Evaluation Boundary and Design Method for Insulating Packages

Liao Pan
Jiangnan University
lpan@rit.edu

Jun Wang
Jiangnan University
wangj_1982@jiangnan.edu.cn

Lixin Lu
Jiangnan University
lulx@jiangnan.edu.cn

ABSTRACT

To evaluate the failure potential of insulated packaging to heat outside, a so-called evaluation boundary for insulating packages was proposed for designing and estimating insulating packages based on the heat transfer law between the environment and a packaged product through packaging. Three evaluation parameters were suggested for describing the failure mechanism of insulating packages. The validity of the presented evaluation boundary was verified by the experimental data. Finally, a new design method of insulating packages based on the boundary was proposed and an application example was performed as a demonstration. The results indicated that the three evaluation parameters (which are thermal load, adsorption ability of phase change material (PCM) and system thermal resistance of insulating packages) are the key parameters for designing insulating package and that the performance of insulating packages is only determined by the thermal load. Moreover, the proposed evaluation boundary shows a good agreement with experimental results, and the availability of the new method to design insulating packages was affirmative through the application example.

KEY WORDS

Evaluation boundary; design method; insulating package; cold chain.
**INTRODUCTION**

Insulating packages with phase change material (PCM) shows some potential significance of the passive cold chain in protecting temperature-sensitive products [1]. Furthermore, the shortcomings of traditional cold chain for the “last one kilometer” also can be overcome by insulating packages [2]. As a result, the research community has shown a renewed interest in the insulating packages used in the cold chain.

The temperature control of insulating packages is substantially based on the heat insulation and phase change [3-5]. The two key parameters of these two processes are the system thermal resistance and the request of PCM. The Ice-melting method presented by Burgess [6] was widely used to experimentally measure the system thermal resistance of insulating packages. However, mathematical models are preferred over experimental in many applications due to their physical basis, rapid and low cost of calculation. Stavish [7] proposed a system thermal resistance model to analyze the impact of the air gap between products and packages. Choi [1] also presented an empirical model considering multi-layer insulation materials. The above two system thermal resistance models are both statistic models, which are convenient to apply but have less physical basis. Thus, an analysis model was established by Qian’s team [8-10]. Qian’s models simplify a three-dimensional cubical insulating package to a one-dimensional ball package or a cylinder package whose system thermal resistance can be analytically calculated. For the request of PCM, Matsunaga [11] developed a method to calculate the weight of PCM required for insulating packages. Besides, an

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**NOMENCLATURE**

- $A_i$: Inside superficial area of the insulating container /m²
- $A_o$: External superficial area of the insulating container /m²
- $b$: Thickness of the insulating container /m
- $C_{total}$: Cost of insulating package /Yuan
- $C_1$: Materials cost /Yuan
- $C_2$: Transport cost /Yuan
- $C_{PCM}$: Cost of PCM /Yuan·kg⁻¹
- $C_w$: Cost of EPS /Yuan·kg⁻¹
- $C_T$: Transport cost of per carriage /Yuan
- $D_o$: External length of the insulating container /m
- $D_p$: External length of the product /m
- $F_T$: Thermal load / K·h
- $h$: Surface heat transfer coefficient/ W·(m²·K)⁻¹
- $H_o$: External height of the insulating container /m
- $H_p$: External height of the product /m
- $k_w$: Thermal conductivity of insulating container /W·(m·K)⁻¹
- $L$: Latent heat of PCM /J·kg⁻¹
- $M_{PCM}$: Mass of PCM /kg
- $M_w$: Mass of insulating container /kg
- $Q$: heat adsorption ability of PCM /J
- $R_s$: System thermal resistance of insulating package / (K·s)·J⁻¹
- $t$: Logistics time /h
- $T_m$: Melting temperature of PCM /K
- $T_o$: Logistics temperature /K
- $\Delta T=T_o-T_m$: Excess temperature /K
- $V_T$: The volume of the van /m³
- $W_o$: External l width of the insulating container /m
- $W_p$: External l width of the product /m
- $\Delta x$: Thickness of the PCM /m
- $\rho_w$: Density of insulating container /kg·m⁻³
- $\rho_{PCM}$: Density of PCM /kg·m⁻³
approximate one-dimensional insulating package model was presented by Mehling [12], and the request of PCM could be indirectly determined through the approximation model.

Previous studies provide a strong theory basis for designing insulating packages. These models are respectively considered insulating packages and the products, and calculate the weight of PCM required based on existing insulating container without considering the size of product.

However, the previous methods of designing the insulating package from the outside (insulating container) to the inside (PCM) show a potential problem: insulating containers cannot be entirely filled with the calculated PCM or they do not have enough space to hold the calculated PCM. Thus, a method which can design insulating packages based on products and calculate package parameters from products inside to packages outside is more practical.

