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Technical Note

A device for the local measurement of water evaporation rate

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Abstract

Evaporation plays a central but largely invisible role in the moisture dynamics of buildings and urban microenvironments. Local evaporation rates control water flux and material damage, and are altered by climate change. While potential evaporation (PE) (or potential evapotranspiration (PET)) can be estimated on the large-scale, there are few if any methods of making local PE measurements. We describe here a simple device (*patch evaporimeter*) for measuring PE at point locations on the surfaces of built structures. The device combines a sintered-quartz disc as a water reservoir and a low-cost remotely-readable humidity sensor to detect the drying time. The patch evaporimeter may be widely useful in monitoring evaporation rates in a variety of microenvironments.

Keywords: evaporation, evaporimeter, drying, porous materials

(Some figures may appear in colour only in the online journal)

1. Introduction

Recent analysis [1–3] of moisture dynamics in built structures shows the central role of evaporation. Evaporation at surfaces provides the main process by which water leaves material structures, and evaporative pumping actively drives capillary migration within porous fabrics such as brick, stone and concrete. Evaporation must play the same central role in the built infrastructure in general. It must likewise be incorporated in water-balance models in the emerging field of urban hydrology [4–6]. Changes in evaporation rate are known to occur in response to climate change [2, 7], but relations at the local scale are unclear, partly for want of field data.

However, evaporation is largely invisible, and the magnitude of evaporative fluxes has not been fully recognised in the environmental physics of buildings. Models of mass transfer invariably require an evaporation boundary condition to describe water exchange with the environment, but this is generally formulated in terms of humidity and air movement. These two quantities are not easily measured by survey at microscale in the field. In any case their use requires an adequate model of boundary layer transport which is usually not available.

We have shown elsewhere [2] that a more robust approach is to use the *potential evaporation* (PE) to describe the evaporation flux at surfaces. The PE is a direct measure of the evaporation from a free-water surface under given environmental conditions. Using the PE sidesteps the need for a mass-transfer model of the structure of the boundary layer. Our analysis shows how such PE data can be used to represent time-varying boundary conditions in moisture dynamics models. This approach is particularly effective in describing the seasonal and geographical variations of stored water and



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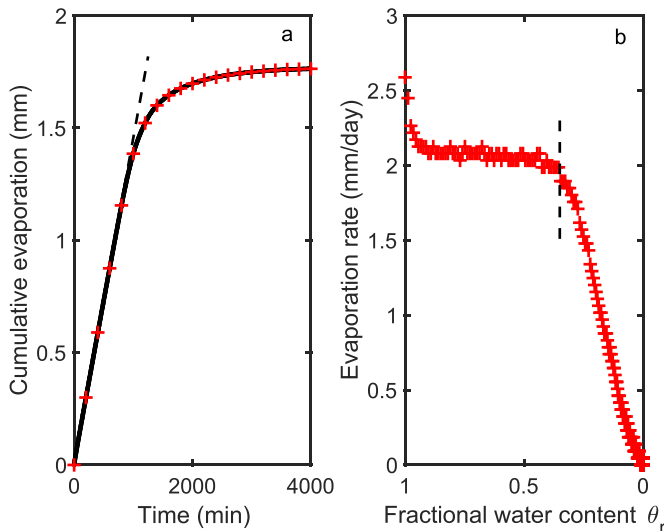


Figure 1. Drying kinetics of a Portland stone block, $50 \times 50 \times 50$ mm, showing stage 1 and stage 2 behaviour. (a) Cumulative evaporated volume vs time, showing initial stage 1 linearity; (b) evaporation rate vs mean fractional water content θ_r , showing crossover from stage 1 to stage 2 behaviour; θ_r is the mean volume water content θ normalized by its saturation value θ_s . Test carried out in an environmental chamber under constant environmental conditions (25°C , 50 per cent relative humidity, constant fan speed), drying from all faces, loss of water measured gravimetrically at 30 s intervals.

water flux in walls. Locality-scale or grid-scale PE values can be obtained from meteorological sources, traceable either to station measurements of pan evaporation or to established calculation methods such as the Penman–Monteith equation [8, 9].

2. Evaporation physics

The drying of a porous material by evaporation of water (or other liquid) from its surface generally shows two distinct stages [10–12]. Under constant environmental conditions, stage 1 exhibits a constant rate of evaporation, while in stage 2 the rate of evaporation falls progressively until the material reaches equilibrium with the environment, the dry state. Figure 1 shows the drying kinetics of a Portland limestone block which behaves in this way.

