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A Simple Approach for Retention of Stored Heat in A Pizza Delivery Bag

Swarnali Mukhopadhyay* and Ravi Gorthala
Tagliatela College of Engineering, University of New Haven, West Haven, USA.

Abstract

The objective of the study is to examine the thermal properties and heat losses in food carriers. As a case study, improvement on the stored heat content with Phase Change Material is discussed. The purpose of a pizza delivery bag is to have the optimum amount of heat retention capabilities to ensure the deliverance of a hot pizza. This study explores the thermal properties of a pizza and the delivery bags. The properties were measured using experimental setup created to measure the thermal resistance of different delivery bags. The thermal resistance of the insulation material for the current delivery bags have been experimental determined to be in the range of 0.08 K.m^2/W. The initial heat losses for the pizza is determined to be 12 W for ambient temperature of 15°C. The quantity of Phase Change Material required to maintain the food temperature for 60 mins is estimated to be 199.07g.

Keywords: *Phase Change Material; pizza; delivery bags.*

Nomenclature

A	Surface area
C_{p_pizza}	Specific heat of pizza
C_{p1}	Specific heat of the fat component in pizza
C_{pa}	Specific heat of ash in pizza
C_{pc}	Specific heat of carbohydrate in pizza
C_{pf}	Specific heat of fiber component in pizza
C_{pl}	Specific heat of PCM in liquid state
C_{pp}	Specific heat of protein component in pizza
C_{pw}	Specific heat of water component in pizza
l	Thickness
m	Mass
Q_{bag}	Heat transfer rate of delivery bag
$Q_{drywall}$	Heat transfer rate of drywall
T	Temperature
t	Time
T_{amb}	Ambient temperature
T_i	Initial temperature of pizza
T_{melt}	Temperature of phase change (solid to liquid)
T_{sup}	Maximum operating temperature of PCM
X_1	Mass fraction of the fat component in pizza
X_a	Mass fraction of ash in pizza
X_c	Mass fraction of carbohydrate in pizza
X_f	Mass fraction of fiber component in pizza
X_p	Mass fraction of protein component in pizza
X_w	Mass faction of water component in pizza
λ	Latent heat of fusion

1. Introduction

There have been constant efforts from the food industry for marketing and delivering fast, hot, and fresh food. More specifically, pizza companies promise to deliver hot pizza to the customer's front door in 30 minutes or less, but the problem is that the delivered food often gets cold due to heat

*Corresponding author
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loss and becomes soggy due to moisture condensation because of the heat losses during the delivery process, especially on cold nights. Many companies began implementing solutions for this problem and the first solution they came up with is to increase the thermal resistance by employing traditional insulation materials that work as a simple thermal barrier that reduces the heat loss rate. But it is not enough to keep food at a desirable temperature for a specified duration.

There are two ways to solve this problem (i) increase the thermal resistance of the insulation material in the bag (ii) provide a heating unit which would generate heat and keep the food warm. This heating unit can be 'passive' or 'active'.

A heating unit can be said 'active' when the unit requires a continuous electrical input to operate the heating unit, which in turn keeps the food warm. A 'passive' heating unit is such that it doesn't require a continuous energy source. They act as capacitors which absorbs and stores heat prior to being exposed to the food product. These heating units do their best to preserve the heat and freshness of the food. The proposed heating unit is made of Phase Change Material (PCM).

Three patents have been reviewed which use PCM in food carriers. The first patent [1] has PCM integrated within the rigid insulation of the food carrier boxes. The second patent [2] adopted a heating unit designed for PCM pouches to be charged electrically in a separate warming unit. The PCM pouches have resistances inside them which would enable its charging. The third patent [3] designed a PCM unit which has a resistance coil inside the pouch which would heat the PCM electrically. The fore-mentioned patents have their charging unit inside the pouches, which increases the weight of the pouch, which could otherwise be used to store more PCM for longer food deliverance period. Smith et al. studied different encapsulation of phase change material in pizza delivery bags and its effect on retaining the temperature of the pizza for a designated time period [4]. This study proposes a unique PCM pouch which can be charged inside the food carrier without any plug ins, heated inductively and could be carried off with ease without needing to put the PCM and saving precious delivery time as well as optimizing the weight of the PCM pouch.

