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ENERGY CONSERVATION

AND

THERMALLY EFFICIENT BUILDING MATERIALS

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ENERGY CONSERVATION AND THERMALLY EFFICIENT BUILDING MATERIALS

by

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INTRODUCTION

Unless it is brought to our attention we seldom stop to consider the wide variety of ways we consume energy. Every time we cook a meal, turn on a light, watch television, take a shower, or wash clothes we consume precious fuels. Each time the weather turns chilly or warm, the wind blows or it rains, we consume energy by adjusting our thermostats to compensate for these conditions.

If an attempt to achieve energy conservation is to be successful, it must be made in full light of the many factors which affect energy consumption. Unless these factors are known and understood, changes made may result in achievements far short of expectations or may actually do more harm than good.

Energy use in buildings is determined, basically, by climatic conditions of the area in which the building is located, and the working environment and business equipment required by tenants. Climatic conditions of a given region are determined by the pattern of variations of several elements and their combinations. The principal climatic elements, when human comfort and building design are being considered, are solar radiation, long wave radiation to the sky, air temperature, humidity, wind and precipitation (rain, snow, etc.) [1]. Neither of these factors is capable of any significant modification.

Figure 1 shows the energy balance for a house in winter and summer. In winter the heat is lost from the house in the following ways: conduction of heat through all the exterior surfaces; leakage of the air through cracks in the windows, walls, doors, etc. (exfiltration): leakage of cold outside air into the house (infiltration); radiation losses to the sky and the surroundings; and finally heat is lost through the water drains in the house. Heat is generated and gained in the house by: heat given off by occupants, and the use of the appliances and lights. The difference between the heat lost and the heat gained must be made up by the heating system if the house is to be maintained in the comfort range.

In summer, many of these same factors are at work. Now, however, the outside temperature is generally hotter than the comfort range, thus heat tends to flow into the structure. If the comfort range is to be maintained, an air conditioner must be employed to remove the internal appliance, occupancy, and weather loads.

All in all, to maintain a comfort range inside a building, energy must be used to run either a heating or a cooling system. The efficiency of energy use is determined by the three basic systems which comprise any functioning building. These three basic systems are:

1- Energized systems, such as those required for heating, cooling, lighting, ventilation, conveyance, business equipment operation, and so on,

2- Nonenergized systems, such as floors, ceilings, walls, roof, window (glazing), etc.

3- Human systems, comprising maintenance, operating and management personnel as well as tenants and other users.

Each of three systems is capable of modification which can lead to a significant savings of energy. Because energized systems are those which utilize energy directly, however, the natural tendency is to concentrate energy conservation efforts in that area [2]. To do so would be a mistake, however, because the efficiency of the equipment involved depends on numerous other factors. In other words, it can be very detrimental to a program of energy conservation to confuse the ends with the means. On the other hand, nonenergized systems would directly influence the sizing and choice of the energized systems. Floors, ceilings, walls, roof, windows (glazing), etc., which will be referred to as the envelope of a building separates the indoor space from the external environment.

The quantitative effect of the envelope depends on its thickness and thermophysical properties. The materials within the internal space, such as floors, partitions and even furniture, also modify the indoor temperatures by affecting the heat capacity of the structure as a whole and the rate of absorption of heat generated or penetrating within the building.

THE BUILDING ENVELOPE

As stated above, the building envelope separates the indoor space from the external environment, and in this way modifies or prevents the direct effect to climatic variables such as outdoor air temperature, humidity, wind, solar radiation, rain, snow, etc.

When the windows of a building are open, there is a flow of outdoor air through the indoor space, but even when the windows are closed they offer a very low resistance to heat flow. Through transparent and through open windows, solar radiation can penetrate and heat the building from the inside. Thus large quantities of heat may enter and leave the building, bypassing the modifying influence of the rest of the envelope.

When the indoor thermal conditions are not controlled by mechanical means, the materials affect the temperature of both the indoor air and surfaces, and thus have a very pronounced effect on the occupant's comfort. Even when control is used, in the form of heating or air-conditioning for instance, the thermophysical properties of the materials used determine the amount of heating or cooling which is provided and also the temperature of the internal surfaces. Therefore, even in these circumstances, the materials have an effect on the comfort of the occupants, as well as on the economical efficiency of the control systems.

Heat transfer through the buildings envelope may take place in four ways, by conduction, convection, radiation and evaporation (or condensation). Evaporation and condensation involve changes of state (from liquid to gas and vice versa), in which heat is absorbed or rejected. During the process of flow the heat may change its mode of transfer. Thus solar energy reaches a wall in the form of radiation, is absorbed at the external surfaces, and flows across the wall material by conduction. If the wall contains an air space, the heat flows across it by convection and radiation, continues, its flow by conduction, and is finally transferred to the indoor air by convection and to the other internal surfaces by radiation.

The properties of materials which affect the rate of heat transfer in and out of a building, and consequently the indoor thermal conditions and comfort of the occupants, are:

- Thermal conductivity, and thermal resistance
- Surface characteristics with respect to radiation-absorptivity, reflectively and emissivity
- Surface convective coefficient
- Heat capacity
- Transparency to radiation of different wavelengths

The building envelope is usually composed of two types of material, opaque and transparent. Both types of materials are discussed below.

Transparent Part of the Building Envelope

One of the characteristics of modern architecture is the widespread use of glazing in the building facades. This, and the increasing use of lightweight structures, has caused considerable changes in the relationship between interior and ambient climates and the problem of overheating has become a major concern even in temperate and cold countries.

Heat transfer through glazing is due to (i) the solar radiation penetrating though glazing when exposed to direct or indirect solar rays (solar gain). (ii) heat transfer by conduction through the glazing material due to the difference in temperatures between the outside and the inside of the building.

Solar gain: The characterizing property of transparent materials such as the glasses and certain plastics is the ability to transmit radiant energy directly; this mainly involves the visible wavelength range, although infra-red radiation may on occasions be transmitted.

On impinging on a transparent or translucent surface, radiant energy is divided into three components: a part is reflected, having no thermal effect on the material; a further component is absorbed by the material, subsequently to be dissipated to either side by convection and longwave radiation; the third component is directly transmitted through the material. From the combined viewpoints of illumination and heating, the principal distinctions between types of transparent materials are their different relative transmittances and ranges of transmitted wavelengths.

The thermal effect of transparent building materials can be considered from two points of view; the actual heat gain of the interior space is important for calculations of the cooling load in air-conditioned buildings, while the resulting indoor temperatures are of more significance to comfort in rooms without mechanical forms of heat control.

Shading: The glass affects the quantity of incident radiation and hence modifies both the heat flow to the interior and the indoor temperatures. The quantitative modifications depends on the location of the shading with respect to the glass, whether internal or external. When shading intercepts radiation outside the glass, part is reflected outwards, part is reflected inwards and the remainder is absorbed, elevating the temperature of the shade. Heat flows, therefore, by convection and radiation from the shade; heat removed by convection with the wind barely affects the glass, and the transparent materials are opaque to the longwave range of radiation. Thus only a small fraction of the incident radiation penetrates externally shaded glazed areas.

When the shading is internal, in the form of venetian blinds or roller shades for instance, solar radiation is transmitted through the glass before interception. The radiation absorbed into the shading material is re-released to the interior and almost all of this heat remains within the space as the opaqueness of the glass prevents longwave radiative heat dissipation. Only the radiation reflected outwards from the shading at the original wavelengths is transmitted in part to the exterior (some is reflected back by the glass and absorbed) and has no internal heating effect. The effectiveness of internal shading is therefore determined by its reflect it (color), and on the whole is much less than that of external shades.

The functional requirements for solar control differ widely with regional climates and, within each region, with seasonal climatic variations. This problem is further complicated because of the different yearly patterns of temperature and solar radiation.

In cold climates, the main problem is to ensure some minimum amount of solar radiation for lighting and heating. In tropical regions, the main problem is to prevent overheating due to solar radiation, while in temperate and sub-tropical areas both problems, of ensuring radiation in winter and preventing overheating in summer, exist although with different relative importance. In other words, just as it is important to let the sun in at the proper time of the year, it is also important to keep it out at other times. In many climatic regions, keeping the sun out during critical warm weather is actually more important to human comfort than letting it in during cold weather. The use of different types of glass for different sun orientation is one of the methods of obtaining shading.

The function of all window glasses is to admit daylight into the building, but inherently they also transmit heat. The absolute and relative transmittances of light and heat differ for different glasses. Glasses used in buildings can thus be divided into several types, according to their spectral transmission, absorption and reflection characteristics, the main types being clear, heat absorbing, heat reflecting and grey or colored glasses. In practice, all types of glasses absorb and reflect solar radiation, but heat-absorbing glasses absorb, and heat-reflecting glasses reflect, infra-red radiation to a greater extent than ordinary clear glass. Grey and colored (anti-glare) glasses absorb more of the visible part of the solar spectrum and may be grey or colored, according to the fraction of the visible light mostly absorbed.

Heat-absorbing glass: It is characterized by the high absorption of the infra-red portion of the solar spectrum, while transmitting most of the visible light. The increased selective infra-red absorption is due to higher content of iron oxide among the ingredients of the glass. In consequence of the absorption the temperature of the glass is elevated significantly above the outdoor air level.

Solar heat gain through heat-absorbing glass comprises two parts: the first is the direct transmission of visible shortwave and infra-red radiation and the second is the inward heat flow by convection and longwave radiation from the heated glass surface.

