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Design and Theoretical Evaluation of Performance of Evaporative Cooling System by Using Cement and Polystyrene (Thermocol)

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ABSTRACT: People in India mostly rely on agriculture and produce many agricultural products. The climate varies from region to region, which helps them produce those products. Due to a lack of cold storage, farmers are unable to hold the product and sell them for better prices. In the old days, farmers used to have a traditional way of storage system that worked on evaporative cooling. The modified cold storage system is a type of pot in a pot refrigerator that uses no electricity. This encourages farmers to do the value addition process. In this paper we primarily focused on changing the material of existing zeer pot cooling system that uses clay and sand. The Thermocol used to construct the outer cylinder whereas concrete for inner cylinder and instead of sand, maize stalk is used as an absorptive material which is placed in between the cylinders. The temperature is reduced by the exchange of heat within the system by evaporation. The temperature in the chamber is monitored by an embedded system. The temperature is dropped from 35°C to 24.3°C (T_{cold}) for the volume of $9.42 \times 10^{-3} \text{ m}^3$ i.e., 0.00197 cubic meters ($r_1 = 0.1 \text{ m}$, $H = 0.3 \text{ m}$) by supplying water. The absorbents are removed and can be used as organic waste, improving soil fertility. Thus, providing efficient cooling to this system can help small scale farmers to store their products in a traditional method.

KEYWORDS: Embedded Systems, Evaporative Cooling, Heat Transfer, Hydraulic Conductivity, Maize stalk.

I. INTRODUCTION

Today, India is one of the top five countries that produce fruits and vegetables in the world. Although fruits and vegetables are abundant in the country, the availability per capita for this produced is low due to postharvest losses. In addition, the quality of a large quantity of produce deteriorates as it reaches the consumer. Perishability is the primary cause of most marketing problems for fruits and vegetables. As there is a lack of cold storages and other cheap ways to store goods, which forces them to spend a lot of money on logistics. Due to which perishability of products causes high marketing costs, market gluts, price fluctuation, and similar issues. There is a necessity for efficient handling of storage and maintenance that occupy less space; cheaper way for storing the agricultural products. A method of using evaporative cooling is one of the ways.

This pot in pot cold storage is created based on the evaporative cooling. The construction of the cooling system that uses clay and sand is difficult due to its weight and size. Changing the material could affect the COP and η of the existing system. As a result of this change, it is easier to construct, and the weight is reduced as well as the storage capacity is increased. The older cold storage systems designed around evaporative cooling have rectangular construction, but this paper focuses mainly on cylindrical construction of the system and experiment was conducted on the small-scale prototype that can hold up 1 kg of fruit/ vegetable.

Initially, two cylinders are placed inside each other; Thermocol used to construct the outer cylinder whereas concrete for inner cylinder the annular space is filled with organic absorptive material such as maize stalk instead of sand. The space inside the inner cylinder is used to store food. Water is poured into the annular space until the saturation point has been achieved. The wet maize stalk in the annular space causes evaporative cooling in the system. This evaporation process results in cooling in the inner pot. The advantages of maize stalk are that it is an agricultural waste and a sustainable way to live in the modern world. Sustainability is considered in the development of cities, and they become eco-friendly.

Water evaporates from the pot's outer surface into the ambient dry air stream as a result of the pot-in-pot system's physical principle. Air-water-cement interfaces produce a cooling effect due to coupled heat and mass transfer



processes. As a result of convection and radiation effects of the ambient atmosphere, the outer wall's surface water molecules evaporate (since the outer wall is made of Thermocol, evaporation takes place slowly), causing cooling at the surface [6].

II. HISTORY

As mentioned above evaporative cooling has been used for millennia. There have been a multitude of ways to utilize evaporation throughout history. From cooling drinking and bathing water in The Far East to storing butter and cheese in Europe. In the late 1970th porous earthen jars were still used to cool water in numerous Asian villages.