In stage 1, the rate of evaporation is similar [13] to that of a free water surface, that is to say the PE, since water forms a more or less continuous film on the porous surface and maintains saturated water vapour pressure at the interface with the external atmosphere. Under these conditions the rate of evaporation is entirely controlled by the structure of the boundary layer, and factors such as the temperature and the far-field humidity. Stage 1 behaviour continues so long as internal capillarity maintains sufficient water at the surface to support the evaporation rate. How long this persists depends on the unsaturated-flow parameters of the material and the thickness of porous structure beneath the surface, as well as the evaporation rate itself.

In stage 2, the water content at the surface is insufficient to maintain saturated water vapour pressure at the air interface, and the surface water content moves to a value at or close to equilibrium with external atmosphere. The evaporation rate is now controlled largely by the internal unsaturated flow or vapour diffusion, subject now to an atmospheric boundary condition set by the external humidity. For many porous materials such as brick, stone and concrete of importance in infrastructure engineering, the surface water content is rather insensitive to the atmospheric humidity and we have an essentially ‘dry’ boundary.

This description of two-stage drying is adequate for our purposes here, but we note for completeness that some recent work [14, 15] refines the description of the underlying mass transfer processes. This elaboration however has no direct bearing on our discussion.

3. Report

3.1. Design

There are many situations (for example in conservation [16]) in which we need to understand moisture dynamics at a small scale. In such cases, we wish to acquire data on the potential evaporation of the immediate microenvironment, and sometimes its distribution over a geometrically complicated structure. While some evapotranspiration meters are available, they are used mainly for grassland management and are not well suited to precise monitoring of microenvironments, especially at or close to surfaces. The purpose of this short paper is to describe a device that meets that need.

Our aim has been to develop a simple device which can measure directly the rate of evaporation of water at point-locations on building surfaces. Such a device would provide a measure of potential evaporation more or less equivalent to that of a meteorological pan evaporimeter. This directly measured PE would reflect the local values of the controlling factors (air speed, humidity and so on) without having to measure them individually. Such a device should ideally be sufficiently simple that many could be used simultaneously to make spot measurements to map the distribution of PE over a small area, for example over the surface a single structure.

In early tests we developed the concept of a ‘patch evaporimeter’, using various meshes and fabrics to hold water. A requirement was that the device could be attached to a surface of interest, and should not interfere with the local air-flow or humidity. This was achieved by using flat patches of absorbent materials, typically 25×25 mm, with an impermeable backing. These patches were saturated with water at the start of a test, and the PE was determined from the time taken for them to dry. The drying of small stone blocks has also been used [16].

Simple patches of this kind provided a useful proof-of-concept, but they were difficult to saturate reproducibly. Patches generally lost water at constant rate in an environmental cabinet under constant conditions, but we did not find an easy and manageable way to detect accurately the time at which they became dry. Tests using colour changes of coloured papers and fabrics were unsuccessful. Manual weighing

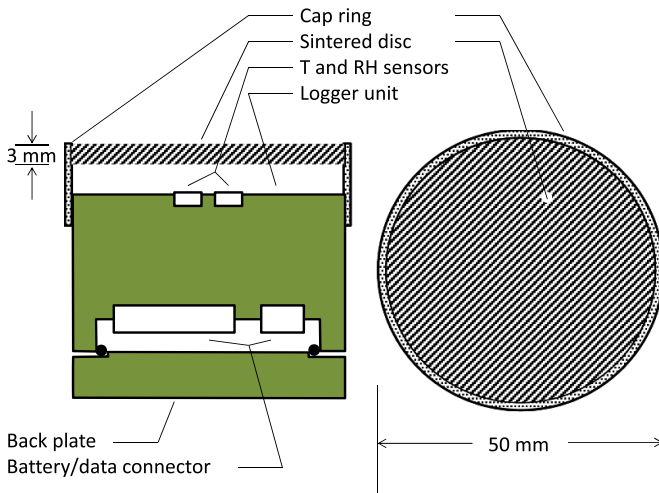


Figure 2. Patch evaporimeter combining a sintered–quartz disc (H Baumbach & Co, Martlesham, UK) with a Humilog sensor (Grant Instruments, Cambridge, UK).

was accurate but laborious and impractical for field use. After many trials, sintered quartz, in the form of discs manufactured for use as filters, was found to be a better patch material than meshes and fabrics. Sintered discs, usually 50 mm dia \times 3 mm thickness, and with volume-fraction porosity 0.31, imbibed a reproducible quantity of water (~ 2.1 g) in a few seconds, and had a reproducible dry weight.

