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ENTHALPY-MODEL SELECTION AND PRACTICAL IDENTIFIABILITY OF A MACROENCAPSULATED RT52 RADIANT FLOOR UNDER UNCERTAIN BRANCH FLOW

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Abstract. A hierarchy of reduced-order models was developed to determine what can—and cannot—be inferred about phase-change behavior from temperature measurements in a solar-driven radiant floor containing macroencapsulated RT52. The hydraulic topology treats the common-line mass flow upstream of a parallel split; the nominal equal split therefore gives a balanced flow in the PCM branch, while a flow-split sensitivity range was retained. Three model levels were compared: a sensible-only counterfactual (M1), a local-thermal-equilibrium enthalpy model with fixed RT52 properties (M2), and a finite PCM–concrete coupling model with a separate PCM state and a latent-participation factor (M3). During the charging-dominant interval, M2 reduced the joint residual sum of squares relative to M1 and was favored by the corrected Akaike Information Criterion AICc under the nominal split. The AICc preference remained positive across the sensitivity range. However, M3 did not justify its additional parameters: the fitted PCM–concrete conductance approached the local-equilibrium limit, the characteristic equilibration time was small compared with the sampling interval, and the finite-coupling formulation was penalized by AICc. Full-cycle stress tests further showed that the inferred latent-participation factor could shift significantly when physically plausible nuisance-parameter bounds were imposed. The charging record therefore supports an enthalpy representation, but PCM mass, finite PCM–concrete conductance, and exact latent participation are not uniquely identifiable from the available data. Model preference and parameter identifiability must be reported separately in PCM thermal-storage experiments.

Keywords: phase change material; enthalpy method; AICc; practical identifiability; RT52; reduced-order model; radiant floor; parameter estimation

Annotatsiya. Makrokapsulalangan RT52 materialini o'z ichiga olgan quyosh energiyasi bilan ishlaydigan nurlanuvchi polda harorat o'lchovlari asosida faza o'zgarishi xulq-atvoridan qanday xulosalar chiqarish mumkinligi va nimalarni aniqlab bo'lmavligini belgilash uchun pasaytirilgan tartibli modellar iyerarxiyasi ishlab chiqildi. Gidravlik topologiya parallel tarmoqlanishdan yuqoridagi umumiy liniya massaviy sarfini hisobga oladi; shuning uchun nominal teng bo'linish Faza O'zgaruvchan Material (FO'M) tarmog'ida teng taqsimlangan sarfni beradi, shu bilan birga sarf bo'linishining sezgirlik diapazoni ham saqlab qolindi. Uchta model darajasi o'zaro solishtirildi: faqat sezilarli issiqlikka asoslangan kontrfaktik model (M1), belgilangan RT52 xossalriga ega lokal issiqlik muvozanati entalpiya modeli (M2) hamda alohida FO'M holati va yashirin issiqlik ishtiroki koeffitsientiga ega bo'lgan chekli FO'M–beton bog'lanishi modeli (M3). Zaryadlanish ustunlik qilgan intervalda M2 modeli M1 ga nisbatan qoldiq kvadratlar yig'indisini kamaytirdi va nominal bo'linishda tuzatilgan Akaike axborot mezoniga AICc ko'ra afzal deb topildi. AICc afzalligi sezgirlik diapazoni bo'yicha ham ijobiy bo'lib qoldi. Biroq M3 modeli o'zining qo'shimcha parametrlarini oqlamadi: FO'M–betonning moslashtirilgan o'tkazuvchanligi lokal muvozanat chegarasiga yaqinlashdi, xarakterli muvozanatlashish vaqti diskretlash intervaliga nisbatan kichik bo'ldi va chekli bog'lanish formulasi AICc tomonidan penalti bilan baholandi. To'liq siklli stress-testlar, shuningdek, fizik jihatdan asosli xalaqit beruvchi parametrlar chegaralari qo'llanilganda, aniqlangan yashirin issiqlik ishtiroki koeffitsienti sezilarli darajada o'zgarishi mumkinligini ko'rsatdi. Shunday qilib, zaryadlanish ma'lumotlari entalpiya tasvirini tasdiqlaydi, ammo FO'M massasi, chekli FO'M–beton o'tkazuvchanligi va aniq yashirin issiqlik ishtirokini mavjud ma'lumotlardan bir qiymatli identifikatsiyalab bo'lmaydi. FO'M issiqlik akkumulyatsiyasi tajribalarida model afzalligi va parametrlarning identifikatsiyalanuvchanligi alohida ko'rsatilishi lozim.