Two clay pots make up the Zeer pot construction which is an electricity free refrigerator [1]. The inner clay pot is smaller in diameter whereas the outer clay pot is bigger in diameter. In the smaller inner pot, the food to be preserved is placed. A layer of sand fills the space between the two pots. Sand helps evaporative cooling by retaining water. The voids present in the sand is filled by pouring water into it. Hydraulic conductivity allows water to flow through the outer clay pot as it is porous [2]. This water evaporates to surrounding by convective and radiative heat transfer Q_m and then makes the inner space cooler where food is to be stored. Food preserved at low temperatures gives off respiratory cooling load q_{load} as sensible heat is removed.

There have been very few attempts to model and quantify this cooling device, despite the fact that it has existed for a very long time in history. This is primarily because multiple processes are occurring simultaneously, which are influenced by various geometrical and material characteristics. Moreover, comprehensive modelling of such processes is extremely complicated because of various multi-physics effects linked with this phenomenon. A simplified algebraic model based on Reynold's flow hypotheses can account for heat and mass transfer in a clay pot refrigerator. The energy balance equation used therein fails to account for evaporation rates of water and is therefore inaccurate in predicting steady-state systems temperatures and effectiveness in response to changing ambient conditions and material parameters [11].

In recent years, eco-cool has been designed as an alternative to refrigerators that are chemically based and use electricity. Eco cool does not require chemicals or electricity for cooling, instead, it uses evaporative cooling to cool the substance. The material used here is the cement for the walls. Users are required to water the concrete roof and walls daily [3].

III. DESIGN CONSIDERATIONS

Materials like thermocol, cement for the construction of walls are considered, so that when water sprayed the evaporative cooling effect takes place and in section V under material properties and their benefits are mentioned. Accordingly, the design in cylindrical shape is used for better performance and also some of the other advantages mentioned in section VII. The temperature is measured with the help of embedded system, which is briefly explained in section VI. Construction is not difficult; it can be constructed by any one with some proper guidance. This helps in reducing the cost.

IV. MATERIALS

4.1 Corn pith

A corn pith is a soft, spongy substance present inside corn stalks, cobs made of maize. It has a relatively low density and is largely made up of the plant's parenchyma tissue. This material helps in the holding of water that is supplied to the system. Corn crops are used in the feeding of animals. The corn pith after a certain time is removed and used as an organic material on the field which increases soil pH value. Besides corn pith cocopeat can be used [5]. Corn pith is a highly porous material that helps in the absorption of water.

The hydraulic conductivity of corn pith is $K_{hy} = 2.8 \times 10^{-8}$ m/s, and its thermal conductivity is $K_{cp} = 0.05$ W/m-K.

4.2 Thermocol / Expanded Polystyrene (EPS)

Thermocol is a synthetic aromatic (benzene derivative) polymer made from monomer styrene. This is a light, cellular plastic material used primarily for sound and heat insulation of ceilings, walls, refrigerators, and air conditioners. Having a compressive strength of 11.7-14.4 N/mm², it is soft, light, strong, and durable. It minimizes the heat entering

into the system from the surroundings. While Thermocol acts as a thermal resistant, it is slow to biodegrade and will gradually absorb water. This intern helps in the evaporation of water at a slower rate [6].

4.3 Cement

As we know, cement is the hardening substance used in construction to attach other materials. Concrete is produced by mixing cement and fine aggregate, or by mixing cement and sand. The most widely used material on earth is concrete, which is second only to water in terms of consumption. This cement material is used for making inner pot so that the vegetables or fruits stored doesn't react with the material. Thermal conductivity decreases with a reduction in relative humidity [7]. The thermal conductivity of cement $k_{Ce} = 1.6 - 2.01$.

V. TECHNOLOGY

The use of embedded systems is so convenient in measuring the temperature inside the system.

Components used:

Temperature Sensor, Arduino UNO, LCD, LED, Battery

5.1 Block diagram of circuit

The figure 1 shows the circuit block diagram of embedded system and the exact CAD Model connections made in circuit by using Tinkercad.

