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Modelling of Evaporative Cooling of Porous Medium Filled with Evaporative Liquid

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Abstract: The cooling effect by evaporative liquid is modeled by considering that heat is transferred from the system to the surrounding due to evaporation of liquid through the pores present in the medium. The variation of cooling rate with cell size, volume fraction of pores and physical conditions has been analyzed. The model demonstrates that it increases with increase in thickness of the foam slab and with increase in velocity of air. It is also observed that cooling effect decreases with decrease in volume fraction of porosity and with increase in relative density, cell size, thermal conductivity and relative humidity.

Nomenclatures

g	amount of water evaporated (Kg/hr)
θ	Evaporation coefficient (Kg/m^2.hr)
V_0	velocity of air above the water surface (km/hr)
A_{eff}	effective area of water surface (m^2)
W_s	humidity ratio in saturated air at same temperature as water surface
W	humidity ratio in air
ϕ	Relative humidity
P_v	partial pressure of water vapour in unsaturated moist air (N/m^2)
P_s	partial pressure of moisture in saturated air (N/m^2)
P_a	atmospheric pressure of moist air (N/m^2)
q_1	heat loss due to evaporation (J)
h_w	heat of water evaporation (J/Kg)
q_2	heat gain due to conduction (J)
A	surface area of material (m^2)
K	thermal conductivity of porous body (w/m °C)
Δt	temperature difference of the faces of body ($\Delta t = dt$)
l	thickness of the body in the direction of flow (m)
q_3	heat loss from the water and body (J)

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m_p	mass of porous body (Kg)
m_w	mass of water (Kg)
s_p	specific heat capacity of porous body (J/Kg °C)
s_w	specific heat capacity of water (J/Kg °C)
ρ_w	density of water (Kg/m^3)
ρ_p	density of porous body (Kg/m^3)
t	diameter or thickness of edges (m)
d	cell size of the unit cell (m)
v	total volume of the porous body (m^3)
k_0	thermal conductivity of dense material (w/m °C)
R_d	relative density
N	number of cells
φ	Porosity
c	water layer thickness (fraction of t) (m)

1 Introduction

Liquid evaporation in porous media has been applied in various engineering applications such as electronic equipments for cooling systems, geothermal operation, heat exchangers etc [Shih and Huang (2002)]. Many industrial and biological phenomena also involve the evaporation of the liquid in porous media [Bennacer and Sefiane (2007)]. Darcy's law, permeability and porosity are used to describe porous media in terms of the flow conductance and connected void spaces [Greenkorn, (eds. 1983)]. In the recent years, considerable attention is being paid towards the development of metal foam for specific applications like electronic packaging, heat exchangers, shock absorbers, catalytic converters, filters etc [Banhart and Baumeister (2000) and Gibson (eds. Anthony Kelly, Car Zwesea)]. These foams draw enormous attentions by the researchers because of their excellent blending of improved mechanical properties and excellent physical properties. Metal foam has porosity in the range of 40 – 90% and the nature of pores may be open or closed. In the case of open cell, the pores are interconnected whereas in case of closed cell, the pores are separated by thin metallic film, which is called cell wall [Gibson (eds. Anthony Kelly, Car Zwesea); Banhart and Baumeister (1998); Gibson and Ashby (1997) and Ashby, Evans, Fleck, Gibson, Hutchinson and Wadley (2000)]. Because of very high porosity and low density of aluminum and its alloys, aluminum foam is an ultra-lightweight multifunctional material having relative density in the range 0.05 – 0.3. Relative density is defined as the ratio of foam density to that of dense matrix alloy with which it is made off. Therefore it can be used not only in application like heat exchangers, for shock and impact absorption in automobile, vibration control etc, but also as structural sandwich panels [Haack, Butcher, Kim and Lu. (2001); Lu., Stone and Ashby (1998); Mahjoob and Vafai (2008) and Miyoshi (1998)]. Because of having better stiffness, the foam structures could be used for making an evaporating chamber, which could provide reasonably good cooling effect. It becomes more suspicious from the understanding of the cooling of human body after evaporation of sweating; the porous structure of human skin also helps in controlling the body temperature. Similar understanding could be made from the observation of cooling of water bodies even in the summer [Heckert (2008)]. The cooling of water in clay pots is another example. This is attributed primarily to the loss of latent heat during evaporation of the liquid from the surface of the water body or from the thin film around the pores of the skins. The cooling effect is affected by various factors like surface area, air circulation speed, humidity, temperature, latent heat of the liquid etc. [Yip and McHugh (2006) and Novak, Sadowshi, Schoonovea, Abdel Khalik and Ghiaasiaan (2008)]. For proper heat transfer the surface area of the foam should be large, so that heat flow could be increased. Open cell foam has the advantage of having large surface area (in the range approximately between 500 to 2000 m^2 /m^3). The effective surface area of the open cell materials would strongly depend on the cell size, porosity fraction and cell wall thickness [Calmidi and Mahajan (1999); Kim, Paek and Kang (2000); Leong and Jin (2006) and Edmundo (2004)]. However, to the best of our knowledge, the evaporation of liquid in a porous body as a function of porous structure characteristics and finally the cooling effect due liquid evaporation has not been studied.

