DEVELOPMENT OF A REFRIGERATION SYSTEM FOR COOLING MILK AT RURAL REGIONS

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ABSTRACT
The present paper presents an experimental evaluation of a solar refrigerator, prototype, based on an intermittent thermodynamic cycle of adsorption, using milk as refrigerant and the mineral zeolite as adsorber. This system uses a mobile adsorber, which is regenerated out of the refrigeration cycle and no condenser is applied. Because the solar regeneration is made in the ambient air for the regeneration, a SK14 solar cooker is considered. The cold chamber, with a capacity of 4 liters, is aimed for cooling milk. The objective is to analyze the advantages and disadvantages of the eventual use of this refrigerator in rural regions of Egypt, where no electricity is available. On the bases of the results obtained, a new prototype of refrigerator for rural regions is designed, based on the same thermodynamic cycle, but including changes in design and operation. According to the experiments Zeolite pan size of 2*20*25 cm proved to be the most optimum, it is the size recommended for use in milk cooler. According to the results of the mathematical modeling of drying of zeolite, the best describing the drying characteristic is Wang and Singh model. The regression equation $R$ (correlation coefficient) indicates the degree of association between the observed and predicted values coefficient of efficient ($C_e$) was 0.999.

INTRODUCTION
The use of sorption processes to produce refrigeration has been extensively studied in the last twenty years as a technological alternative to vapor compression systems. Several theoretical and experimental studies demonstrated the sorption refrigeration systems, especially that using solid-gas heat powered cycles, are well adapted to simple technology applications. They can operate without moving parts and with low-grade heat from different sources such as residual heat or

solar energy. The two main technologies concerning the solid gas sorption concept are the adsorption and the chemical reaction, including metal hydrides. The similarities and differences between these systems, as well as the advantages and disadvantages of each one are extensively described by Meunier (1998). Refrigeration is an interesting application of solar energy because the incident radiation and the need for cold production both reach maximum levels in the same period. Water content of up to 25% (kg water/kg zeolite) can be adsorbed and then desorbed by the adsorption enthalpy (Ming and Mumpton, 1993).

In developing countries, solar refrigeration is an increasingly acknowledged priority in view of the needs for food and vaccine preservation and due to the fact that solar energy is generally widely available in these countries. Different solar refrigeration systems using sorption processes have been proposed and tested with success. In relation to the solar adsorptive refrigeration systems, different types of solid-gas were considered. The zeolite-water and silica gel-water pairs were chosen for cold storage, while the activated carbon-methanol pair was chosen for ice production (Leite, 1996). Once the zeolite is fully saturated within the cooler, it must be removed for regeneration. Zeolite regeneration processes have been mostly done by thermal heating (thermal regeneration) using mechanized equipment (Pons 1996). The activated carbon-ammoniac pair was also employed for different refrigeration applications using solar energy. Zeolite, a micro pours crystalline solid is capable of adsorbing significant amounts of water vapor and other gases in their complex crystal structure.

The adsorptive systems development is still limited by the adsorber solar collector component cost, and by the intermittence of the incident solar radiation, which makes it difficult to be competitive with conventional compression systems. In the present work the description and the operation of a solar adsorptive prototype refrigerator using the zeolite water pair is studied. The system operates under an intermittent cycle,
without heat recovering, and is aimed to regenerate the adsorber with solar energy, using a SK14 solar cooker. The adsorber is mobile and is regenerated out of the refrigerator. No condenser is applied because the solar regeneration is made in the ambient air. The purpose of the refrigerator is to cool milk in rural areas of Egypt, where no electricity is available.

**MATERIAL AND METHODS**

The study was conducted at Nubria research station, Agriculture research center. The experiments was stated at may 2012. Zeolite panes were used in the experiments, with dimensions of P₁ (2, 20, 25), P₂(2, 20, 18) and P₃ (2, 20, 11) in cm Samples mass of 350, 250 and 150 g for the panes respectively.

