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Winterization strategies for bulk storage of cucumber pickles☆

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ABSTRACT

Cucumbers are commercially fermented and stored in bulk in outdoor open top fiberglass tanks. During winter, snow and ice that accumulates around and on top of tanks influence heat transfer in an unpredictable manner, often compromising quality. This study evaluates the performance of inexpensive and resilient fermentation tank insulation and provides an estimate of heat loss associated with strategies for storage and preservation of fermented cucumbers during winter. Three insulation configurations were explored: conical top-cover, flat top-cover, and perimeter insulation. Changes in temperature during storage were experimentally studied in different tank configurations. A mathematical model was developed to simulate temperature profiles and heat loss in an idealized fermentation/storage vessel. Comparisons of the insulated tank configurations suggested a significant difference in temperature between a flat cover and uncovered tank when exposed to temperatures characteristic of the spring season in Pinconning, MI.

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1. Introduction

In the pickle processing industry, storage is essential to preserve quality of the product and provide availability throughout the year. Cucumbers are brined with 5–8% sodium chloride (NaCl), potassium sorbate, and vinegar and held in open top tanks, so that the brine surface is exposed to ultraviolet rays of sunlight to prevent growth of mold and yeast. To maintain year round processing operations, NaCl concentration is increased up to 14% after fermentation to prevent growth of spoilage microorganisms, minimize freezing damage in open-top tanks during winter conditions, and guarantee long term storage and preservation (Fleming et al., 1987). Emerging technologies, such as cucumber fermentation brined with calcium chloride ($CaCl_2$), can reduce the amount of salt needed during fermentation and storage of brined cucumbers while diminishing chloride concentrations in the wastewater (McFeeters and Pérez-Díaz, 2010; Pérez-Díaz et al., 2015). However, maintaining the quality of pickles stored at freezing temperatures without salt and at low levels of $CaCl_2$ during winter represents a challenge. Thermal performance of low salt fermentations has not been explored. Different winterization approaches to preserve the quality of pickles have been used, including burying of tanks, to provide insulation and geothermal heat, and covering the top of the tanks with fiberglass domes to decrease convection losses. However, adoption of these techniques is currently cost prohibitive for pickle processors (personal communication). Experimental studies have shown that brines prepared with 1.1% $CaCl_2$ have a freezing point of 29 °F (unpublished). In order to match the freezing point of the 6% (wt.) NaCl cover brines (14 °F), about 18% (wt.) $CaCl_2$ or 14% v/v glycerin is needed. Increasing the $CaCl_2$ and glycerin content to maintain the temperature of cover brines above the freezing point during storage through the winter are neither cost efficient nor environmentally sustainable.

We theorize that modifying the exposed tanks may help in reducing in-tank freezing, salt levels, environmental footprint, and processing cost. Visual observations indicate that ice is mainly formed at the top and the internal perimeter of the tanks, impeding the removal of fermented stocks and increasing processing costs. To overcome these problems, a new winterization strategy is needed to prevent water and snow intrusion, capture heat from solar radiation at the top, and reduce heat transfer by convection at the top of the tanks. A removable greenhouse cover is a potential solution to keep the surface of brine in the tanks at temperatures above the freezing point of the cover brines by trapping solar heat and

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protecting the top surface area from wind, thereby minimizing heat dissipation. Polycarbonate, fiberglass, glass, acrylic, vinyl, and polyethylene have been widely used as greenhouse covering materials. The choice of material will mainly depend on the application, ambient conditions, and budget. In Michigan, where temperatures during winter are below freezing, evaluating the impact of insulation and thermal behavior of the tanks is crucial.

This study aimed at designing and building inexpensive and resilient insulation tank covers to prevent or ameliorate freezing, monitoring in-tanks temperature changes as a function of time and insulating design, and developing a heat transfer model using a mathematical computational fluid dynamic tool (COMSOL Multiphysics v5.2) to simulate cold weather fermented cucumber bulk storage and calculate heat losses. The collective new knowledge serves as a tool for providing recommendations for processors on effective enhancements for outdoor tank insulation used for bulk storage.

