Utilization of Al/SiO_2 Reaction in Self-Heating Cylinder to Warm up Beverages

Amery, Haniyeh; Azizi, Mohammad Hossein*+*

Department of Food Science and Technology, Tarbiat Modares University, Tehran, I.R. IRAN

Salimi, Azadeh

Veterinary Department, Semnan University, Semnan, I.R. IRAN

ABSTRACT: *With the advancement of technology, food packaging has gradually changed to make changes for the consumer's convenience. Self-heating packages allow customers to heat drinks by using exothermic reactions. In this study, a cylinder made of 316L stainless steel was used to heat 200 mL tea and 200 mL low-fat pasteurized milk using silicon dioxide and aluminum reactions. For this purpose, after pouring the reactive material and closing the cylinder lid, the heating process began by placing it inside the beverage. As a result, the temperature inside the cylinder after 82 s (1 minute and 22 s) increased from 28.1 °C to 122.6 °C and this amount of heat led to an increase in the temperature of the tea from 26.3 °C to 40.9 °C in 277 s (4 min and 37 s). Also, after 563 s (9 min and 23 s), the milk temperature increased from 24.8 °C to 38.1 °C. Then, the heating of the cylinder containing this reaction inside the mentioned beverages was simulated and modeled using COMSOL Multiphysics software. It has been determined that the experimental data and simulated models were properly fitted.*

KEYWORDS: *Self-heating; Exothermic reaction; Kinetics; Simulation.*

INTRODUCTION

Consumer demand and market trends are constantly evolving in the direction of convenience foods, which require easier maintenance and should have new features. In the last two decades, the concept of active packaging has been recommended as an innovative concept for food packaging according to these demands [1].

Self-heating packaging is a type of active food packaging that is able to heat food without the need to use an external heat source. This type of canned food is usually useful for mountaineers and people who do not have access to microwaves and stoves (heating appliances) [2]. The major limitation of this heating system is that the major part of the package space is engrossed by the heating device [3].

Various solid-state chemical reactions might be used to supply a compact, lightweight, and powerful heat source [4]. One of these solid-state exothermic reactions is the aluminum and silicon dioxide reaction. Brody's studies in 2012 [5] showed that by using aluminum and silica, the exothermic reaction could heat a glass of coffee or a bowl of soup in less than 2 min.

In 2013, *Coffey et al.* [6] described the mechanism of activating a type of self-heating can containing a solid-state reaction. The can consist of a plunger coupled to the canister, the blister containing the starter fluid, absorbent material, and a solid-state reaction mixture.

* *To whom correspondence should be addressed.*

\+ *E-mail: azizit_m@modares.ac.ir*

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Table 1: Cylinder dimensions.

Full dimensions of the cylinder with lid (mm)	*Total height*	*84*
	Internal diameter	*30*
	External diameter	*39*
	Thickness	*4.5*
Dimensions of the cylinder without lid (mm)	*Internal height*	*73*
	External height	*76*
Lid dimensions (mm)	*Internal height*	*11.8*
	External height	*17.5*
	Internal diameter	*38*
	External diameter	*45*
	Thickness	*3.5*

Fig. 1: Cylinder made of stainless steel 316L.

When the plunger was pressed by the user, the blister was ruptured and the sequence resulted in the chemical reaction between the fluid out of the blister and the absorbent material. Thus, by generating intense localized heat, the reaction of the solid-state reaction mixture and heat generation began.

In 2015, *Huselton* [7] described a heating bag containing a thermal element that reacted with water to generate heat or steam in a multi-step chemical reaction process. The most desirable ratios in this field included a heating element with 30-45% aluminum powder, 10-20% calcium oxide powder, 15-25% calcium carbonate powder, 10-15% calcium dihydroxide, 10-15% sodium carbonate powder and 0.1-1% sodium hydroxide based on the total weight of the heating element (approximately 50 g) which were in contact with approximately 6 oz (177.44 mL) of water. The reaction could reach a temperature of approximately 212 °F (100 °C). According to his study, temperatures above 200 °F could be maintained for at least 25 min and temperatures above 175 °F for at least 50 min.

Concerning the aluminum and silicon dioxide reaction, in 2021, *West et al*. [8] offered a heat-generating formulation comprising a mixture containing 15-25% aluminum, with a particle size of 2-30 microns, 20-30% silicon dioxide, 25-45% alumina and additives and reaction aids such as potassium chlorate, calcium fluoride, and barium peroxide.

The main problem with self-heating cans is that they are disposable and also limited to a specific type of beverage inside the package and the volume of the container. Therefore, the aim of this study was to make a reusable cylinder made of stainless steel in which reactive materials including silica and aluminum were poured, and thus the exothermic reaction took place inside the cylinder. The cylinder was then inserted into the beverage and heated it. This cylinder has advantages more than self-heating packaging including portability, the ability to use it in different containers and most importantly its repeated usage for more than one time. According to studies, heretofore, no device like the present cylinder has been made to use in beverages to warm up them.

EXPERIMENTAL SECTION

Materials

In this study, chemicals including aluminum powder (Merck), silicon dioxide (Merck), alumina (Merck), potassium chlorate (Merck), calcium fluoride (Merck), barium peroxide (Merck), and sodium hydroxide (Merck) were prepared.

