The use of physical simulation to evaluate thermal properties of food containers in cold chain logistics

N Chaitanoo, P Ongkunaruk, D Leingpibul

1Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna, Chiang Mai 50300, Thailand
2Department of Agro-Industrial Technology, Faculty of Agro-Industry, Kasetsart University, 50 Ngam Wong Wan Rd. Lad Yao, Chatuchak, Bangkok 10900, Thailand
3Haworth College of Business, Western Michigan University, Kalamazoo, MI 49008, USA

*Corresponding author: pornthipa.o@ku.ac.th

Abstract. Cold chain logistics has gained significant attention among all stakeholders in the food and pharmaceutical delivery industries due to the stricter food safety enforcement and tighter quality assurance [1-3]. Most cold chain logistics providers seek to determine the right packaging that ensures temperature control delivery in order to gain and/or retain their competitive advantage in the market place. Nowadays, materials such as Polystyrene Foam (PS), Polyethylene-Nylon (PE-Nylon), and Vacuum Insulation Panels (VIP) are widely used in the construction of delivery boxes. The objective of this study is to use a physical simulation approach to determine which materials are most suitable for delivery boxes. First, three delivery boxes with different materials (PS, PE-Nylon and VIP) were used as test subjects in this study. Second, the cold chain delivery process was simulated for each box and the temperature at each critical point had been measured throughout the delivery process. Third, data analysis was performed by comparing the temperature pattern among all three subjects. The thermal conductivity data for each box was calculated by mathematical equations to help interpret the results. The result showed that the box made from VIP material showed the best thermal resistance. The application of this thermal conductivity estimation procedure might help guide food delivery related practitioners to determine the best materials for their delivery box equipment and the findings might help effectively and efficiently improve their delivery services.

1. Introduction

The current global trend of urbanization accelerates the growth of last-mile food delivery in many large cities [1]. With the exponential growth in temperature-controlled food delivery, the proper delivery box plays a critical role to help ensure food safety and minimize food loss [2,3]. Any temperature control issue in cold chain logistics will increase food loss in the food industry sector and elevate the food safety risk in the consumer sector [3]. The delivery box is considered the primary protection of food safety. Practitioners need to understand which box/material should fit their delivery conditions. Therefore, research in this area is urgently needed to support the fast-growing numbers of new business operations that will critically impact such a large number of stakeholders worldwide. For the delivery providers, the box selection process involves several factors such as cost, dimension, strength, design, and insulation properties. There are many materials used as insulation for food delivery such as Expanded
Polystyrene Foam (EPS) [5]. Non-woven feather fiber packaging liners from the poultry industry is a sustainable material with a comparable thermal conductivity as the EPS [6]. The insulation property is traditionally determined by the thermal conductivity resistance factor (R) or thermal conductivity constant (k) by practitioners. This research proposes a more holistic approach by conducting a physical delivery simulation along with the use of traditional R and k for thermal properties. This particular research aims to answer, “Which material (VIP, PE-Nylon, and PS) best insulates chilled food?” according to the results of a physical delivery simulation approach.

2. Methodology
The three different commonly used delivery boxes made of VIP, PE-Nylon, and PS materials were selected as the subjects of study to replicate industry usage. Based on focus group interviews, the sizes of three boxes are comparable and fall into the same small category delivery box. For each box, weight, dimension, thickness, and volume were carefully measured and recorded in Table 1. Then, the thermal conductivity experiment was conducted using the following approaches.

Table 1. Weight, dimension, thickness, and volume of three delivery boxes

| Delivery Box | Weight (kg) | Internal Dimension (m) | External Dimension (m) | Thickness (cm) | Volume (m³) |
|--------------|-------------|------------------------|------------------------|----------------|-------------|
|              |             | Width | Length | Depth | Width | Length | Depth |           |             |
| VIP          | 5.70        | 0.46  | 0.25   | 0.35  | 0.53  | 0.32   | 0.39   | 4.00       | 0.04         |
| PE-Nylon     | 0.33        | 0.24  | 0.32   | 0.28  | 0.26  | 0.34   | 0.30   | 0.80       | 0.02         |
| PS           | 0.29        | 0.26  | 0.30   | 0.30  | 0.30  | 0.38   | 0.34   | 2.00       | 0.02         |

2.1 Experimentation
To minimize the impact from the ambient temperature and replicate the delivery condition in Thailand, the temperature in the lab was controlled at 25±1.5°C during the whole physical simulation experiment. Next, each box was filled with 1000 ml of cold water (8.0±1.5°C) as a cold food item. The water is used to minimize the interference of thermal conductivity from uneven food physical properties. Four data loggers were placed throughout the box and the temperatures were recorded every 5 min interval over the simulation period of 3 h for each box. There are recommended by the practitioner focus groups. The positions of the data logger were evenly distributed as shown in Figure 1.

