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## Accepted Manuscript

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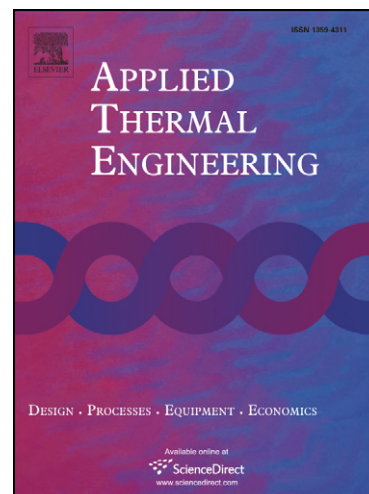
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1 **Transient numerical and physical modelling of temperature profile evolution in**  
2 **stabilised rammed earth walls**

3  
4 **M R Hall <sup>a\*</sup> and D Allinson <sup>b</sup>**

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10  
11 **Abstract**

12 Three established stabilised rammed earth (SRE) mix types (433, 613, 703) were  
13 identified for analysis, in the form of 300mm thick test walls, by being subjected to  
14 different static air temperature and relative humidity differentials. The predictive  
15 numerical model outputs from WUFI Pro v4.1 hygrothermal simulations displayed  
16 good accuracy when validated against experimental data from physical modelling  
17 conducted using test walls in a climatic simulation chamber. The wall temperature  
18 profile evolution and resultant steady state gradients were very similar regardless of  
19 mix type indicating that the majority of the wall remained relatively dry. Unless liquid  
20 water is present, the thermal resistance and heat capacity of these materials does not  
21 change sufficiently to make significant differences to temperature profile evolution  
22 regardless of soil mix type. Little scope exists to intelligently modify the ability of  
23 SRE walls to absorb and store heat energy simply by manipulation of particle size  
24 distribution (PSD) and the resultant bulk density/void ratio relationships, under these  
25 conditions. Only the outer layers of the walls appear to interact with moisture in the  
26 air, and the predicted transient responses indicate that significant potential exists to

27 intelligently modify the ability of SRE walls to absorb, store and release moisture  
28 vapour from the surrounding air simply by manipulation of PSD and the resultant bulk  
29 density/void ratio relationships.

30

31 **Keywords:** transient thermal modelling; stabilised rammed earth; hygrothermal  
32 properties; climatic simulation chamber, temperature buffering; WUFI

33

### 34 **Nomenclature**

35  $D_\phi$  liquid conduction coefficient

36  $H$  enthalpy (J)

37  $H_{\text{vap}}$  enthalpy of vaporisation (J)

38  $p_{\text{sat}}$  saturation vapour pressure (Pa)

39  $t$  time (s)

40  $T$  temperature ( $^{\circ}\text{C}$ )

41  $w$  specific moisture content ( $\text{kg}/\text{m}^3$ )

42  $\phi$  relative humidity (decimal)

43  $\lambda$  thermal conductivity ( $\text{W}/\text{m K}$ )

44  $\delta_p$  water vapour permeability ( $\text{kg}/\text{m s Pa}$ )

45

### 46 **1. Introduction**

47 SRE (soil-based) materials have a good potential to buffer air temperature and relative  
48 humidity fluctuations in response to climatic variables in a controlled environment, e.g. inside  
49 an occupied building, industrial premises, or for the archiving/storage of sensitive media [1,  
50 2]. The passive buffering of relative humidity inside earth buildings has been reported [3] and  
51 the role of other absorbent building materials measured [4, 5]. It is hypothesised that the

52 functional properties controlling this behaviour are a product of controllable material  
53 characteristics in earth materials and that these can be optimised to suit the application. In  
54 order to begin to understand this requires a transient hygrothermal approach for predictive  
55 numerical modelling, which therefore requires validation by coupled physical modelling. One  
56 must consider both the climatic conditions and the material properties, both of which  
57 dynamically change as a function of time.

58  
59 The authors have previously shown that whilst the dry-state thermal conductivity for  
60 compacted earth material types appears to vary little, their moisture-dependent thermal  
61 conductivity varies significantly due to the wide range of possible internal pore structures. As  
62 a result, the moisture-dependent volumetric heat capacity can experience even greater  
63 fluctuations [1, 6]. The authors have also previously found that (by analogy) the reverse is  
64 true for moisture, where the sorption isotherms between possible SRE types varies little, but  
65 that liquid water sorptivity/desorptivity, and also water vapour permeability, can vary over a  
66 significantly large range. Since temperature gradients induce mass transfer inside the material,  
67 and the thermal properties are moisture content-dependent, one can appreciate the fully  
68 transient nature of the coupled heat & mass transport phenomena associated with material  
69 behaviour in relation to air temperature and relative humidity buffering. The diagram in figure  
70 1 illustrates hygrothermal behaviour in relation to the wall of a building [7]. In addition, phase  
71 change of moisture transporting within the material has to be considered in relation to the heat  
72 flux associated with its enthalpy of vaporisation.

73  
74 This paper describes how a transient hygrothermal numerical model was used to simulate the  
75 behaviour of walls, made from three contrasting SRE material types, in response to changes in  
76 adjacent environmental conditions. These simulations were replicated as a full-scale physical  
77 model by constructing the said walls in a climatic simulation chamber and imposing realistic

78 indoor/outdoor environments either side of the walls. The objective of the modelling exercises  
79 was to validate the numerical predictions for temperature profile evolution by assessing the  
80 hygrothermal behaviour of the materials.