As illustrated in Fig. 1, first of all, a cylinder made of stainless steel 316L with the dimensions listed in Table 1 was made.

Methods

First, the reactants were combined in a certain ratio and the amount of heat generated in different states was measured by the digital thermometer (TP101 model made in China). Then, the kinetics of temperature changes in containers with a certain volume, containing tea and low-fat milk, has been investigated. Since some errors like the purity of reactants and excess moisture were important to access trustworthy results, we used high-quality materials as mentioned before. Moreover, all of the experiments were repeated 2-3 times and the reproducibility of the experiments was checked on different times and days.

Lastly, the heating of the cylinder containing this reaction inside the mentioned beverages has been simulated and modeled using COMSOL Multiphysics software and the obtained results have been studied.

To perform the reaction of silicon dioxide and aluminum, by adapting to Huselton's findings in 2015 [7], sodium hydroxide and aluminum were used for activation. For this purpose, some solid sodium hydroxide was first mixed with distilled water to form a supersaturated and pasty state. Then, certain amounts of sodium hydroxide and aluminum were combined and the rate of temperature increase was investigated. According to the studies the best result was obtained for a ratio of 8 to 1 ((sodium hydroxide/aluminum) (w/w)) and therefore this ratio was used for subsequent reactions.

To perform the reaction of aluminum and silicon dioxide, by adapting to *West et al*., findings in 2021 [8] 1.5 g of aluminum, 2 g of silicon dioxide, and 2.5 g of alumina with reaction aids including potassium chlorate, calcium fluoride and barium peroxide in the amount of 0.2 g each, (a total of 6.6 g) were weighed in a beaker by a laboratory scale (with a sensitivity of 0.01 made by Electronic Balance Iran) and then were combined.

The experiment was performed in 4 cases, as follows.

Block 1. Combining reactants + aids at once with sodium hydroxide and aluminum; Block 2. Combining reactants at once with sodium hydroxide and aluminum; Block 3. Carrying out the reaction of sodium hydroxide and aluminum, raising the temperature to the maximum and then adding reactants + aids; Block 4. Performing the reaction of sodium hydroxide and aluminum, raising t he temperature to the maximum, and then add the reactants.

Then, to understand the effect of adding each of the reactants (aluminum, silicon dioxide, and alumina) to the mixture of sodium hydroxide and aluminum, each of these materials was added to the mixture separately.

In the last step, to perform the reaction inside the cylinder and to transfer heat to all parts of the cylinder uniformly, 6 g of sodium hydroxide in a ratio of 1 to 1 was combined with distilled water and to dissolve sodium hydroxide in water completely, an electric magnetic heater (MS-H-S model made by China Dragon Lab Company) was used at ambient temperature. Then, this solution was added to other materials with the same values as before to check the temperature increase.

Investigating the heating of reactions inside the beverage

To investigate the behavior of aluminum and silicon dioxide reaction in beverages, an aqueous solution consisting of 6 g of sodium hydroxide in a 1:1 ratio was prepared with distilled water and poured gently into the cylinder containing reactants + aids. Then, the lid of the cylinder was closed and to heat the drink, the cylinder was immediately placed in a disposable 330 mL paper glass containing 200 mL of tea and once again in 200 mL of low-fat pasteurized milk at room temperature. Then, a graph of temperature changes over time (kinetics) was drawn in Microsoft Excel 2019 software [9].

Performing simulation and modeling of heat transfer

At this stage, according to studies by *Ho et al.* in 2010 [10], the heat transfer from reactants to the cylinder and food samples was stimulated by COMSOL Multiphysics 5.5 software [11].

For modeling in the software, the whole system after placing the cylinder inside the beverage consisted of the following 3 parts:

- Inside the cylinder, which was the site of the exothermic chemical reaction.
- Cylinder body.
- Beverage.

In general, the theory of heat transfer in fluids and solids follows Fourier's law:

$$Q=\rho C_p \frac{\partial T}{\partial t} + \nabla.q \tag{1}$$

$$q= -k\nabla T \tag{2}$$

where ρ is density in kg/m^3, C_p is heat capacity at constant pressure in J/(kg K), T is the temperature in Kelvin, t is time in s, q is heat flux in W/m^2, Q is the amount of heat produced in terms of W/m^3 and k is the thermal conductivity in W/(m K).

Inside the cylinder (c), the reactants were mixed and the chemical reaction took place:

$$Q=\rho_c C_{p,c} \frac{\partial T_c}{\partial t} + \nabla.q_c \tag{3}$$

In Equation (3), the amount of heat generated (Q) was equal to the amount of heat generated by the reaction (Q_0):

$$Q=Q_0 \tag{4}$$

$$Q_0 = -r.H \tag{5}$$

where r is the reaction rate in mol/(m^3 s) and H is the enthalpy of reaction in J/mol.