1. Material
   1.1. Adsorbent
   Zeolite is a mineral consisting of SiO₂ groups and alkali-ions. It is capable of adsorbing water vapor and other gas molecules in the cavities of its complex crystal structure. Water content up to 25% (kg water/kg zeolite) can be adsorbed and then it is heated up by the adsorption enthalpy. It's produced synthetically and the crystalline powder is pressed to pellets of about 0.5 mm diameter. Huge quantities of Zeolite are produced by chemical industries and used as molecular sieves or for washing detergents. Zeolite ingredients for used type can be shown in Table (1).

   1.2. SK14 cooker
   The SK14 is durable although light, cost effective to build and easy to use. Its production capacity is approx. 600 Watts. The total aperture is 1.53 M² and with mass of 18 kg. The focal point of heat for the SK14 is only 28cm wide. This means that if the maximum amount of energy is desired, the dish must only be moved every 15-25 minutes to face the new position of the sun.
Table (1): The Zeolite characteristics.

<table>
<thead>
<tr>
<th>Specification</th>
<th>The sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula per unit cell content</td>
<td>Na$_{12}$[(AlO$<em>2$)$</em>{12}$] 27H$_2$O</td>
</tr>
<tr>
<td>Appearance</td>
<td>White powder</td>
</tr>
<tr>
<td>Relative Brightness</td>
<td>98%</td>
</tr>
<tr>
<td>Anhydrous zeolite content</td>
<td>80%</td>
</tr>
<tr>
<td>Loss at 800°C</td>
<td>20%</td>
</tr>
<tr>
<td>Calcium exchange capacity</td>
<td></td>
</tr>
<tr>
<td>2 minutes</td>
<td>297 mgCaCO$_3$/g min</td>
</tr>
<tr>
<td>10 minutes</td>
<td>210 mgCaCO$_3$/g min</td>
</tr>
<tr>
<td></td>
<td>225 mgCaCO$_3$/g min</td>
</tr>
<tr>
<td>Heavy metals</td>
<td>&lt; 0.5 ppm</td>
</tr>
<tr>
<td>PH 5% in water</td>
<td>11</td>
</tr>
<tr>
<td>Bulk density</td>
<td>300 – 400 Kg/m$^3$</td>
</tr>
<tr>
<td>Particle size</td>
<td>Media diameter</td>
</tr>
<tr>
<td></td>
<td>Above 10 micron</td>
</tr>
<tr>
<td></td>
<td>Below 1 micron</td>
</tr>
</tbody>
</table>

1.3. Instruments

Environmental conditions of temperature, relative humidity, air velocity and solar radiation were recorded at 20 minutes intervals Table (2). In the measurements of temperature, a J type iron-constant thermocouple was used with a manually controlled channel automatic digital thermometer with reading accuracy of ±0.1 °C (Mini Thermo – Anemometer).

Table (2): The environmental of experiments.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Velocity:</td>
<td>0.5 to 28 m/s.</td>
</tr>
<tr>
<td>Humidity:</td>
<td>10% to 95%.</td>
</tr>
<tr>
<td>Dew Point:</td>
<td>0.0°C to 50°C.</td>
</tr>
<tr>
<td>Temperature:</td>
<td>-18°C to 50°C.</td>
</tr>
</tbody>
</table>

A radiation meter was used to monitor the variation of solar radiation over the entire drying. Moisture loss was also recorded at 20 minutes intervals during drying for determination of drying curves by a digital balance in the measurement range of 0.2 Kg – 10 Kg and an accuracy of ± 0.02 g.

2. Methods

2.1. Adsorption cycle

The prototype of solar refrigerator was constructed at Nubria research station, Agriculture research. The adsorber of refrigerator is mobile, to
allow the regenerating process out of the system. Therefore, no condenser is used because the desorbed water is transferred to ambient air. In principle, the refrigerator may be constructed out of two vessels, the evaporator and the absorber, which are connected by a tube and a valve Figure (1-a). In the evaporator only the vapor pressure of the water is present, when the valve is opened, the water vapor in the evaporator is absorbed by the zeolite and thus the pressure is reduced. The milk starts cools down to approximately 10 ºC. the cooling chamber capacity is 4 liter and rest of the chamber volume allow releasing the vapor from the milk. When the adsorbent is saturated, the refrigeration process stops. Now the adsorbed vessel is heated up. The desorbed water vapor condenses in the connecting tube or in the evaporator at ambient temperature. Then by opening the valve the refrigeration process can start again. In practice the Zeolite can be regenerated during the day using solar energy Fig (1-b), at day time and at night the refrigeration process can be started. The thermal insulation and the thermal capacity of refrigeration chamber must be sufficient enough to avoid a big increase in temperature during the day.

