Melt System for a Countertop Water Treatment Appliance using Directional Freeze Crystallization

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ABSTRACT

Consumers spend more than $3 billion annually for alternatives to drinking tap water. Directional Freeze Crystallization (DFC) technology makes it possible to meet this need with low maintenance, energy efficient drinking water appliances. DFC uses conventional vapor compression refrigeration and does not require consumable filters or membranes. In an appliance, tap water fills a chamber and about half the water is purified via freeze crystallization. The unfrozen portion is discarded and then the ice is melted for drinking. A key element of DFC is the melting system, which must be compact, reliable, efficient, and must not overheat the melted water.

This paper describes the design and operation of a novel melting system for a countertop appliance employing DFC. An ice crystal grows downward from a horizontal freeze plate into a water filled tray. After the concentrated waste water is drained from the tray, the ice falls onto a melter bar mounted in the tray. Heat from the melter bar splits the ice into two pieces. The ice pieces are then directed against both sides of the melter bar by inclined rails. Experimental data from an instrumented prototype of the appliance are presented to show the performance of the melt system.

INTRODUCTION

Previously, we described Directional Freeze Crystallization (DFC) methods that could lead to new drinking water appliances [1,2]. Potential applications include refrigerator water dispensers, bottleless water coolers, built-in appliances, and portable appliances. The DFC method purifies water by alternately freezing and thawing a fraction of the feedwater. DFC uses conventional vapor compression refrigeration equipment in an optimized batch process. By using reliable, proven components, and avoiding replaceable filters or membranes, the DFC method is ideally suited for drinking water appliances.

Freeze crystallization is a separation method for purifying or concentrating liquids. It works on the differences in solubility of impurities between liquid phase water and solid phase ice. Typically, contaminants are one to two orders of magnitude more soluble in the liquid phase than in the solid phase. When applied to drinking water appliances, freeze crystallization has some particular advantages.

- **Performance** — Crystallization removes high percentages of a wide variety of contaminants without the need for expendable filters or membranes.
- **Reliability** — Cooling is provided by conventional household type refrigeration systems.
- **Efficiency** — Freezing uses only one-seventh as much energy as boiling, and heat can be recovered to melt the crystals.
- **Water Temperature** — The melted crystals are prechilled, and drinking water can be readily kept cold within an insulated appliance.

Water is treated by the DFC process in a batches [3] as shown in Figure 1. DFC operates in a repeating sequence of four steps.

- **Fill.** A chamber is filled with the water to be treated.
- **Freeze.** A refrigeration system freezes about half of the water, concentrating the impurities in the unfrozen fraction.
- **Drain.** The unfrozen water is drained from the chamber.
- **Melt.** The frozen, purified, ice is melted.

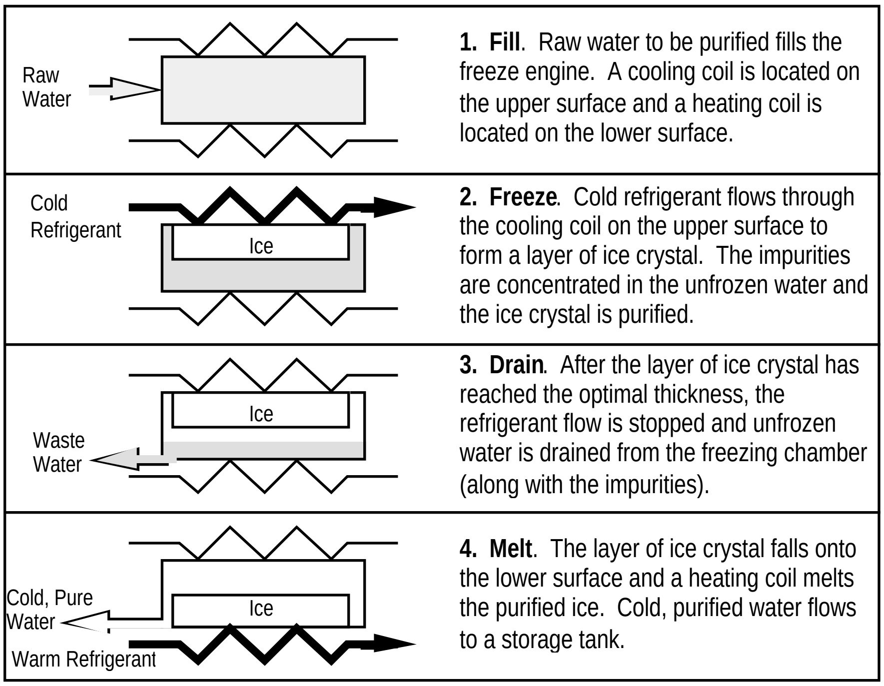

Figure 1. Directional Freeze Crystallization sequentially repeats four steps (Fill, Freeze, Drain, Melt) to separate impurities from water.