The methodology which was followed for the study was experimentation to evaluate the thermal resistance of insulation of a standard delivery bag, followed by analytical simulation to estimate transient temperature with different ambient temperatures. Reduction in heat loss by increasing R_{bag} (l/k) of the delivery bag are assessed and initial heat loss in calculated. Using estimated heat loss, the PCM quantity is determined.

2. Study Methodology

The study consists of the following methodology to determine the requirement of PCM to keep the pizza at a constant temperature of 60℃.

1. Review of existing technologies and patents.
2. Estimation of thermo-physical properties of pizza.
3. Experimental determination of thermal resistance of delivery bag.
4. Estimation of cooling transient temperature curve of the pizza using lumped parameter approach.
5. Estimation of heat loss from the pizza.
6. Estimation of amount of Phase Change Material for delivery period.

3. Result and Discussion

3.1. Thermo-physical property assessment for pizza

The typical pizza consists of two separate components a shell and sauce [5]. Shell is about 55% of the pizza and the rest 45% is sauce. The composition of different ingredients of dough and sauce is furnished in Table 1.

The specific heat is estimated by the following equation

$$C_p = X_p c_{pp} + X_1 c_{p1} + X_c c_{pc} + X_f c_{pf} + X_a c_{pa} + X_w c_{pw} \quad (1)$$

$$C_{pp} = 2.0082 + 1.208e^{-3}T - 1.3129e^{-6}T^2 \quad (2)$$

$$C_{p1} = 1.9842 + 1.4733e^{-3}T - 4.8008e^{-6}T^2 \quad (3)$$

$$C_{pc} = 1.5488 + 1.962e^{-3}T - 5.9399e^{-6}T^2 \quad (4)$$

$$C_{pf} = 1.8459 + 1.8306e^{-3}T - 4.5509e^{-6}T^2 \quad (5)$$

$$C_{pa} = 1.0926 + 1.8896e^{-3}T - 3.6817e^{-6}T^2 \quad (6)$$

$$C_{pw} = 4.1289 - 9.0864e^{-5}T - 1.3129e^{-6}T^2 \quad (7)$$

The thermal properties of the pizza have been calculated for a range of temperature, 30°C - 70°C as listed in the Table 2. The average specific heat capacity values of the pizza are determined with above set of equations the mass fraction of ingredients as furnished in Table 1.

Table1. Mass fraction of dough and sauce.

Composition	Dough (mass fraction)	Sauce (mass fraction)
Carbohydrates X_c	0.438	0.072
Protein X_p	0.082	0.013
Fiber X_f	0.015	0.013
Fat X_1	0.034	0.002
Ash X_a	0.002	0.01
Water X_w	0.34	0.89

Table 2. Specific heat capacity for different components of the pizza.

Temperature (°C)	Protein (J/kgK)	Fat (J/kgK)	Carbs (J/kgK)	Fiber (J/kgK)	Ash (J/kgK)	Water (J/kgK)	Dough (J/kgK)	Sauce (J/kgK)
30	2.043	2.024	1.602	1.844	1.146	4.125	2.371	3.853
40	2.054	2.035	1.618	1.840	1.162	4.123	2.378	3.852
50	2.065	2.046	1.632	1.836	1.178	4.121	2.385	3.852
60	2.076	2.055	1.645	1.831	1.193	4.119	2.391	3.851
70	2.086	2.064	1.657	1.825	1.207	4.116	2.396	3.850

It can be inferred from Table 2 that there is little difference between the specific heat for the different temperatures. Hence, it can be concluded that the specific heat for the pizza is insensitive to the range of temperatures.

3.2. Experimental determination of thermal resistance

Two samples of pizza delivery bag were examined. The dimensions of these bags were taken and the R_{bag}(l/k) values were calculated from an experimental set up that was constructed solely for this purpose. A wooden box was built with insulation panels inside where the heat source a halogen lamp is kept. The opening of the box has a panel of drywall over which the testing samples was kept. Over the testing sample a plexi glass lid was built to limit the heat losses through convection and the sides were sealed with insulation to make the sample air tight as illustrated in the figure 2.

