EVAPORATIVE COOLING COMPUTATIONAL ANALYSIS – TOWARDS OFF-GRID MILK FRESHNESS PRESERVATION

by

Edison John Sempiira

(Under the Direction of William S. Kisaalita)

Abstract

An approach to off-grid milk preservation for rural sub-Saharan African dairy farmers was developed. This approach branded as EvaKuula, involves a combination of two microbiostatic processes: thermization and evaporative cooling. The EvaKuula allows for extended storage of raw milk. Contrary to the chilling process, the EvaKuula process involves addition of heat to the milk (thermization) – followed by evaporative cooling. Although thermization is practiced in commercial dairies for extended storage of raw milk before processing, the application of thermization coupled with evaporative cooling for off-grid preservation of milk in the hands of smallholder farmers is an innovation.

In this research, we use computation fluid dynamics (CFD) to understand the mass, energy and momentum transfer between air and water during the evaporative cooling process in the context of milk preservation. We consider both the current design with a fan and a design with a static vent. CFD analysis was done using Ansys fluent code 19.2. We also measure the biochemical and microbial quality of milk to understand the degree of freshness of milk from the process. Milk biochemical parameters were measured with an ultrasound milk analyzer and microbial quality were analyzed following standard procedures.

The results for performance of the evaporative cooler with a modified vent were enough for milk preservation in terms of drop in air temperature (maximum 8.3^{0}C). The change in temperature is due to the exchange of mass and energy between air and water. The results for milk freshness showed that biochemical (fat at 4.25) and microbial quality (Total viable counts at 13000 cfu/ml), qualify evakuuled milk for grade one (top quality) fresh milk classification.

Potential impacts of these findings are; the results of milk freshness provide a science driven evidence in supports of inclusion of evakuuled milk in the raw milk quality standard. Additionally, results of the performance provide evidence for value engineering a new cost-effective prototype of the evaporative cooler with a static vent. Inclusion of Evakuuled milk in the standard may improve product confidence among sector players. This coupled with a potential of a low retail price can accelerate product diffusion among rural Sub-Saharan African farmers.

Index words: Off-grid milk preservation, Microbiostatic, Computational fluid dynamics, thermization and evaporative cooling, Smallholder farmers, , Biochemical and microbial quality

EVAPORATIVE COOLING COMPUTATIONAL ANALYSIS – TOWARDS OFF-GRID MILK FRESHNESS PRESERVATION

by

EDISON JOHN SEMPIIRA
B.S., Makerere University, Uganda, 2014

Dissertation Submitted to the Graduate Faculty of The University of Georgia in
Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

Athens, Georgia

2019

EVAPORATIVE COOLING COMPUTATIONAL ANALYSIS – TOWARDS OFF-GRID MILK FRESHNESS PRESERVATION

by

EDISON JOHN SEMPIIRA

Major Professor: William S. Kisaalita
Committee: Cheryl Gomillion
Ramana Pidaparti
K C. Das

Electronic Version Approved:

Ron Walcott

Interim Dean of the Graduate School

The University of Georgia

December 2019

DEDICATION

To friends and family

ACKNOWLEDGEMENTS

I express my sincere gratitude to my advisor Prof. William Kisaalita for the continuous support in my research. You went from being a mentor to a father. Your patience, motivation, enthusiasm, and immense knowledge has greatly shaped my career. I am forever grateful.

Besides my advisor, I would like to thank my committee: Prof. Cheryl Gomillion, Prof. Ramana Pidaparti and Prof. K C. Das for their encouragement, insightful comments, and constructive questions that have shaped my doctoral work.

I would like to appreciate the funding from: USAID Powering Agriculture Energy Grand Challenge Program (#AID-OAA-A-13-00066), NSF Alliances-Minority Participation Program (#1619689), and Doctoral summer research travel grant – University of Georgia Graduate School.

I also in a special way would like to thank, Prof Noble Banadda and Dr. Kiggundu Nicholas of Makerere University, Kampala - Uganda for their mentorship and logistical assistance during my long academic Journey.

I thank My lab mate Dana Jill Mugisa for being that shoulder to lean on in everything. I am grateful for having worked with you for all these years. And to all my research assistants, Joseph Galiwango and Abia Katimbo, thank you for that service above self.

I would also like to appreciate my family for supporting me financially, emotionally, and spiritually throughout my life especially this academic journey. You have been so supportive, may the good Lord reward you abundantly

Above all, I give the glory and honor to the almighty God for bringing me this far. Without you Lord, Life is meaningless.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1:

INTRODUCTION AND OBJECTIVES

An off-grid preservation system for milk known as the EvaKuula kit was developed purposely to serve rural smallholder farmers of sub-Saharan Africa (Kisaalita et al 2018). The EvaKuula process involves two Micro-biostatic steps; thermization and evaporative cooling. Thermization involves an indirect heat treatment (heating over a water bath) of milk and evaporative cooling involves lowering the subsequent temperature to about 10 degrees below the room temperature. Thermization therefore reduces the population of spoilage microorganisms (Chouliara et al. 2010, and Walstra et al. 2013) whereas evaporative cooling provides an environment that minimizes growth (Wayua et al. 2012). The EvaKuula kit has been deployed in Uganda. A resasurin test suggested that milk from the EvaKuula process was of good quality (Kisaalita et al 2018). Thermised milk is not defined in the East African milk quality standard (EAS 67:2000) as a grade of raw milk. However, literature supports that thermization with subsequent storage at 8^0C and below maintains the keeping quality of raw milk (Brennan 2006) for three days. We hypothesized that when we store the milk at evaporative cooling temperatures after thermization, we still maintain the quality attributes of raw milk the next day.

The thermization process requires a fuel source to boil the water used for indirect heat-treatment of milk. Firewood, charcoal, LPG, biogas and kerosene are the locally available energy sources in Uganda. The EvaKuula was designed with biogas as the fuel source in mind because of its enormous benefits as a central component in a smallholder farm ecosystem. In the initial field deployment studies (Kisaalita et al 2018), it was noted that the need to invest in both a domestic biogas plant and EvaKuula at the same time was limiting the adoption of EvaKuula. Therefore, we needed to assess the other accessible energy sources to recommend to EvaKuula potential adoptees.

The performance of the evaporative cooler is driven by the air flow properties. The current design of the evaporative cooler was adopted from manuwa et al., (2012). The mass and energy transfer for the cooler is based on the temperature and relative humidity of the ambient air and these influence the performance of the evaporative cooler. The wind driven fan on the top of the fan drives the air flow pattern in the evaporative cooler. We proposed eliminating the fan in the design to replace it with a cost-effective vent. Because the operating height of the evaporative is about 1 m from the ground, our thinking was that the wind speeds at this height are not enough to produce the desired air flow, thus the fan acts like a static vent. We hypothesized that we can have desired efficiency of the Evaporative cooler without the fan.

This research projects therefore aimed to address three objectives;

1.1 Objective 1:

To understand the biochemical and microbial quality of milk from the EvaKuula process. Specifically, to; a) Establish the optimum temperature of thermization for the process and b) Establish the “degree of freshness” of milk after the process based on quality attributes of the East African milk quality standard (EAS 67:2000).

1.2 Objective 2:

To determine the next fuel option for the thermization process from the locally available energy sources in reference to biogas. Specifically, to; a) Quantify energy source consumption and resulting emissions for each fuel source, and b) Determine the fuel with the least cost per liter; combining “market cost” and “social carbon cost”

1.3 Objective 3:

To model the evaporative cooling process using computational fluid dynamics (CFD) software. Specifically, to; a) to develop a computer fluid dynamic Model for the current design of the evaporative cooler to understand the temperature and humidity distribution in the context of milk preservation and b) to determine the effectiveness of the cooler with and without the fan for a given time of day.

The results of milk freshness can provide a science driven evidence that would support the inclusion of evakuuled milk in the fresh milk quality standard for the East African region. Additionally, results of the performance can provide evidence for value engineering a new cost – effective prototype of the evaporative cooler with a static vent. Inclusion of Evakuuled milk in the standard may improve product confidence among sector players. This coupled with a low retail price may accelerate the diffusion of the EvaKuula among rural Sub-Saharan African farmers.

1.4 References

Brennan, J. G. (2006). Food Processing Handbook, Wiley.

Chouliara, E. G., K. G. Kanellopoulou, N. Kontominas, M, G. (2010). "Effect of ultrasonication on microbiological, chemical and sensory properties of raw, thermized and pasteurized milk." International Dairy Journal 20(5): pp307-313.

EAS 67: 2006. East African Standard. Raw cow milk – Specification. Available at: https://law.resource.org/pub/eac/ibr/eas.67.2006.pdf

Kisaalita, W.S., Katimbo, A., Sempiira, E., Mugisa, D. (2018). EvaKuula saves Ugandan smallholder farmers evening milk. Sustainable energy technologies and assesements 29 (2018) pp 155–163 https://doi.org/10.1016/j.seta.2018.08.002 ,.

Manuwa, S. I., & Odey, S. O. (2012). Evaluation of pads and geometrical shapes for constructing evaporative cooling system. Modern Applied Science, 6(6), 45.

Walstra P, T. J. G., A. Noomen, A. Jellema, M.A.J.S.Van Boekel (2013). Dairy Technology: Ponciples of Milk Properties and Processes. Taylor anf Francis, Marcel Dekker. Inc 270 Madison Avanue, Newyork, NY 10016.

Wayua Francis O, Okoth Michael W and Wangoh, John. (2012). Design and Performance Assessment of a Low Cost Evaporative Cooler for Storage of Camel Milk in Arid Pastoral Areas of Kenya. International Journal of Food Engineering. 8.

CHAPTER 2: LITERATURE REVIEW

OFF-GRID MILK PRESERVATION SOLUTIONS FOR SMALLHOLDER FARMERS OF SUB-SAHARAN AFRICA

Sempiira J. E, J. D. Mugisa, J. Galiwango, A. Katimbo and W. S. Kisaalita. Submitted to *Renewable & Sustainable Energy Reviews*.

Abstract

Milk production in sub-Saharan Africa countries has received attention in previous years both in the private and public sectors. The emphasis has been on devising avenues to increase production within the dairy value chain. One of the value-chain interventions for mitigating against post-harvest milk losses on smallholder farms that has received great attention is milk-freshness preservation overnight. Most smallholder farms are in the rural areas with no or limited access to grid-electricity. Therefore, solutions that address this problem have predominantly relied on renewable energy resources. Current solutions vary in capacities, ranging from 2.5 to 500 liters. Smallholder farmers of Uganda are an excellent representation of other farmers in many sub-Saharan African countries with similarly structured dairy milk value-chains. These farmers can be divided into different architypes based on number of cows and farm management practices. A common archetype are farmers with about 10 dairy cows farming on about 2 hectares of land. Current solutions or technologies targeting these farmers have sometimes not met their capacities or are sometimes offered at prices way above the economic price-point. Therefore, even in presence of these technologies, the post-harvest losses are still prevalent. We establish a representative solution price-point and review the current solutions or technologies in view of the price-point. We further provide recommendation for solution developers to consider to reduce bottlenecks for technology up-take in low-resource settings.

Key words: Smallholder dairy farmers; milk post-harvest losses; on-farm and transportation milk freshness preservation; renewable energy-powered milk cooling; and

development engineering in low-resource settings.

2.0 Introduction

Smallholder farmers of sub-Saharan Africa, farming 2-5 hectares, produce 70% of the food calories consumed by sub-Saharan Africans (Samberg et al 2016). The world population is projected to increase by 34% to 9.7 billion by 2050 (Desa et al 2015) and most of the increase will occur in developing counties. Food production will have to increase by 70% to meet demand (Thornton et al 2018). A similar projection has been published by the Food and Agricultural Organization (Alexandratos and Bruinsma, 2012). Smallholder farmers are increasingly practicing mixed agriculture – mixing crop and livestock. Adding livestock production to crop farming enhances household resilience through diversification of products from animals such as milk, beef, butter, hide and skins and manure for crop fertilizer. To accelerate mixed agriculture, governments in developing countries are putting in place incentives such as subsidies (Devendra, 2000).

The incentives are producing the desired outcomes. For example, in Uganda milk production has increased from 395 million liters in 1986 to 1.08 billion liters in 2010; with an annual growth of 4.9% (Balikowa, 2011). However, the increase would be even higher, but these farmers experience unacceptable post-harvest losses. FAO reported that Uganda, Kenya and Tanzania, have post-harvest losses estimated at $23, $22.4, and $14.7 million per year, respectively. The highest percentage of about 5.8% and 11% is directly incurred by smallholder dairy farmers at the farm level and during transportation, respectively (Ndyabawe and Kisaalita). Some of their milk (mostly the evening milk) goes to waste just because they don’t have an on-farm means to keep it fresh. In sub-Saharan Africa, most farmers live in rural areas with no access to grid electricity. Also, these farmers stay far from town centers with collection points housing cooling facilities; they cannot transport the milk in the night because it becomes unsafe and in addition the roads become impassable in the rainy season when production is at the peak (Ndyabawe and Kisaalita). As such, these farmers end up processing the milk into low value products such as ghee or consume it.

Off-grid preservation technologies developed for these smallholder farmers do not usually fit within their financial means. Smallholder farmers are likely to adopt technologies that are consistent with their cash flows. In view of the projection by the Food and Agricultural Organization that milk demand in the developing world will double by the year 2030 (Alexandratos and Bruinsma, 2012), several interventions have been developed to eliminate the post-harvest loss. We review several solutions or technologies commercialized or ready for commercialization to highlight the critical factors to consider by solution developers toward improving technology up-take.

2.1 Who is a smallholder dairy farmer?

Smallholder farmers can be defined in several ways depending on the context, country and/or ecological zone. In the context of diary production in a country like Uganda, smallholder farming has been grouped based on production systems (Garcia et al 2008). There are two production systems: 1) Intensive, which is further subdivided into smallholder intensive, medium-holder intensive and large-scale intensive; and 2) extensive, which is further subdivided into smallholder extensive, medium holder extensive, pastoralists and agro-pastoralists. The intensive production systems are mainly common in the peri-urban areas while the extensive production systems are commonly found in the rural areas (Garcia et al 2008). However, typical dairy farms in Uganda are mainly smallholder extensive types (Ndambi et al 2007). Farmers who practice smallholder extensive farming usually owns about 2 hectares of land with about 10 local dairy cows, but they also have an option of grazing from larger public lands (Ndambi et al 2007). These farmers usually sell their milk locally to vendors/middlemen who collect from the farms once a day because they are far from the major cities with markets. We base our analysis on this typical farmer and examine how the developed technologies can be appropriate in terms of capacity and cost. Similar production systems can be found in numerous sub-Saharan African countries and as such we consider Uganda to be an excellent representative model.

2.2 Technologies

Solutions can be subdivided into two categories: devices powered by solar energy and others powered by biogas or other off-grid energy sources. Solar energy can be utilized through photovoltaic (PV) sun energy to electric energy conversion that operate conventional vapor-compression refrigeration system (Mohanty and Padhiary, 2015) or through direct use of concentrated sun heat that operate ammonia-water refrigeration systems (Kulkarni and Ganesh, 2013). The trend of decreasing PV panel prices is fueling increased use of vapor-compression systems (Toledo, 2018, Abdul-Wahab et al, 2009), especially in places where grid-electricity is expensive or in short supply or unreliable (Gupta, 2012, Koroneos et al 2010). Biogas-powered cooling is a more recent development. Milk freshness preservation by biogas is achieved through two methods: mild heat treatment of milk followed by low-cost evaporative cooling or direct heating to drive ammonia-water refrigeration. Following are brief descriptions of currently commercialized or commercializable systems.

2.2.0 Solar PV-based energy systems

Solar farm milk chillers

Sundanzer Refrigeration Inc. (https://sundanzer.com) developed a solar-powered farm milk chiller (FMC). The device uses a vapor compression cycle powered by electricity from PV panels. A micro-processor control allows the solar panels to connect directly to a DC compressor. The technology behind FMC was originally developed by scientists at NASA to transform space technology to earth use (Foster et al 2015). The solar panels are exposed to at least five hours of sunlight a day and form ice is stored in the walls of the refrigerator. Water is used as a phase change material that is integrated in the insulated refrigerator walls. The quantity of ice formed is enough to maintain low temperatures to run the chiller overnight with a load of 40 liters of milk. Brine bags that do not freeze at 0^0C (Foster et al 2015) are placed close to milk cans in the cooling chamber to increase heat transfer. FMC devices have been field tested in Kenya and Rwanda. Over 82 units are in operation in these two countries. Each unit is estimated to cost USD 1,850 including complete installation (Foster et al 2015).

Rapid milk chiller

Promethean Power Systems manufactures and markets the rapid milk chiller (https://coolectrica.com). The system uses a phase change material to store thermal energy in form of ice that is used in times of low electricity. When connected to grid electricity, the systems forms ice as a “thermal battery.” When the grid electricity operation is interrupted, the formed ice is used for chilling. A fully charged thermal battery is achieved in five hour of grid-electric operation and can chill 500 liters of milk (Mohanty and Padhiary, 2015). Promethean Power Systems has deployed about 3000 units in various parts of rural India through major dairy processors like Amul and Chitale (Mohanty and Padhiary, 2015). In 2013, each unit costs USD $7,000. Promethean Power System is dedicated to developing a device that will be off-grid and be fully solar energy-powered.

