Architectural Thermodynamics and Human Comfort in Hot Climates

The properties of matter and energy must be considered in order to fully understand climatic phenomena. Heat, radiation, pressure, humidity, and wind, among other factors, interact mutually to establish climate conditions near the Earth's surface.

In this environment of continuously changing pressure, wind movement, temperature, humidity, and cloud cover, an architect places a fixed building. Such a rigid structure is intended to provide a comfortable internal environment over a wide range of these external variables. Two factors facilitate this task: first, in temperate and subtropical zones, ordinary buildings offer fair protection from climatic extremes, and, second, the human body has a considerable margin of tolerance for these variables. However, special treatment is required, particularly in tropical zones.

When considering the architectural design of a building, as well as in town and regional planning, other elements should be considered. The continuous daily motion of the population, which has properties analogous to the humidity concepts of saturation, evaporation, and condensation, must be accommodated in houses, towns, and regions.

Any living organism continuously adapts itself to the flux of its environment. Once constructed, however, a man-made object can no longer adjust itself. This inflexibility of human creation is at once its weakness and its strength. A design can succeed in uniting the particular and permanent with the universal and continuously changing. Yet another design, by failing to sense the forces at work or to create a harmonious union, can isolate and alienate human life.

Before considering the application of scientific concepts to architectural design and town planning, it is useful to briefly examine some basic concepts of architectural thermodynamics and human comfort.

Temperature

The concept of *temperature* describes the degree of heat contained in a body or a fluid medium or some region thereof, but a clear definition usually is a description of the operations performed in its measurement. Since heat flows from hotter to colder bodies or substances, temperatures can be measured by bringing a thermometer into intimate contact with the body or substance. The thermometer is then assumed to acquire the same temperature.

Scientists use two conveniently reproducible temperatures, the freezing and boiling points of water, to establish temperature scales. On the Celsius scale, the first was taken to be 0° and the second 100°. On the Fahrenheit scale, these values are 32° and 212°, respectively. The temperature of a body so cold that it is incapable of giving up any heat is called absolute zero, −273.15 °C or −459.67 °F. However, no limit for maximum temperature is known to exist.

The air temperature range of interest here is that of the extremes in the usual human habitats. Meteorologists have observed air temperatures of −93 °C (−135 °F) and 57 °C (135 °F) at the Earth's surface, a range of merely 150 C° or 270 F°. But narrow though this range may be, it is enormous in comparison with the variation of temperature that the human body can endure within itself. The body maintains a constant temperature of about 36 °C (98.6 °F) at the mouth, increasing to about 37.2 °C (99 °F) in the deep tissues, and can rarely survive if this temperature varies even by 1 C° (about 2 F°) for prolonged periods.

Thermal Conduction and Resistance

The concepts of thermal conduction and resistance are important in attempting to provide a comfortable environment for the inhabitants of hot, arid regions. These heat-flow concepts are based on the movement of a *quantity of heat*.[1]

The *specific heat* of a substance is the quantity of heat energy

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[1] The symbol for quantity of heat is q. In the metric system, the joule (J) and the kilocalorie (kcal) are used to measure the quantity of heat; in the British system, the British thermal unit (Btu) is used. One kilocalorie is defined as the quantity of heat energy required to raise 1 kilogram of water at 15 °C by 1 Celsius degree, or as 4186.8 J. One Btu is defined as the quantity of heat energy required to raise 1 pound of water at 60 °F by 1 Fahrenheit degree, or as 0.252 kcal or 1055 J.

required to raise the temperature of one unit mass of the substance by one degree of temperature.[2]

When considering heat-flow concepts, the notion of *rate of heat flow* is useful. It equals the rate of displacement of a quantity of heat.[3]

Conduction is the process by which heat flows through a material, or from one material to another with which it is in contact. Some materials, such as metals, are good thermal conductors, while others, like air, are poor thermal conductors. *Thermal conductivity* is a specific property of a material and is a measure of the rate at which heat will flow through a material when a difference in temperature exists between its surfaces. It is defined as the quantity of heat that will flow through a unit area in a unit time, or equivalently, as the rate of heat flow through a unit area, when a unit of temperature difference exists between the faces of the material of unit thickness,[4] such as the wall

