

COMMON-LINE CALORIMETRY OF A TWO-BRANCH SOLAR RADIANT FLOOR: WHY SYSTEM ENERGY IS ROBUST AND BRANCH ENERGY IS NOT

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Abstract. In many laboratory radiant-floor rigs a single flowmeter serves several parallel floor circuits. We show, for a solar-driven rig with a conventional and a PCM-integrated branch, how this hydraulic arrangement limits water-side calorimetry. Treating the unmeasured branch split f as a parameter, the system charging energy changes only between 4.369 and 4.055 MJ for $0.40 \leq f \leq 0.60$, whereas the PCM-minus-control difference changes sign at $f_{\text{crit}} = 0.593$. Continuous overnight pumping turns the night into a circulating-recovery regime with -8.249 MJ returned to the water by 06:00. System-level energy is therefore a reliable result; branch-level energy is not, unless each branch is metered.

Keywords: hydronic calorimetry; parallel branches; flow split; heat-flow reversal; radiant floor; PCM

Introduction. Water-side calorimetry, $\dot{Q} = \dot{m}c_p\Delta T$, is the standard way of measuring how much heat a hydronic floor absorbs or releases [1–3]. When

a PCM-integrated floor is tested against a reference floor, it is tempting to compare the two branch energies directly and attribute the difference to latent storage [1,2,4]. This comparison silently assumes that the mass flow through each branch is known. In practice, many rigs have one flowmeter in the common supply line, and if the common-line flow is used for each branch, the total flow is double-counted and the branch energies are biased [3,5].

A second issue arises in solar-driven rigs where the pump keeps running after sunset. The floor then becomes a heat source for the circulating water, and a negative water-side temperature difference describes real heat recovery rather than passive cooling [6,7]. This thesis formulates a hydraulically consistent energy balance for such a rig and identifies which energy results survive the lack of branch flowmeters.

Hydraulic model and energy balance. The solar receiver heats water that passes a single flowmeter ($\dot{m}_{\text{tot}} = 0.026 \text{ kg s}^{-1}$) and then splits into a conventional branch (N) and a PCM-integrated branch (P). With the unmeasured control-branch fraction f ,

$$\dot{m}_N = f \dot{m}_{\text{tot}}, \quad \dot{m}_P = (1 - f) \dot{m}_{\text{tot}}, \quad T_{\text{ret}} = f T_2 + (1 - f) T_3 \quad (1)$$

where T_1 is the common supply and T_2, T_3 are the branch returns. The mixed return T_{ret} was not measured and is reconstructed. The heat rates (positive for water $\rightarrow$ floor) follow as

$$\begin{aligned} \dot{Q}_N &= f \dot{m}_{\text{tot}} c_p (T_1 - T_2), & \dot{Q}_P &= (1 - f) \dot{m}_{\text{tot}} c_p (T_1 - T_3), & \dot{Q}_{\text{tot}} \\ &= \dot{m}_{\text{tot}} c_p (T_1 - T_{\text{ret}}) \end{aligned} \quad (2)$$

with $c_p = 4180 \text{ J kg}^{-1} \text{ K}^{-1}$. Note that $\dot{Q}_{\text{tot}} = \dot{Q}_N + \dot{Q}_P$ holds identically for any f : the closure of the balance is algebraic and cannot be used to verify the split. The reversal time t_{rev} is the zero crossing of $\dot{Q}_{\text{tot}}$, and the charging and recovery energies are

$$E_{i,\text{ch}} = \int_{t_0}^{t_{\text{rev},i}} \max[\dot{Q}_i, 0] dt, \quad E_{i,\text{rec}} = \int_{t_{\text{rev}}}^{t_f} \dot{Q}_i dt \quad (3)$$

Because f is constant in time, the branch charging energies factorize into the flow fraction and unit-fraction integrals A_N and A_P , which leads to a closed-form critical split and a simple robustness index for the system total:

$$\begin{aligned} E_{N,\text{ch}} &= f A_N, & E_{P,\text{ch}} &= (1 - f) A_P, & f_{\text{crit}} &= \frac{A_P}{A_N + A_P}, & R_E &= \\ &= \frac{E_{\text{max}} - E_{\text{min}}}{E_{\text{nom}}} \end{aligned} \quad (4)$$

The sensitivity of the system heat rate to the split, $\partial \dot{Q}_{\text{tot}} / \partial f = -\dot{m}_{\text{tot}} c_p (T_2 - T_3)$, is proportional only to the difference between the two return temperatures. Whenever the two returns are close, the system balance is insensitive to f , even though each branch balance scales directly with f or $1 - f$.