2. Materials and methods

2.1. Brining of cucumbers

Cucumbers were fermented in 10,000 gallon fiberglass tanks. Each of the tanks contained 3B (1.75″–2″ diameter) cucumbers that were brined to give a 60:40 pack out ratio (by weight of cucumbers to cover brine). The composition of cover brines used in the study are presented in Table 1.

2.2. Experimental protocol and data collection

Seven commercial cucumber fermentation tanks, four buried and three exposed tanks (one with a greenhouse conical top-cover), were examined in Pinconning, MI from January 18th-25th, 2016. Also, three commercial exposed tanks (uncovered, flat top-cover, and insulated perimeter) were examined in Mount Olive, NC from March 1st-29th, 2016 to test the potential to extend the pickle processing season later into the fall/winter and earlier in the spring in the South. The conical top-cover, flat top-cover, and perimeter insulation prototypes were constructed with a commercial 5 mm high density polyethylene (Solexx) material (Solexx Greenhouse and Greenhouse Covering, GSR-240-4, Salem, OR). The conical structure (12′ diameter and 2.5′ tall) was constructed on an untreated pine frame and installed in Pinconning, MI (Fig. 1A). The flat top-cover structure (12′ diameter) was constructed on a PVC frame and installed in Mount Olive, NC (Fig. 1B). The covers were placed on top of the tanks and the insulated perimeter was wrapped with Solexx material around the tank and held in place with PVC rings. To determine temperature inside the tanks, 15 thermocouples were mounted at five different radial locations, 2 feet away from the walls of the tank, and three heights from the surface (2, 5, and 9 feet) inside PVC pipes (three thermocouples per PVC pipe) and placed inside the tanks. The cover brine temperature was monitored using type K thermocouples. Temperatures were recorded every minute using a computer-based data acquisition system (TempScan/1100, iOtech, Cleveland, OH). Average cover brine temperatures during the most extreme weather conditions were used for modeling.

2.3. Numerical model

Heat transfer under varying environmental conditions in outdoor fiberglass tanks containing fermented cucumbers in winter conditions was modeled. Four tank models were created (buried with $CaCl_2$ cover brine, buried with NaCl cover brine, exposed tank without cover and with NaCl cover brine, and exposed tank with Solexx conical top-cover with NaCl brine) with a cylindrical geometry (10′ tall, 12′ in diameter, and 2″ thick) in 3D interface. The remainder of the model geometry was a rectangle whose material properties were defined as air (turbulent flow). The boundaries between the tank and air were defined as a continuous boundary. The computational domain included the brine, tank walls, and insulation material. The properties of the cover brine were as follows: $\rho = 1040$ kg/m^3, $k = 0.64$ W/m°K, and $cp = 4230$ J/kg°K. Material properties of the tank walls (fiberglass) was used as listed in COMSOL's material library. Thermal conductivity values were obtained from experimental data using a KD2 pro thermal analyzer (Decagon Devices, Inc., Pullman, WA) and the density and specific heat were obtained from the literature (Humphries and Fleming, 1991; Fasina and Fleming, 2001).

The temperature changes in cover brine were simulated using heat transfer with surface-to-surface radiation module in COMSOL Multiphysics, which considered external radiation using the coordinates of Pinconning, MI (latitude 43° N, longitude 83° W), time zone, and day of the year to compute the direction of incident solar radiation. In the energy equation, the external ambient temperature and the superficial heat transfer coefficient have been imposed on the tank's walls, the top, and the base, considering the radiation heat transfer between the tank and the ambient. The modes of heat transfer considered in the heat loss calculations were conduction, convection, and surface-to-surface radiation. Thermal losses from the tank to the environment were analyzed and minimized in order to improve insulation efficiency.

