Performance improvement of a PCM cold box by two bilayers configuration

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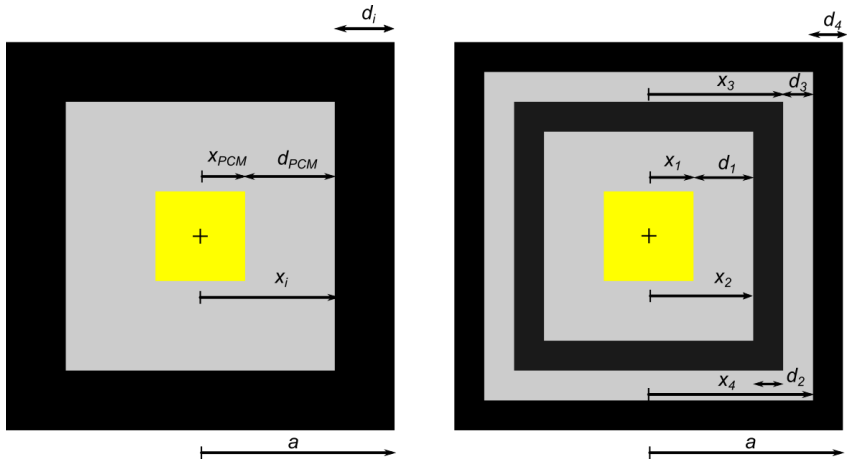

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Sometimes simple things are overlooked for centuries!