81

## 82 **2. Transient numerical modelling of heat & mass transport/storage**

83 When considering simultaneous transient modelling of heat & mass transport/storage in  
84 porous media the thermodynamic behaviour is referred to as hygrothermal. Transient  
85 hygrothermal simulation tools include the following transport and storage phenomena:

86

- 87 • heat storage in dry, unsaturated and saturated porous media
- 88 • dry and moisture-dependent thermal conductivity (heat transport)
- 89 • latent heat transport as a result of vapour diffusion (including phase change due  
90 to vapour evaporation/condensation)
- 91 • water (mass) storage by water vapour sorption and liquid capillarity
- 92 • water vapour transport by diffusion
- 93 • liquid transport by surface diffusion and capillary conduction

94

95 Numerous models exist for the definition of these phenomena (see [8] for a good summary).

96 Note that the benchmark standard BS EN 15026:2007 assumes that there is no total pressure  
97 difference across the component under consideration and air movement is ignored [9]. The

98 well-established WUFI<sup>®</sup> model [10, 11] uses two coupled equations; one for heat transport

99 (Eq 1) and the other for mass transport (Eq 2). They are solved simultaneously and

100 numerically using an implicit finite volume method of discretisation with a tridiagonal matrix

101 algorithm (known as the Thomas algorithm).

102

$$103 \quad \frac{\partial w}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot (D_{\varphi} \nabla \varphi + \delta_p \nabla (\varphi p_{sat})) \quad (\text{Eq. 1})$$

104

$$105 \quad \frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + H_{\text{vap}} \nabla \cdot (\delta_p \nabla (\varphi p_{sat})) \quad (\text{Eq. 2})$$

106

107 In equation 1, the left side of the moisture balance terms represents water storage which is  
 108 proportional to the derivative of the water retention curve ( $\partial w / \partial \varphi$ ), i.e. defined by the sorption  
 109 isotherm. The divergence of liquid and vapour flow is computed using the transport terms on  
 110 the right side of equation 1. The partial vapour pressure differential is the motivational force  
 111 for vapour diffusion, and is strongly temperature dependent since  $p_{sat} \approx \exp(T)$ . Liquid flow,  
 112 on the other hand, is dominated by capillary forces which are chiefly a function of relative  
 113 humidity  $\varphi$  (Kelvin equation). Note that the WUFI model ignores the influence of temperature  
 114 on capillary-induced liquid flow. In equation 2, the sensible heat flow is simply represented  
 115 by the divergence of heat conduction, whilst the divergence of vapour flow multiplied by the  
 116 enthalpy of vaporisation represents the latent heat term on the right hand side. The derivative  
 117 of total enthalpy, on the left hand side of equation 2, represents energy storage and contains  
 118 the heat capacity of the dry material plus the enthalpy of absorbed water, which is itself  
 119 phase-dependent (i.e. solid, liquid or vapour).

120

121 The hygrothermal material properties for each of the three SRE material types are taken from  
 122 published data by the authors [1] and were used as the input parameters for the WUFI Pro  
 123 simulations. As with most porous civil engineering materials (e.g. concrete, brick, soil) SRE  
 124 is not homogenous because the pore size distribution and tortuosity vary greatly within the  
 125 material. The conventional, accepted approach to measuring coefficients related to transport  
 126 processes is to test a representative sample of the material and use this output as the volume  
 127 averaged coefficient for that material, e.g. thermal conductivity. Obviously, no one individual

128 part of the material has this property because it has effectively been statistically weighted, but  
129 across a representative area at full scale it is valid. The higher the sample population during  
130 testing, the greater the accuracy of the mean value. The required number of samples needed to  
131 achieve this, as detailed in the relevant BS EN ISO standards, was used for the testing  
132 conducted by the authors for this work [15].

133

134 Both in the numerical model (WUFI Pro) and the physical model (climate chamber tests), the  
135 indoor and outdoor initial conditions for the simulation were taken as 21°C and 45% relative  
136 humidity. At time,  $t = 0$  the outside climatic set points were adjusted to 8°C and 70% RH.  
137 Further set point changes were introduced at 48 hours and 72 hours, when temperatures were  
138 reduced to 0°C and -8°C respectively whilst maintaining a constant 70% RH. The simulations  
139 ran for a total of 96 hours. The surface resistances for heat transfer and vapour diffusion were  
140 given typical values of 0.125m<sup>2</sup> K/W and 45.45x10<sup>6</sup> m<sup>2</sup> s Pa/kg respectively. These values  
141 were the same for both sides of the test walls to suit the conditions found in the climatic  
142 simulation chamber experiments.

143

### 144 **3. Physical modelling in the climatic simulation chamber**

145 The simulation chamber itself is composed of two self-contained halves called the ‘design’  
146 side and the ‘climate side’ that join together on either side of the test specimen. The  
147 dimensions of each chamber are 4m long, 3m wide and 2.6m in height. The normal operating  
148 temperature range is +20°C to -15°C ( $\pm 5^\circ\text{C}$ ) depending on the internal conditions specified  
149 [12]. A schematic diagram illustrating the basic operation of the climatic simulation chamber  
150 is shown in Figure 2. Full-scale test components (e.g. walls) can be constructed inside the  
151 climatic simulation chamber following normal construction practices, and realistic climatic  
152 effects (on both sides of the walls) including various weather conditions can be accurately  
153 simulated and monitored under controlled laboratory conditions [13, 14]. The design side of



154 the simulation chamber represents the interior conditions of a building and is typically  
155 configured to maintain standard indoor room conditions of  $20^{\circ}\text{C} \pm 1^{\circ}$  and  $45\% \text{ RH} \pm 5\%$ . The  
156 climate side of the simulation chamber creates realistic sequences of different external  
157 weather conditions that can run in a fixed mode, sequence mode, or cyclic mode. The  
158 advantage of this is that the start and finish temperatures can be specified, as well as the rates  
159 of change of other weather components such as air pressure, relative humidity and rainfall.

