

Summary of Findings... Understanding Heat Drying Systems

Summary of findings by Dr Ian Hopkin (Ref 1), Managing Director, DBK Technitherm Limited; of the research paper: Water Movement in Porous Building Materials--VI. Evaporation and Drying in Brick and Block Materials (Manchester University UK), (Ref: 2), along with a brief appraisal of its relevance to the Drymatic Heat Drying System.

In brief the two main conclusions that can be drawn from the research is that at the beginning of the drying process where there is a lot of free water not bound in the materials, a 10°C temperature increase causes a doubling of the evaporative rate (equivalent to quadrupling the number of airmovers). Following this towards the end of the process where evaporation is decreased due to water being bound in the materials the terminal drying rate increases rapidly with increases in temperature.

The research referenced is an academic paper from 1984, but the science hasn't changed. The mathematics in the paper is detailed but the top level equations, graphs and conclusions in the main text are very informative. The paper's authors have given a detailed explanation of the different drying methods and their effects on porous building materials. Here we consider the relevance to the Drymatic Heat Drying System.

The important first concept that the authors convey is that in structural drying there are two phases, Phase I is a linear phase and Phase II is a stage where the rate of water loss decreases with time. The length of Phase I, i.e. the time before we enter the phase of decreasing rate, is a function of the material, which is shown by the different bricks employed in the basic tests used to corroborate the model.

Phase I

Phase I is a purely evaporative phase and the rates are the same as evaporating from a solid surface. The rate of water loss is dependent on air flow, RH (or Humidity Factor = $1 - \text{RH}\%/100$) and highly dependent on temperature. In this phase the standard approach to drying of using air movers (increasing air flow) and dehumidifying the air can be explained. Both will increase the rate of evaporation. There is no criticism of the use of dehumidifiers in this context.

In this phase heat drying systems will also generate the right conditions, and used in a controlled system like Drymatic, Heat Drying Systems can produce enhanced conditions for increased evaporation. Air movement is increased by the circulating fans, and I note that the authors state that opening windows is sufficient to increase the laminar flow sufficiently to increase evaporation. So the use of excessive numbers of fans is questionable as it is only laminar air flow that is required rather than highly turbulent.

The other important point is that the evaporative rate is a function of RH (or Humidity Factor), not Specific Humidity, and increasing the temperature significantly reduces the RH and thus promotes evaporation. Furthermore the evaporative rate is itself highly dependent on temperature. As an example, if we look at the test conditions in the paper; stated as 23.5C, RH 55%. If the ambient temperature is increased by 10°C then the RH would fall to 30.8%, so that the humidity factor increases from 0.45 to 0.692, which according to Fig 4 increases the evaporation rate by just over 50%.

This is before we take into account how temperature itself increases evaporation due to making the molecules more energetic, hence the authors' conclusion that a 10°C temperature increase causes a doubling of the evaporative rate (equivalent to a quadrupling of the air flow. Not covered in the paper but an argument that can be put forward is that our heat source also replaces the absorbed heat due to evaporation (which normally cools the material and hence reduces the evaporative rate). The recirculation mode of the Drymatic Heat Drying System is particularly useful here. Of course with the increased evaporation due to heat, the room RH will soon start increasing, hence the need to replenish the air (exhaust mode).

Phase II

In phase II the evaporative rate decreases with time and with the remaining water content. In phase I you are looking simply at a surface evaporation process so that diffusion within the material is not a factor. By the time we get to phase II, in the later part of your job, this is no longer the case. Now the rate of evaporation is dependent of the transport of the liquid phase water within the material, and in many materials (apart from extremely porous ones) this becomes the dominant factor. Simply put if the water doesn't get to the surface fast enough it can't evaporate. Hence the loss in dependence on room relative humidity, it simply is not the dominant factor in this phase. You can dehumidify and lower the humidity of the ambient air as much as you want; it doesn't increase water loss from the structure. Of course we are all used to measuring the success of drying by measuring the output of our dehumidifiers in terms of grain depression, but in phase II drying the authors claim this is not relevant.

What is critical in phase II drying is increasing the temperature and I quote the last sentence in the conclusion of the paper; "The main conclusion to be drawn is that the terminal drying rate (like the stage I drying rate) increases rapidly with temperature". The fact that the Drymatic Heat Drying System returns periodically to the recirculation mode, thus increasing the temperature, results in a reduction in the tail of the Phase II drying stage.

Combination of Systems

A further point that has interest is, can you combine the heat drying in Phase I with a dehumidifier in the same room? Bearing in mind that any increase in temperature in the both Phase I and Phase II of the job is going to increase the rate of evaporation. What needs to be taken into account is the limitations of the dehumidifier in terms of its inability to function efficiently above ambient temperatures of 30 °C. Furthermore we need to consider the size and type of dehumidifier required to ensure it keeps up with the level of evaporation and thus ensure a balanced drying system is in place.

If you consider the conditions used in the paper (23.5°C, 55%RH) then the dew point is 13.9 °C. Increasing the temperature of the air to 33.5 reduces the RH, but the specific humidity is the same so the dew point remains the same. But now the delta T requirement across the heat exchanger increases from 9.6°C to 19.6°C, combined with the latent heat given up at the point of condensation, this may exceed the power capability of the dehumidifier. However, we have used dehumidifiers to "pre-condition" the replenishment air in an unaffected area of a building and this worked very well.

References.

