Sustainable Energy Technologies and Assessments 34 (2019) 126–132

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Biogas-powered evaporative cooling for smallholder dairy farmers' evening milk: Zeolite characterization and regeneration

Kenneth Ndyabawe[a], Ryan Brush[a,1], Richard E. Ssonko[b,2], William S. Kisaalita[a,c,*]

[a] University of Georgia, College of Engineering, Driftmier Engineering Center, Athens, GA 30602, USA
[b] Smallholder Fortunes, Nsangi Trading Center on Masaka Road, P.O. Box 30385, Kampala, Uganda
[c] Makerere University, College of Agricultural & Environmental Sciences, School of Food Technology, Nutrition & Bioengineering, P.O. Box 7062, Kampala, Uganda

ARTICLE INFO

Keywords:
Zeolite
Evaporative cooling
Food security
Dairy farming
Alternative energy

ABSTRACT

A low-capacity (15.5-L) evaporative cooler, utilizing zeolite as an adsorbent, for saving smallholder dairy farmers' evening milk, was not well received due several factors, addressed in the second generation higher capacity (> 50 L) design. Like the first generation the new design uses zeolite and is powered by biogas. The first development step was to establish a protocol for testing commercially available zeolites to determine zeolite suitability for use in the design and to characterize the performance of a zeolite biogas-powered regenerator. Using an in-house developed protocol, zeolite beads of diameters 2.5–5 mm were tested and we found that 10 angstrom (Å) zeolites have a higher water adsorption capacity (6–7%) in comparison to 3 Å zeolite beads, suggesting that larger pore zeolites provide higher cooling capacity. However, large pore zeolite beads showed up to 18 times variance in repeat water adsorption compared to 3 Å zeolite, indicating that zeolite of small pores may provide more cooling cycles. Our biogas powered regenerator achieved and maintained the regeneration temperature of 200 °C when tested with both propane and biogas. This result affirms that our system can be operated on the farm using biogas as the energy source.

Introduction

Sub-Saharan African smallholder dairy farmers incur unacceptable milk post-harvest losses, especially for the evening milk that cannot be kept fresh, till the next day, for market [1]. One solution to reducing these losses and increase incomes for these farmers lies in installation of low capacity cooling systems powered by renewable energy sources. We previously reported on the diffusion of such a system, a low capacity evaporative cooler (15.5 L), branded as "CoolChurn" [1]. Our work showed that the cooling technology was satisfactory in preserving milk over 24 h for entry into the cold chain. However most of the farmers with low milk production (15.5 l or less) seemed to lie in the "late majority" and/or "laggards" characterization by Rogers (2003) in his diffusion of innovations construct [2]. Late majority are skeptics; they are open to new ideas but their decision to participate is motivated by peer pressure. Laggards are traditional. They are suspicious of change agents partly because they tend to have limited resources and need to be certain that an innovation works well before they invest into it.

Cooling with the CoolChurn was a batch process. To cool again, the CoolChurn had to be regenerated by heat. The purpose of heating was to free the zeolite of the water adsorbed during the evaporative cooling, condensing the water, and reestablishing the vacuum responsible for water evaporation at room temperature that resulted in the evaporative cooling effect. Since all the inner workings of the device were sealed, all the farmer was required of was to fill up the device with the milk, flip a switch, and the cooling process would begin. In our diffusion model, the farmer carried the whole device with the milk to a milk collection center, where the milk entered the cold chain and the device was exchanged with a regenerated one. The device that the farmer would bring in that day would be electrically regenerated to be available to the farmer the next day.

The diffusion of the CoolChurn was not successful. Focus group discussions with the farmers revealed two main factors. First, lack of a means to regenerate the cooler on the farm made the use of the device inconvenient in rural settings. Therefore, we speculated that on-farm (biogas) powered regeneration was worthy of serious consideration in the second-generation design, as an alternative for electrical regeneration. Second, the low capacity was unattractive to farmers that

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[*] Corresponding author at: University of Georgia, College of Engineering, Driftmier Engineering Center, Athens, GA 30602, USA.
E-mail address: williamk@engr.uga.edu (W.S. Kisaalita).

[1] Current Address: Anheuser Busch Corporate Office, 1 Busch Drive, St. Louis, MO 63118, USA.

[2] Current Address: Rift Valley Railways (Uganda) Ltd., Station Approach Road, Station Building One, P.O. Box 7891, Kampala, Uganda.

https://doi.org/10.1016/j.seta.2019.05.003
Received 12 October 2017; Received in revised form 22 April 2019; Accepted 16 May 2019

