“New and Novel Freezing and Cooling Technologies”

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Abstract

Unilever is aiming to decrease its environmental footprint and is looking for a novel cooling and freezing method that does not require external power and can be used globally. The proposed solution is a refrigerator based on the concept of evaporative cooling. As water evaporates, energy is absorbed, cooling the system. In this design, a layer of wet sand is placed between the outer and inner walls of the fridge. The water in the sand evaporates, leaving the inside of the fridge cool. To maximize efficiency, a water irrigation system, an airtight door and vents are components of this device. This design of a non-electric fridge provides an innovative solution to this problem, and is a step in the right direction for Unilever to reach their goal of becoming carbon positive.

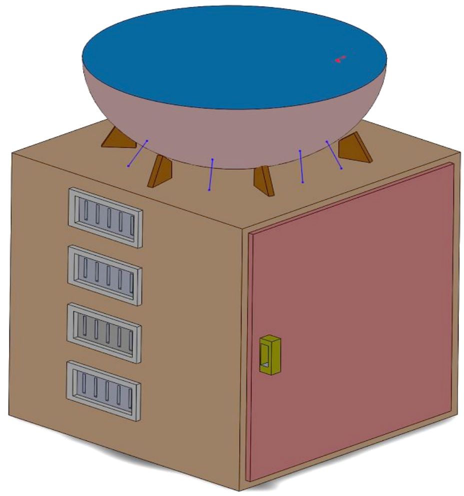

Figure 1: CAD drawing of fridge design

Background of Problem

Carbon pollution is a growing concern that pushes companies to develop more environmentally-friendly technologies. Unilever is seeking a new and revolutionary method to cool and refrigerate without the use of electricity or other forms of external power. As they aim to become carbon positive by 2030, Unilever has developed the challenge of creating a method of refrigeration to maintain low temperatures of -18 degrees Celsius with no grid supply.

Refrigeration is mainly used for preservation of food and is an essential aspect of food safety. However, cooling and freezing techniques are currently dependent on different types of power supplies. This reliance on external power can be unsustainable and minimally effective in areas with either intermittent or no access to power. The development of a globally viable, powerless refrigeration system would truly revolutionize the industry, and lead to a cleaner, healthier planet.

Theory

Evaporation

The principles of evaporation are at the core of this design, and it is this process that causes the interior of the fridge to decrease in temperature. The fridge will have a layer of sand, which will initially be soaked, surrounding the interior of the fridge. As shown in the sketch, the moving air around the system causes water in the sand to evaporate.

The molecules of water are in constant motion, and collide frequently. Through a series of collisions, molecules at the surface will gain enough kinetic energy to overcome the intermolecular forces, causing the molecules to evaporate out of the system. As kinetic energy continues to leave the system through evaporation, the system will decrease in temperature, allowing the interior of the fridge to become colder. This process is similar to sweating, the body's natural cooling system. As a body heats up, it sweats, moving moisture to the skin and exposing it to air. As sweat evaporates, the body is cooled as energy is taken away by the endothermic evaporation process.

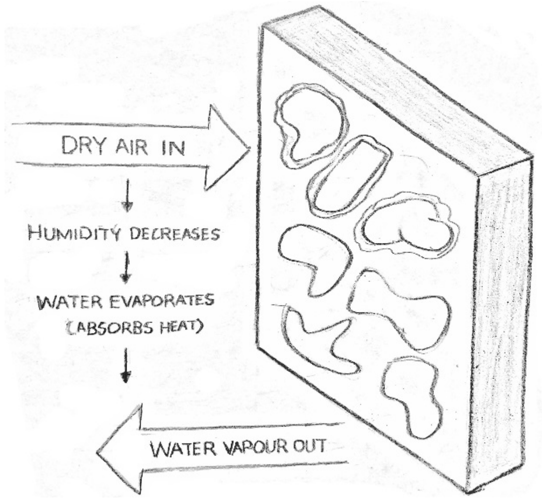

Figure 2: Sketch of evaporation process

Wet Bulb Temperature

The wet bulb temperature is a property of air that is related to the ambient temperature and relative humidity of the surrounding air. It is the minimum temperature attainable through the evaporation of water. The higher the ambient temperature and relative humidity are, the higher the wet bulb temperature will be, resulting in an evaporative process which does not significantly decrease the temperature in the fridge. The optimal conditions for the lowest wet bulb temperature occur when the ambient temperature and relative humidity are lowest. Since this property will greatly impact the performance of the fridge, the placement of the fridge must be observed carefully to gain the most cooling from the device.