The main aim of the present study is to propose an evaluation boundary and provide a design method for designing insulating packages from products based on the evaluation boundary.

### EVALUATION BOUNDARY

Previous study [1] shows that an insulating package can be approximatively simplified into a one-dimensional model. Thus, the shelf life of the insulating package can be written as [13]

\[
  t = \frac{M_{PCM}L}{3600\Delta T} \quad ...(1)
\]

Where, \( R_s \) is an intrinsic parameter influenced by the structure of insulating containers, and \( L \) is a constant determined by the kind of PCMs.

There is one logistics parameter (\( \Delta T \)) determined by the transport condition, and one object parameter (\( t \)) requested by products. Based on the logistics parameter and object parameter, three package parameters (\( M_{PCM} \), \( L \), and \( R_s \)) need to be designed.

The complicated parameters in Equation (1) are inconvenient for package designing. Thus, three groups of recombinational parameters can be proposed.

The first one is thermal load, which is defined by the product of excess temperature (the temperature difference between the outside and inside of the insulating package) and logistics time as the following equation.

\[
  F_T = \Delta T \cdot t \quad ...(2)
\]

The second one is the heat adsorption ability of PCM shown in Equation (2), which can be calculated by the phase change theory of PCM.

\[
  Q = M_{PCM} \cdot L \quad ...(3)
\]

The third one is the system thermal resistance as the innate parameter which has been lucubrated in many literatures [14-16].

\[
  R_s = \frac{1}{hA_o} + \frac{b}{k_wA} \quad ...(4)
\]

where,

\[
  A = \sqrt{A_oA_i} \quad [17]
\]

\[
  h = (e^{-1.386b/k_w} + 1.654)(0.5359 \sqrt{\Delta T} - 0.03081\Delta T)
\]

According to Equation (2) and Equation (3), Equation (1) can be transformed as the following equation

\[
  Q = \frac{3600F_T}{R_s} \quad ...(5)
\]

Equation (5) shows that the heat of absorption required from the PCM decreases with the improvement of system thermal resistance and is in direct proportion to the thermal load of logistics. Through Equation (5), the evaluation boundary of insulating...
under different thermal loads can be proposed in Figure 1. The evaluation boundary is a solution set, and every point on the curves is one reliable solution meeting the corresponding logistics condition. The area above the boundary is the safety solution region for an insulating package. Oppositely, the insulating package will be invalidated during the logistics.

**EXPERIMENTAL METHOD AND MATERIALS**

The reliability of the evaluation boundary is discussed through the ice-melting method proposed by Burgess [6].

**Materials**

The insulating containers (Figure 2) are made by expanded polystyrene (EPS, provided by Suzhou Antek Packaging Co., Ltd.). The thermo-physical properties of the containers provided by Antek are shown in Table 1.

**Table 1: The thermo-physical properties of the containers**

<table>
<thead>
<tr>
<th>Samples</th>
<th>D₀ x W₀ x H₀/m</th>
<th>b/m</th>
<th>ρ_w/kg·m⁻³</th>
<th>k_w/W·(m·K)⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.290x0.153x0.188</td>
<td>0.02</td>
<td>12.77</td>
<td>0.031</td>
</tr>
<tr>
<td>P2</td>
<td>0.400x0.400x0.400</td>
<td>0.05</td>
<td>20.81</td>
<td>0.034</td>
</tr>
<tr>
<td>P3</td>
<td>0.460x0.425x0.345</td>
<td>0.06</td>
<td>14.34</td>
<td>0.032</td>
</tr>
<tr>
<td>P4</td>
<td>0.560x0.485x0.425</td>
<td>0.06</td>
<td>23.84</td>
<td>0.038</td>
</tr>
</tbody>
</table>
The PCM used in the experiment is deionized water (HACH-272-56, Sinopharm Chemical Reagent Co., Ltd). The thermo-physical properties of pure water and ice are determined with a DSC (Q2000, TA, USA), and the results are shown in Table 2.

**Table 2: The thermo-physical properties of pure water and ice under melting temperature**

<table>
<thead>
<tr>
<th>Thermo-physical properties</th>
<th>$\rho_{PCM}/$kg$\cdot$m$^{-3}$</th>
<th>$T_m$/K</th>
<th>L/J$\cdot$kg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>$1.00\times10^3$</td>
<td>273</td>
<td>$3.31\times10^5$</td>
</tr>
<tr>
<td>ice</td>
<td>$0.92\times10^3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Equipment**

Two types of electronic balances (ML6001E and AB204-N, Mettler Toledo, Switzerland) are used to measure the mass respectively in the range of 5g~6200 g with an accuracy of 1 g and 0g~210 g with an accuracy of 0.1 mg.
A programmable temperature chamber (THS-D7C-100AS, KSON, Taiwan) can control temperatures in the range of 203 K~423 K, with an accuracy of ±0.2 K.

