Phase Change Evaporator Design for Natural Refrigeration System

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Abstract

Natural refrigeration is an age old process and the recent interest is due to green and alternate energy initiatives. The Phase change physical phenomena is an effective approach to thermal energy management for innovative engineering applications. One of the major application of Phase change physics is Evaporative Cooling. Evaporative cooling phenomena plays a major role for cooling of liquid particles in a Natural refrigeration system design. Refrigeration is the process of transferring heat from one source to another as per requirement for desired application. Evaporative cooling process comes with various technical challenges. Ambient temperature, Relative Humidity, Thermal Conductivity & Evaporating Surface medium affects the cooling process. In this paper, the cooling performance of two designs has compared considering the different surface area of evaporating medium while keeping other parameters as constant.

1.0 Introduction

With onset of energy crisis and environment problems caused by conventional refrigerators, importance of evaporative cooling has grown. Conventional refrigeration comes with it's own disadvantages affecting natural environments by disposing chemical gases, which will harm the Ozone layer. Refrigeration by evaporating cooling has proved to be a successful alternative to conventional refrigerator. Evaporative cooling process is inexpensive, environment friendly & an effective way to preserve food, agricultural products. Though the methods of evaporating cooling has been in use from a decade ago, the improvement in various design and cooling performance to preserve food & medicines are the main focus in recent development.

Traditional refrigerators require electricity to run, which is increasing electricity demand in this age of energy scarcity. Most of the underdeveloped countries and rural areas does not have sufficient even if minimal access to electricity. Preservation of food and agricultural products in rural areas is an obstacle to human life sustenance, exploring alternative to commercial refrigerators. Natural refrigerators will play an important role in future to preserve food items, which will leads to revolution in refrigeration industry. These refrigerators will be inexpensive, easily available and should be environment friendly. Refrigeration by evaporative cooling is found to be successful for this purpose.

1.2 Evaporative Cooling

Evaporative cooling is a heat and mass transfer process in which some sensible heat from the surrounding of a wet surface is used to evaporate moisture into the air thus it is converted to latent heat of the moisture. This is a adiabatic saturation process in which heat is taken from the wet surface to the ambient air, hence increasing moisture content and wet-bulb temperature of the surrounding air. In this process some energy lost due to phase change of water molecules, hence create a cooling effects for the water particle lay behind and the process continue, to create a cool region. Considering the above process a Natural refrigerator can be designed to preserve food products for several hours without losing the nutrients.

1.3 Working Principle of Natural Refrigeration

The working principle of natural refrigeration by evaporative cooling involves a storage space covered by two single layers of porous and non-porous medium with evaporative liquid (water) in between. The bottom portion and inside non-porous layers will not allow the seepage of the evaporative liquid to outside environment as well as inside storage of the refrigerator respectively. The opening of the refrigerator is either covered with a polymer or porous media as required. *Figure.1* shows the working principle of a Natural refrigeration system design.

When the refrigerator is subjected to ambient dry air, the water diffuses through the porous medium to the outer surface and evaporated into the surrounding air.
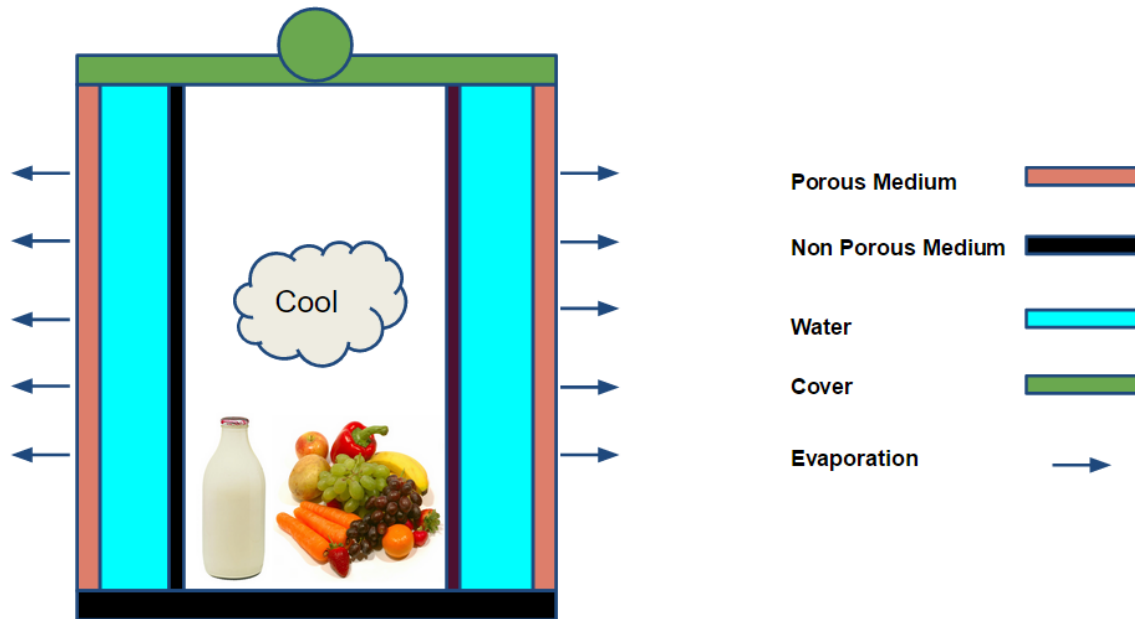
Figure.1 Working principle of evaporative cooling natural refrigerator.

