Modelling of Honeycomb Devices for Building Applications

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ABSTRACT

The Rayleigh-Benard convection in a fluid (air) layer bound by transparent cellular structure (honeycomb) is examined for the engineering design of honeycomb devices. Absorptance transmittance product and heat loss coefficient are another characteristics of TIM devices. The main parameter related to engineering design is aspect ratio of the cell, which is correlated to wave number. The relations have been developed for critical rayleigh number. The results highlight a new facet that the resultant Rayleigh numbers can be used to estimate the critical Rayleigh number for fluid layer with honeycomb structure. The honeycomb structure of aspect ratio 10-15 seems suitable for suppression of convection in air layer of depth 5-15 cm for the temperature difference in the range of 20^0 to 120^0. Further computational results for open south window concluded that the inside room temperature is higher for closed window system as compared to the system with open window. Since the effect of former is more pronounced than the latter, therefore window should be kept closed in a mild winter day.

Keywords: Transparent insulation materials, Honeycomb panel, Critical Rayleigh number.

INTRODUCTION

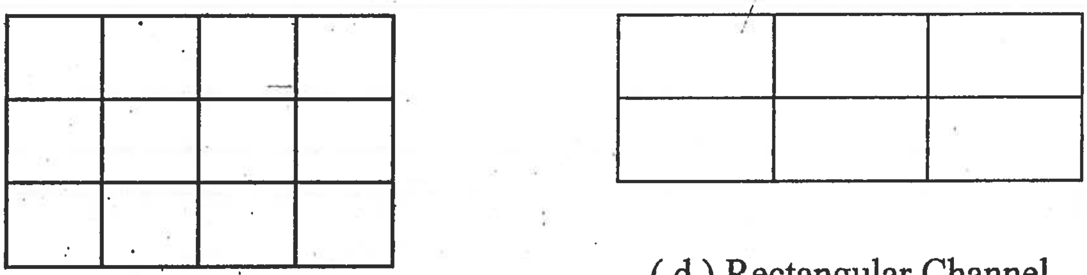
A conventional insulation material device is characterized by the heat transfer coefficient across it. However to evaluate the thermal performance of a transparent insulation material (TIM) device it is necessary to derive a quantitative analysis of solar optical and thermal behavior of the device. The TIM device is, therefore, characterized by the following parameters:

1. Convective effects in honeycomb device for the given application
2. Solar absorptance transmittance product of the device.
3. Heat loss coefficient across the device.

Following Hollands (1965) [12] extensive experimental as well as theoretical research on honeycomb devices and their effectiveness for suppressing both infra red radiation and convection have been carried out. The glass and the plastic materials have been used for the fabrication of honeycomb devices. Honeycomb made of non-transparent reflecting materials were used by Buchberg et al. (1971) [4]. Glass tube thick walled (0.2mm-0.3mm) material was used by Francia (1961)[10]. Hollands (1961,1979) used thin walled plastic material like mylar, Teflon etc. Several cell shapes have been investigated. Hexagonal shape of bee honeycomb is often cited by engineers as most economical use of two dimensional space. The hexagonal cross-section was, therefore, one of the earliest to be considered for the shape of cells in honeycomb array of TIM. Subsequently, amongst others Cylindrical (Ostrach and Pneulir (1963)[18]; Buchburg and Edwards (1975), square(Charters and Peterson(1972)[7] and rectangular(Arnold et al,(1976)[3] cells have been investigated. Some of cell Shapes are illustrated in Fig. 1