2.2 Experimental procedures

At the beginning, the zeolite was saturated with water \( C_h=20\% \). The solar collector was heated up by solar simulator and after six hours the temperature of zeolite reaches 175ºC. the water vapor pressure was 50 mbar. The condenser was not cooled and the water vapor condensed at approximately 30ºC. During this process the water content decreased to \( C_1= 8\% \). At t= 6h the valve was closed and the sun was switched off. At t=8h the collector had cooled down by opening the valve, the refrigeration process was started. Due to the adsorption enthalpy the temperature of the zeolite increased up to 70ºC, at which point, the rate of adsorption decreased and the adsorber temperature slowly tended to ambient temperature. The refrigerant was quickly cooled down to -3ºC (under cooled milk). Over time the cooling power decreased and due to the heat flow from the surroundings the temperature of the refrigerant slowly increased to 10ºC after 12 hours. This experimental procedure was repeated for different desorption temperatures and different kinds of Zeolite as well as of silica gel.
Fig. (1-a): Scheme of functioning of the Zeolite solar refrigerator for cooling milk

Fig. (1-b): Regeneration process of Zeolite using solar energy
2.3. Measurements
The amount of water removed from the drying material was calculated as follows:

\[
\Delta W = W \times \frac{M_1 - M_2}{100 - M_2}
\]

Where:
- \(M_1\) = Initial moisture content of drying material, % wb
- \(M_2\) = Final moisture content of drying material, % wb
- \(W\) = The amount of wet material to be dried, kg

The drying kinetics relates the moisture ratio to the drying time. The moisture ratio is formulized as follows:

\[
MR = \frac{M - M_e}{M_0 - M_e}
\]

Where:
- \(M\) = Moisture content of drying material at any sampling time, % db
- \(M_e\) = The equilibrium moisture content of drying material based on drying conditions.
- \(M_0\) = Initial moisture content of drying material at any sampling time, % db

The values of the equilibrium moisture content, \(M_e\), are relatively small compared to \(M\) and \(M_0\). Thus, moisture ratio can be calculated as follows (Doymaz and Pala 2002):

\[
MR = \frac{M - M_e}{M_0 - M_e}
\]

The weather conditions during the experiments were, solar radiation ranged from 900 to 1000 W/m\(^2\), wind speeds from 2.8 to 3.9 m/s while the ambient air temperature ranged from 2.5 to 3.5 °C.

RESULTS AND DISCSINOS
Zeolite drying curves
Figure (2) shows drying curves of the used Zeolite 80 obtained at atmospheric pressure with small three panes of \(P_1\), \(P_2\) and \(P_3\) samples of
Zeolite put at solar cover for regenerating the adsorbent (Figure 1). From these curves it can be concluded that it is not recommended to reduce the humidity from its initial (20%) dry matter at saturation to below 2%. Further drying would result only in a small improvement of the capacity of the Zeolite to all sorbs water.

The moisture content decrease continuously with drying time and there was no constant rate period in drying for all the sizes. The moisture ratio also varied in the same way (Fig 3).
All the drying processes occurred in the falling rate period. In this period the zeolite surface was no longer saturated with water and drying rate was controlled by diffusion of moisture from the interior of the solid to the surface. The drying rate is higher at the beginning of the regeneration process and decreases continuously with increasing drying time because of at the beginning of drying process the water is easy to remove from zeolite and as the end of drying zeolites catch water stronger than earlier time shown in (Fig 4).

As expected size $P_1$, $P_2$ comparing with $P_3$ had both the highest moisture content and the fastest drying rate. This is due to the small size of the sample particles of $P_3$ that presents a large surface area for absorption and evaporation of moisture.

