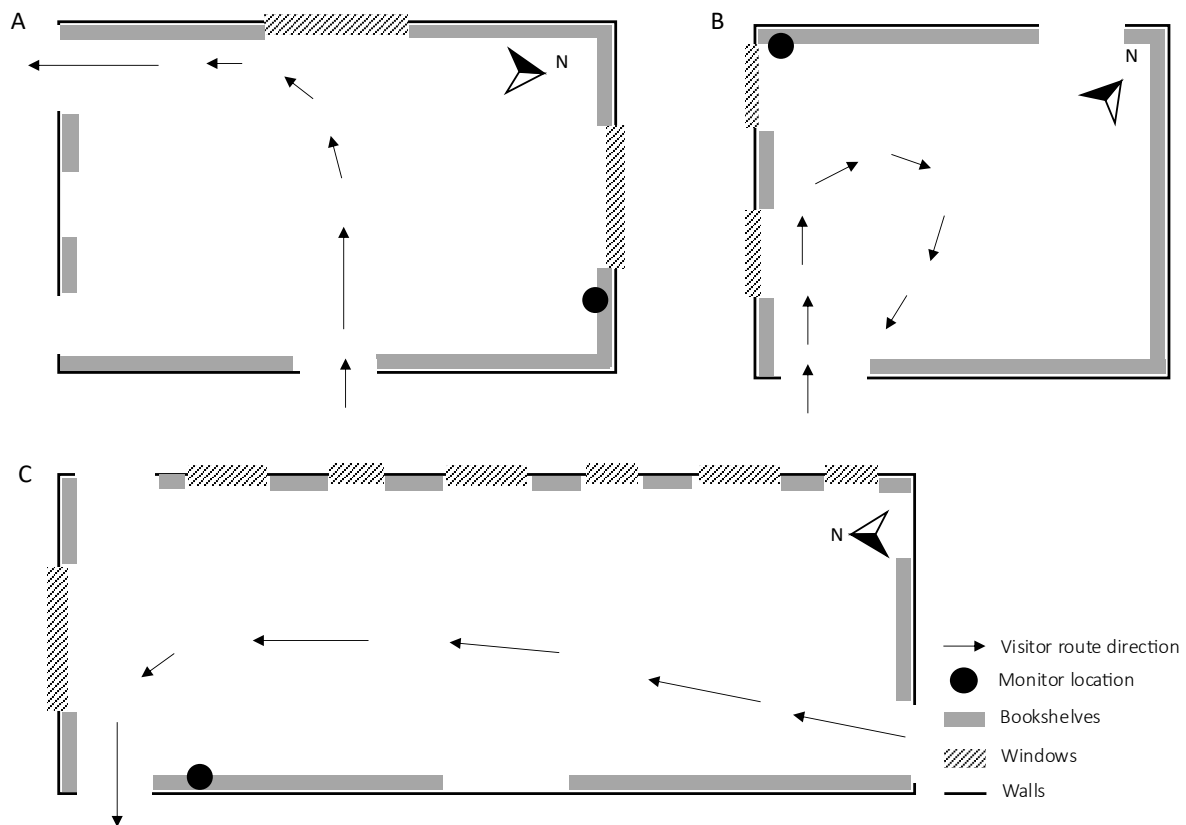


Figure 1 - Floor plans of Charlecote Park library (A), Ham House library (B) and Blickling Hall long gallery (C) with location of the bookshelves monitored and visitor routes (approximate scale).

Ham House (HH)

Ham House is a property built in the 1600s, located on the bank of the River Thames, in Ham (English Heritage, 1998). The library at Ham House faces southwest and is situated on the first floor of the historic property. There are two doors on opposite walls (northwest where the bookshelf is located and

southeast) and two windows on the southwest wall. All walls are covered with bookshelves with books. Visitors use the same entrance when entering and exiting the library and do not reach the monitored bookshelf (**Error! Reference source not found.**B).

