

MUHANDISLIK

& IQTISODIYOT

ijtimoiy-iqtisodiy, innovatsion texnik,
fan va ta'limga oid ilmiy-amaliy jurnal

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- 05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
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- 08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
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Ma'lumot uchun, OAK
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CONTINUOUS-CIRCULATION CALORIMETRY AND FLOW-SPLIT UNCERTAINTY IN A TWO-BRANCH SOLAR RADIANT-FLOOR SYSTEM WITH MACROENCAPSULATED RT52

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Abstract. A solar-driven hydronic radiant-floor experiment was re-analysed using a hydraulically explicit calorimetric framework in which the measured mass flow rate m belongs to the common line upstream of a split into conventional and PCM-integrated floor branches. The branch flow fraction f_{PCM} was therefore treated as an unmeasured quantity, with $f_{PCM} = 0.50$ used only as the nominal case and $f_{PCM} [0.30, 0.70]$ retained for sensitivity analysis. Because circulation continued overnight, the late-afternoon transition was identified as a genuine reversal of water-to-floor heat transfer rather than a pump shutdown. Under $f_{PCM} = 0.50$, the control, system and PCM heat-flow reversals occurred at approximately 17:14, 17:15 and 17:16, respectively. The analysis provides a reproducible framework for separating exact hydraulic closure, conditional branch energetics and genuinely measured quantities in PCM-enhanced solar radiant-floor experiments.

Keywords: hydronic radiant floor; calorimetry; parallel branches; flow-split uncertainty; heat-flow reversal; continuous circulation; PCM; solar heating.

Annotatsiya. Quyosh energiyasida ishlaydigan gidravlik nurlanuvchi pol tajribasi gidravlik jihatdan aniq kalorimetrik karkas yordamida qayta tahlil qilindi. Unda o'lgangan massaviy sarf m oddiy va FOT (fazaviy o'tuvchi material) integratsiya qilingan pol tarmoqlariga bo'linishdan yuqoridagi umumiy quvurga tegishli. Shu sababli, tarmoqdagi oqim ulushi f_{PCM} o'lchanmagan kattalik sifatida qaraldi; $f_{PCM} = 0.50$ faqat nominal holat sifatida va $f_{PCM} = [0.30, 0.70]$ sezgirlik tahlili uchun saqlab qolindi. Sirkulyatsiya tunda ham davom etgani sababli, tushdan keyingi kechki o'tish nasosning o'chishi emas, balki suvdan polga issiqlik uzatishning haqiqiy teskari yo'nalishda o'zgarishi sifatida belgilandi. $f_{PCM} = 0.50$ bo'lganda, nazorat, tizim va FOT issiqlik oqimining teskari o'zgarishi mos ravishda taxminan 17:14, 17:15 va 17:16 da sodir bo'ldi. Shunday qilib, faqat umumiy quvurdagi sarf o'lgagich mavjud bo'lganda, tizim darajasidagi kalorimetriya tarmoqqa xos yashirin energiya xulosasiga qaraganda ancha barqarordir. Tahlil FOT bilan kuchaytirilgan quyosh nurlanuvchi pol tajribalarida aniq gidravlik yopilish, shartli tarmoq energetikasi va haqiqatan ham o'lgangan kattaliklarni ajratish uchun qayta hosil qilinadigan karkasni taqdim etadi.

Kalit so'zlar: gidravlik nurlanuvchi pol; kalorimetriya; parallel tarmoqlar; oqim bo'linishi noaniqligi; issiqlik oqimining teskari o'zgarishi; uzluksiz sirkulyatsiya; FOT; quyosh bilan isitish.

Аннотация. Эксперимент с гидравлическим солнечным теплым полом был повторно проанализирован с использованием гидравлически явной калориметрической структуры, в которой измеренный массовый расход m относится к общей линии выше по потоку от разделения на обычную ветвь и ветвь с фазопереходным материалом (ФПМ). Таким образом, доля расхода в ветви f_{PCM} рассматривалась как неизмеряемая величина; $f_{PCM} = 0.50$ использовалась только в качестве номинального случая, а $f_{PCM} [0.30, 0.70]$ сохранялась для анализа чувствительности. Поскольку циркуляция продолжалась в течение ночи, переход в позднее время суток был идентифицирован как истинное изменение направления теплопередачи от воды к полу, а не как остановка насоса. При $f_{PCM} = 0.50$ изменение направления теплового потока в контрольной ветви, системе и ветви с ФПМ произошло приблизительно в 17:14, 17:15 и 17:16 соответственно. Таким образом, калориметрия на уровне системы значительно более надежна, чем определение скрытой энергии для конкретной ветви, когда доступен только расходомер на общей линии. Анализ обеспечивает воспроизводимую структуру для разделения точного гидравлического замыкания, условной энергетики ветвей и действительно измеренных величин в экспериментах

с солнечным теплым полом, усиленным ФПМ.