Heat-reflecting glasses: It is obtained by depositing very fine, semi-transparent metallic coatings on the surface of the glass, which reflects selectively a greater portion of the infra-red radiation. As the coating is sensitive to mechanical damage, reflecting glass requires protection either by double glazing with an air space or by lamination.

The ratio of the total transmitted heat to the transmitted light thus differs for the different types of glass and is lowest for heat-reflecting and highest for grey (anti-glare) glasses.

Table 1 summarizes typical values of heat gain through various types of glasses, divided into the portion directly transmitted through the glass and that resulting from the radiation absorbed in the glass.

The shading coefficient is an important way of determining the relative effectiveness of various shading devices. A single layer of clear, double-strength glass has a shading coefficient of 1.00. The shading coefficient for any other glazing system in combination with shading devices is the ratio of the solar heat gain through that system to the solar heat gain through the double-strength glass. Thus, solar heat gain through glazing systems is the product of its shading coefficient times the solar heat gain factors listed in the ASHRAE Handbooks of Fundamentals for clear, double-strength glass [3]. Table 2, shows some typical shading coefficients for various shading conditions.

Table 1

Heat gain through various types of glasses, per cent of radiation at normal incidence [1]

Types of glass	Direct transmission	Due to absorbed radiation	Total
Clear glass	74	9	83
Window glass	85	3	88
Light heat-absorbing glass	20	25	45
Grey glass	30	30	60
Lacquered glass	38	17	55

Table 2

Typical shading coefficients for various shading conditions

Shading conditions	Shading coefficient
3mm unshaded, double strength, clear glass	1.00
6mm clear, unshaded plate/float glass	0.95
6mm clear insulating glass, two lights 6mm plate/float,	0.83
clear glass with dark interior draperies 6mm heat-absorbing plate/float, unshaded	0.70
6mm blue reflective glass, unshaded clear glass with light interior venetian blinds	0.575
12mm heavy duty grey heat-absorbing, unshaded	0.50
12mm heavy duty grey heat-absorbing, with interior medium venetian blinds or dark draperies	0.40
clear insulating glass with light between-glass venetian blinds	0.33
6mm silver reflective glass	0.23
6mm silver reflective glass with interior venetian blinds or draperies	0.18
clear glass with exterior shading device	0.075

Multiple glazing: Since the glass has a low thermal resistance, heat is conducted through in larger rates than the rest of the building envelope. With the high conductivity of glass, adding layers of glass in contact with each other is of negligible thermal benefit. However, if the glass layers are separated by air spaces, the path of conduction is interrupted, and the rate of heat flow is reduced.

In practice, most of the multiple glazing units use two layers of glass, which is usually called double glazing. Double glazing basically consists of two panes of glass with a cavity between them which contains still air. This still air acts as a barrier against gain of heat and reduces the level of sound transmission. Condensation takes place usually when moist air comes into contact with a surface colder than the dew point of the air. Double glazing prevents condensation because the inner pane of the double glazing is generally at a higher temperature than the outer pane. Thus, the air in the room can contain a greater moisture content before condensation occurs.

Existing single glazed windows may be converted permanently to double glazed windows by the additions of a new glazing frame to accept the additional pane of glass. The space between the glazing should be vented and drained to the outside, and provisions should be made for cleaning both sides of each sheet of glass.

The Opaque Part of the Building Envelope:

This part of the envelope includes all non-transparent materials which form floors, roofs, walls, doors, etc. In most buildings this accounts for more than 90% of the total envelope area, and thus contributes the major portion of heat transfer through the building's envelope, especially in residential buildings [4]. This portion may differ from one type of building to another according to the function of the building as shown in Table 3.

The two most important properties which greatly influence the heat transfer rate by conduction through any material is the thermal conductivity and the thermal capacity and the combination of both in the thermal diffusivity.

Thermal Conductivity, and Thermal Resistance

Thermal conductivity (k) is the property of a material which determines the heat flow in unit time by conduction through unit thickness of a unit area of the material, across a unit temperature gradient. It is expressed in the English system by Btu/h ft °F, and in the SI system by $W/m^{o}C$. It is assumed that the temperatures on either side of the material and the distribution of temperature throughout the material, are uniform and constant with time (steady state conditions).

Table 3

The contribution of external and internal loads to the total cooling load, considering a traditional way of construction with: U walls = 2.84 $W/m^2.^{\circ}C$; U roof = 1.7 $W/m^2.^{\circ}c$

Types of Building	Internal Load %	External Load Heat Transfer Through Bldg. Envelope %	 Ventilation %
Hospital	30	30	40
Office Building	33	32	35
Mosque	44	15	41
Movie Theatre	47	30	23
School	39	40	21
Apartment Building	15	70	15
Villa	10	83	7
Low Income House	10	72	18

1- three-story building
2- multi-story building
3- two-story building
4- one-story building

The reciprocal of the thermal conductivity (1/k) is the thermal resistivity (R) of the material. Both conductivity and resistivity are independent of the size and thickness of the building elements.

The actual heat flow across a given building element (wall or roof) depends not only on the thermal conductivity of the material, but also on the thickness (L) of the element. The greater the thickness, the lower will be the rate of heat flow. Therefore, the thermal resistance of the element (i.e. its resistance to heat flow) is defined by:

$$R = \frac{L}{k}$$

The flow of heat under steady state conditions across a wall element of surface area A and thickness L, built of a material having a given value of k and subjected to a temperature different of $T_2 - T_1$, is then given by the formula:

$$q = A \frac{k}{L} (T_2 - T_1)$$

where q is the rate of heat flow from the warmer to the colder surface in W or Btu/h.

In calculating the rate of heat flow between the indoor and outdoor air, the thermal resistance of air layers adjacent to the surfaces must also be taken into account. The overall heat transfer coefficient U will be given by :

$$U = \frac{1}{R} = \frac{1}{\frac{1}{h_i} + \frac{Li}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3} + \frac{1}{h_o}}$$

where L_1 , L_2 and L_3 , k_1 , k_2, and k_3 are the thickness and conductivity of the wall layers. h_i and h_o are the film coefficient of the inside and outside surfaces.

The Heat Capacity

The term heat capacity of a wall or roof refers to the amount of heat required to elevate the temperature of a unit volume of the wall, or unit area of the surface, by one degree. In the first case, it is referred to as the volumetric heat capacity of the material (C_v) and in the second, as the heat capacity of the wall (C_w).

The unit of C_v is $KJ/m^3.^oK$ and of C_w is $KJ/m^2.^oK$. The first term is used in the description of a material and the second in the description of building components. The two components of the heat capacity are the specific heat (c) expressed in KJ/Kg^oK and the density (ρ) expressed in Kg/m^3.

The heat capacities of materials are only significant when thermal conditions are fluctuating. Under conditions approaching a steady state, as when there is a great difference between the outdoor temperature and the indoor (kept nearly constant by heating or air-conditioning), the heat capacity has little effect on internal thermal conditions. The heat flow and temperature distribution depend in this case mainly on the overall heat transfer coefficient of the building envelope and on the amount of heating. But under fluctuating conditions, when the structure is heated and cooled periodically as a result of variations in outdoor temperature and solar radiation, or intermittent heating, the heat capacity has a decisive effect in determining indoor thermal conditions.

__The Thermal Diffusivity__: The combined effect of thermal conductivity and heat capacity of homogeneous walls is expressed in the thermal diffusivity which is defined as

$$\alpha = \frac{k}{\rho c}$$

where

k = Thermal conductivity
ρ = Density
c = Specific heat.

The effect of the thermal diffusivity on the heat transfere through the material can be explained better after understanding the process of heat flow through this material. The heat flow through a wall from the external surface at an elevated temperature may be visualized by considering the building envelope divided into several layers. The heat flow into each layer causes an elevation of its temperature and the heat used for this is stored in the layer; the excess heat is subsequently transferred to the next, colder layer. Thus each layer receives less heat and is subject to a smaller temperature rise than the layer externally adjacent to it. As a result of this heat storage within the structure of the envelope, less heat reaches the innermost layer than crosses the outermost one, and its temperature elevations are smaller.

Because of the continuously varying nature of the external thermal environment the outside surface temperature is continuously changing. Consequently, the value of the air conditioning load thus changes not only in value but also in-phase with the external weather cycle. The time delay between a change in the external weather conditions and the resultant heat gain or loss to the building, influences the time profile of the building thermal load. This time delay is mainly caused by the storage of heat in the building envelope and its content. The storage capacity of the building envelope will depends on the thermal diffusivity (α) of the materials used to construct the building, while the value of the overall heat transfer coefficient, U, will control the total heat transmitted through the building's envelope.

To illustrate the effect of U and α on the heat transfer characteristics through the building envelope, several building materials are being studied, to find the effect of the change in outside weather conditions on the heat transfer through them.

Generally, the two principal factors of the outside environment are outdoor air temperature and solar radiation intensity. Both are subject to fluctuations. On clear days the solar radiation intensity impending on a given surface together with the outdoor temperature follow a periodic variation. Figure 2 shows a typical outdoor and sol-air temperatures variation for a horizontal surface, based upon a solar absorptivity of 0.9.

For a horizontal wall (Figure 3) exposed to such a thermal environment, the temperature distribution within it could be described by the diffusion equation [6].

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial \theta}$$

where

T = Temperature

α = Thermal diffusivity and

θ = Time

The diffusion equation is subjected to the two boundary conditions which consist of a constant inside temperature T_i and a varying outside temperature T_o (Figure 2).

The solution of this equation will enable us to calculate the heat transfer from the inner wall surface. Using actual weather for a typical sunny day in June in Kwwait, the solution was used to calculate the rate of heat transferred from the inner surface of a flat horizontal slab made of the materials listed in Table 4.

