Hand warmers are used in cold environmental conditions to warm hands. Disposable air activated hand warmers and reusable hand warmers which generate heat by crystallization are present in the market. In the present study utilizing heat of wetting of silica gel and zeolites in warming hands was tested in a system simulated to warm hands by inserting warmer packages in knitted wool gloves. Sodium acetate solution was also tested as a reusable hand warmer by melting and recrystallization. While the commercial warmers released heat slowly for long period, dry silica gel and dry zeolite 4A released heat fast. Around 25% water and inert dilution materials should be used to limit the temperature rise in silica gel and zeolite 4A within reasonable limits.

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INTRODUCTION

Hand warmers are small packets, creating heat when needed, to warm the cold hands. They are activated by opening to air or triggering crystallization or dissolution depending on their type. They are placed in hands under a glow after heat activation. Exothermic reactions take place in hand warmers. There are various exothermic reaction such as air oxidation of charcoal [1], iron [2], gasoline [3,4], redox reactions of ingredients [5], salt dissolution [6] or crystallization in water [7]. Preventing heat transfer from hands by a heat insulator is another method of keeping hands warm in cold [8].

AIR ACTIVATED HAND WARMERS

Charcoal hand warmer
First hand warmers provide heat up to 6 h by slow combustion of charcoal. A charcoal stick was used for this purpose. The stick was lit from one or two ends and then extinguished for slow combustion. The slow burning stick was placed inside metal case coated with felt. The combustion was continued to create heat for long periods [1].

Iron powder hand warmer
Disposable hand warmers in the market such as Grabber Mycoal(™) or heat factory(™) gives the heat by the reaction of iron and oxygen. Iron powder, salt, water, an
enthalpy change of $-798.0 \pm 6.6 \text{ kJ mol}^{-1}$ [12].

With 50% iron powder, 25% distilled water, 20% activated wood, polyacrylate or vermiculite are present in the mixture. Pulverized powder with carbon. Adsorbent material which could be vermiculite slows down the heat dissipation [9-11]. Pulverized wood, polyacrylate or vermiculite are present in the mixture to control moisture [2]. Weiland et al. [2] and Tam et al. [11] reported an example for the composition of hand warmers to control moisture.

The iron oxidation reaction shown in Equation 1 has an enthalpy change of $-798.0 \pm 6.6 \text{ kJ mol}^{-1}$ [12].

$$2\text{Fe} + \frac{3}{2}\text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 \quad (1)$$

The reaction rate depends on the surface area of metallic iron and oxygen pressure. While at atmospheric pressure the maximum temperature attained was around 48°C, for pure oxygen at 3 bar pressure it was above 110°C [13]. The effects of temperature and the humidity of the air medium were investigated by Klarzak et al. [14]. It was found that temperature rather than the humidity significantly affected the heat effect of the air activated hand warmers. The shape of the hand warmer rather than its presence in a protective glove impaired the skill of using hands [15].

Gasoline hand warmers

The PEACOCK(™) and Zippo (™) pocket warmers make use of the flameless combustion of gasoline vapor to carbon dioxide and water with the catalytic effect of platinum. The activation of the catalyst is done by heating gasoline with a match, cigarette lighter or an electric cell. The PEACOCK(™) pocket warmer utilizes oxidation heat generated during the catalytic process. This is an advanced pocket warmer, safe, clean, and environmentally friendly [3,4].

Redox reaction hand warmers

Hypochlorite salts such as sodium hypochlorite or calcium hypochlorite in water and lignocellulosic material mixture is a source of exothermic reaction. The alcohol groups of cellulose are oxidized to ketones first than carboxylic acids with hypochlorite by an exothermic reaction. It was possible to obtain different temperatures for different periods by regulating the proportions of the reactants [5].

Heat of solution of crystals hand warmers

Vannatta et al. [6] designed a hand warmer by using the exothermic heat of solution of anhydrous calcium chloride in water. Dynarax(TM) heat pack in the market uses heat of solution of magnesium sulphate in water. Water present in a rupturable container is mixed with salt by squeezing the package.