After generating heat due to a chemical reaction, the heat was transferred to the cylinder body (s) (no heat was generated in the cylinder body):

$$\rho_s C_{p,s} \frac{\partial T_s}{\partial t} = -(\nabla.q_s) \tag{6}$$

In the cylinder body, heat transfer was done in the form of conduction. The general equation for this type of heat

Table 2: Investigation of the composition of different ratios of sodium hydroxide and aluminum.

Ratio	Amount of sodium hydroxide (g)	Amount of aluminum (g)	Initial temperature (°C)	Final temperature (°C)	Temperature changes (°C)
1 to 1	0.5	0.5	19.5	No temperature change	0
2 to 1	1	0.5	19.5	25.8	6.3
3 to 1	1.5	0.5	19.5	27.9	8.4
4 to 1	2	0.5	19.5	54.5	35
6 to 1	3	0.5	19.5	76.3	56.8
8 to 1	4	0.5	19.5	108.9	89.4

transfer was Equation (2), but this Equation was defined as a surface with a thickness:

$$Q^{\cdot} = -kA\frac{\partial T}{\partial x} \tag{7}$$

In this Equation, $Q^{\cdot}$ is the amount of heat transferred in terms of W, A is the area in terms of m^2 and x is wall thickness in terms of m.

Since most of the heat transfer from inside the cylinder to the beverage was done by the cylinder body, Fourier's law was written as follows:

$$Q^{\cdot}_{cyl} = \frac{T_1 - T_2}{R_{cyl}} \tag{8}$$

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi kL} \tag{9}$$

In these Equations, $Q^{\cdot}_{cyl}$ is the amount of heat transferred in the cylinder body in terms of W, T_1 is the temperature inside the cylinder in terms of Kelvin, T_2 is the temperature outside the cylinder in terms of Kelvin, R_{cyl} is the conduction resistance of the cylinder in terms of K/W, r_1 is the inner radius of the cylinder in terms of m, r_2 is the outer radius of the cylinder in terms of m and L is the length of the cylinder in terms of m.

The heat generated was then transferred to the beverage (f) (no heat was generated in the beverage):

$$\rho_f C_{p,f}\frac{\partial T_f}{\partial t} = -(\nabla . q_f) \tag{10}$$

Because the heat transfer inside the beverage was in the form of convection, the heat flux relation (q) was written as follows:

$$-n.q = h(T_{ext} - T) \tag{11}$$

In this Equation ,is unit normal vector on the boundary wall, h is hthe eat transfer coefficient in W/(m^2 K), T is the temperature in the boundary wall (cylinder body) in Kelvin and T_{ext} is fluid temperature away from the boundary wall in Kelvin.

It should be noted that the simulation was performed in optimal and closed conditions and also heat loss was eliminated. Therefore, all disposable glass walls with bottom and top were closed and considered as thermal insulation:

$$-n.q = 0 \tag{12}$$

All of these Equations were based on information obtained from the COMSOL Multiphysics software and the COMSOL Multiphysics 5.4 software manual entitled Heat Transfer Module, published in 2018, *Ho et al.* studies in 2010, and *Bahrami* studies in 2009 [10-13].

RESULTS AND DISCUSSION

In this section, the results of performing the chemical reaction, heat generation of the reaction within the beverage and heat transfer simulation and modeling are provided and it should be noted that all of the experiments were repeated 2-3 times and the reproducibility of the experiments was checked on different times and days.

Performing the chemical reaction

The results obtained from the combination of sodium hydroxide and aluminum can be seen in Table 2.

After selecting the ratio used for sodium hydroxide and aluminum, the reaction of aluminum and silicon dioxide was investigated.

According to studies by *Zhang et al.* in 2016 [14], the Al/SiO_2 reaction in adiabatic conditions is associated with significant self-heating after weakening of the primary structures under different initial temperatures, which shows a large amount of heat production after the thermite reaction occurs.

The results of the study of 4 test cases in 45 min were as follows.

According to Fig. 2 and the explanations provided in Table 3, the results obtained from block 1 showed higher temperature levels than other blocks, therefore the first block was selected for other experiments.

The results of comparing mixing aluminum, silicon dioxide and alumina with sodium hydroxide and aluminum separately in 45 min are illustrated in Fig. 3.

Table 3: Investigation of the warming capacity of aluminum and silicon dioxide reaction in 4 test cases.

Test cases	Initial temperature (°C)	Final temperature (°C)	Temperature changes (°C)	The time to reach the maximum temperature	Explanations
Block 1	19.9	176.8	156.9	107 s (1 min and 47 s)	Combining reactants + aids at once with sodium hydroxide and aluminum.
Block 2	24	140.8	116.8	85 s (1 min and 25 s)	Combining reactants at once with sodium hydroxide and aluminum. The time to reach the maximum temperature was faster than in the first case, but the maximum temperature was lower and the amount of gas production, in this case, was higher than in the previous case.
Block 3	20.8	130.1	109.3	95 s (1 min and 35 s)	Carrying out the reaction of sodium hydroxide and aluminum, raising the temperature to the maximum (130.1 °C) and then adding reactants + aids. The time to reach the maximum temperature was faster than in the first case, but the maximum reaction temperature was lower and, contrary to expectations, after adding the reaction materials, the temperature did not exceed 130.1 °C and then decreasing of temperature started.
	130.1	-	-	- Total time: 95 s (1 min and 35 s)	
Block 4	21.1	135.3	114.2	86 s (1 min and 26 s)	Performing the reaction of sodium hydroxide and aluminum, raising the temperature to the maximum (135.3 °C) and then adding the reactants. In this case, after the temperature dropped to 130.5 °C, the temperature started to rise again and reached 165.9 °C after 27 s. The total time to reach the maximum temperature was 113 s (1 min and 53 s), which took more time than all the previous blocks and also the maximum temperature was lower than the first block. In this case, also, due to the lack of reaction aids, the amount of gas produced was higher.
	130.5	165.9	35.4	27 s Total time: 113 s (1 min and 53 s)	