160

161 The 300mm-thick SRE test walls were constructed inside the climatic simulation chamber on  
162 top of a concrete plinth, as described in previous work published by Hall [14]. The walls were  
163 made using the 433, 613 and 703 mix types detailed in previous studies [1, 6, 14, 15]. The  
164 aggregates and silty clay, along with the mix types, were specified and controlled to be  
165 precisely the same as those used for the small representative test specimens. Prior to  
166 compaction the soils were mixed to their optimum moisture content and placed in layers  
167 150mm thick inside oiled proprietary formwork and compacted using an Atlas Copco RAM30  
168 pneumatic tamper. The test walls were separated from one another by a 100mm thick timber-  
169 frame incorporating the formwork end boards. Following their completion, the test walls were  
170 allowed to cure for a minimum period of 28 days in laboratory conditions at  $22^{\circ}\text{C} \pm 1^{\circ}$  and  
171  $40\% \text{ RH} \pm 5\%$ . The wall edges were sealed with phenolic resin-coated plywood and caulked  
172 with silicone sealant. The remaining height above the test walls was completed with timber  
173 frame walling and covered with 1200g damp proof membrane sealed with black cloth tape.  
174 The resultant dimensions for the exposed test face of each wall were 500mm wide by 900mm  
175 high (area =  $0.45\text{m}^2$ ).

176

177 An array of electronic sensors was retrofitted to each of the four rammed earth test walls by  
178 drilling a small hole from the inside of the wall to the required depth and then carefully  
179 inserting the sensor using metal rod marked at different depths. Once in place the sensor hole

180 was capped and sealed using silicone caulking. In each wall, six type-T copper/constantan  
181 thermocouples (protected by hollow plastic tubing) were installed to depths of 25mm, 50mm,  
182 75mm, 100mm, 125mm, and 150mm. In addition, armoured thermocouples were mounted  
183 onto both the internal and external wall faces.

184

185 The simulation parameters involved creating various fixed temperature & humidity gradients  
186 across the test walls. This was achieved in the climate chamber by maintaining a difference in  
187 temperature/humidity between the design side and the climate side of the chamber for a 24-  
188 hour period. All of this testing was performed in the absence of any rainfall or pressure  
189 differential. The indoor (design side) conditions were maintained at  $20^{\circ}\text{C} \pm 1^{\circ}$  and 40% RH  
190  $\pm 5\%$  to represent a comfortable indoor living environment. The outdoor conditions (climate  
191 side) were kept at a constantly high level of relative humidity:  $75\% \pm 5\%$  to represent a damp,  
192 temperate climate. The test run lasted for a total period of four days and included three  
193 different outdoor temperature set points. On days 1 and 2 the 'outdoor' conditions were set to  
194  $8^{\circ}\text{C}$  75% RH, on day 3 they were set to  $0^{\circ}\text{C}$  75% RH, and on day 4 they were set to  $-8^{\circ}\text{C}$  75%  
195 RH, during which snowfall began to occur. During all four days of the test run the sensor  
196 array was used for recording the performance of the test walls.

197

#### 198 **4. Analysis of simulated temperature and moisture profile evolution**

199 The predictive numerical model outputs from WUFI Pro simulations were compared with  
200 experimental data from the physical model using the climatic simulation chamber. The  
201 temperature of the inside surface, mid-point and outside surface of each wall are plotted  
202 against elapsed time in Figures 3, 4 and 5, for each of the test walls. It can be seen that the  
203 simulation mainly predicts the temperatures to a good level of accuracy in relation to the  
204 recorded data from the climatic simulation tests.

205

206 The temperature profile evolution, as a function of time, was calculated for the three walls and  
207 representative values at 0, 2, 6, 12, 24, 48, 72 and 96 hours were plotted on the graphs in  
208 Figures 6, 7, and 8. It is notable that the temperature profiles do not become linear (i.e.  
209 apparent steady state conditions) until around 48 hours after the first temperature set points  
210 were initiated, and then at 72 and 96 hours respectively in response to the second and third  
211 temperature set point initiations. This enforces the important point that steady state heat loss  
212 assumptions are (in the absence of static temperature gradients) inappropriate for simulating  
213 the thermal behaviour under the varying environmental conditions that occur in nature. The  
214 small variations in volumetric heat capacity of the three soil mix types tested here appeared to  
215 make little difference to the time-dependent evolution of the apparent steady state temperature  
216 profiles. This suggests that little scope exists to intelligently modify the ability of SRE walls  
217 to absorb and store heat energy simply by manipulation of PSD and the resultant bulk  
218 density/void ratio relationships.

219

220 The apparent steady state temperature depth profiles appeared to be remarkably similar to one  
221 another for each soil mix type. This is consistent with previous findings for dry-state thermal  
222 conductivity on these soil mix types [1], and hence the thermal resistance of each wall is very  
223 similar indicating that the majority of the wall remained relatively dry. The presence of  
224 significant quantities capillary-domain water can cause large increases in the thermal  
225 conductivity of the material, which is significantly different between soil mix types according  
226 to their void characteristics.