The simulation was set up as a time-dependent study to examine the temperature inside the tank as a function of time (3 h during the most extreme weather conditions observed, 8 °F and 37 °F). The model was meshed, solved, and then analyzed. For this analysis, all of the elements were free triangular meshed.

The following assumptions were made: mass transfer and volume changes are negligible and properties (density, porosity, permeability, dynamic viscosity, diffusion) do not change with temperature. The model created was verified by comparing predicted time-temperature history throughout the tank to existing experimental data. The data points for each thermocouple were averaged to create an average temperature history to compare with the results of the COMSOL model.

3. Results and discussion

The experimental data collected at Pinconning, MI showed that cover brine temperatures during the coldest night (ambient temperature 8 °F) were on average 22, 23 and 25 °F for exposed, top-covered, and buried tanks, respectively (Fig. 2 and Table 2). The

Table 1
Equilibrated cover brine composition observed at the locations included in this study.

Location	Cover brine composition
Mount Olive, NC	NaCl cover brine: 5.8% wt. NaCl, 6 mM potassium sorbate
Pinconning, MI	NaCl cover brine: 8% wt. NaCl, 6 mM potassium sorbate and 15 mM acetic acid as vinegar
	$CaCl_2$ cover brine: 1.1% wt. $CaCl_2$, 6 mM potassium sorbate

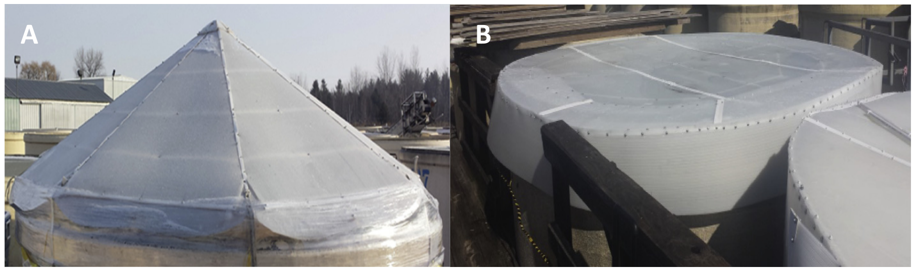

Fig. 1. Conical top cover installed in Pinconning, MI (A) and flat top-cover structure installed in Mount Olive, NC (B).