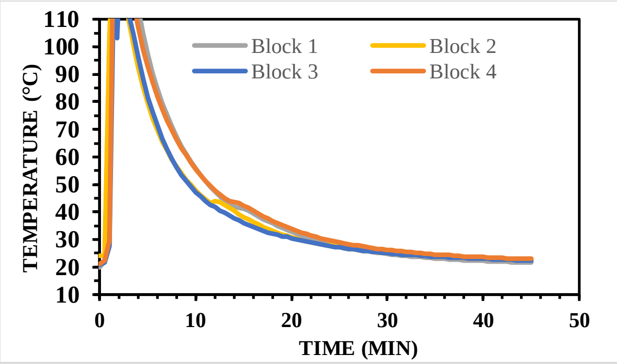

Fig. 2: Kinetic of temperature changes (the aluminum and silicon dioxide reaction).

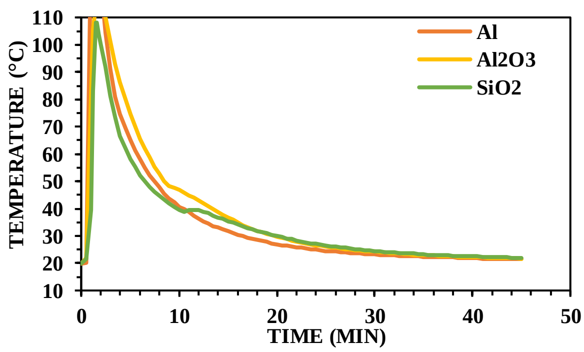

Fig. 3: Kinetic of temperature changes of aluminum, silicon dioxide and alumina.

As shown in Fig. 3, the temperature of the aluminum rose from 19.8 °C to a maximum temperature of 169.9 °C in 73 s (1 min and 13 s). The temperature of alumina and silicon dioxide increased from 19.9 °C to 117.6 and 108.1 °C in 107 s (1 min and 47 s) and 91 s (1 min and 31 s), respectively. As a result, the time to reach the maximum temperature in aluminum was shorter and the maximum temperature was higher than others.

Since the materials after mixing were often solid, heat transfer to all parts of the cylinder and outside it was not done well, therefore after combining all the reactants and aids, an aqueous solution with 6 g of sodium hydroxide was mixed with distilled water in a ratio of 1:1 and added to other reactants in the cylinder.

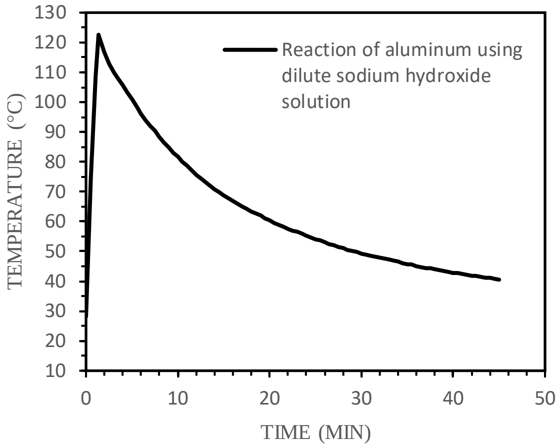

Fig. 4: Kinetic of temperature changes of reaction using sodium hydroxide solution with new ratio.

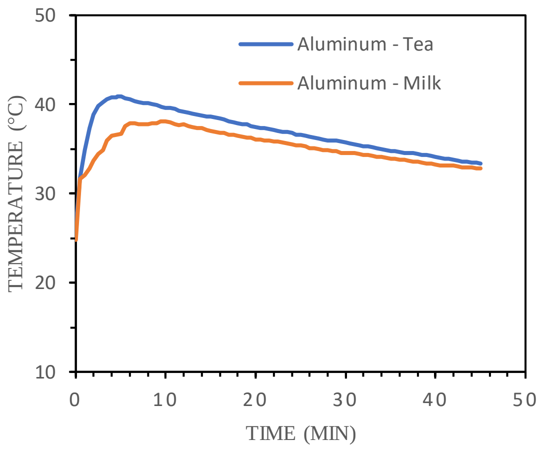

Fig. 5: Kinetics of the temperature changes of tea and milk in the reaction of silicon dioxide and aluminum.