1. Dr Ian Hopkin, Managing Director, DBK Technitherm Ltd., Unpublished Communication.
2. C. Hall, W. D. Hoff M. R. Nixon, Water Movement in Porous Building Materials--VI. Evaporation and Drying in Brick and Block Materials; Building and Environment, Vol. 19, No. 1, pp. 13 20, 1984

Water Movement in Porous Building Materials—VI. Evaporation and Drying in Brick and Block Materials

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The processes of evaporation and drying from porous building materials are discussed. Experimental results are reported which confirm the existence of at least two distinct stages of drying, and relative effects of humidity, temperature and farstream air speed on drying rates are described. The cumulative desorption of water during the second stage of drying is discussed in terms of a desorptivity parameter and the thermal effects of the evaporation process are examined.

1. INTRODUCTION

IN EARLIER papers in this series [1-5] we have looked in detail at several aspects of the movement of liquid water within porous building materials. Of course, as was recognized in the introduction to the first of these papers, the flow of water in the fabric of buildings is often strongly influenced by *evaporation* into the surrounding air, and a complete analysis of water movement in buildings must embrace both liquid phase transport and evaporation. To begin with, an understanding of evaporation physics is directly relevant to the drying of damp-affected buildings and control of fabric dampness by ventilation and/or heating; but it has wider significance. Almost all water entering porous building materials ultimately leaves by evaporation. Evaporation therefore plays a crucial role in controlling all water balances and rates of water exchange between environment and structure.

It is recognized that large amounts of water may be present in the fabric of newly constructed buildings [6], and this water must be lost by evaporation before the building fabric may be regarded as being satisfactorily dry. Relatively low levels of moisture content are desirable to ensure a healthy environment and also to provide a suitable background for decorative finishes. In older buildings that have undergone major remedial treatments for dampness—particularly rising damp—very much higher moisture contents may be present in some parts of the fabric. Work in our laboratories [7] and our field studies have indicated that brickwork around d.p.c. level may become totally saturated with water as a result of long term capillary absorption. In these circumstances, considerable amounts of water must evaporate to bring the internal fabric of the building to a satisfactory state.

Although general recommendations have been made in respect of the drying out of buildings [6] these only provide

the most general guidelines and emphasize that drying periods may be very long. Various methods of reducing drying times are suggested including, for example, the use of dehumidifiers and heating systems, but there is a lack of quantitative data from which the critical factors which affect the drying process can be identified. The work described in this paper investigates some of the fundamentals of drying, and attempts to identify the main factors which control drying rates in practice.

2. EVAPORATION FROM POROUS BUILDING MATERIALS

2.1. General description of drying

By *drying* we mean the transfer of a liquid (normally water) from the pores of a solid material to the surrounding air. The process generally includes: unsaturated flow of liquid within the porous solid; vapour flow within the porous solid; the liquid-vapour phase change; and convective-diffusive transfer of vapour from the surface of the solid to the surroundings. The first of these sub-processes may be described in terms of the concepts of unsaturated flow theory which we have discussed previously. The second appears to present no great difficulties because vapour phase permeability in porous solids is conceptually simple. It is in the third and fourth of these sub-processes (to which, taken together, the term *evaporation* may be applied) that new considerations arise. The liquid-vapour phase change involves the absorption of heat, and we must consider the magnitude of the heat inputs required in detail. Furthermore, the transfer of water vapour to the surroundings is strongly influenced by the air flow across the drying surface and this introduces environmental and aerodynamic considerations. Thus drying may be expected to depend markedly on external factors as well as on material properties. The difficulty in developing a theory of the drying of building materials is in avoiding needless complexity while retaining physical

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validity. In this paper we discuss new experimental data in terms of a simple model of evaporation and drying.

2.2. Drying behaviour of typical materials

Figure 1 shows three typical drying curves for clay bricks of differing porosities. The specimens were first saturated with water under vacuum and then dried under constant conditions of air temperature, air flow and humidity, as detailed in the figure caption.

We note that the initial drying rate in each case is about $215 \text{ g m}^{-2} \text{ h}^{-1}$; that the first part of the drying curve (i_d vs t) is approximately linear and that there is a fairly well-defined transition to a period in which the drying rate falls with time.

The idea that drying under constant external conditions occurs in at least two distinct stages, called the *constant drying rate period* (stage I) and the *falling drying rate period* (stage II), is well established in the scientific literature of drying and for building materials can be traced back at least to the paper of Cooling [8] of 1930. The evidence for stage I behaviour has recently been discussed at length by van Brakel [9]; under the moderate drying conditions and for the sample dimensions which we have used in our work on brick and building stones the initial constant rate drying period is normally found. We discuss in Section 6 the factors determining the transition from stage I to stage II behaviour.

3. STAGE I DRYING

There is now considerable evidence [9] that the stage I drying rate in a wide range of porous materials is equal to the evaporation rate of a free water surface under the same conditions. The question of whether the rates are precisely the same need not concern us here (but for discussion see van Brakel [9]). Figures 1 and 2 show some new results from which it appears that there is little variation in initial

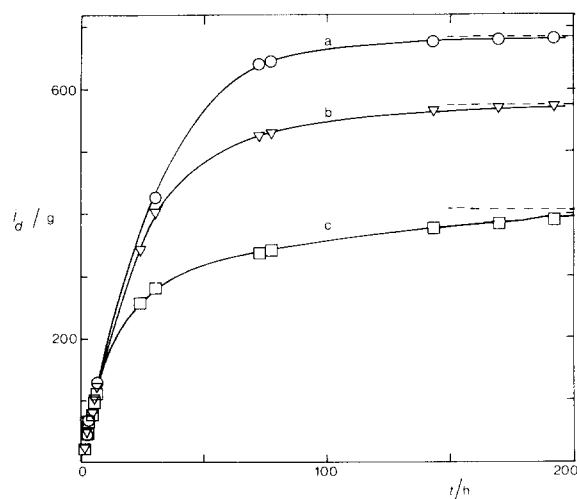


Fig. 1. Drying of three types of clay brick at 23.5°C dry bulb temperature 55% relative humidity. Cumulative evaporation i_d from bricks initially vacuum saturated with water drying through all faces. Maximum water content in each case shown by dashed line. Curve (a) shows results for a solid facing brick classified as unsuitable for extreme conditions of exposure. Curves (b) and (c) show results from two types of solid clay common.