IMPLEMENTATION

The DFC process is implemented with three major systems as shown in Figure 2: a vapor compression refrigerator, a “Freeze Engine,” and a control system. The Freeze Engine is central system, and is where the water treatment takes place. The Freeze Engine consists of a Freeze Plate, Freeze Tray, and Valve Assembly. The Freeze Plate is the evaporator of a conventional refrigeration system, and the ice crystals are grown downward from the plate. The Freeze Tray holds the water to be treated, and includes a melt system to melt the ice crystal. The Valve Assembly directs water into and out of the Engine.

The control system sequences the valves, compressor and melter. The refrigeration capacity, Freeze Engine dimensions, and refrigerant evaporation temperature are matched to maximize the production capacity [4]. Previous papers have focused primarily on the freezing step, describing the optimal refrigeration characteristics and the factors that influence the growth of high quality ice crystals. This paper addresses the melting aspects of the DFC process, including analysis, design and operation of a melt system for a countertop appliance.

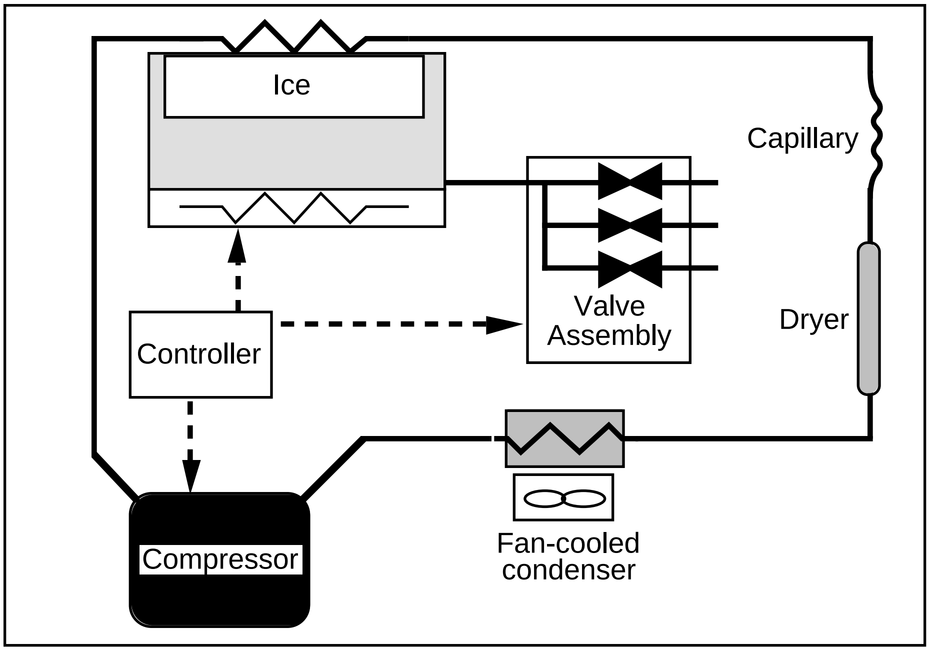

Figure 2. The DFC process is implemented with a conventional vapor compression refrigeration system. The "Freeze Engine" is where the directional freeze crystallization occurs. A controller sequences the valves, compressor and melter.

PRODUCT DEFINITION

To provide a context for the development of a melt system, some background information on the target product configuration is useful. Our market research indicated there was an attractive opportunity for a drinking water appliance with the following characteristics.

- **Low Maintenance.** Consumers prefer not to change filters or membranes.
- **Capacity.** Production capacity should be sufficient for a typical American family's daily needs.
- **Water on Demand.** A storage tank should be large enough to provide a buffer to meet instantaneous demand for water, based on typical daily usage patterns.
- **Cold Water.** Consumer preferences indicated that treated water should be chilled.
- **Easy Installation.** To reach consumers through a variety of retail channels, easy installation, without tools was an essential element.

We determined that a portable countertop kitchen appliance, employing DFC, would satisfy these basic requirements. This appliance, illustrated in Figure 3, would have the following key features.

- **Capacity.** Usage studies identified the needs of typical families and their consumption patterns. We concluded that a daily production capacity of three gallons, and a storage tank of 1.5 gallons would be satisfactory.
- **Cost.** To reduce cost, drainage of waste and product water, and dispensing of chilled water would be by gravity.
- **Dispensing.** To easily fill tall glasses, pitchers and stock pots, the bottom of the storage tank is approximately 10 inches above the countertop.
- **Size.** To compete for counter space, the product must have the smallest possible footprint. After consulting with retailers, we targeted a 12 inch square maximum plan. The typical distance from countertop to cabinets is about 18 inches. To assure that the product fit on non-

standard countertops, a maximum height of 15.75 inches was selected.

- **Efficiency.** We found that consumers were more sensitive to first cost than operating costs. Rather than recover the latent heat of fusion from the freezing step, an electric resistance heater was selected. Even so, operating cost would still be only one-third of an electric distiller.
- **Conservation.** We found that consumers are moderately sensitive to water consumption, more so during droughts. We targeted conversion of fifty percent of incoming water into product. This compares favorably to typical residential reverse osmosis systems (10 to 20%) and still provides room for future improvement.

