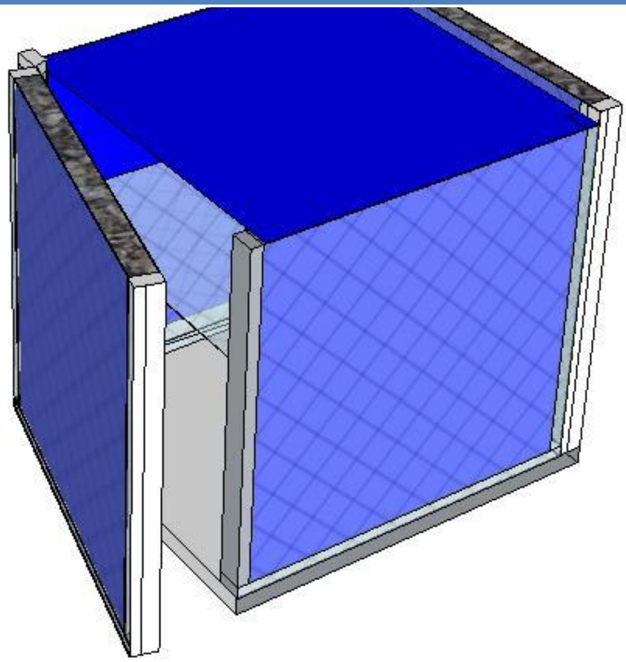
Charcoal Cooler

Scientific Principals and Analytical Model



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1.0 Scientific Principles

Evaporative cooling is based on the principle that water requires heat energy to evaporate. In hot, relatively dry climates the evaporation of water into hot, dry air can create a cooing effect, suitable for space conditioning or refrigeration. The heat removed from a space due to the evaporation of water is given by equation 1.

$$\dot{Q} = \dot{m}_e h_{we} \qquad (1)$$

Where $\dot{Q}$ is the heat removed in kW, $\dot{m}_e$is the rate of evaporation of water in kg/s, and h_{we} is the latent heat of evaporation for water (~2270kJ/kg) [1]. The cooling capacity is therefore approximately proportional to the rate of evaporation of water, which depends on:

- Ambient temperature
- Ambient humidity
- Surface area
- Evaporative media
- Air movement (natural, or artificial)

To maximize the cooling effects these variables must be optimized for a given application.

1.1 Psychometrics

Evaporation, the process of changing water from a liquid to a gas, requires heat from the surrounding environment. Psychometric properties of moist air, as well as the principals of heat and mass transfer apply to the evaporation of water for cooling. Understanding the properties of moist air is key in understanding how evaporative cooling works.

Moist air is air consisting of water vapour, and dry air. The total pressure of the air is the sum of the partial pressures of the water and the vapour, as shown by equation 2.

$$P = P_a + P_v \qquad (2)$$

Saturated air is a mixture of dry air and saturated water vapour. When air is saturated the vapour pressure P_v is equal to the saturation pressure ($P_{v,max}$) of water at the temperature of the air. Since saturation pressure increases with temperature, air at a higher temperature has the capacity to hold more moisture.

Humidity refers to the amount of moisture in the air, and can be expressed in two ways. Relative humidity, equation 3, is the ratio of moisture in the air to moisture in saturated air at the same temperature.

$$RH = \frac{P_v}{P_{v,max}} \qquad (3)$$

Relative humidity is therefore a function of both temperature and moisture content.

Absolute humidity is the ratio of the mass of water to mass of dry air, and is given by equation 4.

$$\omega = \frac{m_v}{m_a} = 0.622\frac{P_v}{P-P_v} \quad (4)$$

Absolute humidity is therefore only a function of the moisture content.

The driving force behind the evaporation of air is the difference in vapour pressures between the air and water. Air at a higher temperature and lower relative humidity is able to evaporate more moisture than cool or moist air. The potential for evaporation is proportional to the difference in dry bulb and wet bulb temperatures. The dry bulb temperature measures the temperature of the air stream whereas the wet bulb temperature is representative of both the temperature and humidity. Wet bulb temperature can be measured by placing a moist cloth on the end of a thermometer and allowing air to pass over it while reading the temperature. The relative humidity and absolute humidity can then be determined from a psychometric chart.