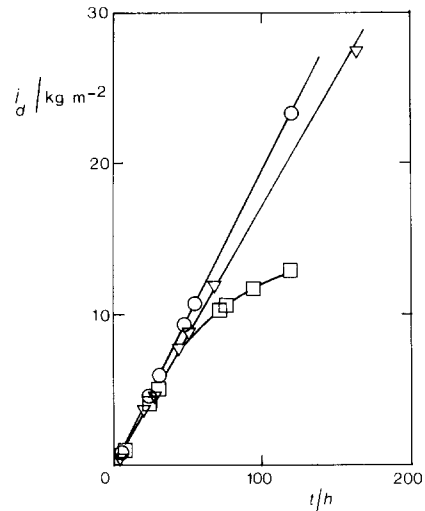


Fig. 2. Cumulative evaporation i_d from a free water surface ∇ , a clay brick specimen \square , and an autoclaved aerated concrete specimen \circ . In each case the measurements were made at 23°C dry bulb temperature 75% relative humidity.

drying rate for different types of clay brick, and that there is a close similarity between initial drying rates and the evaporation from a free water surface. Only the evaporation rate for aac block seems somewhat higher. The higher evaporation rate for aac block is considered to be due to two effects. The large aeration pores provide a larger effective evaporating surface area on the surface of the specimen; they also provide internal voids into which vapour can evaporate and diffuse to the surface. It is likely that this increase in effective surface area both on or near to the surface layers of the block accounts for the increased evaporation rate during stage I.

Because the first stage of drying appears to be essentially uninfluenced by material properties, it is generally accepted that free evaporation of liquid is occurring at the solid surface. Thus, the rate of drying is controlled by the vapour properties of the evaporating substance—its saturated vapour pressure p_0 and its binary diffusion coefficient in air D_v —together with environmental factors. A simple model is described in the Appendix.

3.1. Evaporation of water and other liquids

In order to test this model of stage I drying, we have compared the rates of evaporation of three organic liquids from clay brick with that of water from the same brick, with results given in Fig. 3.

Under identical air flow conditions and at the same temperature the rates of evaporation of an organic liquid A and water are expected to be in the ratio

$$\frac{r_A}{r_w} = \frac{M_A D_{vA} p_{0A}}{M_w D_{vw} p_{0w} (1 - h/100)} \quad (1)$$

where M is the molar mass and h the percent relative humidity. It is assumed that the partial pressure of organic vapour in the incoming air stream is zero. Figure 3 shows that the initial evaporation rates of the three organic liquids (on a weight or volume basis) are much greater than that of water, as is predicted from equation (1) in view of their higher vapour pressures and molar masses. The

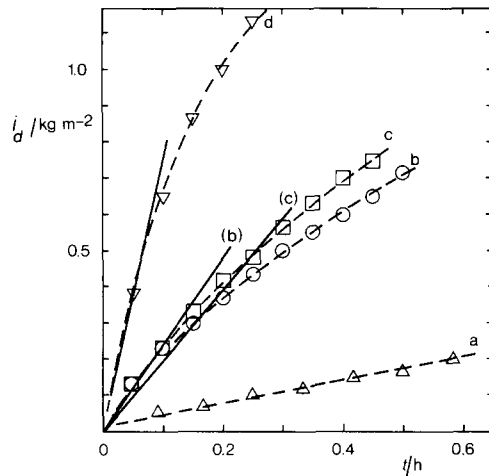


Fig. 3. Evaporation of organic liquids and water from a brick surface. Cumulative weight loss per unit area i_d . (a) water, (b) ethanol, (c) *iso*-propanol, (d) ethyl acetate. Experiments carried out at constant laminar air flow velocity (approximately 1.4 ms^{-1}) and 21°C dry bulb temperature 55% relative humidity.

constant rate period is barely discernible, probably in part because the high evaporative cooling depresses the vapour pressure, but chiefly because for such volatile liquids stage I drying is of short duration (see Section 6). Nevertheless, the calculated stage I drying rates plotted in Fig. 3 lie close to the initial slopes of the observed drying curves. Expressing the results numerically, the observed stage I evaporation losses for clay brick on a weight basis at $t = 0.1 \text{ h}$ for water, ethanol, *iso*-propanol and ethyl acetate are in the ratios 1 : 5.2 : 5.2 : 14.4, compared with calculated values [equation (1)] 1 : 6.9 : 5.7 : 16.0; all values at 20°C .

In contrast, the rate of a capillary transport process varies as the quantity $(\sigma/\eta)^{1/2}$, where σ is the surface tension and η the viscosity of the liquid. For these four liquids this is in the ratio 1 : 0.48 : 0.35 : 0.81, completely at variance with the observed relative initial drying rates. These results are strong evidence of a free evaporation mechanism of stage I drying in which capillary effects are absent.

3.2. Dependence of drying rate on relative humidity

Equation (A7) predicts a simple linear dependence of stage I constant drying rate on the humidity factor H . Some experimental data confirming this for the drying of brick are shown in Fig. 4.

3.3. Dependence of drying rate on air flow

The complexities of air flow near surfaces make the dependence of drying rate on air flow difficult to capture in a single parameter. Nevertheless, we show in the Appendix that for a simple laminar flow model r_1 increases as $u_*^{1/2}$, the square root of the farstream air velocity.