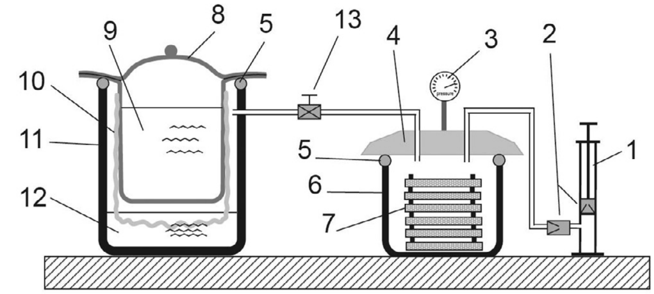

Fig. 1. Schematic of second generation cooler. 1 = hand operated vacuum pump; 2 = one-way valves; 3 = vacuum gauge; 4 = zeolite-vacuum chamber cover; 5 = vacuum seals; 6 = zeolite-vacuum chamber; 7 = zeolite plates (two perforated plates held together with screws and containing 3 mm-diameter zeolite particles); 8 = milk chamber and its cover, which can be made from stainless steel, aluminum alloy 1050, or any other material that is functionary satisfactory and price-competitive; 9 = milk - for purposes of design simplicity, no continuous temperature monitoring provision is envisioned, milk temperature is measured at the end of the cooling with a simple digital thermometer; 10 = wick material to put water in close contact with the chamber wall; 11 = cooler water container chamber; 12 = water; 13 = manual valve. With the zeolite chamber under vacuum, the manual valve (13) is opened, subjecting the water to a low pressure, resulting into evaporation and the milk providing the heat, and cooling of the milk. To maintain the cooling, the vapor is adsorbed by the zeolite. To cool another batch of milk, the zeolite has to be regenerated (dried), separately in a biogas powered regenerator (Fig. 3). The fact that there are no valves for milk to flow through makes cleaning the milk chamber simple by hand with a mild detergent.

were more educated, had more milk, and were “influential.” We speculated that design of a larger capacity milk cooler was necessary in shifting our clientele towards “innovators” and/or “early adopters”. As described in the Roger (2003) construct, innovators are characterized by a venturesome attitude and considerably large financial resources to absorb potential loss associated with uncertainty of innovation. The salient role of innovators is to import and expose their community to new ideas. Early adopters hold great opinion leadership in society and are considered the most important in diffusion of change agents. They are respectable and involved with the local community.

The schematic in Fig. 1 shows the concept of the second-generation evaporative cooler that we came-up with. As in our first-generation device, the principle of operation of this design involves exposing water to sub-atmospheric pressures, causing the water to vaporize at room temperature in a chamber of fixed volume. The vaporization heat is supplied by warm milk, which is cooled in the process. Saturation in the evaporation chamber is prevented by rapid adsorption using crystalline metal aluminosilicates (also known as zeolite). In this design, we increased the capacity to 50–100 l. Sealing in the inner workings would have made the device too big to handle by hand. So we “unsealed” it and offered the generation of the vacuum by hand. We packaged the zeolite in perforated plates, where the wet zeolite after cooling can easily be handled and regenerated while in plate in a biogas-powered generator. This design offered the possibility to use a second fresh plated zeolite in a single cooling to increase the capacity to cool to the desired cooling, if the desired temperature for the cooled product is not achieved with the first plated zeolite.

The cost of investing in a domestic biogas plant would not only be justified by milk cooling only, but by cooking and lighting as well, if the plant is large enough to support both. Also, installation of the biogas plant would provide a suitable way to handle animal waste (in form of digester feed for biogas production) while the resultant biogas digester slurry provides manure to support growth of more animal feed and other crop produce. However, caution should be exercised in handling slurry; it should only be used as fertilizer for crops, not consumed raw and not indiscriminately discharged into water systems. Although there is limited data on the efficacy of biogas digestion, with respect to reducing pathogens in sub-Saharan Africa [3]), studies in Asia with slurry from pig and human excreta biogas digestion have shown reduction of