As shown in Fig. 4, by examining this ratio over a period of 45 min, it was found that after 82 s (1 min and 22 s), the temperature of this compound increased from 28.1 °C to 122.6 °C. Despite the lower maximum temperature in comparison to the concentrated sodium hydroxide solution, as mentioned, in order to transfer the temperature evenly to all parts of the cylinder, the new ratio was selected for further experiments.

According to the obtained results, the cylinder containing reactive materials with a closed lid was tested outdoors and it was concluded that this amount of gas production did not cause the closed cylinder to explode and the cylinder can be used for in-drink testing.

Investigating the heat generation of the reaction within the beverage

The kinetic of temperature changes in food samples (tea and milk) in the case of silicon dioxide and aluminum reactions in the cylinder is illustrated in Fig. 5.

According to Fig. 5, after placing the cylinder in the glass containing the tea, the beverage temperature increased from 26.3° C to 40.9 °C in 277 s (4 min and 37 s).

According to this diagram, the warming time of the milk sample was longer than tea and after 563 s (9 min and 23 s) the milk temperature increased from 24.8 °C to 38.1 °C. Thus, temperature increase in tea and milk were 14.6 °C and 13.3 °C, respectively.

The results were close to the results of studies by *Coffey et al*. in 2014 [15], which used the Al/SiO_2 reaction to heat 120 g of water. After activating the reaction using an electric current, the water temperature rose from about 23 °C to about 46 °C in less than 2 min.

Also, according to studies by Wida in 2020 [16], a self-heating coffee can was heated to 130 °F (54.4 °C) in 2 min by an oxidation process (reaction of silicon dioxide and aluminum).

In 2021, *Defrin et al*. [17] surveyed 115 healthy volunteers to investigate the desired temperature for drinking tea and several other foods. The threshold for warm sensations (WST) and the threshold for heat-pain sensations (HPT) were also measured on their tongues. They concluded that individuals differed in terms of temperature preferences for reasons still unknown and that these preferences may be inherent. Participants were divided into three sub-categories: low, medium and high in terms of tea temperature selection. Of the 115 participants in this study, 19 preferred the temperature of 40-50 °C, 76 preferred the temperature of 51-71 °C, and 20 preferred the temperature of 72-82 °C to drink tea. People in the "low temperature" category had significantly lower WST and HPT in the tongue and hands than those in the "medium temperature" and "high temperature" category (i.e., people who preferred to drink hot or boiling tea, respectively). As a result, a similar gradual pattern was observed for the reported preferences, in which "low temperature" people preferred to consume other beverages and foods at a much lower temperature than "medium temperature" and "high temperature" individuals.

As shown in Fig. 5, tea temperature raised higher and

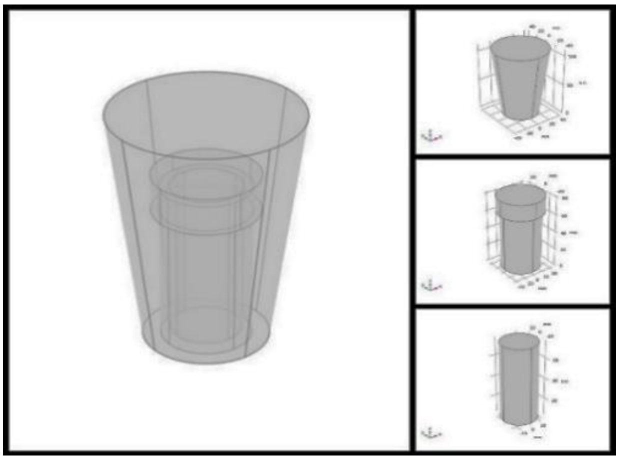

Fig. 6: Virtual image of the glass and the cylinder before starting the process.

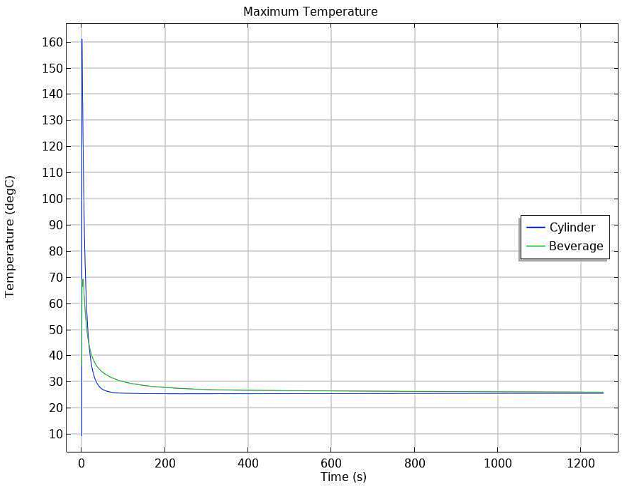

Fig. 7: Simulated kinetic of temperature changes in cylinder and tea in 1200 s.

in a shorter period of time than milk. This was in contrast to the results of Mahnoor Asghar's study in 2021 [18], which reported that although milk has a higher boiling point than water when it comes to boiling, milk boils faster than water. The reason for this is a phenomenon known as "specific heat capacity". While the specific heat of water is 4.184 kJ/K kg, it is 3.93 kJ/K kg for milk. Thus, milk boils faster than water.

