Effectiveness of a vertical passive solar panel containing $CaCl_2.6H_2O$ [for room heating by latent heat exchange]

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Abstract

A small passive vertical wall thermal panel comprising tubes containing $CaCl_2.6H_2O$ (of melting temperature 29.8°C, i.e. close to ambient temperatures in Johannesburg at the time of the experiment) to transfer heat to a simulated living space ('room') on recrystallisation at night was built and tested. This chemical was chosen on account of its small volume change during phase change and for its suitability in relation to the diurnal temperature range. The chemical was contained in pipes behind glass, with natural or forced convection to distribute heating. Operation was satisfactory, with the temperature of the air discharged to the 'room' raised by up to 12°C higher than ambient, but under the test conditions employed the efficiency (conversion of incident solar energy to heat) was only in the neighbourhood of 12%.

Nomenclature

a	solar altitude angle, degree
A	panel area, m^2
A'	'no atmosphere' correction factor, values given in (3)
B'	'atmosphere' correction factor, values given in (3)
C_p	specific heat, kJ/kg K
d	declination angle, degree
F_r	empirical correction factor
h	solar hour angle, degree
I	solar intensity (normal), W/m^2
i_{if}	latent heat, kJ/kg
L	latitude, degree
n	number of storage tubes
N	number of day (Jan. 1 = 1)
q	energy rate, W
t	temperature, °C
U	overall collector heat transfer coefficient, W/m^{2}K
V	volume, m^3
z	azimuth angle, degree
α	absorptivity
η	efficiency
ρ	density, kg/m^3
τ	transmissivity

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Subscripts

amb	ambient
av	average
eff	effective
L	latent
s	sensible
surf	collector surface

Introduction

Many latent heat solar energy systems have been suggested (see e.g. [1]) involving $LiNO_3$, H_2O, $Na_2SO_4.10H_2O$, etc. Calcium chloride hexahydrate was chosen as having a phase change temperature (29.8°C) within the local diurnal temperature range of 15 to 35°C; this chemical was readily available and is non-corrosive, with only a small volumetric change at solid to liquid phase change. The following properties are also relevant:

Latent heat	170 kJ/kg
Density (solid)	1 519 kg/m^3
Specific heat (0 – 29°C)	2.17 kJ/kg K
Thermal conductivity (liquid)	0.54 W/mK
Thermal conductivity (solid)	1.01 W/mK

Theory

To provide a comparison with the actual energy absorption, insolation calculations made use of the following equations:[2; 3; 4]

Insolation intensity (normal):

$$I = \frac{A}{\exp\left(B / \sin a\right)} \tag{1}$$

Solar altitude:

$$\sin a = \sin d \sin L + \cos d \cos L \cos h \tag{2}$$

Declination:

$$d = 23.45 \sin\left(360° \times \frac{(284 + N)}{365.25}\right) \tag{3}$$

Effective reflectivity of 1 glass panel:

$$\rho_1 = \frac{\rho\left(1 + ((1-\rho)\,\tau)\right)}{(1 - \rho^2\tau^2)} \tag{4}$$

Effective transmissivity of 1 glass panel:

$$\tau_1 = \tau\left(\frac{(1-\rho)}{(1+\rho)}\right)\left(\frac{(1-\rho^2)}{(1-\rho^2\tau^2)}\right) \tag{5}$$

Effective absorptivity of 1 glass panel:

$$\alpha_1 = 1 - \rho_1 - \tau_1 \tag{6}$$

Effective reflectivity of 2 glass panels:

$$\rho_{11} = \rho_1 + \frac{(\rho_1\tau_1^2)}{(1-\rho_1^2)} \tag{7}$$

Effective transmissivity of 2 glass panels:

$$\tau_{11} = \frac{\tau_1}{(1-\rho_1^2)} \tag{8}$$

Effective absorptivity of 2 glass panels:

$$\alpha_{11} = 1 - \rho_{11} - \tau_{11} \tag{9}$$

Efficiency of collector:

$$\begin{aligned}\eta &= \frac{(q/A)}{I} \\ &= \left[\frac{(\tau\alpha)_{eff} - U(t_{surf} - t_{amb})}{I}\right] F_r\end{aligned} \tag{10}$$

where $(\tau\alpha)_{eff} = \frac{\alpha\tau_{11}}{(1-(1-\alpha)\rho_{11})}$ and F_r may be taken as 0.9.