Ключевые слова: гидравлический теплый пол; калориметрия; параллельные ветви; неопределенность разделения потока; изменение направления теплового потока; непрерывная циркуляция; ФПМ; солнечное отопление.

INTRODUCTION

Hydronic radiant floors are well suited to renewable and low-temperature heat sources because their large active surface can operate with relatively small temperature differences [1–9]. When phase change materials (PCMs) are integrated into the slab, water-side calorimetry provides a direct measure of charging and recovery. However, branch calorimetry relies heavily on the accuracy of the underlying hydraulic information. In parallel floor circuits, a single common-line flowmeter does not determine the individual branch flows; treating the common flow as if it were present in each branch double-counts the mass flow and distorts the inferred storage energy [1–8,10–14].

This issue is important in solar-driven experiments because inlet temperature and available heat vary continuously with solar input, while the floor itself can subsequently become the heat source for the circulating fluid [15–25]. A negative water-side temperature difference after sunset is physically meaningful if the pump remains operational, requiring a distinct interpretation from passive cooling after pump shutdown. Differentiating between measured, reconstructed, and assumption-dependent quantities is essential for uncertainty-aware PCM validation [10–14,18–20].

LITERATURE REVIEW

Rebelo et al. experimentally evaluated a radiant-floor system incorporating macroencapsulated phase change materials and demonstrated the potential of PCM integration to improve thermal storage and regulate heating and cooling performance [1]. Earlier, Mazo et al. developed a numerical model of a PCM-integrated radiant-floor system coupled with a heat pump, showing that PCM behavior and operating conditions significantly influence heat-storage and release processes [2]. In a subsequent experimental study, Rebelo et al. examined the thermal performance and energy efficiency of PCM-enhanced radiant floors, providing further evidence that latent heat storage can modify the temporal distribution of heat transfer within hydronic floor systems [3].

Jin et al. combined experimental and numerical approaches to investigate thermal energy storage in a radiant-floor heating system using a novel phase change material, highlighting the importance of PCM thermophysical characteristics and heat-transfer conditions for effective energy storage [4]. Chen et al. similarly investigated a radiant-floor heating system integrated with macroencapsulated PCM and demonstrated how the incorporation of discrete PCM units affects thermal response and heat-storage behavior [5]. Collectively, these studies establish a strong basis for PCM-enhanced radiant-floor design; however, the interpretation of systems with continuous circulation and multiple hydraulic branches also requires explicit consideration of branch-flow allocation and its associated uncertainty when calorimetric energy quantities are derived from measurements.

RESEARCH METHODOLOGY

Experimental hydraulic configuration.

Parallel branch topology: Water heated by the solar receiver passes through a common line containing the flowmeter and then divides into the conventional (N) and PCM-integrated (P) floor branches; the branch returns recombine before the fluid returns to the receiver (Fig. 1). The measured total mass flow is $\dot{m}_{\text{tot}}$, so the branch flows satisfy

	$\dot{m}_N + \dot{m}_P = \dot{m}_{\text{tot}}, \quad \dot{m}_N = f \dot{m}_{\text{tot}}, \quad \dot{m}_P = (1 - f) \dot{m}_{\text{tot}}$	(1)
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where f is the unknown fraction of the total flow through the conventional branch. The nominal equal split, $f=0.50$, gives 0.013 kg s^{-1} per branch; the interval $0.40 \leq f \leq 0.60$ is used to expose the impact of plausible hydraulic imbalance (Figure 1).