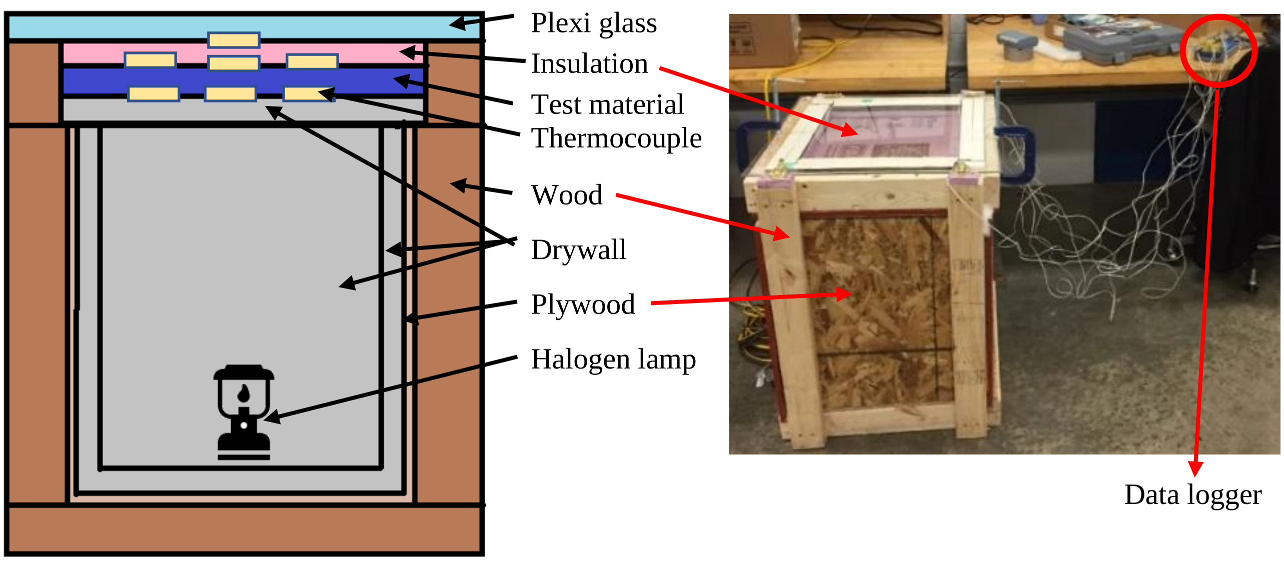

Figure 2. Schematic and photograph of test set up.

7 K-type thermocouples with 1.0 mm diameter are attached on the top and bottom side of the dry wall and top side of the test material (delivery bag panels). 3 thermocouples are placed equidistant from each other on the bottom of the drywall and 3 thermocouples on the top of the drywall, heat transfer rate (Q) is estimated using equation 8. The temperature difference across the thickness of the test material is obtained by the 3 thermocouples on the top side of dry wall and 1 thermocouple placed on the top of the test material. Using the equation 10, R_{bag} is estimated by plugging in the heat loss rate (Q) obtained from the drywall. Figure. 3 shows the average reading of thermocouples from each side of drywall and test material.

$$Q_{drywall} = \frac{A\,(T_{b\_drywall} - T_{t\_drywall})}{R_{drywall}} \tag{8}$$

where $T_{b\_drywall}$ is the average of three thermocouples attached to bottom and $T_{t_drywall}$is average of three thermocouples attached to top. The heat loss is calculated using the equation 8 where thermal resistance of drywall (R) is 0.17 Km^2/W [6].

$$Q_{bag} = Q_{drywall} \tag{9}$$

$$Q_{bag} = \frac{A(T_{t\_bag} - T_{b\_bag})}{R_{bag}} \quad (10)$$

where T_{t_bag} is temperature at Top and $T_{b_bag}$is average of Middle 1,2 and 3; the temperature difference of either side of the test material. R_{bag} is calculated from the other two known values using equation 10.