Hohenhein solar cooling system

The Institute of Agricultural Engineering of the University of Hohenhein developed and has field-tested the Hohenhein solar cooling system (https://www.uni-hohenheim.de/en) in Kenya (Salvatierra et al, 2018). The system uses a solar powered DC- freezer. The freezer has a volume of 166 liters and can generate up to 13 kg of ice required for preserving 60 liters of milk per day (total system capacity). The freezer is equipped with a control unit to customize use of the available solar energy. The system comes with 25 reusable plastic blocks of 2 kg and two 30-liter insulated milk cans with a removable ice-holding component. Therefore, the freezer can produce 50 kg of ice for use in 5 days of low solar radiation (Torres-Toledo et al 2018). To operate the system, milk is placed in an insulated traditional 30-liter can and the ice-holding compartment with the ice blocks is inserted into the milk and covered. Stainless steel material is used for the cans and ice-holding component to maintain food grade surface in contact with the milk. The system can be operated in two modes; the 6-hour mode is for milk transportation purposes; the 12-hour mode is for storage of evening milk purposes. In the 6-hour mode, the 6 kg of ice are used to lower milk temperature from 35 to <19^{0}C. In the 12-hour mode, 8 kg of ice are used to lower the milk temperature to <13^{0}C (Torres-Toledo et al 2018). The cost of the system is USD 1,560 based in Kenya but can cost up to USD 2245 when directly imported as a finished product (Salvatierra et al, 2018).

2.2.1 Solar thermal refrigeration system

ISAAC solar ice maker

ISAAC stands for “intermittent solar ammonia absorption cycle (Torres-Toledo et al 2018). The device was developed by Energy Concepts Inc. (http://eci-info.com/wordpress2) to operate purely without electricity. It is based on the intermittent ammonia/water absorption refrigeration technology, which is driven by heat rather that electricity. The device is composed of a parabolic trough that captures solar energy that is used to generate ammonia refrigerant during day. The refrigerant is then cycled back to the generator and ice is made in the night. The generated ice is then placed in the ice bags and can be used to cool milk. Milk is chilled by immersing milk in milk cans into the ice bath. On a sunny day, the daily production per square meter of solar collector is 5 kg. The cost of production of the 11 square meters ISAAC, is approximately USD 7,000 in low-wage places like sub-Saharan Africa. In a pilot study at the Kenyan coast, 50 kg of ice cooled 100 liters of milk (Erickson, 2009).

2.2.2 Biogas powered systems

CoolChurn

The Coolchurn is a modification of an existing evaporative cooling technology originally developed for beer consumers in Europe and Asia. The cool system developed in Germany was re-engineered by researchers from the University of Georgia to provide a cooling system for off-grid smallholder farmers. The CoolChurn has a capacity of 15.5 liters and weighs about 22 kg when empty (Ndyabawe and Kisaalita, 2014). The CoolChurn is based on evaporative cooling principles. It is a three-changer device. The center chamber is where the product to be cooled is housed. Next to the product chamber is the “refrigerant” water chamber connected by a pressure sensitive valve to the outer most chamber that houses a water adsorber like zeolite. The zeolite chamber is maintained under sealed vacuum. The valve is operated by a switch, which exposes the zeolite chamber vacuum to the water in the water chamber. At this vacuum and room temperature, the water vaporizes, and the vapor is adsorbed by the zeolite. The heat of vaporization is provided by the warm product, whose temperature drops. To be used again the device needs to be regenerated. Regeneration involves closing the valve followed by heating the whole unit to approximately 200^0 C. The heat causes the adsorber or zeolite to free the water, which returns to the water chamber via the pressure sensitive valve. Cold water is the product chamber is used to condense the returning vapor from the adsorber (Ndyabawe et al 2019). Regeneration can be achieved with electricity or biogas or charcoal heating. Use of the biogas powered brick oven for regeneration has been successfully demonstrated (Ndyabawe et al 2019). The device was deployed in a pilot study in the southwestern Uganda (Ndyabawe et al 2019). The price per unit was a little over USD 2,000. Feedback from the pilot study user participants informed the development of the EvaKuula, described below.

Biogas milk chiller

Simgas B.V. (https://simgas.org) based in the Netherlands developed the biogas milk chiller. The chiller utilizes the standard ammonia-water cycle to cool milk from approximately 35^oC to 4^oC within 3 hours using biogas as an energy source. The biogas is used to provide the heat needed to evaporate the refrigerant. The cold is generated during the day and is stored in form of ice in the compact system. The ice is then used in the night for cooling. The chiller can hold two, five liter cans and therefore has a capacity ranges between 2.5 to 10 liters. The technology has been pilot tested in Tanzania, Kenya and Rwanda. Unfortunately, at the time of writing, the company has filed for bankruptcy in Amsterdam under insolvency number F.13/18/359.

EvaKuula

The EvaKuula process combines thermization and evaporative cooling to preserve milk freshness. The EvaKuula kit consists of two main components; the thermization drum, which is made up of a deep round aluminum pan and wooden insulation; and an evaporative cooling unit made up of a wind-powered mechanical air extraction fan, water troughs surrounded by jute pads on each side of the cooling chamber (Kisaalita et al 2018). Thermization is achieved by heating water in the deep pan over a biogas burner to boiling (approximately 96 °C). The deep pan is then quickly transferred to the wooden insulation drum and a can filled with a desired quantity of milk is placed inside the drum that is covered. Milk is kept in the drum for 45 minutes and then transferred to the evaporative cooler for cooling to approximately 10 to 14 ^{o}C, below room temperature and stored until the next day. The thermization drum can accommodate one 20-liter milk can at a time, but the evaporative cooler can accommodate four 20-liter cans at a time. Therefore, the maximum EvaKuula capacity is 80-liters (Kisaalita et al 2018).

In the initial field deployment studies, it was noted that the need to invest in both a domestic biogas plant and EvaKuula at the same time was limiting up-take (Kisaalita et al 2018). To overcome this problem, thermization has been accomplished with woody biomass in efficient stoves with the goal of transitioning to biogas, once the EvaKuula has been paid off. In comparison to devices described above, EvaKuula is unique and as such more studies are needed to support inclusion in established fresh milk standards for regulatory purposes. The production cost of the EvaKuula unit piloted in Uganda was USD 790 (Kisaalita et al 2018). Although the EvaKuula is promising in terms of cost and capacity, in comparison to the other devices described above, lowering the production cost further will greatly improve affordability and subsequently technology up-take.

2.3 Price-point for off-grid milk freshness preservation solutions

We are assuming Ugandan smallholder farmers are an accurate representation of other sub-Saharan African smallholder farmers with similar milk value-chains, such as Rwanda, Kenya and Ethiopia. On average, such farmer households possess five milking cows at any one time. Conservatively, each cow produces 7.7 liters of milk (Grimaud et al 2007); 54% and 46% of this milk is morning and evening milk, respectively (Cziszter et al 2013) or 4.2 liters in the morning and about 3.5 liters in the evening. Assuming all the morning milk goes towards financing the daily household needs and the evening milk sale goes to servicing payment of a milk freshness preservation technology, the total evening daily production will be approximately ($0.46 x 7.7 x 5$ cows = 17.7 liters). This estimate is consistent with literature values of 16 and 11.1 liters of morning and evening milk, respectively [7, 21] for smallholder farmers. According to the Diary Development Authority (DDA) of Uganda, the southwest and central contribute about 50% of Uganda’s national production. For an average farm-gate price of 700 Uganda shillings per liter (central and southwest average), the total evening milk sales per day come to 12,390 UGX (USD 3.69) translating to 371,700 UGX (USD 110.63) per month. From the analysis, the minimum capacity for an average typical farmer is about 18 liters and the available extra monthly income to make payments for a cooling technology is USD

110.63. There are two possible ways farmers can finance the devices. Either through rent-to-own or direct purchase. Most smallholder households cannot pay cash up-front for devices in the rages shown above. Rent-to-own is preferred because it allows small payments consistent with smallholder household cash flow. Smallholder farmers are hesitant to acquire loans, especially if the payments extend over two or more growing seasons - they have experiences of unpredictable poor growing seasons (e.g., poor rains), putting them in situations where they are unable to pay and financial institutions (e.g., microcredit finance) going for their assets (Werneck et al 2012).

At the time of writing, most of the devices featured above had no established retail prices in the Ugandan market. This is because the majority of the device developers were concluding pilot studies and pricing reported was for the regions in which the devices were being piloted. However, the above analysis provides the extra income available to pay for an off-grid milk freshness preservation device by a typical Ugandan farmer of not more than USD 110 per month in a rent-to-own business model. This is further constrained with preferable shorter pay-back period of less than a year. Considering half a year (one growing season) as the target payback period, an ideal market price for product should not go over USD 600 as the total retail price. The half a year period is based on the production seasons that are on average 6 months. Within a production season, production of milk is sustainable and therefore income to sustain pay back will readily be available.

Based on the technology's milk holding capacity, the Solar ice maker, Hohenhein solar cooling system, EvaKuula and the solar farm milk chillers have capacities that meet the cooling needs of a typical smallholder farmers (Table 1). However, as farmers increase their production above 100 liters, these devices fall short. Devices such as the larger solar farm milk chiller or rapid milk chiller are applicable at this level of production and may be affordable. At this level, these farmers can be either medium holder extensive or pastoralist or agro-pastoralists.

2.4 Concluding remarks

The current off-grid milk freshness preservation technologies have the potential to address the evening milk problem in rural sub-Saharan Africa. However, wide up-take will only be possible if the technology developers address several roadblocks. First, our analysis suggests that a device priced higher than the price-point of USD 600 is not likely to be sustainable. Solution developers should strive to produce below the price-point to leave room for those in the value chain such as distributors. Second, solution developers can consider an integrated approach, where smaller affordable solution can be deployed on the farm and larger capacity solutions are located at trading center as bulking points. The smaller units can feed the larger capacity units. If the larger capacity units are co-owned by farmers, the affordability issue may be resolved by cost-sharing. Because larger units attract a higher capital costs, using them for aggregation allows for cost sharing. With this approach, farmers can keep their milk fresh for prolonged hours in times when collection is not done on time.

2.5 References

Abdul-Wahab SA, Elkamel A, Al-Damkhi A M, Al-Habsi I A, Al-Rubai'ey H S, Al-Battashi AK. Design and experimental investigation of portable solar thermoelectric refrigerator. Renew. Energy. 2009; 34:30–4.

Alexandratos N, Bruinsma J. World agriculture towards 2030/2050: the 2012 revision.

Balikowa D. Dairy development in Uganda. A review of Uganda’s dairy industry. Dairy Dev. Authority Uganda; 2011: 3202(1).

Cziszter LT, Neamt RI, Ilie DE, Gavojdian D, Acatincai S, Erina S, et al. Estimating the Lactation Curve on am/pm milking in Dairy Cows. Scientific papers Anim. Sci. and Biotechnol. 2013; 46: 296-301.

DESA U. United nations department of economic and social affairs, population division. world population prospects: The 2015 revision, key findings and advance tables. In Technical Report 2015. Working Paper No. ESA/P/WP. 241.

Devendra C. Smallholder dairy production systems in developing countries: characteristics, potential and opportunities for improvement. Asian Australasian J. of Anim. Sci. 2000; 14:104-113.

Erickson C. Rural milk preservation with the ISAAC solar icemaker. Energy for Sustainable Development 2009; 13: 287-291.

Foster R, Jensen B, Dugdill B, Knight B, Faraj A, Mwove JK, Hadley W. Solar Milk Cooling: Smallholder Dairy Farmer Experience in Kenya. InISES Solar World Congress 2015 (p. 11).

Garcia O, Balikowa D, Kiconco D, Ndambi A, Hemme T. Milk production in Uganda: dairy farming economics and development policy impacts. IGAD Livestock Policy Initiative 2008.

Grimaud P, Mpairwe D, Chalimbaud J, Messad S, Faye B. The place of Sanga cattle in dairy production in Uganda. Tropical Anim. Health and Production, 2007; 39: 217-227.

Gupta SK. Enhancing the Performance of Solar Refrigeration System. Int. J of Sci and Res. 2012; 3(6):2319-7064. https://simgas.org/projects/biogas-milk-chilling/ accessed on July 2018.

Kisaalita WS, Katimbo A, Sempiira E, Mugisa D EvaKuula saves Ugandan smallholder farmers evening milk. Sustainable energy technologies and assess 2018; 29: 155–163 https://doi.org/10.1016/j.seta.2018.08.002 .

Koroneos C, Nanaki E, Xydis G. Solar air conditioning systems and their applicability—an energy approach. Resources, Conservation and Recycling. 2010; 55:74–82

Kulkarni NK, Ganesh U. Villgro Innovations Foundation Case Study Series – Promethean Power Systems. 2013.

Mohanty DK, Padhiary A. Thermodynamic Performance Analysis of a Solar Vapor Absorption Refrigeration System. Int. J. of Enhanced Res. in Sci. Technol. & Eng. 2015; 2319-7463.

Ndambi, OA, Garcia O, Balikowa D, Kiconco D, Hemme T, Latacz-Lohmann, U. Milk production systems in Central Uganda: a farm economic analysis. Tropical Anim. Health and Production. 2007; 40: 269-279.

Ndyabawe K, Brush R, Ssonko RE, Kisaalita WS. Biogas-powered evaporative cooling for smallholder dairy farmers' evening milk: Zeolite characterization and regeneration. Sustainable Energy Technologies and Assess. 2019; 34:126-32.

Ndyabawe K, Kisaalita WS. Diffusion of an evaporative cooler innovation among smallholder dairy farmers of Western Uganda. Technol. in Soc. 2014; 38:1-10.

Salvatierra Rojas A, Torres Toledo V, Mrabet F, Müller J. Improving milk value chains through solar milk cooling: 2018 (No. 276621). University of Bonn, Center for Development Research (ZEF).

Samberg LH, James SG, Navin R, Mario H, Paul CW. Subnational distribution of average farm size and smallholder contributions to global food production, Environmental Research Letters 11 (124010): 2016; 1-12. http://dx.doi.org/10.1088/1748-9326/11/12/124010

Thornton PK, Whitbread A, Baedeker T, Cairns J, Claessens L, Baethgen W, et al. A framework for priority-setting in climate smart agriculture research. Agricultural systems. 2018; 167:161-75.

Toledo, V.T. PV-Solar Chillers for Milk Cooling. BSW Solar Special Exhibition. “Off-Grid Power Solutions”. Case Studies and technical solutions. Available at https://energypedia.info/images/2/21/PV_Solar_Chillers_for_Milk_Cooling.pdf, Accessed on 10.11.2018

Torres-Toledo V, Hack A, Mrabet F, Salvatierra-Rojas A, Müller J. On-farm milk cooling solution based on insulated cans with integrated ice compartment. Int. J. of Refrigeration. 2018; 90: 22-31.

Werneck F. The potential for microfinance as a channel for carbon payments. Climate Change Mitigation and Agriculture, New York. 2012:164.

Table 1: Off-grid milk freshness preservation technologies.

Technology	Max. Capacity (liters)	Current status	Region	References
PV-based solar energy-powered systems				
Solar farm milk chillers	40	Commercially available	East Africa (Kenya/Rwanda/ Tanzania)	Foster et al., 2015
Rapid milk chiller	500	Commercially available	Rural India	Kulkarni et al 2013
Hohenhein solar cooling system	30	Piloted	East Africa (Kenya)	Salvatierra et al., 2018, Torres-Toledo et al., 2018
Solar thermal-powered systems				
ISAAC Solar Ice Maker	100	Piloted	East Africa (Kenya)	Erickson 2009
Biogas-powered systems				
CoolChurn	15.5	Piloted	East Africa (Uganda)	Ndyabawe and Kisaalita, 2014, Ndyabawe et al., 2018
Biogas milk chiller	10	Piloted	East Africa (Kenya)	https://simgas.org/projects/biogas-milk-chilling/
EvaKuula	80	Piloted	East Africa (Uganda)	Kisaalita et al 2018

CHAPTER 3:

ASSESSING ENERGY SOURCES FOR POWERING "EVAKUULA"

Sempiira E. J, C. Ononye, J. Robinson, A. Aralu, D. J. Mugisa, A. Katimbo,
J. Galiwango, C. Gomillion and W. S. Kisaalita. To be submitted to *Renewable Energy Journal*

Abstract

A combination of thermization and low-cost evaporative cooling, termed "Evakuuling," was developed to enable rural smallholder dairy farmers to preserve their evening milk in the absence of grid-electricity. The "EvaKuula" was configured to be powered by biogas. Domestic biogas set-ups are relatively high capital investments and as such a financial barrier to co-adoption with the EvaKuula. To lower this barrier, other energy sources have been considered. The purpose of this study was to assess alternative energy sources to power the EvaKuula. The list of energy sources considered included: biogas, butane, kerosene, charcoal, and firewood. These energy sources were assessed with respect to the sum of the social and market costs. The product of a unit of fuel cost and the units consumed represented the "market cost." The product of the long-term social carbon cost and total carbon dioxide emission equivalence represented the "social cost." Regular and improved stoves were included in the charcoal and firewood analysis. As expected, biogas ranked on top of the list and butane and kerosene ranked next to biogas. However, butane and kerosene are not easily accessible in rural setting, making firewood combusted in improved stoves the next best choice.

Key words: alternative energy; evaporative cooling; thermization; sustainable development; food security; sub-Saharan Africa.

3.0 Introduction

A milk-freshness preservation devices kit was developed for sub-Saharan African rural smallholder farmers, who are typically off grid, and is being deployed in Uganda. The kit or system has been branded as “EvaKuula.” The kit consists of two main components: thermization and an evaporative cooler (Kisaalita et al., 2018). The thermization process involves use of boiled water to indirectly heat-treat the milk. The thermization water can in principle be boiled using any accessible fuel. The range of accessible fuels in Uganda include: firewood, charcoal, kerosene, butane, and biogas. The choice of a fuel for household energy needs depends on a number of factors, such as accessibility and cost (Schlag and Zuzarte, 2008). Whereas smallholder farmers typically care about fuel cost and access, a number or their stakeholders also care about the fuel environmental “friendliness.” The promotion of any fuel needs to be equally informed by both the priorities of the farmers and their stakeholders.

In Uganda, firewood is the most commonly consumed primary fuel, estimated at 28 million tons of tree biomass and an additional 16 million tons of wood converted to charcoal (MEMD, 2014). This is mainly because most smallholder farmers fall below the poverty line (Ndambi et al. 2007) and cannot afford improved cooking devices with their associated advanced fuels. The traditional three-stone fire, with very low efficiency of approximately 15% (MEMD, 2014) is common. The low efficiency is due to most of the energy being dispersed before it gets to the cooking pan.