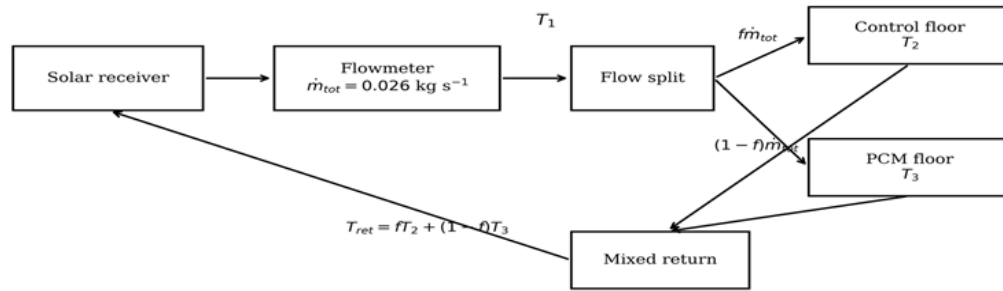


Fig. 1. Hydraulic topology used for the calorimetric analysis. The flowmeter measures the common-line total flow before the split; branch flows are therefore conditional on the split fraction

2.2. Measured and reconstructed temperatures: : T_1 is the common supply temperature upstream of the split, while T_2 and T_3 are the conventional and PCM branch return temperatures. Because the mixed return was not independently instrumented, it is reconstructed from the branch temperatures and the assumed split:

$$T_{\text{ret}} = f T_2 + (1 - f) T_3 \quad (2)$$

This reconstruction is an algebraic identity rather than an independent validation measurement; mass and energy closure based on T_{ret} cannot identify f . This observability limitation is retained explicitly throughout the analysis. The fixed quantities and the sign convention are listed in Table 1.

Table 1
Fixed quantities and sign convention

Quantity	Value	Role
Total measured mass flow,	0.026 kg s^{-1}	Measured in the common line
Nominal control-branch fraction,	0.50	Central scenario only
Sensitivity range of	0.40–0.60	Hydraulic uncertainty
Water specific heat,	$4180 \text{ J kg}^{-1} \text{ K}^{-1}$	Calorimetric conversion
Pump after reversal	ON	Continuous-circulation recovery
Positive heat-rate sign	water $\rightarrow$ floor	Charging
Negative heat-rate sign	floor $\rightarrow$ water	Circulating recovery

Calorimetric formulation.

Branch and system heat rates: With the sign convention of Table 1, the branch and system heat-transfer rates (in) are

$$\dot{Q}_N = f \dot{m}_{\text{tot}} c_p (T_1 - T_2), \quad \dot{Q}_P = (1 - f) \dot{m}_{\text{tot}} c_p (T_1 - T_3) \quad (3)$$

$$\dot{Q}_{\text{tot}} = \dot{m}_{\text{tot}} c_p (T_1 - T_{\text{ret}}) = \dot{Q}_N + \dot{Q}_P, \quad \Delta \dot{Q}_{P-N} = \dot{Q}_P - \dot{Q}_N \quad (4)$$

The closure in Eq. (4) is exact for any assumed because the same split is used in the branch and mixed-return definitions; it is not independent evidence that the assumed split is correct.

Heat-flow reversal and energy integrals: The system and branch reversals are defined by the instants at which the corresponding net water-to-floor heat rate becomes zero; linear interpolation between adjacent samples is used to locate the zero crossings:

$$\dot{Q}_{\text{tot}}(t_{\text{rev}}) = 0, \quad \dot{Q}_i(t_{\text{rev},i}) = 0, \quad i \in \{N, P\} \quad (5)$$

Cumulative signed energy, positive charging energy and signed recovery energy (in) are

$$E_i(t) = \int_{t_0}^t \dot{Q}_i(\tau) d\tau, \quad E_{i,\text{ch}} = \int_{t_0}^{t_{\text{rev},i}} \max[\dot{Q}_i(t), 0] dt \quad (6)$$

$$E_{\text{tot},\text{ch}} = \int_{t_0}^{t_{\text{rev}}} \max[\dot{Q}_{\text{tot}}(t), 0] dt, \quad E_{i,\text{rec}} = \int_{t_{\text{rev}}}^{t_f} \dot{Q}_i(t) dt \quad (7)$$

where t_0 and t_f are the start and end of the record. The recovery integral is intentionally signed: negative values denote net heat transfer from the floor back to the circulating water, which avoids describing the night-time interval as passive discharge.