![Figure 1. The position of data logger in the box.](image)

2.2 Heat transfer model
According to the Zeroth law of thermodynamics [7], when temperatures of two points in the nearby location are different, the heat will be transferred from the higher point to the lower heat point until the transfer process reaches thermal equilibrium. The changes in the water temperature indicated that heat transfer exists inside the box. This transfer can be explained by the heat capacity [7] as in Equation (1).

\[
Q = mC_p \frac{dT}{dt}
\]
The water temperature rises due to heat from the external air traveling through the box walls with some of that heat being absorbed by the box wall itself. However, these factors are still insufficient to identify the overall thermal property. This heat transfer can be calculated further using Fourier’s law as in Equation (2). Then, the thermal conductivity \( k \) can be derived from Equation (3). Next, the thermal resistance \( R \) can be derived by Equation (4) [8]. These thermal properties can be used to compare box performance. The thermal conductivity implies how much heat can be absorbed, hence in this case, lower absorption is better. Finally, the thermal resistance identifies how much the heat will be resisted (or insulated) in the box; hence, higher resistance is better:

\[
Q = kA \frac{dT}{dx} \quad (2)
\]

\[
mC_p \frac{dT}{dt} = kA \frac{dT}{dx} \quad (3)
\]

\[
R = \frac{\Delta x}{k} \quad (4)
\]

where \( Q \) = The heat transfer (W), \( k \) = Thermal conductivity (W/m⋅K), \( R \) = thermal resistance, \( A \) = Surface of box (m\(^2\)), \( x \) = Box thickness (m), \( dT/dx \) = Temperature gradient (K/m), \( m \) = Mass of water (kg), \( C_p \) = Specific heat of water (kJ/kg⋅K), \( dT/dt \) = The change in temperature (°C) during a time interval (dt) or 5 min in our study. Then, the time-temperature profiles of each box are analysed and calculated for the values of \( k \), \( R \) and temperature increment. Finally, the statistical analysis is performed on all three boxes using a one-way analysis of variance (ANOVA) followed by a Tukey’s test at a 95% confidence level.

3. Results and Discussion

3.1 Time-temperature profile of three materials
During the first 20 min, thermal equilibrium occurred since the inside box temperature was slightly decreased as shown in Figure 2(a) and 2(b). The heat transfer to the chilled water results in temperature increasing as shown in Figure 2(d). When the temperature at two sides of the boxes is significantly different, then heat transfer occurs. In Figure 2(c), the upper outer box temperature is average at 25±1.5°C while the upper inner average temperature of VIP, PE-Nylon, and PS are 20.07±0.76°C, 23.81±0.24°C and 22.04±0.37°C respectively. For the side inner box, the average temperatures are 19.08±0.92°C, 22.87±0.24°C and 21.10±0.37°C for VIP, PE-Nylon, and PS, respectively. The box with the best performance is of VIP construction, which has the smallest incremental temperature in 3 h for 7.53±0.61°C. The next best performance is PS at 8.41±0.17°C and finally PE-Nylon at 8.91±0.22°C.

3.2 Thermal properties of the delivery box
The thermal conductivity property of delivery boxes plays an important role in raising the temperature of chilled water inside three boxes. The highest temperature differences between the inside and outside temperatures occurred at the VIP box (~5°C) while the PE-Nylon and PS show a lower temperature differences at ~2°C for PS and ~1°C for PE-Nylon, the inner wall of VIP box also maintains the same low temperature for over an hour (Figure 2(a) and 2(b)). The temperature of the chilled water inside the VIP box raised only 1.5°C (Figure 2(d)). These temperature values perform according to \( R \) (and \( k \) in an inverse relationship to \( R \)) of each material. As shown in Table 2, VIP has the lowest \( k \) and the highest \( R \) the same \( R/k \) inverse relationship also applies in PE-Nylon and PS cases.

| Table 2. Comparison the thermal conductivity, thermal resistance and temperature increment of 3 types of box |
|-----------------|-----------------|-----------------|-----------------|
| Delivery Box    | \( k \) (W/m-K) | \( R \) (m²-K/W) | Temperature Increment (°C) |
| VIP             | 0.029±0.011\( \text{b} \) | 1.614±0.740\( \text{a} \) | 7.53±0.61\( \text{a} \) |
| PE-Nylon        | 0.054±0.021\( \text{a} \) | 0.179±0.097\( \text{c} \) | 8.91±0.22\( \text{a} \) |
| PS              | 0.038±0.011\( \text{b} \) | 0.583±0.238\( \text{b} \) | 8.41±0.17\( \text{a} \) |

*the same character indicate no significant difference at 95% confidence interval*
Figure 2. Comparison of changing the temperature by time at each location (a) upper inner box (b) side inner box (c) upper outer box and (d) difference of water temperature.

4. Conclusion

Based on the $R$ and $k$ concept, three boxes of VIP, PE Nylon, and PS materials should perform heat insulation differently. The temperature increment of chilled water should be significantly different among three boxes with the lowest temperature with the high $R$. However, the results show that the temperature chilled water in three boxes is not significantly different at the 95% confidence interval, among three boxes, based upon the physical simulation approach. While the $R$ and $k$ thermal properties concept is used to differentiate materials scientifically, the usage condition also plays very important role in helping define which materials are the best performer. Practically, the high $R$ material also comes with a higher price; therefore, the premium price of a VIP box might yield similar results to less expensive boxes such as NE-Nylon or PS. The finding recommends the effective selection of a delivery box should involve a holistic approach by using $R$ and $k$ along with a physical delivery simulation since the $R$ and $k$ concept alone might be misleading and prompt the selection of a non-economically viable option.

5. References

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