For glass, it is assumed $\tau = 0.86$ and $\rho = 0.08$. Then, using a value for α of 0.95 (black acrylic paint), $(\alpha\tau)_{eff} = 0.522$.

The calculation of U [2] involved consideration of the number of panels used, the emissivities of the glass panels and of the collector, an assumed value of the wind velocity past the panels and the thickness and conductivity of the insulation used. A typical value so determined was 3.52 $W/m^2 K$ – which compares well with experimental values listed in [5] for double glazing (3–4 $W/m^2 K$).

Experimental set-up

As shown in Figure 1, the solar collector was combined with the heat storage medium, with – to align with a normal wall – 1 or 2 vertical glass panels of dimensions 860 mm (high) × 600 mm (wide), facing North. The depth of the chamber containing tubes and insulation panels (as measured normal to the glass panel(s)) was 270 mm. The collector could be used under conditions of natural or forced air circulation. At night the panel was insulated by a 50 mm thick polystyrene panel inserted between the tubes and the glass. Likewise, during the day, the upper and lower openings to the polystyrene insulated 'room' (of dimensions 1 220 × 60 × 860 mm = 0.63 m^3) were blocked to seal in the tubes.

The experiment was conducted at an altitude of 1 700 m (average barometric pressure: 864 mb) and a latitude of 26°S. The chemical was stored in 7 (out of 12 available) PVC pipes of 63 mm OD, each pipe containing 0.001 43 m^3 of crystalline $CaCl_2.6H_2O$; the available energy storage (see Appendix) was 2 585 + 33 Δt kJ. The temperature sensors used were of National (semi-conductor) type LM35. Seven temperatures [ambient, 'room', pipes, inside and outside of glass panel(s), and air temperature in the collector chamber (high and low positions)] were read at 30 min intervals. During the period of testing (early summer, i.e. October 24 to November 1), the maximum altitude of the sun (see Appendix) ranged between 76.73° and 79.23° (with consequent high reflection of energy away from the vertical collector); to improve the level of solar energy entering the collector, the latter was mounted on a reflector comprising a flat roof coated with aluminium paint. (Such a reflector is obviously even more necessary as the summer solstice is approached – when the solar altitude is 87.5° at local noon.)

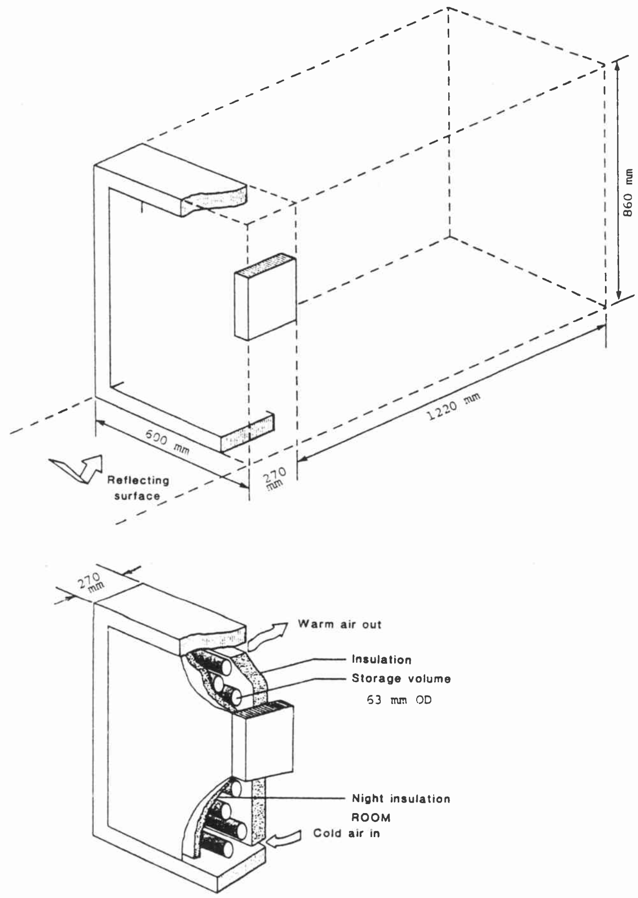

Figure 1 Experimental equipment

Results

Figure 2 shows a typical diurnal insolation pattern, using calculated values of I for a horizontal surface. (The 'triangular' shape shown is typical of a fixed flat collector – whereas a tracking collector would yield an insolation curve that is much more flat-topped for much of the day.) Table 1 summarises the results obtained; in this table η_{av} was determined by averaging the value of η at half-hourly intervals over the number of such intervals in the heating period.