227

228 The change across three external climate set points ( $8^{\circ}\text{C}$  75% RH;  $0^{\circ}\text{C}$  75% RH; and  $-8^{\circ}\text{C}$   
229 75% RH) presented a situation where the partial vapour pressure, and hence absolute moisture  
230 content, of the air on one side of the walls was significantly reduced in each case, as  
231 illustrated by the psychrometric chart in Figure 9. Figures 10, 11 and 12 show the transient

232 simulation results for relative humidity (of the internal pore structure) and moisture content of  
233 each test wall at 48, 72 and 96 hour increments. It is apparent that only the internal and  
234 external outer layers (approx. 5cm thick) were involved in the interaction with changing  
235 humidity over a daily period. One can appreciate the drying appears to occur on the external  
236 side when the temperature (and hence the air moisture content at 75% RH) is sufficiently low,  
237 and the absorption that occurs on the internal side as a result of the vapour pressure  
238 differential across the wall. Interestingly, there appears to be a large disparity between the  
239 three soil mix types in terms of i) the mass of absorbed water in the wall core, and ii) the rate  
240 of change in moisture content and relative humidity in the outer wall layers. This suggests that  
241 significant potential exists to intelligently modify the ability of SRE walls to absorb, store and  
242 release moisture vapour from the surrounding air simply by manipulation of PSD and the  
243 resultant bulk density/void ratio relationships. This merits further investigation into  
244 optimisation of the moisture buffering capacity of SRE materials and possible applications.

245  
246 Some small discrepancies appeared between numerically and physically modelled  
247 temperature data, which could be explained by a number of specific issues. Due to a brief start  
248 up period prior to the beginning of the climate chamber simulations, a gradual decrease in the  
249 outside wall surface temperatures had already begun whereas for the computer simulation an  
250 instantaneous temperature drop from 21°C to 8°C was assumed. The climate side and design  
251 side air temperatures within the simulation chamber were not steady state throughout the test  
252 period, reflected by the small periodic fluctuation in the recorded wall surface temperatures  
253 (i.e. on/off cycling of the control plant). Also, some temperature stratification could  
254 reasonably be expected due to imperfect mixing of the air in the chamber and the induced  
255 temperature step changes did not occur instantaneously, as they did in the model.

256

257 Previous research found that the macro-scale properties of dry density and porosity of large  
258 scale SRE test walls could be matched very closely to small Proctor test specimens by  
259 accurately controlling PSD and optimum moisture content, regardless of varying compaction  
260 input energy. However, other scale effects such as surface finish, compaction layer thickness  
261 and degree of homogeneity could reasonably cause disparity between functional hygrothermal  
262 properties of the SRE test walls compared to the 1 litre test specimens used to determine the  
263 input parameters for the WUFI Pro simulations. Whilst the degree of accuracy in  
264 hygrothermally modelling temperature profiles in SRE materials is acceptably accurate, the  
265 opportunities for further improvements outlined above require much further research.

266

## 267 **5. Conclusions**

268 The numerically modelled data from WUFI Pro v4.1 has been validated to a good level  
269 accuracy against the physically modelled experimental data from the climatic simulation  
270 chamber. Experimentally determined hygrothermal properties for SRE materials can be  
271 inputted to WUFI Pro and used to accurately simulate transient behaviour of full sized test  
272 walls in response to changes in climatic conditions as a function of time.

273

274 The temperature profile evolution and resultant steady state gradients, in each test wall, were  
275 very similar regardless of soil mix type indicating that the majority of the wall remained  
276 relatively dry. This is further supported by the predicted liquid and relative humidity content  
277 and distribution within each test wall. From previous research [1, 6] it is known that unless  
278 liquid water is present, the thermal resistance and volumetric heat capacity of these materials  
279 does not change sufficiently to make significant differences to temperature profile evolution  
280 regardless of soil mix type. Therefore, there appears to be little scope to intelligently modify  
281 the ability of SRE walls to absorb and store heat energy simply by manipulation of PSD and  
282 the resultant bulk density/void ratio relationships, under these conditions.

283

284 Only the outer layers of the walls appear to interact with moisture in the air. The predicted  
285 transient response of material moisture content indicate that significant potential exists to  
286 intelligently modify the ability of SRE walls to absorb, store and release moisture vapour  
287 from the surrounding air simply by manipulation of PSD and the resultant bulk density/void  
288 ratio relationships. The WUFI Pro model appears to show that the relationship between  
289 thermal and hygric (hygrothermal) functional properties must be simultaneously balanced in  
290 order to control the moisture sorption/desorption rates and storage capacity that govern air  
291 temperature and relative humidity buffering. Future research must attempt to scale up the  
292 simulation so that whole building modelling and real weather data can be included, and  
293 seasonal or annual timeframes can be modelled. Liquid water transport will also be studied so  
294 that rain fall absorption can be simulated, which will necessitate modelling over periods of  
295 many months. The potential of SRE walls to offer improved thermal comfort and operational  
296 energy savings from air conditioning inside buildings is still to be quantified. This work has  
297 identified the use of a hygrothermal approach to tackle this problem and has proven that data  
298 from numerical and physical models can be accurately validated under controlled climatic  
299 scenarios.

300

### 301 **Acknowledgements**

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303 Research Council for the research presented in this paper.

304

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344



345 **Figure Captions**

346 Figure 1: Hygrothermal behaviour illustrating the relevant fluxes acting on the wall of a  
347 building [4]

348 Figure 2: Schematic cross-sectional diagram of the climatic simulation chamber [12]

349 Figure 3: Comparison between numerically and physically modelled temperature depth  
350 profiles for the 433 mix type

351 Figure 4: Comparison between numerically and physically modelled temperature depth  
352 profiles for the 613 mix type

353 Figure 5: Comparison between numerically and physically modelled temperature depth  
354 profiles for the 703 mix type