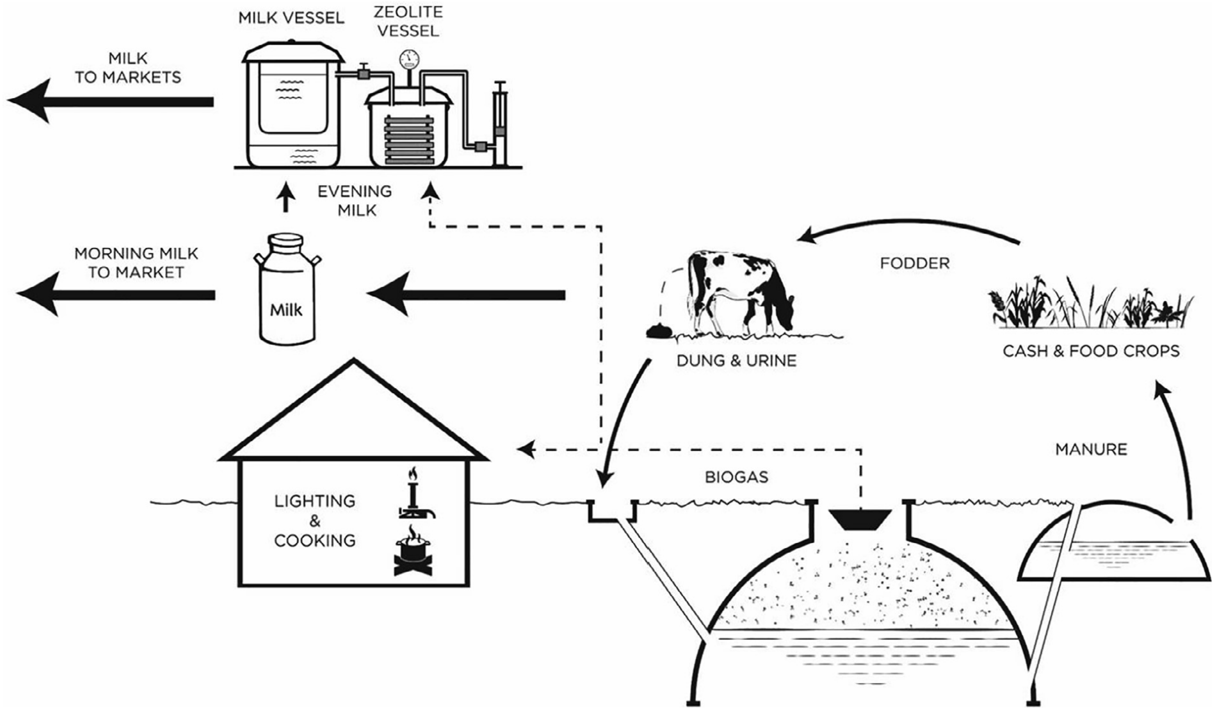

Fig. 2. Smallholder dairy farm ecosystem. While morning milk harvests are easily delivered to the market chain, evening milk (which may otherwise waste away due to limited demand and poor transport, among others) may be preserved in the cooler for up to about 24 h and delivered to the market when it safe. A biogas system is required to charge the cooling system on-farm but may also provide the household’s energy needs, a constant source of farm manure and a “green” disposal for organic waste. The application of biogas to a household income generating application is likely to provide a financial incentive for investment in biogas technologies in developing countries, creating a sustainable farm ecosystem in which the cooler, the biogas system and the animals have a mutualistic symbiotic relationship.

E. coli and spores of Clostridium perfringens by only 1–2 log10-units in comparison to raw slurry [4]. Fig. 2 illustrates how the system fits in a smallholder farm ecosystem, creating a mutualistic symbiotic relationship between farm animals, biogas, and the cooler, to the benefit of the farmer.

Desirable properties of zeolites for use in our second-generation evaporative cooler are: 1) high capacity for holding water – expressed as percentage of dry zeolite weight, 2) high affinity for water as reflected in short times to saturation, and 3) complete and fast drying (regeneration) at low temperatures (e.g., 200 °C). Adsorption kinetics is dependent on the physical characteristics of the zeolites (e.g., pore size/volume, pore structure and mesh size) [5–7]. There are many commercially available zeolites with water adsorption capacity claims that are sometimes unverifiable due to absence of a well-established standard protocol for water adsorption capacity characterization in low resource settings. Common volumetric and gravimetric methods used to characterize zeolite capacity for water vapor adsorption have been demonstrated using sophisticated apparatuses, such as sorption-isotem tank [9], coulometric Karl Fisher titrator [10] and Gorbach et al.'s equilibrium apparatus [8], which are not readily available to inform decision making at smallholder farms in developing countries. The purpose of this phase of our study was two-fold: 1) to establish a simple protocol for characterizing the water adsorption capacity and the rate of this adsorption, and to apply this protocol to several commercially available zeolites to identify the best zeolite for our application, and 2) to confirm that the selected zeolite can be regenerated at a previously established temperature of 200 °C and confirm if this temperature can be generated in a low-cost biogas-powered regenerator.

Materials and methods

Zeolites and their regeneration

Zeolite beads of 3 Å (3A 4 × 8 mesh, Sigma Aldrich) and 10 Å purchased from Sigma Aldrich and Zeotech (13X 8 × 12 mesh, 13X 4 × 8 mesh – purchased from Sigma Aldrich – and 13X 4 × 8 mesh – purchased from Zeotech) were used for our study. Four perforated stainless steel plates (10 in. in diameter) were fabricated – model shown in Fig. 3a. Each plate was filled with 250 g of zeolite (all the four plates were filled with the same type of zeolite). The plates were maintained in a saturated incubator kept at 40 °C for 24 h; they were weighed every two hours for the first eight hours, after which, weight was measured every after 4 h. The water adsorption was quantified as a percentage of zeolite weight in each plate. After 24 h in the incubator, the zeolite-filled plates were heated in an electric oven at 200 °C for 12 h and allowed to cool for 12 h in an airtight vessel to avoid water re-adsorption during cooling. During the heating, each plate was weighed every 30 min until all the water was evaporated. After cooling, the plates were weighed again and the cycle of incubation in a saturated chamber to regeneration was repeated several times using the same zeolite to simulate reuse of zeolite in a cooler installed on a farm.