This paper depicts the various parameters effecting the evaporation of liquid through porous media and producing the cooling effect by conducting heat from the system to the surroundings. The heat required for evaporation is taken from water and porous structures and the structures gets cooled. Some amount of heat is continuously supplied to the body due to heat of conduction, radiation and convection from the surrounding. The cooling effect varies with the rate of evaporation and also the latent heat of the liquid. In order to have better understanding of these facts and to also have correlation of cooling rate with several factors related to the surrounding, porous materials and structures, and the liquid characteristics, an attempts has been made to simulate and model analytically the cooling effect in a chamber made of porous body associated with continuous and very slow fluid flow. The cooling effect within the chamber of open cell aluminum foam has been examined for validation of the model.

Attempts was made [Tian, Han, Long and Xie (2009)] for analysis of heat conduction on plates with functionally graded materials using hybrid numerical method. Singular superposition, boundary element method was also used by some researchers for analysis of multidimensional heat flux for application to film cooling holes [Silieti, Divo and Kassab (2009)]. All these methods are numerical and deals with extensive mathematical calculation and computation. Additionally these methods have used in dense materials.

2 Analytical Model

A schematic diagram of liquid evaporation system is shown in Fig.1. It considers the heat transfer processes of a wetted wall (in saturated porous media). A thin film of liquid is maintained over the surfaces of the pores of the foam panel. Therefore liquid is supplied continuously and slowly. Furthermore, for facilitating the analysis, the following assumptions are made:

1. The conduction of heat takes place under steady state condition and heat transfer due to radiation and convection is not considered.
2. The liquid film is extremely thin and heat loss is primarily due to evaporation of liquid from the pore surface.
3. There is no internal heat generation.
4. The material is homogenous and isotropic (thermal conductivity is constant in all direction)

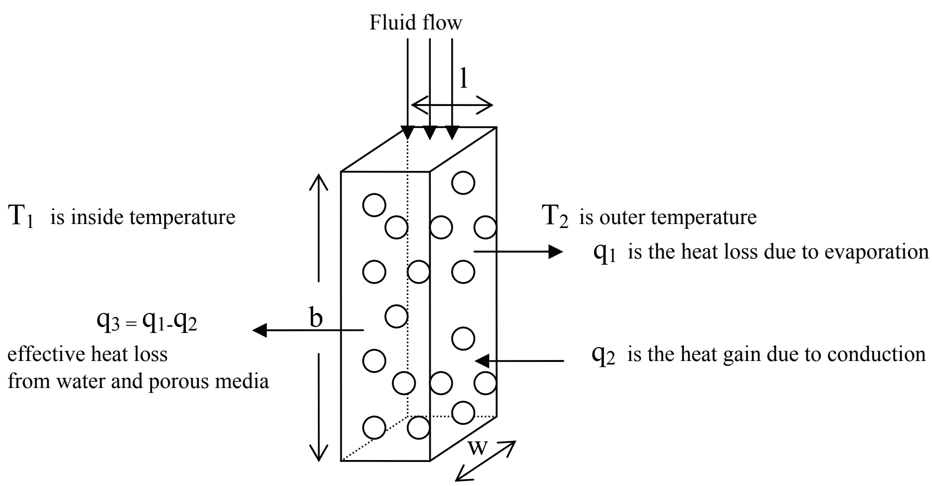

Figure 1: A schematic diagram of liquid evaporation system.

Consider a metal foam slab (as shown in Fig. 1) having thickness 'l' and face area 'A' partially filled with an evaporative liquid (water). It is considered that the temperature on side 1 and side 2 are T_1 and T_2 respectively. Then from the basics of thermodynamics the system shown above can be summarized as follows:

$$q_3 = q_1 - q_2 \tag{1}$$

Where, q_1 is the heat loss due to evaporation, q_2 is the heat gain due to conduction and q_3 is the effective heat loss from water and porous body.

2.1 Heat loss due to evaporation

Most of the heat required for evaporation is taken from the water envelope in the wall of pores of the foam. To maintain the water temperature heat must be supplied. The heat-supplied q_1 for evaporation of water can be calculated as:

$$q_1 = h_w.g \tag{2}$$

Where h_w is the heat of water evaporation (2500 KJ/Kg) and g is the amount of water evaporated. During the process, the foam body will also receive heat due to conduction.

2.2 Amount of water evaporated

The amount of water evaporated (g) from the foam surface is given by the following equation [Www. Engineering Tool Box.com]:

$$g = \theta A_{eff}(W_s - W) \tag{3}$$

Where A_{eff} is total surface area of pores surfaces or effective area, W_s is humidity ratio in saturated air and W is humidity ratio in unsaturated air.
Where θ is the coefficient of water evaporation expressed as a function of air circulation velocity (V_o) with following relation [Www. Engineering Tool Box.com]:

$$\theta = 25 + 19V_0 \tag{4}$$

2.3 Heat gain due to conduction

Conduction of heat from the surrounding could be obtained through Fourier's law.
According to Fourier's law "the rate of flow of heat (q_2) through a simple homogenous solid is directly proportional to the area of the section at right angles to the

direction of heat flow and to change of temperature with respect to the length of the path of the heat flow" It can be expressed by the following relation [Verma (2007)]:

$$q_2 = kA\Delta t/l \tag{5}$$

Where, q_2 is heat flow through a body per unit time, A is surface area of heat flow, Δt is the temperature difference of the faces of block of thickness (l) through which heat flows and k is the thermal conductivity of body.