355 Figure 6: Transient temperature profile evolution as a function of time for the 433 mix type

356 Figure 7: Transient temperature profile evolution as a function of time for the 613 mix type

357 Figure 8: Transient temperature profile evolution as a function of time for the 703 mix type

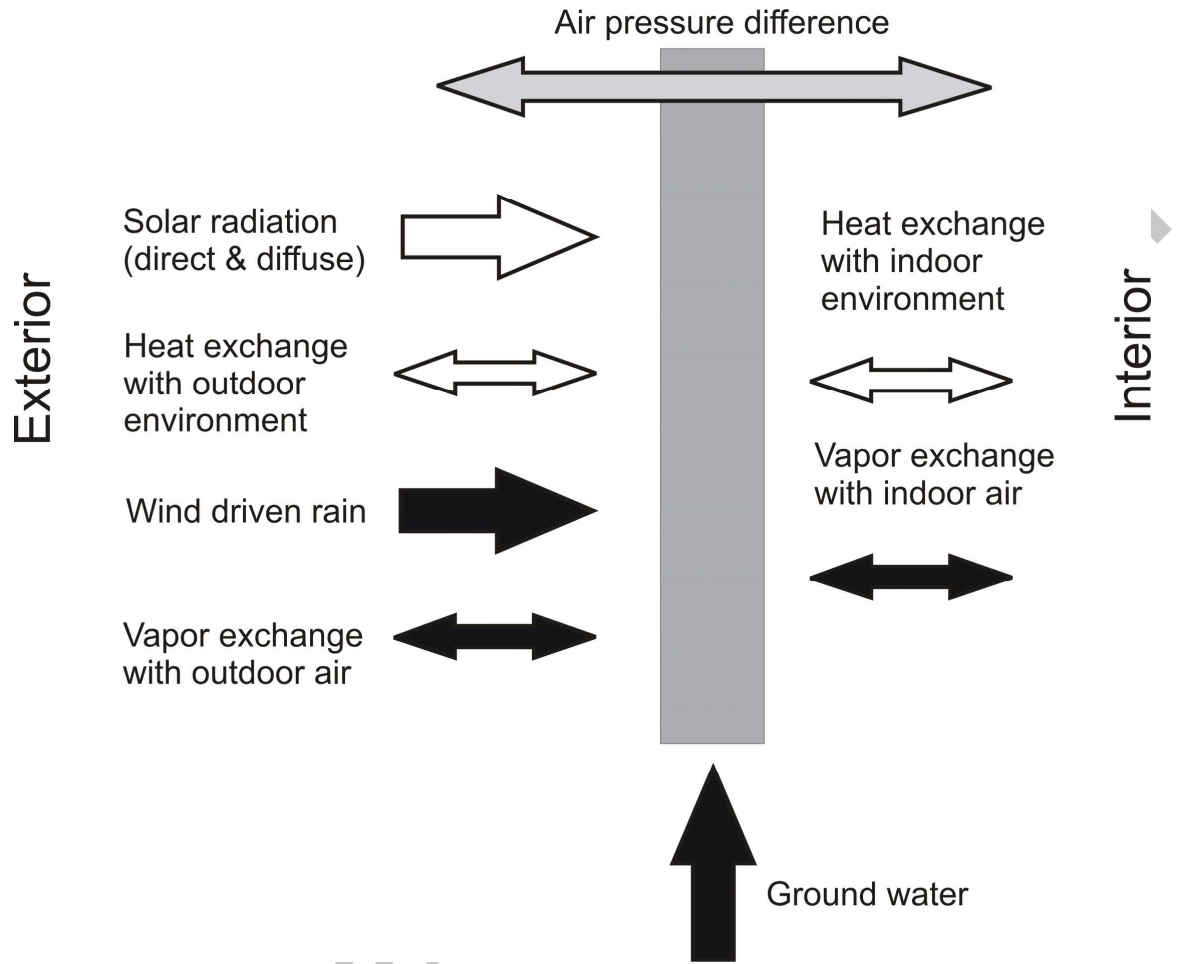
358 Figure 9: A psychrometric chart to illustrate the change in environmental conditions in  
359 response to the outdoor temperature and RH set points

360 Figure 10: Transient liquid water and RH inside the pore structure of the 433 mix type in  
361 response to the changes in outdoor temperature and RH set points

362 Figure 11: Transient liquid water and RH inside the pore structure of the 613 mix type in  
363 response to the changes in outdoor temperature and RH set points

364 Figure 12: Transient liquid water and RH inside the pore structure of the 703 mix type in  
365 response to the changes in outdoor temperature and RH set points