Heat of Crystallization Hand Warmers

Sodium acetate trihydrate hand warmers

Sodium acetate trihydrate is also used in making hand warmers. When it is heated above 58°C it starts to lose its water of hydration and dissolves in that water up to 79°C. When the solution temperature is lowered to 20°C, it is unsaturated with respect to anhydrous sodium acetate, but it is supersaturated with respect to sodium acetate trihydrate. When a seed crystal of sodium acetate trihydrate is added, sodium acetate trihydrate crystallizes out with an exothermic reaction releasing 19.7 kJ mole$^{-1}$ energy [16]. If a flexible metal disc is placed in supersaturated solution and it is bended, the crystallization of sodium acetate trihydrate is triggered as indicated by Equation 2.

$$\text{Na}^+\text(aq) + \text{CH}_3\text{COO}^-\text(aq) \rightarrow \text{Na}^+\text{CH}_3\text{COO}^- \cdot 3\text{H}_2\text{O} \quad (2)$$

The latent heat of phase change for sodium acetate trihydrate for 25% and 33% aqueous solutions was reported as 243 kJ kg$^{-1}$ and 264 kJ kg$^{-1}$ respectively [7] or 237-243 kJ kg$^{-1}$ [17]. The seed crystals trapped in metal disc act as nucleation centers. Various metal appliances such as screws, paper clips etc. also triggered the crystallization of sodium acetate trihydrate [18].

Thermal energy can be stored in supercooled liquids where the material is in thermal equilibrium with its surroundings [7]. The stored latent heat of fusion is released by triggering the crystallization of the supercooled substance. Enthalpy-temperature curves including the effect of supercooling are measured for some well-known supercooling salt hydrates (disodium hydrogen phosphate dodecahydrate, sodium acetate trihydrate and STL-47) by Sandnes and Rekstad [7]. It was found that the maximum temperature reached during crystallization generally decreases with increased degree of supercooling. The supercooling and nucleation of sodium acetate can be controlled by nucleating agents such as disodium hydrogen phosphate (DSP), tetrasodium pyrophosphate decahydrate (TPD), anhydrous sodium acetate (SAA), sodium tetraborate decahydrate (STD), sodium metasilicate nonahydrate (SMN) and the viscosity can be controlled by carboxymethyl cellulose sodium (CMC), polyacrylic acid sodium salt (PASS), xanthan gum (XG) and polyglykorsìte (PSK) thickeners [19]. Bentonite and starch were successfully used as thickener with a loss of 20-35% loss in enthalpy [17].

Nano-copper (Nano-Cu), which possesses high thermal and electrical conductivity, as an additive, can improve the supercooling properties of sodium acetate trihydrate (CH$_3$COONa$\cdot$3H$_2$O), SAT and enhance its thermal conductivity. Nano-Cu can be used for enhancing thermal conductivity of SAT [20]. To investigate the effect of Nano-Cu content on the degree of supercooling of SAT, composite phase change materials containing SAT, Nano-Cu (0.4%, 0.5%, 0.6%, 0.7% and 0.8%), carboxymethyl cellulose (CMC) (thickening agent) and sodium dodecyl sulfate (C$_{12}$H$_{25}$NaO$_3$S, dispersant)
were prepared by Cui et al. [20]. Carboxymethyl cellulose, extra water, liquid polymer HD 310, metal-based graphite flakes, and silicone oil were applied as additives to form the different sodium acetate trihydrate compositions [21]. The volume change of sodium acetate trihydrate on crystallization can be controlled by using additives. While the volume reduction was 16.2% for pure sodium acetate trihydrate, it is reduced to 11.6% for the mixture of sodium acetate trihydrate, xanthan gum and disodium hydrogen phosphate [19]. The densities of solid and liquid sodium acetate trihydrate are 1.636 and 1.406 g cm\(^{-3}\) respectively. On the other hand the mixture had solid and liquid densities of 1.406 and 1.268 g cm\(^{-3}\) respectively [19].

**Disodium hydrogen phosphate hand warmers**

Disodium hydrogen phosphate dodecahydrate (Na\(_2\)HPO\(_4\)·12H\(_2\)O) is an attractive candidate for phase change materials [22]. Additives such as sodium polyacrylate, sodium alginate and water are used as additives to keep heat storage capacities constant [22].

**Heat Insulating Hand Warmers**

Hand warmers made out of beavers fur could be used for long periods when they were placed in gloves with the fiber side contacting with the palm [8]. The warming is the result of very high insulating ability of heat by the fibers and the skin of the beaver’s fur.