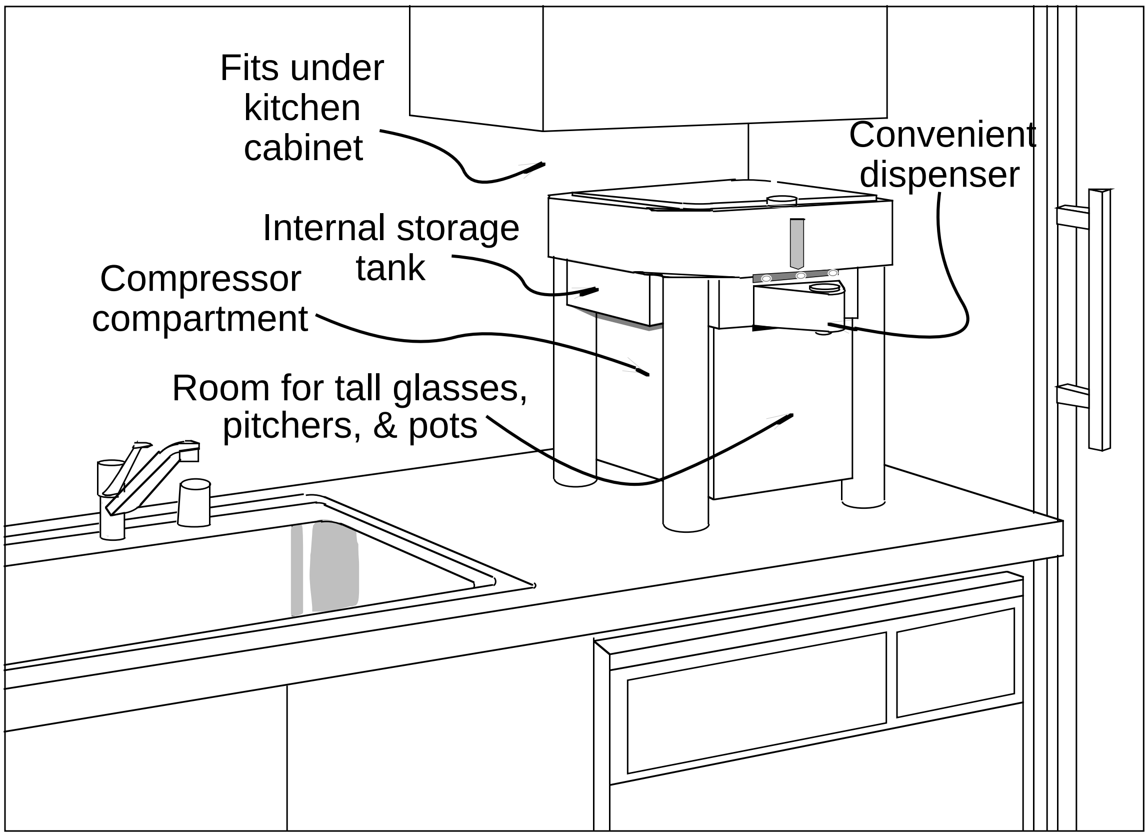

Figure 3. A portable appliance employing DFC would fit on a countertop under kitchen cabinets, and conveniently dispense cold water.

MELT SYSTEM REQUIREMENTS

A basic function of the Freeze Engine is to melt the purified ice after it detaches from the Freeze Plate. Within the above context, we identified specific requirements for the melt system.

- **Space.** Compactness of the melt system is essential. Thermal insulation under the Freeze Tray must be very thin while minimizing leakage of heat to the Storage Tank.
- **Product Temperature.** The product water must be dispensed cold, so the ice must be melted without heating water excessively.
- **Efficiency.** Most of the heat must be used for melting ice. Heating of the water or components wastes heating energy and increases the energy to be removed during the freezing

step.

- **Assembly/Service.** The heater element should be easy to install and replace without extensive disassembly. There should be excellent thermal contact between the heating element and the Freeze Tray. Adhesives or thermal greases used for attachment or heat transfer should last for the lifetime of the appliance. They must also be free of odors that could impart an adverse taste to the purified water.
- **Growth Path.** It is desirable to develop a melt system that can use a variety of heat sources for melting. Electric heating has the advantage of being cheap and easy to control, with a wide variety of elements available commercially. However, recycling the latent heat of fusion reduces energy use. Ideally, a melt system would be readily adaptable for either approach.

ANALYSIS OF UNIFORM ICE MELTING

Figure 3 illustrates the melting of a uniform ice sheet in a Freeze Engine. In the figure, the ice is resting on the Freeze Tray after detaching from the Freeze Plate. The heat source is assumed to be uniformly distributed on the bottom of the Freeze Tray, and to have the same cross-sectional area as the Freeze Plate. The heat source provides a gentle warming through the bottom of the tray to melt a liquid film on which the ice is resting. The inner surface of the tray is slightly inclined so the liquid film drains away as the ice melts.