It is determined that a normal pizza delivery bag's R-value is 0.08 (Km^2/W).

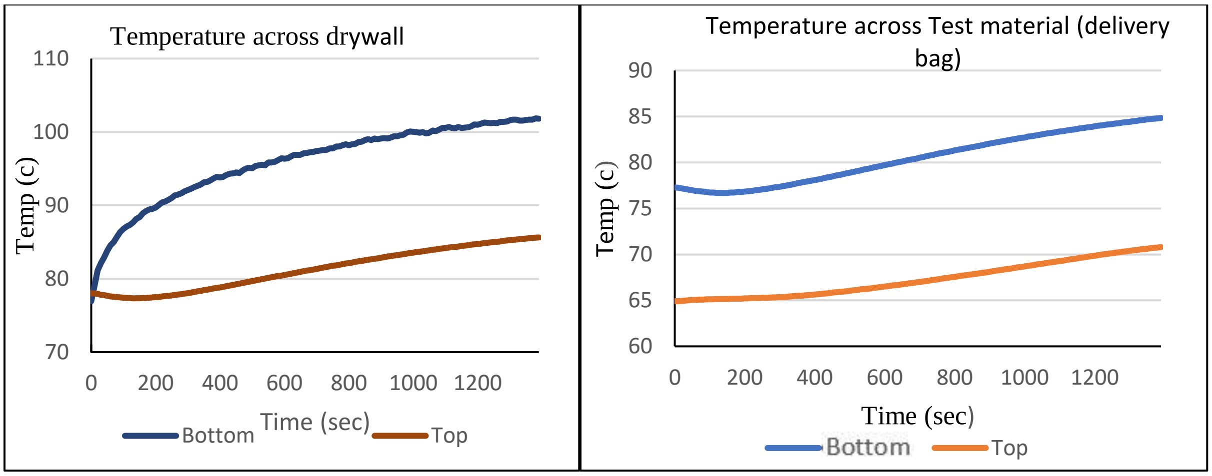

Figure 3. Temperature across thickness of drywall and test material.

3.3. Influence of ambient temperatures and thermal resistance

This study is done to understand the cooling behavior of the pizza at different environment temperatures for a standard bag. Equation 11 is the analytical solution of the lumped heat method which considers the heat transfer from the pizza to the ambient through the air space present between the pizza and the delivery bag. Following analytical equation 11 is used for assessment.

$$T(t) = (T_i - T_{amb})e^{\left(\frac{A\,t}{mc_{p\_pizza}(R_{air}+R_{bag})}\right)} + T_{amb} \quad (11)$$

where R_{air} (1/hA) is considered constant over the time with natural convection heat transfer coefficient (h) of 5 W/m^2 K. The constant thermo-physical properties of the pizza (C_P = 6.242 J/kgK), following temperature transients (figure 4) are obtained at ambient temperatures of 15 ℃, 20 ℃ and 27 ℃ for a pizza of 0.68kg.

A marginal improvement on heat loss is assessed by increasing the insulation resistances from 0.08 to 0.53(Km^2/W). Following figure 4 shows the pizza temperature variations with time for different ambient temperature 15 ℃, 20 ℃ and 27 ℃.

The cooling transients show that for a delivery period of 60 minutes the increase in R_{bag} values do not have much effect on the pizza cooling for all environment temperatures. However, for early delivery period of 20 minutes the pizza remains warmer by 5 – 10 ℃ for highest value of R_{bag} (0.53) as compared to existing R_{bag} value (0.08). The study indicates that enhancement of R_{bag} value by nearly 6.6 times of the present bag R_{bag} value does not have much bearing on prevention of heat loss from pizza. A combination of higher R_{bag} values and constant energy source is required to compensate the heat loss.