**Heat of Wetting Hand Warmers**

Heat of wetting of adsorbents such as zeolites and silica gel can also be used as heat source for warming hands. The dried adsorbents can be wetted by rupturing the microcapsules with water and the released heat of wetting could be used for warming hands. For example zeolite 4A and natural clinoptilolite could be used for this purpose [23]. The energy storage intensity was measured by flow micro calorimetry in the range 464-201 J g\(^{-1}\) and 48-97 J g\(^{-1}\) for zeolite 4A and the tuff respectively. Specific heats of zeolite 4A and the zeolitic tuff were measured as 1.42 and 1.01 J g\(^{-1}\) K\(^{-1}\), respectively [23]. Silica gel had 94.3 ±15 J g\(^{-1}\) heat of wetting of water [27].

**Table 1. Hand warmers present in the market**

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Additives</th>
<th>Reaction</th>
<th>Heat released</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose, calcium hypochloride</td>
<td></td>
<td>Oxidation</td>
<td>n.a.</td>
<td>[5]</td>
</tr>
<tr>
<td>Calcium chloride and water</td>
<td></td>
<td>Dissolution of crystals in water</td>
<td>81.8 kJ mol(^{-1})</td>
<td>[6]</td>
</tr>
<tr>
<td>Magnesium sulfate and water</td>
<td></td>
<td>Dissolution of crystals in water</td>
<td>85 kJ mol(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Gasoline and air</td>
<td></td>
<td>Oxidation with platinum catalyst</td>
<td>5460 kJ mol(^{-1})</td>
<td>[3,4]</td>
</tr>
</tbody>
</table>
| Iron and air                    | Graphite                           | Oxidation with sodium chloride  | 798 kJ mol\(^{-1}\) | [10], [11, [2]
| Sodium acetate trihydrate       | Nucleating agents                  | Cystallization of supercooled  | 19.7 kJ mol\(^{-1}\) | [7], [16], [24]|
| Sodium acetate trihydrate 25% aqueous solution | Viscosity regulators dispersants | Cystallization of supercooled liquid | 243 kJ kg\(^{-1}\) | [7]  |
| Sodium acetate trihydrate 33% aqueous solution |                                    | Cystallization of supercooled liquid | 264 kJ kg\(^{-1}\) | [7]  |
| Sodium acetate trihydrate 60% in urea |                                    | Crystallization of supercooled material | 226 J g\(^{-1}\) | [25] |
| Sodium acetate trihydrate 50% in urea |                                    | Crystallization of supercooled material | 255 J kg\(^{-1}\) | [25] |
| Sodium acetate trihydrate       | Bentonite starch                   | Cystallization of supercooled liquid | 153-237 kJ kg\(^{-1}\) | [17] |
| Sodium acetate trihydrate       | Water CMC                          | Cystallization of supercooled liquid | 161-216 J g\(^{-1}\) | [26] |
| Sodium acetate trihydrate       | Xantan gum Tartaric acid EDTA      | Cystallization of supercooled liquid | 200 J g\(^{-1}\) | [22], [7] |
| Disodium hydrogen phosphate dodecahydrate | Sodium polyacrylate | Cystallization of supercooled liquid | 94.43±15 J g\(^{-1}\) | [27] |
| Silica gel                      |                                    | Heat of wetting                  |                |      |
In Table 1 hand warmer types, the reaction occurring, additives used and the amount of heat released per unit mass are summarized.

Other Applications of Hand Warmers

There are cases for the use of hand warmers for cancer treatment [28]. Phase change material hand warmers were used for external heating of blood without any side effects [29]. Hand warmers could be used as heat patches to treat headaches. Phase change material mixed mortar had better insulating ability from hot and cold of the walls of the buildings [30].

Developing disposable and reusable hand warmers is aimed in the present study. Since the composition of commercial hand warmers are not publicly known, practical hand warmers from powder form and granular silica gel and zeolite A were aimed to be developed by utilizing their heat of wetting with water. A simple test system was used to show the heating effect obtained by wetting silica gel and zeolite 4A with water for disposable hand warmer. Also heat release by sodium acetate trihydrate supersaturated solution crystallization is shown to be used as reusable hand warmer.