1.2 Evaporation

A simple empirical correlation can be used to estimate the rate of evaporation of water from a surface. Figure 1 shows a schematic.

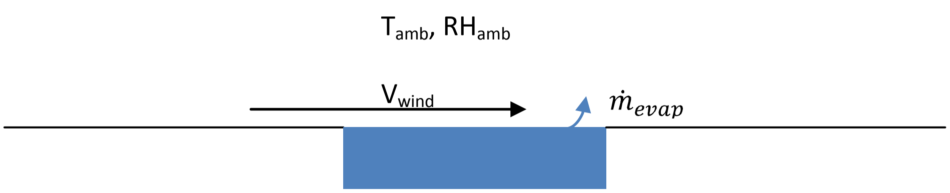

Figure 1: Schematic for Equation 5

Equation 5 gives the empirical correlation for the evaporation rate $\dot{m}_{evap}$ in kg/h [2].

$$\dot{m}_{evap} = A(25 + 19V_{wind})(\omega_{sat} - \omega) \quad (5)$$

ω_{sat} is the saturation absolute humidity at the ambient temperature and ω is the actual absolute humidity. A is the water surface area.

Many evaporative cooling units pass air through a porous soaked pad that is kept replenished with water. Figure 2 shows a schematic.

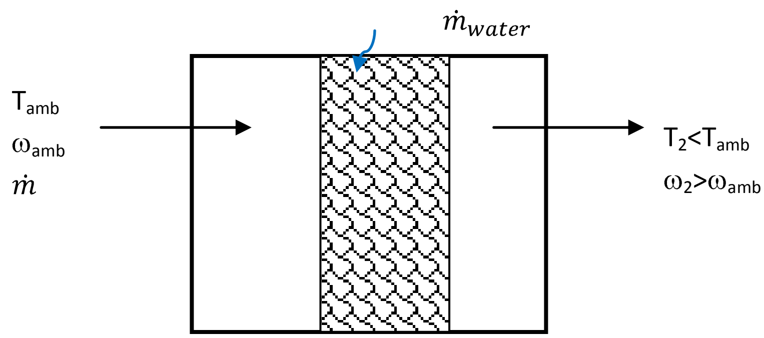

Figure 2: Schematic For Equation 6

The evaporative efficiency of the medium is given by equation 6.

$$Eff = \frac{T_1 - T_2}{T_1 - T_{wet\ bulb\ 1}} \qquad (6)$$

It should be possible to achieve 60-90% efficiency; however efficiency values for specific media can be determined experimentally [3].

An energy balance on the air stream gives equation 7.

$$\dot{m}_{water} = \dot{m}_{air}(\omega_1 - \omega_1) = C_{p,air}(T_1 - T_2) - C_{p,water}(\omega_1 T_1 - \omega_2 T_2) \quad (7)$$

C_p is the specific heat at constant pressure for air and water respectively.

1.3 Fundamental Heat Transfer

Heat is transferred through conduction, convection and radiation. Often the effects of radiation can be ignored, as they are small when compared to other forms of heat transfer.

Conduction occurs through a solid surface and is given by equation 8.

$$Q = \frac{kA}{t}(\Delta T) \qquad (8)$$

Where Q is the heat transferred in Watts (W), k is the conduction coefficient in W/mK, t is the thickness of the solid and delta T is the temperature difference across the solid. The conduction coefficient is a property of the material and can be found from tables or experimentally.

Convection occurs from a fluid passing over a solid object and is given by equation 9.

$$Q = hA(T - T_\infty) \qquad (9)$$

Where h is the convection coefficient, A is the area of the surface, T is the temperature of the solid object and T_∞ is the temperature of the fluid. The convection coefficient is a function of the fluid velocity, fluid properties, and object dimensions. It can be determined experimentally or from derived correlations.