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[2] The symbol for specific heat is c. In the metric system, specific heats are measured in joules/kilogram · Celsius degree $[\mathrm{J \cdot kg^{-1} \cdot (C\ deg)^{-1}}]$ or in kilocalories/kilogram · Celsius degree $[\mathrm{kcal \cdot kg^{-1} \cdot (C\ deg)^{-1}}]$. In the British system, specific heat is measured in British thermal units/pound · Fahrenheit degree $[\mathrm{Btu \cdot lb^{-1} \cdot (F\ deg)^{-1}}]$. Owing to the definitions of the kilocalorie and the Btu above, the units of specific heat determined using these quantity-of-heat units are identical, and thus the numerical value of the specific heat is the same in either of these units, i.e.:

$$1 \frac{\mathrm{kcal}}{\mathrm{kg \cdot C\ deg}} = 1 \frac{\mathrm{Btu}}{\mathrm{lb \cdot F\ deg}}.$$

However, since 1 kcal = 4186.8 J, this is not true for the specific heat measured in $\mathrm{J \cdot kg^{-1} \cdot (C\ deg)^{-1}}$, which is

$$1 \frac{\mathrm{kcal}}{\mathrm{kg \cdot C\ deg}} = 4186.8 \frac{\mathrm{J}}{\mathrm{kg \cdot C\ deg}}.$$

Thus, the quantity of heat necessary to raise the temperature of a mass, m, of a substance by a temperature difference ΔT is obtained using the equation,

$$q = cm\Delta T. \tag{1}$$

[3] The symbol for rate of heat flow is Q. This is expressed in joules/second (J/s), defined as watts (W) or kilocalories/second (kcal/s) in the metric system, and in British thermal units/second (Btu/s) in the British system.

[4] Thermal conductivity is commonly expressed by the symbol k and is measured, in metric units, in joules/second · meter · Celsius degree $[\mathrm{J \cdot s^{-1} \cdot m^{-1} \cdot (C\ deg)^{-1}}]$, equivalent to watts/meter · Celsius degree $[\mathrm{W \cdot m^{-1} \cdot (C\ deg)^{-1}}]$, in kilocalories/second · meter · Celsius degree $[\mathrm{kcal \cdot s^{-1} \cdot m^{-1} \cdot (C}$

shown in figure 1. The thermal conductivity varies with the density, porosity, and moisture content of the material and also with the absolute temperature. The quantity of moisture contained in a material can have a considerable effect on the thermal conductivity of the material; the higher the moisture content, the greater the thermal conductivity. This is important because rain penetration, high humidity within a building, and condensation may result in an appreciable amount of moisture in the building structure. The average temperature of a material is another factor influencing the rate of heat flow; the thermal conductivity may be considerably greater at high than at low temperatures. However, the variation of the thermal conductivity over the range of temperatures commonly occurring in buildings is comparatively small, and thus the thermal-conductivity values measured at normal atmospheric temperature are generally used when considering structural insulation.

In calculations, it is often convenient to use the reciprocal of the thermal conductivity which is called the *thermal resistivity*.[5] The thermal resistivity may be regarded as either the time required for the transmission of one unit of quantity of heat through one unit area of a rectangular solid material of unit thickness, when the difference between the temperatures of the surfaces perpendicular to the direction of heat flow is one degree of temperature; or the number of degrees difference between these surfaces of the material of unit thickness when one unit of quantity of heat flows through one unit area in one unit of time. Thus resistivity, like conductivity, is a property inherent to a material and is independent of its thickness.