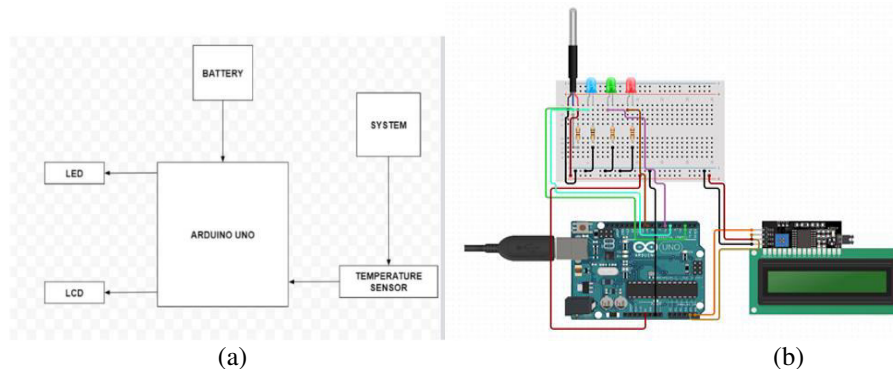


Figure 1.(a) Circuit block diagram of embedded system (b) Circuit CAD Model of embedded systems from Tinkercad

5.2 Temperature sensor

The temperature sensor used is DS18B20 which is a digital and waterproof type. It can measure temperature ranging from -55°C to $+125^{\circ}\text{C}$ with an accuracy of $\pm 5\%$ [8]. The signal received from the sensor is read and displayed using a ARDUINO board.

5.3 Arduino UNO

Arduino UNO which is the commonly used board that is also known as classic. The Arduino UNO is a controller based on the ATmega328 microcontroller and has 14 digital input/output pins, 6 and the Arduino Quartz generator with 16MHz, USB port, voltage port., ICSP port and reload button. A temperature sensor input signal is read and displayed on a LCD display panel. It is an easy-to-use hardware and software.

5.4 LCD display

LCD1602 is an industrial display used to display output. LCDs (Liquid Crystal Display) operate on the principle that the display area of the liquid crystal is controlled by the voltage applied to it [9].



5.5 LED

Light Emitting Diodes (LEDs) are the semiconductor devices that emit light when they are powered by a current. These are used for indicating the temperature ranges which are set to the system. Here red LED blinks when the range goes beyond the set value and blue LED blinks when the range goes below the set value. Green LED blinks when the temperature is within the set value.

5.6 Battery/ Power bank

A Battery is an energy storage device. The battery/power bank is used to supply the power to the ARDUINO. So that the work of ARDUINO is done.

VI. EXPERIMENTAL SETUP

The traditional cold storage system like pot in pot works on no electricity. This paper mainly focuses on how it works on some modifications done like material and the addition of embedded systems. The experiment setup consists of cement, coco pith, thermocol, Arduino, temperature sensor. When the water is supplied in between the two cylinders, the transfer of heat occurs, resulting in the decrease of inside temperature T_{cold} . The temperature is measured using a temperature sensor and displayed on LCD using Arduino UNO. When water is supplied to the system the heat transfer takes place and the temperature is brought down. The extra water is removed out at the bottom by arranging the pipe.

6.1 Design

Design plays a key role in cold storage. The structure of this system is cylindrical geometry. Since cylindrical construction have less surface area compared to floor space, thus the surface area in contact with the weather outside is lesser. Therefore, it consumes less energy to maintain their interior temperatures. Besides being more aerodynamic, roundhouses are also more energy-efficient since they admit fewer draughts [4].

6.2 CAD Design

Before working on the actual design in practical terms. For better understanding and putting the idea in visual a cad model is designed in cad software SOLIDWORKS 2021 considering all the geometrical dimensions mentioned in calculations. Figure 2 (a) depicts the line diagram of the model.

6.3 Prototype

After designing the cad model, the prototype is made using the materials and technologies mentioned in the section of material and technology. The Figure 2 (b) shown is the prototype developed for this experiment.