Kalit soʻzlar: faza oʻzgaruvchan material; entalpiya usuli; AICc; amaliy identifikatsiyalanuvchanlik; RT52; pasaytirilgan tartibli model; nurlanuvchi pol; parametrlarni baholash

Аннотация. Иерархия моделей пониженного порядка была разработана для определения того, что может и что не может быть выведено о фазовом переходе на основе измерений температуры в солнечном излучающем полу с макрокапсулированным RT52. Гидравлическая топология учитывает массовый расход в общей линии выше параллельного разветвления; таким образом, номинальное равное разделение обеспечивает сбалансированный расход в ветви с материалом с фазовым переходом (ФПМ), в то время как диапазон чувствительности разделения потока был сохранен. Сравнивались три уровня моделей: контрфактическая модель только с ощутимым теплом (M1), энтальпийная модель локального теплового равновесия с фиксированными свойствами RT52 (M2) и модель конечной связи ФПМ–бетон с отдельным состоянием ФПМ и коэффициентом скрытого участия (M3). В течение интервала с преобладанием зарядки M2 снизила совместную сумму квадратов остатков по сравнению с M1 и получила преимущество по скорректированному информационному критерию Акаике AICc при номинальном разделении. Предпочтительность по AICc оставалась положительной во всем диапазоне чувствительности. Однако M3 не оправдала своих дополнительных параметров: подобранная проводимость ФПМ–бетон приблизилась к пределу локального равновесия, характеристическое время установления равновесия было малым по сравнению с интервалом дискретизации, а формулировка с конечной связью получила штраф по AICc. Полноцикловые стресс-тесты также показали, что рассчитанный коэффициент скрытого участия может существенно смещаться при наложении физически правдоподобных ограничений на мешающие параметры. Таким образом, данные процесса зарядки подтверждают энтальпийное описание, однако масса ФПМ, конечная проводимость ФПМ–бетон и точное скрытое участие не являются однозначно идентифицируемыми по имеющимся данным. Предпочтительность модели и идентифицируемость параметров должны указываться отдельно в экспериментах по тепловому аккумулярованию с ФПМ.

Ключевые слова: фазопереходный материал; метод энтальпии; AICc; практическая идентифицируемость; RT52; модель пониженного порядка; излучающий пол; оценивание параметров

INTRODUCTION

Highlights.

- An equal-complexity sensible-only/enthalpy comparison isolates the information added by phase change.
- The enthalpy model is preferred during charging by at the nominal hydraulic split.
- The preference remains positive across the full flow-split interval.
- A finite PCM–concrete coupling state is not resolved at the available observation scale.
- Full-cycle latent participation is practically non-identifiable despite low temperature RMSE.

Phase-change-material models used in building and thermal-storage applications range from detailed finite-volume formulations to enthalpy, apparent-heat-capacity and reduced-order resistance–capacitance representations [1–9]. The modelling choice matters because latent heat is distributed over a finite transition interval and because hysteresis, incomplete melting, uncertain thermophysical properties and heat-transfer resistance can produce similar macroscopic temperature responses [2,4–12]. For active radiant floors, the inference problem is further complicated by embedded piping, concrete thermal mass, macroencapsulation and time-varying heat-source conditions [13–21].