The *thermal resistance* is a measure of the resistance to heat flow of a

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deg)$^{-1}$], or in British thermal units/second · foot · Fahrenheit degree [Btu · s^{-1} · ft^{-1} · (F deg)$^{-1}$]. Therefore, k can be determined by

$$k = \frac{Q\ L}{A\,\Delta T}, \tag{2}$$

where L is the thickness of the material, and A is its area.

[5] For a constant flow of quantity of heat, the thermal resistivity, $1/k$ is

$$\frac{1}{k} = \frac{tA\,\Delta T}{qL} = \frac{A\,\Delta T}{QL}. \tag{3}$$

Thermal resistivity is measured in units of C deg · m · s · J^{-1} or C deg · m · W^{-1}, C deg · m · s · kcal^{-1}, or F deg · ft · s · Btu^{-1}.

material or a combination of materials.[6] The thermal resistance may be regarded as either the time required for the transmission of one unit of quantity of heat through one unit area of material when the temperature difference between surfaces perpendicular to the direction of heat flow is one degree of temperature; or the number of degrees difference in temperature between these surfaces when one unit of quantity of heat flows through one unit area in one unit time. If the thickness of the material is increased there is a corresponding proportional increase in its thermal resistance. If several materials are placed together in layers, as, e.g., in a plastered and rendered solid brick wall, as illustrated in figure 2, the total thermal resistance of the wall may be obtained by adding the resistances for each component, i.e., of the plastering, rendering, and brick masonry.[7]

The *thermal conductance* is the rate of heat flow through a material or a combination of materials and is therefore the reciprocal of the thermal resistance.[8] The thermal conductance is the quantity of heat that will flow per unit time per unit area of a material for a one degree temperature difference between its surfaces. If the thickness of the material is increased, its conductance decreases proportionately.

The thermal conductance and resistance and thermal conductivity and resistivity already considered have been related to the tempera-

[6] Thermal resistance, R, is defined as

$$R = \frac{L}{k}. \tag{4}$$

However, substituting for the resistivity from eq. (3) in fn. 5 gives

$$R = \frac{tA\,\Delta TL}{qL} = \frac{tA\,\Delta T}{q} = \frac{A\,\Delta TL}{QL} = \frac{A\,\Delta T}{Q}. \tag{5}$$

This is measured in units of $\mathrm{C\,deg \cdot m^2 \cdot s \cdot J^{-1}}$ or $\mathrm{C\,deg \cdot m^2 \cdot W^{-1}}$, $\mathrm{C\,deg \cdot m^2 \cdot s \cdot kcal^{-1}}$, or $\mathrm{F\,deg \cdot ft^2 \cdot s \cdot Btu^{-1}}$.

[7] The total thermal resistance of the 1, 2, . . . , n components of a wall with thermal resistances of R_1, R_2, . . . , and R_n, respectively, will then be

$$R = R_1 + R_2 \ldots + R_n. \tag{6}$$

[8] Thermal conductance, C, is thus

$$C = \frac{1}{R} = \frac{k}{L} = \frac{q}{tA\,\Delta T} = \frac{Q}{A\,\Delta T}, \tag{7}$$

and is measured in $\mathrm{J \cdot s^{-1} \cdot m^{-2} \cdot (C\,deg)^{-1}}$ or $\mathrm{W \cdot m^{-2} \cdot (C\,deg)^{-1}}$, $\mathrm{kcal \cdot s^{-1} \cdot m^{-2} \cdot (C\,deg)^{-1}}$, or $\mathrm{Btu \cdot ft^{-2} \cdot s^{-1} \cdot (F\,deg)^{-1}}$.

tures at the material surfaces. The surface temperatures of a building usually are not known. For purposes of heat-loss calculations, therefore, the inside and outside air temperatures are used. In this situation, heat transfer from the warmer to the cooler air mass occurs in three steps: first from the warmer air to the structure, then through the structure, and finally from the structure to the cooler air. Both the inside and outside air-surface interfaces provide some resistance to heat flow.