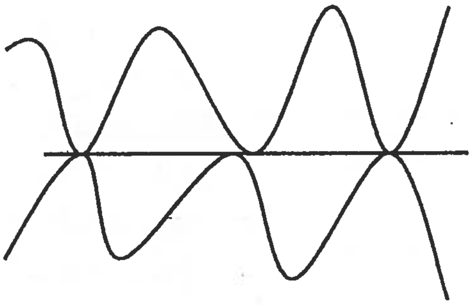
(a) Circular Tubes

(b) Hexagonal



(c) Square Tubes

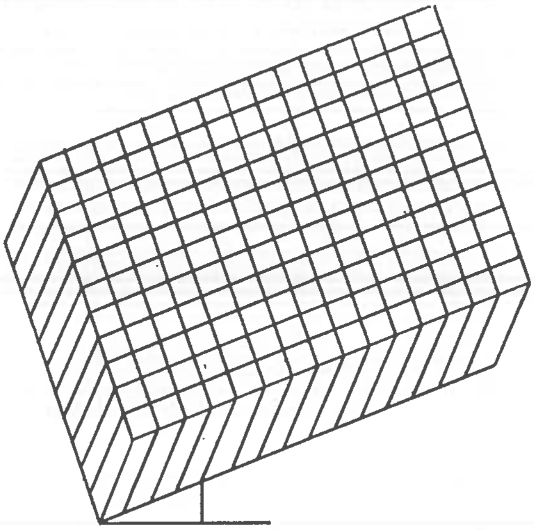
(d) Rectangular Channel



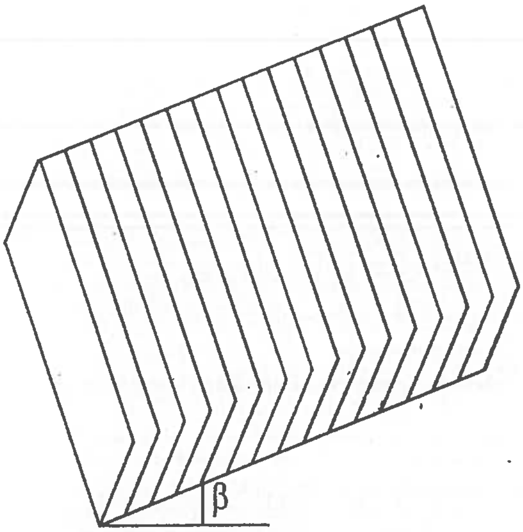
(e) Horizontal Strips

Fig.1 Cell Configuration

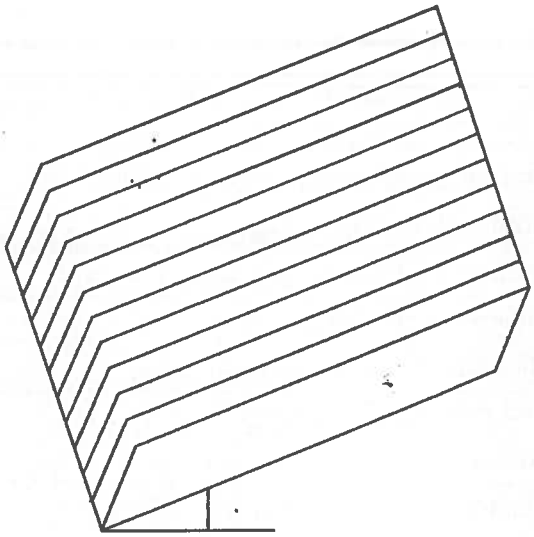
These types of cellular structures can be fabricated from glass material by joining simple individual shapes like round tubes and rectangular channels. This is a rather cumbersome method. Fabrication of the device from plastic material is relatively easier but the device exhibits problems like the loss of transmittance due to weather ability etc. Charters(1977)[8] has reviewed the investigations of natural convection across an air layer confined between the solar collector glazing and absorber plate in horizontal as well as inclined planes. He pointed out that in case of inclined solar absorber the motion is mainly upslope. Therefore parallel slat honeycombs (Figs.(2b, 2c)) are quite sufficient to suppress fluid motion in practical situation. The resultant device would involve a considerably simplified fabrication procedure and cut far less insolation (reaching the absorber) than the conventional three dimensional honeycomb (Fig. 2a).



(a) Square honeycomb



(b) Transverse slat



(c) Up slope slat

Fig. 2 Schematic of cellular structures

1 Convective effects in honeycomb devices

The main parameter related to convective effects in honeycomb devices for building applications is critical rayleigh number which depends on the physical shape and aspect ratio(A=L/d) of honeycomb cell as well as on the thickness and other thermo physical properties of the cell walls. Following Ostrach and Pnueli (1963)[18]; Edward and Catton (1969)[9]; Pawan Kumar and Kaushika (2005)[19]; may be expressed as

$$R_c = \frac{(m^2 h^2 + 23.9)^3}{(m^2 h^2 + 7.97)} \text{ where } h = \pi\sqrt{5}A \text{ and } 0.75 \leq m \leq 1 \qquad \ldots(1.1)$$

The computed values of R_C for m=0.75 in eq. (1.1) are found to be in close agreement with experimentally measured values of Heitz and Westwater (1971) [1], as shown in Table1.

Aspect Ratio of the Panel		0	1	2	4	6	8
Exp. values of R_c obtained by Heitz & Westwater		1700	3800	2.1×10^4	2.1×10^5	1.1×10^6	3.3×10^6
Computed values of R_c	M=0.75	1713	3859	2.06×10^4	2.27×10^5	1.06×10^6	3.27×10^6
	M=0.85	1713	4842	3.07×10^4	3.63×10^5	1.73×10^6	5.35×10^6
	M=1.0	1713	6857	5.28×10^4	6.75×10^5	3.27×10^6	1.02×10^7