LITERATURE REVIEW

A low prediction error is therefore not equivalent to a uniquely identified latent mechanism. Different combinations of enthalpy shape, transfer coefficients, hidden initial states and environmental boundary conditions may reproduce the same measured temperatures [6–12,22–25]. Information criteria determine whether extra model structure improves predictive description, whereas identifiability analysis asks whether internal parameters are uniquely recoverable from the available observations [10–12,26–30]. Because the present limitations arise from finite sampling, sparse outputs and unmeasured boundary conditions rather than from the model structure alone, the relevant concept is practical (data-limited) identifiability.

The present work separates these questions. First, a sensible-only model and an otherwise equal-complexity enthalpy model are compared during a charging-dominant interval. Second, a finite PCM–concrete coupling model is tested to determine whether the measurements resolve a distinct PCM temperature state. Third, the hierarchy is stressed over the full continuous-circulation cycle to determine whether latent participation is stable to plausible treatment of unmeasured boundary conditions. The aim is not to force a numerical latent fraction from the data, but to establish the strongest physically defensible inference supported by the experiment.

RESEARCH METHODOLOGY

Experimental and modelling framework.

Hydraulic topology and observations: The total measured mass flow, $\dot{m}$, belongs to the common line downstream of the solar receiver and upstream of the split into the conventional and PCM-integrated floor branches. Branch flows were not measured, so the control-branch fraction f is treated as an uncertainty variable rather than a fitted quantity:

$$\dot{m}_N = f \dot{m}_{\text{tot}}, \quad \dot{m}_P = (1 - f) \dot{m}_{\text{tot}}, \quad 0.40 \leq f \leq 0.60 \quad (1)$$

The principal calibration record is the 3–4 July charging-dominant interval from 10:25 to 17:11. The common supply temperature T_1 , the PCM-branch return T_3 and the PCM-panel surface T_5 are measured; the reduced-order core and PCM temperatures are hidden states. The measured temperatures enter the nominal RT52 transition interval (Fig. 1a), but this alone does not prove that the entire PCM inventory follows the measured water or surface temperature.

Model hierarchy: M1 contains only sensible storage for the PCM-side assembly. M2 preserves the same reduced-order structure and fitted-parameter count but activates a fixed enthalpy function for RT52. M3 introduces a separate PCM temperature state, a finite PCM–concrete conductance and an effective latent-participation factor. The PCM-branch outlet is represented by an effectiveness–NTU relation referenced to the hidden concrete-core temperature:

$$T_{3,m} = T_{c,P} + (T_1 - T_{c,P})e^{-NTUP} \quad (2)$$

For the local-equilibrium models M1 and M2, the core and surface states satisfy

$$C_{c,P} \frac{dT_{c,P}}{dt} = \dot{m}_P c_p (T_1 - T_{3,m}) - K_{cs,P} (T_{c,P} - T_{s,P}) - K_{b,P} (T_{c,P} - T_{eq}) \quad (3)$$

$$C_{s,P} \frac{dT_{s,P}}{dt} = K_{cs,P} (T_{c,P} - T_{s,P}) - H_{s,P} (T_{s,P} - T_{eq}) \quad (4)$$

The effective boundary T_{eq} is a reduced-order nuisance boundary, not a measured room-air temperature, because no full ambient-temperature series was available for 3–4 July. M1 removes latent storage ($L=0$) while preserving the sensible capacities of the thicker slab, steel capsules and paraffin. M2 activates a fixed latent contribution:

$$h(T) = c_p (T - T_{\text{ref}}) + L f_l(T), \quad c_{p,\text{app}}(T) = \frac{dh}{dT} = c_p + L \frac{df_l}{dT} \quad (5)$$

$$f_l(T) = \begin{cases} 0, & T \leq T_s \\ 3\xi^2 - 2\xi^3, & T_s < T < T_l \\ 1, & T \geq T_l \end{cases}, \quad \xi = \frac{T - T_s}{T_l - T_s} \quad (6)$$

$$\text{M2: } L = 172 \text{ kJ kg}^{-1}, \quad T_s = 44 \text{ }^\circ\text{C}, \quad T_l = 56 \text{ }^\circ\text{C} \quad (7)$$

The cubic liquid-fraction interpolation avoids a discontinuous apparent heat capacity at the transition boundaries. The latent heat and transition interval are fixed inputs, so that poorly identifiable PCM properties are constrained by independent information rather than inflated during fitting [1–12,29–31] (Figure 1a, 1b).