Surface Area and Volume

In this design, for the process of water evaporation, surface area is the amount of sand saturated with water which is exposed to the air. Since the outer layer is permeable to air, the surface area then becomes dependent on its shape. Volume is the amount of space contained in the fridge which must be cooled. Given these parameters, the fridge will work best if the surface area is maximized and the volume is minimized, meaning there will be more evaporative surface per unit of volume. The size, shape, and material of the fridge are factors that must be considered to maximize the surface area to volume ratio.

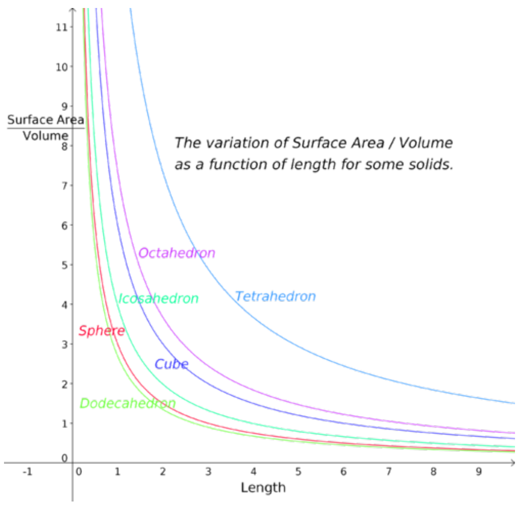

Figure 3

Source: http://rebuildingcivilization.com/sites/default/files/500px-Surface-area-length.png

As the graph (Figure 3) shows, a tetrahedral shape is the most optimal, but a cubic shape was chosen because of its practicality and its relatively high surface area to volume ratio.

Design

Box Design

The fridge was designed to be a cube since it provides an ideal surface area and volume ratio allowing for a greater surface for evaporation to take place without sacrificing usable space to store items. In addition, the cubic shape mimics the regular frame of the electric fridge and serves as a practical storage unit for consumers. The material used for the outer box is earthenware clay. This material is porous allowing evaporation to take place within the surface. The porous properties effectively raises the evaporative surface area as it is permeable to both water and air. Earthenware clay also provides good insulation to retain the cool air inside the fridge.

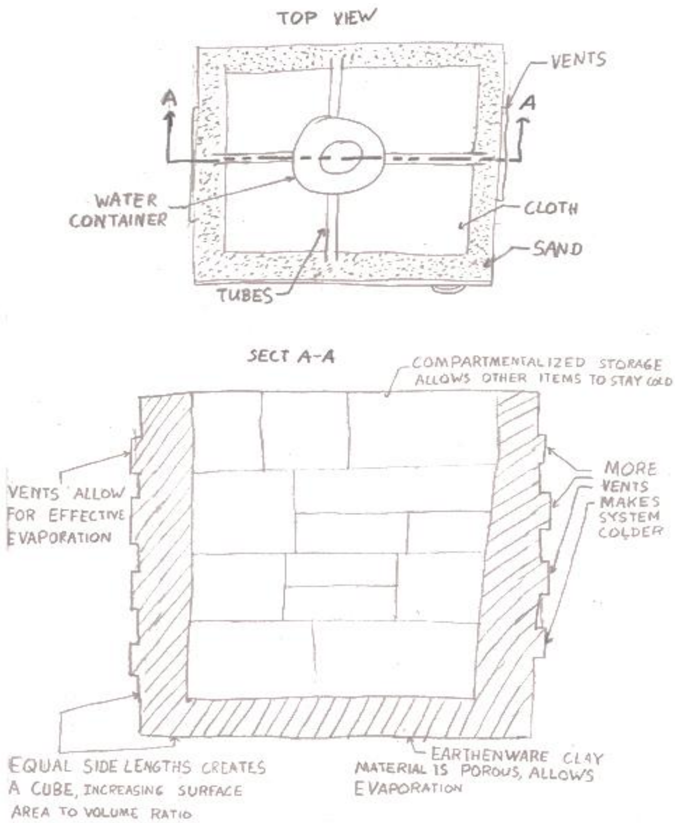

Figure 4: Cross sectional view of fridge

Furthermore, the box is designed with vents on the surface which leave the moist sand exposed. The purpose of the vents are to allow for the direct contact between the moist sand and outside air. This will improve the rate of evaporation and the overall rate of cooling of the fridge. When the design was tested, it was found that the number of vents greatly affected the cooling temperature and allowed for the inside to be colder.