2.0 Model Development

An EES model of the charcoal cooler was developed to determine the effect of various design variables as well as ambient conditions. The charcoal cooler was modeled as a control volume with one face normal to the ambient wind. Figure 3 shows a schematic of the modeled system.

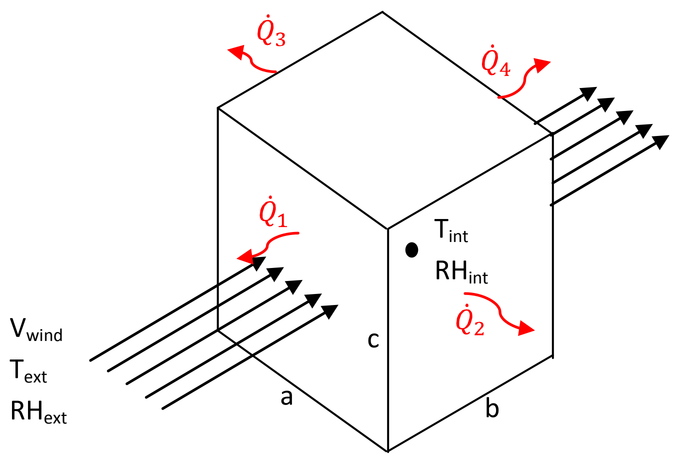

Figure 3: Model Schematic

The following assumptions were made for the analysis:

- The conditions are at steady state
- The cooler will be placed in a shaded region and radiation effects are negligible
- The top and bottom of the cooler are insulated (no heat transfer)
- The heat of vaporization of water is constant and 2270kJ/kg
- No heat is generated inside the cooler
- The entire system operates at atmospheric pressure
- The charcoal is kept continually moist (water flow = rate of evaporation)

The heat transfer through each side of the cooler was considered individually, and is explained below.

2.1 Side 1

The front side of the cooler can be modeled as air flow through a moist pad. Figure 2, above, is therefore a schematic for the air flow through the front of the cooler. The equations listed in Evaporation through a Transfer Medium apply. The heat transfer $\dot{Q}_1$ is equal to the rate of evaporation times the enthalpy of vaporization. The temperature internal to the cooler T_{int} is calculated based on the evaporative efficiency and ambient conditions, as given by equation 6. This temperature is assumed to be constant over the width of the cooler. The internal temperature is therefore dependent on the ambient conditions and evaporative efficiency.

2.2 Sides 2 and 3

Sides 2 and 3 of the cooler have the same heat transfer rate, however unlike side 1 the rate of heat transfer is dependent on more than the rate of evaporation. Figure 4 shows a schematic of the side wall as viewed from the top.

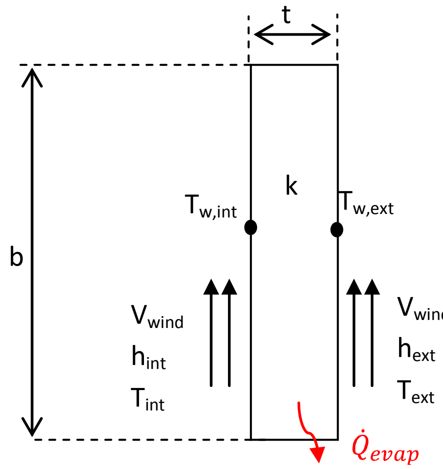

Figure 4: Side Wall Schematic

As shown in the figure, there is convection over the surface, as well as evaporative heat loss from within the wall. It was assumed that the evaporation only occurs on the inside and outside surfaces of the wall, and that it could be modeled using equation 5, the correlation for free surface evaporation. This assumption will be discussed further in model analysis.

The convection coefficients were calculated using the empirical correlation for forced convection over a flat plate with constant Heat Flux Conditions, as given by equation 11 [4].

$$\frac{hb}{k} = Nu = 0.0308 Re^{\frac{4}{5}} Pr^{\frac{1}{3}}$$

Nu is the Nusselt number, Re is the Reynolds number and Pr is the Prandlt number.