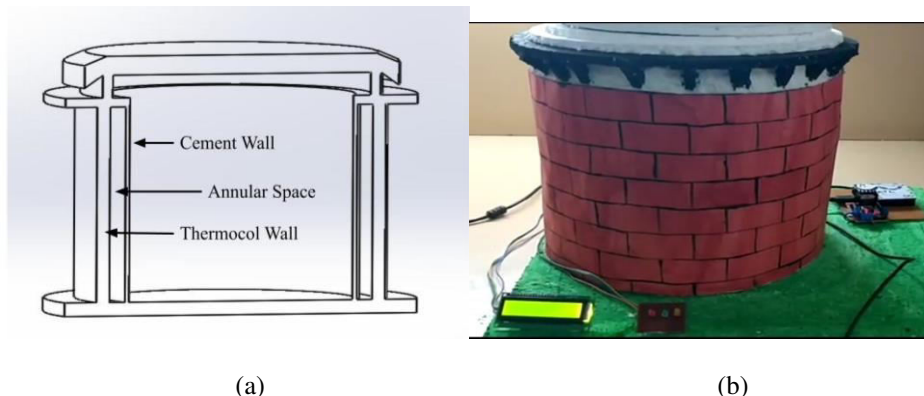


Figure 2.(a) Line Diagram of CAD Model (b) Prototype

6.4 Arduino setup

The embedded system helped in measuring the temperature inside the system. The temperature sensor is placed inside from the top. This sensor is connected to the Arduino UNO to convert the input from a sensor into output and display on LCD. The LED lights are also connected to indicate the temperature is within the range. This total setup shown below in Figure 3 is given with power supply using the power bank.

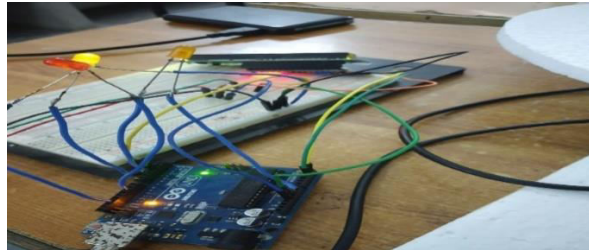


Figure 3. Embedded System connections

6.5 Observations

The observations made from these experiments are:

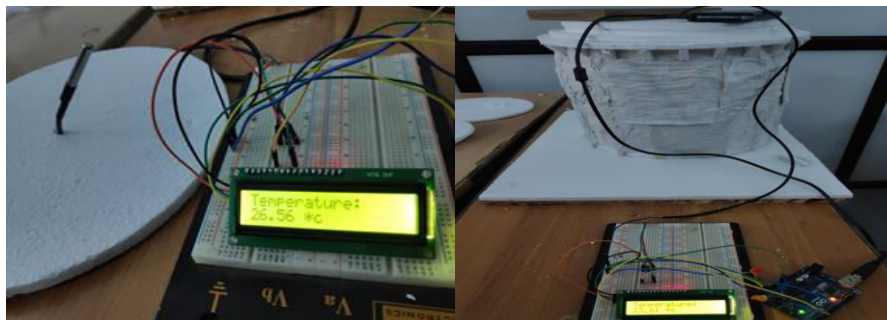
The evaporation process is slow. The water stored in the material does not evaporate too fast as compared to the clay made pot-in-pot due to the thermocol wall. The Figure 4 shown below is the water absorptive material.



Figure 4. Corn pith removed from system

The surrounding temperature is measured by placing the sensor outside. The temperature is around 26.6°C as shown in figure 5 (a).

When the temperature sensor is placed inside the system the temperature compared to surroundings is less than the surrounding temperature. The Figure 5(b) shown is taken during the experiment.



(a) (b)

Figure 5. (a) Surroundings temperature 26.56°C (b) The Temperature inside the system 23.8°C