Table 4

Thermal and physical properties of the materials used in the comparison [7 - 11]

	K $(\frac{W}{m.K})$	ρ $(\frac{kg}{m^3})$	c $(\frac{J}{kg^oK})$	$\alpha\,(\frac{m^2}{S})$
Perlite based block	0.096	1150	945	8.834×10^{-8}
Aerated sand lime block	0.129	497	837	3.1×10^{-7}
Vermiculite	0.06	120	835	5.99×10^{-7}
Fiberglass	0.036	20	668	2.7×10^{-6}
Polyurethane	0.023	20	1045	1.1×10^{-6}
Polystyrene	0.031	20	1210	1.28×10^{-6}
Concrete	1.8	2240	880	9.13×10^{-7}
Foamed Concrete	0.12	400	880	3.41×10^{-7}
Foamed Concrete	0.17	650	880	2.97×10^{-7}

To illustrate the importance of the overall heat transfer coefficent the flat surface was assumed to be built using perlite cement blocks. The rate of heat transfer was then calculated for different values of U. The results are shown in Figure 4. It is clear that the lower the U value the less will be the amount of heat transferred through the wall. On the other hand, the value of U did not influence the time at which the peak occurs.

To show the effect of the thermal diffusivity (α) on the storage capacity of the material, a comparison was made between several materials. When $\alpha = 2.7 \times 10^{-6}$ m^2/s the material did not show any significant storage capability. Consequently, there was almost no change either in the peak-value or its location and the heat transfer rate was almost in phase with the steady state solution and with the sol-air temperature (Figure 5-a). The storage capability increases with the decrease of α as shown in both Figure 5-b and Figure 5-c, and the heat transfer rate is not any more in phase with the steady state solution or with the sol-air temperature.

Figure 6 shows the effect of the thermal diffusivity (α) and the location and the value of the peak heat transfer for different materials. Since the U-value used is the same for the material, the total amount of heat transferred during the twenty-four hours is the same. But due to the fact that these materials have different thermal diffusivities, the location of the peak and its value are changing. It is obvious that the lower the value of α, the better heat transfer characteristics the material will have. It can be seen from the Figure that a material with $\alpha = 8.8834 \times 10^{-6}$ m^2/s will have a peak value which is only 65% of the peak value of a material having $\alpha = 2.7 \times 10^{-8}$. Together with that, the peak was shifted from around noon-time to almost 8 o'clock in the evening. The importance of reducing the peak comes from the fact that the peak values are those which determine the installed capacity of the country's power plants. To have a low value for α, the material must have one of the following:

1) High density
2) High specific heat
3) High heat capacity

THERMAL INSULATION MATERIALS

Thermal insulations are those materials or combinations of materials which, when properly applied, retard the flow of heat energy by conductive, convective, and radiative transfer modes. Such materials may be fibrous, particulate, film or sheet, block or monolithic, open or closed cell, or composites thereof, which may be chemically or mechanically bound or supported.

By retarding heat flow, thermal insulations may serve one or more of the following thermal functions:

1. Conserve energy by reducing heat loss or gain of piping, ducts, vessels, equipment, and structures.
2. Control surface temperatures of equipment and structures for personal protection and comfort.
3. Prevent vapor condensation at surfaces having a temperature below the dew point of the surrounding atmosphere.
4. Reduce temperature fluctuations within an enclosure when heating or cooling is not needed or available.

5. Reduce noise and vibration.

Buildings in hot countries such as Kuwait account for more than 85% of the total electrical energy consumed in the country. According to the experts' consensus more than 80% of this energy is being used for air-conditioning in these buildings [12].

Due to the above fact, reducing the cooling load for the building is the most effective contribution to energy conservation. Several techniques could be adopted for the purpose of reducing the building cooling loads. Of all these basic techniques for reducing the energy consumption in buildings, thermal insulation is the most generally effective and the most generally applicable. It probably yields the greatest long-term economy of all capital investment that can be made in a building. In some instances, the reduced air conditioning capacity resulting from improved thermal insulation may outweigh the added insulation cost.

The object of applying insulation is to reduce the energy requirements of a building. The degree to which insulation can achieve this depends on the thermal resistance of the materials chosen and the thickness used, and it will also depend on the type of building to which it is applied and its use.

Table 5 shows the effect of added insulation on reducing the cooling loads in some typical Kuwaiti buildings. The table shows that a saving of between 11 - 64% of the total air conditioning system capacity could be achieved depending on the type of building under consideration. It is also clear from Table 6 that the application of insulation to a residential building in Kuwait resulted in a large saving in the peak cooling load [13].

Table 5

The effect of thermal insulation on reducing the cooling load of different Kuwait buildings.

Building Type	Hospital	Office Building	Mosque	Movie Threater	School	Apartment Building	Villa	Low Income Housing
% Saving in Coding Load	2.15	22.5	11.25	19.5	31	49	64	55.4

Table 6

Effect of insulation on peak cooling load

Insulation location	Peak cooling Load (kW)	Saving (%)	Yearly cooling energy (kW.h)	Saving (%)
No insulation	86.66	-	203,097	-
In walls	77.75	10.3	170,421	16.69
In roof	77.20	10.9	169,336	16.60
In walls and roofs	68.30	21.2	137,029	32.53

It should be, however, known that the application of insulation to the envelope of a building which is without backup heating or cooling may have an adverse effect on its inside floating temperature [14]. This is clearly shown in Tables 7 and 8 and Figure 7. Table 7 shows the bi-hourly temperature inside an uninsulated residential building when no mechanical cooling or heating is involved, while Table 8 is showing this temperature if the building is insulated. Figure 7 shows that the addition of insulation to the building envelope has produced higher mean temperature. This shows that the addition of insulation does not necessarily contribute to the comfort of passively designed houses in hot climates.

Another important element to be considered in applying insulation to buildings is that it should be adequately protected from weather and from normal wear and tear. In this respect some insulation materials are more vulnerable than others so that the situations in which they can be used may be restricted. Some may require special protection to guard against, for example, excessive moisture absorption or to reduce fire risks.

In the following sections two types of building materials which serve as insulation materials will be considered mainly

Table 7

The bi-hourly temperature inside an uninsulated building

Time	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
M	13·9	16	19·4	23·8	32·3	34	37·4	35·4	33	31·9	22·4	20·8
2	13·5	15·5	18·9	23·2	31·8	33·6	36·9	34·7	32·4	31·1	21·9	20·4
4	13·1	15·1	18·6	22·9	31·4	33	36·6	34·3	32	30·6	21·6	20·1
6	13·1	15·1	18·6	23	31·5	33·1	36·5	34·3	32·1	30·4	21·6	20
8	13·2	15·4	19	23·5	31·7	33·6	36·9	34·7	32·7	30·8	21·9	20·3
10	14·7	16·0	19·7	24·2	32·9	34·4	37·3	35·4	33·5	31·6	22·5	20·9
N	14·3	16·7	20·4	25	33·7	35·2	38·2	36·2	34·3	32·5	23·1	21·5
14	14·8	17·2	20·9	25·5	34·3	35·8	38·7	36·8	34·9	33·3	23·5	21·9
16	14·9	17·4	21	25·8	34·5	36	39	37·1	35·1	33·6	23·6	22
18	14·9	17·3	20·9	25·6	34·2	35·9	38·9	36·8	34·9	33·6	23·6	21·9
20	14·8	16·9	20·5	25·1	33·7	35·4	38·5	36·6	34·4	33·3	23·5	21·6
22	14·3	16·5	20	24·5	33	34·7	38	36	33·7	32·7	23·2	21·2
T_m	14	16·5	19·8	24·3	32·9	34·6	37·8	35·7	33·6	32·1	22·6	21·1

Table 8

The bi-hourly temperature inside an insulated building

Time	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
M	14·5	16·6	20·1	24·6	33·1	34·7	38·2	36·1	33·8	32·4	23	21·4
2	14·1	16·2	19·7	24·1	32·6	34·3	37·7	35·6	33·3	31·9	22·7	21·1
4	13·9	16	19·5	23·9	32·4	34	37·5	35·3	33·1	31·5	22·5	20·9
6	13·8	15·9	19·6	24	32·5	34·2	37·5	35·4	33·2	31·5	22·4	20·8
8	14	16·2	19·9	24·4	33	34·6	37·8	35·7	33·7	32	22·7	21·1
10	14·6	16·2	20·5	25	33·7	35·3	37·8	36·4	34·4	32·7	23·3	21·6
N	15	17·3	20·9	25·7	34·3	35·9	38·9	37	35·1	33·5	23·8	22·1
14	15·3	17·17	21·4	26·1	34·8	36·4	39·3	37·5	35·5	34	24·1	22·4
16	15·4	17·8	21·5	26·2	34·9	36·6	39·5	37·7	35·6	34·1	24·1	22·4
18	15·2	17·7	21·5	26	34·7	36·3	39·4	37·5	35·3	34	24	22·2
20	15·1	17·4	21	25·6	34·2	35·8	39	37·1	34·9	33·6	23·7	21·1
22	14·8	17	20·5	25·1	33·6	35·3	38·6	36·6	34·4	33·1	23·4	21·8
T_m	14·6	16·9	20·4	25·1	33·7	35·3	38·4	36·5	34·3	32·9	23·6	21·7

because they both have a high storage capacity.