2.4 Effective heat loss from water and porous body

Heat loss from the porous body partially filled with water envelope in terms of specific heat capacity and mass of body could be written as follows:

$$q_3 = (m_p.s_p + m_w.s_w)\Delta t \tag{6}$$

Mass of water could be computed as:

$$m_w = A_{eff}.c.t.\rho_w \tag{7}$$

Mass of porous body can be computed as:

$$m_p = v.R_d.\rho_p \tag{8}$$

Where, m_w is the mass of water, m_p is the mass of porous body, s_w is the specific heat capacity of water, s_p is the specific heat capacity of porous body, c is a fractional constant, ρ_w is density of water, ρ_p is density of porous body, t is diameter or thickness of edges, R_d is relative density, v is total volume of the porous body.
Substituting the expression for q_1, q_2, q_3 in (Eq.1) we gets:

$$(m_p.s_p + m_w s_w)\Delta t = h_w.g - kA\Delta t/l \tag{9}$$

The (Eq.9) can be rearranged as follows:

$$\Delta t = h_w.g/(m_p.s_p + m_w.s_w + kA/l) \tag{10}$$

Substituting the expression for g in (Eq.10) and rearranged as follows:

$$\Delta t = \frac{h_w.\theta A_{eff}(W_s - W)l}{3600((m_p.s_p + m_w.s_w)l + kA)} \tag{11}$$

Substituting the expression for θ, m_p and m_w in (Eq.11) one gets:

$$\Delta t = \frac{h_w.(25 + 19V_o)A_{eff}(W_s - W)l}{3600((vR_d.\rho_p s_p + A_{eff}.c.t\rho_w.s_w.l) + kA)} \tag{12}$$

The terms 3600 comes into the expression as the velocity of air considered here as Km/hr. The above relation states that Δt is a strong function of R_d, A_{eff}, cell size (d), A (area of the slab) and etc. It is considered that metal slab has open cell pores. For convenience it is assumed that the cells are cubic in shape and distributed in cubical arrays. The cubic unit cell is shown schematically in Fig.2. This is the simplest form and is used for getting solutions in a complex structure. The simple cubic unit cell consists of 12 edges. Four neighboring cubic cells share each edge. Thus the effective edges per unit cells are three. Let the cell size (empty portion) of the unit cell is 'd' and the thickness or diameter of the edges is 't'. Then we can find out the effective area and relative density of foam in terms of d and t. The three cell edges can be considered as three equivalent cylinders for solving the problem.

2.4.1 Effective surface Area and Relative density of open cell foam

From the Fig.2, The surface area of each edge of unit cell is πtd and the surface area of edges per unit cell is 3πtd. Thus the effective surface area of pore in the slab = 3Nπtd

Where N is the number of cells in the given volume, N can be expressed as follows:

$$N = \frac{v}{(d+t)^3} \tag{13}$$

$$v = A.l \tag{14}$$

Finally Total effective Surface Area could be written as follows:

$$A_{eff} = \frac{3v\pi.t.d}{(d+t)^3} \tag{15}$$

2.4.2 Relative Density

Relative density (R_d) is the ratio of the density of foam to the density of dense material with which the foam is made off. It is also found to be equivalent to the solid fraction in the foam. The volume of each edges of unit cell is $\pi(d+t)t^2/4$ and the volume of edges per unit cell is $3\pi(d+t)t^2/4$.

The solid fraction or relative density (R_d) is then computed as:

$$R_d = \frac{3.\pi.t^2(d+t)}{4.(d+t)^3}, \quad R_d = \frac{3.\pi.t^2}{4.(d+t)^2} \tag{16}$$

2.4.3 Porosity

It is ratio of volume of void space to the total volume of the medium.

$$\varphi = V_p/v \tag{17}$$

The porosity can be obtained in terms of relative density as follow as:

$$\varphi = 1 - R_d \tag{18}$$

Substituting the expression for R_d in (Eq.18)

$$\varphi = 1 - \frac{3.\pi.t^2}{4.(d+t)^2} \tag{19}$$

2.5 Calculation of relative humidity

Relative Humidity ϕ is the ratio of actual mass of water vapour in a given volume of unsaturated moist air to the mass of the water vapour in the same volume of saturated air at same temperature and pressure. It can also be expressed in terms of partial pressure as follows [Khurmi and Gupta (2005)]:

$$\phi = m_v/m_s \quad \text{or} \quad \phi = P_v/P_s \tag{20}$$

Where P_v is the partial pressure of water vapour in unsaturated moist air and P_s is partial pressure of moisture in saturated air.
Humidity ratio is the ratio of mass of water vapour to mass of dry air in a given volume of the air-vapour mixture and can be expressed as follows.
Humidity ratio of unsaturated air [Khurmi and Gupta (2005)]:

$$W = m_v/m_a = (R_a.P_v)/(R_v.P_a) \tag{21}$$

Substitute R_a = 0.287 KJ/Kg.K for dry air, R_v = 0.461 KJ/Kg.K for water vapour.
According to Dalton law of partial pressures:

$$P_b = P_a + P_v \tag{22}$$

Substitute the value of R_a, R_v and P_a in (Eq.21) we get:

$$W = \frac{0.622P_v}{P_b - P_v} \tag{23}$$

Where P_b = atmospheric pressure of moist air.
The maximum amount of water vapour in the air is achieved when $P_v = P_s$.
Humidity ratio of saturated air:

$$W_s = \frac{0.622P_s}{P_b - P_s} \tag{24}$$

Substituting the expression for A_{eff} in (Eq.12) and then rearranging one gets:

$$\Delta t = \frac{h_w.3v\pi.td(25+19V_o)(W_s-W).l}{3600((vR_d\rho_p.s_p(d+t)^3+3v\pi.d.c.t^2.\rho_w.s_w).l+k(d+t)^3A)} \tag{25}$$