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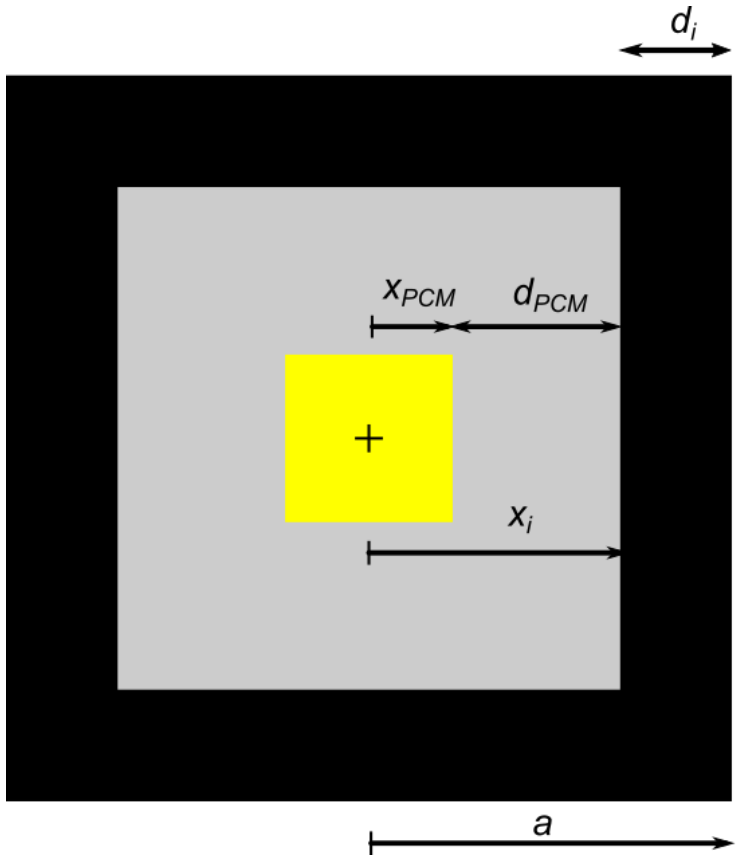
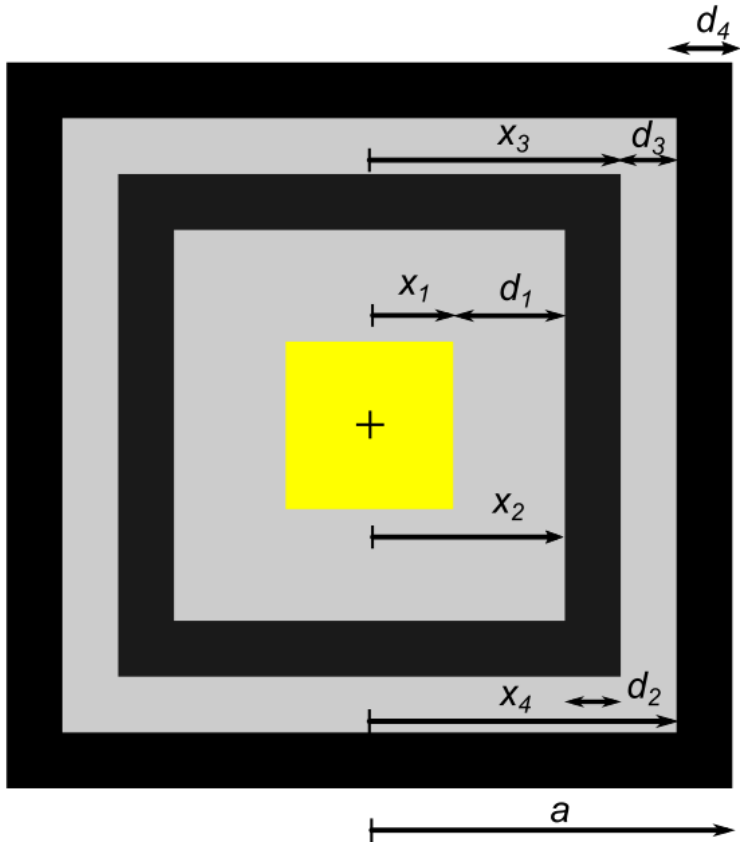