VII. CALCULATIONS

7.1 Parametric values

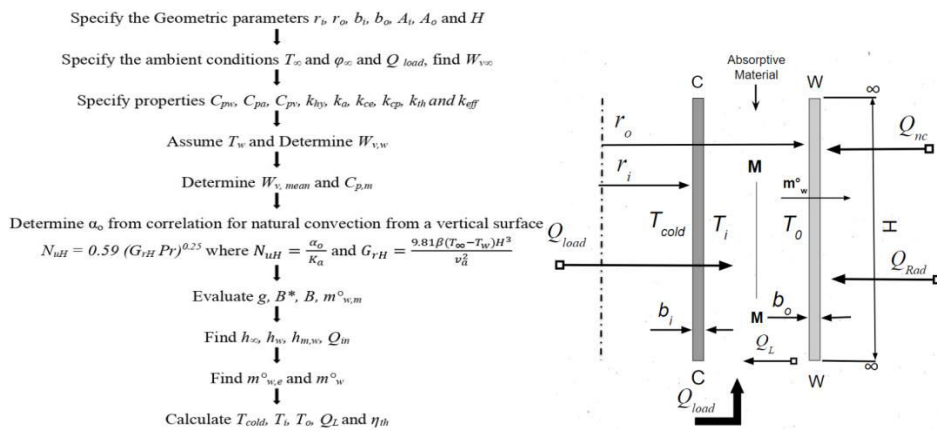
For evaluation of the performance of the system the reference and some of the parametric values are mentioned in Table 1. Solution procedure and Reynold’s flow model of the system are shown in figure 6(a) (b) respectively.

Table 1. Parametric values - reference case

Geometry(m)	SpecificHeat(J/kgK)	ThermalConductivityW/m-k	HydraulicConductivitym/s	Others
$r_i=0.1$ m		$K_{co}=0.05$		$Q_{load}=1$ W
$r_o=0.135$ m	$C_{pa}=1005$	$K_{ce}=2$		$T_{ref}=0^0$ c
$b_i=0.01$ m	$C_{pv}=1880$	$K_{Tl}=0.03$	$K_H=3.28 \times 10^{-5}$ (ms ⁻¹)	$\lambda_{ref}=2503$ KJ/Kg
$b_o=0.015$ m	$C_{pw}=4186$	$K_{eff}=K_w+K_{co}=0.05$		$\sigma=5.67 \times 10^{-8}$ W/m ² k ⁴
$H=0.3$ m		$K_a=0.027$		

7.2 Formulae

Below is the algebraic model representation of Reynolds flow is used to represent mass transfer (kg/s) across interfaces between the transferring substance (water in this case) and the considered phase (stagnant surrounding air). The below are taken from the reference [10-12].



(a) (b)

Figure 6.(a) Solution Procedure for obtaining temperature (b)Reynold’s flow model

7.3 Steady-State Assumption

- 1.Water is continuously injected into the annular space between the pots at the rate that exactly equals the rate of evaporation $m' w$.
2. The injected water temperature exactly equals imaginary mean temperature T_M .

The first assumption ensures that height (H) of the water-column in the annular space remains constant. The second assumption ensures that imaginary temperature T_M remains constant.

7.4 Mass conservation formulae

$$W_{v,\infty} = \frac{W_{\infty}}{1 + W_{\infty}} \tag{1}$$



$$(Substituted) w_{\infty} = 0.622 \times \frac{P_{v,\infty}}{P_{total} - P_{v,\infty}} \quad (2)$$

$$\frac{P_{v,\infty}}{P_{sat}} = \frac{\Phi_{\infty}}{100}; \frac{P_{sat}}{P_{cr}} = \exp \left[\frac{F}{1-\tau} \right] \quad (3)$$

$$\tau = 1 - \frac{T_{\infty}}{T_{cr}} \quad (4)$$

$$W_{v,w} = 3.416 \times 10^{-3} + (2.7308 \times 10^{-4}) T_w + (1.372 \times 10^{-5}) T_w^2 + (8.256 \times 10^{-8}) T_w^3 - (6.9092 \times 10^{-9}) T_w^4 + (3.5313 \times 10^{-10}) T_w^5 - (3.703 \times 10^{-12}) T_w^6 + (6.1923 \times 10^{-15}) T_w^7 + (9.9349 \times 10^{-15}) T_w^8 \quad (5)$$

$$F = a_1 \times \tau + a_2 \times \tau^{1.5} + a_3 \times \tau^3 + a_4 \times \tau^{3.5} + a_5 \times \tau^4 + a_6 \times \tau^{7.5} \quad (6)$$