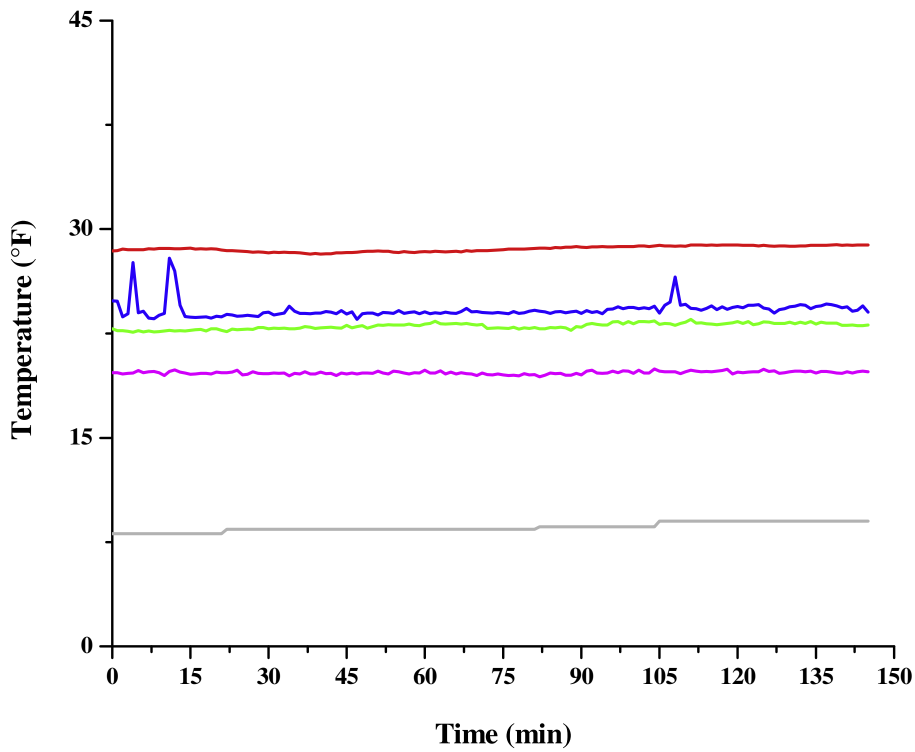

Fig. 2. Temperature history for different tank configurations: buried - NaCl cover brine (—), buried - $CaCl_2$ cover brine (—), exposed - NaCl cover brine (—), and exposed - NaCl cover brine and Solexx cover (—) and ambient temperature of 8 °F (—) (01/19/2016).

Table 2
Average temperature (°F) reached inside tanks equipped with different insulating systems and description of the cover brine composition contained in the tanks exposed to ambient temperatures of 8 and 37 °F.

Ambient Temperature (°F)	Average Temperature (°F)			
	Exposed Tanks		Buried Tanks	
	NaCl cover brine, no insulation	NaCl cover brine and Solexx insulating tank cover	NaCl cover brine	$CaCl_2$ cover brine
8	20	23	24	28
37	25	38	30	33

covered tank supplemented about 7 °F of heat compared to the buried and uncovered tanks, keeping the NaCl cover brine above the freezing point (30 °F), when ambient temperatures reached 23 °F (data not shown); but temperatures were not uniform across the tank height. Experimental data also shows that temperatures in the tanks containing cucumbers brined with $CaCl_2$ were 3–4 °F higher than those tanks with NaCl cover brine at an ambient temperature of 8 °F. Similar thickness of ice (3″) was observed at the top of the buried tanks regardless of the type of cover brine used. These observations suggest that increasing salt content in cover brines (up to 8% wt. NaCl) does not help to reduce ice formation. Studies show that thermal conductivity of the $CaCl_2$ (1.1% wt.) cover brine is similar to NaCl (6%wt.) (unpublished), indicating that tank configuration and insulation other than cover brine composition may be the main factors contributing differences in the internal tank temperatures observed.

During the hottest day (ambient temperature of 37 °F), the cover brine at the top of the covered tanks reached 48 °F; which was 13 °F