Blickling Hall (BH)

Blickling Hall, in Norfolk, is a Jacobean building built in the early 1600's (Stanley-Millson and Newman, 1986). Its main entrance faces south. The library is in the long gallery on the first floor with windows facing east. The monitored bookshelf is on the west wall with no windows. Visitors are allowed to circulate in the library with no restricted area next to the bookshelves that cover both walls in the long room (Figure 1).

2.2 Monitoring methods

For each case study, air movement, relative humidity, and temperature were monitored to characterise the bookshelf and the general room environments. These environmental parameters were monitored simultaneously behind the books in each bookshelf and the room, in the space right next to each bookshelf. Monitors were placed at 1 to 2 m high to increase the chances of detecting air movement caused by visitors in the space.

Air movement (m/s) was monitored every second with two WindSonic Ultrasonic anemometers (accuracy: $\pm 2\%$ at 12 m/s; resolution: 0.01 m/s; threshold: 0.01 m/s; response time: 0.25 s; range: 0 – 60 m/s), each with a SpaceLogger.W8.Wireless logger to record the collected data. On shelves, the anemometer was placed against the back of the bookshelves, as seen in Figure 2. The space taken by the anemometer, from where books were removed, was covered with a piece of foam (h 28 cm, w 17 cm), placed flush with the spine of the books to close this space and mimic the presence of books.

A second anemometer was placed in front of each bookshelf monitored to measure the air movement in the room. At HH, the anemometer was placed at 50 cm from the shelf, at 100 cm height (measured at the centre of the anemometer), using a tripod. The anemometer was used horizontally to measure the air movement on a vertical plane, perpendicular to the bookshelf. In BH, the anemometer was hung from the bookshelf, at 220 cm height, since it was not possible to place it in the space next to the bookshelf given the visitors' circulation. In CP, the anemometer was placed at 106 cm from the bookshelf, at 126 cm high. Temperature and relative humidity were monitored within the bookshelf, next to the head of the anemometer, at intervals of one minute using a HOBO MX CO₂ data logger

(temperature: $\pm 0.35^\circ\text{C}$ from 0° to 50°C ; resolution: 0.03°C at 25°C ; relative humidity: $\pm 2.5\%$ from 10% to 90% RH; resolution: 0.05%).

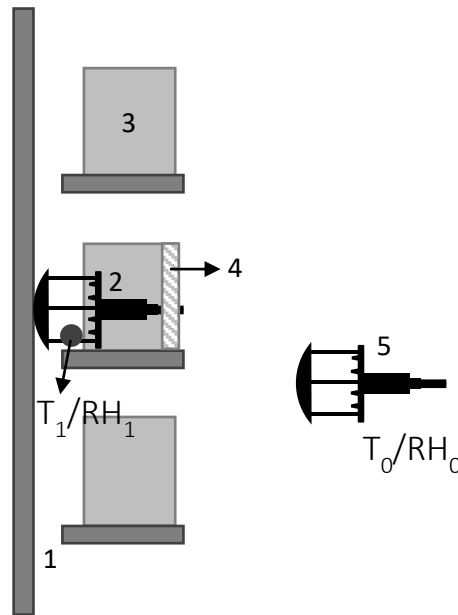


Figure 2 – Cross section of bookshelf with gaps behind the shelves (1); anemometer installed in shelf (2) next to books (3) and with a piece of foam covering the space taken by the anemometer (4); temperature and RH of the shelf (T_1/RH_1) measured next to the anemometer; anemometer installed in the room (5) where temperature and RH was also measured (T_0/RH_0).

2.3 Modelling the Stack Effect

To understand air movement in the shelves, air velocities (m/s) for the monitored period were predicted using the following equation, which was adapted from an equation used to calculate the draft flow rate caused by thermal forces alone (ASHRAE, 2009).