An improved device was next achieved by combining a sintered-quartz disc with a humidity sensor (figure 2). The sensor first used was a Humilog unit, a compact free-standing battery-powered logger that reads and stores humidity and temperature data. In the first realisation of this concept the disc was mounted on a ring so as to form a sealed cavity between the back of the disc and the humidity sensor. The sensor therefore registers the humidity of the water in the disc, which remains high and roughly constant until the disc is completely dry, at which time it falls abruptly.

In a second realisation (figure 3), a much smaller Tempo DiscTM humidity sensor was used, with the important feature that humidity and temperature can be read remotely via Bluetooth, and logged data can be downloaded without disassembling the sensor from the sintered disc. It is therefore easy to monitor the drying of the disc from a distance. The sintered disc can be resaturated by a few seconds contact with water. Occasional check-weighings of the assembled device are easy to make, for example on a portable 50 g carat balance reading to 0.001 g. The performance of the Tempo humidity sensor has been assessed in tests with salt solutions providing known water vapour pressures [17]. When adjusted by means of a single-point calibration (for example at 75 per cent RH at 25 °C using a saturated aqueous NaCl solution), the sensor reports the relative humidity over the entire RH range 20–95 per cent to within about ± 1 per cent. In any case, high absolute accuracy of RH is not required for this device; the main performance requirement is that the sensor should be sensitive to small changes in RH, particularly in the RH range 80–95 per cent. In this regard, the sensor performs as required, and responds

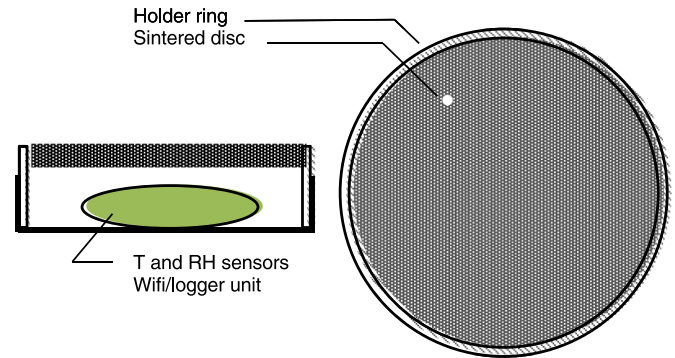


Figure 3. Patch evaporimeter built on a Tempo DiscTM humidity sensor (Blue Maestro, London, UK).

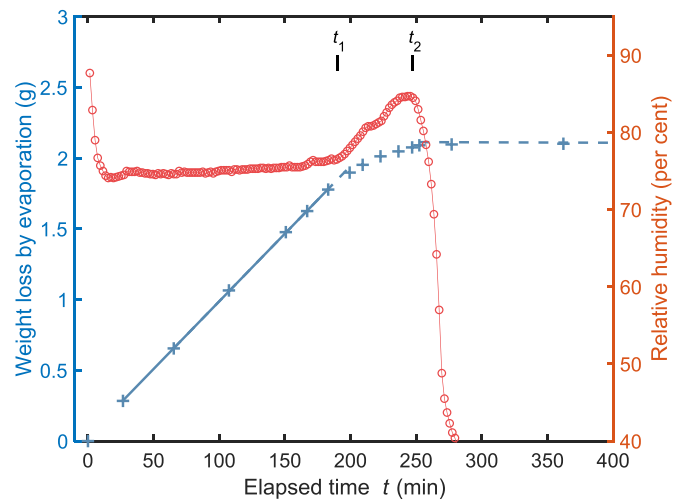


Figure 4. Evaporation weight loss and humidity signature in a PE measurement test: environmental chamber conditions, 24.8 °C, 24.5 per cent RH, constant fan speed.

rapidly to changes as small as 0.1 per cent. Similarly, the temperature sensor detects temperature changes of ± 0.1 °C.