In comparison to firewood, charcoal has advantages of smokeless burning, ease of storage, affordability, portability, and simplicity of charcoal stoves; making it the most preferred form of energy in urban households (MEMD, 2014). The main tree species utilized for charcoal productions in Uganda include: *Combretum, Terminalia, Albiza, Acacia*, *Allophylus and Grewia spp* (Shively et al, 2010), the most common within Uganda's woodlands. In addition to charcoal, some urban households use kerosene with specialized kerosene stoves for mainly cooking quick and/or light meals. Households in the middle-income status and above (earning more than five ppp $ per day, according to Banerjee and Duflo, 2008), tend to use energy sources, such as, a mix of butane and grid electricity which are further up the energy ladder (Schlag and Zuzarte, 2008).

A decade ago, Pandey et al. (2007) estimated approximately 600 installed biogas plants (digesters) in Uganda with capacities ranging between 6 and 16 m^3. The most popular size was 12 m^3. But not all the 600 were operational. Uganda had a technical potential of more than 200,000 household biogas digesters and the potential was expected to increase as the zero-grazing movement and dairy industry expanded. Using the Pandey et al. (2007) report as a basis, the Netherlands Development Organization (SNV) is implementing a national program to develop and disseminate domestic biogas in rural and semi-urban areas, "offering the Ugandan population the benefits derived from the use of clean biogas for cooking and lighting and using bio-slurry or biogas plant effluent (fertilizer) to increase agricultural yields with the ultimate goal to establish a sustainable and commercial biogas sector in Uganda." This is not the first time a major development organization has attempted to build a viable commercial biogas sector. Previous efforts have had little success as evidenced by the gap between the installed capacity and potential. A possible explanation is that the cost of cooking with woody biomass has been and is till perceived to be low in comparison to the investment needed for installing a biogas plant. Even when government policies are put in place to change behavior, lack of enforcement and/or corruption have often defeated the purpose. Additionally, cooking and lighting applications do not directly generate cash incomes, making it impossible for farmers to qualify for microcredit loans. The idea of cooling milk with biogas is likely to be a “killer application,” because the extra income generated by the evening milk is expected to make microcredit borrowing for biogas plant construction attainable. As such, adding milk cooling to cooking and lighting will make an investment into a biogas plant very attractive and therefore will quickly enable the narrowing of the gap between installed capacity of 600 and potential of 200,000 plants.

The EvaKuula was designed with biogas as a fuel in mind because of its potential as a central component of the smallholder farm eco-system (Fig. 1). However, as outlined above, few smallholder farmers have domestic biogas plants on their farms. In our initial field deployment studies, we found that the need to invest in a domestic biogas plant and EvaKuula at the same time was limiting the adoption of EvaKuula, due to the high capital cost needed for the biogas plant. (Kisaalita et al., 2018) Therefore, the purpose of this study was to assess the accessible energy sources to recommend to EvaKuula potential adoptees to reduce the adoption “activation energy” and as a first step, from which farmers can be encouraged to install domestic biogas plants after paying off the EvaKuula. We have evaluated firewood, kerosene, butane and charcoal in comparison to biogas with respect to cost and environmental friendliness (greenhouse gas (GHG) emissions) per liter of preserved milk. Our findings and recommendations are presented herein.

3.1 Methodology

3.1.0 Energy quantity measurement

We determined the amount of fuel needed to bring a given thermization water volume to boil. Volumes of water required for 10- and 20-liter milk loads were previously determined to be 14.18 and 26.26 liters, respectively (Kisaalita et al., 2018). The required water volume in a deep pan was heated with a given fuel to boil. The consumed fuel was measured as the difference between the initial and final weight/volume. The different stoves used are presented in Figure 4.

Charcoal and wood were weighted before. After water boiling, the remaining burning charcoal/wood was extinguished using water and dried under the sun for at least 2 days. The moisture during drying was monitored till the desired levels were reached. The dried charcoal/wood was measured to determine how much fuel was consumed. Charcoal was combusted within the traditional and improved stoves, shown in Figs. 2A and 2B. Wood was also combusted within in the three-stone fire stove (Fig. 2C) and the improved firewood stove, (Rocket Lorena type), developed in partnership with Green Energy (www.greenbioenergy.org) (Fig 2D). The Rocket Lorena stove type was selected because previous studies have reported it to reduce firewood consumption as high as 33%, in comparison to the three-stone fire arrangement (McCarty et al., 2010). Charcoal and wood were burnt in open well-ventilated spaces. The improved kerosene stove (cotton fiber wick type; Fig 2E) was used and fuel consumed was determined by measuring the kerosene volume before and after water boiling. Butane, alternatively called Liquefied Petroleum Gas (LPG), is sold in gas cylinders of different weight denominations. Butane consumption was determined by weighing the cylinder (Fig. 2E) before and after. The floating dome biogas digester was used to evaluate the biogas as an energy source. Figs. 2G and 2H show the floating dome domestic biogas plant and the biogas burner, used for our studies, respectively. Bricks were placed on the floating component of the digester to provide pressure to drive the gas through the pipe network to the burner. The experiments were repeated at least three times for each energy source/burner, and the consumed weights/volumes were averaged. The volume of the biogas consumed was calculated as surface area of the floating cylinder, multiplied by its change in height. Butane, biogas and kerosene where burnt in an enclosed but ventilated room.

3.1.1 Energy cost calculations

Current wood and charcoal costs were determined from market survey from Nsangi town (on Masaka highway, approximately 18 kilometers from Kampala), the closest trading center to Smallholder Fortunes Research/Demonstration Facility. Kerosene and butane costs were surveyed from eight fuel stations situated in Nsangi, Kitemu, and Kyengera towns along Masaka Highway, within 10 kilometers between Nsangi and Kampala. To establish biogas cost, we assumed a CAMARTEC digester design that has been heavily promoted in Uganda through an SNV (Netherland Development Agency)-backed biogas industry development program. According to SNV, the current digester construction costs are $604, $788 and $876 for the 6, 9 and 12 m^3 capacities, respectively (Smith et al, 2013). In tropical climates, fixed dome digesters like CAMARTECH produces 0.4 to 0.5 m^3 biogas per day per $1m^3$ of digester volume (Otim et al, 2015). Using an average production rate of 0.45 m^3/day per $1m^3$, the production of a 6 m^3 digester comes to 2.7 m^3 (6 x 0.45) per day. For a 20-year life time of the digester

(Smith et al, 2013), the total production throughout the life time comes to 19,440 m^3 (20 years x 12 months x 30 days x 2.7m^3 per day). Therefore, a simple cost of biogas comes to \$0.03 per m^3 (\$604/19440m^3) = \$0.03 per kg (density =1.15kg/m^3). We use the term "market cost" to represent the cost of fuel consumed during thermization. We calculate the market cost as the product of the cost per kg of fuel and the consumption of the fuel in kg. For example, for biogas, the market cost comes to \$0.03 per kg x consumed biogas in kg.

3.1.2 Environmental impact determination

We evaluated the total greenhouse gas emissions for each fuel studied, based on liters of milk preserved. We considered the following gases: CO_2, CH_4 and N_2O because they are the most prominent greenhouse gases emitted during stationary combustion (EPA 2016). According to EPA, CO_2 accounts for highest percentage, contributing about 76% of the global emissions (EPA, 2012). CO_2 is therefore the most concentrated gas in the atmosphere and can stay in the atmosphere for over 100 years. Gas emissions from firewood, butane, kerosene and biogas energy sources were calculated using equation 1 (EPA 2016). Emission factors for biogas are approximated to Landfill gas because they have similar composition. For charcoal, Emissions were calculated using equation 2. This is because for charcoal, emission factors for stationary combustion were available in units based on mass of fuel consumed. The EPA recommends Equation 1 for estimating emissions from stationary combustion; because emissions factors are based on energy units. However, in circumstance where only consumption is known in mass or volume units, Equation 2 can be used (EPA 2016). Estimations using both equations do not differ significantly. The emission factors and high heating values used in equation 1 and 2 are presented in Table 2. Based on 100-year time horizon, the global warming potentials (GWP) relative to CO_2 for CH_4 and N_2O are; 21 and 310 (IPCC, 2007). The emissions from equation 1 for each energy source were then converted to CO_2 equivalence [CO_2 emission + (21 x CH_4 emissions) + (310 x N_2O emissions].

Emissions = Fuel consumption x High heating value x EF_1 ---------------- (3.1)

Emissions = Fuel consumption x EF_2 --- (3.2)

EF_1; Emission factors per energy unit of the fuel and EF_2; Emission factor per mass of fuel

We use the term “social carbon cost” to reflect the environmental impact of a fuel. Using the long-term social carbon cost for carbon dioxide emissions of Euro 614/ton of CO_2 (Isacs et al., 2016), equivalent to USD 0.54/kg of CO_2 (Euro 1 = USD1.14) and the total equivalent CO_2 emission for each fuel, we calculate the fuel social carbon cost as the product of the long-term social carbon cost for the equivalence carbon dioxide emissions and the total carbon dioxide emissions [i.e., the social cost of a fuel = \$0.54/kg of CO_2 x Carbon dioxide emission equivalence (kg)),

3.1.3 Determination of cost per liter of milk preserved

We use the term “aggregate cost” to represent the sum of the market and the environmental impact (social carbon cost) of a fuel. Since the fuel consumption does not linearly scale between 10 and 20 liters of milk, the calculations were done for both capacities. The cost per liter of milk preserved for each energy source is the Aggregate cost divided by the quantity of milk thermized (i.e. Aggregate cost/10 or 20). The aggregate cost and cost per liter for each energy source are presented as averages. The difference in cost per liter of milk on average between energy sources was established with Analysis of Variance comparisons.

3.2 Results and Discussion

3.2.0 Energy cost

The results of the survey showed that butane cost was higher (10,000 UGX/kg) compared to the other fuels. This is because, butane is sold in a purified form, and in addition, it is an imported fuel as the case is for kerosene. Kerosene comes second (2,808 UGX/kg) followed by Charcoal (857 UGX/kg), firewood (203 UGX/kg) and biogas, estimated at 90 UGX/kg. The cost for biogas was approximated by depreciation of the capital cost over the approximate lifetime of digester. The assumption was that there is no extra cost added to the digester. This is because for smallholder farmers who mainly use family labor on the farm (common of smallholder farmers in Uganda and sub-Saharan Africa as a whole), feeding of the digester usually comes with no extra cost. The marketing of biogas in balloon-like containers, in its initial stages in India, has not yet taken any roots in Uganda. Biogas packaged in this manner would provide more accurate price figures for this analysis.

Results for fuel consumption per liter of milk are presented in Table 3. The consumption of the fuel decreased in the order of firewood, charcoal, biogas, kerosene and butane for both the 10- and 20-liter milk capacities. The decrease in the amount needed for each fuel can be attributed mainly to the difference in the calorific values. Firewood has a gross calorific value between 14.4 and 17.4 MJ/kg when dry and charcoal, kerosene, butane and biogas have calorific values of 29.6, 46.2 ,49.5 (The Engineering Toolbox, 2005) and 19.1MJ/kg (Banks, 2009), respectively.

3.2.1 Market costs

The market cost for each fuel used for either 10- or 20-liter milk loads are presented in Table 4. Using biogas (originally intended energy source for powering the EvaKuula) as the datum, the market cost for butane, charcoal in a regular stove, kerosene, charcoal in an efficient stove, firewood in the three stone firewood stove, and firewood in the Rocket Lorena stove were 51, 27, 25, 17, 16 and 10 fold, respectively, for 10-liter milk load. However, for 20-liter milk load, again with biogas as the datum, the market cost for butane, charcoal in a regular charcoal stove, kerosene, firewood in the Rocket Lorena stove, firewood in the three stone firewood stove, and firewood in the Rocket Lorena stove came to 31, 14, 12, 9, 8 and 5 fold, respectively. Therefore, the consumption trends were similar for both 10- and 20-liter milk loads as shown in Fig 3 A. The high butane cost was not surprising. It was also not surprising for the firewood in Rocket Lorena stove cost to be lower than that for firewood in the three stone stove. The Rocket Lorena stove yielded firewood savings of 21% and 30% for 10- and 20-liter milk loads, respectively. However, repeated Rocket Lorena stove use soon after the first use – when still warm – yielded firewood savings of 21.09% and 36.5% for 10- and 20-liter milk loads, respectively. The high firewood saving because of repeat use is likely to be highly characteristic for a typical farmer. Farmers will use the stove for normal household cooking, followed by water boiling for the milk thermization process. In our analysis in this paper, Rocket Lorena firewood costs were based on first use - from cold stove - to be consistent with other stoves that were started from the cold state.

3.2.2 Social costs

In Table 4, we present the GWPs of selected greenhouse gas emissions expressed in kilograms of carbon dioxide resulting from thermization for both the 10- and 20-liter milk load. Generally, the GWP in terms of kilograms of carbon dioxide increased in order of charcoal, firewood, kerosene, butane and biogas. Charcoal is considered a dirty fuel because of its high carbon content. This explains why charcoal presents a higher GWP compared to other fuels. Charcoal is followed by firewood, kerosene, butane and biogas. This means that biogas is a cleaner fuel compared to the others. The results are similar to those reported in literature. For example; the energy ladder has ranked these fuels in a similar pattern (Van der Kroon et al., 2013). A higher GWP is associated with a higher social cost. With biogas as the datum, fold increases of the social cost for butane, kerosene, firewood in a Rocket Lorena stove, firewood in a three stone stove, charcoal in an efficient stove, and charcoal in a regular stove, were 1, 3,8,11,10 and 16, respectively, for a 10-liter milk load. A similar fold increase trend was observed with 20-liter milk load of 1, 1, 5, 7, 6 and 10 in the same order respectively. The higher the social cost associated with the energy source, the more “unfriendly” use of the energy source is to the environment. Therefore, for EvaKuula application, based on environmental friendliness, energy sources can be ranked as biogas, butane, kerosene, firewood in a Rocket stove, firewood in a three-stone stove, charcoal in an efficient stove and charcoal in a regular stove as shown in fig 3 B.

3.2.3 Aggregate costs

We present the aggregate cost per liter of cooled milk for both the 10- and 20-liter milk loads in Table 4. The aggregate cost (sum of social and market costs). With biogas as the datum, the aggregate cost for energy sources increased in folds of 17, 11, 12, 8, 4 and 4 for charcoal in a regular stove, charcoal in an efficient stove, firewood in a three-stone stove, firewood in a Rocket Lorena stove, kerosene, and butane, respectively for 10-liter of milk load. While for 20-liter milk loads, the fold increases were 9, 6, 6, 4, 2 and 2 in same order.

Analysis of variance (ANOVA) revealed that there is a significant difference in the cost per liter depending on the energy source used, p value < 0.001 (Table 4). Post-hoc analysis suggested that there is a significant difference in cost per liter between charcoal use and other fuels, and between firewood and other fuels, p value < 0.05. However, biogas was not significantly different from butane and kerosene, p value > 0.05. Charcoal and firewood fuels' use were significantly different between regular charcoal and improved stoves that save about 36% of the fuel. As expected, using improved stove to power the EvaKuula result into savings for the household both environmentally and economically. However, an improved charcoal stove is not significantly different from firewood in three-stone stoves. For biogas, the cost per liter for the energy sources increased in folds of 17, 11, 12, 8, 4 and 4 for charcoal in a regular stove, charcoal in an efficient stove, firewood in a three-stone stove, firewood in a Rocket Lorena stove, kerosene and butane, respectively, for 10-Lmilk batches. While for 20-L load batches, the fold increases were 9, 6, 6, 4, 2 and 2 in same order. Energy sources can be ranked from the least aggregate cost per liter after biogas as; butane, kerosene, firewood in rocket stove, charcoal in an efficient stove, firewood in a three-stone stove and charcoal in a regular stove as shown in fig. 3C

3.4 Concluding Remarks

In conclusion, we rank these fuels using cost per liter beginning with the most preferred in the order of biogas, butane, kerosene, firewood and charcoal. This suggests that the next alternative to power the EvaKuula unit can either be kerosene or butane. Studies conducted among rural sub-Saharan African farmers have placed firewood as the most common fuel used to meet domestic needs like cooking. Approximately 76% of household rely on this fuel source for cooking. Butane and kerosene are predominantly used by people in urban and peri-urban areas, due to accessibility and affordability. Incomes are typically higher among urban dwellers. Therefore, with butane and kerosene not readily available to the target EvaKuula users, the next best option is firewood. However, using firewood to power the EvaKuula can only be economical and environmentally friendly when combusted in an efficient stove.