$$v = C \sqrt{2gh \frac{T_i - T_0}{T_i}} \quad (1)$$

where C is the discharge coefficient (usually from 0.65 to 0.70), g the gravitational acceleration (9.81 m/s^2), h the height or distance (m), T_i the average inside temperature (K) and T_0 the outside air temperature (K) (ASHRAE, 2009). In buildings, h is taken as the height of the air column. In this case, we have used the height of the bookshelves. This is an arbitrary choice, and it could be argued that other dimensions, such as the height of an individual shelf, could also be appropriate. To estimate the discharge coefficient C for each of the case studies, Eq. 1 was re-arranged in the shape of a linear equation of slope k :

$$v = k \sqrt{\frac{T_i - T_0}{T_i}} \quad (2)$$

where $k = C\sqrt{2gh}$. This equation is normally used in air columns, where the internal temperature is measured at the base of the column and the external temperature is measured at the top. In our case, we use the internal temperature of the shelf as T_i and the external temperature as T_0 . With the available data this equation provides a good approximation to the driving thermal flow in this geometry. The comparison with the measurements allows a discussion on potential improvements to this simple model.

3. Results

3.1 Temperature and Relative Humidity

In general, the temperature and humidity in the bookshelves follow the conditions in the room, both during summer and winter. This is clearly seen in Figure 3. The results show that shelves in general have a buffering effect (Lloyd *et al.*, 2007) generating dampened fluctuation amplitudes of temperature (T) and relative humidity (RH). This is especially clear in the T fluctuations in Charlecote Park (CP), and the T and RH fluctuations in Ham House (HH) in summer.

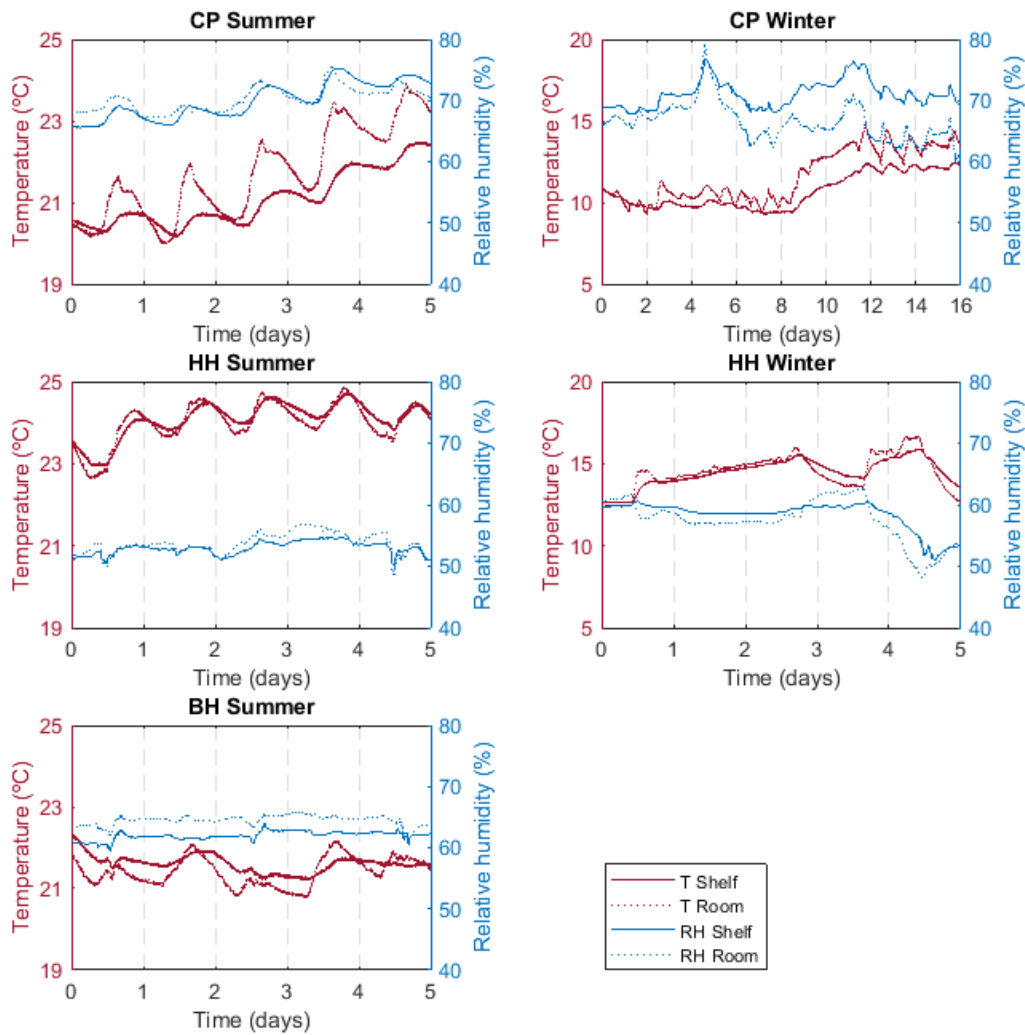


Figure 3 - Temperature and Relative Humidity inside the bookshelves and within the rooms (vertical lines correspond to the night period, 00:00 am).