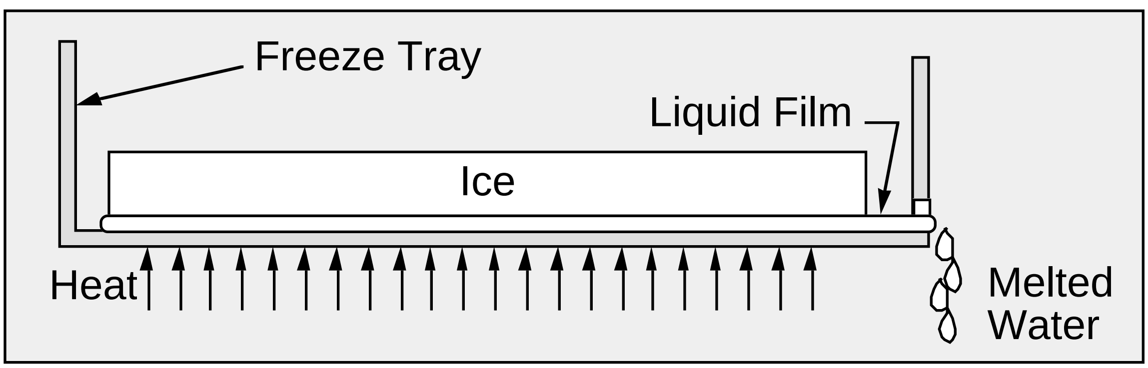

Figure 4. Melting of purified ice by a uniform heat source on the bottom of the Freeze Tray.

Melt Time. The time required to melt the ice is given by

$$\theta_{melt} = \rho_s \bullet A \bullet \Delta x \bullet h_{fs} \div q_{melt} \quad (1)$$

where,

q_{melt} is the heat addition capacity of the melting device
Δx is the ice thickness,
A is the area of the freeze plate,
ρ_s is the density of the solid ice
h_{fs} is the latent heat of fusion of the ice.

Melt Rate. The rate at which the ice is melted is given by

$$Q_{melt} = q_{melt} \div [h_{fs} \bullet \rho_s] \quad (2)$$

where,

Q_{melt} is the volumetric flow rate of melt water.

Heat Conduction. Heat is conducted from the heat source on the lower side of the tray, through the tray, across the liquid film, and then to the ice surface. The rate of heat flow is governed by the heat conduction equation.

$$q_{melt} = U \bullet A \bullet \Delta T \qquad (3)$$

where,

U	is the overall conductance,
A	is the surface area through which the heat is flowing,
ΔT	is the temperature difference across which the heat is flowing.

The conductance is defined as

$$U^{-1} = \Delta x_t \div k_t + \Delta x_f \div k_f \qquad (4)$$

where

Δx_t	is the thickness of the tray,
k_t	is the thermal conductivity of the tray,
Δx_f	is the thickness of the liquid film, assumed to be 0.031 inch,
k_f	is the thermal conductivity of the film.

Melt System Temperatures. The ice-water interface is always 32°F, and the conductivity of the liquid film is fixed, 0.319 Btu/ft-hr°F. The film thickness depends on surface tension and the rate of drainage, which is proportional to the slope of the Freeze Tray. The temperature at the tray-heater interface depends on the thickness and thermal conductivity of the Freeze Tray. To evaluate the possibility of injection molding a plastic Freeze Tray, several temperature profiles were calculated. For the Tray, a thickness of 0.1 inch and a thermal conductivity of 0.85 Btu/ft-hr-°F were assumed. The thickness of the liquid film was assumed to be one thirty-second inch. The temperature profiles are shown in Figure 5 for power densities ranging from 2.5 to 5 watts per square inch. The tray surface temperatures were predicted to be within the material limits for thermoplastics.