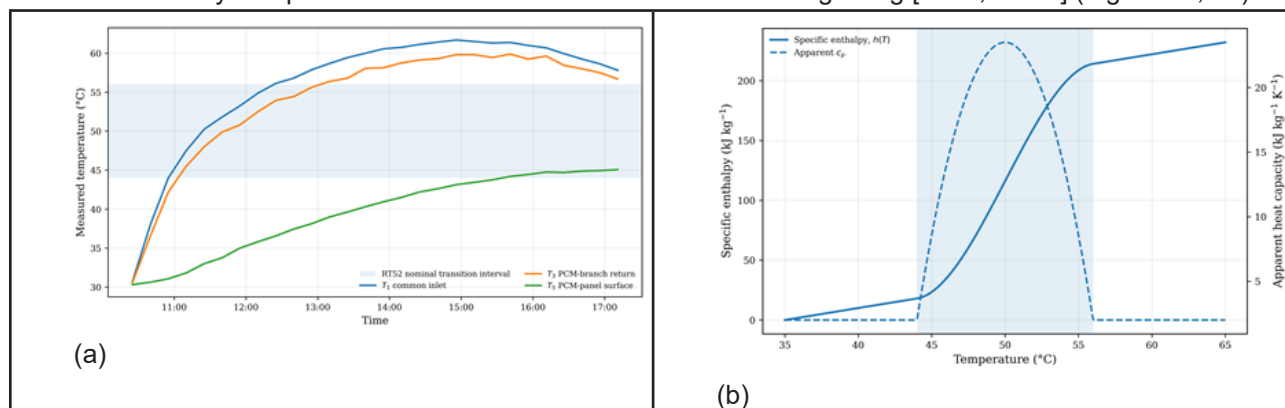


Figure 1. (a) Measured charging-period temperatures relative to the nominal RT52 transition interval; the shaded

band is a material-model interval, not a measured PCM-core temperature. (b) RT52 enthalpy and apparent heat capacity used in M2/M3

Finite PCM–concrete coupling (M3): M3 tests whether the data resolve a distinct PCM thermal state. The surface equation (Eq. (4)) is retained, while the core and PCM states become

$$C_{c,P} \frac{dT_{c,P}}{dt} = \dot{m}_P c_P (T_1 - T_{3,m}) - K_{cs,P} (T_{c,P} - T_{s,P}) - K_{cP} (T_{c,P} - T_{PCM}) - K_{b,P} (T_{c,P} - T_{eq}) \quad (8)$$

$$\left[C_{steel} + m_{PCM} \left(c_{p,PCM} + \alpha_L L \frac{df_l}{dT} \right) \right] \frac{dT_{PCM}}{dt} = K_{cP} (T_{c,P} - T_{PCM}), \quad 0 \leq \alpha_L \leq 1 \quad (9)$$

The characteristic PCM–concrete equilibration time is approximated by

$$\tau_{cP} \approx \frac{C_{PCM,app}}{K_{cP}} \quad (10)$$

where $C_{PCM,app}$ is the bracketed apparent capacity in Eq. (9). If τ_{cP} is much shorter than the sampling interval, K_{cP} cannot be estimated precisely from sparse external temperatures, and the finite-coupling model collapses toward local equilibrium [6–12].