In CP, the RH recorded in summer was mostly lower on the shelf than in the room. In winter, we can see that RH in the shelf is higher than in the room, possibly due to lower T influenced by the external wall. In HH, the temperatures in the room and the shelf show a daily oscillation in summer with a small delay in the T within the shelf. The RH in both are also similar, with minimal differences, which are close to the error of the equipment ($\pm 0.35^{\circ}\text{C}$ and $\pm 2.5\%$ RH). In BH, the T and RH both in the room and the shelf are very stable, with values in the shelf slightly higher but with a smoother behaviour, which could be evidence of buffering likely due to the thermal insulation properties and hygroscopic nature of the books.

Data of wind conditions obtained from the Met Office weather stations near the properties for the monitored periods showed no correlation with the indoor air movement measured. During the winter period, indoor conditions of RH in CP and HH showed no correlation with the external RH. During the summer, only the RH conditions in CP followed the outside trend but with delays. HH and BH showed no correlation with exterior RH. In the winter, temperatures indoors showed no correlation with the exterior temperature conditions in all three libraries. During the summer period, a correlation was observed in all three libraries showing an influence of the external temperature on the indoor temperature.

The monitored properties display a diversity of hygrothermal conditions, as seen in Figure 3. However, it is possible to use this data to explore whether air movement within the shelves is related to air movement within the room.

3.2 Air velocity in the bookshelves and the rooms

Air movement in the rooms usually displays a daily pattern that coincides with the opening hours of the libraries. This relationship is consistent in the three properties in Summer (Figure 4), when the buildings are open to visitors. In these cases, air velocities in the shelf follow the changes in air velocities in the room. In winter, the air velocity in the rooms is lower and it loses the periodicity. The air movement within the shelves is always an order of magnitude smaller than in the room, often close to the measurement threshold of the instrument (0.01 m/s).

In some properties, there is a correlation between the air movement in the room and the air movement within the shelf. This is most obvious in CP in the summer, where air movement in the shelf is more active whenever there is air movement in the room. It can be hypothesized that the pressure differences caused in the room either by the movement of visitors or the room's ventilation from doors being open and closed directly affect the air movement within the shelf.