The *thermal transmittance* includes these surface resistances and is the rate per unit area at which heat will flow from the air on one side of the structure to the air on the other side. It may be defined as the quantity of heat that will flow per unit time per unit area through the material when one unit of temperature difference exists between the air on each side.[9] In fact, the thermal transmittance may be regarded as the overall air-to-air conductance, which is the reciprocal of the overall air-to-air resistance.[10] The thermal transmittance is of considerable practical importance. It provides a basis both for comparing the insulating capabilities of different wall, floor, and room constructions; and for calculating heat loss from a building for heating purposes in cold climates, and heat gain for cooling purposes in hot climates.

Radiation

All matter emits electromagnetic waves which are generated by the thermal motion of molecules composing the material. Such radiation is called thermal radiation. The intensity and wavelength distribution of this radiation depend on the nature and temperature of the material.

A perfectly opaque material with a totally absorbing and therefore totally nonreflecting surface, which is usually called a black body, emits radiation at the maximum possible rate for any given temperature. This black body is a convenient concept used as an idealized standard, but which should not be confused with an actual object with a black-colored surface. For such an object, the rate of radiation

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[9] Thermal transmittance, U, is thus measured in the same units as thermal conductance.

[10] Thus, following relation (6) in fn. 7, with all these components included in the summation, the total air-to-air thermal transmittance is

$$U = \frac{1}{R_1 + R_2 + \ldots + R_n}. \tag{8}$$

emission depends only on the fourth power of its absolute temperature.

As the temperature of the radiating object increases, the wavelength of maximum radiation intensity becomes shorter, and the distribution changes so that a greater proportion of the energy is radiated at shorter wavelengths (i.e., with higher energy). At temperatures below about 500 °C (about 900 °F), the emission consists almost entirely of wavelengths too long to be observed as light. At about 700 °C (about 1300 °F), the object glows with a dull red color. As the temperature increases further, the wavelength of maximum emission decreases, and the color shifts successively to bright red, yellow, and white.

The energy emitted by a radiating body ultimately impinges on other matter, which absorbs it, reconverting the energy into heat. In this way heat is transferred from one place to another by radiation.

At ordinary temperatures, most nonmetallic surfaces, including painted surfaces, radiate virtually as black bodies—their emissivity is high, and they are good absorbers for long wavelength radiation. Thus, various paints ranging from black to white are found to be indistinguishable as regards heat radiation at temperatures up to 100 °C (212 °F). However, whereas dark paints absorb most of the short wavelength radiation received from the sun, white pigments reflect most of it. And, at temperatures up to 100 °C (212 °F) aluminum and other metallic paints have an emissivity only about one-half that of a black surface. On the other hand, highly polished metals are strong reflectors of radiation, and many such surfaces are almost perfect reflectors of the long wavelength (low-energy thermal) radiation emitted by bodies at ordinary room temperature.

Emissivity, Absorptivity, and Reflectivity

Reference has been made to the importance of surfaces for heat transfer by radiation. To evaluate their emissive, absorptive, and reflective properties, surfaces can be compared with the properties of a black body, which absorbs all radiation falling on its surface and therefore reflects none.

The emissivity of a surface at a given temperature is equivalent to its absorptivity for radiation from another body at the same temperature, since two bodies at the same temperature will remain in thermal equilibrium with each other. The emissivity, and hence the absorptivity, of a black body has by definition, a value of unity, with the values of all real surfaces being in practice less than this value. Radiation falling on an opaque surface is partly absorbed, and the remainder is reflected. Since the incoming radiation can only be absorbed or reflected, the sum of the absorptivity and reflectivity must equal unity. For example, at normal temperatures, an aluminum foil may have an emissivity of 0.05, and thus its absorptivity will also be 0.05, but its reflectivity will be 0.95. This means that it emits by radiation only 5% of the amount a black body emits at normal temperatures. Also, it absorbs only 5% of the radiant energy falling on it (from another body at normal termperatures), and it reflects the other 95%.