**Experimental Procedure**

1. Fill the four insulating containers (P1, P2, P3 and P4) with deionized water to the 90% maximal volume of each container. Appropriate head space should be reserved to prevent the expanding of ice.
2. Place the insulating containers at 261 K until the water completely freezes;
3. Place the insulating containers at 273 K for at least 24 h to reach equilibrium;
4. Increase the environmental temperature up to the logistics temperature, and hold the temperature for a certain time. The test conditions are shown in Table 3;
5. Measure the total weight of every container as $m_0$. Then pour away the melted water, and measure the rest weight of every container (including the unmelted ice and the container) as $m_1$. Finally, the weight of the melted water which is equal to the requests of PCM can be calculated by Equation (6).

$$M_{PCM} = m_0 - m_1 \quad \ldots (6)$$

**RESULTS**

According to the measured $M_{PCM}$ in Equation (3), the experimental heat adsorption of PCM can be calculated through Equation (3). The thermal load is determined by the test condition of Table 3, and the system thermal resistance of the containers shown in Table 1 also can be calculated by Equation (4). By comparing the experimental data and model curves, the presented evaluation boundary curves agree with the experimental results and the request of heat adsorption can be uniquely determined by the thermal load for a certain insulating container. Thus, the thermal load is the critical parameter of the insulating package design.

$$\begin{array}{c|c|c|c|c}
T_0/K & 293 & 303 & 313 & F/K\cdot h \\
T/h & 10.00 & 20.00 & 30.00 & 600 \\
& 20.00 & 33.33 & 46.67 & 1000 \\
& 15.00 & 25.00 & 35.00 & 1400 \\
\end{array}$$

**Table 3: Test conditions**

![Figure 3: Evaluation boundary curves of insulating packages](image-url)
METHODOLOGY

Based on the evaluation boundary curves, a reliable design method of insulating packages is proposed in the following procedure (Figure 4).

1. Determining the product information and logistics condition;
   - The product information includes the size of the product and the suitable storage temperature of the product. The logistics condition is divided into the logistics temperature and logistics time.

2. Selecting the packaging material
   - The insulating material and the PCM are determined through the package request and storage temperature of the product.

3. Building the evaluation boundary
   - According to the logistics condition, the thermal load is calculated by the following equation.
     \[ F_T = \sum_{i=1}^{n} \Delta T_i \cdot t_i \] ...(7)
   - where, \( i \) is the logistics step, and \( n \) is the total steps of the logistics.
   - Then, the evaluation boundary can be built through Equation (5).

4. Designing the insulating package
   - The mapping relation between the system resistance and the request of PCM can be established from the proposed evaluation boundary. As described in Equation (4), the system resistance is affected by the structure sizes of the insulating container. Thus, the relationship between the request of PCM and the structure size of the insulating container is determined mathematically.

   As a classic insulating package structure [18] showed in Figure 5, the structure sizes required in Equation (4) can be calculated through Equation (8) by considering the geometrical relation between the product and the insulating container.

\[
\begin{align*}
A_i &= 2(D_p + 2\Delta x)(W_p + 2\Delta x) \\
&+ (D_p + 2\Delta x)(H_p + 2\Delta x) \\
&+ (W_p + 2\Delta x)(H_p + 2\Delta x)] \\
A_o &= 2(D_o W_o + D_o H_o + W_o H_o) \\
\end{align*}
\] ...(8)

Where,

\[
\Delta x = \frac{M}{2\rho_{PCM}(D_p W_p + D_p H_p + W_p H_p)}.
\]

\[
D_o = D_p + 2(\Delta x + b) \\
W_o = W_p + 2(\Delta x + b) \\
H_o = H_p + 2(\Delta x + b)
\]

Combining the evaluation boundary, Equation (4) and Equation (8), the structure sizes...
of insulating containers can be calculated while the request of PCM and one insulating package solution will be determined.

(5) Solution optimizing

Every point on the evaluation boundary curve built through step (3) can correspond one insulating package solution. Besides, the cost, volume, mass and other constraint conditions of every solution can be conveniently calculated. Finally, the best among the solutions can be determined by considering these constraint conditions.

(6) Experiment

A storage experiment should be performed to test the reliability of the designed insulating package.

APPLICATION

For directly demonstrating the presented procedure, one application example is described in the following paragraphs.