On the other hand, the boiling point of milk is higher than the boiling point of water due to a phenomenon called "boiling point elevation". Thus, whenever a non-volatile chemical is dissolved in a liquid, an increase in the number of particles in the liquid causes it to boil at a higher temperature [19].

Heat transfer simulation and modeling

In order to simulate the heat transfer in the mentioned reaction, first a shape of a glass containing a drink with a cylinder inside was drawn, according to the dimensions mentioned before. In Fig. 6, the virtual image of the dimensions of the cylinder in a glass (containing 200 mL of drink) is illustrated.

Reaction rates and enthalpies of aluminum and sodium hydroxide reaction, as well as silicon dioxide and aluminum reaction, were required to simulate the heat transfer.

In 2014, *Махов et al*. [20] reported the heat output of the reaction of aluminum and sodium hydroxide as 422 kJ/mol. In 2003, *Aleksandrov et al*. [21] found the rate of this reaction as 6 mL/(s g). In 2000, *Li* and Ming [22] reported the heat output of silicon dioxide and aluminum reaction as 7.61×10^2 kJ/mol. In 2015, *Apakashev* and *Davydov* [23] found the rate of this reaction as 5.7×10^{-1} mol/(m^2 s).

In order to obtain the temperature inside the cylinder (reaction temperature), a point with coordinates (0,0,4) inside the cylinder was selected and the temperature was measured at that point during the simulation. This point was almost identical to the location of the thermometer during laboratory tests (near the bottom of the cylinder).

Since in this simulation the heat transfer was done in a closed environment without heat exchange with the surrounding environment, the time to reach the maximum temperature was faster than the results obtained in the laboratory.

As can be seen in Fig. 7, during the simulation of the heat transfer due to this reaction in the tea container, after 0.36 s, the temperature inside the cylinder increased from 25 °C to a maximum temperature of 161.04 °C. The temperature of the beverage has reached from 25 °C to the maximum temperature of 69.23 °C in 2.87 s.

By comparing Fig. 4 and Fig. 5 with Fig. 7, it can be seen that the reaction behavior in both graphs was almost similar to each other and their difference was in the rate of reaching maximum temperature and final temperature. The difference between the experimental data and the proposed model might be due to the failure to calculate the heat loss.

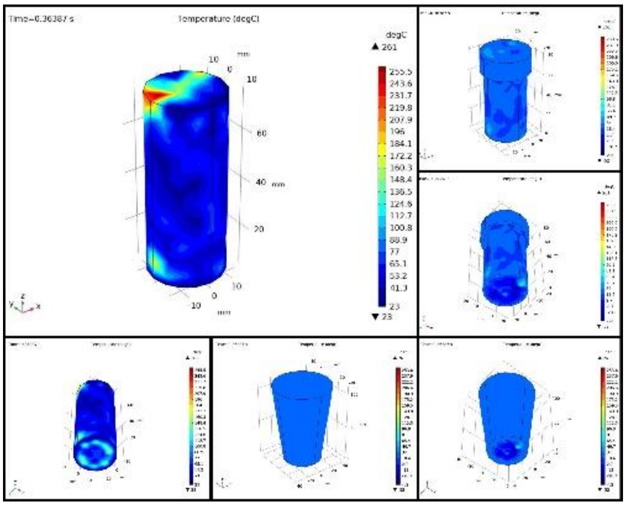

Fig. 8: Heat distribution at the maximum temperature inside the cylinder (tea).

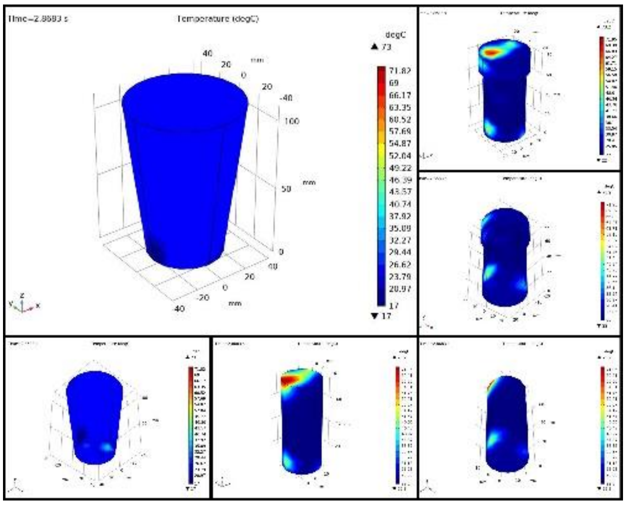

Fig. 9: Heat distribution at the maximum temperature of the beverage (tea).

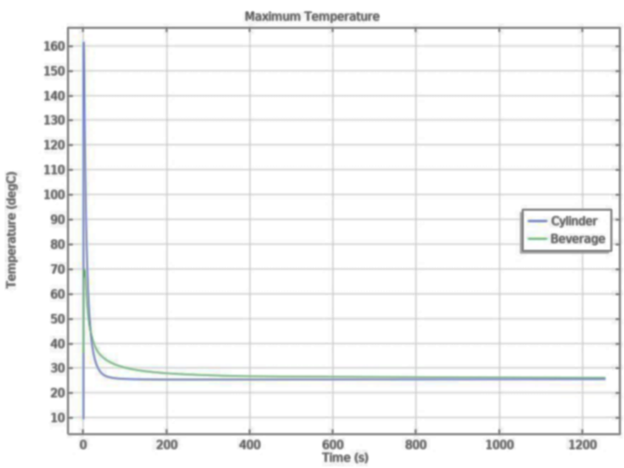

Fig. 10: Simulated kinetic of temperature changes in cylinder and milk in 1200 s.