Table1: Computed and experimental values of critical Rayleigh number

In this paper we have developed an alternative approach for the evaluation of critical Rayleigh numbers of air layers bound by honeycomb panels. The model is purely mathematical situation based on normal mode technique of hydrodynamic stability of fluid layer of horizontal infinite extent . Following Chandrasekhar (1961)[6]; it involves numerical solution for higher wave numbers of transcendental characteristic equations of normal mode analysis of Rayleigh Benard problem for rigid surfaces given by

$$(D^2-h^2)^3V+h^2RV \;=0 \qquad \ldots(1.2)$$

$$V=DV=(D^2-h^2)^2V=0 \; at \;\; y=\pm1/2 \quad \ldots(1.3)$$

Assuming $V=A\cos q_0y+B\cosh qy+\bar{B}\cosh\bar{q}y$

as even solution and as odd solution

$$V=A\sin q_0y+B\sinh qy+\bar{B}\sinh\bar{q}y$$

for eq. (1.2), where A, B are arbitrary constants, is a root of the eq.and is given by $q=q_1+iq_2$ such that

$$q_1=\tfrac{1}{\sqrt{2}}h\{\sqrt{(1+n+n^2)}+1+\tfrac{1}{2}n\}^{\frac{1}{2}},q_2=$$

$$\tfrac{1}{\sqrt{2}}h\{\sqrt{(1+n+n^2)}-(1+\tfrac{1}{2}n)\}^{\frac{1}{2}}\;\&\;q_0^2=h^2(n-1) \qquad \ldots(1.4)$$

The characteristic eqs for even and odd solutions of eq. (1.2) obtained by using eq. (1.4) are as follows:

Even characteristic equation:

$$\mathrm{im}\{(\sqrt{3}+i)q\tanh\tfrac{1}{2}q\}+q_0\tan\tfrac{1}{2}q_0=0 \quad \ldots(1.5)$$

Odd characteristic equation :

$$q_0\cot\tfrac{1}{2}q_0-\mathrm{Im}[(\sqrt{3}+i)\times q(\frac{\sinh q_1-i\sin q_2}{\cosh q_1-\cos q_2})=0 \qquad \ldots(1.6)$$

if real part of eigen values obtained from characteristic eq. (1.5) and eq.(1.6) are positive, the mode is unstable and consequently the flow is unstable. Otherwise the flow is stable. The maximum value of R for some Pr for which real part of eigen value is non positive is called the critical Rayleigh Number. Below this number the flow is stable. If Rayleigh Number exceeds this number, Perturbation will occur which do not decay with time and the system will become unstable. If real part of eigen value is zero, The perturbation neither grow nor decay with time and the system is at marginal state.

Here we have used the bisection method to find the characteristic values of transcendental eqs (1.5) and (1.6).The results are in the form of Rayleigh number as a function of wave number h. Chandrasekhar (1961)[6] has reported the results of such solutions for the values of wave numbers in the range 0-8. The computed results for Rayleigh number of even solution as well as odd solution for higher wave numbers are represented by fig.3.

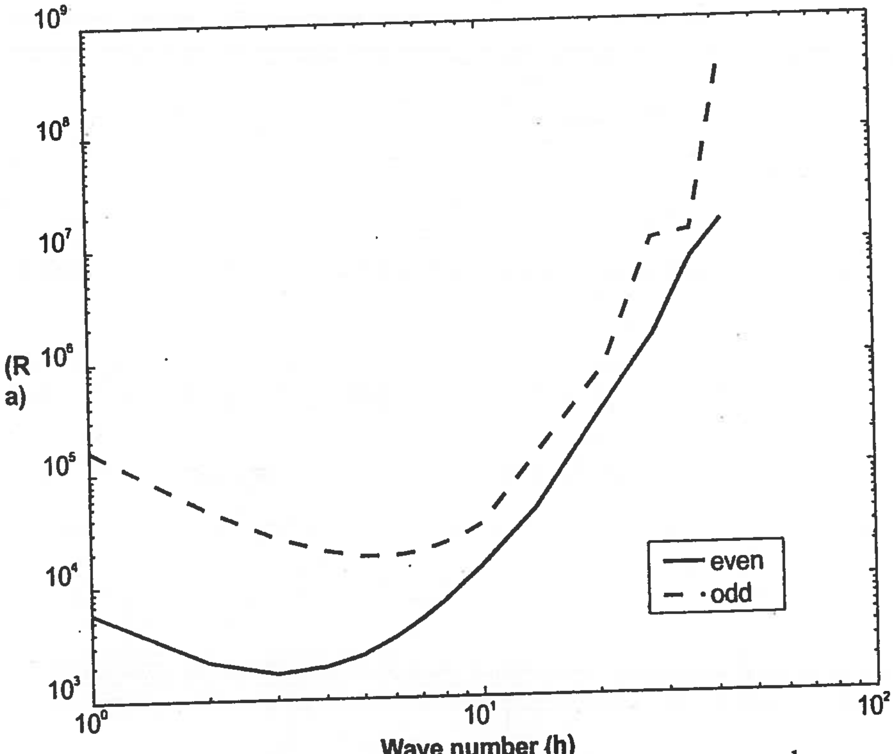


Fig.3 Rayleigh numbers corresponding to wave numbers

We see that the even perturbations are more adverse to the stability than the odd perturbations and hence we will use the value of critical Rayleigh numbers corresponding to the wave numbers for odd solution in further calculations.