Error metrics, information criteria and identifiability diagnostics: Model performance was evaluated with the residual sum of squares and conventional prediction metrics, where y_i and $\hat{y}_i$ are measured and predicted temperatures:

$$RSS = \sum_{i=1}^n (y_i - \hat{y}_i)^2, \quad RMSE = \sqrt{RSS/n}, \quad R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (11)$$

Model complexity was penalized with information criteria, where k is the number of fitted parameters; AIC_c is emphasized because the calibration window is finite [26–28]:

$$AIC = n \ln \left(\frac{RSS}{n} \right) + 2k, \quad AIC_c = AIC + \frac{2k(k+1)}{n-k-1}, \quad BIC = n \ln \left(\frac{RSS}{n} \right) + k \ln n \quad (12)$$

$$\Delta AIC_c = AIC_{c,M1} - AIC_{c,M2}, \quad w_i = \frac{\exp(-\Delta_i/2)}{\sum_j \exp(-\Delta_j/2)} \quad (13)$$

where $\Delta_i = AIC_{c,i} - \min_j AIC_{c,j}$ and w_i is the Akaike weight. Residual independence was audited with the Durbin–Watson and Ljung–Box statistics [29], with e_t the residuals and $\hat{\rho}_k$ their lag- k autocorrelation:

$$DW = \frac{\sum_{t=2}^n (e_t - e_{t-1})^2}{\sum_{t=1}^n e_t^2}, \quad Q_{LB} = n(n+2) \sum_{k=1}^h \frac{\hat{\rho}_k^2}{n-k} \quad (14)$$

Identifiability was assessed from boundary behaviour and conditional profiles rather than by reporting optimizer output as a measured property, using the profile increment and the likelihood-ratio statistic based on the log-likelihood ℓ :

$$\Delta RSS(m_{PCM}) = RSS(m_{PCM}) - RSS_{min}, \quad \Lambda(\theta) = 2[\ell(\hat{\theta}) - \ell(\theta)] \quad (15)$$

ANALYSIS AND RESULTS

Charging-period comparison of M1 and M2: Under the nominal split ($f=0.50$), M1 and M2 used the same number of fitted parameters ($k=3$, joint $n=54$). M1 returned $NTU_P=0.1483$, $K_{cs,P}=6.02 \text{ WK}^{-1}$ and $H_{s,P}=6.25 \text{ WK}^{-1}$; M2 returned $NTU_P=0.1403$, $K_{cs,P}=9.20 \text{ WK}^{-1}$ and $H_{s,P}=6.01 \text{ WK}^{-1}$. The water-return prediction was already excellent in both models; the principal gain from the enthalpy formulation occurred in the surface response (Table 1, Figure 2a).

Table 1

Equal-complexity charging-period comparison of the sensible-only and enthalpy models at

Metric	M1 sensible-only	M2 enthalpy
RMSE(T_3), °C	0.207	0.214
$R^2(T_3)$	0.99875	0.99867
RMSE(T_5), °C	0.516	0.394
$R^2(T_5)$	0.98788	0.99293
Joint RSS, K^2	8.348	5.429
AIC _c	-94.34	-117.57
BIC	-88.85	-112.08

The nominal differences were $\Delta AIC_c = \Delta BIC = 23.23$ in favour of M2; they are identical because the penalty terms cancel at equal k . The improvement therefore arises from the enthalpy representation itself, not from additional free coefficients. The result supports an enthalpy contribution during charging but does not quantify how much of the nominal RT52 latent capacity participates.

Robustness to branch-flow uncertainty: Because the common-line flowmeter does not identify the PCM-branch flow, the comparison was repeated over $0.40 \leq f \leq 0.60$ (Table 2, Fig. 2b). M2 remained preferred throughout: ΔAIC_c decreased from 33.49 at $f=0.40$ to 8.38 at $f=0.60$ and remained positive in every case.

Table 2

Sensitivity of the charging-period model preference to the unmeasured branch-flow split.

f	PCM-branch flow, kg s^{-1}	ΔAIC_c
0.40	0.0156	33.49
0.45	0.0143	27.88
0.50	0.0130	23.23
0.55	0.0117	18.00
0.60	0.0104	8.38