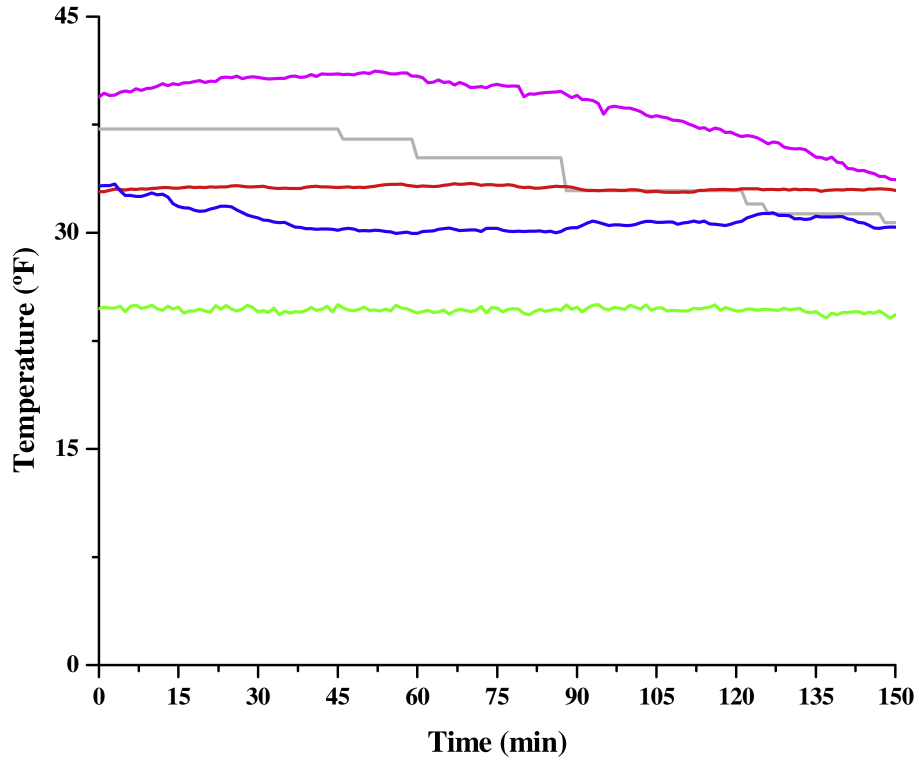

Fig. 3. Temperature history for different tank configurations: buried - NaCl cover brine (—), buried - CaCl2 cover brine (—), exposed - NaCl cover brine (—), and exposed - NaCl cover brine and Solexx cover (—) and ambient temperature of 37 °F (—) (01/23/2016).

and 21 °F above the temperatures in buried and uncovered tanks, respectively. The temperature at the middle of the tank remained at 32 °F, which is 3 °F below that in the buried and 10 °F above that in the uncovered exposed tanks (Fig. 3). Heat was lost at night in the covered and buried tanks with temperatures remaining at 26 °F, which is 3 °F above the temperature in the exposed uncovered tanks. Cold air infiltration on the cover structure may have driven heat loss. The buried tank with $CaCl_2$ cover brine showed a constant temperature of 33 °F. The minimum local temperatures occur near the tank surfaces, consequently inducing ice formation at the top of the tanks. Comparison of ice formation at the top of the $CaCl_2$ and NaCl cover brines at an ambient temperature of 28 °F in Pinconning,