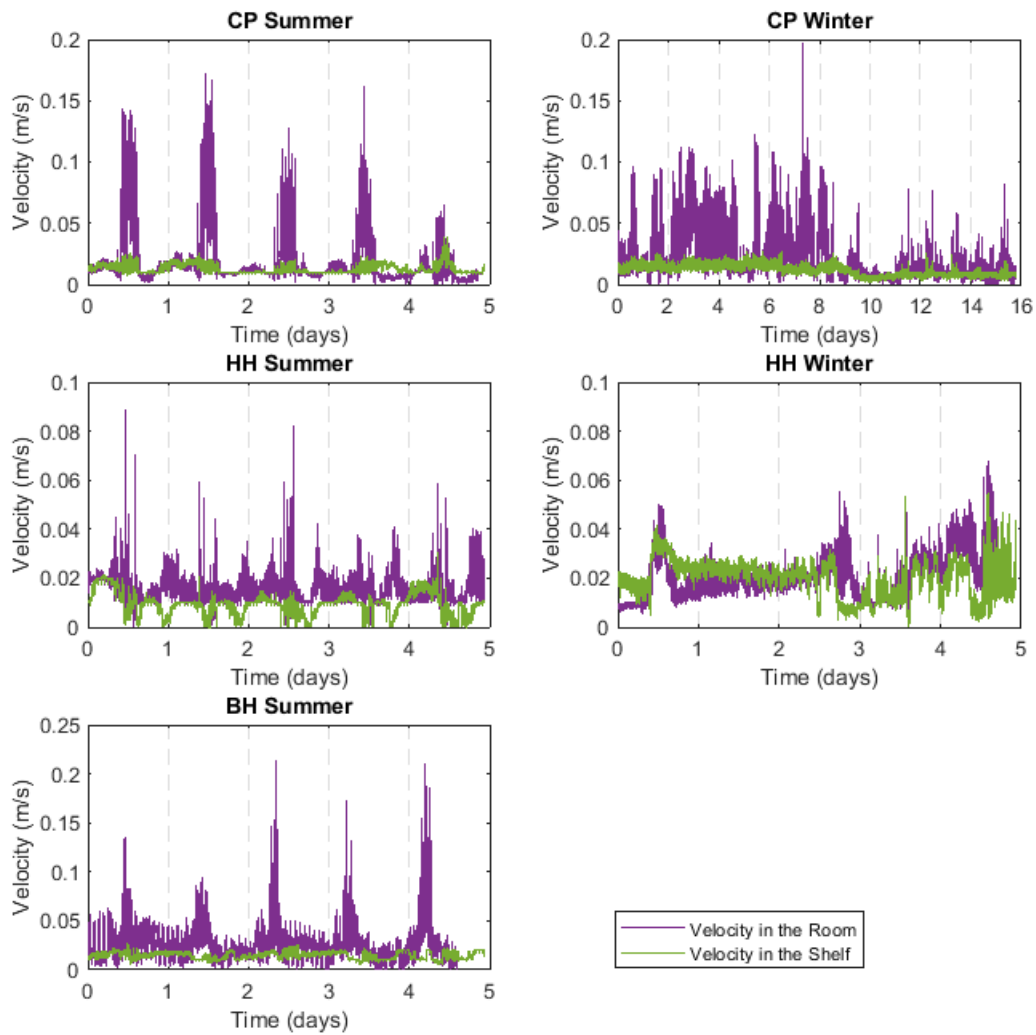


Figure 4 - Air velocity measured inside the bookshelves and in front of them (vertical lines correspond to the night period, 00:00 am).

It is possible that the increase in air movement during open hours, corresponding to the peaks monitored in the room are the results of other activities within the building; the library in CP is adjacent to the Great hall, where people enter the building. So, the increased air velocities observed during visiting hours in the rooms (and in the bookshelf with a smaller amplitude) could be due to general movement in the building, such as opening and closing the external doors, rather than exclusively due to people moving (walking) in the library.

During the winter period, when CP is closed to visitors (first four days of monitoring: 05-08/02/20), air movement was higher both in the room and the shelf, compared with open days. This could be explained by the work carried out by staff during this period preparing the room before reopening it to

the public. The increase of air movement occurred mainly around midday, coinciding with working hours and the opening and closing of the external and interior doors, similarly to the summer period.

The air movement in the HH and BH rooms does not seem to be correlated with the air movement recorded in the shelves. In fact, in the summer period, the air movement in the HH shelf decreases when in the room increases. In this case, the air movement in the shelf does not seem to be caused by increased air movement in the room. During this period, the property was closed to the public, but the staff were involved in works in an adjacent room and the library was used as a passageway. Their circulation in the room may explain the variation of air movement measured during this period. Therefore, air motion in the rooms alone does not explain the air movement detected within the shelves in all cases. To explore other possible causes, it is necessary to examine the differences in temperature between the shelf and the room.

3.3 Air velocity and temperature differences

As seen in Figure 3, it is difficult to generalize about the temperatures of the bookshelves in relation to the room. The temperature difference changes throughout the day, with most shelves experiencing periods where they are warmer or colder than the rooms. We have used Equation 1 to explore whether these temperature differences are sufficient to cause the observed air movements. Figure 5 shows the relationship between the measured air velocity and temperature differences in each monitoring location. Note that the temperature differences between the rooms and the shelves are expressed in terms of $\sqrt{(T_i - T_o)/T_i}$. This allows the calculation of $C\sqrt{2gh}$ as the slope of the linear regression. It can be observed that in all the libraries during the summer, there is a relationship between air velocity and the temperature difference between the shelf and the room. While the Pearson correlation coefficients are considered moderate to strong (r^2 ranges from 0.51 to 0.68) (Akoglu, 2018) it is evident that there exists a connection between these two variables. However, in winter (CP and HH), this relationship is non-existent, so we have not conducted the regression analysis.