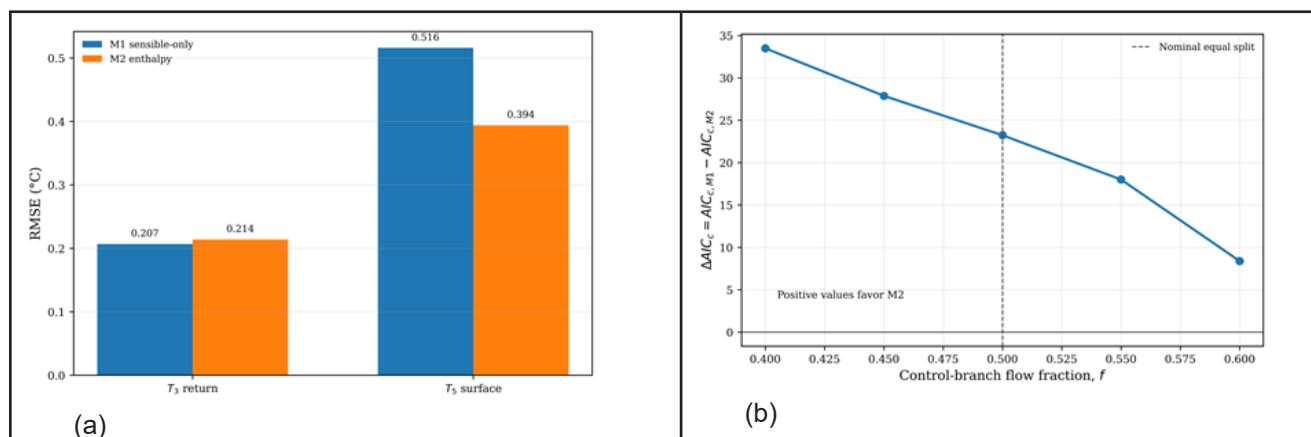


Figure 2. (a) Charging-period RMSE of the return-water and surface outputs; the enthalpy model mainly improves the surface response. (b) Flow-split robustness of the charging-period preference; positive values favour M2

PCM mass and finite coupling are not identified: Allowing the PCM inventory to vary produced a monotonic improvement in fit as the assumed mass approached the geometry-based upper bound: RSS=7.73, 5.90, 5.51 and 5.43 K^2 at 0.50, 3.09, 4.65 and 5.17 kg. Because the profile minimum lies on the imposed bound rather

than in the interior of the admissible interval, the data do not identify PCM mass independently of the other storage terms.

The finite-coupling M3 fit ($k=5$) drove K_{cp} to approximately $5.9 \times 10^2 \text{ WK}^{-1}$ and α_L to its upper bound. The implied equilibration time, $\tau^{cp} \approx 3.5 \text{ min}$, is much shorter than the 15 min sampling interval, so the experiment does not temporally resolve the internal PCM–concrete lag. M3 also failed the information-criterion test against M2: RSS was 5.509 versus 5.429 K^2 , and AIC_c worsened from -117.57 to -112.01. Within M3, removing latent storage at equal complexity increased the charging RSS from 5.509 to 7.259 K^2 , which again indicates that a latent term is supported while the finite-coupling parameters are not (Figure 3a, 3b)