Figure 5 shows some new results on clay brick which broadly conform to expectations.

3.4. Temperature dependence of the drying rate

We can predict the effect of a change of temperature on the stage I drying rate from equations (A9)–(A11). The quantities p_0 , D_v , ρ_a , η_a , which appear in equation (A9), all change appreciably with temperature. p_0 is the dominant

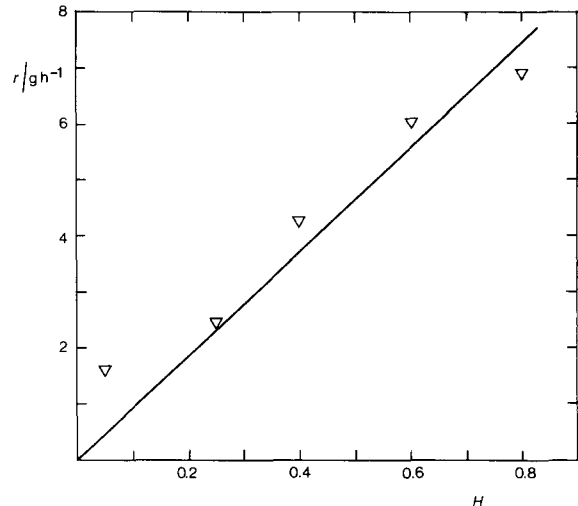


Fig. 4. Variation of stage I drying rate r from a clay brick surface with humidity factor H [$= 1 - (\% \text{ R.H.}/100)$]. Experiments were carried out at a dry bulb temperature of 23.5°C .

factor. We may safely neglect the influence of $(\rho_a/\eta_a)^{1/6}$. Substituting equations (A10) and (A11) into (A9) leads to

$$\ln(\bar{r}_1/H) = \ln A' - \frac{C}{T} + \frac{1}{2} \ln u_* \quad (2)$$

where $A' = A/l^{1/2}$.

This equation shows clearly the dependence of \bar{r}_1 on temperature and air flow velocity. It is, of course, derived from equation (A9) which assumes a particular laminar air flow geometry, and consequently equation (2) is not of completely general validity.

The temperature term $-C/T$ is independent of these geometrical and aerodynamic assumptions. The last term $\frac{1}{2} \ln u_*$, however, arises from an $Re^{1/2}$ dependence of the

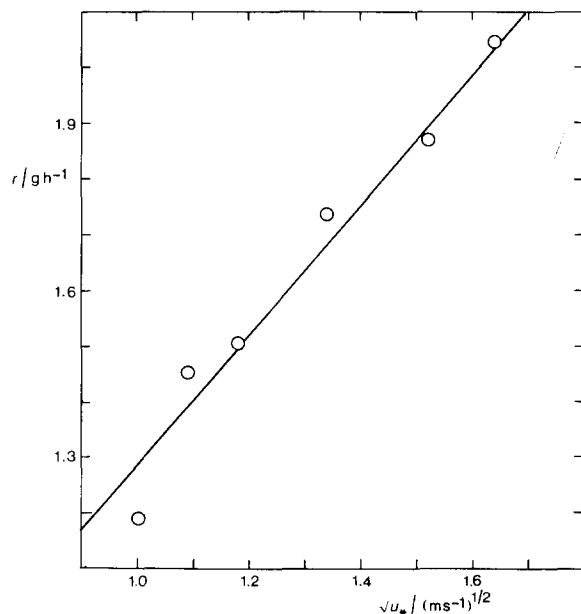


Fig. 5. Variation of drying rate r under conditions of varying laminar air flow velocity u_* . The relative humidity was 55% and dry bulb temperature 20.5°C .

boundary layer thickness, and the coefficient $\frac{1}{2}$ may need to be established empirically for air flows typical of those which occur within and around buildings. This lies in the future. We note that Penman [10], in his well-known review of meteorological evaporation theory, suggests that the evaporation rate does generally increase as $u_*^{1/2}$ in turbulent air streams. On the other hand, Asano and Fujita have shown in an experimental study [11] that the evaporation rate depends on $Sc^{1/2}Re^{2/3}$, rather than $Sc^{1/3}Re^{1/2}$ as predicted by simple theory.

In Fig. 6 we depict graphically the relation between \bar{r}_1/H and u_* and T shown in equation (2). The figure shows lines of constant \bar{r}_1/H (drying rate normalized for the effects of humidity) on a $\ln u_* - 1/T$ field. In constructing this figure we have used a value of \bar{r}_1 determined empirically for a particular specimen geometry (i.e. particular value of A).

4. STAGE II DRYING

In the drying curve shown in Fig. 1 we see that the drying rate r eventually ceases to be constant and begins to decrease. The change in r marks the beginning of stage II drying. We have suggested (in Section 3) that in stage I the evaporation rate is controlled by vapour phase diffusion *above the surface*. We believe that in stage II the rate of unsaturated flow *within the porous solid* limits the drying rate (see Appendix).

The rate of unsaturated flow of the evaporating liquid towards the drying surface is determined by the material properties Ψ and K (or D) and, therefore, these desorption parameters fundamentally determine the stage II drying rate.