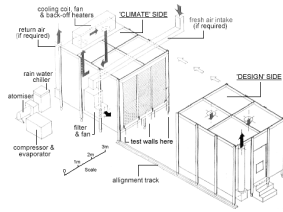
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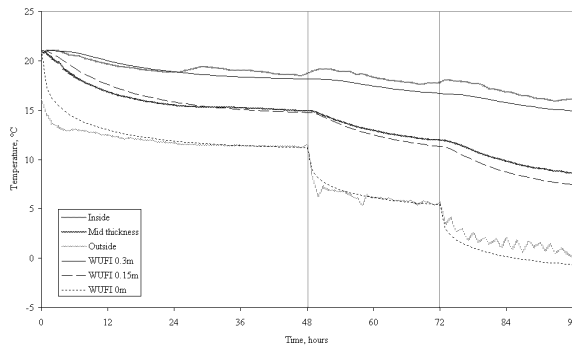
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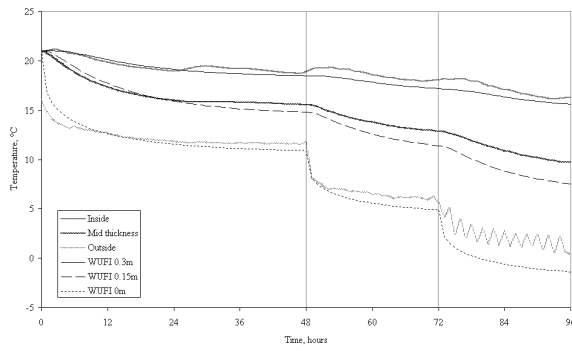
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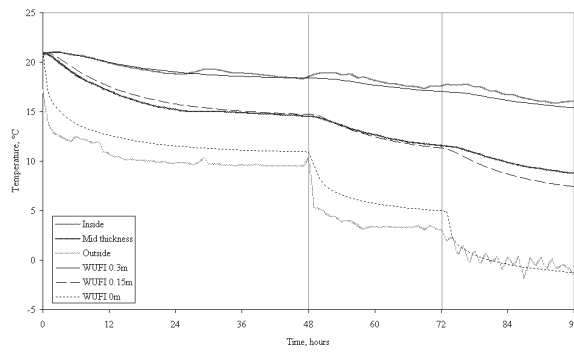
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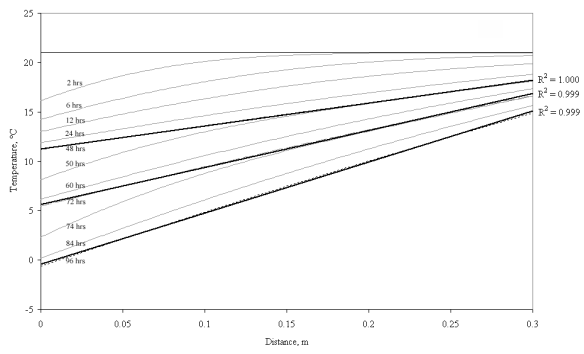
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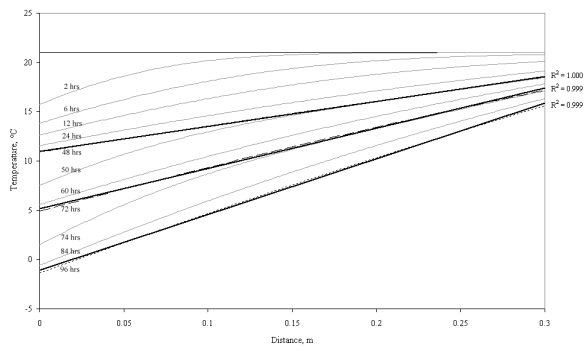
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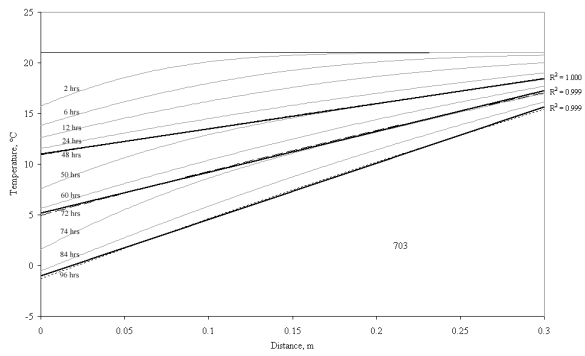


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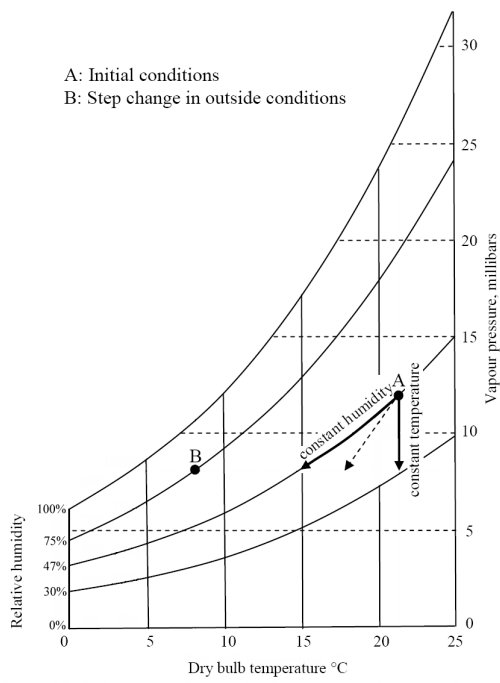
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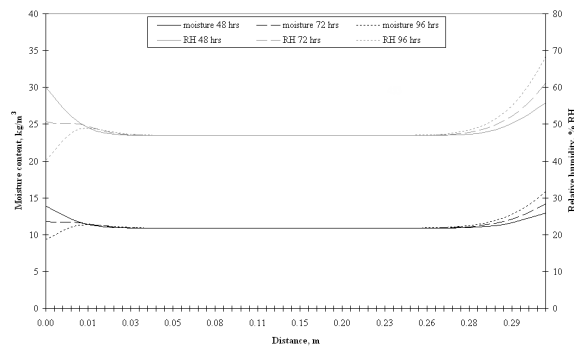
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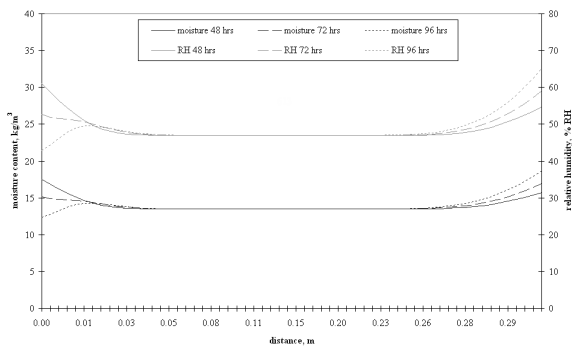
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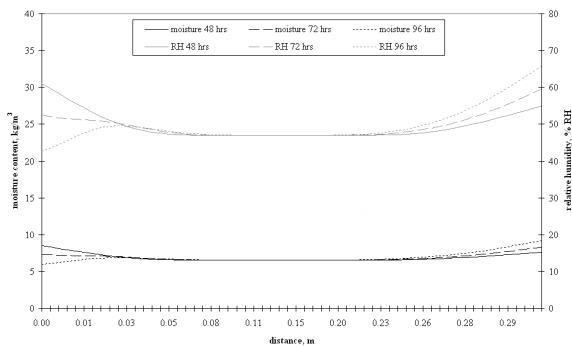
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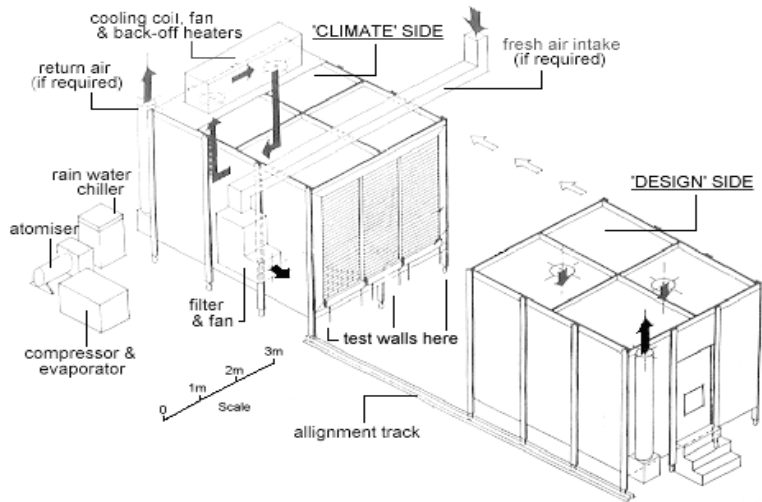
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ACCEPTED MANUSCRIPT