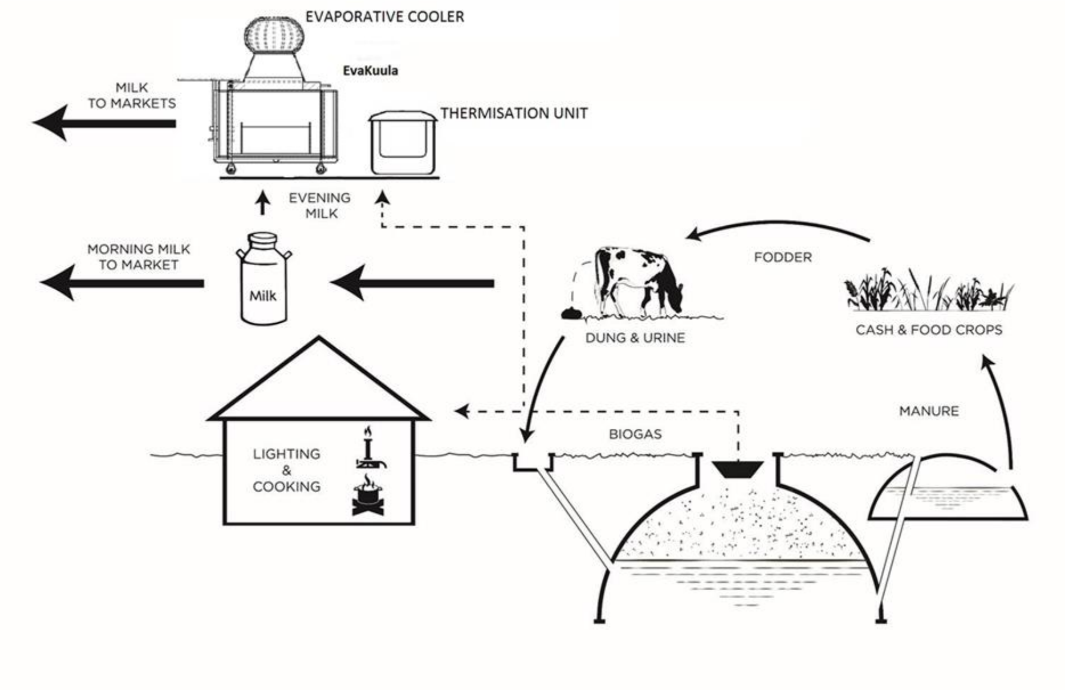


Figure 1: Schematic of the renewable energy (biogas) powered milk cooler and the smallholder dairy farm ecosystem. From the cycle on the right (thin arrows), the cow feeds on the fodder, produces cow-dung that is fermented in the domestic plant to produce biogas; the slurry from the digester fertilizes crops/fodder that is consumed by the cow. From the digester, the biogas can be used for lighting and cooking, as well as milk cooling (dotted lines). While the morning milk (thick arrows) easily enters the market or cold chain, the evening milk cannot without the cooler, as it cannot be kept fresh until the next day, when the roads are passable, and it is safer. The use of biogas to cool the evening milk generates additional income, enabling investment in biogas technologies in low-resource settings, and creating a sustainable farm ecosystem in which the cooler, the biogas system, and the animals have symbiotic relationships.

Figure 2: Possible EvaKuula fuel/burner combinations evaluated. A - regular charcoal stove, B - improved charcoal stove, C - three stone stove, D - improved firewood stove (Rocket Lorena stove type), E - kerosene stove, F - butane cylinder with burner, G - biogas digester floating dome type, with block on top to increase pressure under the done, and H - biogas burner connected to the biogas digester.

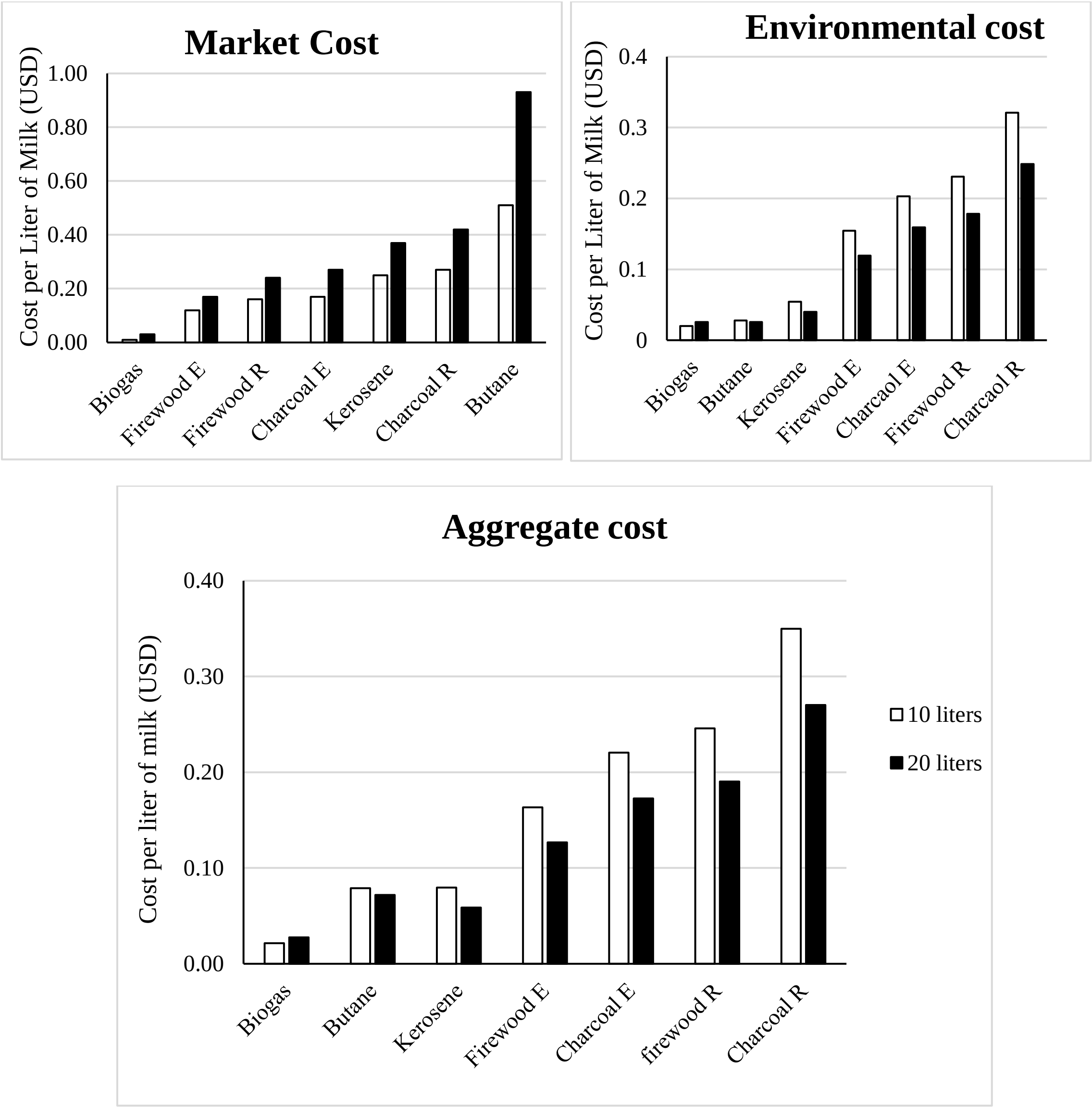


Figure 3: Bar graphs showing the Market, Environmental (social) and Aggregate cost per liter of milk for energy source. There was a similar trend in the market, social and aggregate cost per liter when thermizing both the 10 and 20 liters of milk. From graph A, Butane had the highest cost per liter. This is because butane as a fuel costs relatively high per kilogram on the local Ugandan market compared to other fuels. Based on the market cost, Firewood E (firewood in an efficient stove) offered the next alternative after biogas. From graph B, Firewood R (firewood in a regular 3-stone stove) presented the highest

social cost per liter. This means that using a 3-stove for thermization would be the most environmentally damaging. Butane and kerosene presented the least environmental cost per liter after biogas. From graph C, the aggregated cost per liter suggested that butane presented the next alternative to biogas whereas Charcoal R (Charcoal in the regular stove) presented the worst choice.

Table 2: Emission factors of greenhouse gases for each fuel.

Fuel	**Emission factors (kg of emissions/mmbtu)**			**High Heating value (mmbtu/kg of fuel)**	**Reference**
	CO_2	**CH_4**	**N_2O**		
Butane	64.77	0.0003	0.00006	0.047	(EPA, 2016)
Biogas	52.07	0.0032	0.0006	0.016	(EPA, 2016)
firewood	93.8	0.0072	0.0036	0.017	(EPA, 2016)
Kerosene	75.2	0.0003	0.00006	0.045	(EPA, 2016)
Charcoal*	4.337	0.055	0.0004	-	(Akagi et al 2010)

* Emission factors (EF_2) expressed in kg of emissions per Kg of fuel

Table 3: Fuel consumption

Fuel	**Ten-liter milk load** (kg of fuel)	**Twenty-liter milk load** (kg of fuel)
Charcoal[1] (kg)	1.06±0.13	1.64±0.05
Charcoal[2] (kg)	0.67±0.05	1.05±0.25
Biogas (kg)	0.45±0.03	1.17±0.13
Kerosene (kg)	0.23±0.02	0.44±0.02
Firewood[3] (kg)	2.56±0.15	3.97±0.23
Firewood[4] (kg)	2.03±0.07	2.78±0.03
Butane (kg)	0.17±0.00	0.31±0.01

[1]Regular inefficient stove; [2]Efficient stove; [3]Three-stone stove; [4]Rochet Lorena stove

Table 4: Emissions, global warming potential (GWP), market cost, social cost, and aggregate.

Fuel	**Emissions (kg)**			**Total emissions (equivalent-Kg CO2)**	**Cost (USD)**			
	CO_2	**CH_4**	**N_2O**		**Market**	**Social**	**Aggregate**	**Per liter***
				10-liter milk load				
Charcoal[1]	4.597	0.058	0.004	5.946	0.27	3.21	3.48	0.35[a]
Charcoal[2]	2.906	0.037	0.003	3.759	0.17	2.03	2.20	0.22[b]
Biogas	0.367	0.000	0.000	0.369	0.01	0.20	0.21	0.02[e]
Kerosene	1.005	0.000	0.000	1.008	0.25	0.54	0.79	0.08[d]
Firewood[3]	4.214	0.000	0.000	4.271	0.16	2.31	2.47	0.25[b]
Firewood[4]	2.820	0.000	0.000	2.858	0.12	1.54	1.66	0.17[c]
Butane	0.517	0.000	0.000	0.519	0.51	0.28	0.79	0.08[d]
				20-liter milk load				
Charcoal[1]	7.113	0.090	0.006	9.200	0.42	4.97	5.39	0.27[f]
Charcoal[2]	4.554	0.058	0.004	5.890	0.27	3.18	3.45	0.17[gh]
Biogas	0.954	0.000	0.000	0.958	0.03	0.52	0.55	0.03[i]
Kerosene	1.474	0.000	0.000	1.479	0.37	0.80	1.17	0.06[i]
Firewood[3]	6.509	0.000	0.000	6.597	0.24	3.56	3.80	0.19[g]
Firewood[4]	4.361	0.000	0.000	4.420	0.17	2.39	2.56	0.13[h]
Butane	0.942	0.000	0.000	0.946	0.93	0.51	1.44	0.07[i]

[1]Regular stove; [2]Efficient stove; [3]Three-stone stove; [4]Rochet stove; *Values with the same letters are not significantly different from each other (P value < 0.05, n = 3 for each fuel.

3.5 References

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., ... & Wennberg, P. O. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmospheric Chemistry and Physics; 201111(9), 4039-4072.

Banerjee AV, Duflo E. What is middle class about the middle classes around the world? The Journal of Economic Perspectives 2008; 22(2):3-28.

EPA (Environmental Protection Agency). Direct Emissions from Stationary Combustion Sources. U.S. EPA Center for Corporate Climate Leadership – Greenhouse Gas Inventory Guidance; 2016. https://www.epa.gov/sites/production/files/2016-03/documents/stationaryemissions_3_2016.pdf. Accessed on 1/13/19

EPA (Environment Protection Agency). Overview of greenhouse gases, EPA 1, http://doi.org/10.1017/CBO9781107415324.004; 2012 [accessed 11.19.16]

IPCC. Intergovernmental Panel on Climate Change (2007) - The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC (Climate Change 2007), United Kingdom, Cambridge: Cambridge University Press, 2007.

Isacs L, Finnveden G, Dahllof L, Hakansson C, Petersson L. Steen B, Swanstrom L., Wikstrom A. Choosing a monetary value of greenhouse gases in assessment tools: A comprehensive review. Journal of Cleaner Production; 2016 127:37-48.

Kisaalita, W. S., Katimbo, A., Sempiira, E., & Mugisa, D. EvaKuula saves Ugandan smallholder farmers' evening milk. Sustainable Energy Technologies and Assessments; 2018. 29, 155-163.

MEMD (Ministry of Energy & Mineral Development). Biomass Energy Strategy (BEST) - Uganda. A report produced with support from UNDP 2014.

Ndambi OA, Garcia O, Balikowa D, Kiconco D, Hemme T, Latacz-Lohmann U. Milk production systems in Central Uganda: a farm economic analysis. Tropical Animal Health and Production 2007; 40:269-279.

Otim G, Okaka D, Kayima J. Design of biogas plant for rural households in Uganda (case study: Apac District). Paper presnted at the Second International Conference on Advances in Engineering and Technology (January 31 – February 2), Makarere University, Kampala, Uganda, http://www.build-a-biogas-plant.com/PDF/Biogas_Uganda.pdf; 2015 [accessed 10-12.17].

Pandey, B., Subedi, P.S., Sengendo, M. and Monroe, I. Biogas for Better Life: An African Initiative. Report prepared for the Dutch Ministry of Foreign Affairs 2007.

Schlag N, Zuzarte F. Market barriers to clean cooking fuels in sub-Saharan Africa: a review of literature. Report prepared for the Stockholm Environment Institute 2008.

Smith J, Balana BB, Black H. von Blottnitz H, Casson E, Glenk K, Yongabi KA. The potential of small-scale biogas digesters to alleviate poverty and improve long term sustainability of ecosystem services in Sub-Saharan Africa. Bioresource Technology 2013; 5(0):22. http://doi.org/10.1002/bbb

The Engineering Toolbox. Fuels - Higher Calorific Values, http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html on 10/10/16; 2005 [accessed 11.19.16].

Van Der Kroon B, Brouwer R, Van Beukerring PJH. The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. Renewable and Sustainable Energy Reviews 2013; 20:504-513.

CHAPTER 4:

MILK FRESHNESS PRESERVATION BY COMBINED THERMIZATION AND EVAPORATIVE COOLING

Sempiira E. J, D. J. Mugisa, J. Galiwango, and W. S. Kisaalita. To be submitted to *Journal of Food Processing and Preservation*

Abstract

The EvaKuula was developed to address the problem of off-grid milk preservation. The EvaKuula combines thermization and evaporative cooling to preserve fresh milk. Evakuuled milk tested with the resazurin test was of good quality and successfully entered the cold chain. Thermization is an established commercial process for extending the life of raw milk for several days before processing. At a commercial scale, raw milk is thermized and stored at below 8^0C for a maximum of 3 days. For the EvaKuula process, the milk quality profile when stored at the evaporative temperatures was not well known. For proper regulation, a more exact profile of thermized milk in the hands of smallholders is necessary. We hypothesized that we achieve good quality milk when we store at evaporative cooler temperature. This paper therefore aimed at establishing the milk quality-profile of Evakuuled milk. Milk samples were evakuuled and then analyzed for microbial load (total viable and Psychotrophic counts) and bio-chemical composition (fat, protein and pH). Thermization was done using temperatures between 55 and 70^0C. Evakuuled milk quality-profile was compared to chilled and fresh milk. A consumer sensory test was also performed to evaluate consumer preference. The results showed that milk thermized with temperatures within the recommended range for thermization (57-68^0C) was of good quality. Milk thermized at 65^0C produced the best quality profile overall. Also, the milk quality-profile of the Evakuuled milk was indistinguishable from chilled and fresh milk. A consumer preference test scored evakuuled, fresh and chilled milks on average equal in terms of taste, appearance, aroma, and general acceptability. The study concludes that the evakuuled milk is indistinguishable from fresh or chilled milk. These results therefore support inclusion of thermized milk in the East African milk quality standard.

Key words:

Off-grid Preservation, Evakuuled, Quality-profile, Thermization, Evaporative cooling, East African milk quality standard, regulation

4.0 Introduction

Current commercialized solutions for on-farm milk freshness preservation developed for rural smallholder dairy farmers include: Solar ISAAC (Erickson 2009), Promethean rapid milk chiller (Kulkarni, et al. 2013), Sun Danzer solar refrigerator, Cool Churn (Ndyabawe and Kisaalita 2014), and the Hohenhein solar cooling system (Salvatierra et al., 2018). These solutions have been found to be costly and, in some cases, limited in capacity in the context of sub-Saharan smallholder farmers (Sempiira et al 2019). These available solutions have therefore not been widely adopted by smallholders. This explains why even with these solutions on the market, smallholder farmers still lose a substantial amount of milk due to spoilage because they can't preserve their milk freshness at the farm. For example, In Uganda, these milk losses have been approximated to 27% at the farm level, translating to $23 million per year (Kisaalita et al 2018). A system that combines two micro-biostatic steps of thermization and evaporative cooling as a solution has been developed (Kisaalita et al., 2018). Thermization works to reduces the population of spoilage microorganisms (Chouliara et al. 2010 and Walstra et al. 2004) and evaporative cooling minimizes microbial growth, increasing the shelf life of raw milk (Wayua et al. 2012).

Thermization refers to the mild heat treatment at temperatures in the range of 57 – 68^{0}C with holding times of 15 – 30s. Thermization is used in commercial dairy processing to prolong the quality of raw milk for an extra 24 – 72 hours after receipt at processing plants (Walstra et al. 2004). Because this process results in the reduction of bacteria (psychotrophs) in milk (Chouliara et al. 2010 and Walstra et al. 2004). Evaporative cooling occurs when warm dry air is blown through a wetted porous medium, lowering the air temperature and increasing the relative humidity. Evaporative coolers will only provide a maximum drop in temperature of about 13^{0}C below room temperature on a hot dry day (Ndukwu et al. 2013 and Manuwa et al. 2012). Application of evaporative cooling for milk preservation has been demonstrated with camel milk (Wayua et al. 2012). While evaporative cooling will not reduce bacteria count, storage of milk below room temperature will reduces the rate of bacteria growth compared to when stored at room temperature (Wayua et al. 2012). Although evaporative cooling provided promising results, milk preserved with evaporative cooling alone may not achieve the desired attributes for milk to enter the cold chain.

Milk that comes immediately from the cow contains a few bacteria but can be easily contaminated through handling. Psychotrophic bacteria (pseudomonas species) represent a substantial percentage of bacteria (65-70%) in raw milk (Ledenbach and Marshall, 2009). Studies have correlated the presence of psychotrophic bacteria in pasteurized milk to the levels of lipids and protein (Michael Lu et al, 2013), therefore, psychotrophic bacteria are used in the determination of the shelf life of milk. Psychotrophs produce lipase and protease enzymes which break down the lipids and proteins and reduce their concentration levels in the milk. The by-products of these hydrolysis reactions increase the milk acidity and directly correlate to milk spoilage (Michael Lu et al, 2013). Most forms of bacteria can thrive at the pH of 6. At low pH levels, lactic acid bacteria can grow rapidly and produce lactic acid which further lower the milk pH resulting in spoilage (Michael Lu et al, 2013).