Propane – powered regenerator design

To test regenerator performance in absence of biogas, we first developed a propane-powered regenerator, fabricated using aluminum and stainless steel sheets, and insulated using fiber glass (TaoFiber, NJ, USA The design of the regenerator is shown in Fig. 3b–d; the regenerator dimensions are 500 mm by 610 mm and 550 mm high; the cover and chimney are 1933 mm high. This regenerator was loaded with 20–30 plates containing 250 g of zeolite each and heated with a propane gas burner. The heating was done for 2, 3 and 4 h to ascertain that the regenerator was capable of raising the regeneration temperature used with the electric regenerator (200 °C). A biogas-powered low-cost regenerator of similar design (shown in Fig. 3e) was constructed using local materials (clay bricks, concrete, mild steel top and clay-saw dust mixture insulation) in Uganda. The performance of the low-cost biogas-powered regenerator was characterized with respect to its ability to raise and maintain temperatures in the range of 200 °C.

Results

10 Å pore zeolite is better adsorbent in evaporative cooling For convenience, we'll refer to 3 Å 4 × 8 mesh molecular sieves as zeolite A, Sigma Aldrich's 13X 4 × 8 mesh as B, Zeotech 13X 4 × 8 mesh molecular sieves as C and Sigma Aldrich's 13X 8 × 12 as D. Beads of 4 × 8 and 8 × 12 mesh sizes are 2.5–5 mm and 2–3 mm in diameter, respectively. 10 Å pore zeolite adsorbed more water (26.38 ± 1.16%, 26.59 ± 1.90%, 26.46 ± 1.2% – n = 4 – for B, C and D in 24 h, respectively) in comparison to 3 Å pore zeolite (A) whose adsorption was 20.54 ± 0.45% (see Fig. 4(i). According to raw milk safety standard, milk should be cooled to below 10 °C within 4 h of commencement of first milking [11]; we compared the adsorption kinetics at 2 and 4 h to see which zeolite is likely to facilitate a fast cooling process. At 4 h, the results were consistent with observations at 24 h (B, C and D adsorbed more water – 21.43 ± 1.43%, 21.58 ± 0.72%, 22.3 ± 1.31%, n = 4) and approached their saturation points; At 2 h however, A, C and D adsorbed more water, indicating slower kinetics in B – as evident in Fig. 4(ii) (15.46%, 15.02%, 14.22% and 12.08% water adsorbed as percent of zeolite, for C, D, A and B respectively). Taken together, these results show that for a 24-h evaporative cooling cycle, zeolite B, C and D are better adsorbents compared to A, which adsorbed the least amount of water in 4- and 24-h adsorption cycles (Fig. 4(i) and (ii)). However, in cooling systems where evaporative cooling is required in a very short time (less than 4–5 h as in milk cooling), zeolite C and D would provide better adsorbents.

All zeolite types were regenerated in 2.5 h at 200 °C

We investigated zeolite regeneration with respect to the time it takes for complete water desorption. We were interested in the regeneration time because not only can it influence the scheduling of farm activities, but it has cost implications. The lower the time, the lower the energy requirement, the smaller the biogas plant and the lower the initial investment capital. The time for Zeolites C and D did not differ significantly. In fact, all the zeolites were fully devoid of water in 2.5 h as shown in Fig. 4(iii). We noted however, that type D tended to disintegrate during handling. Ideal zeolite should be fully dehydrated at 200 °C or lower temperature in the least amount of time.

Regenerator temperature profiles

The propane regenerator reached and maintained the desired temperature of 200 °C. Higher temperatures were possible with increased gas flow rate. Zeolite regeneration temperatures are in the range of 150–315 °C but for our experiments, the 200 °C minimum temperature requirement was established with a high temperature electric regenerator with precise temperature control. The propane regenerator utilized 0.515 kg, 0.825 kg and 0.995 kg of propane for 1 h, 2 h, and 3 h regeneration cycles respectively. Using net calorific values for propane and biogas (assuming a methane composition of 60%, average of measurements), the propane consumption was used to estimate the volume of biogas required to operate the regenerator at similar conditions. Interestingly, the biogas consumption observed with our biogas regenerator constructed in Uganda was consistent with the estimates from the propane laboratory model. At 2 h for example, the mean biogas consumption was 1.78 ± 0.07, a 6.5% relative error when compared to the estimate obtained using the propane model. Table 1 below shows the amount of propane that was consumed and the equivalent biogas volume at room temperature and one atmosphere. Like the propane model, the biogas regenerator heated and maintained zeolite at 200 °C. However, the propane regenerator reached the target