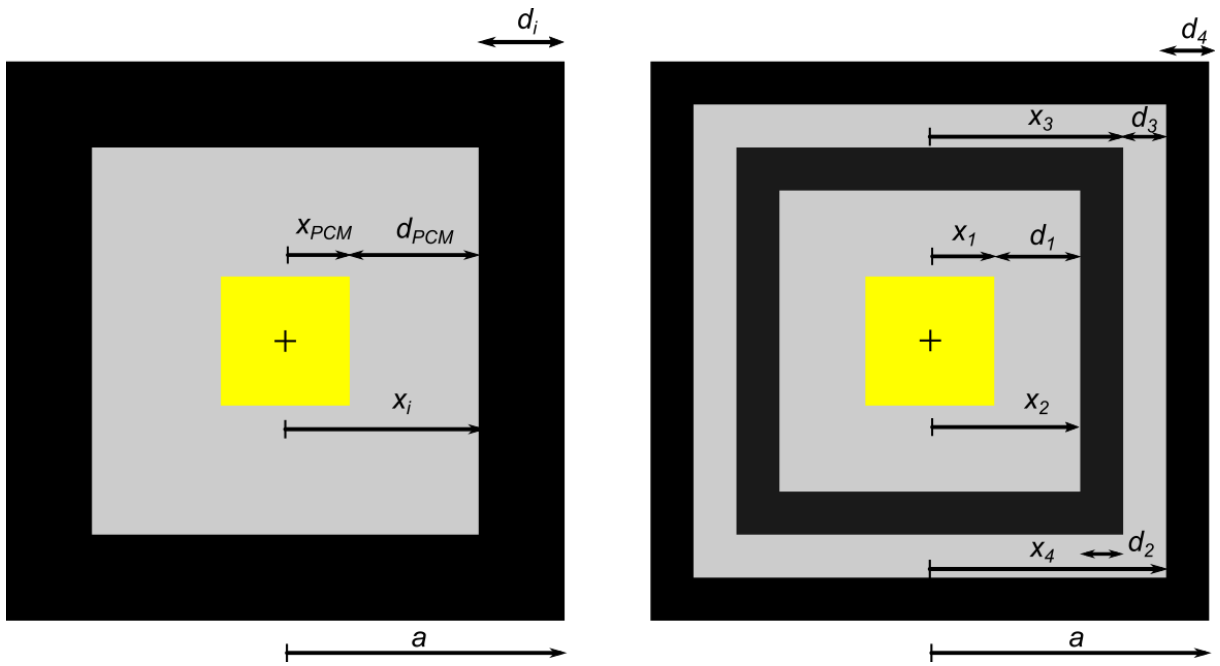




The PCM cold box we have been using for centuries can be improved by redesigning!