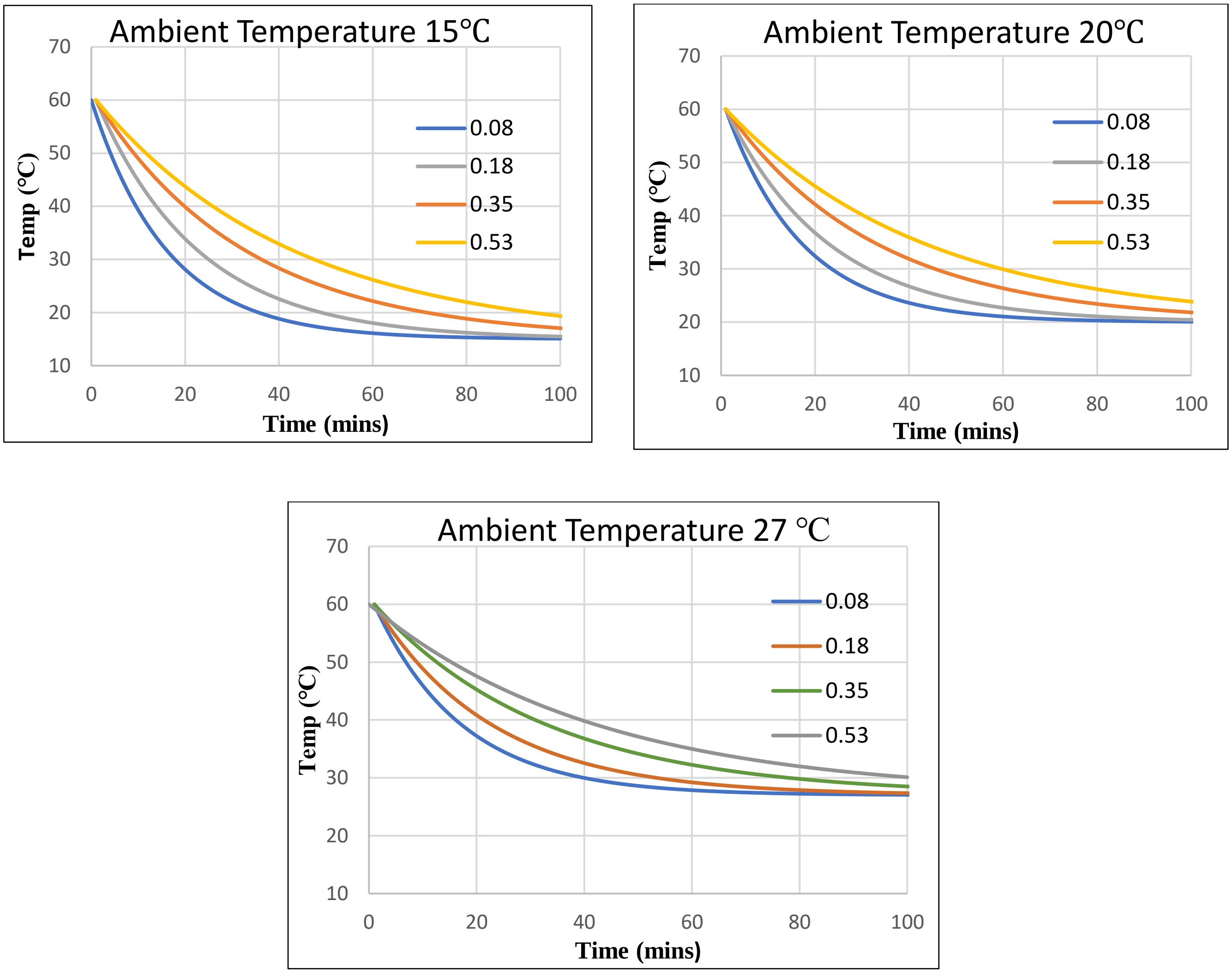

Figure 4. Transient cooling temperature profile of pizza for different R_{bag} and various ambient temperatures.

3.4. Estimation of heat loss

A heat loss estimation for an initial pizza temperature is done with the following equation 12 for different ambient temperatures.

$$Q_{loss} = \frac{A\,(T_{pizza} - T_{amb})}{(R_{bag} + R_{air})} \tag{12}$$

The results of the heat loss estimation for different thermal resistances (R_{bag}) and the ambient temperatures are presented in figure 5. The graphs show that maximum heat loss (12W) occurs for minimum R_{bag} value and minimum ambient temperature; and minimum heat loss (3.2W) for maximum R_{bag} values and maximum ambient temperature.