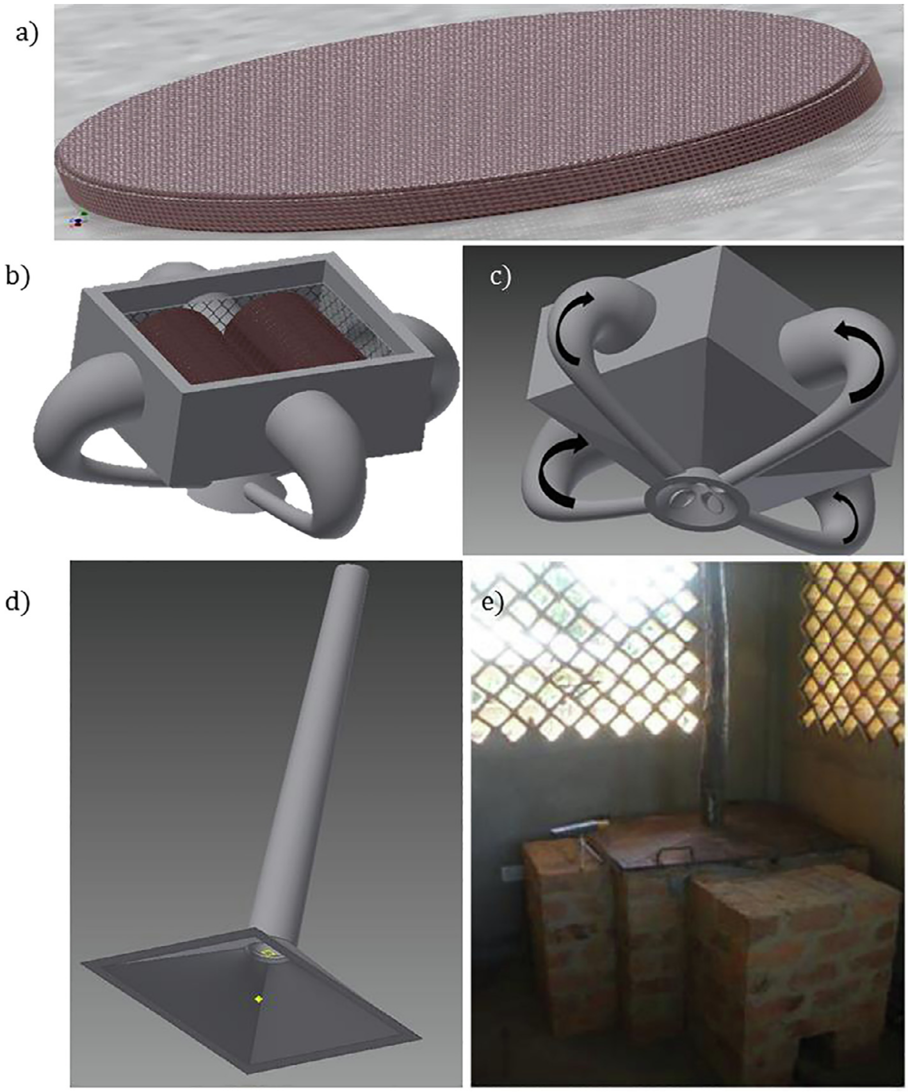

Fig. 3. Regenerator design. a) a model zeolite cell made of 250 g of zeolite enclosed in a 10-inch diameter perforated stainless steel plate; b–d) regenerator design model used as the basis for construction of the propane and biogas powered regenerators. The designs features a heating chamber is shown in (b), multidirectional flow of hot air into the heating chamber to enhance isotropic heating: hot air from the heating element placed at the bottom is delivered through ducts to the chamber containing zeolite plates (indicated with black arrows in c) and a detachable cover and chimney (d). e). Biogas powered regenerator constructed of brick masonry and insulated using clay-saw dust mixture.

temperature in about 15–25 min while the biogas required 30–50 min. Typical temperature profiles for both the biogas and propane regenerators are shown in Fig. 5.

Discussion

From Fig. 5, the biogas regenerator, compared to the propane regenerator, required longer time to reach 200 °C. We suspect that the difference in time to reach regeneration temperatures is due to difference in construction material, the lower net calorific value of biogas, as well as biogas methane content, compared to propane. Since the biogas regenerator was constructed using clay walls, we suspect that the delay is due to the initial temperature gradient as the regenerator walls are raised to the desired temperature. In addition, while the propane regenerator model was used in controlled laboratory conditions, the biogas regenerator was tested on-farm with little control over environment to simulate use at rural farms. Nonetheless, the 30–50 min required to reach regeneration temperatures with the biogas is comparable to our control, the electric regenerator, which raised the temperature in 45 min but fully dehydrated zeolite in about 2.5–3 h. The ability to generate and maintain desirable regeneration temperatures in our biogas regenerator design offers high promise for on-farm regeneration and other specialized procedures that require controlled heat application in rural settings. While a functional low cost on-farm regeneration system is a salient piece of this design, the adoptability of the device is also contingent on: one, efficacy of the cooling system/the choice of zeolite. Zeolite drives the depth of the cooling cycle through its extent of water adsorption. Two, delivery of a device whose operational logistics fit the socio-economic lives of our target adopters.