Perlite and Perlite Based Products

Perlite is a naturally occuring, siliceous, volcanic glass containing between two and five percent water by weight. Perlite ore is composed primarily of aluminum silicate. Crushed ore particles are expanded to between 4 and 20 times their original volume by rapid heating to a temperature of 1000 °C, which vaporizes the occluded water and forms vapor cells in the heat-softened glass.

Expanded perlite can be produced with densities in the range of 32 to 175 kg/m^3. This material has a pellet-like form which contains countless tiny glass-sealed air cells that account for its thermal insulation properties. Non-flammable silicone treatment increases its resistance to water penetration and perlite is claimed to be water repellent and impervious to moisture. Being inorganic, perlite is not vermin, and termite resistant, and is non-combustile. It softens at temperatures between 890°C and 1100°C, and melts between 1280°C and 1350°C.

The thermal conductivity of loose-fill perlite varies with density. This density dependence is illustrated in Figure 8.

Inherent differences in the physical character of perlite from various deposits requires thorough preliminary evaluation of the crude material in a laboratory and pilot mill. Before the perlite can be expanded, the crude material must be crushed to produce particles approximating a cubic shape and the required particular size gradation (secondary crushing), and then sized to specified particle gradation.

The expansion process also creates one of perlite's most distinguishing characteristics: its white color. While the crude rock may range from transparent light gray to glossy black, the color of expanded perlite ranges from snowy white to greyish white.

The tiny air cells or bubbles sealed inside perlite particles resist penetration by water. However, fractured bubbles at the surface of the perlite particle greatly increase the total surface area so that perlite tends to absorb water on the surface rather than trapping it within the particle.

Perlite is used primarily in industrial/commercial buildings as a roof insulation board material. The next largest use is as lightweight insulation concentre where expanded perlite is mixed with Portland Cement. A wide range of density is available. Perlite insulation concrete, both preformed and cast-in-place, is used primarily for roof decks, floor slabs, and wall systems. Low density expanded perlite is used as a loose fill insulation.

Perlite concrete:Perlite aggregate combined with portland cement and water produces a lightweight concrete that is used for lightweight roof and floor fills, lightweight structural roof decks, precast components and for a variety of permanent insulating applications. Perlite concrete roof deck construction offers excellent insulation plus greater strength, rigidity and fire safety than other roof insulation materials. On flat roofs, the thickness of perlite concrete can be varied to provide specific drainage slopes. Perlite concrete makes an excellent monolithic base for conventional built-up roofing. Some of its advantages are:

- lightweight: weighs from 320 - 640 kg/m^3
- insulation: 20 times more insulating than structural concrete.
- Fire Retardant: non-combustible ...permits savings in insurance costs.
- Durable: will not or decay also vermin and termite resistant - Adaptable: can be placed monolithically on flat, uneven, curved or sloping surfaces and with varying density to meet design requirements.
- Good base for roofing: rigidity and firmness provides an excellent base for roofing, and lowest drying shrinkage compared to other insulating concretes.

Typical physical and thermal properties of perlite concrete are given in Table 9.

In Figure 9, a schematic view of a roof construction using lightweight perlite concrete as the insulation and sloping materials. As shown in Table 10 this construction gives an acceptable thermal resistance of 8 m.°C/W, which is recommended by energy conservation codes.

A low density (300 kg/m^3) perlite concrete is an economical and efficient wall fill insulation. It provides a U value which is very compatible with other wall insulation materials. Figure 10 shows the proposed wall construction using perlite concrete as insulation, while Table 11 shows the thermal properties of this wall.

<u>Perlite Block</u>:Expanded perlite can also be mixed with portland cement, sand and a binder to produce lightweight insulating perlite block. A mixture with the following proportions

. Cement	180 kg
. Gravel	135 kg
. Expanded Perlite	1.4 m^3
. Water	
. Admixture	

will produce about 75 hallow two core, blocks. These blocks can

Table 9

Typical physical and thermal properties of perlite concrete [15]

Cement Aggregate by Volume	Dry Density Range kg/m^3	Compressive Strength kPa	Wet Density When Placed kg/m^3	Thermal Conductivity W/m.° C
1:4	544-640	2413-3447	808.0+32.0	0.12
1:5	448-544	1585-2344	728.0+32.0	0.1
1:6	384-448	965-1378	648.0+32.0	0.09
1:8	320-384	552-861	584.0+32.0	0.078

Table 10

Thermal properteis of the roof construction shown in Figure 9

Roof Layer	Density kg/m^3	Thickness cm	Thermal Resistance m.° C/W
Outside air Film	-	-	0.145
Tile (20 x 20)	2500	2	0.04
Mortar (1:4)	2500	2	0.08
Sand Bed	1600	3	0.1
Water Proofing	-	-	0.16
Perlite Concrete	450	20	6.6
Structural Slab	2500	15	0.3
Inside Air Film	-	-	0.53
TOTAL		R =	8.0

Table 11

Thermal properties of the wall construction shown in Figure 10

Wall layer	Density Kg/m^3	Thickness cm	Thermal Resistance m. °C/W
Outside Air Film			0.1
Sand-Lime Brick	2250	10	0.25
Perlite Concrete	300	10	4.6
Ordinary Solid Block	2000	15	0.63
Ordinary Sand-Cement Plaster	1900	2	0.1
Inside Air Film			0.39
TOTAL		R =	6

Table 12

Thermal properties for different types of blocks

Block Type	Density kg/m^3	Thickness cm	Thermal Resistance m·°C/W
Sand-Lime Brick	2250	10	0.25
Perlite Based Solid Block	575	20	5.2
Perlite Based Hollow Block (Cores filled with loosed Perlite)	1150	20	6.5
Ordinary Solid Block	2000	10	0.42
Ordinary Solid Block	2000	15	0.63
Ordinary Solid Block	2000	20	0.84

be used in the construction of walls as shown in Figure 11. A comparison between this block and other ordinary blocks is shown in Table 12.

Aerated Sand-Lime Block:

It is also known as the lightweight insulating block and in Kuwait it is produced under the name "AZEL", which means insulation in Arabic. The block is produced from two basic materials, silica sand and hydrated lime, mixed with portland cement, gypsum, aluminium powder, foaming Agent and water. The sand content in the mixture is between 62 - 76% by weight. It contains a high percentage (85%) of silica (SiO). The hydrated lime must be pure and free of impurities such as calcium carbonate ($CaCo$), magnisum oxide (MgO), aluminium oxide ($Al\ O$) and others.

The Aluminium powder is used a with small percentage (0.05%) from the total mix. It is added to produce hydrogen gas when it reacts with the hydrated lime. Hydrogen helps to produce the voids in the mixtures after curing. These voids give the mix its insulating properties, after curing in a special oven under high pressure.

The structure of aerated concentre is characterised by pores formed by the hydrogen gas, air and water at the casting and rising stage. According to their size and physical characteristics the pores can be divided into micropores and macropores. Micropores may be considered as those which are capillary active, whilst the remaining pore volume may be considered to consist of macropores. The pore structure is of importance for the physical properties of the material such as strength, thermal conductivity, capillarity, frost resistant, etc.

The distribution of sizes within the microscope range is of importance for properties such as freezing and moisture migration. The shape of the macropores is usually almost spherical. Should they, however, consistently show a more oval shape, it can be assumed that the physical characteristics may differ somewhat in the directions of the major and minor axes.

In this connection permeability is the capacity for transmitting gases, particularly air. The permeability varies with the moisture content in the material, being lower the greater the moisture content in the pores. However, even if the material contains no moisture, the permeability at normal pressure differences (eg caused by wind) is so low as to be negligible. Significant penetration can take place, on the other hand, through improperly formed joints and other connections in the building [16].

Certain additives are required to generate the gas, produce the foam and control the setting of the binder. The casting takes place in steel moulds, the mass being cut into the desired products, ie slabs or blocks, after rising and setting, while it still soft.

High pressure steam curing is practically unavoidable if aerated concrete is to be produced with an acceptable level of strength and shrinkage. The reinforcement receives a rust protection prior to casting, but the aerated concrete itself does not contribute to the rust protection of the steel bars. After curing, the products can be further shaped in milling machines, and a surface finish can be applied in the factory.

In order to carry out the casting, cutting and steam curing of this material extensive mechanical equipment, such as moulds, cutting machines, autoclaves, etc, is required. Factory buildings must also maintain constant atmospheric conditions during the casting and cutting process. Therefore concrete must be produced under controlled factory conditions, based on mass production of strictly standardised building units.

Mositure travels in the material partly through capillarity and partly through diffusion. At normal moisture content, the moisture migration is mainly due to diffusion and with increasing moisture content it is due more to capillarity. Above 40% moisture content by weight, it is due almost entirely to capillarity. The migration is also influenced by the pore, structure, the dimensions of the unit, the thermal conductivity of the material, temperature, vapor pressure and movements of the air to which the surfaces of the construction are exposed.

Risk of frost damage can arise if the actual moisture content in any part of the construction exceeds the critical moisture content of the material. For aerated concentre with a density of 500 kg/m tests have shown that the critical moisture content is about 40% by volume. The moisture content in practice is usually highest during construction before the drying out has taken place. However, it rarely exceeds 15 - 20% by volume at this stage. It should be noted that locally, e.g. close to the surface of the unit, under extreme conditions higher moisture contents may occur, increasing the risk of frost damage. The extensive use of aerated concrete in cold climates, however, confirms that the material has good frost resistance in practice.

The thermal conductivity of aerated concentre depends primarily on the density. Other factors which affect the thermal conductivity include moisture, content, temperature level, raw materials, pore structure, etc. The effect of density on the thermal conductivity is shown in figure 12 while Figure 13 shows the effect of moisture content on the thermal conductivity. The compressive, strength depends upon the conditions at which the test is usually made, such as, the moisture content, and the size of the test specimen. The effect of density on the compressive strength is given in Figure 14.