The critical Rayleigh number curve of present analysis corresponding to the onset of instability is compared with the analysis of Edward and Catton(1969)[9] and the results of experiment of Heitz and West water (1971)[11]. The similarity of above results represented by fig. 4 concludes that Table 2 for odd solution may be used for critical Rayleigh number as a function of wave number. The critical Rayleigh number for those wave numbers, which are not given in Table 2, may be calculated iteratively by solving eq. (1.6) for required h.

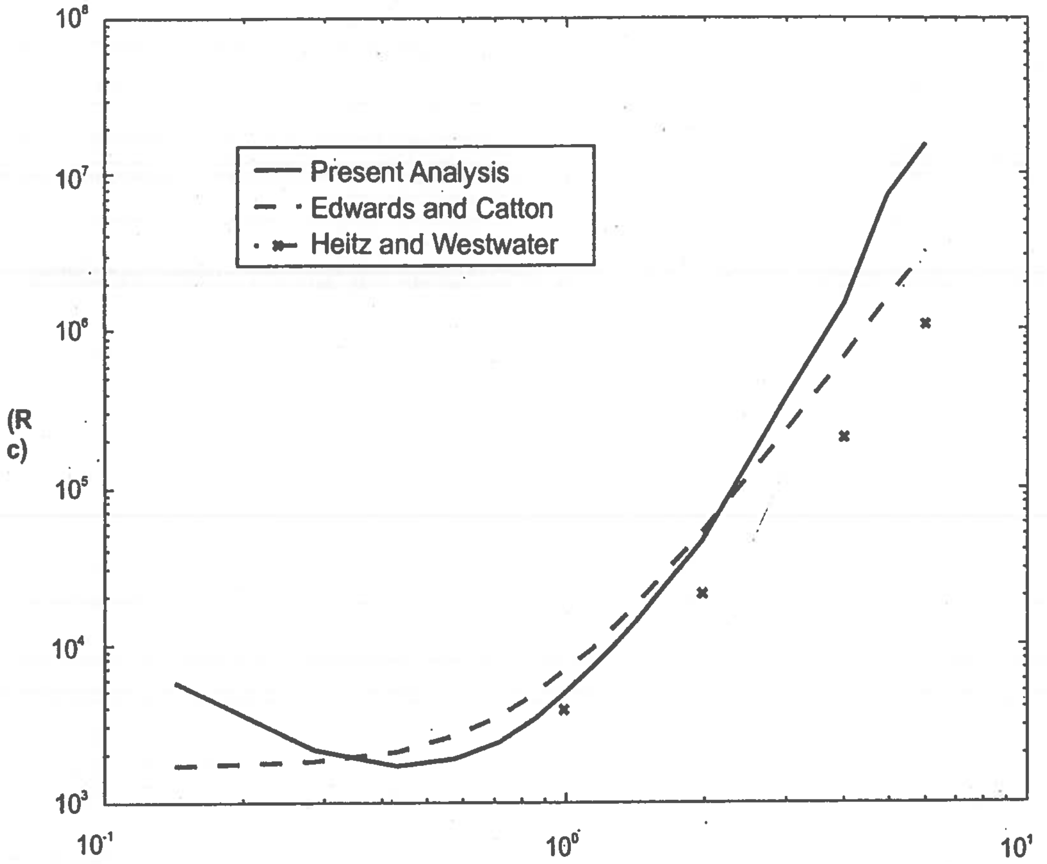


Fig.4 Comparative study of critical Rayleigh numbers as a function of aspect ratio.

Table 2 Rayleigh number versus wave numbers corresponding to the onset of instability

H	*Ra* from even solution	Ra from odd solution	$\bar{h}$	*Ra* from even solution	*Ra* from odd solution
0	∞	∞	8	7084.51	22461.5
1	5854.48	163127.6	9	10089.6	26599.7
2	2177.41	47005.6	10	14134.45	32104.1
3	1711.28	26146.6	14	45599.44	133719
4	1879.26	19684.6	21	354430	807950
5	2439.32	17731.5	28	1468100	10779735
6	3417.98	17933	35	7174150	12338440
7	4918.54	19575.8	42	15405050	430239300

For convection suppression we have

$$(\Delta T)_{\max} = \frac{Rc\kappa\nu}{g\alpha L^3} \qquad \ldots(1.7)$$

For air we have

$$g = 9.8m/s^2, \kappa = 2.67\times10^{-5} m^2/s, \upsilon =$$

$$1.921\times10^{-5} m^2/s, \alpha = (2.97\times10^{-3})^0 C^{-} \ldots(1.8)$$

Hence the value of

$$\frac{\kappa\upsilon}{g\alpha} = 17.622\times10^{-9}\ \xi = \text{(say)} \qquad \ldots(1.9)$$

$$(\Delta T)_{\max} = \frac{\xi R_c}{L^3} \qquad \ldots(1.10)$$

ξ is number having different values fo different materials. The computed (T) $_{\max}$ values of air layer as obtained from eq. (1.10) are illustrated in Fig.5 and Fig.6 respectively. It shows that cell width of 8-10 mm is required to suppress convection for the range of temperature difference as 50-100^{0}C for 2 cm depth of Honeycomb and so on.