The emissivity of a surface at normal temperatures (10–38 °C or 50–100 °F) is not necessarily the same as its absorptivity for radiation received from the sun. Emissivities at normal temperatures are important when considering heat losses from buildings through cavity-wall, floor, or roof constructions. For external surfaces, the absorptivity for solar radiation is important when considering heat gain from the sun. Table 1 gives these characteristics for some common surfaces.

Table 1 shows that the emissivities of white and dark paints are about equal at normal temperatures but that white paint has a much

Table 1. Average emissivities and absorptivities for some common building surfaces under relevant conditions

Surface	Emissivity or Thermal Absorptivity at 10–38 °C (50–100 °F)	Absorptivity for Solar Radiation
Black nonmetallic surfaces	0.90–0.98	0.85–0.98
Red brick, concrete, and stone, dark paints	0.85–0.95	0.65–0.80
Yellow brick and stone	0.85–0.95	0.95–0.70
White brick, tile, paint, whitewash	0.85–0.95	0.30–0.50
Window glass	0.90–0.95	Transparent
Gilt, bronze, or bright aluminum paint	0.40–0.60	0.30–0.50
Dull copper, aluminum, galvanized steel	0.20–0.30	0.40–0.65
Polished copper	0.02–0.05	0.30–0.50
Highly polished aluminum	0.02–0.04	0.10–0.40

Source: *Heating and Air Conditioning Guide*, American Society of Heating and Ventilating Engineers.

Table 2. Reflectivities of various materials and paints

Material or Paint	Reflectivity (%)
Red brick or stone	30–50
Slate	10–20
Asphalt bituminous felt	10–20
Galvanized metals (new)	36
Dark paints	10–20
Aluminum paints	40–50
Polished metals	60–90
Whitewash or white paints	80–90

Source: N. S. Billington, *Journal of the Institute of Heating and Ventilating Engineers* 19, no. 190 (June 1957).

lower absorptivity for solar radiation. A roof coated externally with white paint gains less heat from the sun than if it were a dark color.

Table 2 gives the reflectivities of various materials and paints.

Transparency

Some substances, such as glass, rock salt, liquids, and gases, are more or less transparent to radiation of certain wavelengths. Glass is transparent to wavelengths within the visible range of the spectrum, but absorbs radiation in the infrared or thermal region, while rock salt transmits a high percentage of infrared radiation. Most solids, however, are opaque to thermal radiation, and in such cases the emission and absorption of radiation are surface phenomena. Thus, the low emissivity of a burnished metal surface depends on the cleanliness of the surface. A very thin film of nonmetallic material, e.g., transparent varnish or grease, will increase the emissivity of the metal surface almost to that of a black body.

Clothing and human skin radiate virtually as black surfaces. For radiation at the wavelengths encountered in buildings and other living spaces, the absorption of clothing and skin approximates that of a black object. Indoors, white clothing has no advantage over black. But outdoors in the sun, although both materials radiate heat freely, white clothing reflects most of the solar radiation, while black clothing absorbs the sun's rays.

If the human body emits more radiant energy than it receives from its surroundings, it is, on balance, losing heat by radiation. If, on the other hand, the radiation received exceeds that emitted, there is a net heat gain by the body.

Thermal Convection

Natural or free convection is the process whereby a fluid moves because of differences in its density resulting from temperature changes. If the fluid is moved by mechanical means, e.g., by pumps, fans, or wind, the process is called forced convection. Heat may be transferred by convection between a surface and a liquid or a gas.

Discussions of thermal comfort involve the heat transfer between a surface and the neighboring air. When the surface is at a temperature above that of the air, heat is transferred from the surface to the adjacent air by conduction, thereby changing the density of the heated air. Then, even in otherwise still air, air currents result from the gravitational effects due to the differences in density. These natural convection currents cause much greater heat transfer from the surface than would result from conduction in a perfectly still atmosphere. Obviously, the rate of heat transfer by natural convection depends on the temperature difference between the surface and the neighboring air.