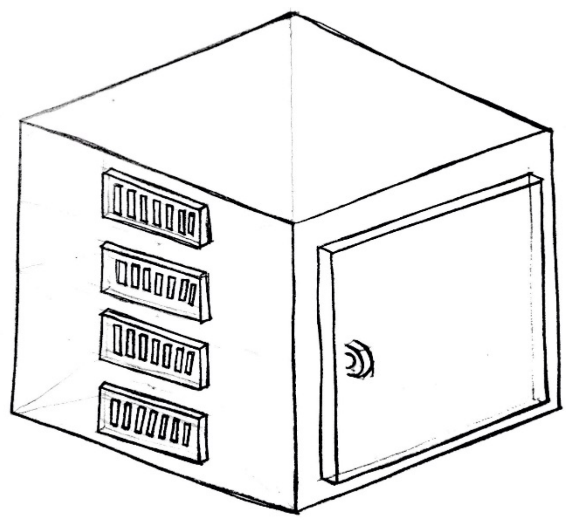

Figure 5: Sketch of the box design

Door Mechanism

The door is a very important part of the design as it will enable the inside of the fridge to stay cool. To prevent cool air from escaping, the door must be airtight, which is why a lever mechanism is used in this design. This mechanism compresses the door onto the inner surface, creating an airtight seal when the door is closed. In addition, there will be door liners made of plastic to further enhance the seal and also to reduce noise whilst the door is closing.

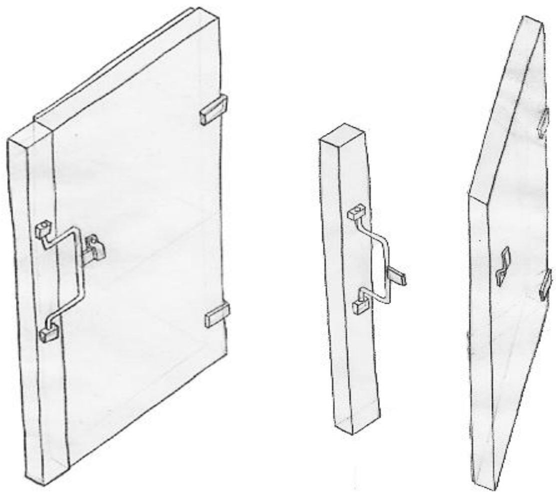

Figure 6: Sketch of Door

Water Absorption

The presence of sand in this fridge is imperative to the evaporation of water and to the resultant cooling. Sand is placed in the empty space between the two boxes, around and under the inner compartment. Water is poured into this area until the sand has reached maximum water capacity. Sand is used because of its relatively high surface area, a factor crucial to the rate of evaporation. This relationship also explains why the sand should be fully saturated, as this maximizes the area in which water will be exposed to the air. Additionally, sand is a cheap and readily available material, making it a practical and feasible choice. As seen in the table below, sand, especially when wet, has a relatively high thermal conductivity, enabling it to transfer heat at a faster rate. The proof-of-concept prototype uses soil instead of sand to absorb the water. While soil is a less effective substance, tests still showed a noticeable decrease of temperature inside the fridge.

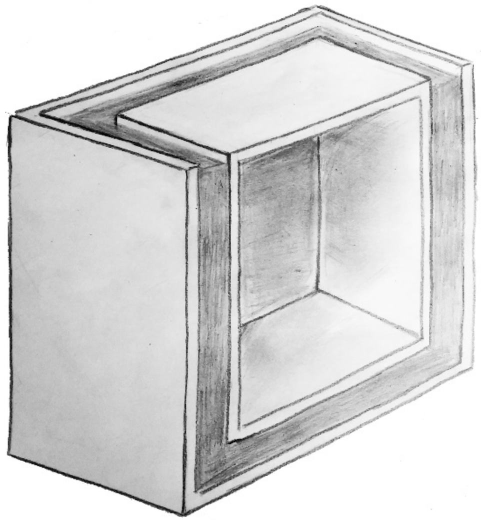

Figure 7: Sketch of layers in fridge

Material	**Thermal Conductivity (W/(mK))**
Sand, dry	0.15-0.25
Sand, moist	0.25-2
Sand, saturated	2-4
Ground or soil, very moist area	1.4
Water	0.58

Source: http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

Drip Irrigation

The initial design required the user to manually inject water into the system at least twice a day. After research, it was determined that a drip irrigation system would be a beneficial addition, as it allows the fridge to operate for extended periods of time while decreasing the frequency at which the user would have to replenish the system's water supply.