As functional requirements are different for different types of buildings no attempt will be made to specify them here, but merely to mention some of the functions that aerated concrete can fulfil in a building.

1. It is loading-bearing within certain limits for floors, walls and roofs.
2. It has:
   a) a high degree of thermal insulation
   b) a high degree of fire protection
   c) a degree of thermal capacity sufficient to reduce day-night variations of temperature.
   d) moisture capacity to reduce variations of relative humidity of indoor air
   e) durability exceeding the normal lifetime of a building
   f) light weight that reduces seismic forces and compression on other structures and foundations.
3. It does not require surface treatment under certain circumstances.
4. It can be used as a base for various types of surface treatments or claddings.
5. It lends itself easily to future changes to a building.
6. It satisfies high requirements of sound insulation.
7. If left without surface treatment it is slightly more sound absorbent than hard materials such as concrete and steel. In combination with other materials and special shaping, it

is sound absorbent to a high degree.

8. The material can be easily cut and shaped and fixings are easily made.

Aerated concrete can be produced as blocks of different sizes, according to the builders, designers, etc. requirements. Figure 15 shows a typical wall construction using the "Azil" block.

Reinforced units are also produced to be used in the building industry, offering high quality roof, floor partition and external wall units.

THERMAL INSULATION AND CONDENSATION

Condensation is a big problem facing buildings and especially residential ones lately. Though it is more widespread in cold countries, hot humid countries face this problem in winter when the temperature may reach 0.0 C, and in summer where the inside is cool and the outside is hot and humid. Condensation is related to the way the buildings are insulated, ventilated and heated.

How Condensation Occurs:

Water vapor, in varying quantities, is always present in the air. Condensation occurs when the high moisture content of the air results in its inability to absorb more moisture. As a result, the body heat loss through sweat evaporation is greatly reduced. To maintain a comfortable environment, the relative humidity inside should be kept between 40% to 70%.

Generally humidity is felt above 70%, and dryness of the throat and lips occurs below RH 40%.

Warm air is capable of carrying more water vapor than cold air. In winter, the inside air is warm and water vapor is introduced to it by the occupants and their activities; bathing, cooking and dishwashing. As a result, vapor pressure in warm air is higher than that of cold air. In summer, the outside air is hot and humid, while the inside air-conditioned space is cool and dehumidified. As a result, vapor pressure outside will be greater than the inside vapor pressure. In both cases, warm moist air is forced through the walls, if it is permeable, taking moisture with it.

As an example, let us take the inside condition of a building to be 25 °C dry-bulb temperature and 50% RH, point A, Fig. 6, the moisture content is 10 g/kg air. At this point air can absorb moisture up to 20 g(H_2O)/kg air (point B). Now if the conditions of the room are given as 15°C dry-bulb and 50% RH, the moisture at the point is 5.4 g(H_2O)/kg air. Hence, air can absorb moisture up to 10.6 g(H_2O)/kg air only before saturation occurs. This shows that warm air is capable of containing more water vapor that cold air does.

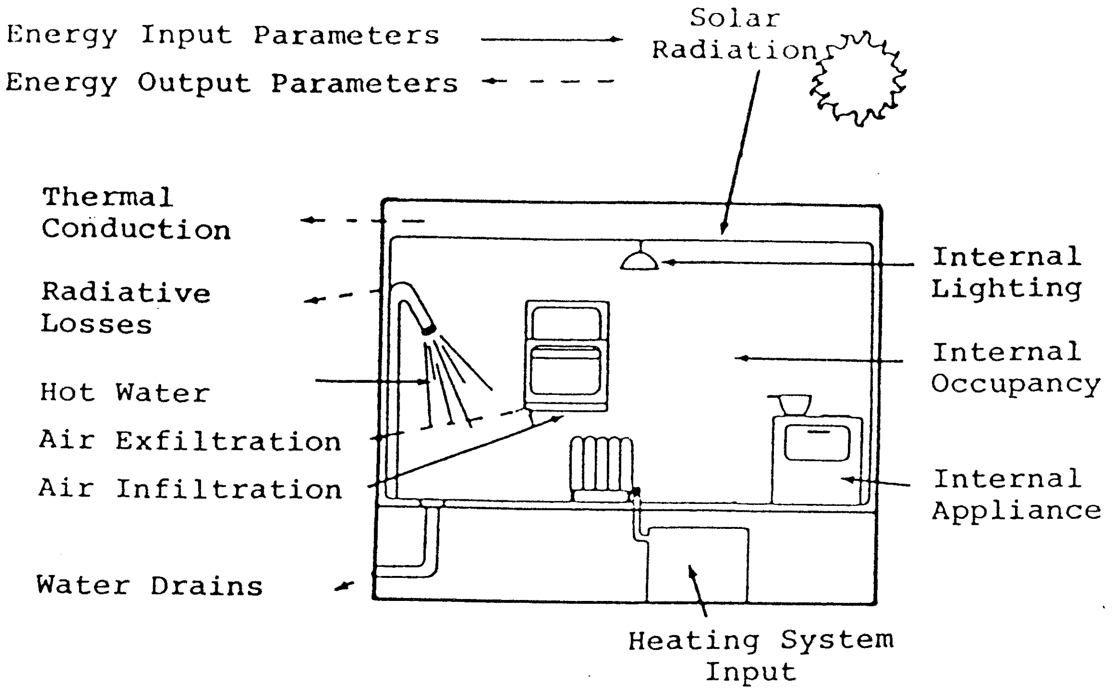
Invisible condensation: Condensation can also happen within the wall or roof thickness of buildings due to the internal (winter) or external (summer) air penetrating through the structure, because of its greater pressure, when, meeting a cold area within the structure. This type of condensation is troublesome and dangerous, and as mentioned before, occurs when the dewpoint temperature exists within the construction and most probably in the insulation section. The materials exposed to the moisture may rot, rust or become strained. If the insulation becomes saturated it loses much of its thermal resistance. If condensation should freeze, the construction may be damaged by the expansion of ice. The invisible condensation danger is particularly acute because its occurence may not be discovered until damage has resulted. This danger exists because ordinary building materials are porous and let water vapor to go through. Consequently, air and water vapor will permanently be within the structure (walls or roofs). An example will be explained with the help of the psychrometric chart of Fig. 16. Considering a Kuwaiti winter room conditions of 25 °C dry-bulb and 50% RH, when the outside temperature is 5 °C. The dewpoint of the room air from the Figure is approximately 14 °C.

Thus, the penetrating air reaches its dew point within the structure, condensation, therefore, will occur in the wall where the temperature is below 14 °C. In summer if the outside temperature is 35°C and the relative humidity is 70%, the dewpoint temperature of the outside air is 28.6 °C. Consequently, condensation will occur in the portion of the wall where the temperature is below 28.6°C. In both cases condensation is most likely to occur within the insulation layer, since it has the largest temperature gradient.

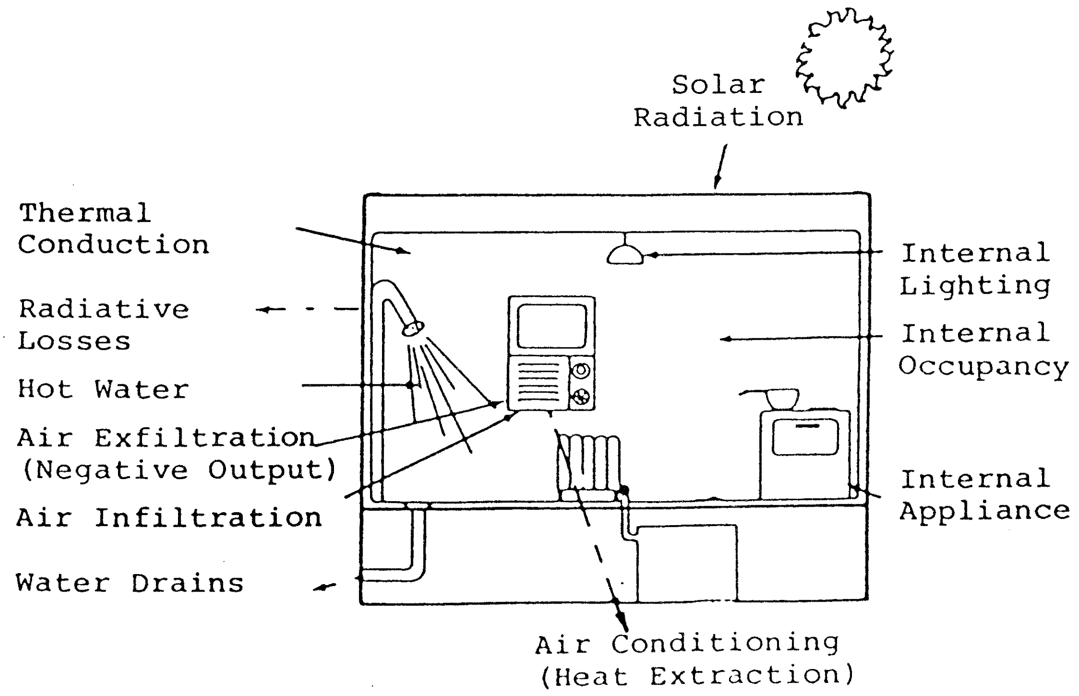
Depending on the degree of humidity in the room or the outside, the condensation may soak the barrier and run down it and collect at the base of the wall. Damage to insulation, and interior and exterior facings may result. It should be noted that in summer the condensation that occurs in the day time, because the dewpoint temperature of the outdoor air exists within the construction, may evaporate during night. Thus, the insulating material must have a high resistance to the transmission of vapor through it.