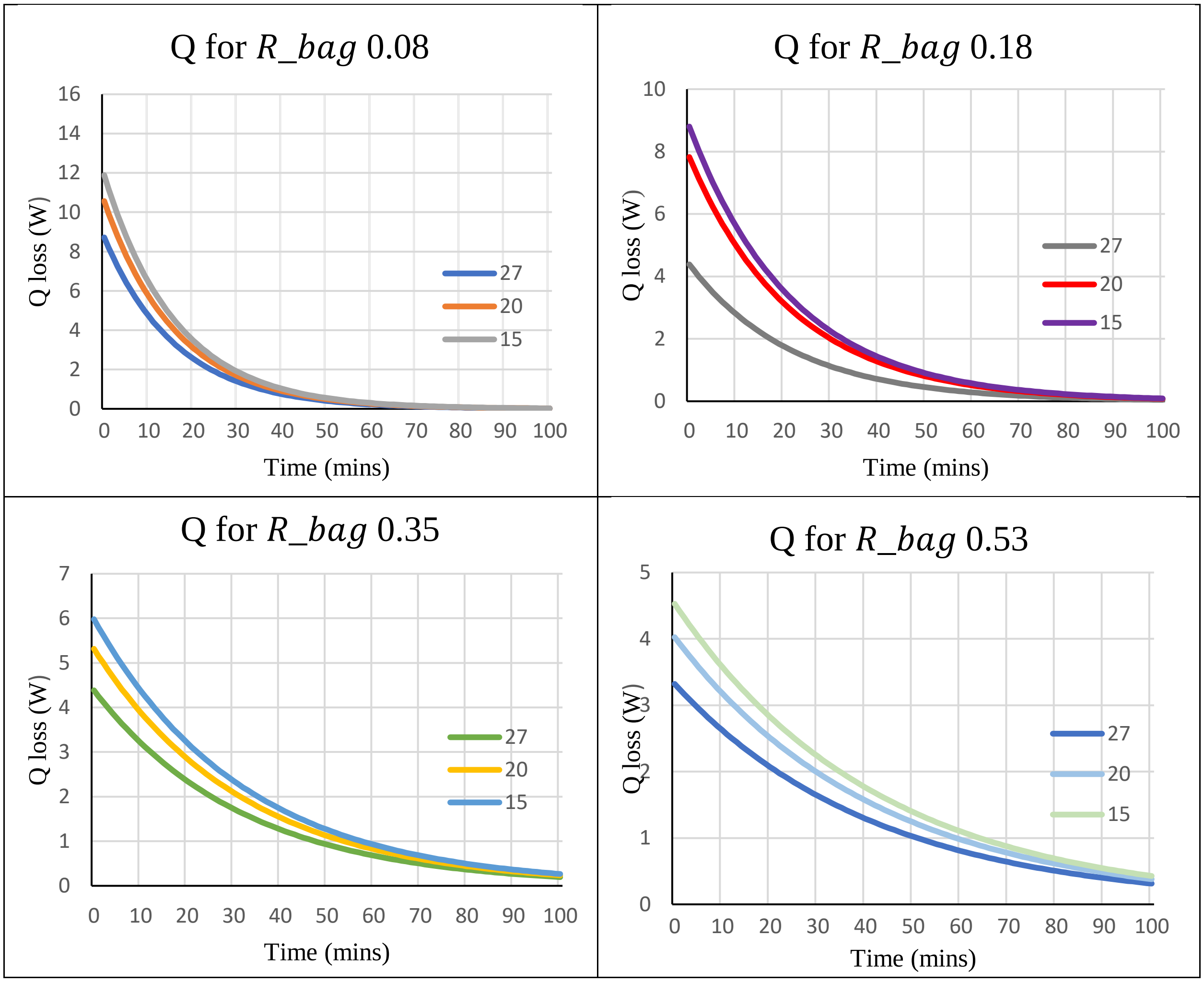

Figure 5. Heat loss in various ambient temperatures for different R_{bag} values.