The combination of thermization and evaporative cooling have been packaged in a kit branded as “EvaKuula”. With the EvaKuula, thermization can be performed in a wooden drum in the hands of the smallholder farmer without sophisticated controls. At the time of writing, EvaKuula has been deployed in Uganda, and according to Kisaalita et al 2018, all evakuuled milk tested with resazurin test was of good quality and successfully entered the cold chain. However, the resulting fat/protein and microbial quality composition of the milk was not well known. Also, the Evakuuled milk consumer preference among the target consumer needs documentation.

The food and drug authority (FDA) of the United States does not recognize thermized milk in the Grade-A Pasteurization Milk ordinance (PMO) as a grade of milk because milk in the United States is not allowed to be sold in the raw state, which is similar with the European union. However, thermization is practiced in commercial processing for extended raw milk storage and cheese processing (Walstra et al. 2004). The FDA and European union have not defined the quality standards for thermized milk. Similarly, the East African standard (EAS) does not define thermized milk as a grade of milk even when the regulators allow retailing of milk in the raw state. In order to be properly regulated, a more exact profile of thermized milk in the hands of smallholders is necessary. Therefore, the purpose of this study was to characterize Evakuuled milk with respect to important regulatory properties of bio-chemical and microbial composition.

4.1 Methodology

4.1.0 Determining the thermization temperature

Milk sample preparation followed a schematic shown in the figure 4. Thermization of milk was done following the procedure by Kisaalita et al (2018). The 20-liter milk can used was equipped with a stainless-steel thermal couple inserted through the top cover to monitor the temperature of the milk during thermization. A data logger (model OMEGA HH309) was connected to the thermocouple to monitor temperature during the process. Thermization temperatures in the recommended range of 57-68^{0}C were used. The specific temperature values used were; 55^{0}C (two degrees below range), lower quartile temperature value (59, average temperature value (63), upper quartile temperature value (65) and 70^{0}C (2^{0}C above the range). Once the required temperature was attained, milk was immediately removed from the thermization drum and taken to an evaporative cooler until the next day. Milk was removed from the evaporative cooler after approximately 12 hours (between 6:00 and 8:00 a.m.) on the following morning. A sample (100ml) was immediately taken off (figure 4) aseptically again and analyzed for microbial and fat and protein composition. Microbial composition was for both Psychotrophic bacteria counts (PBC) and Total viable counts (TVC). The counts were measured as colony forming units per ml (cfu/ml). Results of microbial and fat and protein were analyzed following ANOVA and post-hoc procedures using JMP software to compare milk quality of Evakuuled to chilled and fresh milk controls. Chilled milk was prepared by storage of milk in a solar energy-powered refrigerator that was set at a temperature between 4 ±1 ^{0}C.

4.1.1 Microbiological analysis.

Milk samples (10 ml) were aseptically pipetted into 100 ml sterile dilution bottle and further diluted. Serial dilutions of 10^0, 10^{-1}, 10^{-2} and 10^{-3} were prepared using sterile phosphate buffer. Plating and enumeration of the total viable counts and psychotropic bacteria in the sample was performed following the procedures that were established by Micheal & Frank, 2004. For PBC, the plates were incubated in a solar refrigerator set at 7^0 C ± 2^0 C for 10 days and for TVC, the plates were incubated at 32^0 C ± 1^0 C for 48 hours in an isotherm forced conventional laboratory incubator model OIFA-32L. Colonies were counted using a colony counter model KUNHEWUHUA X-1253.

4.1.2 Fat and protein analysis,

Milk fat and protein were analyzed using a Milktech Ultrasound milk analyzer model MAP250. Additional parameters reported by the analysis included: Lactose, solid-non-fat, solids, density and freezing point depression. Milk pH was measured with a digital glass electrode pH meter (Just Utile, model COMINHKPR137640). The instrument was first calibrated using buffers of pH 6.86 and 4.01. Then the pH of the samples was measured by dipping the electrode of the pH meter into portions of milk samples in a beaker. Between samples, the electrode was rinsed with deionized water and wiped with tissue paper.

4.1.3 Sensory evaluation of milk quality

Consumer preference tests were administered in the school of food science sensory testing laboratory at Makerere University, Kampala-Uganda. A total of 35 undergraduate students were recruited in the study. In order to prepare milk samples for testing, 5 liters of milk samples were obtained in the evening within 5 minutes of milking. Milk was divided into two equal portions. One portion was Evakuuled (thermized and stored in Evaporative cooler) and the other was kept in a refrigerator set to 5^0C. A fresh milk sample (about 3 liters) was also obtained in the morning after milking.

The three samples (Evakuuled, refrigerated and fresh milk) were then prepared in the morning by laboratory pasteurization at 63^0C for 30 minutes followed by cooling to about 10^0C. The three samples were then served in individual cups in quantities of 25 ml at chilled temperature of between 12 and 16^0C. All milk handling was done with aluminum milk cans that were cleaned and dried under the sun. This was to imitate the process of milk handling within the cattle keeping communities. Mineral water at room temperature was provided for palate cleansing in between samples. Throughout the testing session, samples were randomly allocated to participants. An incentive (food) was given to the participants for their time at the end of the testing session. Participants scored the milk samples on a 9-point hedonic scale (9- like extremely to 1- dislike extremely) for four attributes: aroma, taste, appearance and general acceptability. Participants were also asked to rank the samples based on order of preference as either 1, 2 or 3. Data was analyzed with Wilcoxon / Kruskal-Wallis Tests using JMP software at the 5% level of significance.

4.2 Results and Discussion

4.2.0 Thermization temperature range

Table 5 presents results for PBC composition for fresh and after evakuuling the milk. Milk thermized at 55^0C, 59^0C, 63^0C, 65^0C and 70^0C had CFU/ml of PBC after EvaKuula preservation of 140, 17, 3.2, 3.2 and 0.83 thousand cfu/ml respectively. The Food and Drug Authority (FDA) and East African Community (EAC) standard do not define the quality standards for raw milk in terms of number of PBC. However, the European union standard defines high quality raw milk to have a PBC that is lower than $5x10^3$ cfu/ml with $20\ x10^3$ cfu/ml being the acceptable maximum (Samaržija et al., 2012). Therefore, milk preserved after thermization at temperatures of 59^0C, 63^0C, 65^0C and 70^0C will be classified as high quality milk based on the EU regulation.

The temperature, 70^0C presented the lowest cfu/ml followed by 63^0C, 65^0C and 59^0C within the recommended range for thermization ($57\text{-}68^0$C). The findings are similar to results reported by Samelis et al. (2009) who noted a maximum reduction in bacterial load at 67 ^{0}C. A higher results in more reduction in bacteria counts as demonstrated by Samelis et al. (2009). Temperatures of 63^0C and 65^0C presented similar counts after preservation which is attributed to the initial high count for milk used at 63^0C compared to that at 65^0C as shown in Table 5. Temperature of 55^0C presented the highest cfu/ml, this is attributed to the fact that this was the lowest temperature of thermization tested and was outside the recommended range for thermization. At 55^0C of thermization, a reasonable reduction in the PBC was not achieved and hence the high cfu/ml after EvaKuula preservation. From the results, the temperature within the recommended range presented counts/ml within recommended limits.

Table 6 shows the results of the fat and protein analysis. The fat content of the milk reduced when the milk was subjected to the evakuuling process (thermization and evaporative cooling). The minimum change in milk fat on average was experienced at a temperature of 65^0C whereas the maximum on average was experienced at a temperature of 70^0C. Statistical analysis of results suggested that there was no significant difference ($P\text{-value}>0.05$) in the mean change in fat for temperatures of 55^0C, 59^0C and 63^0C. However, there was a significant difference between the change in fat at 55^0C and 65^0C ($P\text{-value} <0.05$). There was also a significant difference between the change in fat at 70^0C and at other temperature values ($P\text{-value} < 0.05$). For milk protein, a significant difference on average between the protein change occurred between 55^0C and other temperature values.

The change in the fat and protein content can be attributed to both increase in cfu/ml in bacteria during storage and thermization temperature used. Heating of milk to temperatures of 70^0C and higher affects the fat globular membrane (FGM) by denaturing the membrane proteins, leading to formation of a layer of denatured whey proteins around the fat globule (Fox et al., 1998) which lowers the fat concentration. However, this effect is usually not an issue with milk heat processing because homogenization of milk after heat processing corrects the damage by creating an artificial layer that mainly constitutes Casein and whey proteins (Fox et al., 1998). Therefore, the EvaKuula process within the recommended range of temperature will deliver milk with desired fat and protein levels. The reduction in fat and protein after evakuuling is not significant because the milk pH that remained relatively constant for all temperature values as shown in table 6. Because the 65^0C temperature value provided the best results overall, we use milk Evakuuled at this temperature to compare to fresh and chilled milk.

4.2.1 Comparison of Evakuuled to chilled and Fresh Milk

Results for comparison of the milk that was preserved by the EvaKuula and chilling respectively with respect to fresh milk are shown in table 7. According to the East African Standard (EAS 67:2000) for raw cow milk (EAS, 2006), milk is graded based on total plate counts as grade I (less than 200,000 counts/ml), grade II (200,000 – 1,000,000 counts per ml) and grade III (1000000 – 2000000 counts per ml). In additions, in terms of bio-chemical composition, milk should contain not less than 3.25% fat, not less than 8.5% Solid non-fat (SNF), shall not contain added water and the freezing point depression shall not be less than -0.525^0C and not more than -0.550^0C. Milk quality parameters such as fat, are affected by a number of factors, such as; Breed of the animal, climate and lactation period (Fox et al., 1998). Milk that was used for analysis came from a Frisian cow in a tropical climate. On average the fresh milk had 4.43% fat, 8.90% SNF, -0.534^{0}C freezing point, 0.0% added water and 1800 cfu/ml of TVC. According to the EAS 67:2000, this fresh raw milk would be classified grade one milk (table 7).

The fat, protein, and pH of Evakuuled and chilled milk were not different on average from that of fresh milk (table 7). There was a detection of added water in both evakuuled and chilled milk. This slight added water can be attributed to the evaporation and condensation of water vapor in the can during evakuuling and chilling respectively; especially in the closed milk can. The authors expect that this is still part of the total percentage of water in the milk. The TVCs for Evakuuled milk were 4 times more than that in chilled milk but within the grade I milk specification limit of less than 200,000 counts/ml. This is as expected because of the expected retarded growth of bacteria when milk is stored at 4^{0}C and below. The results suggested that based on fat and TVC, milk from the EvaKuula process was similar to chilled and fresh milk and is graded as grade 1 based on the EAS.

Results of sensory evaluation are shown in table 4. A total of 33 participants (16 male and 17 female students) were included and had an average age of 23 years (19-29). In terms of the quality attributes, all the milk samples scored above 6.5 on average on the hedonic scale, which means that on average the milk samples were liked by the subjects. Results from the Kruskal-Wallis statistical analysis test suggested that there was no significant difference within the samples in terms of all quality attributes (Pvalue >0.05). The refrigerated sample scored higher on average for appearance, aroma, and acceptability (table 8). This is because most milk is kept cold in a refrigerator, and therefore, most of the subjects' palates were accustomed to refrigerated milk. In terms of ranking for general acceptability, the milk preserved with the EvaKuula ranked the best followed by fresh and then refrigerated milk was last. The results of the ranking are consistent with the comments from the participants (table 9), as the participants reported that the milk samples were indistinguishable, and some reported added water to the EvaKuula and refrigerated sample. Some participants reported presence of solid particles in the EvaKuula and refrigerated samples too, this may be attributed to fat coagulation. This is a common trait to milk stored overnight. The participants reported EvaKuula milk to be acceptable but in general they equally like all the milk samples.

4.3 Concluding remarks

For the EvaKuula process, a thermization temperature within the recommended range will produce desired quality of milk. Therefore, the thermization process can be seamlessly performed in the hands of the smallholder farmers who are characterized by low literacy levels. This is because any temperature within the recommended range delivers fat/protein and Total viable counts that are within acceptable limits of the EAS standard for grade I milk quality.

Milk that was preserved using the EvaKuula had the same quality attributes as fresh or chilled milk and satisfied consumer preference in terms of: aroma, taste appearance and general acceptability. Therefore, the Evakuuled milk was not distinguishable from milk preserved by the standard chilling method based on the quality attributes that were measured. Therefore, the results support inclusion of Evakuuled milk in the EAS standard as a form of raw milk.

4.4 References

Chouliara, E., Georgogianni, K. G., Kanellopoulou, N., & Kontominas, M. G. (2010). Effect of ultrasonication on microbiological, chemical and sensory properties of raw, thermized and pasteurized milk. International Dairy Journal, *20*(5), 307-313.

EAC, (2006). East African Standard EAS 67:2000: Raw Cow milk – Specification. Available at: https://law.resource.org/pub/eac/ibr/eas.67.2006.pdf

Erickson, C. 2009. Rural milk preservation with the ISAAC solar icemaker. Energy for sustainable Development, 13, pp287-291.

Fox, P F., Uniacke-Lowe, T., O'Mahony J A and Mcsweeney, P L H. (1998). Dairy Chemistry and Biochemistry second edition. pp 348. Springer Cham Heidelberg New York Dordrecht London http://doi.org/10.1007/978-3-319-14892-2

Kisaalita, W.S., Katimbo, A., Sempiira, E., and Mugisa, D. (2018). EvaKuula saves Ugandan smallholder farmers evening milk. Sustainable energy technologies and assesements 29 pp 155–163 https://doi.org/10.1016/j.seta.2018.08.002 ,.

Kulkarni, N. K., And Ganesh U. (2013). Villgro Innovations Foundation Case Study Series – Promethean Power Systems (retrieved January 2017).

Ledenbach L H and Marshall RT (2009), Microbiological Spoilage of Dairy Products. In H. W. Sperber & P. M. Doyle (Eds.), Compendium of the Microbiological Spoilage of Foods and Beverages (pp. 41-67). New York, NY: Springer New York.

Michael L., Jacklyn W., Raishay L., Hannah K., Thomas B., Tanya P., Tiffany J., Amy C., Jonathan C., Erin O., Nima S and Nam S W. (2013). Milk Spoilage: Methods and Practices of Detecting Milk Quality. Food and Nutrition Sciences, *4*(47A014), pp 113-123. http://dx.doi.org/10.4236/fns.2013.47A014

Micheal W and Joseph F (2004). Standard methods for the examination of dairy products 17th edition. Washington, D.C: American Public Health Association.

Ndukwu M C., Manuwa S I., Olukunle O J and Oluwalana I B. (2013) Development of an active evaporative cooling system for short-term storage of fruits and vegetable in a tropical climate Agricultural Engineering International: CIGR Journal, 15(4): pp 307－313.

Ndyabawe K and Kisaalita W S. (2014). "Diffusion of an evaporative cooler innovation among smallholder dairy farmers of Western Uganda." Technology in Society 38: 1-10.

Salvatierra Rojas, A., Torres Toledo, V., Mrabet, F., & Müller, J. (2018). Improving milk value chains through solar milk cooling (No. 276621). University of Bonn, Center for Development Research (ZEF).

Samaržija, D., Zamberlin, Š., & Pogačić, T. (2012). Psychrotrophic bacteria and their negative effects on milk and dairy products quality. *Mljekarstvo: časopis za unaprjeđenje proizvodnje i prerade mlijeka*, *62*(2), 77-95.

Samelis J., Lianou A., Kakouri A., Delbes C., Rogelj I., Bogovic-Matijasic B and Montel MC (2009). "Changes in the microbial composition of raw milk induced by thermization treatments applied prior to traditional Greek hard cheese processing." J Food Protection 72(4): 783-790.

Walstra, P., Geurts, T. J., Noomen, A. C., Jellema, A. C., & Boekel, M. A. J. S. (2004). *Dairy Technology: Principles of Milk Properties and Processes* (No. 637.1 W169d Ej. 1 018523). Marcel Dekker.

Wayua Francis O, Okoth Michael W and Wangoh, John. (2012). Design and Performance Assessment of a Low Cost Evaporative Cooler for Storage of Camel Milk in Arid Pastoral Areas of Kenya. International Journal of Food Engineering. 8.

Yagoub S. O., Bellow F. A. and El Zubeir I. (2008) Effect of Temperature and Storage Period on the Constituents of Milk Inoculated with Pseudomonas aeruginosa, Research Journal of Microbiology, 3(1) pp. 30-34.

Table 5: Psychotrophic bacteria CFU for fresh and Evakuuled milk.

Temperature(^{0}C)	**Fresh (CFU/ml)**	**Evakuuled (CFU/ml)**
55.0	880	140,000
59.0	6,200	17,000
63.0	7,500	3,200
65.0	420	3,200
70.0	29,000	830

Table 6: Change in protein and fat for both Fresh and Evakuuled milk

		Temperature(^{0}C)				
Parameters (Mean)	**Milk type**	**55**	**59**	**63**	**65**	**70**
Fat (%)	Fresh	4.30 ± 0.15	4.41 ± 0.27	4.43 ± 0.14	4.28 ± 0.48	4.80 ± 0.12
	Evakuula	3.95 ± 0.15	3.97 ± 0.28	3.95 ± 0.09	4.00 ± 0.52	3.94 ± 0.10
	Change*	0.35 ± 0.11^{bc}	0.45 ± 0.06^{b}	0.48 ± 0.08^{b}	0.28 ± 0.05^{c}	0.86 ± 0.08^{a}
Protein (%)	Fresh	2.85 ± 0.17	3.19 ± 0.20	3.26 ± 0.16	3.08 ± 0.06	3.28 ± 0.13
	Evakuula	2.73 ± 0.05	2.82 ± 0.08	2.85 ± 0.06	2.78 ± 0.02	2.80 ± 0.06
	Change*	0.12 ± 0.13^{b}	0.37 ± 0.12^{a}	0.41 ± 0.13^{a}	0.3 ± 0.04^{a}	0.48 ± 0.13^{a}
pH	Fresh	6.72 ± 0.07	6.66 ± 0.03	6.61 ± 0.03	6.61 ± 0.03	6.62 ± 0.02
	Evakuula	6.86 ± 0.04	6.70 ± 0.11	6.76 ± 0.04	6.77 ± 0.06	6.75 ± 0.03

P value =<0.0001 for fat, P value =0.0003 for protein

* Change is the difference in parameter composition between fresh and Evakuuled milk.