From the above discussion, the condensation risk must be taken into account when installing in the walls or in the roofs. The installation of good vapor resistance material will alter the dewpoint gradient and condensation is prevented. On the other hand, using a bad vapor resistance insulating material will only change the temperature gradient line without any change in the dewpoint gradient line. As a results, condensation will result in the insulation layer (depending on temperature line) and eventually saturate it.

The most effective measure for limiting the amount of condensation that can occur within a construction is the installation of a vapor barrier in the construction. To reduce the amount of vapor that can reach the dewpoint, vapor barriers should be placed from both sides. Vapor barriers should not be torn or scratched, or else water will pass through.



Energy Balance in Winter



Energy Balance in Summer

Figure 1: A schematic diagram of the energy balance for a building in winter and summer seasons.

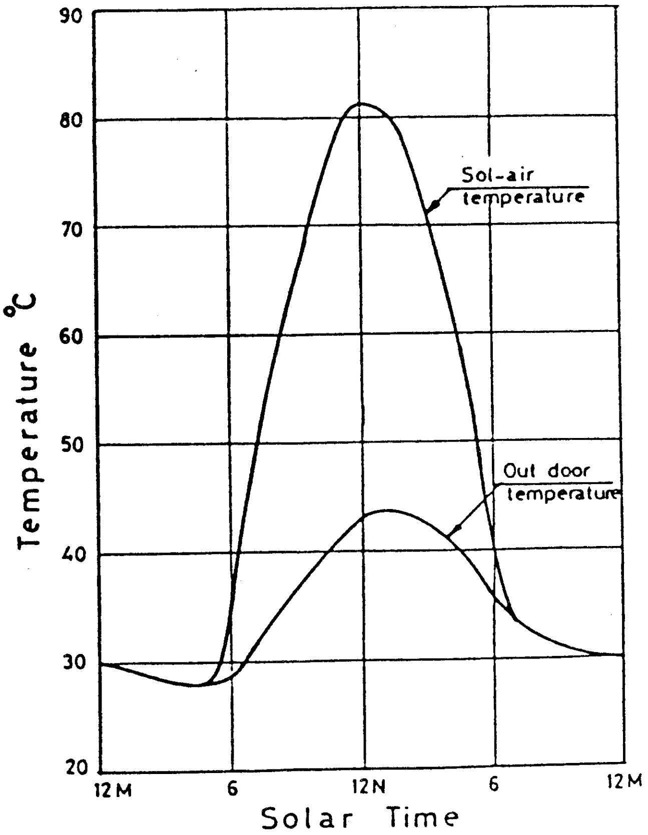


Figure 2: Typical variation of the outdoor and solar-air temperature for a horizontal surface on June 21.

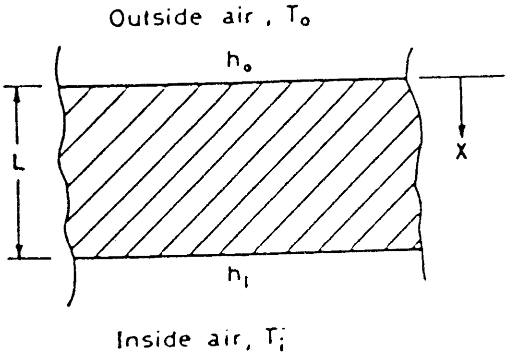


Figure 3: Schematic diagram for the analyzed wall.

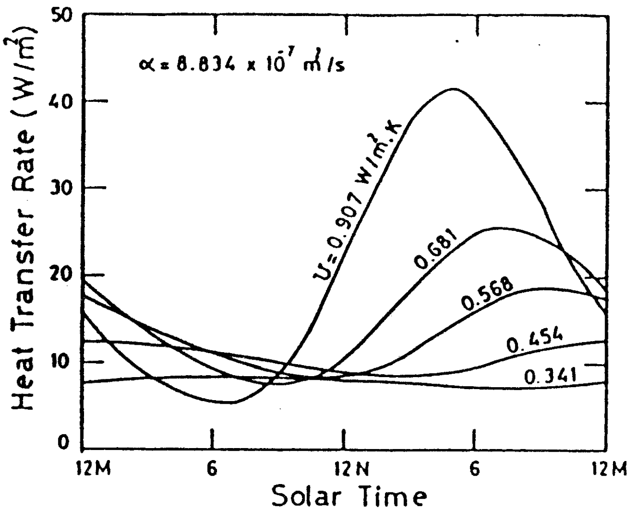


Figure 4: The effect of the heat transfer coefficient U on the heat transfer rate (Perlite Cement Block).

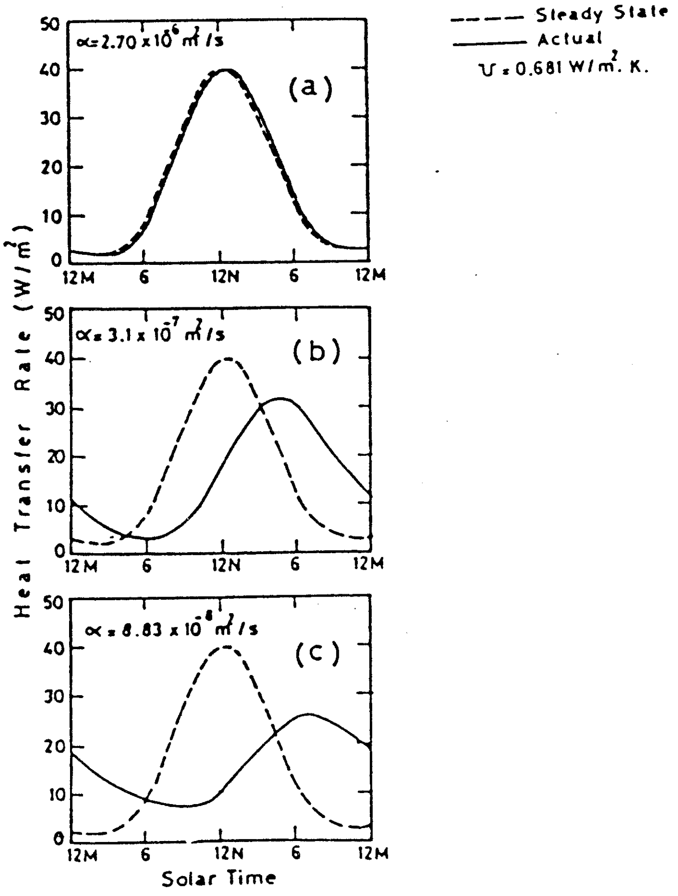


Figure 5: A comparison between the heat transfer characteristics for different insulation materials.

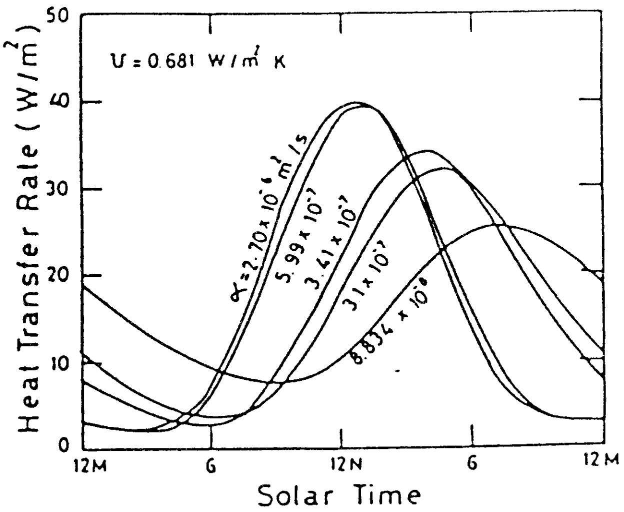


Figure 6: The effect of the thermal diffusivity α on the peak heat transfer rate and its time of occurance.

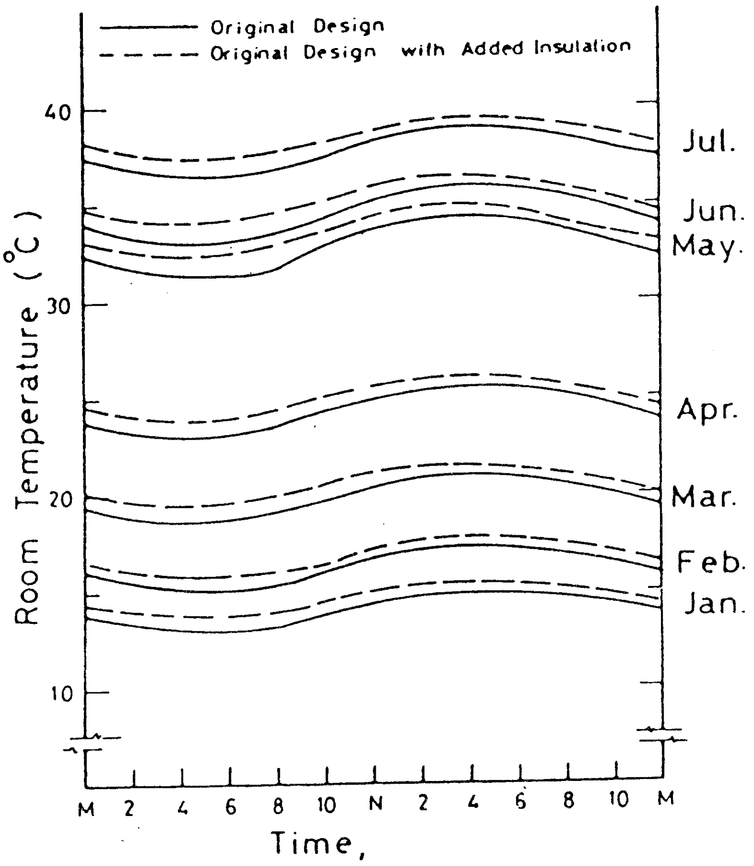


Figure 7: Comparison between the inside temperature of an insulated and uninsulated building.