Table 1 Results

N	Panels	Energy received by collector, kJ	Energy absorbed, kJ	Energy used, kJ	η_{av}	Average % energy used for heating	Convection
293: 20/1 Oct	2	6 243	945	870	0.90	12.1	Natural
294: 21/2 Oct	1	4 897	1318	751	0.70	12.1	Natural
295: 22/3 Oct	1	3 813	985	620	0.55	12.9	Natural
296: 23/4 Oct	1	5 220	833	–30	0.74	–0.5	('Room' sealed off)
303: 30/1 Oct	1	1 767	(767)	995	(0.56)	43.4	Forced
304: 31 Oct/1 Nov	1	757	162	1120	0.11	121.9	Forced

( ) Uncertain

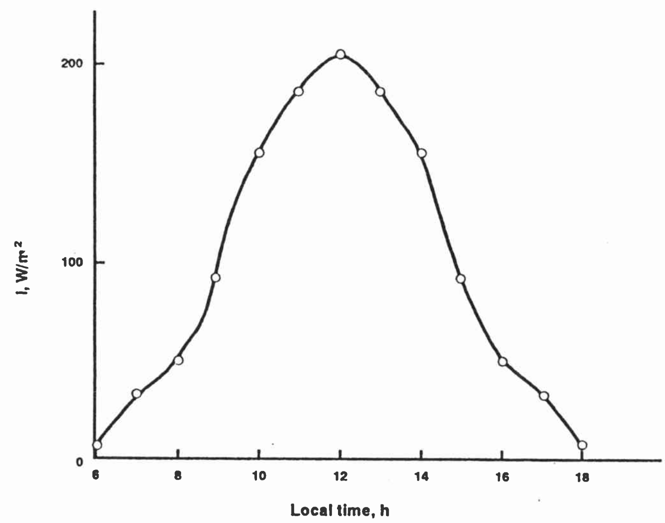

Figure 2 Typical diurnal insolation pattern (Day 296)

Some notes on these results follow.

Day 293

Two glass sheets were used and Figure 3 shows a plot of η versus $\frac{(t_{surf}-t_{amb})}{I}$ as the day advances. (η can be $\succ 1$ early in the morning, when $t_{amb} \succ t_{surf}$). An estimate of the energy reflected from the roof was 3 963 kJ for the day – which is thus $\frac{2}{3}$ of the total energy received. This shows the importance of the reflector when the orientation of the sun is high in the sky for much of the day. Taking into account a value for the diffuse reflectivity of 0.7, the energy actually absorbed by the collector was thus only about 13% of the total incident energy.

Day 294

Only one glass sheet was now used, with a consequent increase in energy absorbed (but this arrangement is likely to be associated with a greater loss to the surroundings in winter). In consequence, the value of $(\tau\alpha)_{eff}$ increased to 0.7.

Day 295

A higher ambient temperature was measured during this test, with consequent reduced natural convection and 'room' temperature.

Day 296

During this test the collector was not opened to the 'room'. The higher 'room' temperature (over ambient) is ascribed to heat loss by conduction.