MATERIALS AND METHODS

Materials

Silica gel powder (Sigma aldrich), Silicagel granules (Sigma aldrich), zeolite 4A powder (Sigma Aldrich), zeolite 4A granules (Sigma Aldrich) were tested as potential hand warmers. Sodium acetate trihydrate ( Merck) was tested as a reusable hand warmer. Commercial air activated hand warmer (Grabber) having 33 g mass with 14 cmx11 cm dimensions with ingredients of iron powder, water, salt, activated charcoal and vermiculite and commercial sodium acetate hand warmer (Touchpack) with 330 g mass were used as reference materials.

Methods

Potential powder hand warmers

5 g material that was dried at 200°C and cooled in a desiccator was placed in plastic bags and mixed with 100 mg drop of water. The bags were placed in a wool knitted cloth instantly after mixing with water. The temperature at the surface of the bags was monitored with a Testo 945 K-type thermocouple with one minute intervals up to 60 minutes. The set up for measurement is shown in Figure 1.

Sodium acetate hand warmer

1.06 grams of sodium acetate trihydrate and 1.8 cm$^3$ water were placed in a bottle. Bottle contents was mixed and heated in a temperature controlled water bath till a clear solution of sodium acetate was obtained. A supersaturated solution was obtained by cooling the sodium acetate solution to room temperature. Bottle was taken from water bath and the lid was opened. The crystallization was triggered as soon as the Testo 945 K-type thermocouple was immersed in solution. The temperature change with time was recorded.

Test for commercial air activated hand warmer

First of all, plastic packaging is opened in the air at 21.2°C. By this way, it was activated by exposing the contents to air. Next, Testo 945 K-type thermocouple was fixed to the chemical warmer via a small square piece of duct tape. The thermocouple and warmer were then placed inside the knitted wool as seen in Figure 2. Temperature was measured at 5 minute intervals via the thermocouple.

Test for commercial sodium acetate bag

The metal disc inside the plastic packet containing sodium acetate solution was snapped to trigger crystallization. By doing this, the crystallization of sodium acetate was activated. Then, the thermocouple was fixed to the surface of the chemical warmer via a small square piece of duct tape. The thermocouple and warmer were then placed

Figure 1. a. Wetting of dry sample by a droplet of water, b. placing thermocouple on wetted sample on knitted wool, c. Covering the sample and thermocouple with knitted wool and recording temperature.
inside the knitted wool. Temperature was monitored at 1 minute intervals by the thermocouple.

**DSC analysis of sodium acetate trihydrate**

2.5 mg sodium acetate trihydrate was heated from 25 °C up to 600 °C at 10 °C min⁻¹ rate up to 600 °C under 50 cm³ min⁻¹ N₂ flow using Shimadzu DSC 60 for DSC analysis.

**RESULTS AND DISCUSSION**

**Results**

**Tests for silica gel and zeolite 4A**

A schematic view of the system used in the present study is shown in Figure 3a. The thermocouple measures the temperature at one point close to the water droplet in the adsorbent layer as a function of time. The temperature increased in a short time due to heat of wetting of silica gel or zeolite by a drop of water. Then it decreased slowly due to heat transfer to nonwetted silica gel or zeolite in hand warmer tests as seen in Figures 4 and 5. The heat transfer to surroundings could be neglected since silica gel or zeolite was covered with wool cloth acting as insulating layer. Higher (8.6 °C) temperature increase (ΔTₘₐₓ) was observed for silica gel in granular form than that of silica gel powder (5.7°C). The temperature increase rate of the silica gel granules was also higher than the silica gel granules. The temperature rise for zeolite 4A was much higher than silica gel due to higher heat of wetting as reported in Table 1. The powder form had higher ΔTₘₐₓ (22.2 °C) than that (19.6 °C) of the granular form of zeolite 4A indicating different heat transfer behavior was present for silica gel and zeolite 4A.

The temperature increased in a short time due to heat of wetting of silica gel or zeolite by a drop of water. Then it decreased slowly due to heat transfer to nonwetted silica gel or zeolite in hand warmer tests as seen in Figures 4 and 5. The heat transfer to surroundings could be neglected since silica gel or zeolite was covered with wool cloth acting as insulating layer. A schematic view of the system used in the present study is shown in Figure 5. The thermocouple measures the temperature at one point close to the water droplet in the adsorbent layer as a function of time. Higher (8.6 °C) temperature increase (ΔTₘₐₓ) was observed for silica gel in granular form than that of silica gel powder (5.7 °C). The temperature increase rate of the silica gel granules was also higher than the silica gel granules. The temperature rise for zeolite 4A was much higher than silica gel due to higher heat of wetting as reported in Table 1. The powder form had higher ΔTₘₐₓ (22.2 °C) than that (19.6 °C) of the granular form of zeolite 4A indicating different heat transfer behavior was present for silica gel and zeolite 4A.