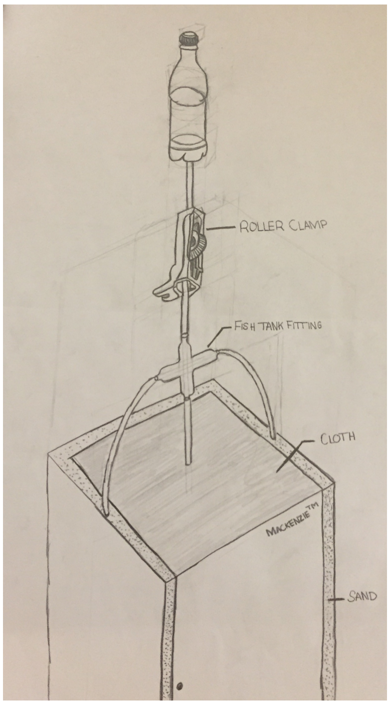

Figure 8: Sketch of drip irrigation system

The drip irrigation system is comprised of three parts and is similar to intravenous drip systems commonly found in hospitals. There is a tube extending from the bottom of the water source, a roller clamp attached to this tube, and a fish tank fitting which splits this one tube into three separate tubes.

The irrigation system is attached to the top of the fridge using four metal rods. These rods come up off of the top of the fridge, forming a square base. The bottle used as the water storage for the system is inserted between the rods, which hold up and support the bottle. This configuration was chosen due to its ease of use, as it makes replacing and/or refilling the bottle a simple task for the user.

To draw water from the bottle, airline tubing is inserted into a hole cut out from the bottom of the bottle. The hole is then coated with silicon to avoid potential leakages. A roller clamp tubing is then attached to the airline tubing. This is followed by a four-way fish tank fitting, with the initial tube attached to the topmost connector. The three other pathways also lead to tubes, with one providing water to the cloth, and the other two to the sand. This drip irrigation system allows for an innovative method to constantly maintain moisture in the sand.

Analysis

Water Quantity

When looking at the rate at which water evaporates from sand, many factors have to be taken into consideration:

1. The temperature of the water
2. The temperature of the sand
3. The area of the holes (where evaporation is occurring)
4. Airflow around the system

Through calculations, an approximate volume of 1240 mL of sand is present in the system. Considering that the density of sand is 2.65 g/cm^3, it can be calculated that the mass of the sand is 3.286 kg. The cloth was placed over the inner container, which has a surface area of approximately 139 cm^3.

In the proof-of-concept prototype, the soil has a water holding capacity of 110 mL (around 9%). The cloth used for this prototype was soaked by 20 mL of water. In the real model, we would want the sand to be filled with about 90% of their relative holding capacities, so that the system doesn't overflow once the irrigation system starts to operate.

With the sand type used for this prototype, the ratio of water to sand is 0.0335 L/kg. For the cloth, the ratio of water to sand is 0.1439 L/kg. If in a real model, these materials were to be used, then the amount of water initially placed into the system could be calculated using those ratios multiplied by 90%.

Figure 9: Pictures of proof-of-concept prototype that was built. Right: View of soil layer. Left: View of entire fridge system.

Drip Rate

The three-temperature model was suggested by scientist Qiu in 1996, and was an equation that demonstrated the sensible heat flux between the evaporating soil, sand in this design, and the atmosphere. The equation proposed was:

$$H = \rho_a c_p \frac{T_s - T_a}{r_a}$$

where H is the sensible flux, $\rho_a c_p$ is the heat capacity, T_s is the evaporating sand temperature, T_a is the air temperature and r_a is the aerodynamic resistance.