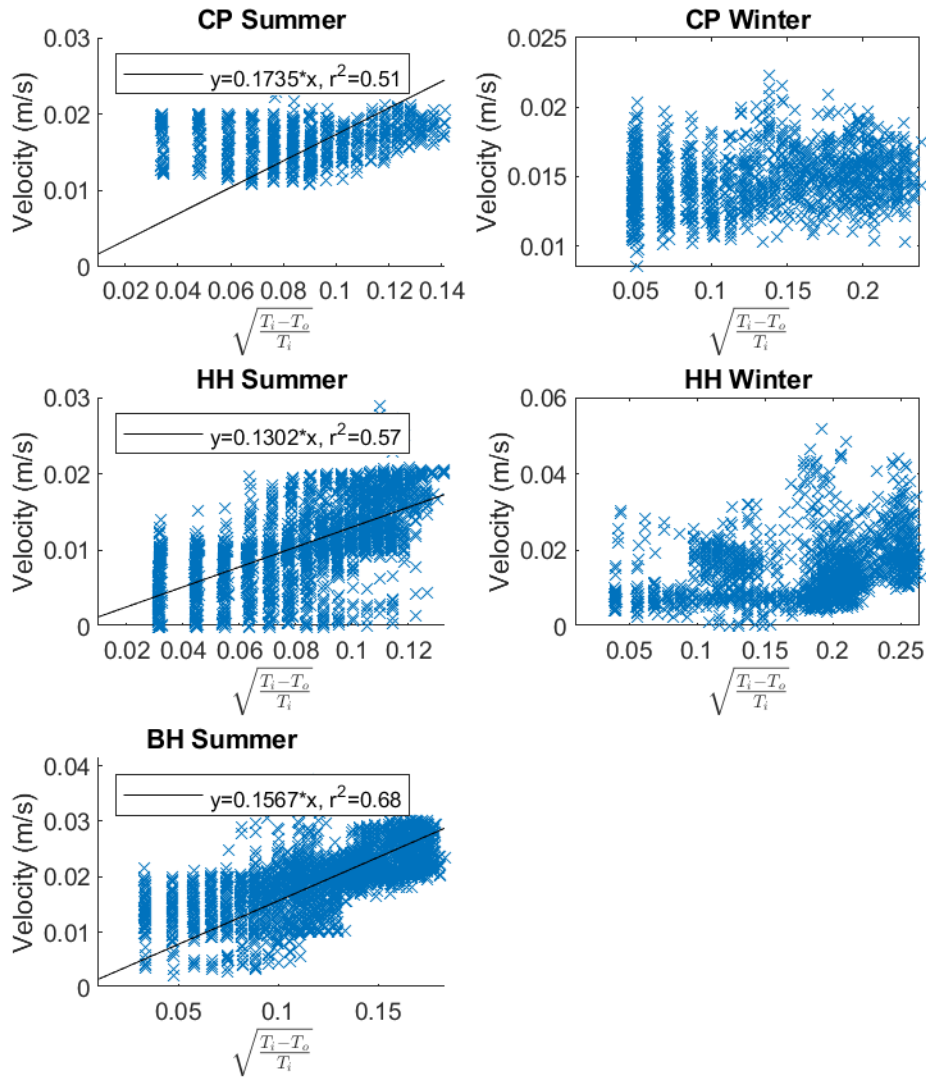


Figure 5 - Scatterplots of velocity and the temperature difference between the interior and the exterior of the bookshelves. A linear regression line is present only in the scenarios that display a potential correlation.