In our previous work on water absorption we have made extensive use of the hydraulic sorptivity parameter S to characterize the capillary absorption property of materials [2]. We now introduce the analogous quantity R , the

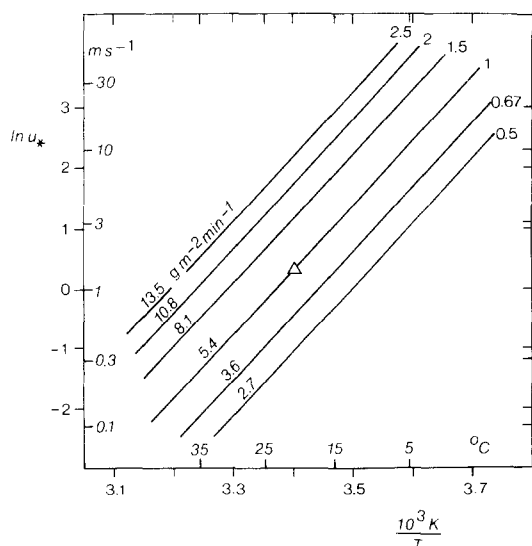


Fig. 6. Effect of air flow velocity u_* and temperature T on the humidity corrected first stage drying rate \bar{r}_1/H . The position of the family of lines has been fixed by an experimental point (Δ). We emphasize that this point depends on specimen geometry but the relative position of the lines is independent of geometry (see text). The italic figures on the lines show drying rates and the figures at the upper ends of the lines indicate relative drying rates.

desorptivity, for the desorption of water. R may be defined by the equation

$$i_d = Rt^{1/2} \quad (3)$$

where i_d is the cumulative desorption from a semi-infinite one-dimensional porous solid (initial water content θ_0 , $x > 0$, $t = 0$) losing water at an end face maintained at a fixed water content θ_1 ($x = 0$, $t > 0$); $\theta_1 < \theta_0$. We note that R and S are not equal. Indeed calculations suggest that for porous inorganic building materials $S/R \approx 10^1-10^2$.

The definition of R presents no difficulty but, unlike S , it is not clear how it may be measured in any direct way. The problem is experimental and lies in establishing suitable initial and boundary conditions.

At the beginning of stage II drying the initial water content distribution is far from being uniform. Therefore the stage II drying rates cannot be expected to depend simply on R , although some complicated dependence on R is likely. Neither can the stage II drying rate be expected to show a simple $t^{1/2}$ dependence on the elapsed time. r may, however, tend towards a $t^{1/2}$ dependence at long times as the influence of the early non-uniform water content distribution diminishes.

5. EXPERIMENTAL WORK

In order to test the validity of the concepts discussed in Sections 1-4 a systematic series of experiments were carried out to determine the effects and relative importance of temperature, relative humidity and farstream air velocity on the evaporation process. The basic drying experiments involved saturating various brick and lightweight block specimens with water using standard vacuum tank saturation procedures. The specimens were then placed in a cabinet under conditions of controlled temperature and humidity, the air in the cabinet being vigorously circulated with a fan. The drying process was monitored by weighing the specimens at regular intervals. Some specimens were allowed to dry through all faces whilst others were coated or wrapped so that drying was restricted to one face only. This latter arrangement more accurately represents the situation under which the masonry units of a wall may dry in real building situations. The experiments to monitor the processes of drying in relation to air speed used samples of brick $96 \times 62 \times 12$ mm thick drying from one face. The specimens were placed in an enclosure through which the air speed across the drying surface could be varied. The arrangement adopted resulted in a laminar flow across the surface as revealed by a smoke tracer. The air speed was measured using an air flow probe and meter. (A similar type of specimen and arrangement was used to obtain the data on evaporation of organic liquids plotted in Fig. 3.)

The results of the simplest type of drying experiment are shown in Fig. 1 and have been briefly referred to earlier. The three bricks used were solid clay bricks without perforations or frogs. Two of the bricks were commons and one was a facing brick of very high porosity classified as unsuitable for extreme conditions of exposure. It is noteworthy that, although there are major differences in the porosities and hence the initial water contents of each brick, they all reached reasonable dryness after approximately the same period of drying. To study the effect of the

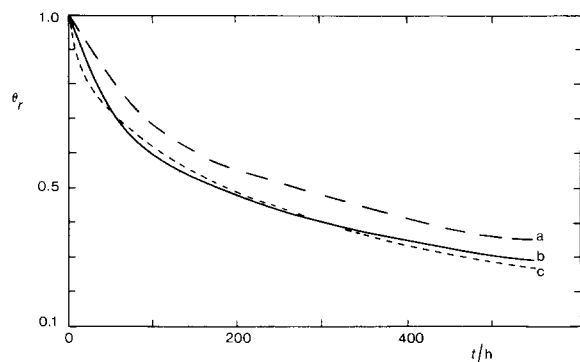


Fig. 7. Common brick drying through one stretcher face under controlled conditions. θ_r is the fractional water content. (—) Drying at 75% relative humidity; (---) drying at 95% relative humidity; (-·-·-) drying at 20% relative humidity. The temperature in each case was 23°C.

relative humidity on the total drying process, a series of measurements were made of the drying of one type of clay common through a stretcher face (all other faces sealed) at 23°C under three controlled humidity levels. The results are shown in Fig. 7 and serve to illustrate that, although stage I drying is affected by relative humidity, the subsequent drying is very similar for all three humidity levels. The effect of humidity level on stage I drying is more fully shown by the results plotted in Fig. 4, which were obtained from a series of measurements of the initial drying through the stretcher face of one type of clay common.

6. THE TRANSITION FROM STAGE I TO STAGE II DRYING

In a comprehensive theory of drying, the transition from stage I to stage II behaviour would emerge naturally. Here we present a simpler view of the transition based on the unsaturated flow theory of the surface water content during stage I.

Stage I drying is characterized by a constant rate of evaporation under constant drying conditions. The evaporating water is transported to the drying surface by unsaturated capillary flow; we assume that the extended Darcy equation applies.