3.5. Estimation of Phase Change Material Requirements

Phase change transition initiates when the amplitude of the crystal lattice particles oscillate at a force having value larger than that of the crystal binding energy, thus breaking its bonds and transforming into liquid phase (melting). The removal of energy results in the solidification of the material (crystallization). The process is broken down into three phases, (I) solid phase (II) liquid phase and (III) mushy phase. Enthalpies are calculated for different temperature points, based on the latent heat energy dissipated.

The specific PCM which has been chosen to serve the purpose of the heating unit for the pizza bag is PCM-HS89P. It is an inorganic, Phase Change Materials (PCMs) manufactured by savENRGTM, which are a uniquely engineered mixture of hydrated salts that have high capacity to store thermal energy as latent heat. This energy is absorbed and/or released at specific temperatures. Inorganic PCMs retain their latent heat without any change in physical or chemical properties for over thousands of cycles. The thermal properties of HS89P are in Table 3.

Table 3. Properties of PCM HS89P.

Property	Value
Melting Temp. (°C)	87
Liquid Density (kg/m^3)	1540
Solid Density (kg/m^3)	1630
Latent Heat (kJ/kg)	180
Specific Heat-Liquid (kcal/kg.K)	0.63
Thermal Conductivity (W/m.K) Liquid	0.5
Thermal Conductivity (W/m.K) Solid	0.65
Max. Operating Temp. (°C)	105

The amount of PCM required in the delivery bag should be able to balance the heat loss (Q_{loss}) through the pizza delivery bag which is estimated in equation (13).

$$Q_{loss} = \frac{m\, C_{pl}\,(T_{sup} - T_{melt}) + m\lambda}{3600} \quad (13)$$

$$m = \frac{(Q_{loss})\, t}{(\,C_{pl}\,(T_{sup} - T_{melt}) + \lambda)} \quad (14)$$

The estimated requirements of PCM to compensate the maximum heat loss is determined using the equation (14), the values are furnished in Table 4. The estimation is done based on the maximum heat loss that occur at the beginning of cooling transient as illustrated in Figure 5. The properties provided in Table 3 are used for estimation of required PCM mass. A T_{sup} of 90°C is considered to calculate the PCM mass. The compensation will keep the pizza warm at the initial delivery bag filling temperature.

Table 4. PCM requirement for each R_{bag}value and different ambient temperatures.

Ambient Temp (°C)	Mass of PCM (g)			
	R_{bag} 0.08	R_{bag} 0.18	R_{bag} 0.35	R_{bag} 0.53
27	145.98	108.27	73.57	55.66
20	176.95	131.24	89.18	67.47
15	199.07	147.65	100.33	75.90

Table 4 shows a variation of requirement from 199.07 g to 55.66 g for a delivery period of 60 minutes, which is a higher estimate for delivery service. The minimum and maximum requirement of PCM depends on the R values and ambient temperatures. The estimation is helpful to use the quantity of PCM to be used for different weather conditions. This in turn will help to optimize the time requirement for its recharge prior to its insertion into the bag. To include other unaccounted heat losses an extra 25% more PCM could be considered as a conservative design.

4. Conclusion

A simple idea is evolved to keep the food warm with PCM with initial induction heating. As a case study, delivery of warm pizza is being discussed. The study shows that with addition of PCM it is possible to keep the pizza warm to its initial temperature. The study further shows that requirement of PCM varies with weather conditions as well the thermal resistance of the delivery bag.

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Biographical Information

Swarnali Mukhopadhyay is currently a PhD student at McMaster University in Mechanical Engineering department. She got her Master of Science degree in mechanical engineering from University of New Haven.

Dr. Ravi Gorthala is an associate professor at the University of New Haven with over 20 years of industry experience having received funding from DOE, DOD, NASA, NIST, ASHRAE, Long Island Power Authority, Electric Power Research Institute and New York State Energy Research and Development Authority. While his research and development interests are diversified (energy, building technologies and polymer composites), his focus is on renewable energy technologies.