Substituting the expression for v in (Eq.25) one gets:

$$\Delta t = \frac{h_w.3\pi.t.d(25+19V_o)(W_s-W).l^2}{3600((R_d\rho_p.s_p(d+t)^3+3\pi.d.ct^2\rho_w s_w)l^2+k(d+t)^3)} \tag{26}$$

The thermal conductivity as a function of porosity can be expressed as [Sumirat, Ando and Shimamura (2006)]:

$$k = k_0(1-\varphi) \quad k = k_oR_d \tag{27}$$

Where, k is thermal conductivity of porous body and k_0 is thermal conductivity of dense material.

Substituting the expression for k in (Eq.26) we get:

$$\Delta t = \frac{h_w.3\pi.t.d(5+19V_o)(W_s-W).l^2}{3600((R_d\rho_p.s_p(d+t)^3+3\pi.d.ct^2\rho_w s_w)l^2+k_0R_d(d+t)^3)} \tag{28}$$

3 Results And Discussion

3.1 Effect of cell size'd'

The variation of the extent of cooling Δt with cell size for foam slab having different relative densities at the air velocity of 8 km/hr are shown in Fig 3. It is evident from this figure that the cooling decreases with increase in cell size. It further depicts that the extent of cooling decreases with increase in relative density. This is attributed to the fact that within a given volume of foam, the effective surface area increases with decrease in cell size and relative density. Thus, more amount of water is expected to be evaporated vis-à-vis more heat would be extracted due to absorption of latent heat of evaporation.

3.2 Effect of Relative Density

The variation of the extent of cooling with relative density for the foam slab having different values of cell size at the air velocities of 4 km/hr is shown in Fig 4. It is evident from the figure that the extent of cooling Δt decreases with increase in relative density. It further depicts that the extent of cooling decreases with increase in cell size. The explanation again due to decrease in effective surface area with increase in cell size and increase relative density.

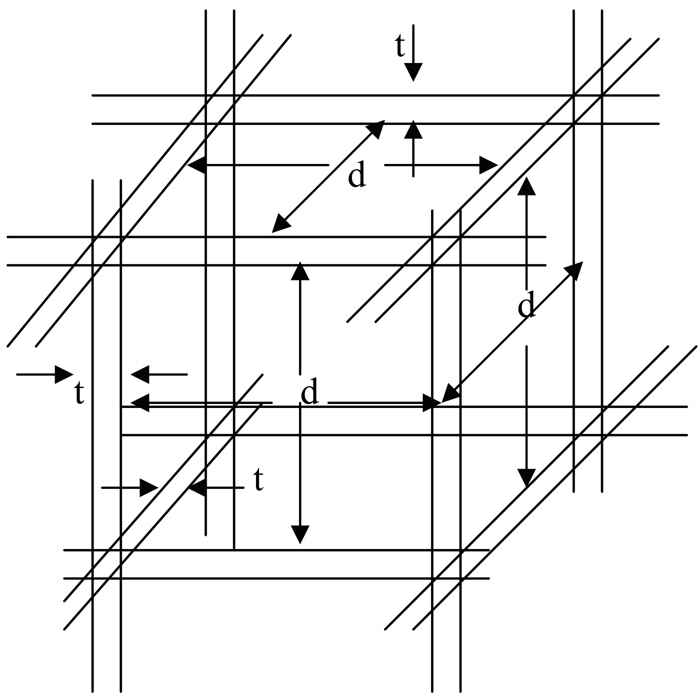

Figure 2: A schematic representation of the cubic unit cell of open cell foam.

3.3 Effect of Air velocity

Fig 5. Demonstrates the variation of Δt with the air circulation velocity above the evaporative liquid within the foam having different values of cell size at relative density 0.1. It is clear that Δt increases with increase in air velocity. It also shows that the extent of cooling decreases with increase in cell size. It is interesting to note that the extent of cooling of the order of 18 °C could be achieved if the cell size of foam could be reduced to 5 mm at the air circulation velocity of 20 Km/hr. This is attributed to the fact that the amount of water evaporation increases with increase in air velocity.