Fitting a linear model to the data allows us to estimate the value of the discharge coefficient, C , which gives an idea of the resistance offered by the shelves to air movement resulting from stack effect. C is an unitless coefficient which ranges from 0 (no air flow) to 1 (no resistance to air flow).

Table 2 summarises these results. The estimated discharge coefficients are significantly lower than the value of 0.65 proposed for buildings in the ASHRAE handbook (ASHRAE, 2009), indicating a high resistance to air flow. This is to be expected given the very narrow spaces available for airflow. We found, however, no statistical relationship between these coefficients and the space available for air flow behind the shelves.

Table 2. Results of the estimated C values, together with the measured gap behind the shelves.

| Location | Estimate of C | Gap Size |
|--------------------------|----------------------|------------------------------|
| Charlecote Park (summer) | 0.027 ± 0.000606 | No gap |
| Ham House (summer) | 0.021 ± 0.000208 | Continuous gap, 1.5 cm wide. |
| Blickling Hall (summer) | 0.019 ± 0.000204 | Continuous gap, 3 cm wide. |

The estimated coefficients can be used within Equation 1 to predict air velocity. The calculated air velocity is shown below next to the measured air velocity (Figure 6). There is a significant overlap in the data for HH in the summer and BH. It is interesting to note that, in these two libraries, there is no apparent relationship between air movement in the room and within the shelves, as seen in Figure 4. There is, however, a remarkable fit between the measured and predicted air movement in the shelves, which could indicate that air motion is caused by temperature differences only. This relationship is not present in HH and CP in winter, with the exception of the first two days in CP in the summer, which could be explained by the activities within the house during those two days.