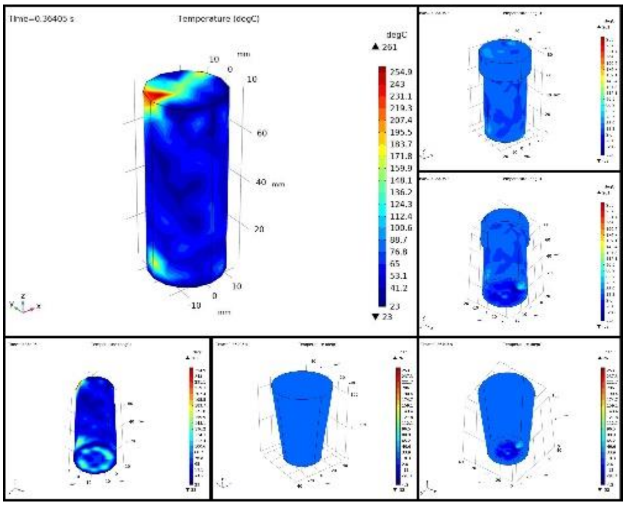

Fig. 11: Heat distribution at the maximum temperature inside the cylinder (milk).

In Fig. 8, the heat distribution in different parts of the cylinder and tea, in 0.36 s (time-related to the maximum temperature inside the cylinder) is illustrated. As can be seen, in some parts of the cylinder, the temperature rises to higher levels in comparison to other parts. This heat might be related to the high gas production in this reaction, followed by the heat due to the accumulation of these vapors.

Fig. 9 also shows the distribution of heat in different parts of the tea and the cylinder in 2.87 s (time-related to the maximum temperature of the beverage).

The kinetic temperature changes in the milk container, which was simulated by software, are illustrated in Fig. 10. The temperature inside the cylinder has reached the maximum temperature of 161.35 °C from 25 °C in 0.36 s. The temperature of milk also increased from 25 °C to 69.99 °C in 0.99 s.

By comparing Fig. 4 and Fig. 5 with Fig. 10, the reaction in both diagrams showed almost the same behavior and according to the reasons mentioned, some differences were observed.

In Fig. 11 and Fig. 12, the heat distribution is illustrated in 0.36 s (time-related to the maximum temperature inside the cylinder) and 0.99 s (time-related to the maximum temperature of the beverage), in different parts of the cylinder and milk. In these Figures, as before, in some parts of the cylinder, a very high temperature was observed.

CONCLUSIONS

Due to the change in lifestyle and the need for rapid preparation of food and beverages, the manufacture and

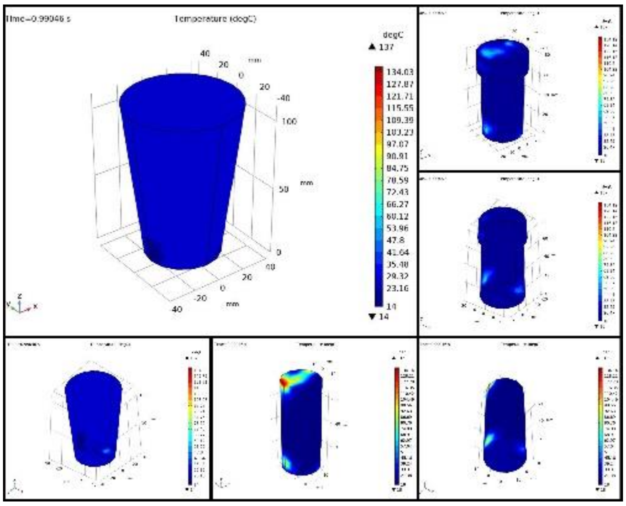

Fig. 12: Heat distribution at the maximum temperature of the beverage (milk).

use of self-heating packaging is a dramatic change in the food industry. In this study, by using a stainless-steel cylinder with aluminum and silicon dioxide reaction, the temperature inside the cylinder in 82 s (1 min and 22 s) increased from 28.1°C to 122.6 °C and by using this amount of heat, the temperature of tea increased from 26.3 °C to 40.9 °C in 277 s (4 min and 37 s). Also, after 563 s (9 min and 23 s), the milk temperature increased from 24.8 °C to 38.1 °C. Thus, temperature increases in tea and milk were 14.6 °C and 13.3 °C, respectively. It has been determined that the experimental data and simulated models were properly fitted.

According to the obtained results and also the innovation in using this device to heat the beverage, more research is needed to increase the final temperature of the drink and make the product safer (in terms of working with sodium hydroxide solution).