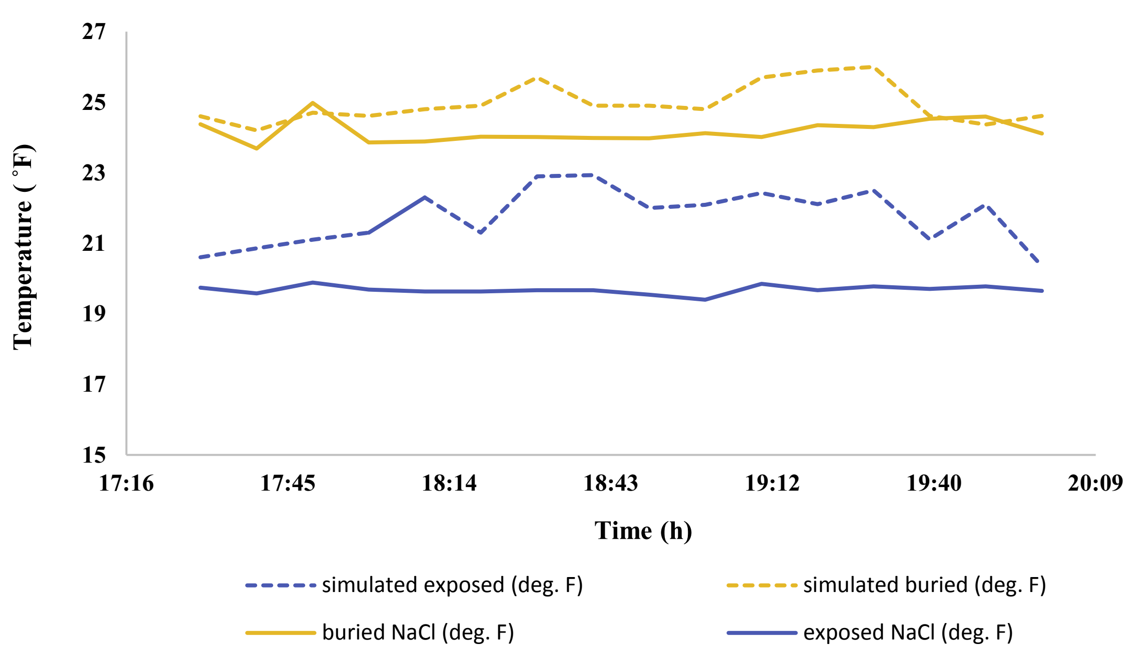

Fig. 4. Comparison between simulated and experimental temperature data: simulated buried ( ), buried - NaCl cover brine (—), simulated exposed ( ), and exposed - NaCl cover brine (—) at ambient temperature of 8 °F.