Benchmarking



- The total weight of the box is fixed.
- The total weight of the PCM (M_{PCM})in the two and single bilayer configuration is the same, implying in a two bilayer configuration $M_1+M_3 = M_{PCM}$

And some mathematics later…

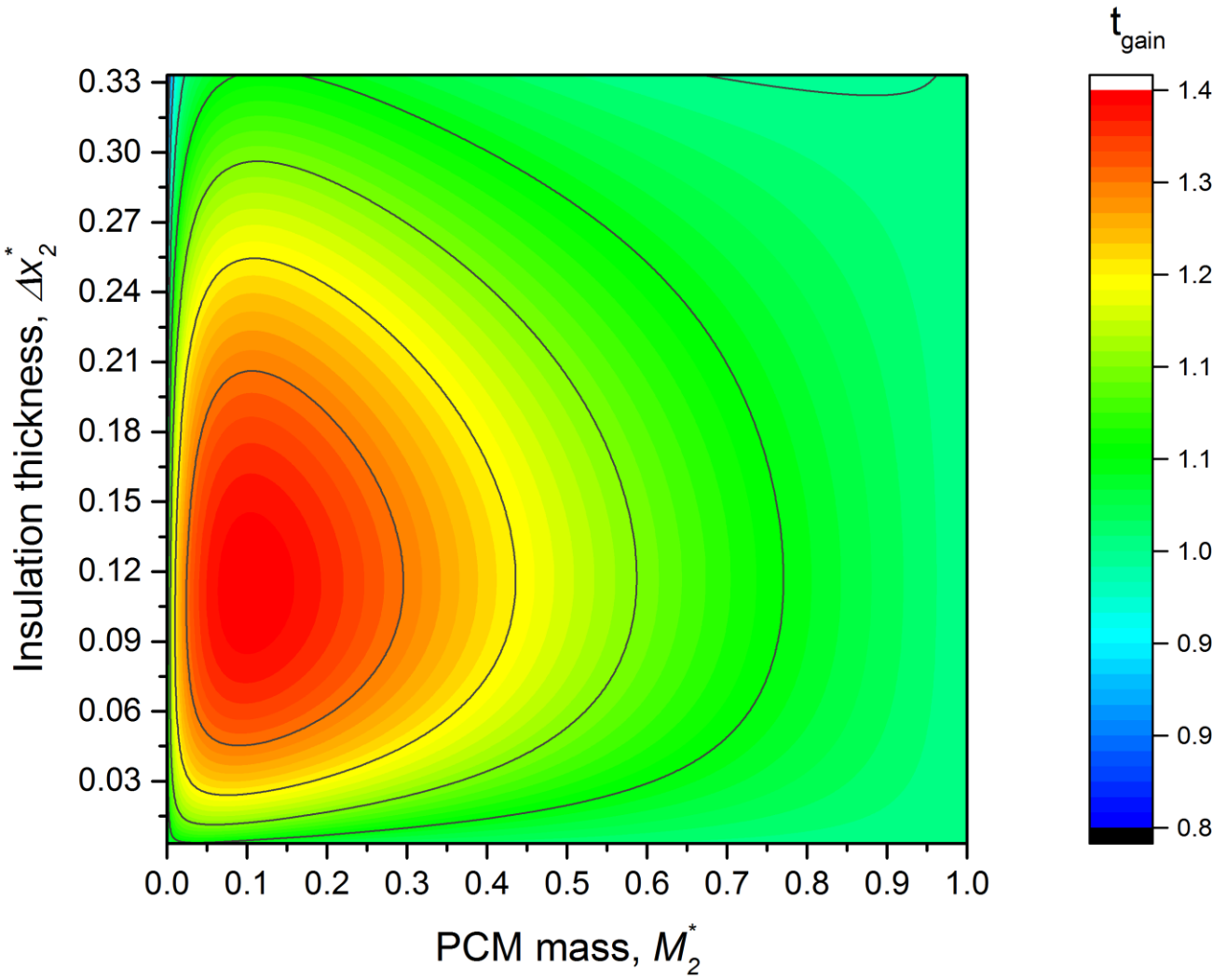


Fig.- Contour plot of the time gain i.e. the ratio of the melting time of a two bilayer box to a single bilayer box as a function of the dimensionless PCM mass $M_1^* = M_1/M_{PCM}$; and insulation thickness $\Delta x_2 = d_2/a$.

Will it also work for cryogenic temperatures?

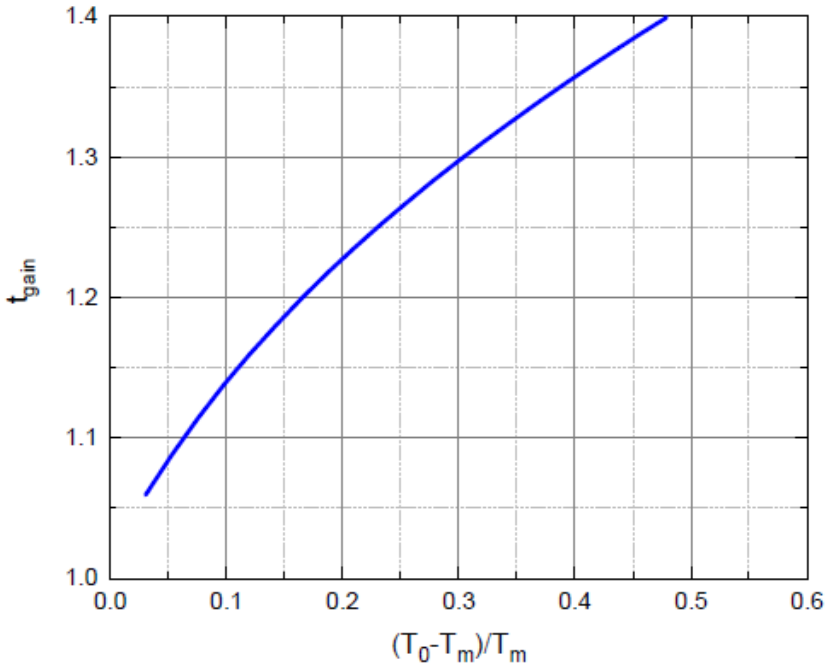


Fig. - The time gain metric as a function of varying ambient temperature T_0.