Applying the stated assumptions, the wall was modeled using a thermal resistance network, as seen in figure 5.

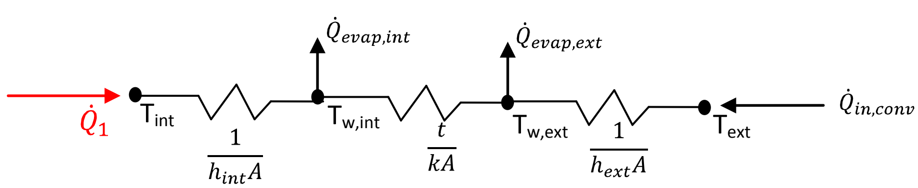

Figure 5: Thermal Resistance Network for Side Face

As evident from the figure, for heat to be removed from the inside of the device, the sum of the evaporative heat removed must be greater than the heat added from convection.

2.3 Side 4

The back of the cooler allows for constant air flow through the device, and may further cool the air stream if air is not saturated. The evaporation would cause cooler air to exit the device but would have a minimal affect on the temperature inside the cooler. The heat transfer through the back face of the charcoal cooler was assumed to be negligible and was not considered in the model. The design of this back face is further discussed in design recommendations.

3.0 Model Analysis

Using the analytical model described in Model Development, the design parameters were analyzed to determine the performance of the device under a variety of conditions.

The rate of heat transfer ($\dot{Q}$) for sides 1, 2, and 3 was calculated and is shown in figure 6 as a function of the ambient temperature (T_1).

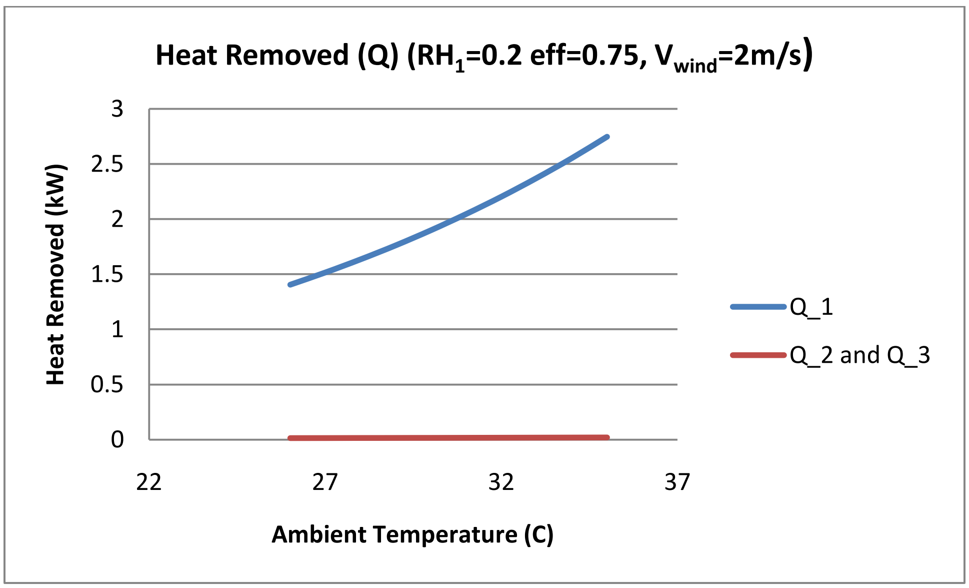

Figure 6: Heat removed for each side of the cooler with ambient humidity of 20% and 75% evaporative efficiency and 2m/s wind speed.

Two interesting observations are displayed in this figure. First, the heat removed by side 1 (facing into the wind) is significantly greater than the heat removed from the sides of the device. **It was therefore assumed for the analysis that temperature inside the cooler is constant, and a function of the evaporation through the front of the cooler.** The evaporation in the sides of the cooler essentially "cancel" out the heat that would otherwise be added to the inside by convection.

Figure 6 also shows that the heat removed from the front increases with temperature, which is explained by the increased evaporation rate with temperature.