It is safe to assume that the drying sand does not affect atmospheric variables. This allows the assumption that the aerodynamic resistance of both the evaporating sand and dry sand are the same. This allows the deduction of the equation:

$$H_d = \rho_a c_p \frac{T_{sd} - T_a}{r_a}$$

where T_{sd} is the temperature of dry soil and H_d is the sensible heat between the dry soil and the atmosphere ($H_d = R_{nd} - G_d$), where G_d is the heat flux in dry soil and R_{nd} is the net radiation of dry soil. This gives the third equation:

$$r_a = \frac{\rho_a c_p (T_{sd} - T_a)}{R_{nd} - G_d}$$

This gives a sensible heat flux equation of:

$$H = (R_{nd} - G_d)\frac{T_s - T_a}{T_{sd} - T_a}$$

This gives a final equation that predicts the evaporation of wet soil as:

$$\ln(E) = R_n - G - (R_{nd} - G_d)\frac{T_s - T_a}{T_{sd} - T_a}$$

Once the rate of evaporation is found, the amount of water needed to be added can be calculated to keep the water soaked to a level of at least 70% at all times, to keep the system cool.

Limitations

The design of this fridge has some constraints and limitations. It cannot be used everywhere in all conditions, and some features had to be adjusted from an optimal design to a practical design. Firstly, the fridge cannot be operated outside under direct sunlight. While sunlight does increase the rate of evaporation, it also causes the wet bulb temperature to rise, increasing the minimal obtainable temperature as well as the temperature of the system as a whole. This counteracts any possible benefit of exposing the fridge to direct sunlight. For the system to remain cool, more water must be used at a faster rate to replenish the water that evaporates. The heat of the sun overpowers the cooling ability of the fridge, so this device performs best while shaded. Water evaporation also requires a constant supply of dry air to replace the humid air that accumulates in the system. In other words, this system needs wind to function properly. If the humid air is not replaced by dry air, the relative humidity of the system goes up, increasing the wet bulb temperature. In a dry, windy climate, the solution would work somewhat consistently, but the climate cannot be controlled, making this fridge not as effective in colder, wetter climates. Additionally, it operates best outdoors, where wind can speed up the rate of evaporation, but refrigerators are generally indoor appliances.

A tetrahedral design was considered for this design since the surface area to volume ratio for this shape is significantly higher than other shapes. However, when building a sketch model of the tetrahedral-shaped fridge, it was observed that the space could not be used effectively since the sides sloped down to a single point.

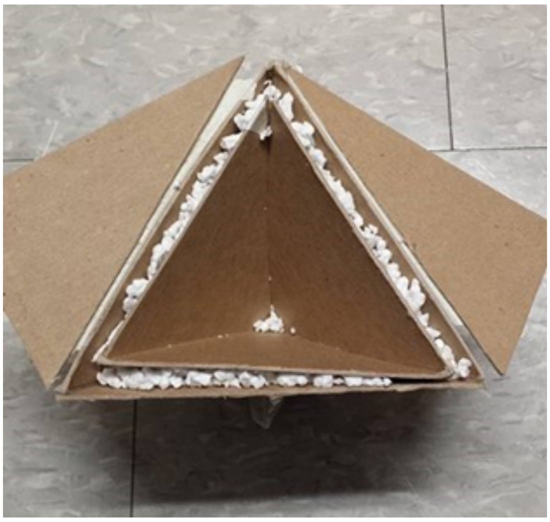

Figure 10: Tetrahedral shaped fridge design

As can be seen from the design, the space at the bottom will be wasted, and the “sand” that fell to the bottom of the sketch model could not be removed without turning the system upside down.

Another limitation with this fridge is that since the surface area to volume ratio must be maximized for effective cooling, the fridge cannot be made to industrial or commercial sizes. Doing so will result in a decrease in temperature. However, using several smaller fridges will preserve the cooling effect and still allow for cooling of many items.

Conclusion

The proposed solution meets the seeker’s broad requirement of being an innovative design capable of lowering temperature. Rather than relying upon external power to cool the fridge, this design relies upon the premise of water evaporation, specifically the endothermic process that occurs as liquid water evaporates into vapor. This continuous cycle enables the fridge to maintain a temperature lower than that of its surroundings. In addition, the other design elements such as the drip irrigation system, air tight door and vents allow for the system to work more efficiently. However, this fridge, and the evaporation process, depends on several conditions: temperature, humidity, and wind, to operate effectively. Although this design does encounter some limitations, it does fulfill all the requirements. This novel refrigerator design provides an innovative solution to the problem of carbon pollution.

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