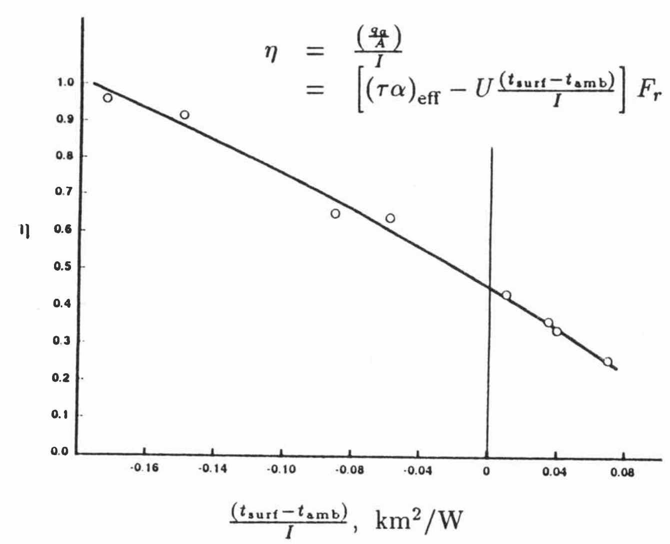

Figure 3 η versus $\frac{(t_{surf}-t_{amb})}{I}$

Day 303

A fan was now used to provide forced convection and a change of shape of the temperature curves is now evident in this and the following test;, these conditions represent a considerable operating improvement. The morning temperature reversal did not occur, while 'room' temperatures were greater than ambient throughout the day – and all temperatures were noticeably closer together throughout the 24 h period.