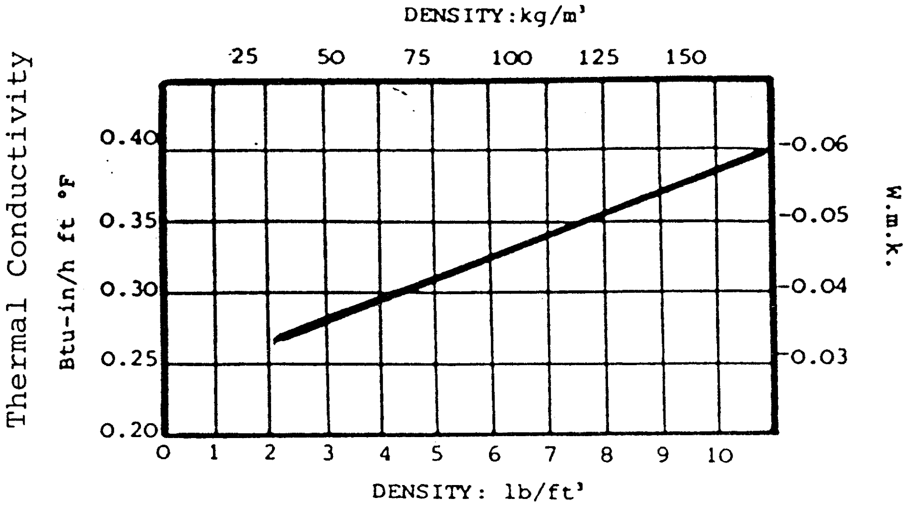


Figure 8: The effect of perlite density on its thermal conductivity.

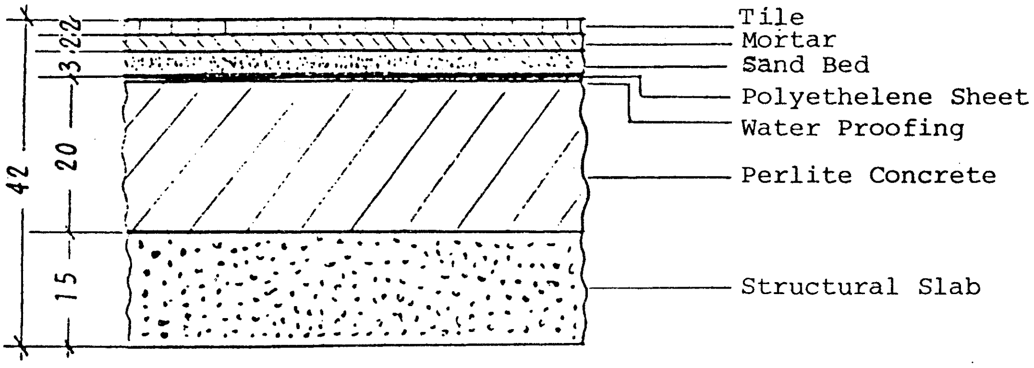


Figure 9: Roof construction using perlite concrete [14].

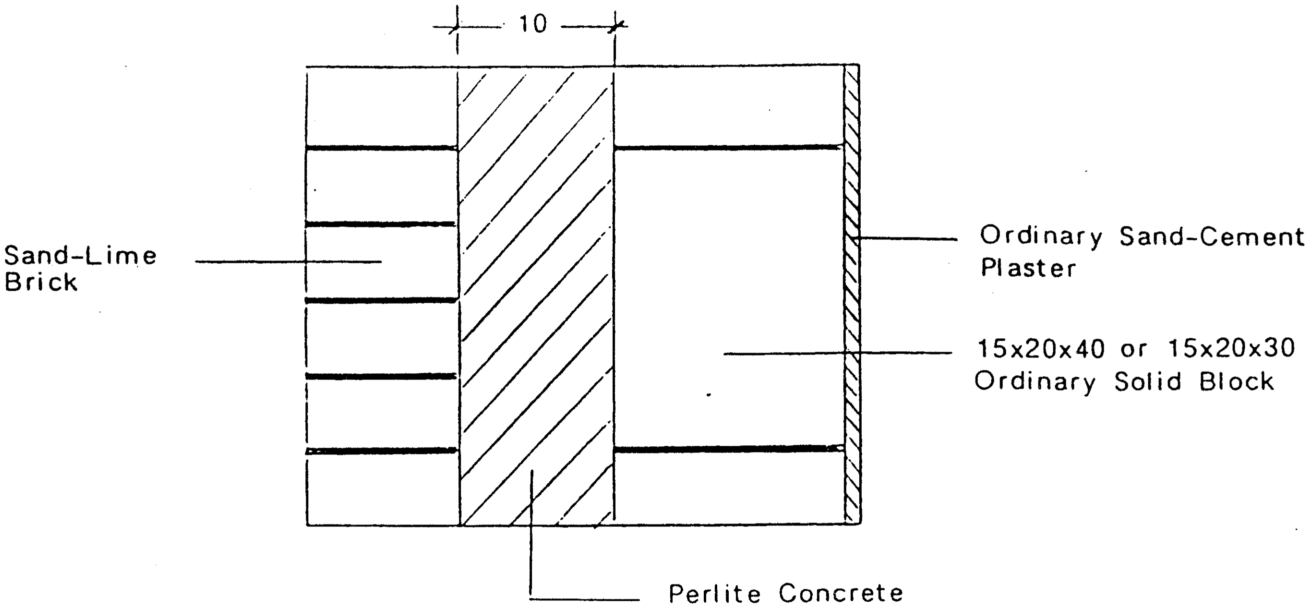


Figure 10: Wall construction using perlite concrete [14].

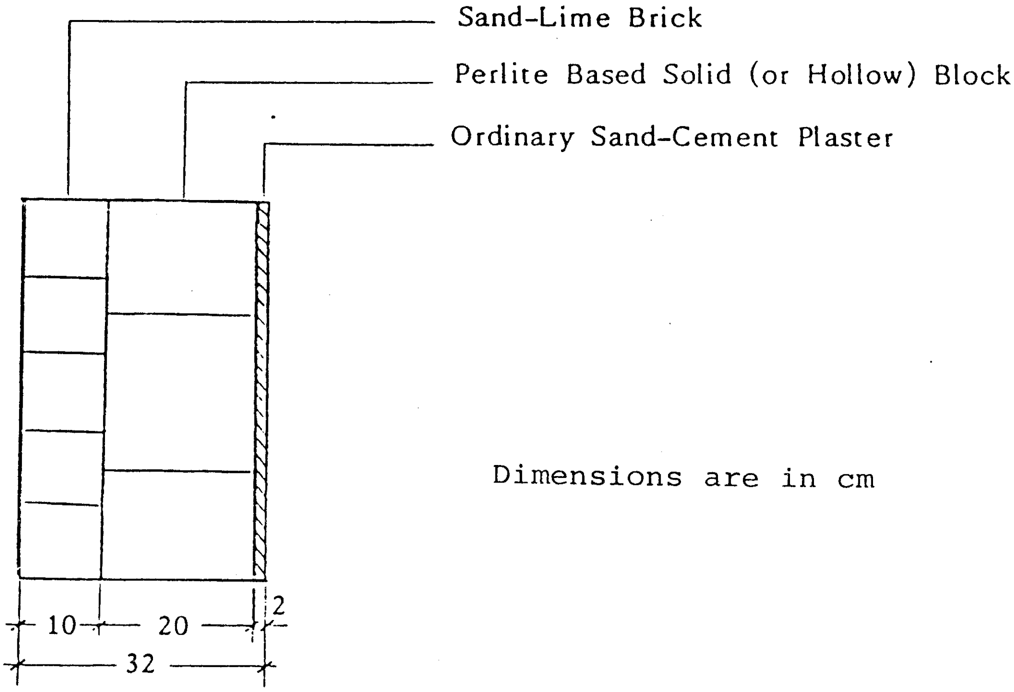


Figure 11: Wall construction using perlite block [14].

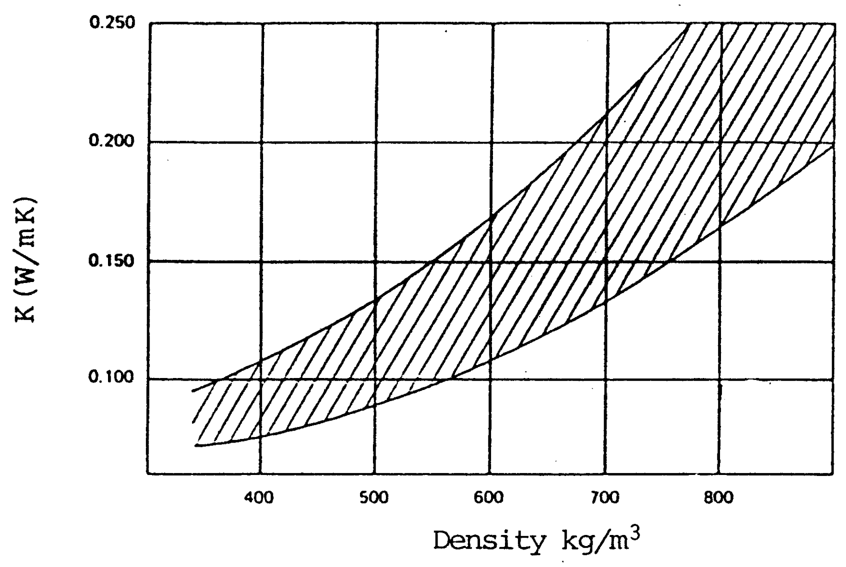


Figure 12: The thermal conductivity k in relation to the density, determined on a dry specimen of aerated concrete [15].