The seepage of water out of the porous medium to the external surface of the refrigerator is caused by the gravitational pressure head and hydraulics force of water inside the liquid chamber. The capillarity and Darcy's Law in porous media plays a major role for seepage of water molecule to external surface of the porous medium. The thermal energy required for the evaporation on the external surface of the refrigerator is drawn from the storage space, hence generate cooling effect inside the storage chamber intended for preserving food items for several hours.

1.4 Factors affecting Evaporative Cooling

Though the concept of evaporative cooling comes with various advantages, we can not ignore the factors affecting in cooling process. The different factors affecting evaporative refrigeration are
- Atmospheric Temperature
- Ambient Relative Humidity
- Geometric Surface area of Evaporating Medium.
- Thermal conductivity of refrigerator physical body.
- Hydraulic Conductivity of porous media.
- Movement of surrounding air.

A. Atmospheric Temperature

The atmospheric temperature plays an important role in evaporative cooling process. Since for evaporating cooling the rate of diffusion of water molecule from the evaporating medium need to be high, hence higher the atmospheric temperature higher will be the rate of evaporation leading to better cooling of the storage space for food preservation. For better performance of evaporative cooling in natural refrigerator the dry-bulb temperature (32℃-40℃) and wet-bulb temperature (<24℃) should be maintain for an extended period of time.

B. Ambient Relative Humidity

Ambient relative humidity describe the amount of water molecule present in the ambient air. Since to maintain mass equilibrium in the system, water molecules need to evaporate from wet surface to the ambient air, hence less will be the ambient relative humidity more will be the rate of evaporation, resulting better cooling performance.

C. Geometric Surface area of Evaporating Medium.

It is proven analytically, the rate of evaporation is directly proportional to the surface area of the evaporating medium, direct in contact with the ambient air.

To obtain a better cooling performance for a certain volume the surface to volume ratio should be high as possible. In this paper an unique design has investigated on the effect of large outside surface area of the Refrigerator.

D. Thermal conductivity of refrigerator physical body.

Low thermal conductivity required for the materials used to construct the physical body of natural refrigerator as possible to obtain pleasant cooling region. Lower will be the thermal conductivity, higher will be the heat dissipation rate and cooling performance.

E. Hydraulic Conductivity of porous media.

To achieve constant diffusion of water molecule to the external surface of the refrigerator, perfect hydraulic conductivity of porous medium is required for proper seepage of water molecule to the ambient air. The seepage of water molecule through porous media should not be too high and too low for a certain amount of water volume.

F. Movement of surrounding air.

The movement of the surrounding air increases the evaporation rate hence increase in cooling performance of the refrigerator. Higher velocity of air around the refrigeration is required to increase the evaporation rate, hence increase in cooling performance.

2.0 Multiphysics Modeling & Simulation

In this paper a model of natural refrigerator has designed and simulated in COMSOL Multiphysics. This experiment describes the simulation of evaporative cooling effects in a natural refrigerator considering water and air as working fluid.
The cooling effect of an innovative design has compared with a standard design. *Figure.2 & 3* shows the comparison between two designs.

Figure 2. Standard evaporating refrigerator design.

Figure 3.Corrugated refrigerator design.

Above are the two axi-symmetric refrigerator designs, investigated in this experiment to compare the cooling performances. These are the 2D cross-sectional profiles of cylindrical refrigerator design, assumed to be cylindrically symmetry. The corrugated type external surface of the refrigerator increases the surface area to volume ratio compared to a conventional design. Large surface area exposed to ambient air flow, evaporates more water molecule to the atmosphere, hence increases the cooling performance.