Because the flow fraction is constant in time, the branch charging energies separate into the flow fraction and a unit-fraction integral A_i :

$$\frac{\partial T_{ret}}{\partial f} = T_2 - T_3, \quad \frac{\partial \dot{Q}_{tot}}{\partial f} = -\dot{m}_{tot} c_p (T_2 - T_3) \quad (8)$$

Because the flow fraction is constant in time, the branch charging energies separate into the flow fraction and a unit-fraction integral :

$$\begin{aligned} A_N &= \dot{m}_{tot} c_p \int_{t_0}^{t_{rev,N}} \max [T_1 - T_2, 0] dt, & A_P \\ &= \dot{m}_{tot} c_p \int_{t_0}^{t_{rev,P}} \max [T_1 - T_3, 0] dt \end{aligned} \quad (9)$$

$$E_{N,ch} = f A_N, \quad E_{P,ch} = (1 - f) A_P, \quad f_{crit} = \frac{A_P}{A_N + A_P} \quad (10)$$

f_{crit} is the split for which both branch charging energies are equal. The spread of system charging energy over the assumed split interval is summarized by

$$R_E = \frac{E_{max} - E_{min}}{E_{nom}} \times 100\% \quad (11)$$

ANALYSIS AND RESULTS

Mixed-return reconstruction and reversal: The reconstructed mixed return follows the common inlet during charging and becomes warmer than the inlet after the solar source weakens. The nominal system reversal occurs at 17:15:14, between the 17:11 and 17:26 measurements; the control and PCM branches reverse at 17:14:09 and 17:16:23. The driving temperature difference changes sign without any interruption of pump operation (Figure 2a, 2b).

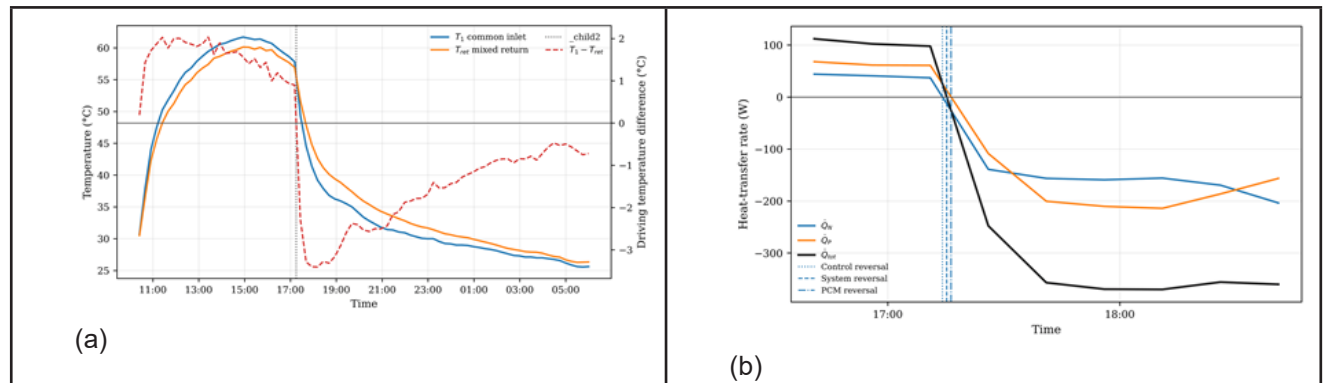


Figure 2(a) Common inlet temperature, reconstructed mixed return and system driving temperature difference; the vertical marker denotes the system-level heat-flow reversal. (b) Expanded view of the transition from charging to circulating recovery, showing the control, system and PCM zero crossings

Full-cycle heat rates and nominal energies: Before reversal, all three heat rates are positive and the water delivers heat to the slabs; after reversal they become negative and the floors return heat to the circulating fluid. At 17:26, the nominal total heat rate is approximately -248 W; by 18:11 its magnitude has increased to about 370 W ($\dot{Q}_{tot} \approx -370$ W), after which the recovery magnitude decays. The cumulative signed energy shows that circulating recovery continues for many hours after solar charging (Figure 3a, 3b).