Above Correlation is valid for $-20^{\circ}\text{C} < T_w < 100^{\circ}\text{C}$ $w_{v,mean}$ indicates the mass fraction or the amount of water vapor a substance possesses in its transferred state.

$$w_{v,mean} = 0.5(w_{v,\infty} + w_{v,w}) \quad (7)$$

$$C_{p,mean} = C_{p,m} = C_{pa}(1-w_{v,mean}) + (C_{pv} \times w_{v,mean}) \quad (8)$$

7.5 Natural convective coefficient (α_o)

By using N_{uH} , G_{rH} , Pr (9)

$$N_{uH} = 0.59 (G_{rH} \times Pr)^{0.25} \quad [\text{at } T_{mean}] \quad (10)$$

$$G_{rH} = \frac{g\beta(T_{\infty} - T_w)H^3}{\nu^2}; \text{ here } g = 9.81 \text{ m/s} \quad (11)$$

$$N_{u} = \frac{\alpha_o H}{K_a} \quad (12)$$

$$g \cong \frac{\alpha_o}{c_{p,m}} \quad (13)$$

(where g = Mass transfer Coefficient) (14)

$$B = \frac{w_{v,w} - w_{v,\infty}}{1 - w_{v,w}} \quad (15)$$

7.6 Mass transfer biot number

$$B_{im} = \frac{g}{\rho_w + K_{hy}} \quad (16)$$

$$m_{w,m}^{\circ} = g A_o B \quad (17)$$

Average mass flow rate over height H is

$$m_{w,m}^{\circ} = g A_o B^* \quad (18)$$

7.7 Energy conversion formulae

$$Q_{in} = (Q_{rad} + Q_{nc}) = (\alpha_{rad} + \alpha_o) A_o (T_{\infty} - T_w) \quad (19)$$



$$h_{\infty} = c_{pa}[T_{\infty} - T_{ref}] + [(c_{pa} - c_{pa}(T_{\infty} - T_{ref}) + \lambda_{ref}) [w_{v,\infty}]] \quad (20)$$

$$h_w = c_{pa}[T_{\infty} - T_{ref}] + [(c_{pa} - c_{pa}(T_w - T_{ref}) + \lambda_{ref}) [w_{v,\infty}]] \quad (21)$$

$$h_{m,w} = c_{pw}[T_{\infty} - T_{ref}] \quad (22)$$

$$m_{we}^{\circ} = \frac{Q_{rad} + Q_{load} + gA_o(h_{\infty} - h_w)}{h_w - h_m} \quad (23)$$

Q_{rad} is the heat caused by radiation that acts on the state w-w.

$$Q_{rad} = \varepsilon\sigma A_o [T_{\infty}^4 - T_w^4] \quad (24)$$

m_w° (kg/s) is taken as the converged evaporation rate of water from mass and energy conservation equations.

$$m_w^{\circ} = \frac{m_w^{\circ} + m_{w,m}^{\circ}}{2} \quad (25)$$

Q_L is the heat transfer between the cement walls and the corn pith-water layer.

Following is the equation to calculate the heat from conduction between wet cement and corn pith layers

$$Q_{load} - Q_L = \frac{-Q_{rad}}{1 + \frac{m_w^{\circ} c_{pw}}{2} \left[\frac{2b_o}{K_{th,w} A_o} + \frac{r_i \ln(r_o/r_i)}{K_{cp,w} A_i} \right]} \quad (26)$$

$$T_w - T_i = \left[\frac{b_o}{K_{th,w} A_o} + \frac{r_i \ln(r_o/r_i)}{K_{cp,w} A_i} \right] (Q_L - Q_{load}) \quad (27)$$

The cold zone temperature at a steady state based on the evaporation rate and temperature of water

$$T_{cold} = T_i + \frac{Q_{load}}{A_i} \left[\frac{1}{\alpha_i} + \frac{b_i}{K_{ce}} \right] \quad (28)$$

$$T_o = T_w + (Q_L + Q_{load}) \left(\frac{b_o}{K_{th} A_o} \right) \quad (29)$$

$$[\text{where } T_m = \frac{T_o + T_i}{2}] \quad (30)$$

The temperatures of the outer surface of the inner pot and the inner surface of the outer pot are given by T_i and T_o , respectively.