Values with the same letters are not significantly different.

Table 7: Milk Quality parameters of fresh, Evakuuled and chilled milk

Parameters	**Fresh**	**Evakuuled**	**Chilled**
Fat (%)[1]	4.43 ± 0.31[1]	4.25 ± 0.43	4.19 ± 0.39
Protein (%)[1]	3.26 ± 0.11	3.06 ± 0.06	3.07 ± 0.04
Solid Non-fat (%)[1]	8.90 ± 0.030	8.34 ± 0.14	8.41 +0.11
Freezing point (^{0}C) [1]	-0.534 ± 0.02	-0.516± 0.01	-0.518± 0.01
Added water* (%)[1]	0.0± 0.00	1.71 ± 0.57	1.33 ± 0.50
TVC** (cfu/ml) [2]	1800 (1200, 2600)	13000 (6800, 24000)	3500 (3100, 4000)

[1] Number of samples = 3, [2] Number of samples =2

*****Added water is a calculated value from the freezing point. Calculated as the percentage reduction from the freezing point base value of -0,525^{0}C. The ultrasonic milk analyzer does not determine the added water directly.

******Calculated as geometric average of the cfu/ml for the two samples. The values in the brackets represent the cfu/ml for the samples tested. Samples of milk used for TVC were different from those used to measure for other quality parameters.

Table 8: Sensory evaluation results

	Mean score on Quality attributes				
Milk type	**Appearance**	**Aroma**	**Taste**	**Acceptability**	**Rank**
EvaKuula	7.5±1.5	6.3±1.7	6.6±1.7	6.9±1.5	1
Fresh	7.6±1.1	6.5±1.5	6.9±1.7	6.9±1.6	2
Refrigerated	7.6±1.1	6.8±1.4	7.0±1.5	7.2±1.3	3

Table 9: Participants comments on milk type preference

404(fresh milk) really has a great flavor and good mouth feel. 202 (evakuuled milk) has solids which may have biased my opinion
All the milk samples are good and pure
Appearances are not easy to tell apart
I prefer 404 (fresh milk) because it has a perfect taste, great Aroma though 303(Refrigerated milk) and 202 (evakuuled milk) still works because people have different tastes
All the milk samples are of very good in quality, but I have issues with the aroma. The samples are lacking aroma
The milk looks watery. 303 (Refrigerated milk) has solid particles. It has no aroma and tastes plain
Sample 202 (evakuuled milk) is super cool and tastes better
Sample 404 (fresh milk) is the best because the aroma is not too much like that immediately from the cow
Product is so good, most like samples 202 (evakuuled milk) and 404 (fresh milk) are acceptable
202 (Evakuuled milk) taste very dilute maybe needs less dilution the rest. 404 (fresh milk) tastes better
Sample 404 (fresh milk) and 303(Refrigerated milk) have the same taste and same aroma but different appearance
They are all slightly different but 303(Refrigerated milk) outstands them all
Sample 303 (Refrigerated milk) is the best due to its aroma and after taste properties

Code: 202 – EvaKuula, 303 – Refrigerated and 404 – fresh

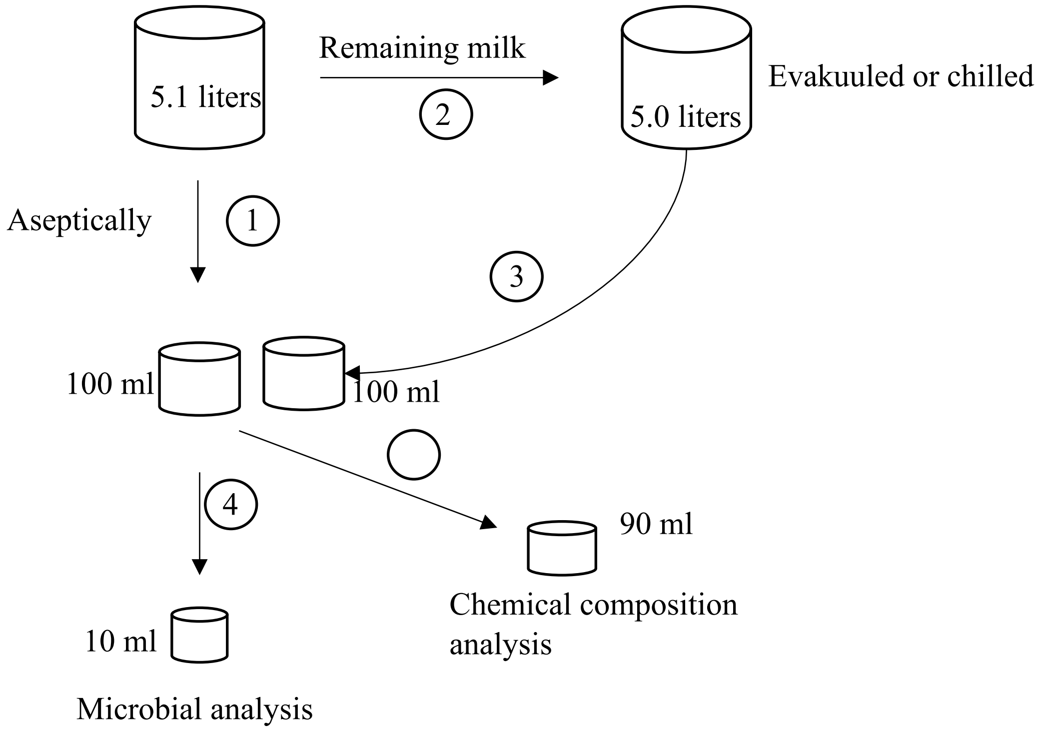


Figure 4: Sample preparation for both microbial and fat and protein composition analysis. 5.1 L of fresh milk were collected immediately after milking. 100 ml were aseptically taken off and subdivided into 10ml and 90ml for both microbial and fat and protein composition analysis respectively. The remaining milk 5.0 L were preserved by EvaKuula or chilling depending on the experiment and also subjected to the same process. The 5 L was used because it is the minimum design volume for the EvaKuula Unit.

CHAPTER 5:

COMPUTATIONAL FLUID DYNAMICS MODELLING OF EVAPORATIVE COOLING

Sempiira E. J, J. Galiwango and W. S Kisaalita. To be submitted to *Renewable Energy Journal*

Abstract

The performance of the evaporative cooler is driven by the air flow properties. The current design of the evaporative cooler used in the EvaKuula process was designed for storage of camel milk in an arid pastoral area of northern Kenya. The wind driven fan on the top of the cooer drives the air flow pattern in the evaporative cooler. Because the operating height of the evaporative is about 1 m from the ground, we proposed eliminating the fan in the design to replace it with a cost-effective vent. Our thinking is that the wind speeds at this height are not enough to drive the fan. We hypothesize that we can have desired efficiency of the evaporative cooler without the fan. Therefore, this study examined the mass, energy and momentum transfer between air and water in the context of milk preservation using Computational fluid dynamics (CFD). The CFD analysis, considered both the current design with a fan and a modified design with a static vent. CFD analysis was performed using the ANSYS fluent code 19.2. Experiments were conducted to validate the mode by measuring both the temperature and relative humidity of the ambient and cooler air plus the temperature of water stored inside the cooler. Revolution made by the fan were also measured.

Results of the fan revolutions were at a maximum rotation of 40 rev/min and a minimum of 0.05 rev/min. Results also suggested that the temperature and relative in the cooler at a given time of the day are not different for both when the fan is static or when freely rotating. However, by doubling the maximum speed (80 rev/min) or increasing it further (160 rev/min), the exit velocity of the air increased but didn’t affect the temperature and humidity in the cooler. Increase in the air exit velocity increases convective heat transfer; increasing the cooling rate. However, the cooling rate will not influence the final temperature of the air/water inside the cooler. For milk preservation the final temperature of the water at the end of the day is important because it determines how fast the milk is cooled after thermization. The results provide a science driven evidence in support of replacing the fan with a cost-effective static vent.

Key words: Computation fluid dynamics, Evaporative cooling, EvaKuula, Static vent, fan, revolutions, mass and energy

5.0 Introduction

Direct evaporative cooling is used in several applications such as: Green houses, residential buildings and for preservation of fruits and vegetables (Bucklin et al., 2004, Anyanwu, 2004). Applications for milk freshness preservation has been demonstrated with camel milk (Wayua et al., 2012). Direct evaporative cooling works by evaporating water into the air. The process of evaporative cooling is different from vapor-compression refrigeration cooling because the coolant fluid for the vapor compression does not evaporate into surroundings, instead, the coolant is reused again into the system by compression and condenser cycles. The evaporative cooler design of interest in this study was adopted from (Wayua et al., 2012). This evaporative cooler (figure.5) is part of the EvaKuula kit (Kisaalita et al., 2018). The EvaKuula is an off-grid milk preservation unit that employs a combination of thermization and evaporative cooling to keep milk fresh. The evaporative cooler is made of the following components; the top plate, the pad and its holding compartments, the base, the fan/vent, the water tank support, the water trough and the water circuitry for wetting the pad (Kisaalita et al., 2018). The cooling pads that are made of jute are kept wet by a water circuitry mounted on top of the structure (figure 5). Jute fiber was used because it is readily available and presents desirable saturation effectiveness of 84% (Manuwa et al., 2012). The air enters through the sides and then moves out through the top of the unit. The inside is fitted with a trough filled with 120 liters of water. During the day, the water is kept cool by the cool humid air coming through the pads. The cooled water is then used to quickly lower the temperature of the milk-can introduced into the evaporative cooler after thermization.

The process of evaporative cooling involves both heat and mass transfer between water and air. When warm ambient dry air is passes through a wetted porous media, air supplies the sensible heat to the water, evaporating it, and in turn the air becomes humid and cooler. This decrease in the air temperature and increase in the specific humidity happens at a constant enthalpy (adiabatic process). The extent of change in air properties depends on temperature and specific humidity of the ambient air (Fouda and Melikyan, 2011). Assuming no heat loss at the air- water interface, the quantity of heat lost by the air will be equal to the quantity of heat passing through the air-water interface. Therefore, Ndukwu et al (2013) has defined the effectiveness η_t of evaporative coolers (equation 1) in terms of the temperature of the air. Where T_{amb} is the temperature of ambient air, T_{cold} is the temperature of the cold air inside the chamber and T_{wb} is the wet bulb temperature of ambient air. The effectiveness is the measure of how the air temperature going through the wet pad approaches the wet-bulb temperature of ambient air. An effectiveness of 100% would mean that the air inside the evaporative cooler will be at the wet bulb temperature of the ambient air. Because the ambient air conditions are varying based on the time of the day, the inside air temperature will vary too.

$$\eta_t = \frac{T_{amb} - T_{cold}}{T_{amb} - T_{wb}} \text{------------------------------(1)}$$

The air movement through the evaporative cooler of the EvaKuula kit is aided by a wind driven ventilator roof fan. The fan presents a large fraction of the total manufacturing cost of the first prototype of the EvaKuula. A high production cost means a high retail cost, and this limits up-take in the context of a smallholder farmer. We have thought about eliminating the fan in the design and depend only on the natural ventilation (stack effect) without compromising effectiveness. Our reasoning is that at the operating height, of 1m above the ground, the effect of the fan is negligible because of the low wind speeds. We hypothesized that we will achieve the desired performance of the evaporative cooler without the fan because it's simply a static vent. The general purpose of this study was to combine experimental and computational fluid dynamics modelling to understand the performance of the evaporative cooler with and without the fan, in the context of milk freshness preservation for smallholder farmers.

5.1 Methodology

5.1.0 Fan rotational speed

The number of fan revolutions per day were measured in the months of September and October 2017 and March and April 2018 for a total of 64 days. The months were selected to representative the wet and dry seasons respectively in the year. Measurements accomplished by attaching a digit resettable mechanical pulling counter on the top fan ensuring that the attachment offered the minimum resistance to the fan rotation. The number of revolutions were recorded at three times of a day; 7:00am, 12:00 pm and 6:00 pm. The 7:00 am readings captured the fan revolutions for the night while the 12:00 pm and 6:00pm captured the morning and afternoon speeds respectively.

5.5.1 Evaporative cooler performance

Experiments with the evaporative cooler were performed during the months of June and July 2019 at Smallholder Fortunes Research site located in Nsangi village, along Masaka road in Wakiso district of Uganda. The two direct evaporative coolers were installed in a circular grass thatched gazebo house of height 11ft and diameter 12ft. The gazebo house is made open on the side with only support columns for the canopy such that the wind can freely move across from either side. The fan of one cooler was held static (to act as just a vent) whereas the other cooler was left to rotate freely, in response to the wind. For the two coolers, the following parameters were monitored: ambient air temperature ($T_{amb,}$ and T_{wb}) relative humidity inside the cooler and for ambient air, temperature of air inside the cooler (T_{cold}), temperature of the water in the trough inside the cooler, pad surface temperature. The air temperature and humidity were monitored using a data logger model OMEGA HH309 and thermal-hygrometers model HT-3000 from Delmhorst Instrument Company respectively. Thermographs were taken to capture temperature distribution inside and outside of the cooler using an Infrared camera, model FLIR ONE Gen 3. Measurement of the parameters was done all day and data was recorded at intervals of 1-hour. Experiments were repeated for at least 3 days and representative average values were considered. We used equation 1 to calculate the effectiveness of the cooler for the two coolers.

5.1.2 Computational fluid dynamics modelling

We use the Computational Fluid Dynamics modelling to solve the Navier- Stokes equations for energy, mass and momentum transport for the air and water vapor flow across the porous media (Jute). For free convection, the general equation for Navier-Stokes equation describing the transport phenomenon in 3 dimensions is shown below (equation 2). (Nikita-Martzopoulou et al 2008).

$$\frac{\partial(U\Phi)}{\partial x}+\frac{\partial(V\Phi)}{\partial y}+\frac{\partial(W\Phi)}{\partial z}=\Gamma\nabla^2\Phi+S_\Phi\text{-----------(2)}$$

Where, Φ represents the transport quantities of energy, mass and continuity in dimensionless form. U, V, W are the velocity vector components in 3 dimensions, Γ is the diffusion coefficient and S_{Φ} is the source term.

We use the Ansys software fluent code 19.2 (academic version) to solve the conservation equations for the different transport quantities of mass, momentum, and energy in two dimensions. The two-dimensional approach is used because of limitations of the academic version on the number of elements and for improved accuracy. The code uses the finite volume method to discretize and solve these governing equations by integrating over a control volume from the domain of interest.

We use the discrete dense model, viscous K-Ɛ model and transport species model. The discrete dense model follows the Euler-Lagrange approach (Ansys, 2013). In this approach, the fluid phase (air) is treated as a continuous phase by solving the Navier-Stokes equations, while the dispersed phase (water droplets) is solved by tracking the water droplets through the calculated flow field. The dispersed phase (water droplets) can exchange momentum, mass, and energy with the fluid phase (air). The turbulent viscous K- Ɛ model caters to the turbulence flow of air and the transport species model caters to air and water vapor mixture interaction (Ansys, 2013). The porous media was incorporated in the model by enabling the porous zone for the porous field and specifying the inertia resistance and permeability of the jute fiber as shown in Table 10.

The domain of interest figure 6 was modelled in workbench and meshed using the structured mesh. The mesh consisted of 25,854 nodes and 25,000 elements. Boundary conditions Table 10 were imposed on the boundary inlet and outlet of the flow domain.

Because wind speed is measured at height of 10 m above the ground, we use equation (3) which is based on Hellmann power law (Bañuelos-Ruedas et al 2011) to estimate the average wind speeds at the operating height of the evaporative cooler

$$v_w(h) = v_{10}\left(\frac{h}{h_{10}}\right)^a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where v_w is the velocity of the wind at height h, v_{10} is the velocity at the height of 10 m equal to 3.5m/s and a is Hellmann exponent which is equal to 0.6 for stable air above human inhabited areas (Bañuelos-Ruedas et al 2011). The calculated speed at an operating height of 1 m is given as 0.8m/s and was used as the velocity at the inlet of the pad surface.

The model was solved at steady state with boundary conditions at a given time in the day (9:00 am and 1: 00 pm) as shown in Table 10. We predicted the temperature and relative humidity at the center of the cooler for comparison with experimental data. This was done for both cases of stationary and rotational fan speeds of 40 rpm. CFD results were validated using the experimental data for temperature and relative humidity. We further use the CFD results to understand the temperature, relative humidity, and velocity distribution at different speeds of the fan in the evaporative cooler. Rotating speeds of 80 and 160 rpm which are based on multiplying the maximum speed by 2 and 4 times respectively were used.

5.2 Results and Discussion

5.2.0 Wind-driven fan performance

Results of the fan revolution are shown in the Table 11. The average fan rotation was 4 and 13 rpm during the night and day respectively. The maximum rpm occurred during the afternoon period and the minimum 0.05 rev/min occurred at night. The increased rpm in the afternoon is consistent with increase in wind speed. The increased wind speeds are brought about by an increase in the earth's surface temperature which reduces the moisture content of the wind making it less dense and therefore increased speed/mobility. During the night, the fan is almost stationary. Therefore, the fan acts as a simple vent during the night.