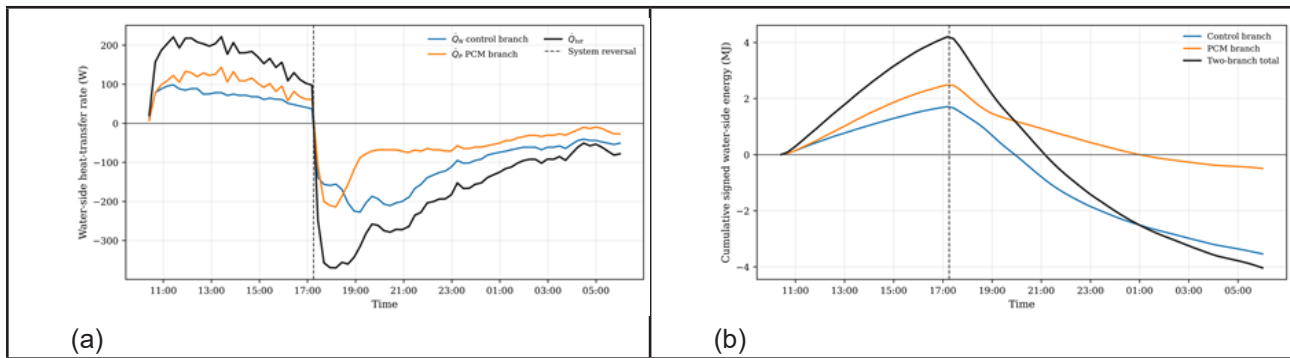


Figure 3. (a) Nominal branch and system water-side heat-transfer rates over the 3–4 July cycle; negative values denote floor-to-water recovery under continuous pumping. (b) Cumulative signed water-side energy

For $f=0.50$ the branch mass flows are 0.013 kg s^{-1} , and the nominal integrated energies are summarized in Table 2. The recovery integrals are larger in magnitude than the charging integrals because they include energy stored in the floor assemblies before the start of the measurement window and heat exchanges not represented by the solar input alone; they are therefore cycle-window balances, not storage efficiencies (Table 2).

Table 2
Nominal () integrated water-side energies and reversal times.

Metric	Control	PCM	System
Positive charging energy,			
Reversal time	17:14:09	17:16:23	17:15:14
Signed recovery energy to 06:00,			

The total system charging energy is much less sensitive to f than the individual branch estimates. Across $0.40 \leq f \leq 0.60$, the system charging energy varies from 4.369 to 4.055 MJ, i.e. $R_E \approx 7.5\%$, or about $\pm 3.7\%$ around the nominal 4.212 MJ. In contrast, the branch allocation changes strongly because the control and PCM branch energies scale directly with f and $1-f$. From the nominal values, $A_N \approx 3.429 \text{ MJ}$ and $A_P \approx 4.998 \text{ MJ}$.

Under the nominal equal split, the PCM branch receives 0.785 MJ more positive charging energy than the control branch. This difference is not invariant: Eq. (10) gives $f_{\text{crit}} = 0.593$. Below this value the calculated PCM branch charging energy exceeds that of the control; above it, the sign reverses. The branch-energy difference therefore cannot be used as a primary latent-heat metric without independent branch-flow measurements (Figure 4a, 4b).

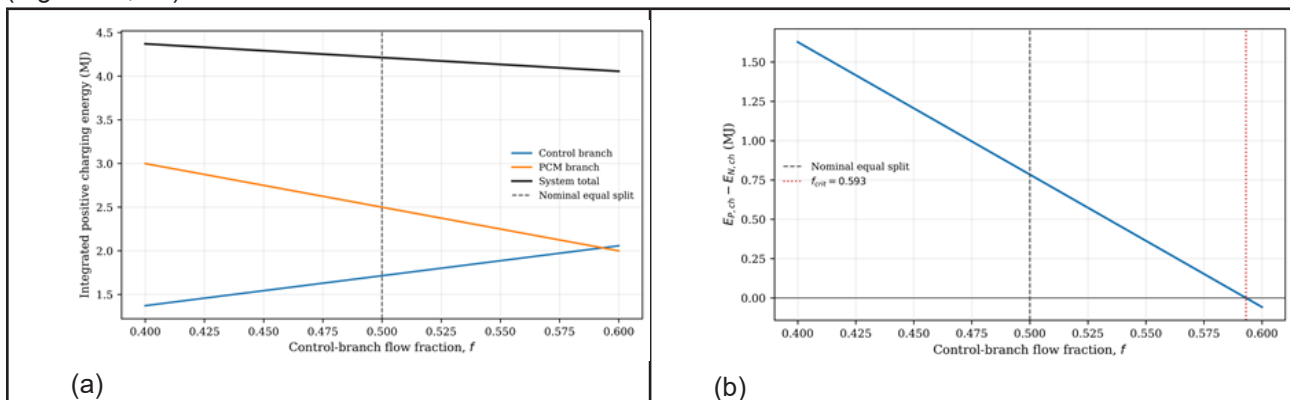


Fig. 4. (a) Sensitivity of integrated positive charging energies to the assumed control-branch flow fraction; the system total is much more robust than the branch allocations. (b) Difference between PCM and control positive charging energies as a function of f ; the sign changes at $f_{\text{crit}} = 0.593$.