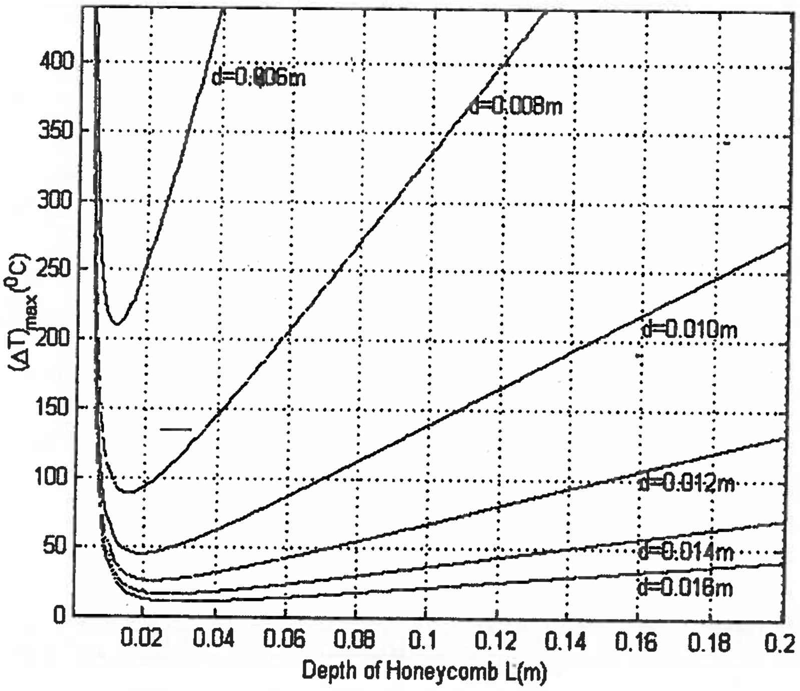


Fig.5 Variation of for honeycomb with its depth(L) and cell size (d)

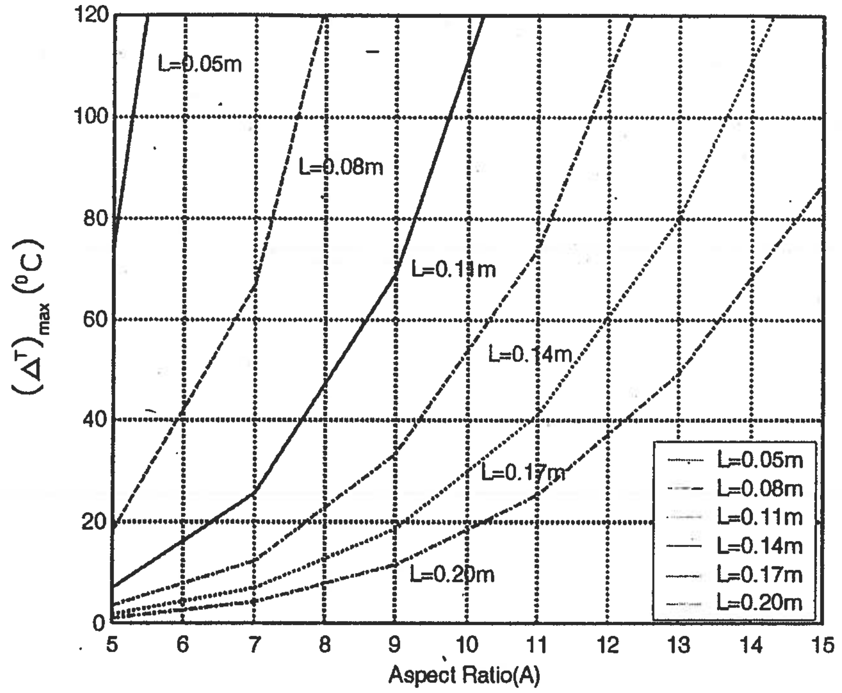


Fig.6 Variation of $(\Delta T)_{\max}$ with aspect ratio (A) for honeycomb of depth(L)

2 Solar absorptance transmittance product of the device.

For the evaluation of $(\alpha\tau)$ of the TIM device containing cellular array with top and bottom covers is represented by Fig. 7.

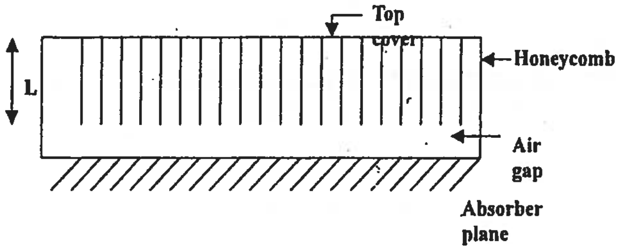


Fig. 7 Schematic of compound honeycomb cover system.