3.2. Humidity record

We noted earlier that the sensor humidity value falls abruptly at the time when the disc becomes completely dry. In fact the humidity record during a complete measurement run has several distinctive features (figure 4). When the saturated disc is first placed in position and evaporation starts, there is a small decrease in the recorded RH. This occurs because the evaporation causes the disc to cool, as shown by the thermal images of figure 5. The cooling in turn reduces the water vapour pressure in the cavity, and this is reported by the sensor as a reduction in RH since the sensor registers the cavity temperature not the temperature of the disc. Water evaporation from the disc then finds a steady state, with steady disc temperature and steady stage 1 drying rate. Changes in external conditions produce only small changes in the recorded relative humidity of the cavity. The sensor RH remains more or less constant during this time, apart from minor sensor drift. At a time t_1 , there is a clear uptick in the recorded cavity RH. This marks the end of

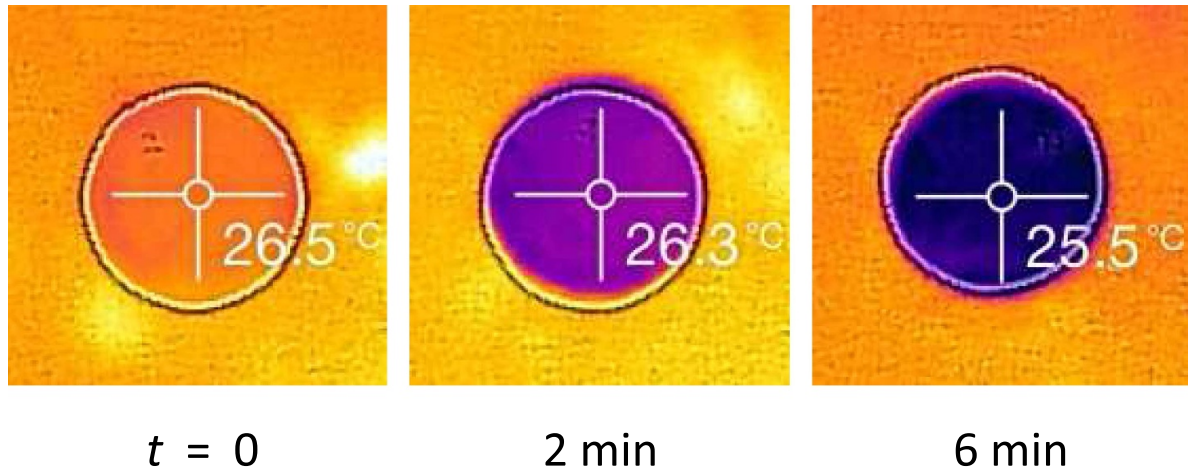


Figure 5. Evaporative cooling of a sintered disc on exposure to air.

Table 1. Examples of potential evaporation (PE) values measured with patch evaporimeter.

| Location | Time t_1 (min) | Time t_2 (min) | PE (mm/day) |
|---|------------------|------------------|-------------|
| Exterior wall (1) | 165 | 220 | 9.6 |
| Exterior wall (2) | 195 | 250 | 8.1 |
| Exterior wall (3) | 1135 | 1250 | 1.4 |
| Exterior wall (4) | 745 | 835 | 2.1 |
| Interior wall (5) | 430 | 490 | 3.7 |
| Interior wall/wall/floor stagnation point | 505 | 560 | 3.1 |
| Controlled environment chamber (6) | 190 | 245 | 6.9 |
| Humidistat (7), 33 per cent RH | 595 | 685 | 2.6 |
| Humidistat (7), 57 per cent RH | 1800 | 1920 | 0.88 |
| Humidistat (7), 75 per cent RH | 3110 | 3390 | 0.50 |

Notes: All measurements made at location 52.1470 N, 0.1494 E, May–June 2020; sensor screened from rain and direct insolation. (1) Elevation 1.6 m, day-time, west facing, temperature 18 °C; (2) elevation 2.0 m, day-time, north facing, temperature 22 °C; (3) elevation 2.0 m, night-time, north facing, mean temperature 17 °C; (4) elevation 2.0 m, day-night, mean temperature 17 °C, mean relative humidity 65 per cent; (5) temperature 20 °C, relative humidity 40 per cent; (6) temperature 25 °C, relative humidity 25 per cent, constant fan speed; (7) temperature 25.0 °C, no forced convection

stage 1 drying, when the rate of evaporation falls sharply. As a result the evaporative cooling of the disc decreases, the vapour pressure of the water remaining in the disc rises: this is detected by the sensor as an increase in RH. Finally, at time t_2 the cavity RH starts to decrease sharply, and rapidly approaches the external RH of the environment. Time t_2 therefore marks the point at which the disc becomes completely dry. In figure 4, we show a complete humidity record on which is superimposed the mass of water in the disc obtained by manual weighing. It is clear that times t_1 and t_2 are well defined, and correspond closely with the end of stages 1 and 2 of the drying process. It is from these times (either or both) that the PE value is estimated by a simple procedure.