Our results suggest that Zeolite C (Zeotech's 13X 4 × 8 mesh) might be a more suitable adsorbent for evaporative cooling system for milk preservation in low resource settings. This zeolite showed consistent superiority in water adsorption in both short (less than 4 h) and long adsorption cycles (up to 24 h); did not disintegrate during handling; like all the other zeolites, it can be regenerated in less than 2.5 h and its price per unit weight is at least one-third the cost of other zeolites. Generally, the 3 Å zeolite beads of 2.5–5 mm diameter (zeolite A) absorbed the least amount of water. We suspect that the superiority of B, C and D with respect to water adsorption capacity is due to their large pore size [7,12,13]. We observed that D showed a higher initial rate of water absorption (approximately 8.3% per hour) in comparison to B (7.4% per hour), its counterpart from the same manufacturer, but not C whose rate was 8.6% per hour, although both C and B have 10 Å pores. This is likely due to the difference in mesh sizes of B and D–B and D being 2.5–5 mm and 2–3 mm in diameter, respectively. This result shows that for the same pore size, smaller pellets adsorb more water per unit time, which may be due to their high surface area. Based on these water adsorption kinetics (zeolite-water absorption of 20–26% of its weight), we estimated between 42 and 54 kg of zeolite to cool 50 L of milk to 4 °C within 4 h at ideal conditions in our design. Such a massive

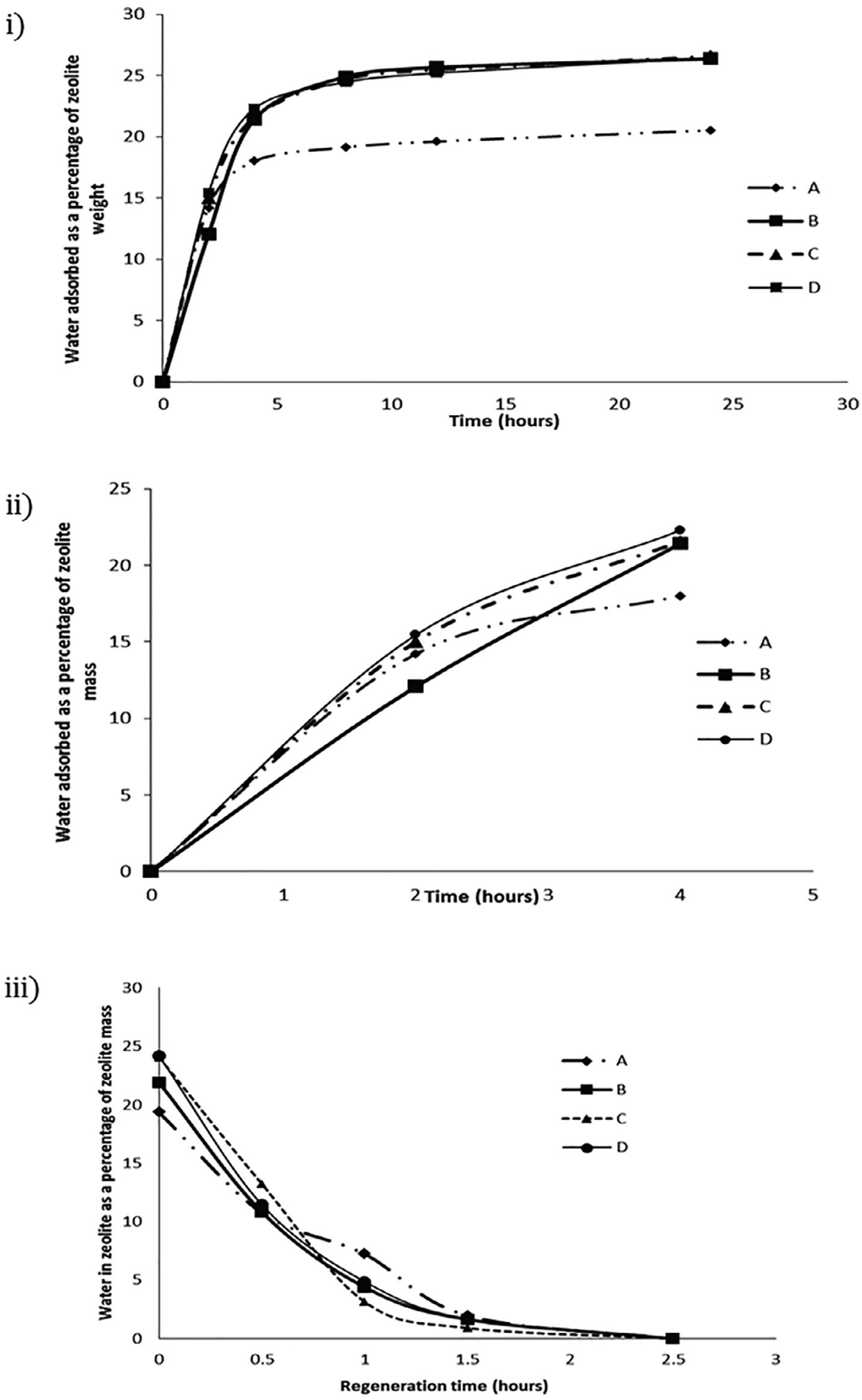

Fig. 4. Zeolite Characterization – water adsorption kinetics and regeneration time comparison of 3A 4 × 8 mesh molecular sieves (A), sigma Aldrich's 13X 4 × 8 mesh (B), Zeotech 13X 4 × 8 mesh molecular sieves (C) and 13X 8 × 12 mesh molecular sieves (D). i). 24-h water adsorption profiles for zeolites A, B, C and D showed that A, a 3 Å pore size zeolite, absorbed about 6–7% less water in comparison to zeolites of larger pore size (10 Å – B, C and D). ii). 4-hour water adsorption profiles for 3A 4 × 8 mesh molecular sieves (A), sigma Aldrich's 13X 4 × 8 mesh (B), Zeotech 13X 4 × 8 mesh molecular sieves (B) and 13X 8 × 12 mesh molecular sieves (D). Zeolites C and D have higher water adsorption in first 4 h and might, therefore, be superior to A and B in fast cooling operations as required in milk cooling. iii). All the zeolites used in the study were all fully regenerated from saturation point in 2.5 h implying that neither of the zeolites. 4 × 8 and 8 × 12 mesh molecular sieves are zeolite beads 2.5–5 mm and 2–3 mm in diameter respectively.