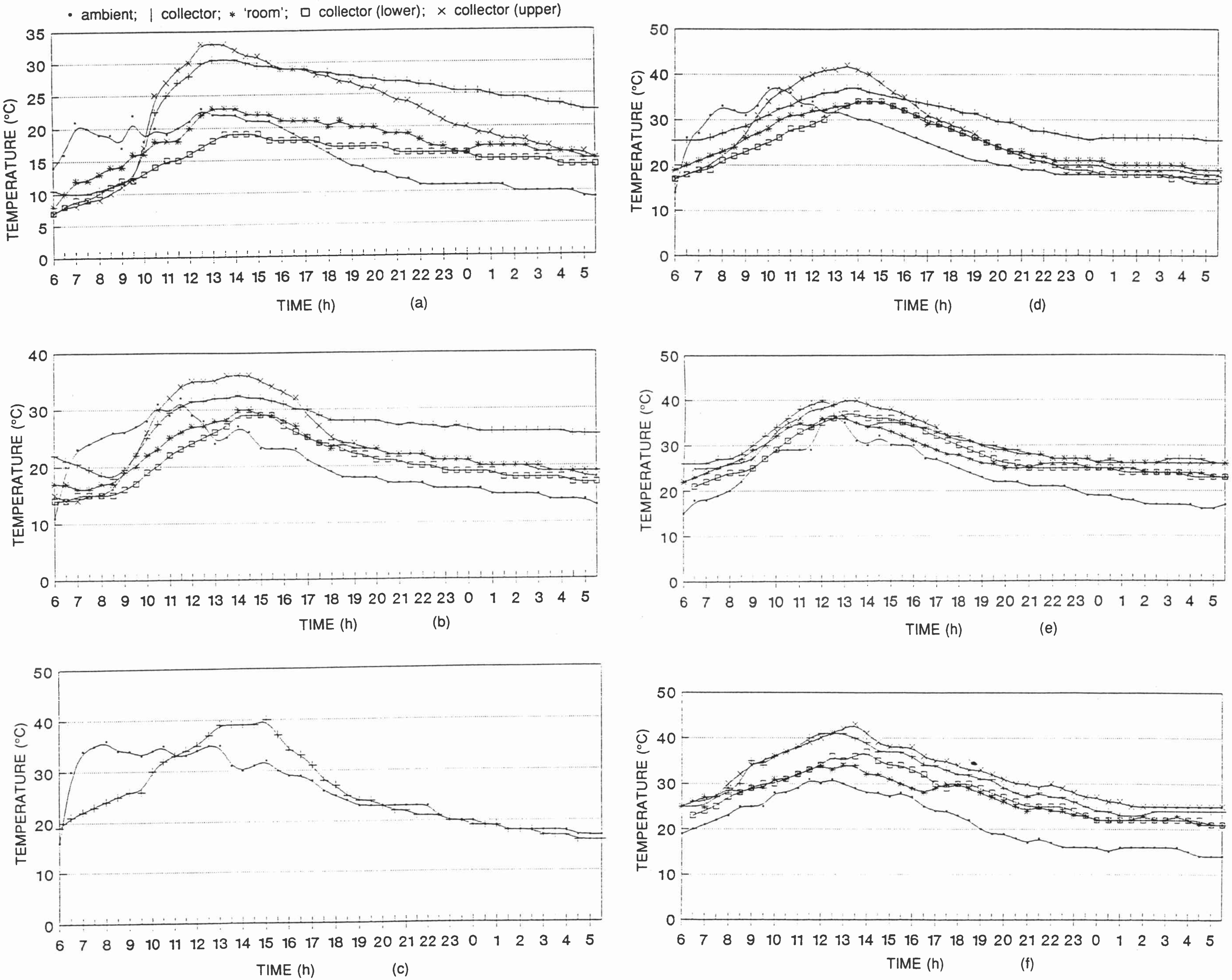

Figure 4 Diurnal temperature outputs. (a) Day 293: Natural convection; (b) Day 294: Natural convection; (c) Day 295: Natural convection; (d) Day 296: Natural convection; (e) Day 303: Forced convection; (f) Day 304: Forced convection.

Day 304

The fan was again used. More energy was used on this occasion in heating the 'room' than was received by insolation – making use of heat stored the previous day.

Figure 4 (a) to (f) shows plots of the various temperatures recorded. These curves roughly follow that of Figure 2 (peaking at noon), but then flatten out, with the temperatures decreasing only slowly through the night. In general, using natural convection, the 'room' temperature was found to be less than ambient before 11h30, and greater than ambient after 11h30, thus meeting the obvious requirements for such an apparatus. However, under forced convection conditions, all internal temperatures were higher than ambient in nearly every reading throughout the period of measurement.

The use of one sheet of glass (at least in the summer) was found to be approximately 20% more effective than the use of two sheets in transmitting solar energy.

Conclusions

Operation of the solar collector fulfilled its purpose, namely, that of 'room' heating after dark by making use of latent heat exchange. Using natural convection, the 'room' temperature was greater than ambient after about noon (after which the differential was several degrees K). With forced convection, a differential of about 7 K between 'room' and ambient temperatures was maintained throughout the 24 h period of diurnal operation (the best difference being obtained after dark). In fact, forced convection operation was generally superior in all respects. The chemical selected was also entirely satisfactory in respect of melting temperature, but the main disadvantage of the design was the vertical orientation of the panel; this made virtually essential the use of an external ground reflector (and particularly so in summer). Even so, however, the absorption of available solar energy was estimated to be only about 13%. The use of one sheet of glass (in place of two) was also found to reduce input energy transmission losses by about 20%.

References

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Appendix

Specimen calculations

Day 297 (Oct 24)

$$\begin{aligned} d &= 23.47 \sin\left[360^\circ \times \frac{(284+297)}{365.25}\right] \\ &= -12.66^\circ, \end{aligned}$$

i.e. the sun is south of the equator.

For $d = -12.66^\circ$, $L = -26^\circ$, $h = 0^\circ$ (noon),

$$\begin{aligned} \sin a &= (-0.2192)(-0.4384) + (0.9757)(0.8988), \\ &= 0.9731 \\ \Rightarrow a &= 76.67^\circ \end{aligned}$$

Day 305 (Nov 1)

$$\begin{aligned} d &= 23.47 \sin\left[360^\circ \times \frac{(284+305)}{365.25}\right] \\ &= -15.25^\circ, \end{aligned}$$

i.e. the sun is south of the equator.

For $d = -15.25^\circ$, $L = -26^\circ$, $h = 0^\circ$ (noon),

$$\begin{aligned} \sin a &= (-0.2631)(-0.4384) + (0.9648)(0.8988) \\ &= 0.9825 \\ \Rightarrow a &= 79.25^\circ \end{aligned}$$

Available energy storage

Latent heat storage capacity

$$\begin{aligned} q_L &= nV\rho i_{if} \\ &= 7 \times 1.43 \times 10^{-3} \times 1\,519 \times 170 \\ &= 2\,585 \text{ kJ} \end{aligned}$$

Sensible heat

$$\begin{aligned} q_s &= nV\rho C_p \Delta t \\ &= 7 \times 1.43 \times 10^{-3} \times 1\,519 \times 2.17\Delta t \\ &= 33\Delta t \text{ kJ} \end{aligned}$$

$\Rightarrow$ Available storage for a solar panel of area 0.516 m^2 = $2\,585 + 33\Delta t$ kJ (or $5\,010 + 64\Delta t$ kJ/m^2).