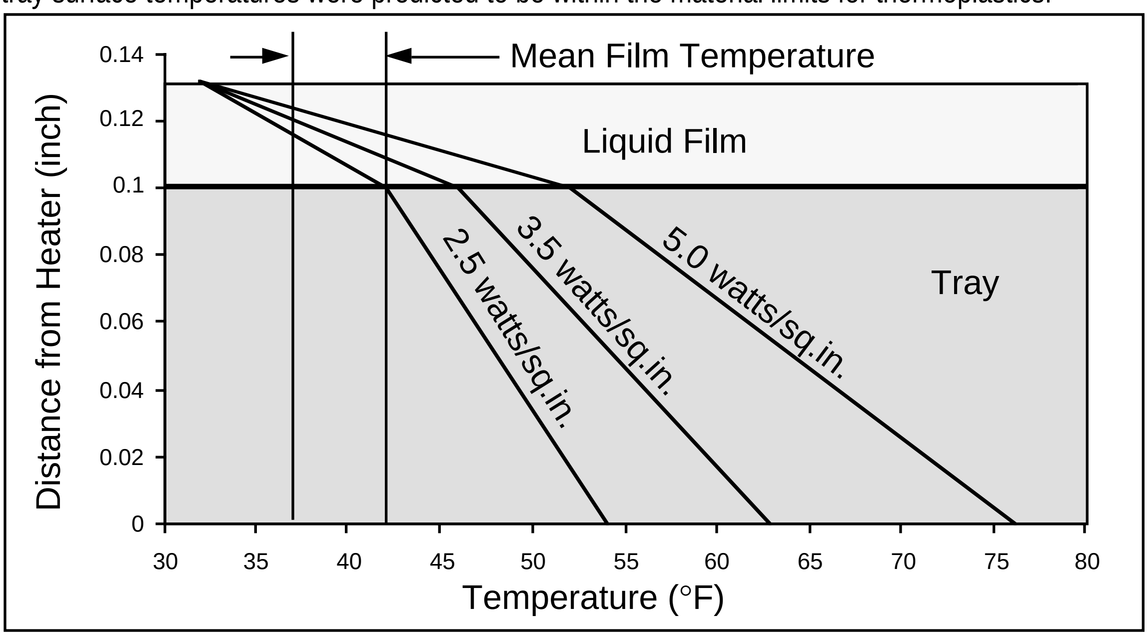

Figure 5. Temperature profiles for uniform melting of ice sheets. The mean film temperature increases from 37°F to 42°F as the power density is increased from 2.5 to 5.0 watts per square inch.

Melter Efficiency. The efficiency of the melt system is measured by how much energy is used for melting ice rather than heating melter components and water. Neglecting the sensible heat imparted to the Freeze Tray and the ice, the efficiency of the melter would be

$$\eta_{melt} = h_{fs} \div [h_{fs} \bullet c_p \, \Delta T_{sensible}] \qquad (5)$$

The temperature of the melted ice is approximately the average of the temperatures at the ice-water and tray-water interfaces. For the assumed materials, the mean liquid film temperature is predicted to be approximately 40°F. The sensible heat addition is 8 Btu per pound, and the melt efficiency would be 95%.

NON-UNIFORM ICE

Several factors lead to non-uniform ice thickness, rather than the ideal ice sheet analysed above.

- **Heat Gain.** Heat gain into the Freeze Engine from the outside slows the ice growth around the periphery of the Freeze Plate.
- **Evaporator Pattern.** Ice growth is fastest directly underneath the refrigerant. Although the flow path can compensate for peripheral heat gain, truly uniform growth is difficult to achieve.
- **Refrigerant Charge.** Variations of the refrigerant charge due to leakage, under charging, capillary tube variances, or ambient temperature changes may cause part of the Freeze Plate to be underutilized.

Non-uniform ice affects the design and operation of an electric melt system in the following ways.

- **Contact Area.** When the ice detaches from the Freeze Plate and lands on the Freeze Tray, the contact area is a fraction of the Freeze Plate area. Since heat can be delivered only to the portions of the ice in contact with the Tray, the effective melt power must be reduced.
- **Contact Location.** The thickest section of the ice sheet may vary depending on the refrigerant charge. Since the initial contact point can change over the life of the product, a control system must be robust enough to respond to systematic changes.
- **Control.** A melt system power controller regulates temperature and determines completion of the melt step. With uniform ice, a single temperature measurement may control the heater power. With non-uniform ice, the melter power must be limited to avoid overheating the areas not in contact with the ice. This could be achieved by dividing the melter into zones, each zone being controlled by a temperature sensor, or by using a self-regulating heater. However, these approaches are complex and expensive.

NON-UNIFORM MELT SYSTEM

A novel melt system was developed to deal with non-uniform ice [5]. Rather than distribute the heat source uniformly, the heat is concentrated. Figure 6 shows a cross-section of the Freeze Engine and the stages of the melting process. After the waste water is drained from the Freeze Engine, the ice sheet detaches from the Freeze Plate and lands on a melter bar. A heat source within the melter bar melts the ice sheet, which splits into two pieces. The ice pieces then are directed by inclined rails against the sides of the melter bar. As the ice melts, the product water drains along a trough to the water outlets on either side of the bar. A temperature sensor is located underneath the melter bar to sense the temperature and control an electric heating element.

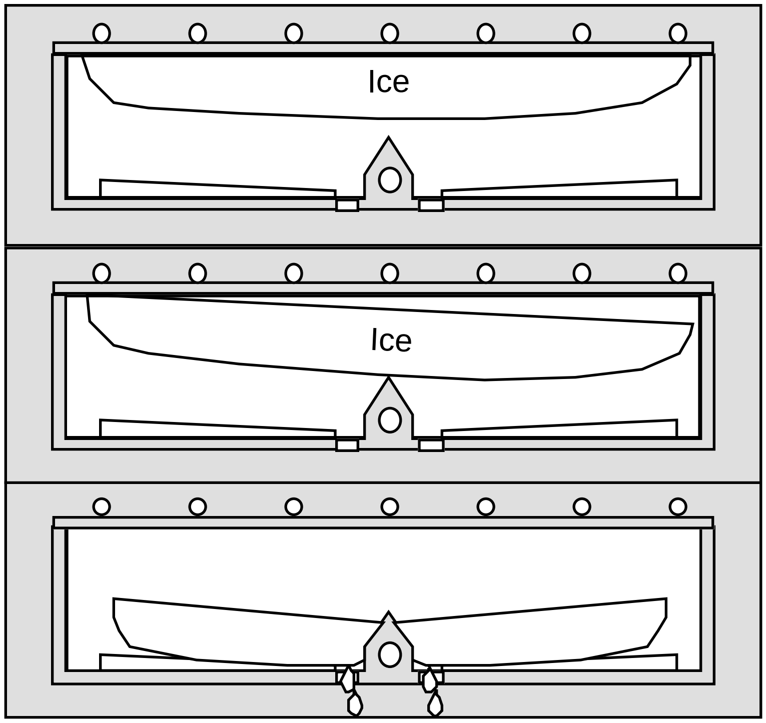

Figure 6. After detaching from the Freeze Plate, the ice sheet is split by the melter bar, and then is directed against the sides of the melter by inclined rails.