Table 1
Amount of propane used during regeneration and equivalent volume of biogas.

Time (hours)	Propane used (kg)	Estimated Biogas (m^3)
1	0.515	1.039785
2	0.825	1.665675
3	0.995	2.008905

amount of zeolite needed to operate the device coupled with the weight of plates and other handling equipment is likely to be a prohibitive factor, more so with the need to regenerate often.

There are other limitations with the second generation design informed by our zeolite characterizations results. Problem one is contamination from repeated use. Our results showed variance of up to 3.6% in 10 Å zeolite (A, B and C) in comparison to 0.2% in the 3 Å zeolite (A). We suspect that the high variance, in 10 Å zeolite (A, B and C) water adsorption, observed between the first adsorption cycle and the subsequent cycles might be due to contamination, which would gradually reduce its performance over time. Larger pore molecular

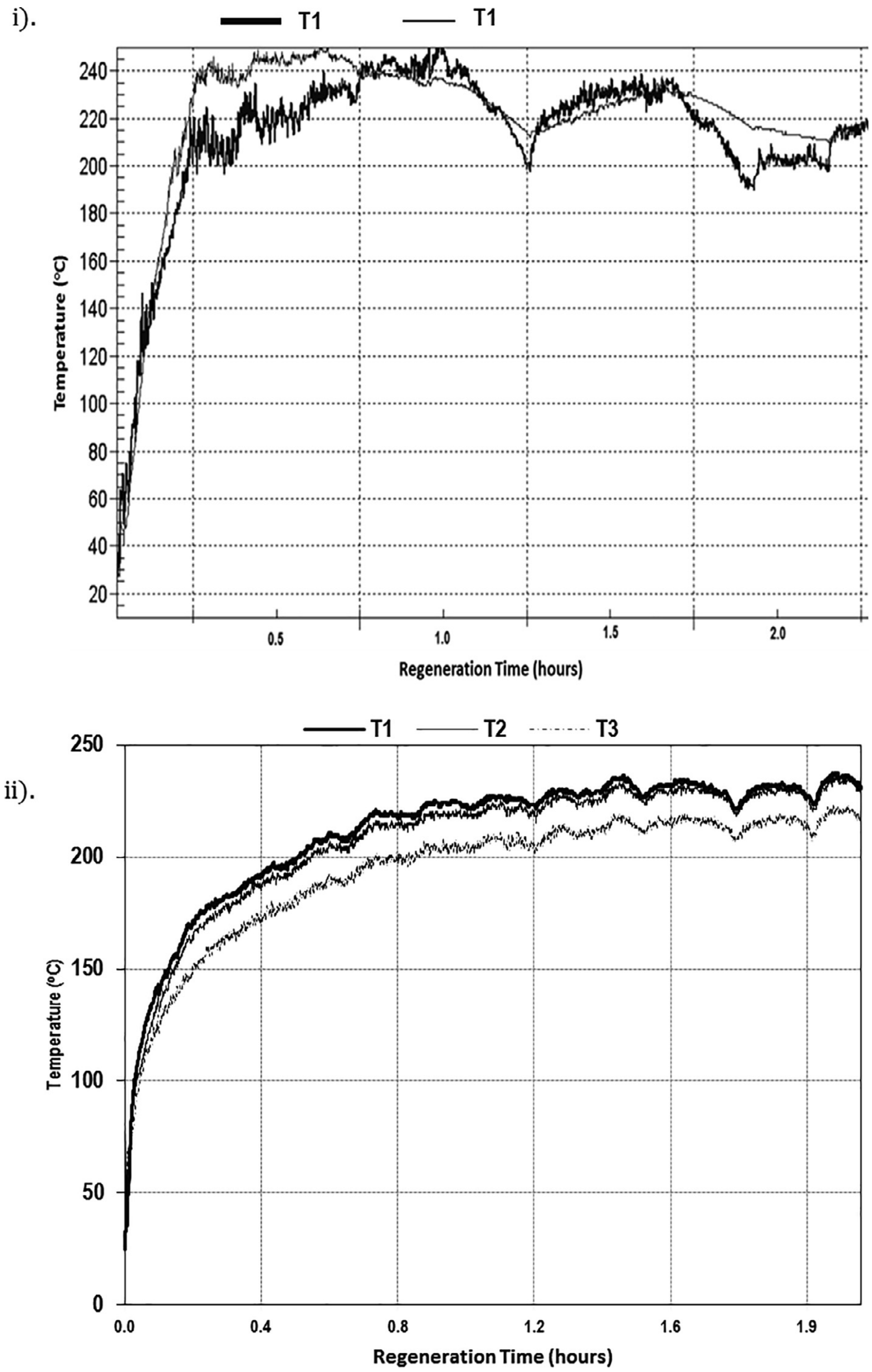

Fig. 5. Typical temperature profiles in zeolite regeneration using a propane and biogas regenerators. i). the propane gas heated regenerator maintained temperatures close to 200 °C, required for zeolite regeneration. T1 and T2 are two arbitrary points in the regenerator at which temperatures were measured and logged using thermocouples; ii) shows a typical temperature profile of the biogas regenerator constructed at a smallholder farm in Uganda. While this design required about 30 min to achieve the desired minimum temperature of 200 °C, the design is superior at maintaining stable temperature in the heating chamber in comparison to the gas powered laboratory regenerator. Also, the 45-min time to rise to 200 °C achieved with this construct was consistent with the profile of our control electric oven regenerator. Taken together, these profiles show that our biogas powered regenerator design is sufficient for complete regeneration of zeolite in about 2.5 h – as seen with the electric regenerator.

sieves are highly susceptible to contamination [14–16]. Since the water container chamber of the evaporative cooler has to be refilled before every cooling cycle, farmers need access to clean water to maintain optimal performance of the zeolite through all the cycles of the cooler. Needless to say, the lack of clean water in developing countries (a well-studied problem [17–20]) which would benefit from such a cooling system, makes use of zeolite highly susceptible to contamination less sustainable. Contamination from unclean water is likely to reduce the cooling cycles for which the optimal performance of this zeolite can be achieved.

Problem two is hygroscopic nature of zeolite [21] – also evident from the fast kinetics of water absorption in the first 2–4 h of exposure to moisture. Pre-exposure to moisture/humid air reduces its adsorption compromising its performance as an adsorbent. The use of zeolite in a cooling system requires structures/protocols to prevent unintended water adsorption from the environment (in-between regeneration and cooling cycles). The consequence is an increase in manufacturing costs due to the need for specialized storage and handling of zeolites. Also during operation, the efficiency of the cooler is likely to be unpredictable since it will depend on handling – exposure of zeolite to humid air leading to poor [cooling] system performance, and ideal performance when not exposed. Our previous 15.5-L cooler design circumvented these two problems by incorporating sealed water and zeolite chambers with the rest of the cooler, however, this increased the dry weight of the cooler immensely and made it inconvenient for farmers to use.