Now the constant stage I evaporation rate effectively imposes a constant flux boundary condition at $x = 0$ on all

Table 1. Variation of vapour pressure p with water content θ and hydraulic potential ψ for one type of clay common brick

θ_r	θ	ψ/m	p/p_0
1.0	0.163	0	1.000
0.9	0.147	-20	0.999
0.5	0.082	-60	0.996
0.3	0.049	-100	0.993
0.2	0.033	-200	0.986

Data taken from Gummerson *et al.* [7].

$$p/p_0 = \exp(-\psi Mg/RT)$$

where $RT/Mg = 13788.1$ m for water at 20°C; p_0 is the saturated vapour pressure of water = 0.023 atm at 20°C; θ is the water content on a weight basis; θ_r the reduced or fractional water content ($\theta_r = \theta/\theta_{sat}$).

flow in the region $x > 0$. As drying proceeds the surface water content θ_s falls with time, eventually approaching θ_* . But, although θ_s falls continuously, ψ_s may change little with θ_s in the early stages of drying for the materials under consideration. We illustrate this in Table 1 for a representative clay common brick. It is clear that from $\theta_r = 1$ to as low as 0.2 the hydraulic potential is much too small to influence significantly the vapour pressure of the pore water.

We emphasize that in order for constant rate drying to be observed it is essential that p_s should be approximately constant over an appreciable range of θ_s . In the case of strongly hygroscopic materials this is not the case, and for such materials no constant rate period can be expected.

7. HEAT FLOW IN DRYING

We have assumed tacitly in developing the model of drying we have described that mass flow and heat flow are uncoupled. This is clearly not rigorously true, since the enthalpy of vaporization must be supplied to the evaporating water and this entails the development of temperature gradients within the drying solid. In the context of evaporation from building surfaces, where drying rates are very variable but often relatively low, how reasonable is the isothermal assumption?

Evaporation cooling is greatest at the highest drying rates and as we have shown these occur in the first stage of drying. At this stage, vaporization of water occurs at or very close to the physical surfaces, and therefore we consider a steady state heat flow model (Fig. 8) in which evaporation constitutes a heat sink uniformly distributed over the building surface. Thus

$$Q_1 - Q_e = Q_2 \quad (4)$$

where Q_e is the rate at which heat is removed by evaporation ($= \Delta H_{vap} \cdot r$), Q_1 is the heat flow through the fabric and Q_2 the heat flow from the surface to the environment. Q_1 and Q_2 are taken positive outwards. If $Q_e > Q_1$ then Q_2 is negative, $T_s < T_a$ and there is a flow of heat from the environment to the building surface. Analysis shows that

$$\Delta T_s = Q_e / (w_r^{-1} + s_r^{-1}) \quad (5)$$

$$\Delta Q_1 = w_r^{-1} \Delta T_s \quad (6)$$

and

$$\Delta Q_1 / Q_1 = Q_e / [s_r^{-1} (T_i - T_a)] \quad (7)$$

where w_r is the thermal resistance of the wall and s_r is the

Table 2. Depression of surface temperature ΔT_s , increase in building heat loss ΔQ_1 , and fractional increase in building heat loss ($\Delta Q_1 / Q_1$) for different drying rates r . Values are calculated from equations (5)–(7), assuming values of $w_r = 0.3$ m² °C W⁻¹ and $s_r = 0.055$ m² °C W⁻¹

Drying rate r (g m ⁻² h ⁻¹)	ΔT_s (°C)	ΔQ_1 (W m ⁻²)	$\Delta Q_1 / Q_1$
600	18.9	6.29	2.23 (223%)
200	6.30	21.0	0.497 (49.7%)
50	1.57	5.24	0.124 (12.4%)
10	0.315	1.05	0.025 (2.5%)
1	0.032	0.105	0.003 (0.3%)

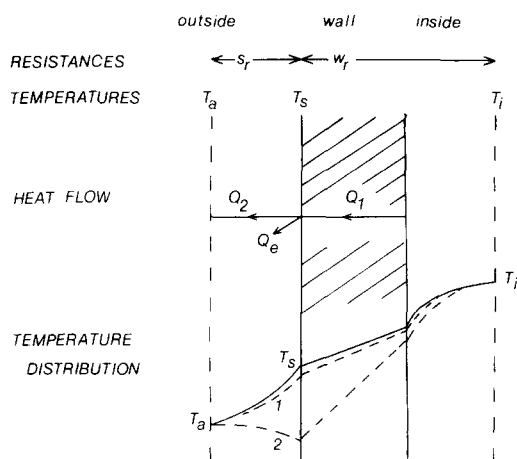


Fig. 8. Steady state heat flow model. Temperature distribution: solid line, no evaporation; (1) slight evaporation; (2) strong evaporation.

external surface resistance. Here ΔT_s is the depression of the surface temperature attributable to evaporation, ΔQ_1 is the evaporative contribution to the heat loss from the building and $(\Delta Q_1/Q_1)$ the fractional increase in heat loss. We note that since s_r^{-1} is generally several times larger than w_r^{-1} , the value of s_r^{-1} largely determines ΔT_s . Note also that $\Delta Q_1/Q_1$ is independent of w_r , and also depends on the value of s_r^{-1} .