3.3. Estimating PE

The sintered-quartz disc used here loses about 90 per cent of its water by stage 1 drying. This occurs over the time t_1 . This provides a direct measure of the average PE over this time interval. We then have $PE = (\beta w_{sat} / \rho_w A_d t_1)$, where the constant $\beta \approx 0.90$, w_{sat} is the total weight of water imbibed by the dry disc at saturation, A_d is the disc area, and ρ_w is the density of water. Alternatively, we can estimate PE from the time t_2 , since the stage 2 drying depends also weakly on external conditions, and we find for this device that $t_2 \approx 1.07t_1 + 30$ min. Examples of measured PE values are given in table 1. In these diverse conditions, we are able to measure a twentyfold variation in PE. Direct measurement errors are small. No uncertainty arises from the measurement of clock time, and uncertainty from weight measurement is at most ~ 0.3 per cent. The sensitivity of the device to small changes in relative humidity is of greater importance than the absolute accuracy, and our experience is that the sensor reliably and rapidly detects changes of relative humidity as small as 0.1 per cent in the important range 80–95 per cent.

3.4. Calibration and traceability

The device we describe measures the evaporation rate directly from a time signature and a known mass of water, as shown in figure 4. Therefore the estimated evaporation rate does not require independent calibration. However, as our immediate aim is to provide a method to estimate stage 1 evaporation rates of porous materials, we show results of several such tests in figure 6. This has immediate confirmatory value, as it demonstrates that the evaporation rates of several representative porous building materials and a free-water surface are in close agreement with that given by the patch evaporimeter.

Of course, if an evaporimeter of the kind we describe were to be widely used, we should want to compare its performance with that of other methods of obtaining evaporation rates. This would be methodologically difficult, as existing methods, both by instrument and by calculation, work on the large scale,

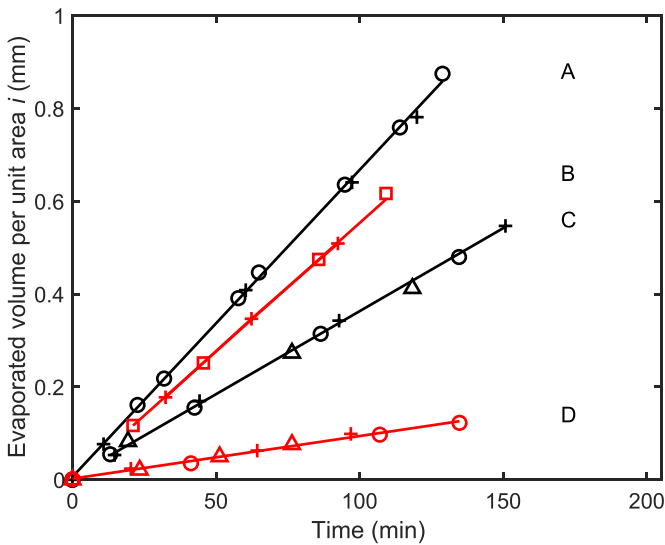


Figure 6. Water evaporation rates: comparison of evaporated volume per unit area $i = \Delta w / (\rho_w A)$ vs time for patch evaporimeter, a water pan, and several porous materials. Data obtained in controlled-environment chamber at four evaporation rates (mm/day) A, 9.5; B, 8.0; C, 5.2; D, 1.3. Symbols: + patch evaporimeter; ○ water pan; □ calcium silicate hydrate [18]; △ Frome limestone.

and do not probe local behaviour. Ultimately, a traceable comparison with a reference evapotranspiration method [9] is also desirable, but it is outside the scope of this note.

4. Conclusions

Our results and our experience show that the patch evaporimeter is a workable device for estimating potential evaporation at point locations. In the implementation described, it is intended for making spot measurements rather than continuous measurements, typically providing a PE value averaged over some hours. The value obtained is an average over the duration of the test, but this can be varied by using sintered discs of different thicknesses. The device is easy to reset to make repeat measurements. It is sufficiently simple and low-cost that it is practical to use a number of them simultaneously to map the variation of evaporation rate within a complex structure. Immediate applications lie in surveys of historic buildings for conservation purposes, but the patch evaporimeter may be widely useful in monitoring evaporation rates in a variety of microenvironments. If widely used, then a comparison with reference PET protocols will be useful.

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