5.2.1 Evaporative cooler performance

The results of temperature distribution of the inside air and water in the trough are shown in figure 7. Figure 7-A shows that the cooler maintains relatively the same temperature variation when the fan is static and when it rotates freely throughout the day. For the cooler with the static fan, the water temperature ranged from 20.5^0C in the morning to 21.6^0C in the evening. This was similar for the cooler with the fan freely rotating. Figure 8-B shows that the temperature of the inside air was slightly higher when the fan was static during the peak sun hours. However, the variation of the inside air temperature for both coolers is very similar. A maximum drop in temperature of 8.3 and 8.1^0C for water was recorded for the cooler with static fan and rotating fan, respectively. For the inside air, the respective maximum drop in temperature was 6 and 6.5^0C. The results show that the temperature difference of the water trough and air was not significantly different between the coolers. The thermographs (figure 8) also showed that the temperature distribution inside the cooler at 9:00 am and 1:00 pm were the same for both coolers. The results are like those reported by Kisaalita et al (2018), and Wayua et al (2012) who respectively reported a maximum drop in temperature of 14^0C and 11^0C with ambient air temperatures of up-to 35^0C. The relative humidity of the inside air for the cooler with the static and rotating fan were similar varying between 94- 84.6% and 97 - 84.2% respectively (figure 7C). The ambient air relative humidity varied between 85 and 72.3%.

The variation of the effectiveness of the coolers with the time of day is shown in the figure 3D. For the coolers with the static fan, the effectiveness was in the range of 50-81% and for the freely rotating fan was 48-83% with an ambient air of up-to 29^{0}C. Both cooler efficiencies were within the range reported by Wayua et al (2012) of 50-87% for ambient air temperature of up-to 35^{0}C with the fan freely rotating. The results suggest that the fan's rotation has no significant impact on the of the effectiveness and the cooling profile of the air and water in the trough inside the cooler.

5.2.2 Model validation

Results of the computational fluid dynamics modelling for the cooler performance parameters of temperature and relative humidity distribution when the fan is static for two different times of the day (9:00am and 1:00pm) are shown in figure 9. The predicted temperature distribution inside the cooler was consistent with the thermographs (figure 8) taken for the inside of the cooler. The air temperature inside the evaporative cooler (at the center) was consistent with the experimental results both when the ambient air temperature was 23.5^{0}C at 9:00 am or at 28.5^{0}C at 1:00 pm (figure 9 A&B). The relative humidity predicted by the model at the center of the cooler was also in agreement with the measured values for the times in the day, with errors in prediction below the 10% Table 12. The increase in relative humidity is due to the water vapor from the evaporating water droplets at the wetted porous media interface. The model also predicts a high relative humidity of the outside air (figure 9 C&D) for both times of the day. This can be attributed to the evaporation of water at the pad surface. The error in predicting the relative humidity by the model (Table 12) is attributed to the fact that the model assumes that the side of the cooler opposite the inlet is a wall and therefore because of continued accumulation of the water vapor, the relative humidity is predicted to increase much more than what was measured in the experiments.

Convergency was analyzed with the residual error and imbalances in the mass flow rate. The residual error reduced to the set absolute limit of below 10^{-3} and the flow domain had imbalances measured as mass flow rate between the inlet and the outlet of less than 1%. Therefore, the solution reached steady state (See supplementary figure 12). Mesh independency was assessed by increasing the number of elements in the mesh while monitoring the final maximum velocity at the outlet of the flow domain. The number of elements were increased by reducing the element sizing to sizes of 0.01, 0.005, and 0.0025 m. This increased the number of elements in the mesh to 25000, 100,000, and 400,000 elements respectively. At 100,000 elements, the mesh size was independent of the maximum outlet velocity. Therefore, this Mesh size of 0.005 m was used in the CFD analysis.

5.2.3 Testing performance at different fan speeds

The predicted temperature values and relative humidity at the center of the cooler were 21.5^{0}C and 100% respectively for all tested rotational speeds of 40, 80 and 160 rpm when measured for inlet air conditions at 9:00am. The CFD results show that for a given time of the day, these performance parameters were not significantly difference from the distributions when the fan was static. However, the maximum exit velocity of the air increased with increase of the rotational speeds (Figure 10&11). The maximum air exit speed from the chamber were 3.33, 3.61, 4.66 and 6.66 m/s at 0, 40, 80 and 160 rpm respectively. The results suggest that the amount of heat extracted by the water from the ambient air is dependent on the difference in temperature and relative humidity of the ambient air and water in the pad. The temperature difference and relative humidity are solely dependent on the prevailing weather conditions of the day. However, increased speeds of the fan allow for increased exit speeds of the air (figure 10&11). Convective heat transfer studies have demonstrated that increasing air exit velocity, increases the convective heat transfer of air. The increase in convective heat transfer will increase rate of cooling of the product inside the cooler. This increase in the cooling rate will have no effect on the final temperature of the water or air in the trough at the end of the day. Therefore, the CFD results agree with the experimental data and thus support replacing the fan with a vent without compromising performance of the cooler.

5.3 Concluding Remarks

The computational fluid dynamics model developed for the evaporative cooler predicted the experimental results with an error of below 10%. Therefore, the model can be used to study other conditions to ensure the cooler will perform as expected especially in other regions with different climatic conditions. The wind-driven fan on the top of the evaporative cooler has little or no effect on the temperature and humidity of the inside air. The fan only provides an exit of the air for continuous flow through the evaporative cooler chamber. The temperature drop achieved in the air is dependent on the temperature difference between the ambient air conditions and water temperature in the pad. Unlike cooling of vegetables where a high cooling rate is needed, for the evaporative cooler intended for use in the Evakuuling process, the cooling rate of the water is not as important as the final temperature of the water trough at the end of the day. The evaporative cooler with a vent achieves the desired temperature and therefore, use of a cost-effective static vent will provide the desired cooling of the water.

5.4 References

Ansys Inc.: Ansys Fluent User's Guide. Ansys Inc. publication, release 15.0, 2013

Anyanwu, E. E. (2004). Design and measured performance of a porous evaporative cooler for preservation of fruits and vegetables. *Energy conversion and management*, *45*(13-14), 2187-2195.

Bañuelos-Ruedas, F., Camacho, C. Á., & Rios-Marcuello, S. (2011). Methodologies used in the extrapolation of wind speed data at different heights and its impact in the wind energy resource assessment in a region (pp. 97-114). InTech Publishers, Rijeka, Croatia.

Bucklin, R. A., Leary, J. D., McConnell, D. B., & Wilkerson, E. G. (2004). Fan and pad greenhouse evaporative cooling systems. Circular 1135. Available at: https://edis.ifas.ufl.edu/ae069

Fouda, A., & Melikyan, Z. (2011). A simplified model for analysis of heat and mass transfer in a direct evaporative cooler. Applied Thermal Engineering, 31(5), 932-936.

Kisaalita, W. S., Katimbo, A., Sempiira, E., & Mugisa, D. (2018). EvaKuula saves Ugandan smallholder farmers' evening milk. Sustainable Energy Technologies and Assessments, 29, 155-163.

Manuwa, S. I., & Odey, S. O. (2012). Evaluation of pads and geometrical shapes for constructing evaporative cooling system. Modern Applied Science, 6(6), 45.

Ndukwu, M. C., Manuwa, S. I., Olukunle, O. J., & Oluwalana, I. B. (2013). Mathematical Model for Direct Evaporative Space Cooling Systems. Nigerian Journal of Technology, 32(3), 403-409.

Nikita-Martzopoulou, C. H., Bartzanas, T., Kittas, C., & Sapounas, A. A. (2008, October). Fan and pad evaporative cooling system for greenhouses: evaluation of a numerical and analytical model. In International Workshop on Greenhouse Environmental Control and Crop Production in Semi-Arid Regions 797 (pp. 131-137).

Wayua, F. O., Okoth, M. W., & Wangoh, J. (2012). Design and performance assessment of a low cost evaporative cooler for storage of camel milk in arid pastoral areas of Kenya. International journal of food engineering, 8(1).

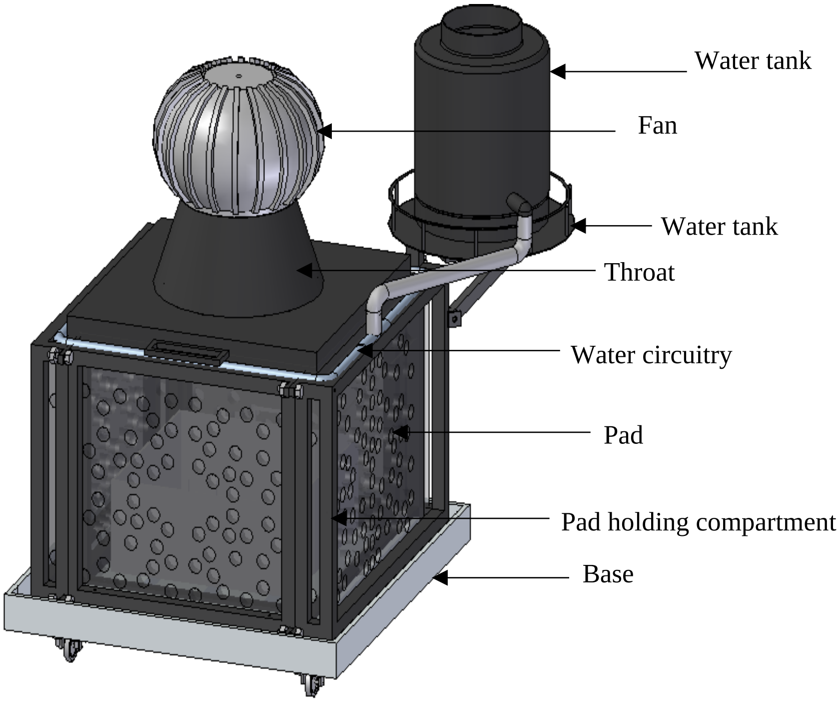


Figure 5: Evaporative cooler structure and its components

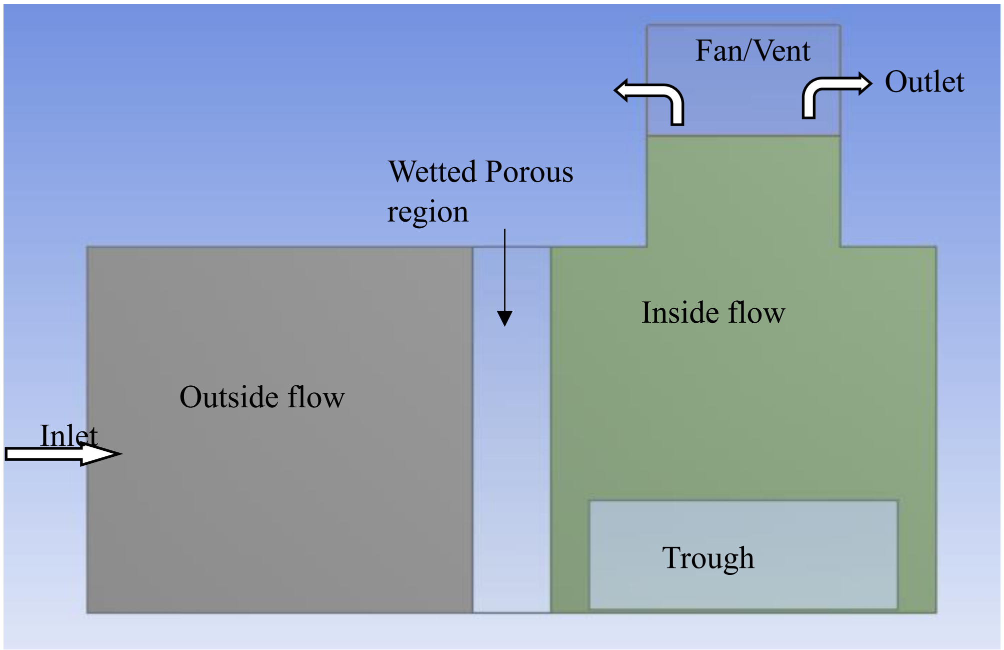


Figure 6: Geometry of the computation domain for the evaporative cooler fluid flow

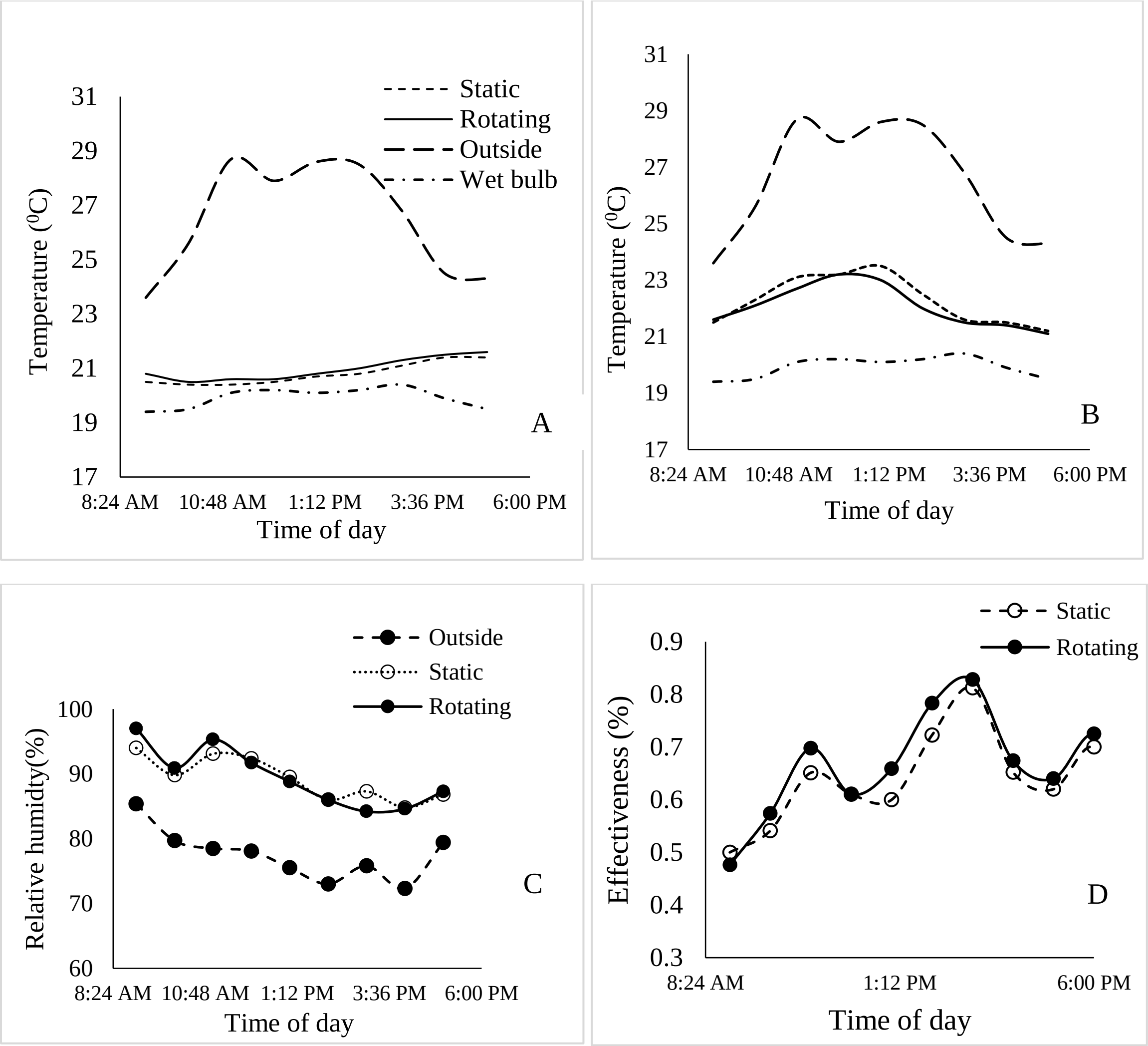


Figure 7: Experimental performance parameters of the cooler, A&B - Temperature distribution in the evaporative cooler. Graph A, the static and rotating is temperature for the water in the trough. Graph B, the static and rotating is temperature for the air inside the cooler. The wet bulb and outside are ambient air temperatures. C & D - relative humidity and effectiveness distribution with time of day. Graph C, relative humidity of the inside and out side air for both coolers over time of day. Outside means ambient air and Graph D, Effectiveness of the evaporative coolers over the time of the day.

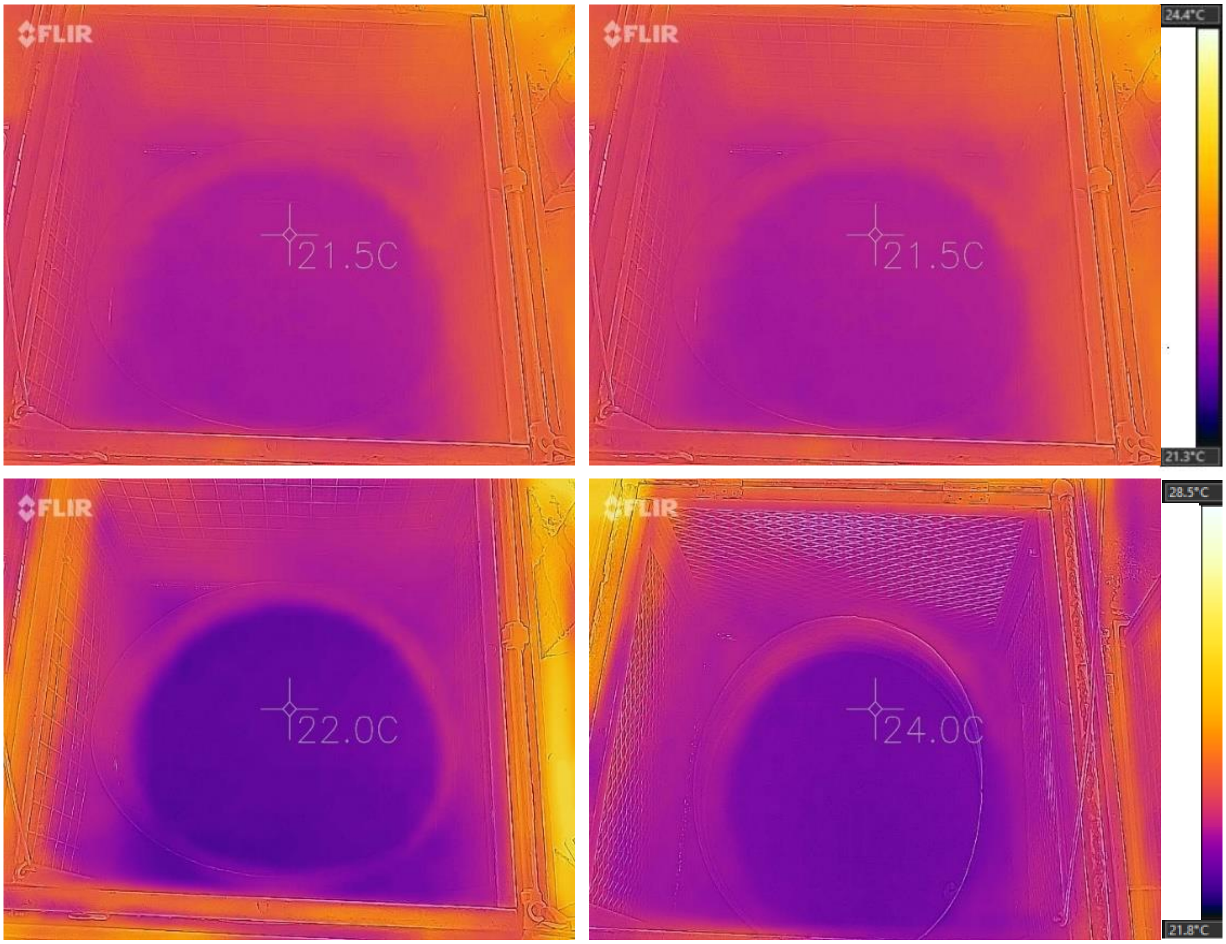


Figure 8: Thermographs showing temperature distribution inside the evaporative cooler. a and c; when the fan is rotating, b and d; when the fan is not rotating. The thermographs a&b are taken at 9:00am, c&d are taken at 1:00pm. The temperature distribution is the same for both coolers when the fan is static and when the fan is rotating at different times in the day.