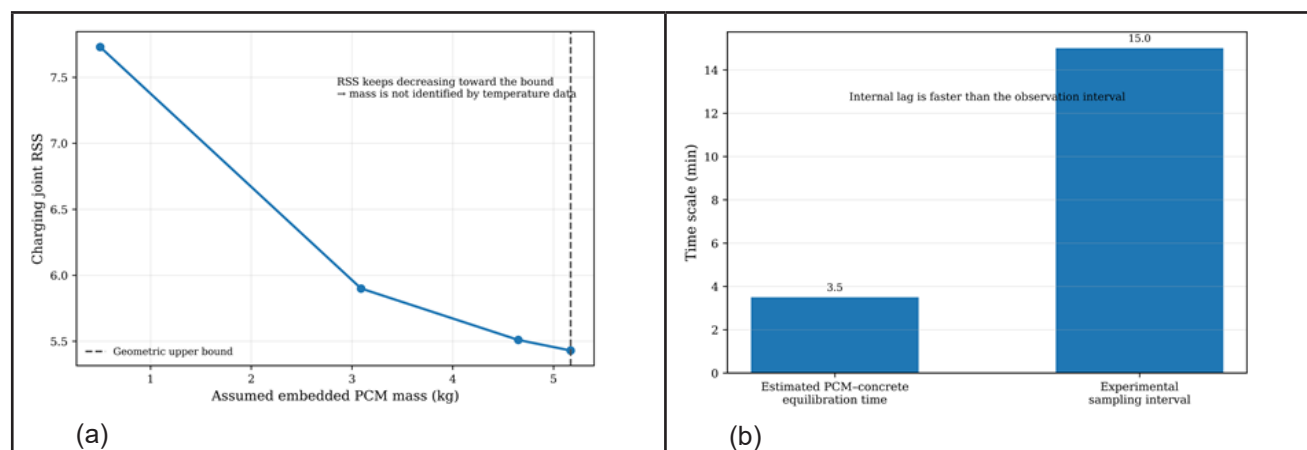


Figure 3. (a) Conditional PCM-mass profile; the continuing decrease of RSS toward the geometric bound indicates non-identifiability of the PCM inventory. (b) Fitted internal equilibration time compared with the observation interval

The return-water residuals passed the whiteness test at the 5% level (Ljung–Box $p \approx 0.075$ for M1 and 0.144 for M2), but the surface residuals remained strongly serially correlated ($p \approx 6.9 \times 10^{-9}$ and 3.4×10^{-7}). The enthalpy model therefore improves T_5 without exhausting the temporal structure of the surface response, which warns against treating the fitted transfer coefficients as material properties.

Full-cycle stress test and practical non-identifiability: The full 10:25–06:00 record was used as a stress test under continuous circulation (Table 3, Fig. 4). With unconstrained nuisance parameters, M1 ranked best and the fitted latent participation in M3 approached zero. When hidden initial temperatures, surface losses and effective-boundary behaviour were restricted to physically narrower ranges, M2 ranked best and the fitted α_L moved to approximately 0.91. Under the unconstrained treatment, the full-cycle RMSE of T_4 was about 0.401 °C for all models, and that of T_5 was 0.272, 0.288 and 0.270 °C for M1, M2 and M3. Similar bulk fit quality is thus compatible with very different internal parameter estimates, so α_L cannot be interpreted as a uniquely measured quantity (Table 3).

Table 3
Full-cycle model-ranking stress test

Full-cycle treatment	M1 AIC _c	M2 AIC _c	M3 AIC _c	M3 α_L
Unconstrained nuisance parameters	-318.86	-312.94	-315.29	≈ 0
Physically bounded stress test	-275.75	-279.16	-273.40	≈ 0.91