2.1 Model Definition

The 2D half cross-sectional models of two refrigeration designs has designed in COMSOL 5.1 CAD Environment, shown in *Figure.4 & 5*
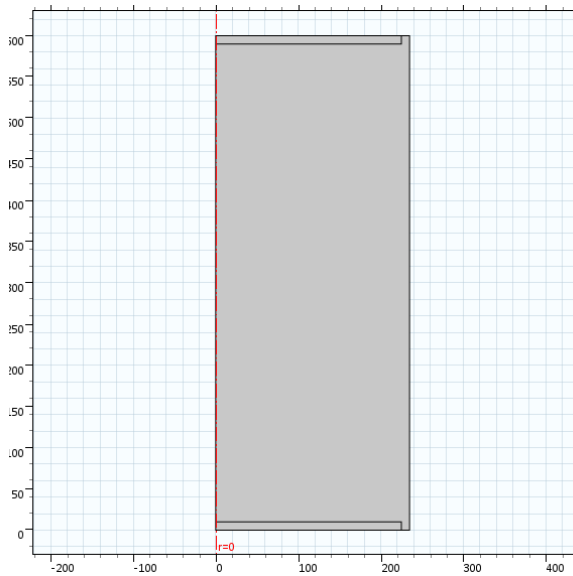
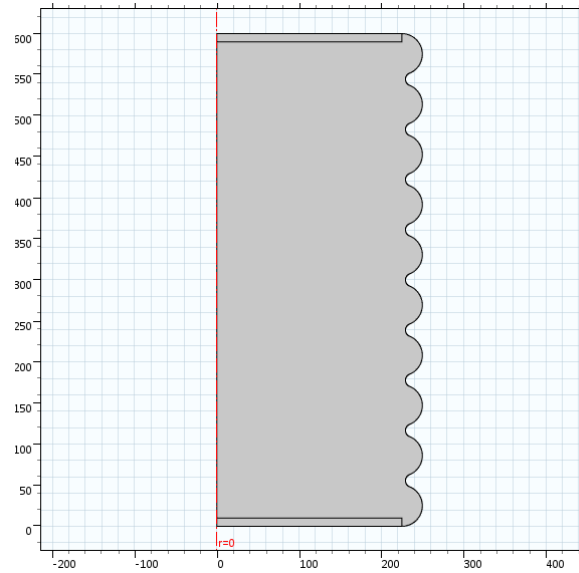**Figure 5**. COMSOL Model of corrugated evaporating external design.

Figure 4. COMSOL Model of Standard evaporating external design

In Multiphysics Simulation of evaporative cooling, three physical effects were taken into account:
- Turbulent flow of air around the refrigerator.
- Heat transfer in all domain of the refrigerator.
- Transport of water vapor to air from external surface of the refrigerator.

2.2 Turbulent Flow

The turbulent flow characteristics of ambient air enhances the diffusion of water molecules to atmosphere increasing the evaporative cooling rate. Turbulent flow, Low Re K-ε interface of COMSOl Multiphysics 5.1 has taken into account to simulate the airflow around the refrigerator. The flow of air and turbulence equation are assumed to be compressible(Ma<0.3) & RANS (Reynolds Averaged Navier Stoke) respectively. This allows to calculate the turbulent flow field around the refrigerator in advance and then can be used as input for the heat transfer and species transport equations.

2.3 Heat Transfer

The heat transfer from external surface of the refrigerator to the ambient air is due to convection and inside the refrigerator is conduction.

The turbulent flow of air increases the heat dissipation rate from external surface of the refrigerator to the atmosphere. During evaporation, latent heat released from the external wet surface due to phase change of water molecules from liquid to vapor, resulting energy loss, which creates cooling effect. The Heat transfer module of COMSOL 5.1 has taken into account to simulate heat transfer phenomena of the refrigerator. Governing equation for heat transfer is given below.

$$-n.(-k\nabla T) = H_{vap}n.(-D\nabla c + uc)$$

Where H_{vap} is the latent heat of vaporization.

2.4 Transport of Water Vapor

The amount of water which is evaporate from the water chamber to air domain, plays an important role to enhance the performance of refrigerator. The water molecule diffusion rate in large surface will be more compared to a planer surface, resulting increase in cooling efficiency of the refrigerator. In this experiment it is proven that, by increasing the surface to volume ratio for a certain amount will increase the evaporation rate. Transport of Diluted Species interface of COMSOl 5.1 has used for air domain to calculate the amount of water transported from the refrigerator to ambient air. In this experiment the concentration is chosen as per an initial relative humidity of 20 %. The ideal gas law at saturation pressure has applied as boundary source of vaporisation to the external surface of the refrigerator.

$$c_{vap} = \frac{P\,sat}{Rg\,T}$$

Where c_{vap} is the specific coefficient of vaporisation, P_{sat} is the constant saturation pressure, R_g is the gas constant and T is the temperature. The transport equations for air domain further uses the flow field results solved with Turbulence Low Re K-ε interface. Later following equation has implemented as turbulent diffusivity to the diffusion tensor.

$$D_T = \frac{vT}{ScT}\,I$$

Where vT is the turbulence kinematic viscosity, ScT is the turbulent Schmidt number and I the Unit matrix.