The temperature inside the chamber was examined as a function of the ambient conditions (temperature and humidity). Figure 7 shows the plot.

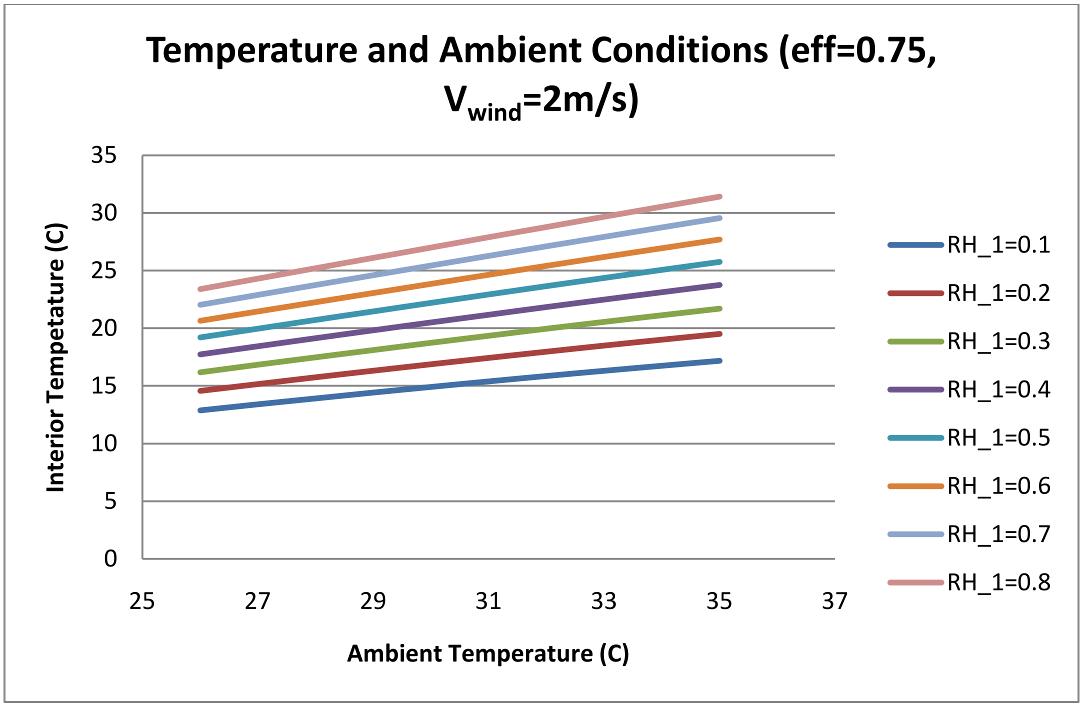

Figure 7: Cooler Conditions and ambient conditions for moderate (2m/s) air flow.

The interior, cooled temperature is therefore much lower for conditions with low relative humidity. While the heat transfer rate increases with temperature (as shown by figure 6), the interior temperature is lower with lower ambient temperatures because the required temperature drop is not as large. At high humidity, the device does not provide enough cooling to successfully refrigerate produce. For the interior temperature to be below 20 degrees Celsius, the humidity must be below 0.5.

For previous figures, the evaporative efficiency was assumed to be 0.75. It should be possible to achieve a value of 0.6-0.9 with charcoal [3]. Figure 8 shows the effect of evaporative efficiency on interior temperature.