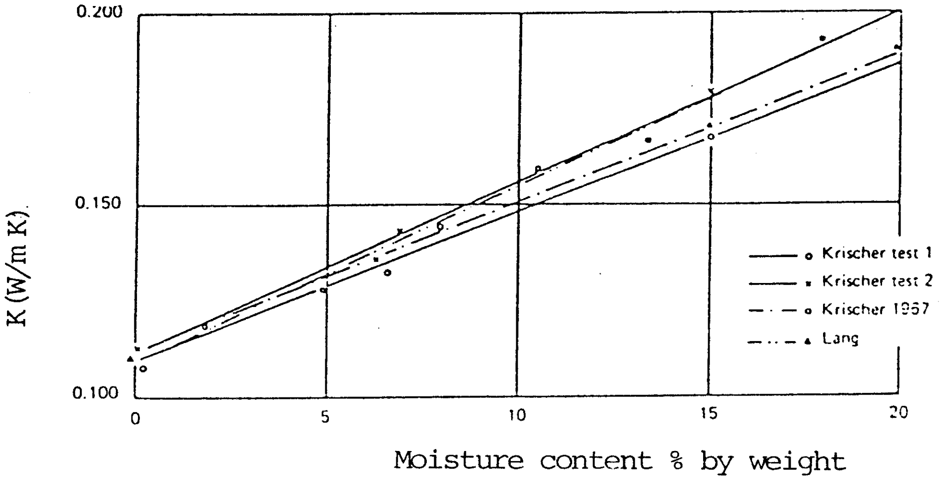


Figure 13: Thermal conductivity k as a function of moisture contents by weight for an aerated concrete with a density of 500 kg/m^3, measured with a Lang apparatus and Krischer apparatus at 10°C [15].

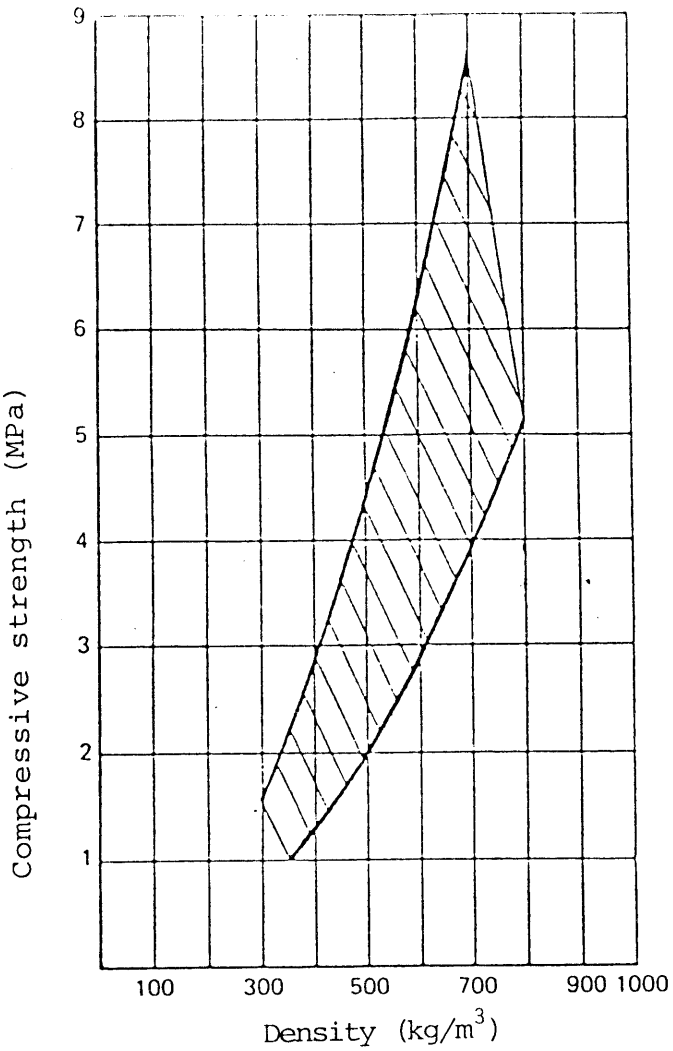


Figure 14: Relationship between the cube compressive strength and the density of aerated concrete [15].

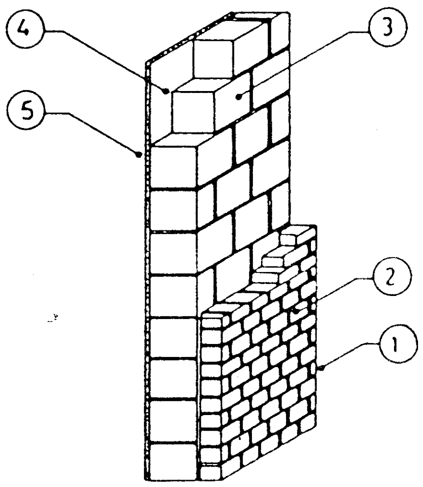


Figure 15: Wall construction using AZEL block

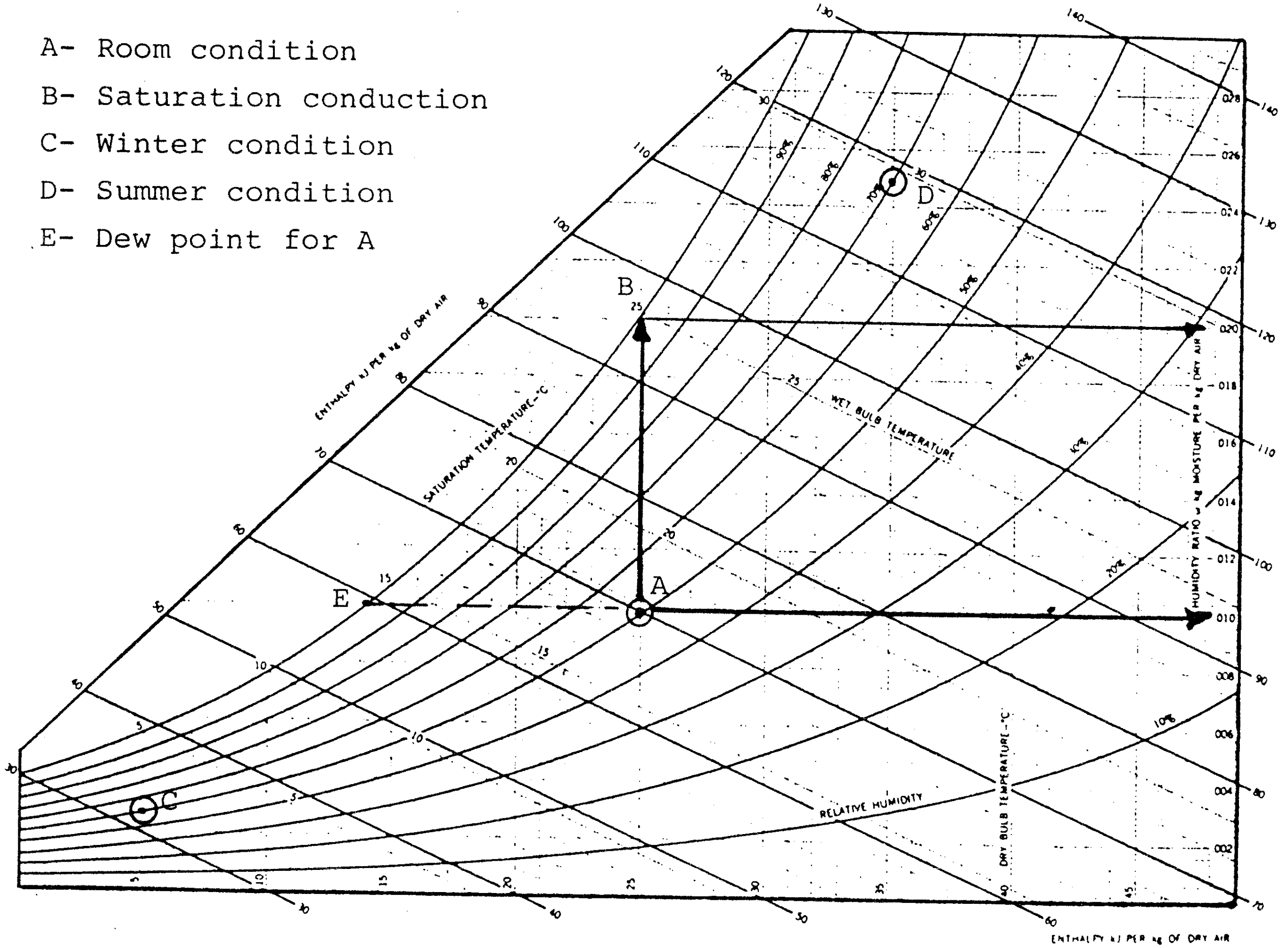


Figure 16: The condensation process shown on the psychrometric chart.

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