Solar beam radiation absorptance-transmittance product, neglecting multiple reflections in the panels,may be expressed as :

$$(\alpha\tau)_b(\theta,r_s)=\tau_b(\theta,r_s)\tau_1(\theta)\tau_2(\theta)\alpha(\theta) \quad ...(2.1)$$

where

$\tau_b(\theta,r_s)$ = the solar beam radiation transmittance of cellular honeycomb arrays

$\tau_1(\theta)$ = the solar beam radiation transmittance of cover plates

$\tau_2(\theta)$ = the transmittance based on absorption of the encapsulating cover plates

$\alpha(\theta)$ = absorptance of the absorber plane=0.98 for black absorber

Following Hollands et al (1978)[3] and Padmapriya (1991)[15], the beam radiation transmittance for honeycomb and parallel slat arrays $\tau_h(\theta,\phi)$ may be expressed as

$$\tau_h(\theta,r_s)=[T_c(\theta,\phi)+ET_w(\theta,r_s)]\frac{1}{(1+E)} \quad ...(2.2)$$

$$T_c(\theta,r_s)=T_d(\theta,r_s)+\rho^d_{\phi e}F[1-T_d(\theta,r_s)]/(\rho^d_{\phi e}+\alpha_\phi) \quad ...(2.3)$$

$$T_d(\theta,r_s)=(\rho^s_{\phi e})^n(n-N+1)+(\rho^s_{\phi e})^{n+1}(N-n) \quad ...(2.4)$$

$E=\delta(\delta+2d)/d^2$ (For square cell)

$E=\delta/d$ (For parallel slat)

$$N=\begin{cases} A\tan\theta=\dfrac{L}{d}\tan\theta & \text{for square honeycomb} \\ A\tan\theta\cos\phi & \text{for parallel slat} \end{cases}$$

$$\cos\phi=\cos(\pi/2-\theta)\cos r_s$$

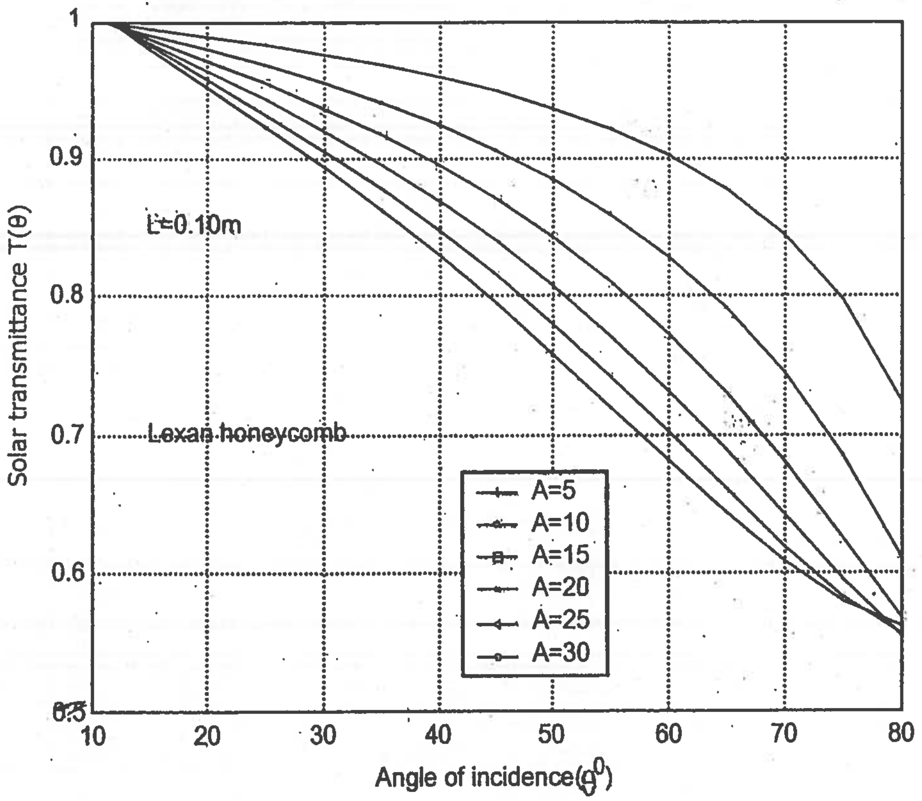


Fig. 8 Variation of solar transmittance of Lexan honeycomb cell with angle of incidence