3.4 Effect of Thermal conductivity

The variation of Δt with the thermal conductivity for foam having different values of cell size at relative density 0.1 and air velocity 12 km/hr is shown in Fig 6. From the figure it is clear that the cooling decreases with increase in the thermal conductivity. This is attributed to the fact the heat gain due to conduction increases

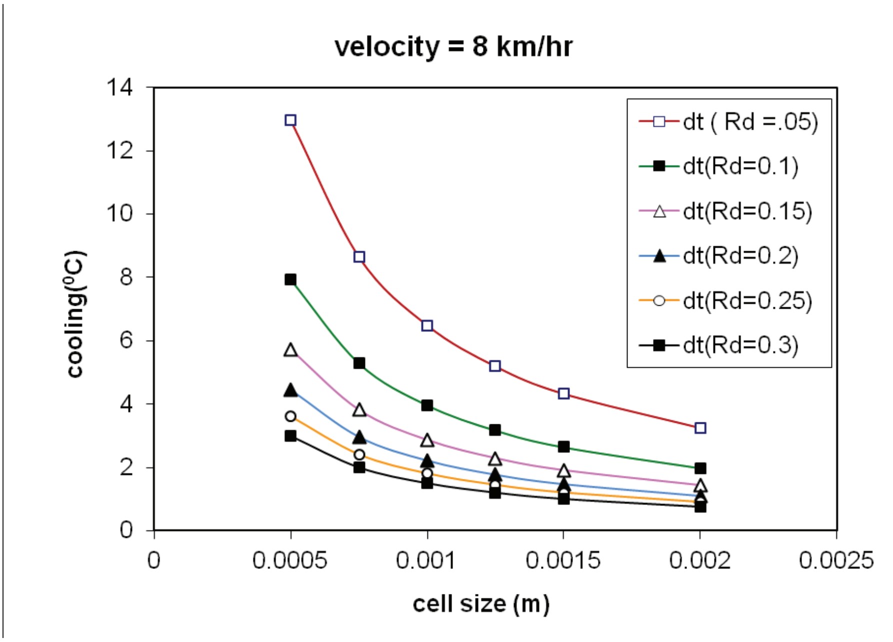

Figure 3: Variation of the extent of cooling with cell size of Al foam slab having different relative densities at the air velocities of 8 km/hr.

with increase in conductivity of dense material with which it is made of. Thus, it is expected, that foam of less conductive material would provide better cooling.

3.5 Effect of Relative Humidity

The variation of the extent of cooling with the relative humidity of the surrounding of the foam having different relative densities at a velocity of 8 km/hr is shown in Fig. 7. It is evident that the cooling decreases linearly with increase in relative humidity. This is attributed to the fact that the extent of evaporation of liquid decreases with increase in relative humidity. The effect of relative humidity has been incorporated using the steam table dependence on temperature of surrounding; then P_s is the partial pressure of air corresponding to saturation temperature can be calculated. Depending on the relative humidity, the W_s and W was calculated and then computed using the Equation (23) and Equation (24). Detailed calculation of P_a, P_v, P_s has been shown in Appendix.

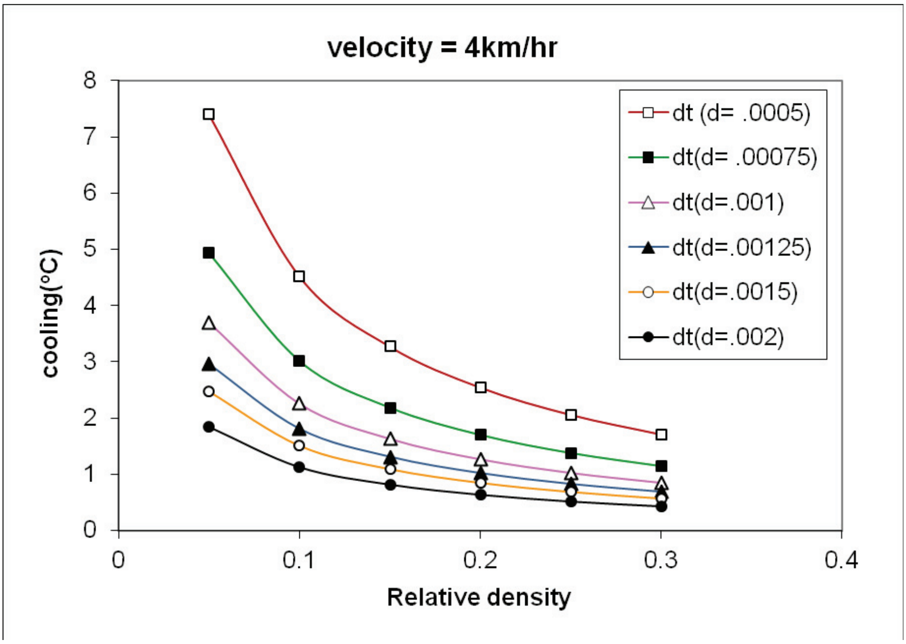

Figure 4: Variation of the extent of cooling with relative density for the Al foam slab having different values of cell size at the air velocities of 4 km/hr.

3.6 *Effect of Slab Thickness*

The variation of the extent of cooling with the thickness of the Al foam slab for different relative densities at a cell size of 0.5 mm for air velocity of 8 km/hr are shown in Fig (8). From the figure it is clear that the cooling increases with increase of slab thickness. This is primarily due to the fact that the amount of A_{eff} vis-à-vis evaporation of liquid increases with increase in slab thickness. It is also due to less extent of heat gain through conduction because of higher slab thickness. The observation made through the different figures computed using Equation (28) is physically meaningful. But, with increase in A_{eff}, requirement of evaporation liquid increases. The model also states that the foam with less conductivity would provide greater intent of cooling.