There are several distinctive features of this melt system.

- **Concentrated Heat.** Rather than disperse the heat, as in the idealized analysis, a concentrated heat source was employed. This heat source is a melter bar running along the centerline of the Freeze Tray. When the ice sheet detaches from the Freeze Plate, the ice is split into two pieces by the melter bar.
- **Inclined Rails.** After the ice is split into two pieces, the ice pieces are supported by inclined rails, which induce the pieces to slide toward the melter bar.
- **Drain Troughs.** Along either side of the melter bar is a drain trough. As the ice pieces are melted, the liquid collects in the drain trough which directs the purified water to the drain port.

This melt system has several advantages over the distributed melting system.

- **Large Contact Area.** The melter bar is in contact with a large surface area of ice, independent of the uniformity of ice thickness or the location of the thickest section.
- **Robustness.** The melt system is insensitive to the location of the thickest ice, or the refrigerant charge.
- **Controllability.** Because the heat source is concentrated, a single temperature measurement is sufficient to control the electric heater.
- **Compactness.** By concentrating the heat source, thermal insulation is needed only immediately below the melter bar. This allows more space to be used for water storage.
- **Efficiency.** The ice is in contact with both sides of the melter bar. This promotes efficient melting by minimizing the heater surface temperatures and the differential from one side of the heater to the other.
- **Cost.** A low cost tubular heating element can be used instead of more expensive flat heaters.
- **Assembly and Service.** The heating element can be easily inserted into the Freeze Tray, and can be replaced without removing the Freeze Tray from the appliance.

- **Adaptability.** The tubular heating element in the melter bar can be replaced with tubes containing condensing refrigerant or heat transfer fluids.
- **Purity.** A much smaller percentage of the Freeze Tray surface is contacted by ice than with the idealized melter. The ice is in contact only with the rails and the melter bar, rather than the entire surface of the Freeze Tray. This reduces the possibility of re-contamination of the treated water through contact with residual drops of waste water.

MECHANICAL IMPLEMENTATION

Figure 7 shows a top perspective view of the freeze tray with the integral melter bar and inclined rails. The key features of each component are described below.

Freeze Tray. The freeze tray is approximately 26.5 cm long by 26.5 cm wide by 3 cm deep. The surface of the freeze tray is pitched toward the melter, and the drain troughs are pitched toward the drain ports. The angle of inclination is sufficient to assure complete drainage, allowing for manufacturing tolerances and mounting on imperfect surfaces. A smooth, non-wetting surface was used to assure complete waste water drainage.

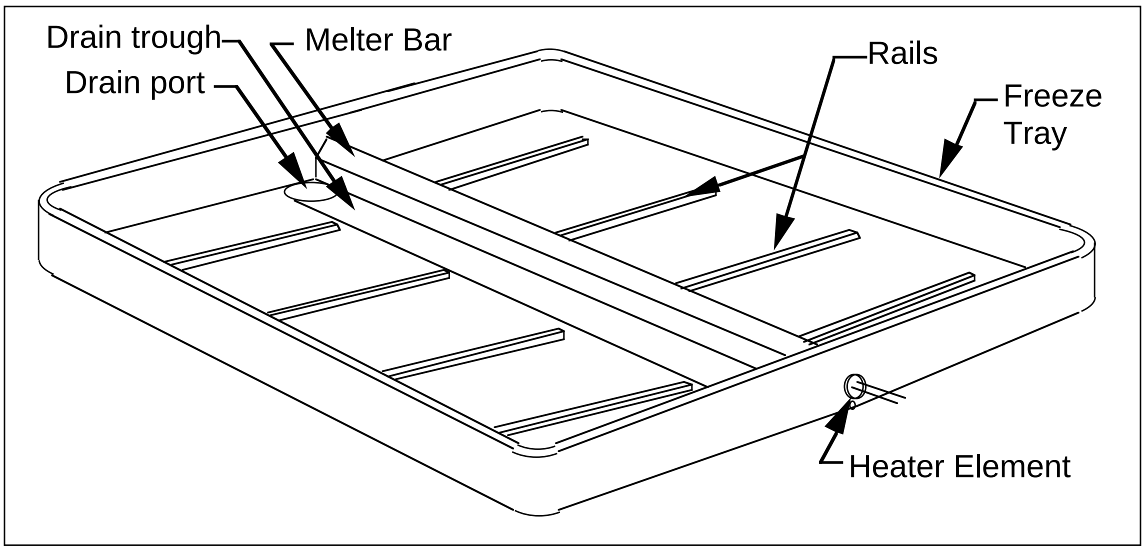

Figure 7. The melter is an integral part of the Freeze Tray. Inclined rails guide the ice sheet against a melter bar which contains a heating element. Melted water flows along the drain trough to the drain port.