W_{in} can be controlled in a conventional refrigerator whereas Q_{in} depends on ambient conditions and, therefore, it is not under its control.

A new efficiency η_{th} is defined here based on thermodynamic considerations to circumvent the above difficulty.

$$\eta_{th} = \frac{T_{\infty} - T_{cold}}{T_{\infty} - T_{dp}} \quad (31)$$

$$T_{dp} = \frac{237.17 \times \gamma}{17.271 - \gamma} \quad (32)$$

$$\gamma = \frac{17.271 \times T_{\infty}}{237.37 + T_{\infty}} + \ln \left(\frac{\%RH}{100} \right) \quad (33)$$

Using heat transfer Q_{in} from the hot and dry surrounding environment, this water evaporates and cools the area inside the inner pot where food is stored.



$$Q_{in} = Q_{rad} + g A_o h_{\infty} \quad (34)$$

The Steady-State Coefficient of Performance (COP) of such a refrigerator may be defined as

$$cop = \frac{Q_{load}}{Q_{in}} \quad (35)$$

7.8 Results for reference case

Table 2. Results for Reference case

$T_w = 35^{\circ}\text{C}$	$m_w^0 = -8.49 \times 10^5 \text{ (kg/s)}$		
$T_o = 23^{\circ}\text{C}$	$Q_L = 1.020$	$\alpha_{rad} = 0.0057$	$g = 0.0038186$
$T_i = 22.9^{\circ}\text{C}$	$Q_{in} = 34.68$	$\eta_{th} = 0.885$	$B = 0.00067$
$T_{cold} = 24.3^{\circ}\text{C}$	$\text{COP} = 0.028$		$B^* = 0.00725$

Table 2 shows results obtained for the considered parametric values.

VII. CONCLUSION

From the present analysis carried out, the following conclusions are drawn. The temperature inside the system is decreased without any addition of electricity. The absorptive material like maize stalk used can be removed and used as the organic in fields, increasing the soil PH and water holding capacity. By using the Reynolds flow model and energy balance equation the pot-in-pot refrigerator is analyzed. The temperature inside is measured and displayed on an LCD screen using Arduino UNO

For any evaporation rate, the heat and mass balance equation that does not converge. According to these results, pot thickness, thermal and hydraulic conductivity, pot height and radius, heat load and radiation heat transfer all play an important role in affecting the temperature in the cold zone. For considered geometrical dimensions, parameters like COP, η_{th} and inner pot temperature T_{cold} are obtained as expected. The Different ambient temperatures (T_{inf}) and relative humidity (RH_{inf}) conditions doesn't affect the COP, η_{th} , T_{cold} . The experimental results and theoretical results are approximately near.

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NOMENCLATURE

A	surface area (m^2)
B	Spalding number
b	clay wall thickness variable, (m)
C_p	specific heat (J/kg K)
g	mass transfer coefficient ($kg/m^2 \cdot s$)
H	pot height (m)
h	Enthalpy of mixture (J/kg)
k	Thermal conductivity (W/m-K)
k_{hy}	hydraulic conductivity (m/s)
m^o	evaporation rate (kg/s)
m	mass (kg)
p	pressure (N/m^2)
Q	heat transfer (W)
r	radius(m)
T	temperature ($^o C$)
$W_{v,w}$	Mass conservation of water & vapour

Greek symbols

α	heat transfer coefficient ($W/m^2 \cdot K$)
β	volumetric coefficient K^{-1}
w	mass fraction
η_{th}	thermodynamic efficiency
Φ	relative humidity

Suffixes

a	air or atmospheric
c	cement
$cold$	inner pot environment
e	energy conservation principle
i	inner pot
o	outer pot
L	load cooling load
m	mass conservation principle or mean
rad	radiation
v	vapour
w	water or w-w state
∞	ambient condition



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