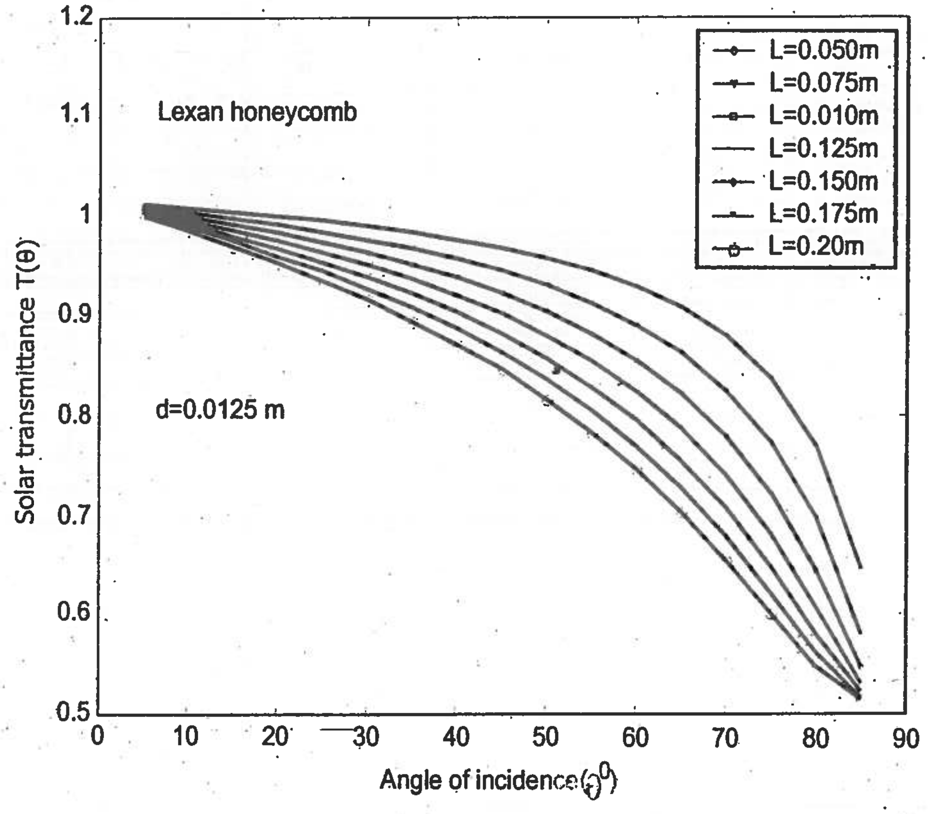


Fig.9 variation of solar transmittance of honeycomb for fixed spacing d=0.0125 m

Table3: Solar beam radiation absorptance- transmittance product with angle of incidence for different aspect ratio fixing cell depth 10 cm of the Lexan TIM device.

Aspect Ratio(A)	5	10	15	20	25	30
Angle of Incidence						
0	0.8213	0.8181	0.8149	0.8118	0.8086	0.8056
5	0.8296	0.8348	0.8400	0.8453	0.8508	0.8562
10	0.8254	0.8264	0.8276	0.8290	0.8307	0.8324
15	0.8208	0.8177	0.8149	0.8125	0.8106	0.8089
20	0.8158	0.8083	0.8014	0.7953	0.7900	0.7852
25	0.8099	0.7977	0.7868	0.7770	0.7684	0.7606
30	0.8029	0.7858	0.7706	0.7570	0.7451	0.7347
35	0.7941	0.7716	0.7519	0.7345	0.7196	0.7067
40	0.7825	0.7542	0.7298	0.7088	0.6910	0.6759
45	0.7669	0.7322	0.7031	0.6786	0.6583	0.6416
50	0.7449	0.7035	0.6697	0.6422	0.6201	0.6026
55	0.7131	0.6649	0.6269	0.5972	0.5743	0.5572
60	0.6663	0.6118	0.5707	0.5404	0.5184	0.5030
65	0.5968	0.5378	0.4964	0.4680	0.4492	0.4373
70	0.4972	0.4381	0.4006	0.3778	0.3646	0.3579
75	0.3661	0.3146	0.2870	0.2732	0.2673	0.2660
80	0.2179	0.1838	0.1709	0.1670	0.1671	0.1689
85	0.0838	0.0743	0.0736	0.0745	0.0757	0.0769