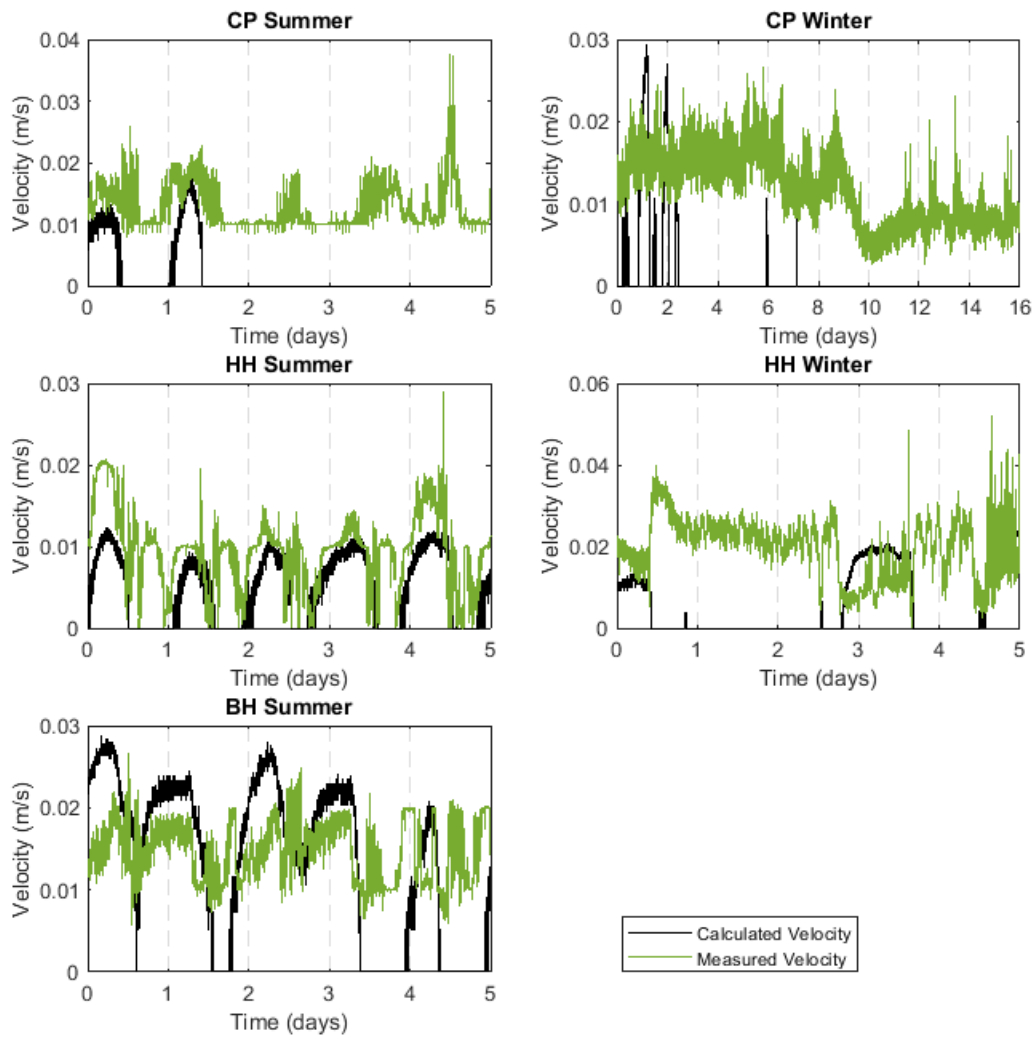


Figure 6 - Modelled and measured air velocities behind the books (vertical lines correspond to the night period, 00:00 am).

This correlation is not observed for the winter period. However, note that this does not necessarily mean no stack effect. It is not possible to determine if the stack effect is not present or if it is present on a smaller scale at the same time as pressure differentials have a stronger influence. It is conceivable that a pressure differential is the main mechanism responsible for the air movement monitored during the winter period, masking any potential stack effect.

4. Conclusions

There are two possible explanations for the observed air movement behind books: stack effect (caused by a temperature differential) and pressure differentials (e.g., people circulating, opening of internal

and external doors during visiting times). Forced convection caused by external pressure differences can be seen most clearly in the summer monitoring data from Charlecote Park. This property shows a correlation between the peaks of air movement measured in the room and the increase of air movement detected in the bookshelf. In this case, a pressure differential is responsible for the motion detected, very likely caused by the movement of visitors and staff members in the room. The shelves monitored in this property have no ventilation gaps. Natural convection caused by temperature gradients (stack effect) is visible in HH. This property presents a different scenario, where an increase of air velocities in the bookshelf does not coincide with the same behaviour in the room. In fact, when air movement increases in the room, the opposite happens in the bookshelf. The air movement at HH during this period can be explained by the temperature differences observed between the interior of the shelf and the room. In this property, the shelves are open behind the books with 1.5 cm continuous gaps. In BH, using the same adapted equation, part of the air movement seems to be explained by a stack effect but not all the monitored days. It is likely that, in reality, all cases of air motion are caused by a combination of the two processes, stack effect and pressure differences. We can recognise these behaviours more clearly when one process has a dominating effect.

The simple mathematical model used to investigate the stack effect is clearly not detailed enough to account for all the physics of the process. The main limitations are that (1) it is designed to operate with temperature differences over vertical columns of air, rather than differences between external and internal spaces, (2) the geometry of the shelves is more complicated than a single air column, with gaps of changing sizes and multiple openings along the way and (3) it is a linear equation which does not fully capture the actual shape of the observed relationships. Despite these limitations, the equation provides remarkably constant estimations of the discharge coefficient C , which are similar across the properties.

Finally, these experiments have shown that it is possible to obtain a measurable air velocity behind books on bookshelves and that gaps in shelves promote air movement. It is yet to be determined whether these low velocities are sufficient to create desirable micro-environments, for example, by inducing better ventilation which may help mitigate pockets of high humidity or cold temperatures. However, it is clear that managers in historic buildings, as well as others dealing with similar types of buildings, can take advantage of small variations in temperature and air velocity to promote air motion in such secluded spaces. This finding opens the door to the design of passive micro-environmental solutions.

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Abbreviations

CP – Charlecote Park

HH – Ham House

BH – Blickling Hall

T – Temperature

RH – Relative humidity

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Authorship Contribution

Morena Ferreira: conceptualization, data analysis, contributed to the manuscript; Josep Grau-Bové: conceptualization, data analysis, contributed to the manuscript; Hector Altamirano-Medina: contribution to the manuscript; Nigel Blades: contribution to the manuscript.