The requirement of clean water refills, specialized storage/handling facilities and heavy weight demand special design strategies to develop a practical product for farmers who are likely to be of low technology acuity; more importantly, special design strategies translate to too high a cost of product for smallholder farmers to afford. In totality, these factors inform a need to redesign a solution to the smallholder farm evening milk problem. We have considered alternative low-cost milk preservation technologies, which utilize renewable energy sources – the Icy Ball and an evaporative cooler branded EvaKuula. Our consideration of Icy Ball utilized 43% ammonia (w/w) and the cooling was achieved via a loss of heat by the cooling load to provide a latent heat of vaporization for ammonia. The system is regenerated using a low temperature heating cycle powered by biogas. The technical details of this technology are specified elsewhere [22]. This idea was, however, abandoned because the potential environmental and health hazards of this technology in the hands of rural farmers are daunting. We have continued to experiment with, and are currently in the process of deploying, the EvaKuula, which combines thermization and low-cost evaporative cooling, using charcoal – which is described in our complimentary manuscript [23].

Concluding remarks

We have developed an easy protocol to test the suitability of zeolite as an adsorbent in evaporative cooling. Our setup utilizes an incubator maintained at low temperatures (40 °C), and water in evaporative pans to simulate air saturation in an evaporative cooling system. The ability to control temperature and pressure makes this system a versatile model for a wide range of operations. Using zeolite beads of diameters 2.5–5 mm, our work showed that 10 Å zeolites have a higher water adsorption capacity (6–7%) in comparison to 3 Å zeolite beads, suggesting that larger pore zeolites may provide higher temperature drop. However, large pore zeolite beads showed up to 18 times variance in water adsorption compared to the 3 Å zeolite, indicating zeolite of small pores may provide more reliable cooling cycles. None of the zeolites showed energy saving advantage as indicated by similar regeneration times in an electric regenerator at 200 °C. To adapt our zeolite evaporative cooling system to rural farms with no access to an electricity power grid, we designed and constructed a regenerator powered by propane and biogas; both regenerators reached and maintained temperatures around 200 °C, suggesting that our regenerator design is suitable for regeneration of zeolite. The results from this study have informed the need to consider a third generation cooler system.

Acknowledgements

The authors acknowledge funding from USAID Powering Agriculture Energy Grand Challenge Program (#AID-OAA-A-13-00066). The authors also acknowledge Prof. Noble Banadda of Makerere University for logistic support.

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