Melter Bar. The melter bar protrudes from the surface of the Freeze Tray far enough to allow the ice sheet to split into two pieces. For example, if the ice thickness is one cm, the melter bar must be somewhat higher than one cm. The heat source is located within the melter bar in a cylindrical bore. The heating element is inside the melter bar, and is in intimate contact with the melter.

Inclined rails. Inclined rails are arranged perpendicular to the melter bar, on both sides. As shown in the figure, the rails are an integral part of the freeze tray. The rails are inclined a few degrees from the horizontal to overcome static friction, to accommodate manufacturing tolerances, and to assure operation on uneven countertops. The rails begin at the trough, and extend away from the melter to slightly past the center of balance of the broken ice piece. This assures that the ice rests on the melter bar, rather than on rails, so the ice sheet splits rapidly into two pieces. By supporting the ice above the surface of the Freeze Tray, contact with residual impurities is minimized. To reduce retention of impurity laden waste water by surface tension, the intersections of the rails with the surface of the Freeze Tray are radiused.

OPERATION

Melting occurs as a sequence of steps.

- **Heat-up.** As the waste water is drained from the Freeze Tray, the melter bar is heated to its set-point. With an electric heat source, power is controlled to regulate the temperature of the melter bar. Throughout this step, the waste water valve is kept open.
- **Detachment.** When the ice detaches from the Freeze Plate, it lands on the melter bar and the temperature decreases. The first droplets of melted ice rinse the melter bar and drain trough, and then the waste water valve is closed and the product water valve is opened.
- **Melting.** The ice pieces melt against the sides of the melter. Droplets of purified water run down the melter, along the drain troughs, through the ports to the product water valve and into the product storage tank. As the ice melts, the ice pieces slide toward the melter until most of the ice has been melted.
- **Completion.** The heating element is regulated at the setpoint until the last pieces of ice are melted. At the end of this last step, the product drain valve is closed and the Freeze Engine can be filled for another batch.

APPARATUS

An engineering prototype of the countertop appliance was fabricated to test the melt system. This prototype included a 1/12 horsepower compressor and fan cooled condenser. A Freeze Engine and Storage Tank were enclosed within urethane foam for thermal insulation. A small circuit board contained a microcontroller and interfaces to drive the compressor, valves, and heater, as well as level and temperature sensing. The prototype was extensively instrumented with thermocouples connected to a Stanford Research Systems Model 630 16 channel scanning temperature monitor.

The Freeze Engine had a capacity of approximately 1.65 liters in a tray similar to Figure 7. The tray was made from an aluminum casting and coated with a low surface energy food grade polymer. A 165 watt cartridge heater was inserted into the bore within the melter bar. A negative temperature coefficient thermistor, thermocouple, and a thermal cut-out were mounted on the underside of the Freeze Tray, directly under the melter bar. The thermistor was connected to a comparator on the circuit board with an adjustable temperature setpoint. A thermal cut-out was provided for safety protection. The general heater control system is shown in Figure 8. Power was measured in 3 watt-hour increments using a General Electric Model AR-3 watt-hour meter and computerized stopwatch. The melt flow rate was obtained by periodic sampling at intervals ranging from two to four minutes, depending on flow rate. Temperature measurements were recorded at 90 second intervals.