What are realistic values of the drying rate r ? Laboratory experiments at air speeds of several m s^{-1} and normal temperatures and humidities suggest that evaporation rates as high as $250\text{--}300 \text{ g m}^{-2} \text{ h}^{-1}$ may occur. This figure is supported by United Kingdom meteorological data on *potential evaporation*, i.e. the evaporative loss from open tanks (Lacy [12], Holland [13]). This lies between 400 and 600 mm yr^{-1} , corresponding to an average rate of $57 \text{ g m}^{-2} \text{ h}^{-1}$ over a full year. However, the midsummer values are much higher: about 85 mm month^{-1} for June and July, giving an average evaporation rate for these two months of $116 \text{ g m}^{-2} \text{ h}^{-1}$. It seems reasonable to assume that short-term evaporation rates from saturated building surfaces under warm windy conditions following driving rain may be at least double this, as high as $250\text{--}300 \text{ g m}^{-2} \text{ h}^{-1}$. Under these conditions surface temperatures will fall by as much as $8\text{--}10^\circ\text{C}$ and the evaporation heat sink will have a marked effect on the thermal balance of the building.

Evaporation rates as high as these are exceptional and will be sustained for short periods only. Mean values will be much lower. Lacy [12] reports data on the rates of drying of brick walls at Garston, which include the following:

for a few hours after driving rain	$68 \text{ g m}^{-2} \text{ h}^{-1}$
over a four day period after driving rain	$20 \text{ g m}^{-2} \text{ h}^{-1}$
other average rates	$1\text{--}7 \text{ g m}^{-2} \text{ h}^{-1}$.

We can state the following conclusions:

(1) At the maximum drying rates attainable in buildings (as in the forced drying-out of buildings and in the drying of walls and other external building surfaces in windy conditions) detailed calculations should take account of the reduction in temperature caused by evaporation, which influences a number of parameters, notably p_0 and S .

(2) For more moderate conditions generally found in buildings the temperature depressions appear not to exceed $1\text{--}2^\circ\text{C}$. We may then neglect the coupling of heat and mass flow and adopt an isothermal mass transfer approach to the drying process.

(3) The contribution of evaporation from exterior surfaces to the overall heat losses from buildings requires separate discussion.

8. PRACTICAL CONCLUSIONS

The results given in this paper clearly show the existence of at least two distinct stages during drying. The rate of drying during the first stage is strongly influenced by both air flow and temperature; both equation (2) and Fig. 6 show that increases in both or either will result in more rapid drying during stage I. Inspection of Fig. 6 shows that increasing the temperature of the wet material by 10°C approximately doubles the drying rate. A similar increase in drying rate results from quadrupling the air speed. The advantages of reducing relative humidity during drying are shown by reference to Fig. 4 which indicates that the first stage drying rate is directly proportional to the humidity factor H . However, practical considerations might suggest that increasing the air speed is likely to be the most cost effective method of increasing the stage I drying rate. This might be achieved by using fans or even by good natural ventilation within a building. For any given material the duration of stage I drying varies inversely as the square of the drying rate and subsequently the drying rate falls with time. The results shown in Fig. 7 illustrate that these later stages of drying are not significantly affected by humidity. Figure 1 also illustrates the complete drying process, in this case for three different brick materials under similar drying conditions and, as has already been noted, these bricks all achieved a reasonably complete dryness after similar times despite different initial water contents. The end of drying is not physically very sharply defined and it may be expected (and is found experimentally) that the process is somewhat protracted. As $\theta(x)$ approaches the hygral equilibrium value θ_* throughout the porous solid, liquid phase capillary continuity is lost and vapour phase diffusion no doubt becomes the only transport mechanism within the pores. The main conclusion to be drawn is that the terminal drying rate (like the stage I drying rate) increases rapidly with temperature.

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APPENDIX

A.1. An isothermal drying model (see Fig. A1)

We take the hydraulic potential ψ as the dependent variable since it may be used in both the unsaturated porous medium and in the vapour phase. We assume that there are no interfacial resistances involving discontinuities in ψ , and thus that ψ varies continuously from the interior of the solid to the air stream distant from the surface.

We consider a porous material in one dimension (x) of length L , where L may be such that the solid is finite or semi-infinite. Drying occurs at the face $x = 0$ into an airstream moving at right angles to x . We assume the existence of a boundary layer of thickness δ .

When drying begins, the water content of the porous solid θ is uniform ($\theta = \theta_i$) and the hydraulic potential is likewise uniform ($\psi = \psi_i$). As drying proceeds, the surface water content θ_s and surface hydraulic potential ψ_s fall, and unsaturated capillary flow is established within the porous solid. Evaporation occurs at the surface $x = 0$ and diffusive or convective transport of water vapour takes place through the boundary layer into the airstream.

Within the porous medium ($x \geq 0$) we assume that flow is described by the extended Darcy equation and hence we apply the unsaturated flow equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial \psi}{\partial x} \right). \quad (\text{A1})$$

Within the vapour phase ($x < 0$) we use Fick's second law

$$\frac{d\rho}{dt} = D_v \frac{d^2\rho}{dx^2} \quad (\text{A2})$$

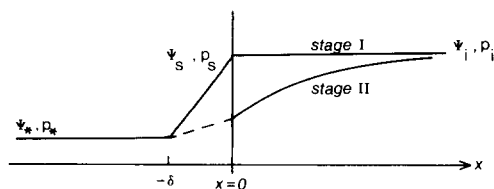
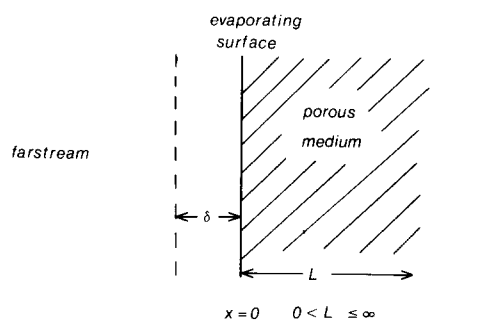


Fig. A1. Isothermal drying model.

where ρ is the vapour density of the evaporating substance (here water) and D_v the binary diffusion of the vapour in air.