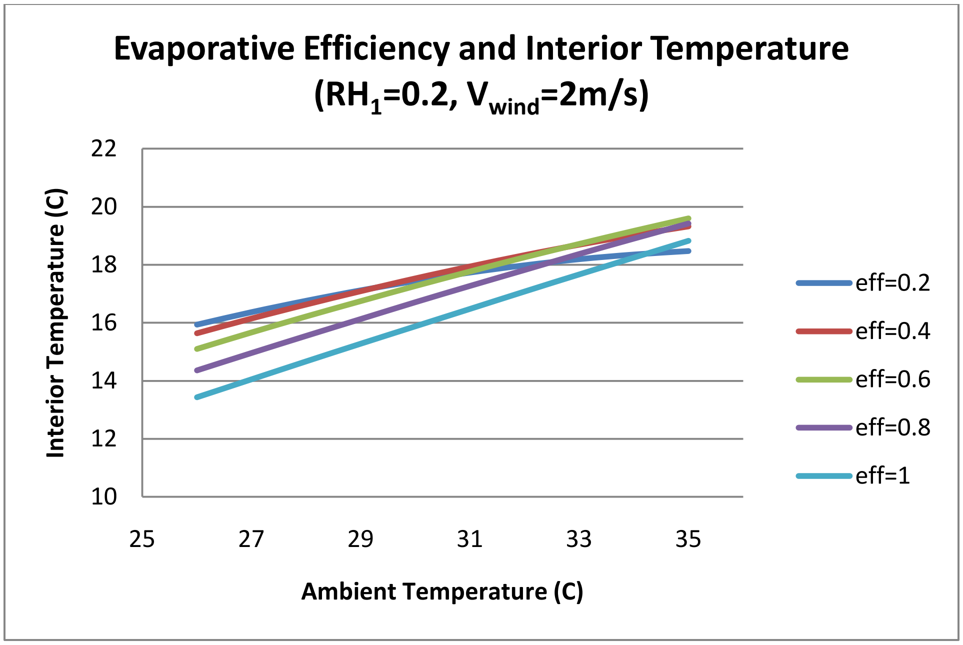

Figure 8: Evaporative efficiency and interior temperature as a function of ambient temperature

Higher evaporative efficiency can significantly increase the cooling capacity of the cooler. Future work should be done to determine the factors that affect this parameter, and how to best optimize the efficiency of the charcoal medium.

Finally, the evaporation rate through each side of the container was examined as a function of the ambient conditions. Figure 9 shows the evaporation rate though the front (side 1) and figure 10 shows the evaporation rate through the sides (2 and 3).

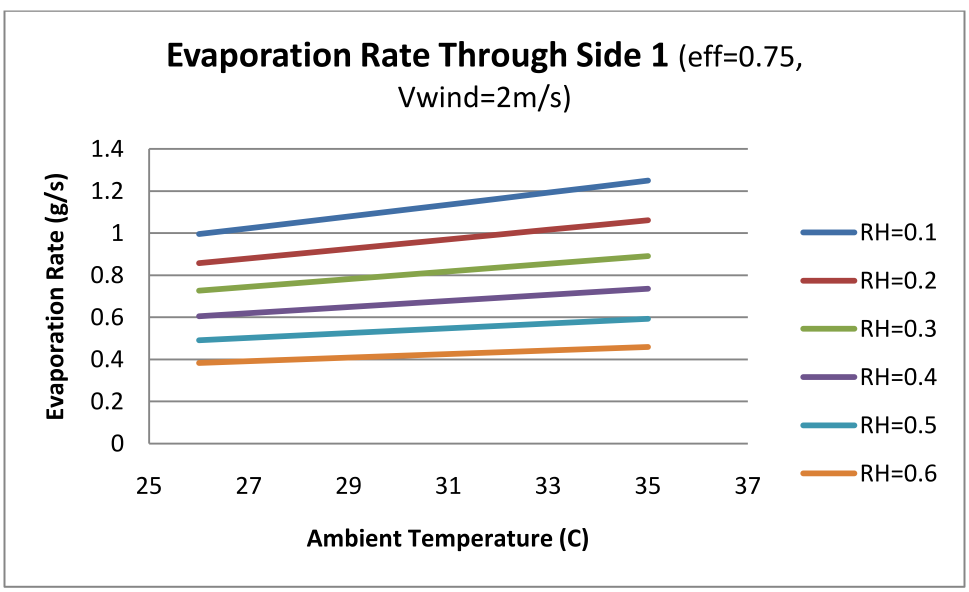

Figure 9: Evaporation rate through the front face of the cooler.