Product description and logistics condition

The product is represented with 6 glass vials filled with 35% (w/w) ethanol solution which should be stored under temperatures between 270K to 273K. The vials are packaged in a corrugated case whose size is 0.35m×0.17m×0.17m (D_p × W_p × H_p). The packaged product is required to meet the logistics condition in Table 4.

Table 4: Logistics of application experiment*

<table>
<thead>
<tr>
<th>NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>t/h</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>T/K</td>
<td>288</td>
<td>301</td>
<td>298</td>
<td>291</td>
<td>285</td>
<td>291</td>
<td>298</td>
<td>301</td>
<td>298</td>
<td>291</td>
</tr>
</tbody>
</table>

* The logistics condition in Table 4 was a simplify real test supplied by Antek Packaging Co.

Packaging material

EPS is selected as the insulating material because of its low thermal conductivity. A kind of gel refrigerant provide by Suzhou Antek Packaging Co., Ltd. is used as the PCM in the insulating package. The thermo-physical properties of the EPS and gel refrigerant are shown in Table 5.

Table 5: The thermo-physical properties of the EPS and gel refrigerant used in the application example

<table>
<thead>
<tr>
<th>Samples</th>
<th>p/ (kg·m⁻³)</th>
<th>k/ (W·m⁻¹·K⁻¹)</th>
<th>Tm/K</th>
<th>L/ (J·kg⁻¹)</th>
<th>C/ (Yuan·kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>12.77</td>
<td>0.031</td>
<td>N/A</td>
<td>N/A</td>
<td>1.50</td>
</tr>
<tr>
<td>Gel refrigerant</td>
<td>930</td>
<td>N/A</td>
<td>272.7</td>
<td>3.19x10⁵</td>
<td>8.00</td>
</tr>
</tbody>
</table>
Evaluation boundary

According to step (3) of the presented procedure, the total thermal load of Table 4 equals 1012 K·h and the corresponding evaluation boundary curve is shown in Figure 6.

![Figure 6: The evaluation boundary curve of the application example](image)

Package design and optimization

According to steps (4) and (5), the final solution can be determined. In this present application example, the cost of the solution is considered as the optimization objective for instance. The cost of insulating packages includes the materials cost and the transport cost, as shown in Equation (9).

\[ C_{\text{total}} = C_1 + C_2 \]  \hspace{1cm} \text{...(9)}

Where,

\[ C_1 = M_{\text{PCM}} C_{\text{PCM}} + M_w C_w \]

\[ C_2 = \frac{C_t}{\text{INT}[V'/(D_o W_o H_o')]} \]

The cost of PCM is more expensive than EPS. Oppositely, the transport cost of EPS is much higher than PCM due to the low density of EPS. Thus, a balanced point between the request PCM and the EPS can be determined in Figure 7, and the optimum solution of insulating packages based on the cost balanced point is shown in Table 6.

![Table 6: The optimum solution of insulating package](image)

<table>
<thead>
<tr>
<th>(M_{\text{PCM}}/\text{kg})</th>
<th>(b/\text{m})</th>
<th>Package Size/m</th>
<th>(C_\text{f}/\text{Yuan})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.43</td>
<td>0.079</td>
<td>(D_o=0.52) (W_o=0.34) (H_o=0.34)</td>
<td>28.74</td>
</tr>
</tbody>
</table>

![Figure 7: Balanced point of insulating package](image)
Experimental verification

According to the parameters in Table 6, an insulating package meeting the logistics condition in Table 4 can be produced (Figure 8). A storage experiment under the logistics condition in Table 4 is performed for testing the reliability of the designed insulating package. A temperature sensor used to measure the temperature change of the product is located on the corner of the corrugated case (previous studies show that the temperature change on the corner is the sharpest [19]), as shown in Figure 9.

As the experimental result shown in Figure 10, the logistics temperature changes from the range of 288K to 301K, however, the temperature in the corner of the product is kept between 272.3K and 273.2K throughout the test. The result indicates that the optimum insulating package designed through the presented design method based evaluation boundary prevents products from thermal damage during logistics.

CONCLUSIONS

An evaluation boundary for insulating packages was proposed for designing and optimizing insulating packages and three evaluation parameters were suggested for describing the failure mechanism of insulating packages. The validity of the presented evaluation boundary was verified by the experimental data. Finally, a new design method of insulating packages based on the boundary was proposed and an application example was performed as a demonstration. The results indicate that the three evaluation parameters (which are thermal load, adsorption ability of PCMs, and system thermal resistance...
of insulating packages) are the key parameters for designing insulating packages, and the performance of insulating package is only determined by the thermal load. Moreover, the proposed evaluation boundary shows a good agreement with the experimental results, and the availability of the new method to design insulating packages was affirmative through the application example.

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