The information obtained in the present study is not sufficient in designing a hand warmer. However the heating effects of the two adsorbents even by a droplet of water are clearly observed. In a real hand warmer sufficient and evenly dispersed water will be added to completely wet the adsorbents to take the full advantage of heat of wetting. Silica gel adsorbed 24±1.5 mass% water at saturation [27]. Thus in order to obtain maximum heat of wetting the total...

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**Figure 2.** Air activated warmer opened to air and placed in knitted wool for measurement of temperature.

**Figure 3.** Schematic view of a. silica gel hand warmer test, b. reusable hand warmer test.
amount of water should be around 25% of dry mass of the silica gel. Using the heat of wetting values of 94.3 J g\(^{-1}\)[27] and 201 J g\(^{-1}\)[23] from Table 1 and specific heats of 0.68 and 1.4 J g\(^{-1}\)°C\(^{-1}\)[23] the temperature rise (ΔT) could be calculated using Equation 3.

\[
q = (m_1c_{p1} + m_2c_{p2})\Delta T
\] (3)

Where \(m_1\) is the mass of dry silica gel or zeolite 4A, \(m_2\) is mass of added water for saturation. Assuming 25% liquid water per dry mass is added and taking the specific heat of water as 4.18 J g\(^{-1}\)°C\(^{-1}\) 54.6 and 82.2 °C temperature rise was calculated for silica gel and zeolites respectively. Since the theoretical temperature rise is above the suitable temperatures for warming hands the silica gel or zeolites should be mixed with an inert material to lower the temperature rise to around body temperature.

**Sodium acetate acetate trihydrate as a reusable hand warmer**

The schematic view of the test made in a bottle for 37% sodium acetate trihydrate solution is shown in Figure 3b and the result of the test is shown in Figure 6. ΔT\(_{\text{max}}\) was observed at the 3rd minute as 9.3 °C. The supercooled sodium acetate solution was crystallized as seen in Equation 2 giving heat to the surroundings. The crystallization occurred as soon as the thermocouple probe was inserted in super saturated solution. This showed that a clean surface without any sodium acetate tri hydrate nuclei [18] can also induce crystallization by mechanical action. The theoretical temperature rise (ΔT) was calculated from Equation 4.

\[
\Delta H_c m_1 = (m_1c_{p1} + m_2c_{p2} + m_3c_{p3})\Delta T
\] (4)

Where \(\Delta H_c\) is enthalpy of crystallization in J g\(^{-1}\) of sodium acetate trihydrate, \(m_1\) and \(m_2\) are mass liquid and solid of sodium acetate trihydrate and \(m_3\) is mass of water in g. \(c_{p1}\) and \(c_{p2}\) are specific heats of of solid and dissolved sodium acetate trihydrate in water and \(c_{p3}\) is the specific heat of water in J g\(^{-1}\)°C\(^{-1}\) in sodium acetate trihydrate solution having crystallized sodium triacetate hydrate. The theoretical temperature rise was found as 5 °C taking specific heat of solid and liquid sodium acetate trihydrate as 2.26 J g\(^{-1}\)°C\(^{-1}\) and 3.3 J g\(^{-1}\)°C [31] and \(\Delta H_c\) as 248 J g\(^{-1}\) as reported in Table 2. When supercooled sodium acetate trihydrate solution is stressed crystals of sodium acetate trihydrate in a saturated solution of sodium triacetate forms [31]. The solubility of sodium triacetate trihydrate in water at 20 °C is 46.5 g 100 g\(^{-1}\) water [31].

A higher temperature rise (9.3 °C) than expected (5°C) was observed since the thermocouple probe immersed in solution measured the temperature at a single point. The system was not heat insulated and cooled with time by dissipating to the surrounding.

Placing and sealing of appropriate amount of sodium acetate trihydrate with few drops of water [31] together with a flexible metal disc into a heat resistant plastic bag in size appropriate to be placed in a wool glove would make it a reusable hand warmer. The crystals will be melted when immersed in hot water and super cooled solution will be obtained on cooling. When the metal disc moved exothermic crystallization will occur. The released heat will be used to warm hands.