Results and discussion.

Reversal under continuous circulation. On 3–4 July the net heat flow reversed at 17:15 (system), with the control and PCM branches reversing about one minute earlier and later (17:14 and 17:16). The pump was not stopped. At 17:26 the system heat rate was already about -248 W, and by 18:11 it reached about -370 W, meaning that the slabs were returning heat to the loop.

Nominal energy budget. For the equal split ($f = 0.50$, i.e. 0.013 kg s^{-1} per branch), the charging energies are 1.714 MJ (control), 2.499 MJ (PCM) and 4.212 MJ (system); the signed recovery energies to 06:00 are -5.255 , -2.994 and -8.249 MJ (Fig. 1). The recovery magnitudes exceed the charging energies because they also include heat stored in the slabs before the logging window began and exchanges with the surroundings; they are balances over the observation window, not storage efficiencies.

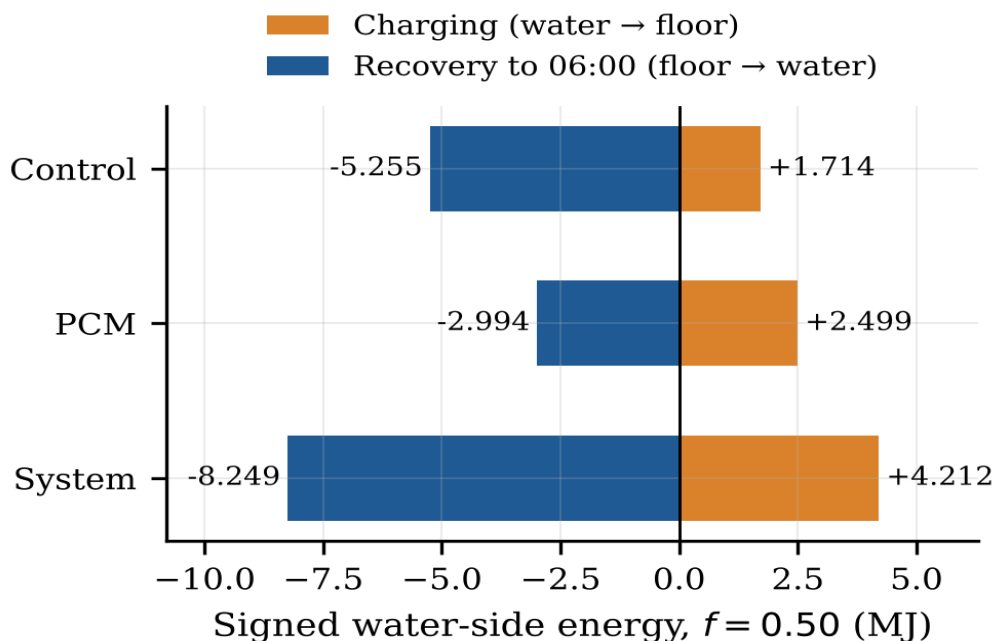


Fig. 1. Nominal ($f = 0.50$) signed energy budget of the two branches and the system: charging (positive) and circulating recovery to 06:00 (negative).

Split sensitivity. From the nominal values, $A_N \approx 3.429$ MJ and $A_P \approx 4.998$ MJ. Figure 2 shows how the same total is divided between the branches as f varies. The total decreases only from 4.37 to 4.06 MJ ($R_E \approx 7.5\%$, about $\pm 3.7\%$ around the nominal value), while the control share grows from 31% to 51%. The PCM branch energy alone changes by about 1.0 MJ, i.e. 40% of its nominal value.