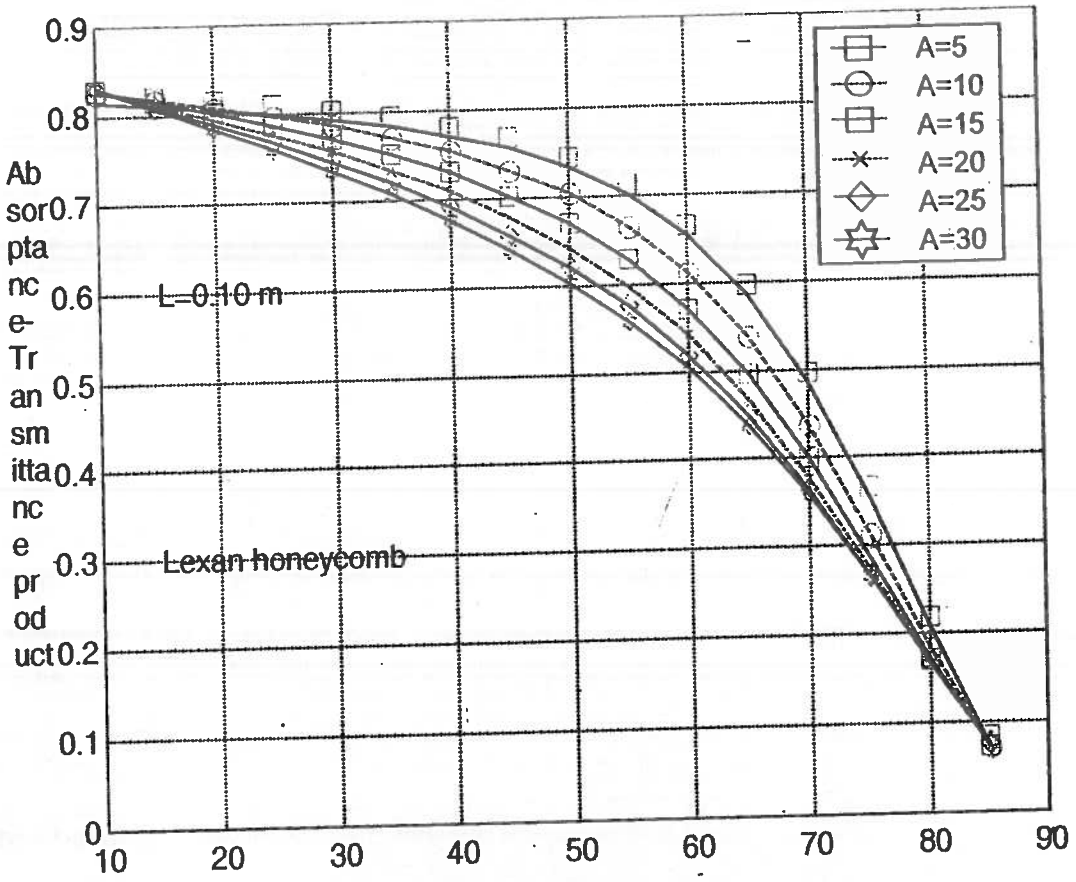


Fig.10 Variation of solar absorptance transmittance product of Lexan honeycomb (depth=10 cm) with angle of incidence

Table 4. Per day thermal units required to maintain comfortable indoor air temperature (20^0 c) for various walls/ roof thickness for thermally uninsulated system (air conditioned building)

Region	Per day thermal units required in kWH			
	Walls/roof thickness			
	4 inches	6 inches	9 inches	14 inches
Leh	9.23	7.61	6.03	4.48
Boulder	7.91	6.53	5.17	3.84
Delhi	0.84	0.69	0.55	0.41

Table 5. Percentage reduction in heat flux load for various walls/ roof thickness and TIM depth on south wall for thermally uninsulated system (air conditioned building)

Region	TIM Depth (cm)	Percentage reduction in heat flux load for walls/roof thickness			
		4 inches	6 inches	9 inches	14 inches
Leh	5	30	31	33	35
	10	32	34	36	39
	15	35	37	41	46
Boulder	5	26	26	28	29
	10	27	29	30	32
	15	30	32	35	38
Delhi	5	No Load	No Load	No Load	No Load
	10	No Load	No Load	No Load	No Load
	15	No Load	No Load	No Load	No Load

Summary and Conclusions

It is seen that placement of TIM insulation device on south wall enhances the heat flux and hence reduces the air conditioning heating load. The computational investigations for steady state analysis gives that the Per day thermal units requirement decreases on increasing wall/roof thickness to maintain comfortable indoor air temperature(20^0 c) for thermally uninsulated system (air conditioned building). Computational results for open south window concluded that the inside room temperature is higher for closed window system as compared to the system with open window. Since the effect of former is more pronounced than the latter, therefore window should be closed in mild winter day in Leh

Nomenclature

θ = angle of incidence of solar radiation on the top surface of panel

r_s = azimuth angle

α_ϕ =Absorptivity of the cell wall at angle

$T_c(\theta,r_s)$ = specular as well as diffuse radiation transmittance through cell at angle

$T_w(\theta,r_s)$ =transmittances through cell walls

$\tau_b(\theta,r_s)$ = total transmittance of honeycomb to radiation incident at an angle(,)

E = fraction of cross section of the honeycomb occupied by wall material

F = Geometrical shape factor of diffuse radiation leaving the vertical walls reaching the bottom of panel directly or by all other means

δ = the wall thickness of the cellular array

ϕ =angle of incidence of solar radiation on panel wall

n =integer representing the lower rounded off value of N

$\rho^{s}_{\phi e}$ = equivalent specular reflectivity of the material of walls

$\rho^{d}_{\phi e}$ = perfectively diffuse reflectivity of the material of walls

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