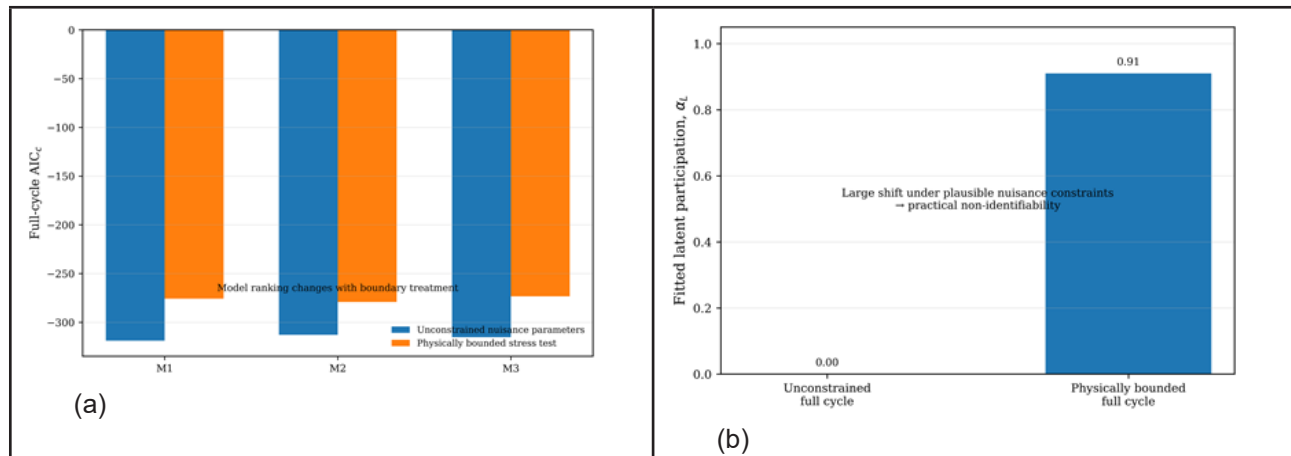


Figure 4. (a) Full-cycle ranking before and after physically bounding the nuisance parameters; the preferred model changes. (b) Fitted latent-participation factor under the two full-cycle treatments

Identifiability audit: The combined evidence supports an asymmetric conclusion. The charging data discriminate between sensible-only and enthalpy representations, but they do not uniquely recover m_{PCM} , K_{CP} or α_L . The effective parameters NTU_P , $K_{CS,P}$ and $H_{S,P}$ can be used as reduced-order predictive coefficients within a declared calibration setting, but not as unique intrinsic properties of the floor assembly (Figure 5).

Identifiability decision matrix				
NTU_P	Usable	Usable	Usable	Conditional
$K_{CS,P}$	Usable	Conditional	Conditional	Not ID
$H_{S,P}$	Usable	Conditional	Conditional	Not ID
m_{PCM}	Not ID	Not ID	Not ID	Not ID
K_{CP}	Not ID	Not ID	Not ID	Not ID
α_L	Conditional	Conditional	Not ID	Not ID
	Charging fit	Flow-split robustness	Finite-coupling test	Full-cycle stress test

Figure 5. Identifiability decision matrix for the principal reduced-order and PCM-specific parameters.

CONCLUSION AND RECOMMENDATIONS

1. Under the parallel-flow topology, the local-equilibrium enthalpy model is strongly preferred to an equal-complexity sensible-only model during charging ($\Delta AIC_c = \Delta BIC = 23.23$ at $f=0.50$).
2. The preference remains positive over $0.40 \leq f \leq 0.60$, with ΔAIC_c from 33.49 to 8.38; the main improvement occurs in the PCM-panel surface temperature.
3. PCM mass is not identifiable, because the conditional RSS profile keeps improving toward the geometry-based upper bound.
4. Finite PCM–concrete conductance is not temporally resolved: $\tau_{CP} \approx 3.5$ min is shorter than the 15 min sampling interval, and AIC_c penalizes the added coupling parameters.
5. Full-cycle latent participation is practically non-identifiable: plausible nuisance constraints move α_L from near zero to approximately 0.91 while RMSE stays low.
6. The defensible model for charging analysis is the local-equilibrium enthalpy formulation; latent participation, K_{CP} and fitted PCM mass should not be reported as measured material quantities.

Table 4
Principal symbols

Symbol	Definition	Unit	Symbol	Definition	Unit
C	Lumped heat capacity	JK^{-1}	L	Latent heat	J kg^{-1}
c_p	Specific heat capacity	$\text{J kg}^{-1} \text{K}^{-1}$	m_{PCM}	PCM mass	kg
f	Control-branch flow fraction	–	$\dot{m}$	Mass flow rate	kg s^{-1}
f_l	Liquid fraction	–	NTU_p	PCM-branch number of transfer units	–
h	Specific enthalpy	J kg^{-1}	T_1, T_3, T_5	Inlet, PCM return, PCM surface temperatures	$^{\circ}\text{C}$
$H_{s,p}$	Effective surface heat-loss coefficient	WK^{-1}	T_{eq}	Effective environmental boundary temperature	$^{\circ}\text{C}$
K_{cp}	PCM–concrete coupling conductance	WK^{-1}	α_L	Effective latent-participation factor	–
$K_{cs,p}$	Core-to-surface conductance	WK^{-1}	T_{cp}	PCM–concrete equilibration time	s

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