In a fully integrated model of drying these two equations would be considered simultaneously. Here we take a somewhat simpler approach, by asserting that

- (i) in stage I drying, the vapour phase diffusion process [equation (A2)] is rate-determining;
- (ii) in stage II drying, the unsaturated flow process [equation (A1)] is rate-determining.

We discuss these two stages separately.

A.2. Stage I drying

At the beginning of drying the surface hydraulic potential $\psi_s \approx \psi_i$, the initial potential, and the main drop in ψ occurs across the boundary layer. The vapour pressure at the surface p_s is related to ψ_s by

$$\psi_s = \frac{RT}{Mg} \ln \frac{p_s}{p_0} \quad (\text{A3})$$

where ψ_s has the dimension [length].

As stage I drying proceeds ψ_s decreases as θ_s falls, in accordance with the drying branch of the water characteristic $\theta(\psi)$; see for example [7]. Nevertheless, so long as $|\psi_s| \ll RT/Mg$, p_s remains almost equal to p_0 , the saturated vapour. Thus evaporation occurs from a source of almost constant vapour pressure. If we disregard transient effects we may replace (A2) by Fick's first law and write, for the stage I drying rate,

$$r_1 = D_v \left(\frac{dp}{dx} \right)_s \quad (\text{A4})$$

$$= \frac{MD_v}{RT} \left(\frac{dp}{dx} \right)_s \quad (\text{A5})$$

Assuming that p varies linearly across the boundary layer,

$$r_1 = \frac{MD_v}{RT} \frac{p_s - p_*}{\delta} \quad (\text{A6})$$

where p_* is the vapour pressure outside the boundary layer.

Finally, for water, writing $p_s = p_0$ and $p_* = p_0 h/1000$ gives

$$r_1 = \frac{MD_v}{RT} \frac{p_0 H}{\delta} \quad (\text{A7})$$

where $H = (1 - h/1000)$ is a humidity factor.

A.3. Air flow

The air flow above the surface has a strong influence on r_1 since it determines $(dp/dx)_s$. In the previous paragraph we expressed the influence of air flow through the parameter δ , the boundary layer thickness. It is desirable to be able to express the effect of air flow on drying in terms of measurable quantities such as the mainstream flow velocity u_* or Reynolds number: that is $(dp/dx)_s = f(p_0, Re \dots)$.

Here we use standard theory [14] to evaluate f for one case,

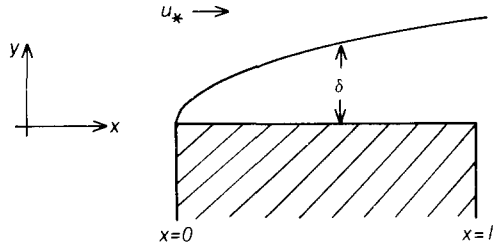


Fig. A2. Development of a boundary layer.

namely laminar air flow in the direction y positive parallel to a plane slab of length l (Fig. A2). The boundary layer thickness δ varies with y , rising from zero at the leading edge ($y = 0$). The mean evaporation rate per unit length is

$$\bar{r}_1 = \frac{MD_v}{RT} p_0 H \frac{0.646 Sc^{1/3} Re^{1/2}}{l^{1/2}} \quad (\text{A8})$$

where $Re = \rho_a u_* l / \mu_a$, $Sc = \mu_a / \rho_a D_v$, and μ_a , ρ_a are the viscosity and density of air.

Thus

$$\bar{r}_1 = A \frac{u_*^{1/2} p_0 H}{l^{1/2}} \quad (\text{A9})$$

where

$$A = \frac{MD_v^{2/3}}{RT} \frac{0.646 \rho_a^{1/6}}{\mu_a^{1/6}}. \quad (\text{A9})$$

Equation (A9) shows the dependence of stage I drying rate on the main environmental factors, u_* and H for one particular

laminar air flow case. The temperature dependence of r_1 is discussed in Section 3.

A.4. Temperature dependence of stage I parameters

The quantities D_v , p_0 , ρ_a and μ_a which appear in equation (A9) all change appreciably with temperature. However, for the purposes of finding dr_1/dT we can neglect the very small contribution arising from $(\rho_a/\mu_a)^{1/6}$ and consider only D_v and p_0 .

Binary diffusion coefficients vary approximately as $T^{3/2}$; thus

$$D_v = aT^{3/2} \quad (\text{A10})$$

and, for water, $a = 4.80 \times 10^{-9} \text{ m}^2 \text{ s}^{-1} \text{ K}^{-3/2}$.

The vapour pressure p_0 obeys the Clapeyron–Clausius equation, assuming ideal gas behaviour and neglecting the small temperature dependence of the heat of vaporization ΔH_v , we have

$$p_0 = b \exp(-C/T). \quad (\text{A11})$$

For water, $b = 1.767 \times 10^6 \text{ atm}$ and $C = \Delta H_v/R = 5320 \text{ K}$.

A.5. Stage II drying

We assume that the unsaturated capillary flow is rate-determining in stage II and that $\psi_s \approx \psi_*$. Thus $p_s \approx p_*$ and the surface is close to hygral equilibrium with the environment. This is tantamount to imposing a constant concentration boundary condition $\theta = \theta_*$ at $x = 0$; water content distribution can then be obtained as solutions to the unsaturated flow equation (A1) subject to this boundary condition. We note that these solutions must always be obtained numerically since the water content distribution $\theta(x)$ at the beginning of stage II (that is, the initial condition) is determined by the course of stage I and cannot be represented by any simple function of x . Nevertheless, there is no difficulty in solving the unsaturated flow equation with a Dirichlet boundary condition and arbitrary initial distribution $\theta(x)$, for example by finite element methods.