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391 Figure 2

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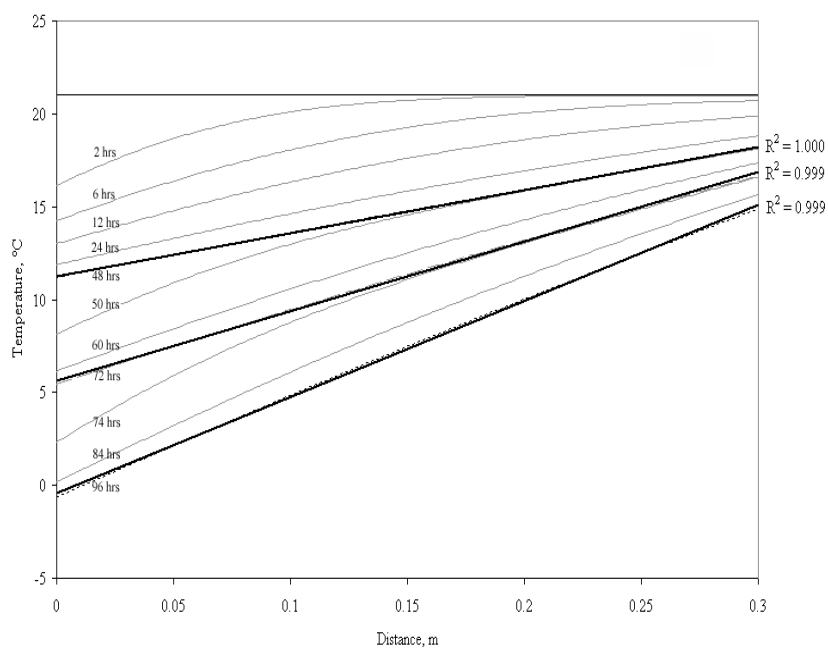
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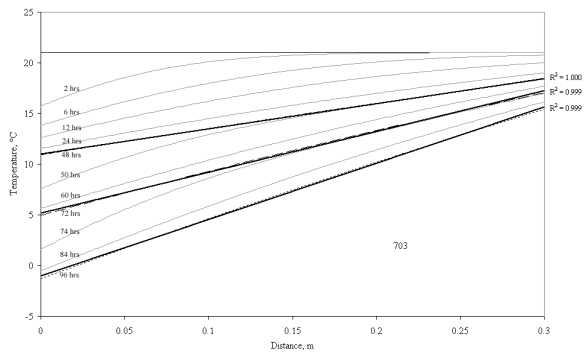