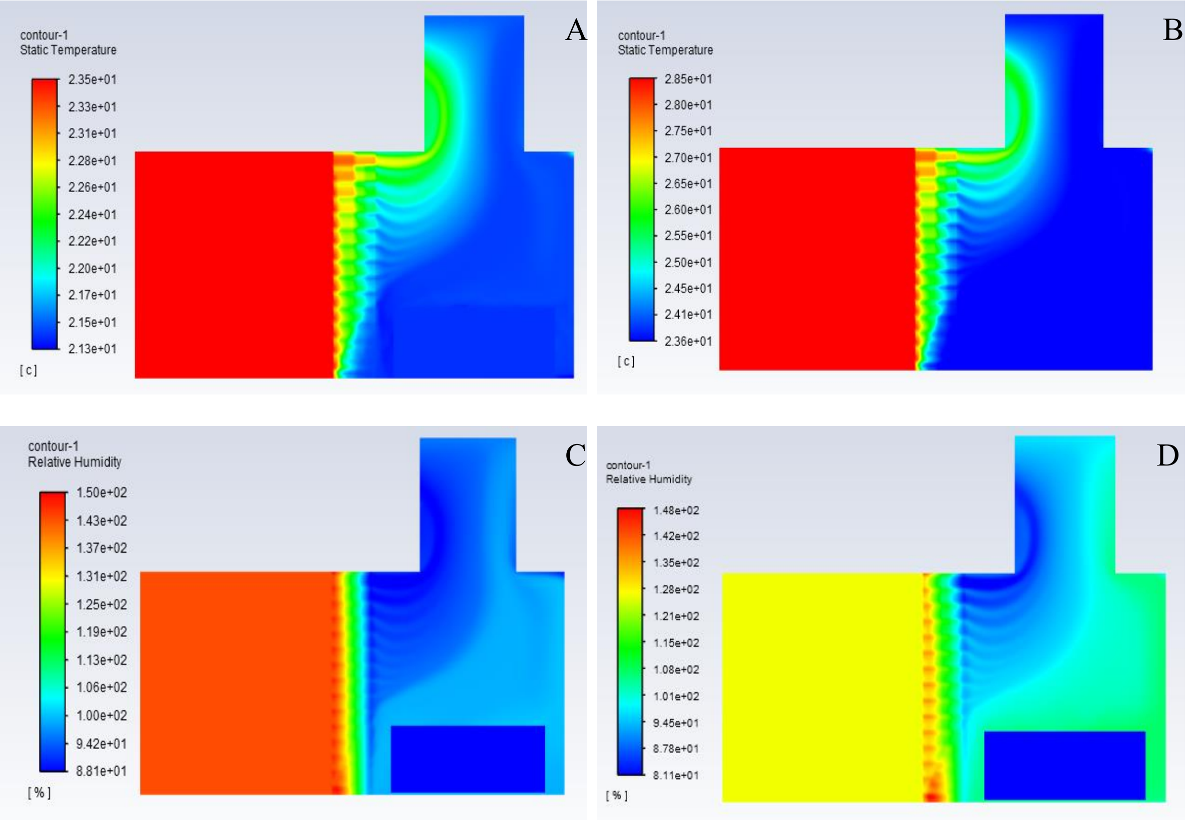


Figure 9: Cooler CFD modeled performance parameters for air. A & B- Temperature distribution, C&D relative humidity distribution (A&C- measured at 9:00am, B&D- measured at 1:00pm)

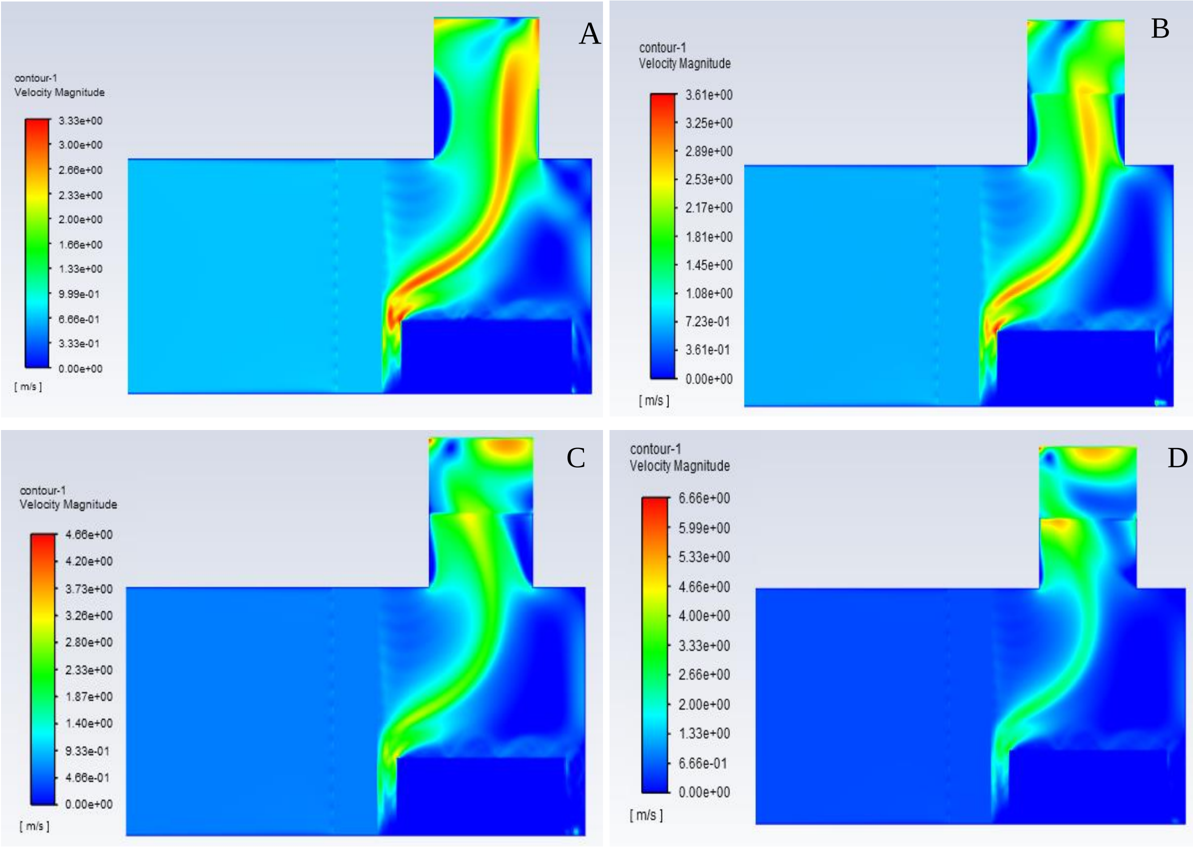


Figure 10: Velocity distribution in the evaporative cooler at different rotational speed of the fan. A - no rotation, B - rotation at 40 rpm, C - rotation at 80 rpm, and D - rotation at 160 rpm

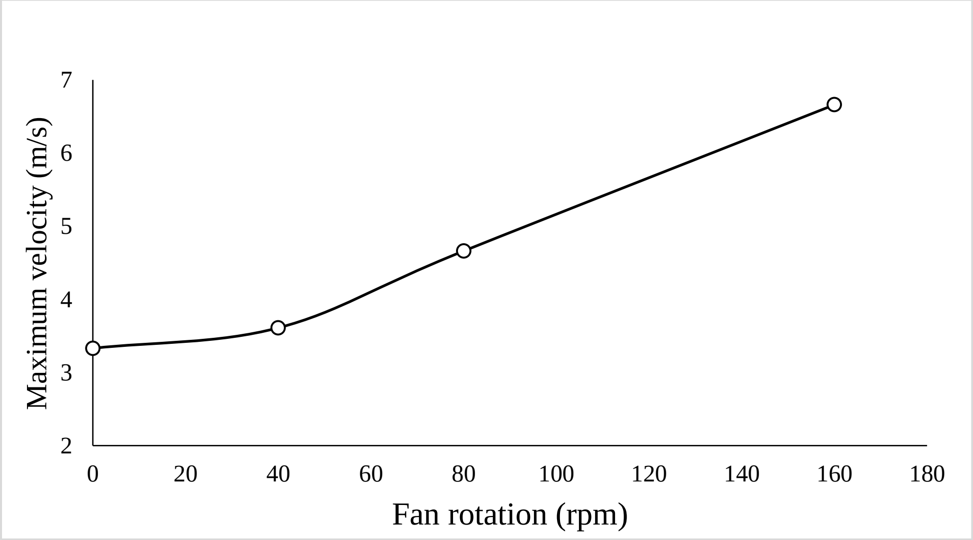


Figure 11: Variation Maximum air exit velocity with Increased rotation of the fan

Table 10: Boundary conditions

Parameters	**Quantity**	
	At 9:00 am	**At 1:00 pm**
Velocity at inlet v_w (m/s)	0.8	0.8
Gauge pressure at outlet (pa)	0	0
Relative humidity (%)	84.2	74.5
Permeability of Jute (inverse)	2.5e+10	2.5e+10
Water droplet diameter (m)	0.001	0.001
Water mass flow rate(kg/s)	0.12	0.12
Inlet air temperature T_{amb} (^{0}C)	23.5	28.5
water temperature (^{0}C)	21.5	23.5

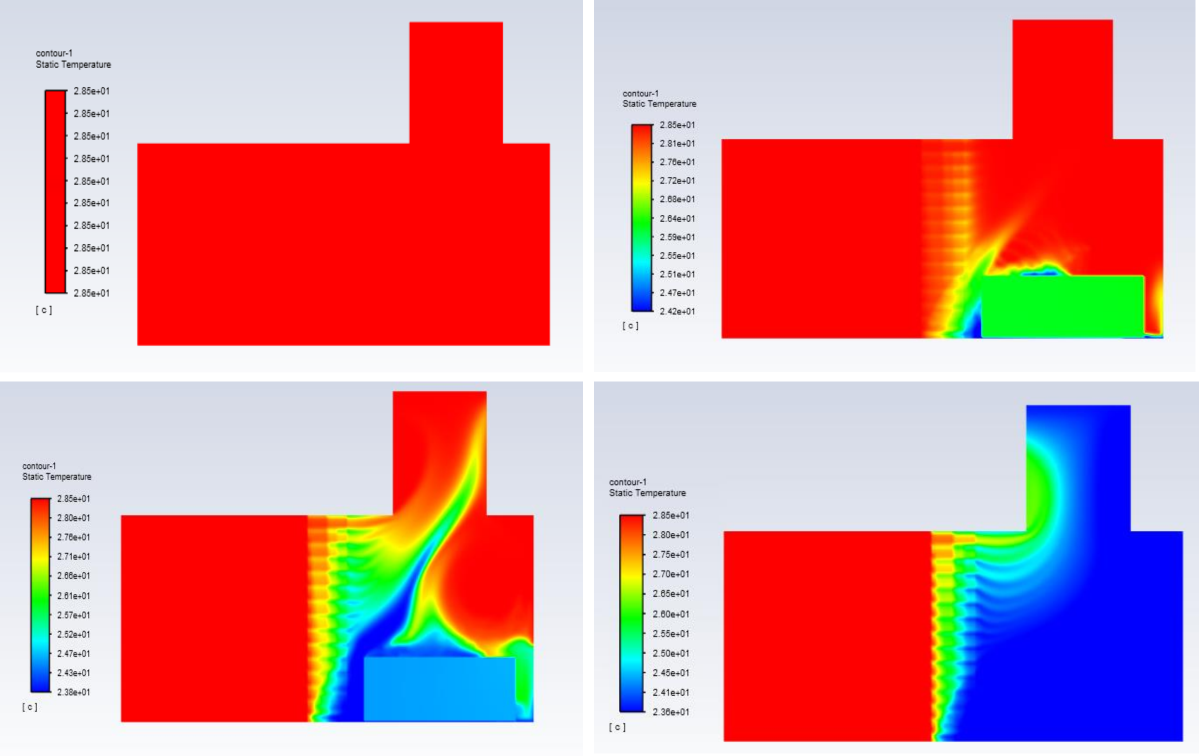
Table 11: Wind-driven fan performance

	Fan revolutions/min		
	7:00 am*	**12:00 pm***	**6:00 pm***
Average	4.0	8.3	17.5
Maximum	21.5	30.0	39.6
Minimum	0.05	0.4	2.3

* The 7:00 am readings captured the fan revolutions for the night while the 12:00 pm and 6:00pm captured the morning and afternoon speeds respectively.

Table 12: Experimental and CFD predicted results at the center of the cooler

Parameter	**Time of day**	**Inlet air**	**Outlet measured**	**Outlet Predicted**	**Error (%)**
Temperature(^{0}C)	9:00am	23.5	21.5	21.3	0.9
	1:00pm	28.5	23.5	23.6	-0.4
Relative humidity (%)	9:00am	84.2	94.4	100	-5.9
	1:00pm	74.2	89.8	98.5	-9.7



Supplementary Figure 12: Snapshots of the cooling of the air inside of the cooler from beginning to steady state. At the beginning (A- 0 iterations), the cooler is in equilibrium with the ambient air outside. When the discrete phase (water) is introduced at the porous media domain, the inside air begins to cool from the bottom (B – 40 iterations). The temperature of the inside air continues to drop (C-250 iterations) as shown in B and C until steady state.

CHAPTER 6

6.0 CONCLUSION AND BROADER IMPACTS

The results of the study showed that the performance of the evaporative cooler with a modified vent was sufficient for milk preservation in terms of drop in temperature of air and increase in the relative humidity. The change in temperature and increase in relative humidity is due to the exchange of mass and energy between air and water. The results for milk freshness showed that based on biochemical parameters (fat at 4.25) and microbial quality (Total viable counts – 13000 cfu/ml), milk after thermization and evaporative cooling meets the grade one (top quality) fresh milk classification. The results also indicated that Farmers without biogas on the site intending to adopt the EvaKuula can cost-effectively (both economically and environmentally) perform the thermization process with an efficient Rocket stove.

Potential impacts of these findings are: the results of milk freshness provide a science driven evidence that can support the inclusion of evakuuled milk in the fresh milk quality standard for the East African region. Additionally, results of the performance may provide evidence for value engineering of a cost – effective prototype of the evaporative cooler with a static vent. Inclusion of Evakuuled milk in the standard may improve product confidence among sector players. The results of energy analysis support use of an alternative energy source to the expensive biogas plant, lowering the capital cost requirement for the unit. The inclusion of EvaKuuled milk coupled with a low retail price may accelerate the diffusion of the EvaKuula among rural Sub-Saharan African farmers.

Future studies can explore examining the product quality in the hands of several farmers to establish the quality of the milk at that level. Milk quality parameters reported in this research were examined at a laboratory scale in a controlled environment. Handling of milk by smallholder farmers in their daily routine is expected to be different and therefore, there will be a variation in product quality.

Appendix A: Other publications

EvaKuula saves Ugandan smallholder farmers' evening milk

Abstract

Smallholder dairy farmers in rural settings of sub-Saharan Africa cannot get their evening milk to markets because of several reasons. They do not have access to grid electricity to power traditional refrigeration systems that preserve their milk for market the next day. They are not able to transport at night due to safety concerns and poor road conditions, especially in the peak production rainy season, marked by high abundance of fodder. A solution involving the combination of thermization (58–63 °C for 30 s) and low-cost evaporative cooling has been shown to be effective and has been successfully tested in the hands of 30 target users in Wakiso, Kiboga, and Rakai districts of Uganda. All cooled evening milk by these farmers has successfully entered the cold chain, after assessment with the Resazurin assay, commonly used for evaluating freshness by collection centers or buyers. Based on the cooling system (EvaKuula) fabrication costs and daily evening milk sales by the early adopters, a payback period of approximately 20 months is needed for farmers to completely own the EvaKuula, in a rent-to-own business model. Work is in progress to further scale-up the EvaKuula adoption in the region.

Keywords: Evaporative cooling, Thermization, User-centered design, Sustainable development, Sub-Saharan Africa, Food security

https://doi.org/10.1016/j.seta.2018.08.002 Sustainable Energy Technologies and Assessments 29 (2018) 155–163