Mathematical modeling of drying curves

According to the results, the best mathematical model for zeolite drying curve is Doymaz (2004) with highest values of $R$ (0.99) and lowest values of the standard error of the estimate ($\sigma_{est} = 0.0112$) best where the model is the following:

$$MR = \exp (-kt^n)$$

Where:
- $MR$ : Dimensionless moisture ratio
- $K$, $n$ : Empirical constants in drying models

The model constants for the tested panes are shown in Table (3).
Table (3): constant value of the mathematical model for the pans

<table>
<thead>
<tr>
<th>MR</th>
<th>P₁</th>
<th>P₂</th>
<th>P₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0.0112</td>
<td>0.11</td>
<td>0.1</td>
</tr>
<tr>
<td>n</td>
<td>1.2</td>
<td>0.69</td>
<td>0.54</td>
</tr>
<tr>
<td>R²</td>
<td>0.9819</td>
<td>0.9855</td>
<td>0.9565</td>
</tr>
</tbody>
</table>

Through moisture ratio modeling based on the drying time, size P₃ recorded highest efficiency. The performance of the model is presented in Figure (5).

![Graph](image)

Fig. (5): Variation of experimental moisture ratio with drying time at different drying conditions.

Reducing four liters of fresh milk having temperature from 37 °C to 10 °C, needs three hours using zeolite pan of P₃. The zeolite pan needs to dry on solar collector 6 hours to get rid of the moisture.

Model verification

The standard error of the estimate is a measure of the accuracy of predictions. Recall that the regression line is the line that minimizes the sum of squared deviations of prediction (also called the sum of squares error). The standard error of the estimate is closely related to this quantity and is defined below:
\[ \sigma_{est} = \sqrt{\frac{\sum(Y - Y')^2}{N}} \]

Where: \( \sigma_{est} \) is the standard error of the estimate, \( Y \) is an actual score, \( Y' \) is a predicted score, and \( N \) is the number of pairs of scores. The numerator is the sum of squared differences between the actual scores and the predicted scores.

To assist further in this evaluation, another index called coefficient of efficient (Ce) was used. This coefficient was proposed by Nash and Sutcliffe (1970) and used by Masheshwari and McMahon (1993), Sharaf (2003). If \( R \) and \( Ce \) are close to each other, the model is free from any bias all or part of the data. \( Ce \) is defined below as:

\[
Ce = \frac{\sum_{i=1}^{n} (X_{oi} - \overline{X}_o)^2 - \sum_{i=1}^{n} (X_{oi} - X_{pi})^2}{\sum_{i=1}^{n} (X_{oi} - \overline{X}_o)^2}
\]

Where:
- \( Ce \) = coefficient of efficient
- \( X_{pi} \) = the value of predicted measurements
- \( n \) = number of observations
- \( X_{oi} \) = the value of observed measurement
- \( \overline{X}_o \) = average observed value

Figure (6) shows the relationship between predicted and measured moisture content. The \( A \) in Table (4) is the line slope and \( B \) is the line intersects with y axis. The results showed by Figure (6) and Table (4) means that the model has very high performance for describing the characteristics of drying curve. It was found that the difference between the predicted and observed values is very low.

Table (4) shows the standard error of estimate linear model \( R^2 \), the standard error of the estimate \( \sigma_{est} \), coefficient of efficient \( Ce \), and correlation coefficient \( R \) of Figure (6).

Table (4): Indicates performance of model predicting

<table>
<thead>
<tr>
<th>( \sigma_{est} )</th>
<th>( Ce )</th>
<th>( R^2 )</th>
<th>( R )</th>
<th>( A )</th>
<th>( B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0112</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Milk cooling curve
Figure (7) show the milk cooling curve during the refrigeration process against time. From the results the milk temperature reached to 10° C after 180 minutes, 14° C after 210 minutes and 18° C after 240 minutes using pan P₁, P₂ and P₃ respectively. After the Zeolite saturated with the vapour, the capability of Zeolite to absorb the vapor decreased then the milk temperature begins to increase gradually. At the moment of increasing milk temperature the Zeolite should be removed and replaced with another dried pan to keep the milk temperature at the minimum temperature obtained.