Perfectly still air is rare. Even in a closed compartment, variations in the temperature of the walls and other surfaces set up air currents, so that there is some air movement. If fans are employed or if there are openings to the outside, the air movement may be considerable. These currents increase heat transfer by convection. The speed of the air current and the temperature difference affect the rate of heat transfer by convection.

Air is a gaseous fluid containing by volume (excluding the water vapor content) 21% oxygen, 78% nitrogen, and a remaining 1% consisting of traces of rare gases (argon, neon, and krypton), carbon dioxide (from 0.3 to 0.4 liters per m^3), and carbon monoxide (about 0.03 liters per m^3 in urban areas and much less in the countryside). Air also contains water vapor from four parts per thousand to two parts per hundred. Dust and soot particles in air are visible as motes in a sunbeam. The oxygen, nitrogen, and other rarer gases are called permanent gases because they only become liquids at temperatures approaching absolute zero, whereas water undergoes continuous change between its gaseous and liquid states within the common range of air temperatures encountered in human climatic zones.

Atmospheric Pressure

Air exerts a pressure on any surface in the atmosphere which corresponds to the weight of the column of air that it supports. Every surface in the neighborhood of sea level carries a load of about 1 kg per cm^2, or 1 ton per ft^2. As the altitude increases above sea level, the atmosphere below no longer contributes to the pressure, which is correspondingly reduced.

Using this concept, atmospheric pressure can be expressed as the height of a column of mercury in a barometer, in millimeters or inches, with the pressure at sea level being 760 mm or 29.9 inches of mercury at a standard temperature of 0 °C (32 °F). The barometer reading must be corrected for the temperature of the mercury as well as for the latitude.

The bar is the unit of pressure in an absolute system of measurement adopted for scientific use to replace the arbitrarily chosen column of mercury. Atmospheric-pressure measurements in meteorological work are normally expressed in units of one millibar. One bar corresponds very nearly to 750 mm or 29.5 inches of mercury at 0 °C (32 °F), or 1019 cm or 401 inches of water, which is the atmospheric pressure a little above sea level.

Water Vapor

At temperatures throughout the climatic range of the normal human habitat, water can exist as solid ice, liquid water, and gaseous water vapor. At the freezing point, ice and water can exist together. Above this temperature ice is completely converted to water, and below it, only ice exists. However, regardless of whether the water is solid or liquid, the air above it contains a certain amount of water vapor.

Generally speaking, the permanent gases in the air produce the pressure indicated by a barometer. However, if water is present at the base of the column of air, that water partially evaporates (becomes water vapor) and contributes to the atmospheric pressure. This share depends on the temperature. Air containing the maximum possible amount of water vapor for its temperature is said to be saturated. The temperature at which condensation begins in a mixture of air and water is termed the dew point.

There are several ways to express the relation between humidity and temperature. The amount of water vapor that a volume of air can support at saturation can be expressed as grams or grains of vapor per volume of air, or as the portion of the total atmospheric pressure that the water vapor contributes. Similarly, the water-vapor content of unsaturated air can always be expressed as the portion of the total pressure that the water vapor contributes, called the vapor pressure, or as the amount of atmospheric water vapor in grams per m^3 or grains per ft^3. These values can also be determined with respect to the dew point, which is the temperature to which air must be reduced, without altering its barometric pressure, to reach saturation. In this way, the water-vapor content of air at a given temperature can be expressed as the ratio of the portion of the total atmospheric pressure contributed by water vapor to the portion necessary to cause saturation at that air temperature. This ratio, most often expressed as a percentage, is called the relative humidity.

Appendix 1 gives the values of water-vapor density and pressure for saturated water vapor over the range of temperatures from −10–34 °C (14–93 °F).

A given volume of water vapor is lighter than the same volume of air at the same temperature and pressure. In the atmosphere, therefore, saturated air is lighter than dry air of the same temperature and pressure. When water evaporates, the vapor simply rises into the air. If this process occurs in open air where there is freedom of motion, the water vapor can displace the equivalent volume of dry air without affecting the atmospheric pressure. Near water surfaces, therefore, rising water vapor is continuously replaced by dry air, which in its turn dampens and rises into the air. This water vapor eventually reaches a certain height, condenses on the floating particles always present in air, and becomes visible as clouds.