In future research, reactive materials can be used with new ratios to achieve higher temperatures. Furthermore, for investigation on heat distribution in beverages, making the cylinder with other materials and changing its size and materials can be performed.

Nomenclature

Area, m^2	A
Heat capacity at constant pressure, J/(kg K)	C_p
Enthalpy of reaction, J/mol	H
Heat transfer coefficient, W/(m^2 K)	h
Thermal conductivity, W/(m K)	k
Length, m	L
Unit normal vector on the boundary	n
Amount of heat produced, W/m^3	Q
Amount of heat transferred, W	Q
Heat flux, W/m^2	q
Conduction resistance, K/W	R
Radius, m	r
Reaction rate, mol/(m^3 s)	r
Temperature, Kelvin	T
Time, s	t
Wall thickness, m	x
Greek symbols	
Density, kg/m^3	ρ
Subscripts	
Reaction	0
Inside/Inner	1
Outside/Outer	2
Cylinder	c
Cylinder	cyl
External	ext
Beverage	f
Cylinder body	s

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REFERENCES

[1] Bodbodak S., Rafiee Z., "3. Recent Trends in Active Packaging in Fruits and Vegetables, In Eco-Friendly Technology for Postharvest Produce Quality", *Academic Press*, 77-125 (2016).

[2] Mohammadian F., Investigation of Heat Generation Process in Self-Heating Packages, *Packag. Sci. Technol*. **4**(13): 44 (2013).

[3] Majid I., Nayik G.A., Dar S.M., Nanda V., Novel Food Packaging Technologies: Innovations and Future Prospective, *J. Saudi Soc. Agric. Sci*. **17**(4): 454-62 (2018).

[4] Coffey, B., Derossi, M., Kwiatkowski, K.C., Ford, B.C., HeatGenie, Inc., High Efficiency Self-Heating Containers, United States Patent US 10,058,209 (2018).

[5] Brody A.L., Packaging-Heating Up (and Cooling Off) Food and Beverage Packaging, *Food Technol.-Chicago*. **66**(4): 81 (2012).

[6] Coffey, B., Kwiatkowski, K.C. and Bookout, T., HeatGenie Inc., Package Heating Device and Chemical Compositions for Use Therewith, United States Patent US 8,555,870 (2013).

[7] Huselton D., inventor, System and Method for Heating Items, United States Patent Application US 14/641,312 (2015).

[8] West J.B., Secker R.E., Kwiatkowski K.C., inventors; HeatGenie Inc, assignee, Self-Heating Package Systems, United States Patent *US 11,009,265* (2021).

[9] Microsoft Corporation, Microsoft Excel (2019).

[10] Ho S.H., Rahman M.M., Sunol A.K., Analysis of Thermal Response of a Food Self-Heating System, *Appl. Therm. Eng.* **30(14-15)**: 2109-15 (2010).

[11] COMSOL AB., COMSOL Multiphysics® v. 5.5, Stockholm, Sweden (2019).

[12] Comsol AB., Comsol Multiphysics-Heat Transfer Module, User's Guide, Version 5.4. (2018).

[13] Bahrami M., Steady Conduction Heat Transfer, ENSC 388 (F09), Retrieved 2021, July 22 (2009).

[14] Zhang J., Si Y., Leng C., Yang B., Molecular Dynamics Simulation of Al–SiO_2 Sandwich Nanostructure Melting and Low-Temperature Energetic Reaction Behavior, *RSC Adv.* **6(64)**: 59313-8 (2016).

[15] Coffey B., Schropp Jr D.R., Kwiatkowski K.C., inventors; HeatGenie Inc, assignee, Solid-State Thermite Composition Based Heating Device, United States Patent *US 8,864,924* (2014).

[16] Wida E.C., La Colombe Launched a Self-Heating Can of Coffee, Retrieved 2020, September 28 (2020).

[17] Defrin R., Dekel-Steinkeller M., Urca G., Some Like It Hot: Preference for Temperature and Pungency Consumption is Associated with Sensitivity to Noxious Heat, *Eur. J. Pain.* **25(2)**: 473-84 (2021).

[18] Asghar M., Why Does Milk Boil Faster than Water, Retrieved 2021, August 19 (2021).

[19] Helmenstine A.M., What Is the Boiling Point of Milk, Retrieved 2021, August 19 (2019).

[20] Махов С.В., Бичурина И.А., Решетов В.А., Теоретический и экспериментальный анализ экзотермических реакций для химической генерации тепла, *Фундаментальные и прикладные исследования: проблемы и результаты*, **(15)**: 161-165 (2014).

[21] Aleksandrov Y.A., Tsyganova E.I., Pisarev A.L., Reaction of Aluminum with Dilute Aqueous NaOH Solutions, *Russ. J. Gen. Chem.*, **73(5)** (2003).

[22] Li M., Ming X.Q., Probe into Measures to Increase Recovery in Vanadium Aluminium Alloy Smelting, *Ferro-alloys*, **4(11)** (2000).

[23] Apakashev R.A., Davydov S.Y., Study of the Interaction of Molten Aluminum with the Contact Surface of a Quartz Refractory, *Refract. Ind. Ceram.* **56(2)**:194-6 (2015).