CONCLUSION
In this study, regeneration of three Zeolite sizes of 2×20×25, 2×20×18 and 2×20×11 cm has successfully investigated. The drying occurred in the falling rate period showing Zeolite 2×20×25 as the optimum size with the fastest drying rate and most efficient. According to the results of the mathematical modeling of drying of zeolite, the best describing the drying characteristic is Doymaz model. The minimum cooling temperature obtained was 10° C after 180 minute using pan of
2×20×25cm. Since zeolite size of P₁ proved to be the most optimum, it is the size recommended for use in milk cooler.

REFERENCES


الملخص العربي
تطوير نظام لتبريد اللبن في المناطق الريفية
محيي الدين محمد مرسي

الهدف من الدراسة هو تبريد اللبن المنتج عند المزارع الصغير عن طريق خفض درجة حرارته كمرحلة انتقالية من مكان الحليب إلى مكان تجميع اللبن تمهدى لنفق لأماكن الاستثمار وذلك باستخدام مادة الزيوليت<std>الشرهة<std> لامتثال رطوبة من الجو المحيط بها والتي ليس لها أي تأثير ضار على المواد الغذائية أو البيئة المحيطة من حيوانات أو طيور واستخدمت ثلاث عيونات من مادة الزيوليت بأشكال مختلفة (20×18 سم) و(20×25 سم) وكانت تخدم باستخدام الطاقة الشمسية بتشبعها بالرطوبة لإعادة استخدامها مرة أخرى للقيام بعملية التبريد، واستخدمت الطاقة الشمسية ممثلة في طبق تجميع توضع فيه المادة المشبعة بالناء عند بويرة المجمع للتخلص من الرطوبة، وذلك توفيرا للطاقة الكهربائية لارتفاع سعرها أو لعدم توافرها وقد أجريت التجارب والقياسات بمحطة البحوث الزراعية بالنوبارية التابعة لمركز البحوث الزراعية ولقد أوضحت النتائج الآتي:
1) لخفض درجة حرارة كتل من اللبن من 37 درجة إلى 10 درجة من 3 ساعات باستخدام العبوء ذو حجم (20×25 سم) وتمكن الحفاظ على درجة حرارة 10 درجة لليين لمدة 3 ساعات كحد أقصى وخفض درجة الحرارة لأكثر من ذلك هذا يتطلب تجفيف أكثر من عبوة بحيث يمكن تَبديلها أثناء عملية التبريد أو تعرض مادة الزيوليت لتجفيف أكبر وهذا يعني تعرض المادة لدرجة حرارة أكبر وأشد فيضي باستخدام مجمع شمسي أكمل أو استخدام مصدر حراري أشد مثل اللهب.
2) كلما زادت فترة تعرض مادة الزيوليت لأشعة الشمس كلما زادت كفاءتها لخفض المحتملي الرطوبتي وزيادة كفاءتها لزيادة التبريد للبن.
3) أفضل النتائج لعملية التبريد كان لحجم مادة الزيوليت (20×25 سم) وللحفاظ على درجة حرارة اللبن عند درجة (10 درجة) لمدة 3 ساعات تجهد مادة الزيوليت ذو الحجم (20×25 سم) مرة أخرى بعرضها من جديد للمصدر الحراري (أشعة الشمس) بواسطة مجمع الشمسي، وpartment of Agricultural Research Center - Faculty of Agriculture - Cairo University.
4) أفضل نموذج لوصف عملية التجفيف لمادة الزيوليت المستخدمة في عملية التبريد هو نموذج (Doymaz) والذي يعرف عنه المعادلة الآتية:

\[ MR = \exp(-kt^n) \]

حيث إن:
- \( t \) = درجة حرارة التسخين
- \( MR \) = المحتملي الرطوبتي النسبي
- \( k \), \( n \) = ثوابت تجريبية

ووجد أن معامل التصحيح (R²) بين النتائج التجريبية ونموذج (Doymaz) كان 0.95 ومعامل التصحيح (C) كان 0.999.

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