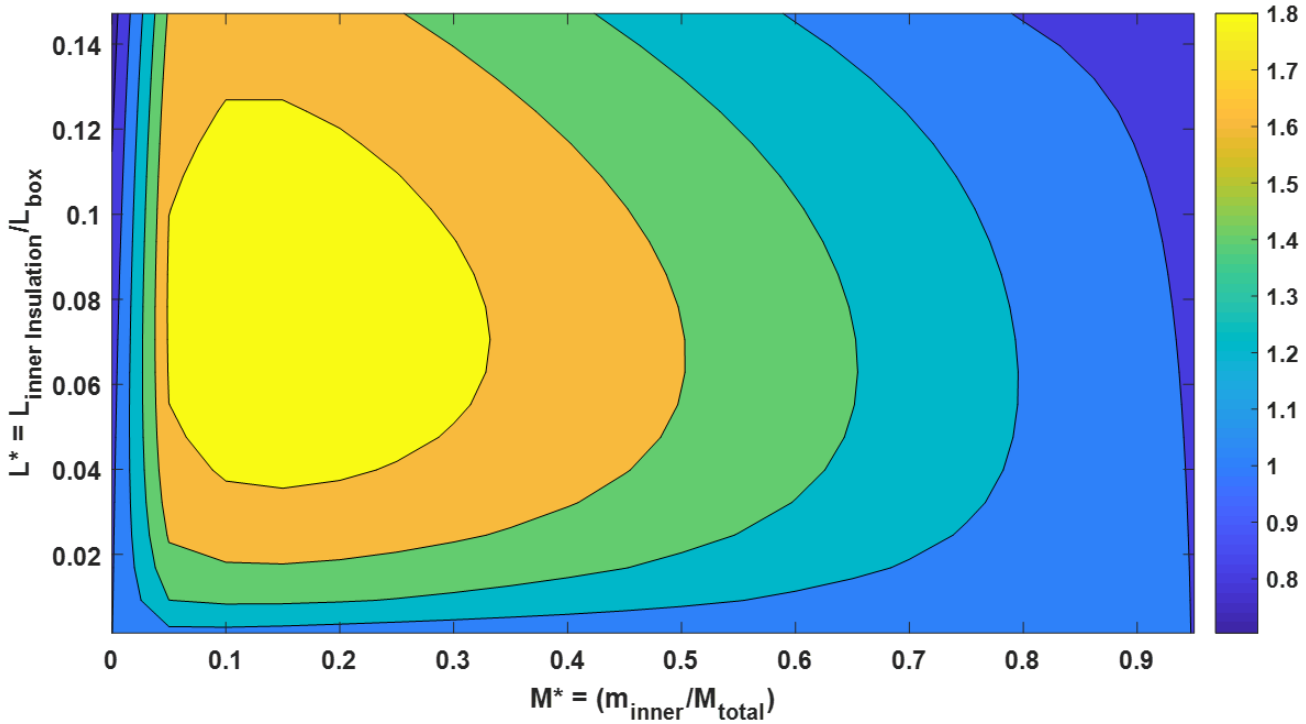


Fig. - Contour plot of the time gain with respect to the dimensionless PCM , and insulation thickness for cryogenic isopentane

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Curious?

- Walk by to our poster!

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Introduction

A method to increase the storage time of a PCM cold box to transport frozen materials maintained at a sub-zero temperature has been investigated in this research. The configuration of a single Phase Change Material (PCM) pack surrounding the payload and subsequently surrounded by an insulation layer is termed as a bilayer configuration and is a traditional design of such cold boxes. Our study shows that by changing the configuration into two bilayers arranged in an onion type geometry, a significant advantage may be gained in terms of the total time for which the payload stays frozen. Such a simple modification to the container decreases the overall effective thermal diffusivity of the box for a fixed amount of PCM and insulation mass. The optimum distribution of the PCM and insulation material in a two bilayer configuration is studied using a simplified mathematical model.

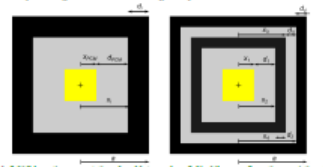

Figure 1: (left) Schematic representation of a cold storage box. (left) a bilayer configuration consisting of PCM and insulation layers (right) a two bilayer configuration consisting of alternating layers of PCM and insulation layers. The subscript to represent PCM layer dimensions in the two bilayer configuration is an odd number and insulation layer dimension is represented by an even number.

Key Assumptions

1. The thermal conductivity of the insulation material is at least two orders of magnitude lower than the PCM.
2. The heat capacity of the insulation material is negligible compared to the PCM.
3. The ambient temperature T_0 is constant.
4. The thermal conductivity and specific heat capacity are not a function of temperature.
5. One dimensional heat diffusion i.e. heat diffuses perpendicular to the surface area of the box.

Results

For a fair assessment of the two bilayer against a single bilayer configuration, the following constraints are imposed. For a given volume of the payload at the center of the box,

1. The total weight of the box is fixed.
2. The total weight of the PCM M_{PCM} in the two and single bilayer configuration is the same, implying in a two bilayer configuration $M_1 + M_3 = M_{PCM}$