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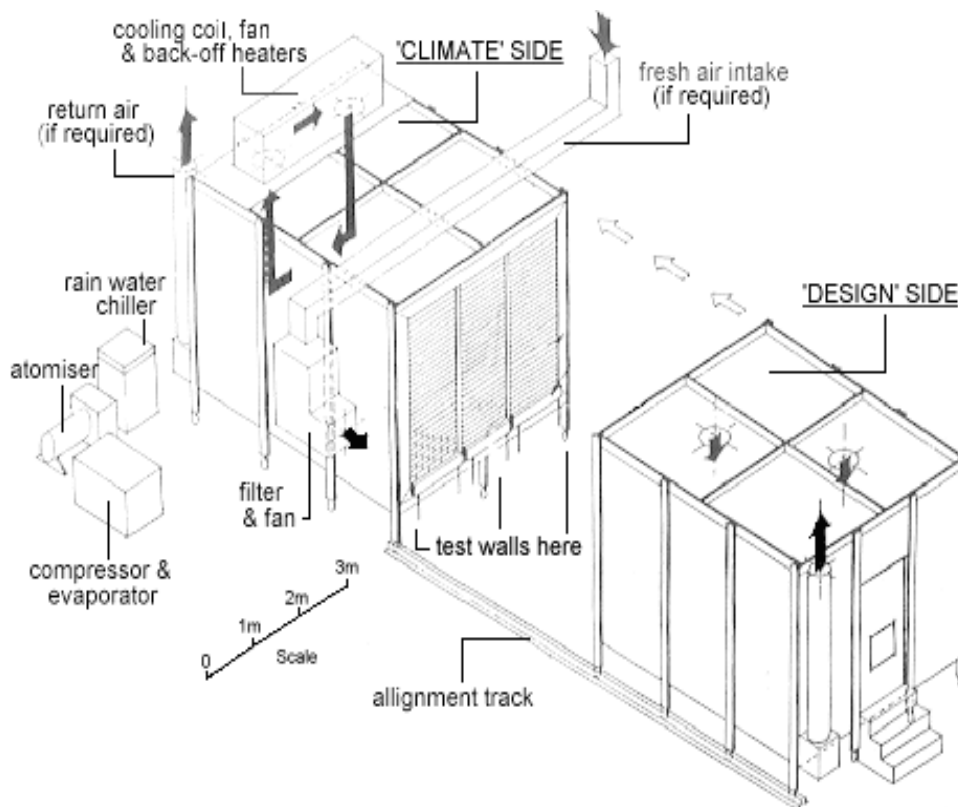
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Figure 2



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Figure 6

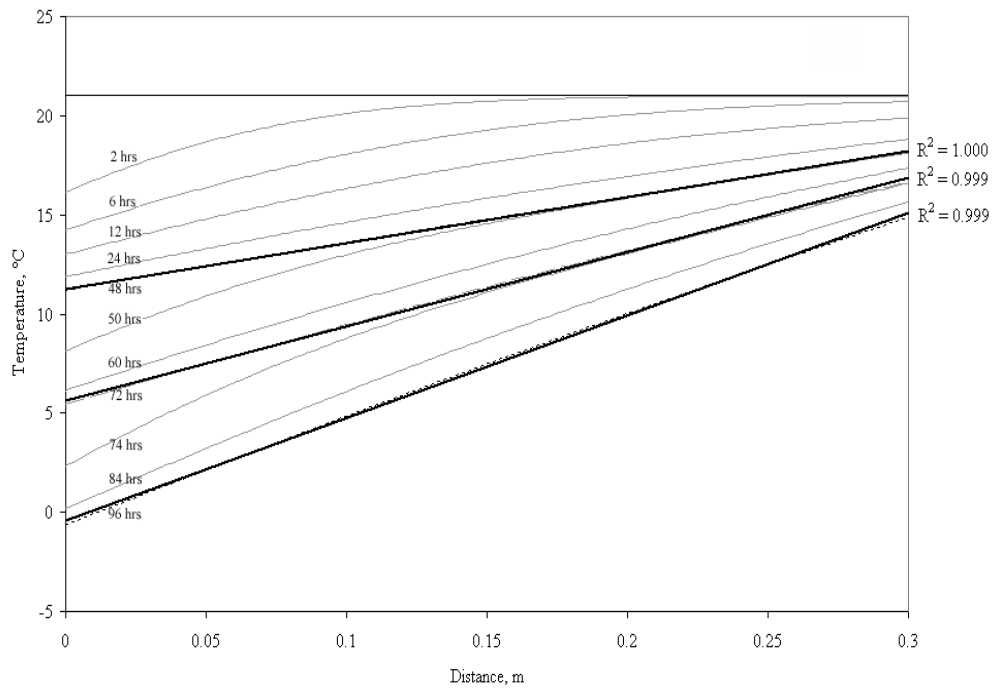


Figure 7

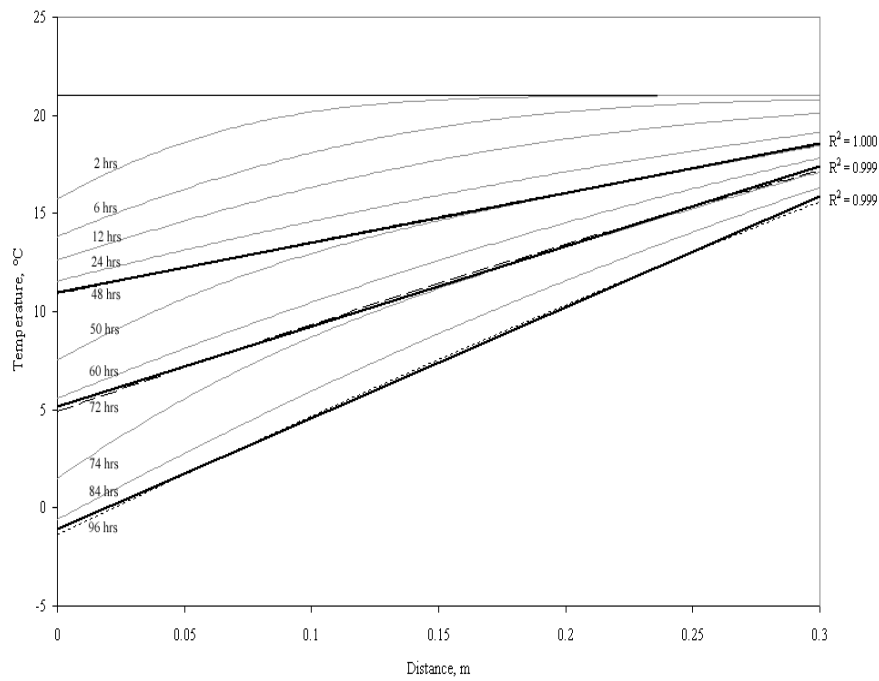


Figure 8