4 Validation

The calculated cooling effect in a chamber of foam slab has been compared with the experimental value. In the present investigation for validation experiment, a foam slab of aluminum with a thickness of 15 mm has been considered for making

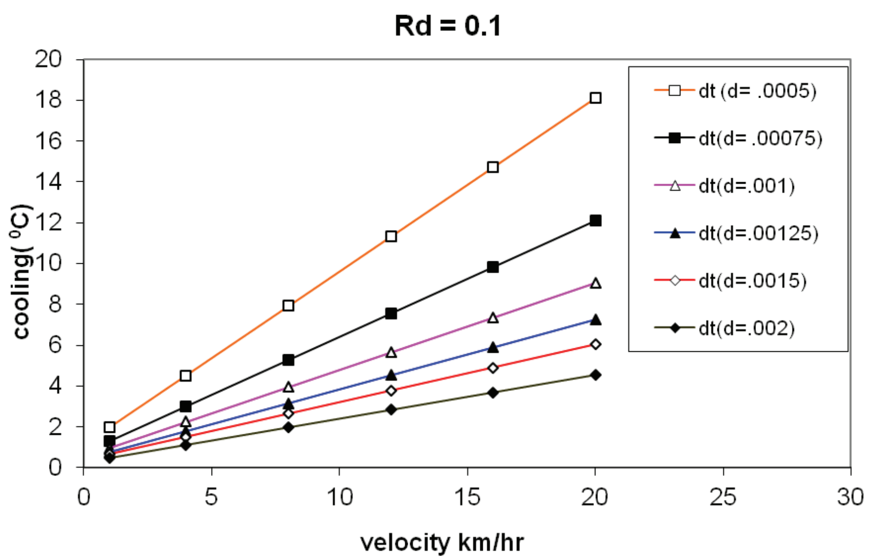

Figure 5: Variation of the extent of cooling with the air circulation velocities above the evaporative liquid with in Al foam having different values of cell size at relative densities of 0.1.

the chamber. The syntactic view of the chamber is shown in Fig. 9. The cooling chamber has dimension of 500 mm x 500 mm x 500 mm. At the top of the chamber a container having dimensions 500 mm x 500 mm x 150 mm is placed. A series of holes of 1 mm are made at the side of the container so that water can pass through these holes and falls on the foam slab. The holes are made so tiny that water can pass drop by drop. For better control of water flow through the holes a series of pins attached on the steel rod are placed on the holes. While the steel rod is moved upward water can pass very slowly drop by drop and finally it just wet the foam slab. If any excess water is there, it will be collected at the container placed at the bottom of the chamber. A thermometer is placed inside the chamber and another one is place outside the chamber. The chamber is placed below a ceiling fan and the speed of the fan is controlled. The air flow speed surrounding the chamber is varied by varying the fan speed. The air flow speed is measured from the movement of the tiny pieces of the paper as a function of time near the chamber. The humidity at the atmosphere is varied by varying the moisture content surrounding the chamber. The tests were conducted during summer when the air is mostly dry. The humidity surrounding the chamber is measured using hygrometer. The temperature in and outside the chamber is measured by using the respective thermometers and the

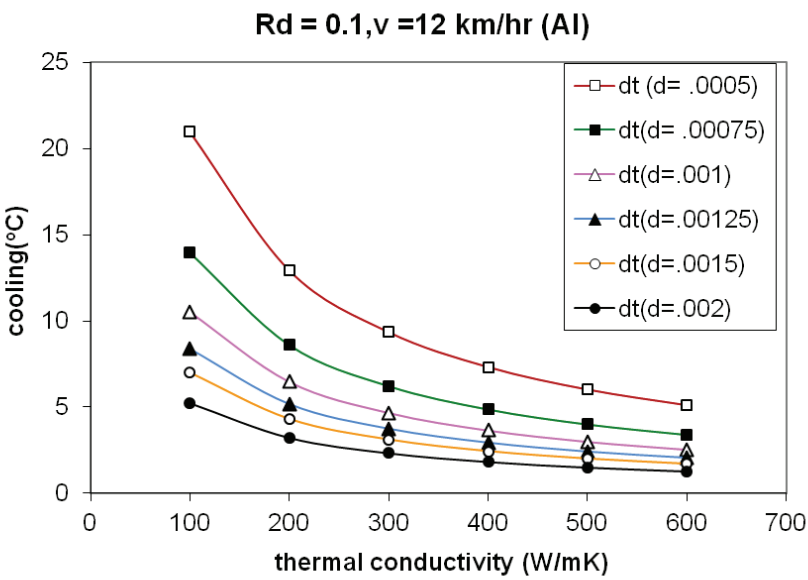

Figure 6: Variation of the extent of cooling with the thermal conductivity of matrix material of foam having different values of cell size at relative density of 0.1 and air velocity 12 km/hr.

temperature difference after one hour is reported. The characteristic of Al foam has been reported in Table 1. Table 1 also includes the process parameters like relative humidity, air velocity and relative density. The experimentally obtained cooling has been compared with the theoretically determined ones again in Table 1. It is noted that the calculated cooling effect in chamber made with Al foam slab is comparable within $\pm$ 5 – 10% variation with the experimental value, irrespective of air velocity, relative density and relative humidity for ambient temperature of 38 °C. This signifies that the proposed model is in good agreement with experiment. Thus the present model could be used for predicting the cooling effect in a chamber made of a porous body, which is continuously and slowly fed with evaporative liquid. The source of deviation from experimental value may be because of the assumption of cubic pores and their existence in cubic array. In practical cases, all the pores are not of cubic shapes and are not of the same size.