The total time taken by a two-bilayer configuration to melt is calculated by summing the melting time of the outer layer t_3 (linear calculation) with the melting time for the inner PCM t_1. To calculate t_1 the heat balance equation of inner layer is used as follow,

$$T_3 = \frac{1}{C_3}\left[\frac{T_2 - T_3}{R_4} - \frac{T_3 - T_m}{R_3}\right] = \alpha - \beta T_3 \qquad (1)$$

where, $\alpha = \frac{1}{C_3}\left(\frac{T_2}{R_4} + \frac{T_m}{R_3}\right)$ and, $\beta = \frac{1}{C_3}\left(\frac{1}{R_4} + \frac{1}{R_3}\right)$

Solving equation 1, T_3 is obtained and substituted in the latent heat equation of the inner PCM layer, which upon integration final leads to the following expression,

$$t_1 = \frac{1}{R_3}\left(\frac{\alpha}{\beta} - T_m\right)\left(t_1 - \frac{1}{\beta}\left(1 - e^{-\beta t_3}\right)\right) \qquad (2)$$

Solving this equation implicitly t_1 is obtained.

Fig.-2 compares the two bilayer configuration with respect to the single bilayer for the constraints mentioned above, using the time gain as a metric, which is the ratio of the total melting time of the PCM in two bilayer configuration to the melting time of PCM of the single bilayer.

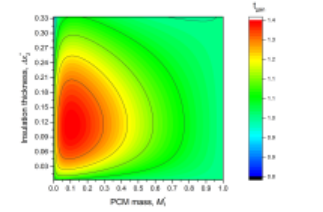

Figure 2: Contour plot of the time gain i.e. the ratio of the melting time of a two bilayer box to a single bilayer box as a function of the dimensionless PCM mass $M_1' = M_1/M_{PCM}$, and insulation thickness $\Delta t_1' = t_2'/t_1$.

It can be clearly seen that two bilayer configuration has a clear advantage over its single bilayer counterpart.

From our analysis we observed that this gain can be attributed to the use of specific heat of the outer PCM to delay the melting process of the PCM and an increase in the effectiveness of the thermal insulation.

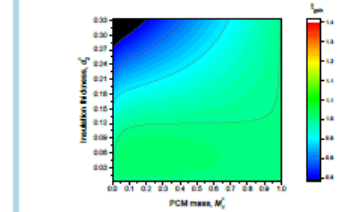

Figure 3: Contour plot of the time gain with respect to the dimensionless PCM mass M_1', and insulation thickness t_2' with specific heat capacity of PCM set to zero value.

Fig.-3 illustrates the time gain for a similar hypothetical system with Zero specific heat capacity. In this case, time gain improvement of only 2 % is achieved, highlighting the importance of the role of specific heat capacity in increasing the time gain of a two bilayer configuration.

As these calculations are done for a subzero non-cryogenic temperature. It is interesting to explore if the same advantages can be carried along for cryogenic temperature. As shown in the Fig.-4, the increase in temperature difference strengthens the gain further. Motivated by the same a further calculation is done for an isopentane based cryogenic system showing a higher gain of upto 80% as shown in the Fig.-5.

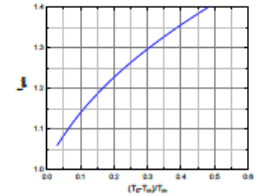

Figure 4: The time gain metric as a function of a varying ambient temperature T_0.

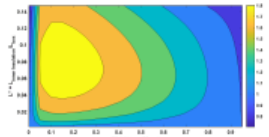

Figure 5: Contour plot of the time gain with respect to the dimensionless PCM mass M_1', and insulation thickness D' for cryogenic isopentane

Conclusion and Outlook

By using simple approximations to the mathematical model of a two bilayer cold box composed of PCM and thermal insulation layers, we show that the melting time of the total PCM can be increased compared to an equivalent single bilayer box. The main reason for this time gain is due to an increase in the effectiveness of thermal insulation and the use of specific heat of the outer PCM to delay the melting process of the PCM. For the selected PCM and insulation material properties, the optimum distribution for maximum time gain is when the inner PCM mass is about 10 percent of the total PCM mass and the inner insulation thickness is about half of the total insulation thickness. The distribution of PCM between the two layers is also independent of the total mass of the system. Further work needs to be done to experimentally verify these results.

Acknowledgments

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