Recovery-energy sensitivity, mixed-return envelope and cross-day timing: The same hydraulic uncertainty affects the distribution of night-time recovery energy: the total recovery remains a system quantity, whereas the branch allocation varies with f . The reconstructed mixed return is less sensitive because T_2 and T_3 are close during much of the cycle; the width of the return-temperature envelope reflects the actual paired return-temperature difference rather than an arbitrary uncertainty inflation. The reversal concept is not unique to the

3–4 July record: the same processing identified system-level reversals near 15:03 on 11 June and 17:14 on 13 June. Reversal time is therefore an operating-state marker that depends on solar forcing and thermal history, not a material constant (Figure 5a, 5b).

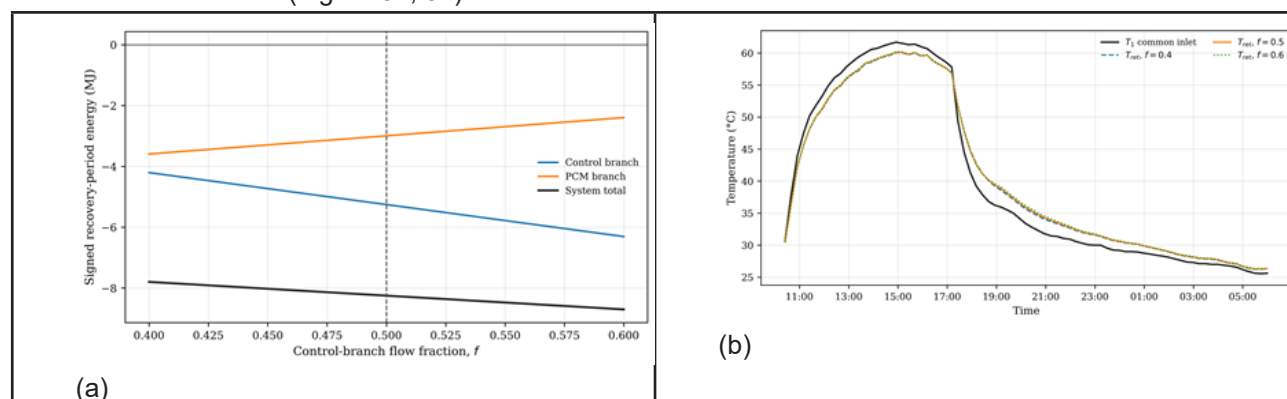


Fig. 5. (a) Sensitivity of signed recovery-period energies to the branch-flow fraction. (b) Reconstructed mixed-return temperature for, and compared with the common inlet temperature.

CONCLUSION AND RECOMMENDATIONS

A hydraulically explicit calorimetric framework was developed for a solar-driven two-branch radiant-floor experiment with continuous overnight circulation. The measured 0.026 kg s^{-1} flow belongs to the common line, so individual branch flows must be represented through an unknown split fraction f . Under the nominal equal split, the branch flows are 0.013 kg s^{-1} , the system reverses from water-to-floor charging to floor-to-water recovery at approximately 17:15, and the positive charging energies are 1.714 MJ (control), 2.499 MJ (PCM) and 4.212 MJ (system). The system total changes only from 4.369 to 4.055 MJ across $f=0.40$ – 0.60 , whereas the branch allocations vary strongly. Equal branch charging energies occur at $f_{\text{crit}} \approx 0.593$, showing that the nominal +0.785 MJ PCM–control difference is conditional on the hydraulic split. Continuous circulation also produces large negative recovery-period integrals, confirming that the night-time regime is circulating recovery rather than passive cooling. The robust conclusion is system-level: total calorimetry and heat-flow reversal can be quantified with useful stability, whereas branch-specific latent-energy inference is not justified without branch-flow measurements.

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