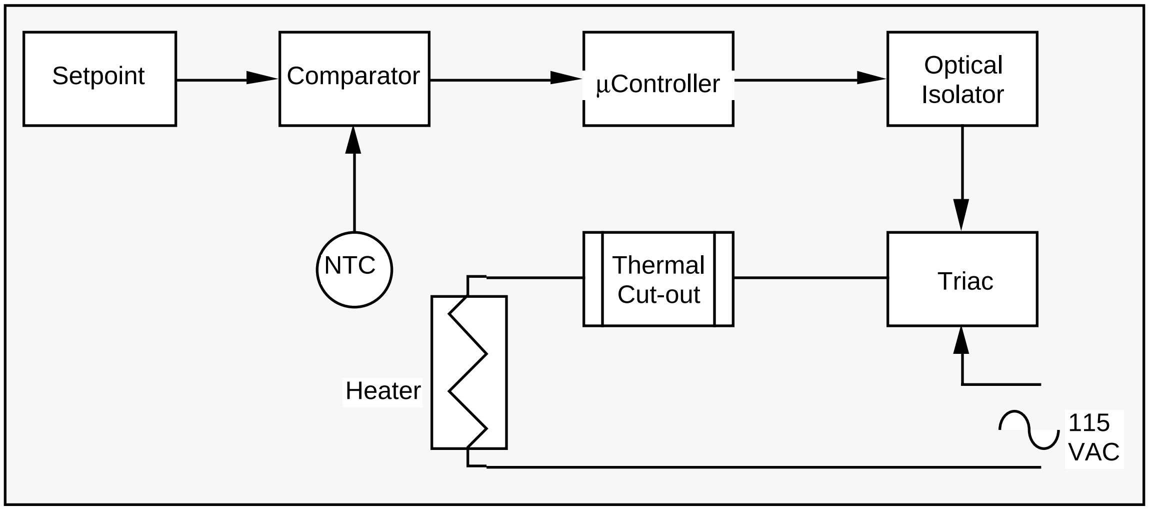

Figure 8. The prototype melter was tested with a temperature controller. A negative temperature coefficient thermistor (NTC) was attached to the bottom of the Freeze Tray to control the melter temperature.

TEST RESULTS

The prototype was extensively tested to verify operation of all components and the controller software. In Figure 9, we show results for one melt step, with curves of temperature, power, and flow rate as a function of time. For this test, the prototype was operated entirely by the microcontroller, including filling, freezing, draining and melting. Before this test, the prototype had operated continuously for several days, so an equilibrium temperature cycle had been established throughout the prototype.

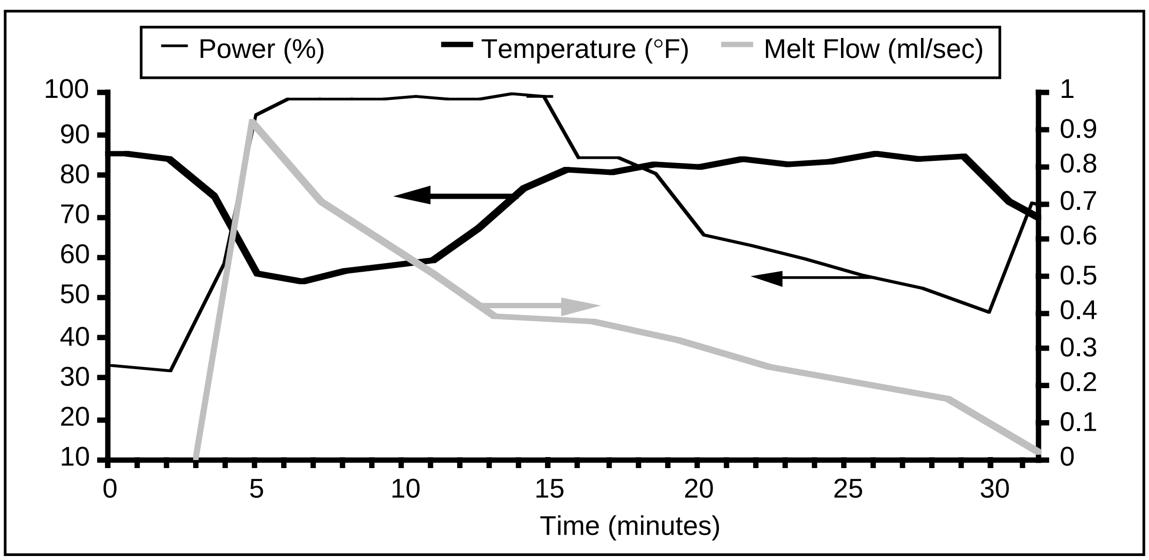

Figure 9. Melt system Temperature, power and flow rate, with 168.75 watt heating element. After the ice detached from the Freeze Plate, the melter bar was rapidly cooled, and product water began to flow.

Before the melt step commenced, the waste water was drained from the Freeze Engine, and the heater was energized causing the melter to reach the setpoint of 85°F. When the ice detached from the Freeze Plate, the melter was rapidly cooled, and the heater power increased in response the applied load. The ice sheet quickly split into two pieces and fell onto the rails with a slightly audible “clunk.” The initial flow rate was very rapid as stored energy was removed from the melter bar. During the first two minutes after ice detachment, the flow rate was equivalent to a heater power of about 310 watts — almost twice the actual power.

Since the ice is thinner near the edges of the Freeze Plate, the amount of ice in contact with the melter decreases as melting progresses. This is shown in the data during the next ten minutes, as the rate of ice melting slowly decreased and the melter temperature slowly approached the setpoint. Subsequently, the temperature remained near the setpoint, until the ice had melted completely. The power increase at the end of melting was caused by the compressor turning on as the controller began another cycle. The average melt water temperature was measured to be 56.1°F. Based on equation (5), the melter efficiency is 86%, which compares favorably to the idealized case.

CONCLUSION

Directional Freeze Crystallization has potential to create a new class of drinking water appliances. A key prerequisite to commercialization of DFC technology is the development of robust, reliable, and efficient melt systems. A novel melt system for a countertop drinking water appliance has been developed and tested. Test data show the melt system to be 86% efficient. This melt system is easy to control, robust, and insensitive to variations in ambient conditions or refrigeration system performance. Because of its compactness, it is well suited to countertop appliance applications. The melt system is also readily adaptable to a variety of heat sources, including electric heating and heat transfer fluids.

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