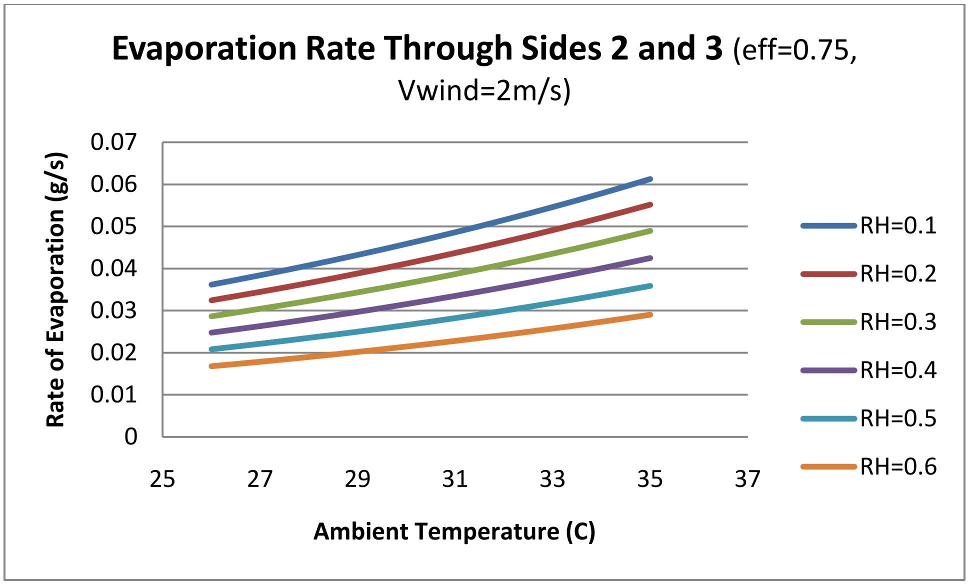

Figure 10: Evaporation rate through the sides of the cooler.

From the figures, it is evident that the evaporation through the front face of the box is significantly higher than the remaining faces. This observation relates to the design of the device as the water should flow into the charcoal sides as quickly as it is evaporating. Therefore the flow rate of water into the front face of the device should be significantly higher than the remaining sides. This concept is discussed further in design recommendations.

4.0 Design Recommendations

Based on the prototype construction and model analysis the following recommendations are made for the design of the cooler:

1. The flow rate of the water into the cooler is an important parameter that depends on ambient conditions and the tubing or tins used. The flow rate should be equal to the rate of evaporation to ensure that water does not leak from the cooler, and that the charcoal does not dry. It is recommended that the holes in the tubing on the front side of the device be made larger and closer together than the other two sides.
2. Depending on the availability of charcoal the back face of the cooler does not require the charcoal medium since evaporation from this face does not contribute to the cooling effect. It may, however, be useful to include charcoal on all sides so that orientation and wind direction does not matter.
3. The tins or bucket of water should be covered to prevent evaporation into the ambient environment.
4. It was found through the model that the dimensions of the cooler do not greatly affect the performance. Some of the model assumptions, however, do not hold true with large dimensions. Based purely on construction, it is easiest to construct a cube-shaped cooler since all pieces of wood can be cut to the same size.

5.0 References

[1] Moran, M. J., Shapiro, H. N. *Fundamentals of Engineering Thermodynamics.* Ed. 6. John Wiley & Sons Inc. USA: 2008. P. 817.

[2] "Evaporation from Water Surfaces." Engineering Toolbox 2005. Accessed Online: April 8th 2010. Available <http://www.engineeringtoolbox.com/evaporation-water-surface-d_690.html>

[3] Rusten, Eric. "Understanding Evaporative Cooling." VITA 1985. Accessed Online: April 8th 2010. Available: <http://www.fastonline.org/CD3WD_40/VITA/EVAPCOOL/EN/EVAPCOOL.HTM>

[4] Incropera, F. P., DeWitt, D. P. *Fundamentals of Heat and Mass Transfer.* Ed. 6. John Wiley & Sons Inc. USA: 2007. P. 413.