Additionally, the presence of water film over the pores would change the thermal conductivity of the foam slab. The convection and radiation mode of heat transfer have been overlooked. Still, the proposed model provides a reasonably good

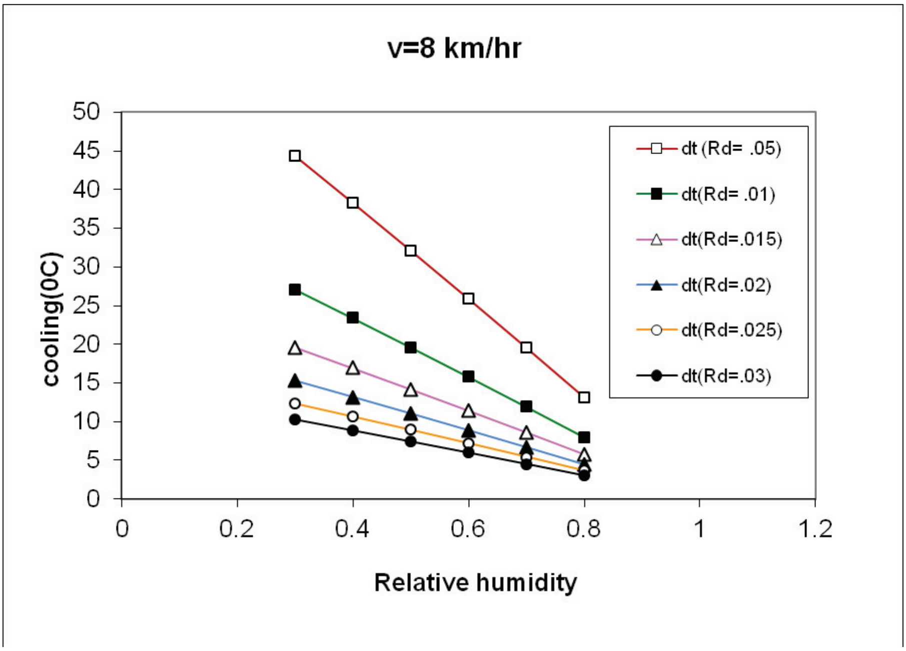

Figure 7: Variation of the extent of cooling with the relative humidity having different values of relative densities of Al foam at a velocity of 8 km/hr.

Table 1: Material properties of aluminum foam at relative density 0.2.

Velocity (Km/hr)	Relative humidity	Relative density	Slab Thickness (m)	Temperature difference Δt (°C) (theoretical)	Temperature difference Δt (°C) (experimental)
8	0.3	0.2	0.015	7.635	8.0 ± 1
8	0.2	0.2	0.015	8.667	8.6 ± 1
8	0.1	0.2	0.015	9.686	11 ± 2
8	0.3	0.1	0.015	13.557	14.1 ± 1
8	0.2	0.1	0.015	15.3886	15.8 ± 1
8	0.1	0.1	0.015	17.1971	16.3 ± 2
4	0.3	0.2	0.015	4.356	5.0 ± 1
4	0.2	0.2	0.015	4.945	5.4 ± 1
4	0.1	0.2	0.015	5.527	6.1 ± 1
4	0.3	0.1	0.015	7.735	7.5 ± 1
4	0.2	0.1	0.015	8.78	9.2 ± 2
4	0.1	0.1	0.015	9.81	11.1 ± 2

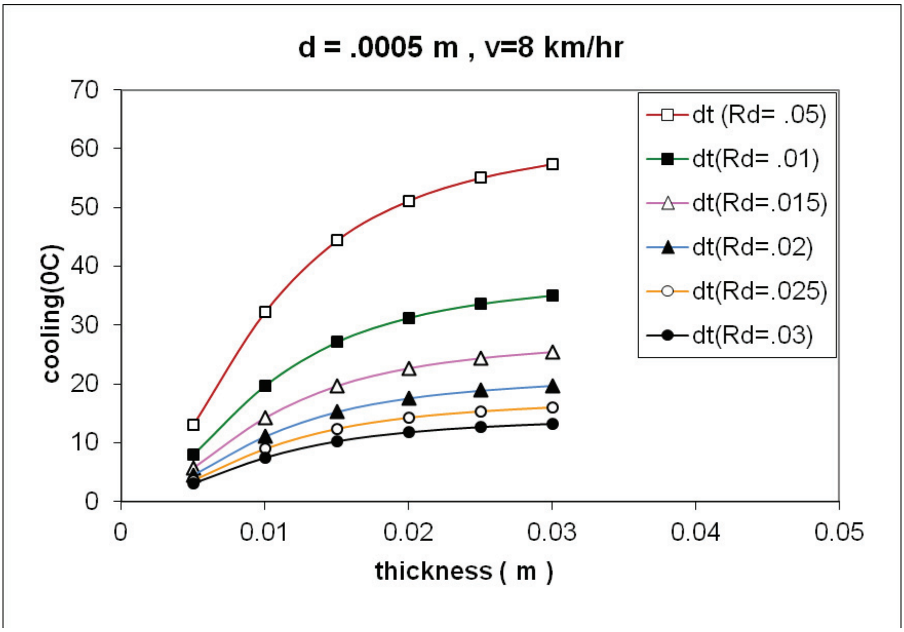

Figure 8: Variation of the extent of cooling with the thickness of the Al foam slab of cell size of 0.0005 m and air velocity of 8 km/hr.

accuracy.