3.0 Result & Discussion

The performance of evaporation cooling has analysed and compared for two different designs. The effects of surface to volume ratio on evaporative cooling performance has manipulated in this experiment. *Figure 6 & 7* represents the temperature distribution for conventional & corrugated surface area refrigerator.
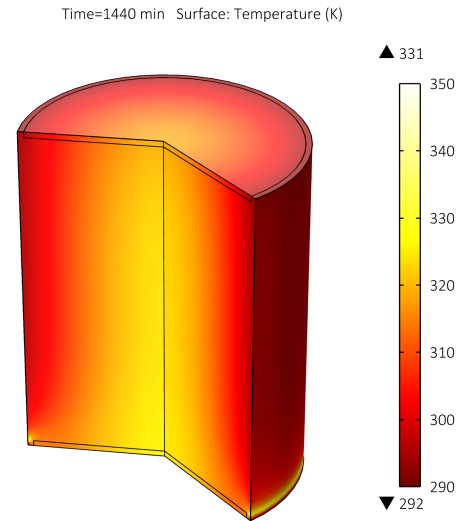

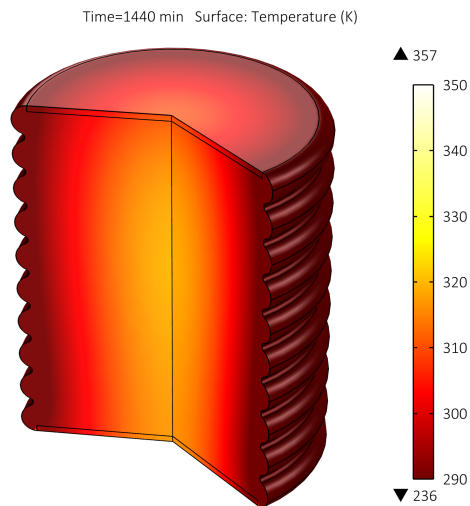Figure 6. Temperature distribution in a standard design.

Figure 7. Temperature distribution in corrugated design.

Simulation results shows the temperature distribution for evaporation cooling in both designs. Natural cooling shows the potential to lower the temperature by about 50℃ from the initial condition. The corrugated design shows potential to further lowering the temperature arout 14%. Temperature difference of 10℃ has obtained with large evaporative surface area compared to standard design.
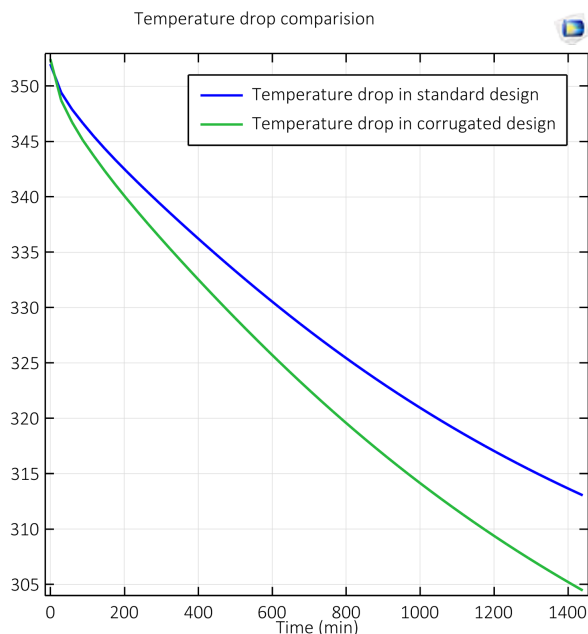

Figure 8. Temperature drop comparison.

The evaporative cooling effects for both designs were evaluated and temperature drop values for both designs for specific time duration has compared as shown in *Figure 8*. From this experiment a temperature difference of 10℃ has achieved. From this experiment it is proven that, evaporative refrigerators made with large evaporative surface area have more cooling rate compared to standard designs.

4.0 Conclusions

The process of evaporative cooling for natural refrigeration system has explained. The effects of large surface to volume ratio in evaporating cooling process has investigated. Two different experimental model has simulated numerically.

The evaporative cooling effects in both designs were compared. The real time coupled multiphysics involved in evaporative cooling process, has solved using COMSOL Multiphysics 5.1 simulation software. The derived results from simulation results were compared respectively. The phase change physics model helped to optimise the evaporator design for efficient performance. The corrugated evaporative surface demonstrated 14% reduction in temperature compared to standard design. This multiphysics modeling methodology can further be used to optimise evaporative cooling based low cost products with superior performance for realistic weather.

5.0 Acknowledgement

6.0 References

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