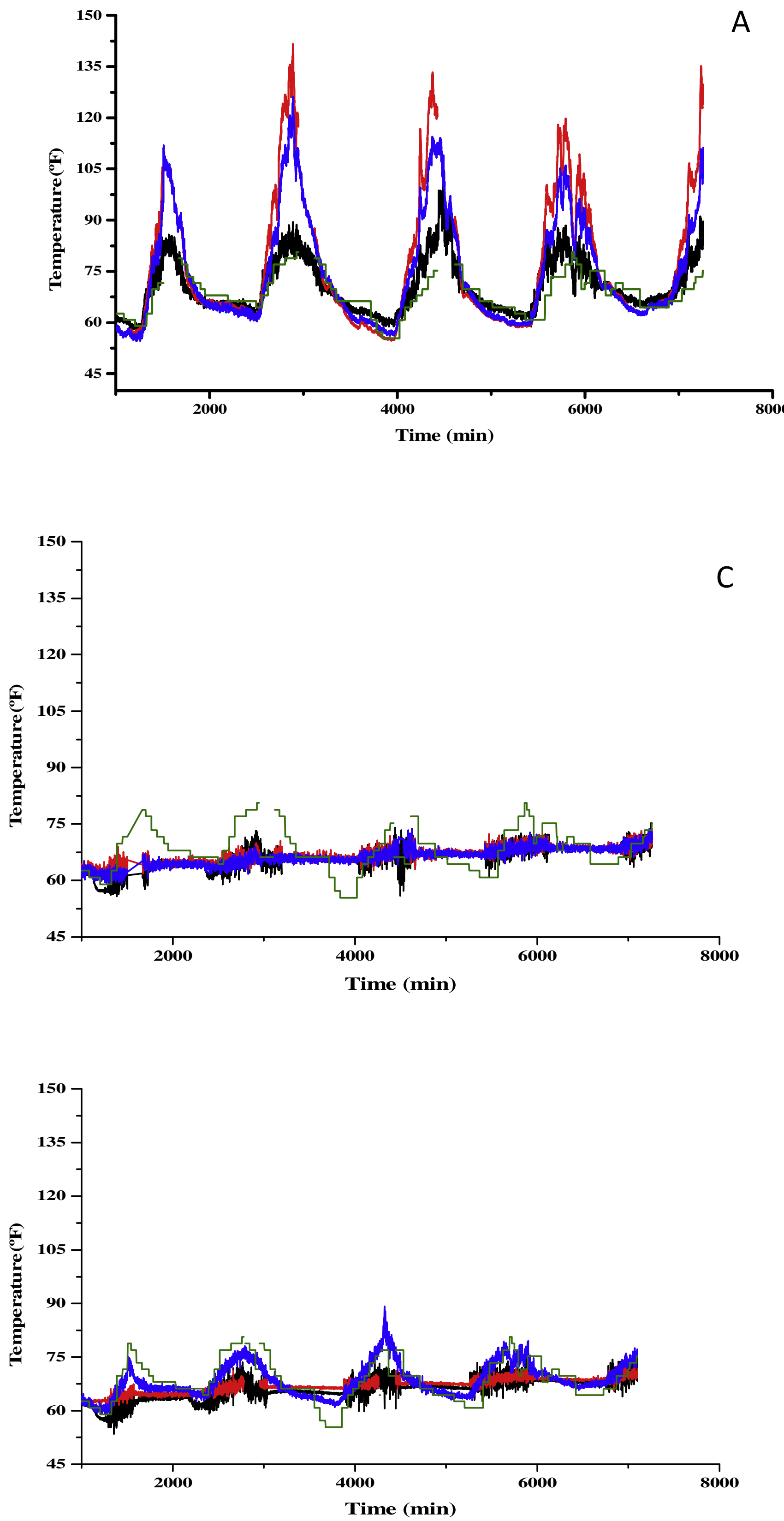

Fig. 5. Temperature history at the surface (A) center plane (B) and bottom (C) of the tanks: Open Top (—), Covered and Perimeter Insulated (—), and Covered (-); exposed at ambient temperature (—) in Mount Olive, NC.

MI showed no significant difference (~3″ and 2 ¾″, respectively).

Three commercial exposed tanks (uncovered, flat top-cover, and insulated perimeter) were examined at ambient temperatures of 31 °F and 68 °F in Mount Olive, NC. The data collected show that temperatures in the control tank was on average 53 °F, almost 10 °F below the completely insulated tank (data not shown). An increase in the in-tank temperature by 20 °F was obtained at ambient temperatures above 60 °F (Fig. 5), indicating that the insulation strategy can potentially enable an early or late winter fermentation.

A numerical model was developed to simulate temperature histories and to predict heat losses during storage of fermented pickles by iterative coupling of heat transfer with surface-to-surface radiation in COMSOL Multiphysics. Comparison between temperature histories obtained by modeling the temperature in the cover brine during the coldest day and experimental data is presented in Fig. 4. The simulated temperature was substantially higher as compared to the experimentally determined values. The difference between the experimental and the numerical temperature for exposed and buried was estimated to be about 3.4% and 1.7%, respectively; with the difference being primarily due to the variation in the solar energy and wind conditions. Thus, the reliability of the present model was validated by relatively positive agreement between the experimental and numerical values. The model was able to predict temperature changes during storage and was used to predict heat loss.

Heat loss calculations were simulated using the lowest and highest ambient temperature observed. Net heat losses for ambient temperature of 8 °F for uncovered, top-covered, and buried tanks were 3.05, 3.05, and 2.17 kW, respectively. A marked difference was observed for ambient temperature of 36 °F where the net heat losses were 1.42, 0.84, and −1.50 kW, respectively. The results show that buried tanks had an approximately 29% reduction in heat loss during the coldest day and heat gain at higher ambient temperatures. The top-cover prototype was able to reduce heat losses by 40% at higher ambient temperatures compared to the exposed, uncovered tank. An external source of energy will be required to compensate for heat loss and to guarantee uniform temperatures in the tank when temperatures are at or below 8 °F.

4. Cost estimate

Estimated cost for the insulated conical top (179 ft^2, 100 lb), conical top (164 ft^2, 45 lb), flat top (78.5 ft^2, 30lb), and insulated perimeter (678 ft^2) were $1000, $700, $400, and $800 plus labor, respectively. The strategies explored were more economical than a commercial fiberglass dome (~$2,400, 350 lb). The potential advantage of using an inexpensive and resilient cover to reduce the release of solar heat gained during the day was promising, but further investigation is needed to obtain an optimized cover design. Preliminary data suggest that an external energy input (e.g. by using submersible heating elements) of approximately 30 kWh/tank/day is necessary when temperatures are at or below 8 °F.

5. Conclusions

- In tanks exposed to same weather conditions, temperature variations in the cover brine were caused by the type of tank configuration and insulation strategy.
- Top-cover insulation could potentially reduce ice formation and minimize heat loss in the cover brine.
- The modeling tool allowed prediction of the temperature history inside the tanks and heat loss during storage.

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