This type of chamber could be used in rural areas particularly where there is no electricity. Even where electricity is available, particularly in urban areas also, it could be used for storage of food, vegetable and cold water for at least two to three days. It would be very beneficial for armies who are in duty in a very remote area for storage of their foods and other items for few days. It do not need any electrical power and hence it could be an energy efficient component for storage purpose especially in the recent time when global warming is threating to the lives on the earth.

5 Conclusions

In order to predict the extent of evaporative cooling in a chamber made with open cell porous structure fed with evaporative liquid, an analytical model has been developed. The model is developed considering cubic cells arrange in cubical arrays, wherein each edges of the cells are cylindrical in nature. The model so developed has been experimentally verified on Al foam fed with water and it was noted that

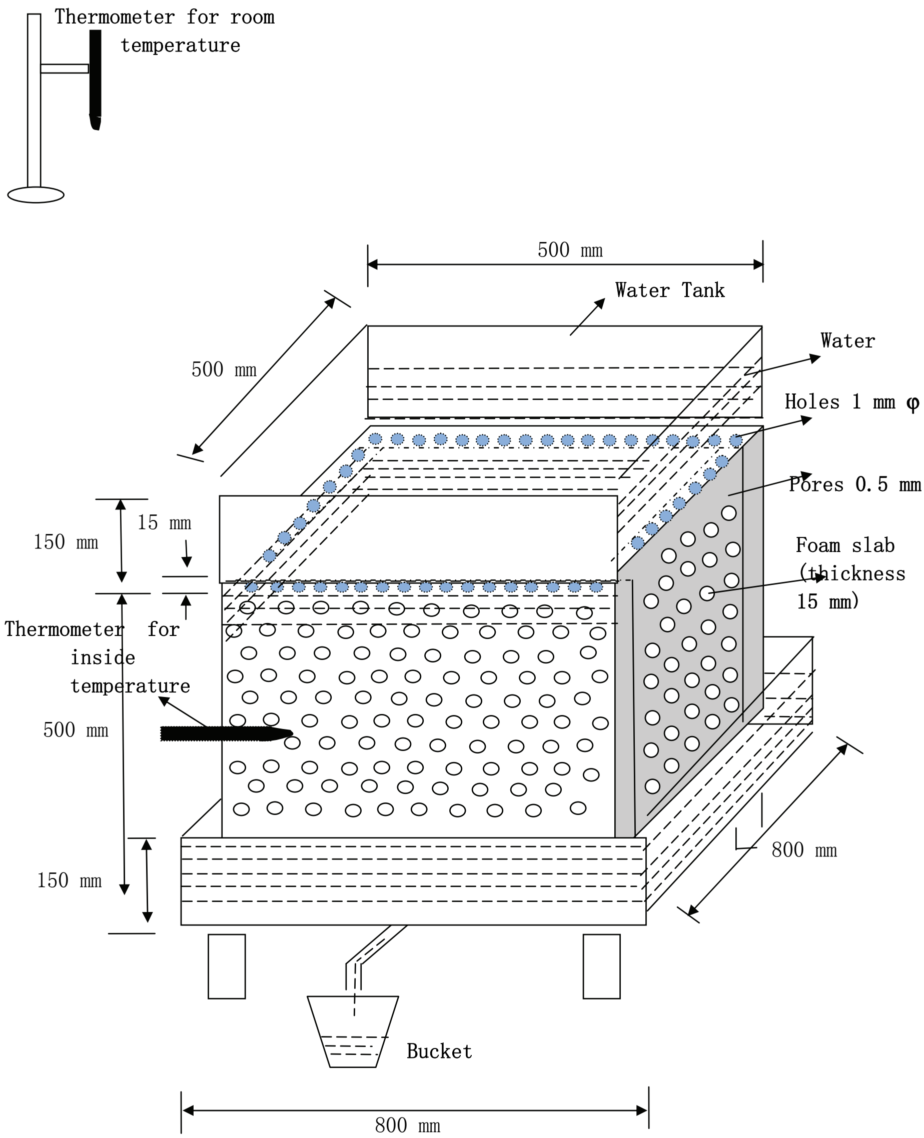

Figure 9: A schematic diagram of the cooling chamber.

the model agees well with experimental values. The model states that the extent of cooling decreases with increase in cell size, relative density, relative humidity and conductivity of the materials. Whereas, the extent of cooling increases with increase in air velocity, foam slab thickness and latent heat of evaporative liquid.

These facts are also physically meaningful. The chamber is an energy efficient component could be used for storage purpose.

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Appendix

V_a, T_a, m_a, R_a, P_a = Volume, Temperature, Mass, Gas constant, Partial Pressure respectively for unsaturated air.

V_v, T_v, m_v, R_v, P_v = Corresponding values for the water vapour
Assume that the unsaturated air and water vapour behave as perfect gas.
For unsaturated air:

$$P_a V_a = m_a R_a \tag{A1}$$

For water vapour:

$$P_v V_v = m_v R_v \tag{A2}$$

Also, $V_a = V_v$, $T_a = T_v = T_d$ (T_d is dry bulb temperature)
Where, V is the volume of unsaturated air or moist air or saturated air.
Dividing the (A2) by (A1) we get:

$$P_v / P_a = (m_v R_v)/(m_a R_a)$$