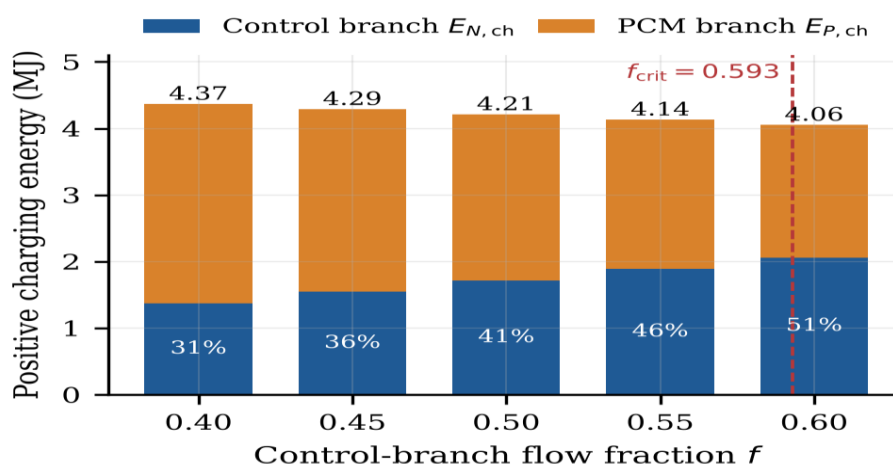


Fig. 2. Division of the positive charging energy between the branches for five assumed flow splits. Numbers above the bars give the system total; percentages give the control-branch share. The dashed line marks f_{crit} .

The stability of the total follows directly from the factorized form: $E_{\text{tot,ch}} \approx A_P - f(A_P - A_N)$, so its slope with respect to f is only $-(A_P - A_N) \approx -1.57$ MJ per unit of f , whereas each branch energy changes with a slope of A_N or $-A_P$, i.e. 3.4 to 5.0 MJ per unit of f . Physically, the two branch returns differ on average by only about 0.6 °C during charging, so redistributing the flow between the branches hardly changes the mixed return.

Critical split. At $f = 0.50$ the PCM branch appears to absorb 0.785 MJ more than the control. However, with $f_{\text{crit}} = 0.593$ the difference vanishes, and for $f > 0.593$ it changes sign. A balancing error of less than ten percentage points, which is entirely plausible for two hand-balanced floor circuits, is therefore enough to reverse the conclusion that the PCM branch stores more energy. The branch difference cannot be used as a latent-heat metric with this instrumentation [5,8].

Table 1. Information levels of the calorimetric quantities.

Table-1

Quantity	Status	Dependence on f
$T_1, T_2, T_3, \dot{m}_{\text{tot}}$	measured	none
$T_{\text{ret}}, \dot{Q}_{\text{tot}}, E_{\text{tot,ch}}$	reconstructed	weak ($R_E \approx 7.5\%$)
$\dot{Q}_N, \dot{Q}_P, E_{N,\text{ch}}, E_{P,\text{ch}}$	conditional	proportional to f or $1 - f$
$E_{P,\text{ch}} - E_{N,\text{ch}}$	conditional	sign changes at f_{crit}

Information levels. Table 1 summarizes what the instrumentation can and cannot deliver. Measured quantities are independent of f ; the reconstructed system quantities depend on it only weakly, because the two branch returns enter as a weighted mean; the branch quantities inherit the full uncertainty of the split. The reversal time is also an operating-state marker rather than a material property: on 11 June and 13 June the system reversal occurred near 15:03 and 17:14, following the different solar histories of those days.

Recommendations. For future two-branch tests we recommend (i) a flowmeter in each branch, or calibrated balancing valves with periodic verification of branch flow; (ii) an independent sensor on the mixed return, which turns the algebraic closure into a genuine check; (iii) synchronized ambient and solar measurements; and (iv) faster logging around the evening reversal, so that zero crossings are not interpolated over a 15 min gap [3,8]. A pump-off night test would require a different model, because the present equations assume continuous circulation.

Conclusions.

With a single common-line flowmeter, the system charging energy of a two-branch solar radiant floor can be determined robustly (4.212 MJ nominal, within about $\pm 4\%$ for $0.40 \leq f \leq 0.60$), together with the time of heat-flow reversal under continuous pumping. Branch energies, and especially their difference, are conditional on the unmeasured split: the nominal +0.785 MJ PCM excess disappears at $f_{\text{crit}} = 0.593$. Claims about latent storage based on branch calorimetry therefore require branch-level flow measurement.

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