**Commercial air activated hand warmer, grabber**

The temperature increased at a fast rate from 21.2 °C to 31.5 °C in 5 minutes and at a slow rate to maximum 37 °C in 25 minutes for air activated hand warmer as seen in Figure 7. ΔT\(_{\text{max}}\) was 15.8 °C for it. The temperature decreased towards ambient temperature at a very slow rate due to
slow exothermic reaction of iron powder in its contents according to reaction 1. There are simultaneous heat and mass transfer reactions occurring in this hand warmer that contains iron powder, purified water, activated carbon, vermiculite and sodium chloride [2, 11]. Rather than explaining the reactions, the heat generation characteristics were determined to determine the limits for future design of the hand formers in the present study.

**Commercial sodium acetate trihydrate hand warmer**

A commercial reusable warmer with 330 g mass was tested for comparison. Its size was bigger than a hand warmer but it showed as how a commercial reusable warmer acted. It was activated by flexing the metal disc inside the clear solution. As seen in Figure 6 temperature was increased to 51.8 °C in 1 minute and it reached to maximum 54.8 °C in 8 minutes. ΔT\text{max} was 30.7 °C for commercial reusable hand warmer. The warmer kept its high temperature till the end of the test period due to its low heat transfer area per unit mass. The temperature was 53.3 °C at the 60th minutes. Also there could be transparent additives to control viscosity, density and heat capacity of sodium acetate trihydrate solution.

In Table 2 the experimental results obtained from potential hand warmers silica gel and zeolite 4A, sodium acetate trihydrate and commercial hand warmers are reported.

**DSC analysis of sodium acetate trihydrate**

DSC analysis curve of sodium acetate trihydrate used in the present study is shown in Figure 8. The onset, peak and end set temperatures for the first peak which is the fusion endotherm of sodium acetate trihydrate are 58.55, 63.59 and 100.36 °C respectively in Figure 8. The enthalpy change of the melting of sodium acetate trihydrate was calculated as 227 J g\(^{-1}\) considering the area of the first peak in the range of 53 to 70 °C since evaporation

![Figure 6. Temperature change with time after activation for super saturated sodium acetate Commercial air activated hand warmer, Grabber.](image)

![Figure 7. Temperature versus time after air activation of grabber hand warmer and mechanical activation of commercial sodium acetate.](image)

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Time, min</th>
<th>(T_{\text{max}}), °C</th>
<th>(\Delta T_{\text{max}}), °C</th>
<th>Specific heat, Sample mass, g Jg(^{-1})°C(^{-1})</th>
<th>Adiabatic temperature rise</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica gel granules</td>
<td>2</td>
<td>33.1</td>
<td>8.6</td>
<td>0.68</td>
<td>5</td>
<td>54.6</td>
</tr>
<tr>
<td>Silica gel powder</td>
<td>4</td>
<td>30.2</td>
<td>5.7</td>
<td>0.68</td>
<td>5</td>
<td>54.6</td>
</tr>
<tr>
<td>Zeolite 4A powder</td>
<td>4</td>
<td>44.7</td>
<td>22.2</td>
<td>1.4 [23]</td>
<td>5</td>
<td>82.2</td>
</tr>
<tr>
<td>Zeolite 4 A granules</td>
<td>4</td>
<td>42.2</td>
<td>19.6</td>
<td>1.4 [23]</td>
<td>5</td>
<td>82.2</td>
</tr>
<tr>
<td>Sodium acetate trihydrate</td>
<td>3</td>
<td>30.1</td>
<td>9.3</td>
<td>3.33 ((l))</td>
<td>2.86</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.26 ((s)) [32]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grabber</td>
<td>25</td>
<td>37.0</td>
<td>15.8</td>
<td>0.5</td>
<td>30</td>
<td>--</td>
</tr>
</tbody>
</table>
of water was considerable at higher temperatures. During melting of sodium acetate three mols of water is separated and sodium acetate was dissolved by ionizing in this water. In cooling this solution without making any disturbance the supersaturated solution is obtained.

Hua et al. [19] also measured heat of fusion of sodium acetate trihydrate and reported the heat of fusion as 268.8 J g⁻¹. They found the starting and termination temperature of fusion of sodium acetate trihydrate as 58.8 °C and 68.2 °C respectively. Jin et al. [33] reported that SAT started to melt at about 59.0 °C. The maximum heat-flow point occurred at a temperature of about 63.0 °C. The calculated heat of fusion was 257.2 kJ kg⁻¹ with a melting temperature range of 58.9 °C to 67.3 °C. During the cooling process, the results showed that SAT did not release the latent heat even when it was cooled to −40 °C. However, if it is partially molten it releases heat on cooling due to nucleating effect of remaining SAT crystals. The additives to avoid precipitation of sodium acetate trihydrate also changed its enthalpy of fusion. Kong et al. [26] reported the heat of crystallization of sodium acetate trihydrate with different additives as 161-216 J g⁻¹.

Engmair et al. [21] determined maximum water content as 40.8% of the commercial sodium acetate trihydrate stored in laboratory for different periods up to 26 months after drying at 120 °C.

The DSC curve of sodium acetate trihydrate in Figure 8 has a second endothermic peak with 95.21 °C onset, 108.65 °C peak and 110°C endset temperature belonging to evaporation of released crystal water. The enthalpy change for this second peak is -366 J g⁻¹.

**DISCUSSION**

In the present study a water droplet was added to the dried silica gel and zeolite 4A to test the temperature rise effect for warming hands. However both silica gel and zeolite 4A had much higher capacity of water for complete wetting. Thus when a real hand warmer is produced this effect should be taken in consideration. Water encapsulated in microcapsules could be placed together with silica gel or zeolite 4A in a water impermeable package. Also an inert material should be present in the mixture to limit the temperature rise to plausible limits. The warming effect could be obtained releasing water by crushing the microcapsules by squeezing the package between fingers.

Sodium acetate trihydrate hand warmer could be produced and tested for different solution concentrations by placing in packages in suitable size to be placed between the glove and the hand.

For air activated hand warmers iron powder and other additives are placed in an air permeable bag and placed in a second package impermeable to air. When the impermeable bag is opened air enters through the permeable bag to react with iron powder to create heat. The heat effects produced could be measured and predicted using temperature-time data, specific heats reported in Table 2 and reaction heats.

There are previous studies testing commercial air activated hand and foot warmers present in the market [10] or use of different semipermeable covering [9] or their effect in human comfort [15]. However in the present study new materials silica gel, zeolite 4A are tested for their potential use in hand warmers Future experimental and model work about hand warmers should be planned and done by considering the previous studies [34] and the results of the present study.

**CONCLUSION**

The commercial hand warmers and potential hand warmers were tested for heat release, maximum temperature attained and the amount of heat released in one hour. Supersaturated sodium acetate hand warmer gives more heat than the air-activated one. Since the sodium acetate trihydrate hand warmer can be used repeatedly, and air activated hand warmer can be used once, it should be preferred when there are means for melting by heating. Air activated ones are efficient in circumstances when reheating is not possible, such as on top of a mountain. Silica gel and zeolite 4A in their powder and granule form could be one use hand warmers releasing sufficient heat to worm hands in cold weather. While the commercial warmers released heat slowly for long term and dry silica gel and dry zeolite 4A could be used for short term heating of hands by placing them in gloves.

**NOMENCLATURE**

\[ cp_1 \quad \text{Specific heat of specific heat of silica gel or zeolite 4A, or solid sodium acetate trihydrate in of solid in J g}^{-1}\text{oC}^{-1} \]

\[ cp_2 \quad \text{Specific heat of water or dissolved sodium acetate trihydrate, J g}^{-1}\text{oC}^{-1} \]

\[ cp_3 \quad \text{Specific heat of water in mixture of solid, liquid and water mixture, J g}^{-1}\text{oC}^{-1} \]
$m_1$ Mass of dry silica gel or zeolite 4A or mass of liquid sodium acetate trihydrate, g

$m_2$ Mass of added water for saturation of silica gel or zeolite 4A or the mass of crystalline sodium acetate trihydrate, g

$m_3$ Mass of water in the mixture of partially crystallized sodium acetate trihydrate and water, g

$\Delta H_c$ Enthalpy of crystallization in J g$^{-1}$ of sodium acetate

$q$ Heat, J

$T$ Temperature, °C

$t$ Time, sec

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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