The processes involved in weather phenomena are not so simple. Such factors as heat, radiation, pressure, and wind interact to establish relative balances in the atmosphere, resulting in the constant recycling of water by evaporation, cloud formation, cloud motion, and precipitation.

Water vapor and temperature, pressure, and air movement are very important to the study of the climate and the microclimate both outside and inside buildings. They are key to an understanding of the formation of clouds, rain, dew, frost, and nearly all other meteorological phenomena. The behavior of water vapor must be understood to comprehend the physical and physiological processes of cooling by evaporation—the phenomenon upon which thermal comfort in hot climates largely depends. If air in a room is saturated with water vapor and its temperature decreases, then some water vapor will condense, leaving in the air only the amount that can be accommodated at the new temperature. However, if the air temperature rises, the air can accommodate additional water vapor and is called "dry air." This air can be described as "thirsty" until its temperature falls or it encounters water from which it can absorb vapor.

In winter, a dry feeling in the throat can result when moisture from the human body evaporates in a room overheated by a stove. A heated kettle of evaporating water can reestablish the moisture content of the air, corresponding to its increased temperature. The same feeling of dryness occurs in hot weather when evaporation of perspiration is necessary to lower body temperature. Here a parched throat indicates the need to drink water to maintain the supply of perspiration.

When air temperature drops below the saturation point, water collects in droplets on the dust particles always floating in the air. Or, if the air is in contact with a sufficiently cold surface, water vapor will condense on that surface. Thus water condenses on cold walls just as on a drinking glass containing a liquid cooled by ice. Similarly, when an amount of water vapor exceeding the saturation limit is introduced into air in an enclosed space, the excess vapor will condense, as on a bathroom mirror in winter or on the inner surfaces of the windows of a closed automobile with many people.

Cooling by Evaporation

Water will evaporate from a wet surface if it is exposed to air with a dew point lower than the surface temperature. The rate at which water evaporates from the surface depends on the relative humidity of the neighboring air, the surface temperature, and the velocity of air movement. Thus, for a wet surface at a given temperature, a reduction in relative humidity or an increase in air velocity both increase evaporation.

Energy is needed to convert water from liquid to vapor. This latent heat of evaporation must be supplied by the wet surface, which thus loses heat or is cooled. This process is called adiabatic cooling, because it does not involve a transfer of heat to or from the air participating in the process. Therefore, the air is allowed to cool as it expands and to heat as it contracts, and the temperature, pressure, and relative humidity of the air change without varying the total heat content.

This phenomenon is used for cooling in hot dry areas such as in Iraq, where the people place against the windows panels of dried desert plants, which are kept moist by water dripping from perforated pipes positioned above them. In the grasslands of Australia, where farmers cannot obtain ice, butter is kept cool in food chests with sides of chicken-wire netting filled with charcoal. When the chests are placed in the shade outside and their sides are kept moist with occasional sprinkles, a sufficiently cool environment is maintained in the chest.

Thermal Gain

The various ways in which the interior of a building can gain heat without recourse to internal heating devices can be examined. Solar radiation is the principal source of heat in hot arid zones, and this heat can be transmitted during the day to the building interior in a number of ways.

The most important is by conduction of the absorbed solar radiation through the walls or roof at a rate determined by the thermal conductance (or thermal resistivity) of the building material used, the surface area receiving solar radiation, and the properties of the surface, principally its color and texture. The relationship involving the incoming and reflected solar radiation, absorbed and reemitted heat and heat gain is shown in figure 3 for the case of a typical white painted surface. In this case, it is seen that 3% of the incident energy is transformed into heating the structure. Obviously, shading can be used to prevent solar radiation from directly falling on building surfaces.

If any openings permit the solar radiation to penetrate into the interior, then heat gain results from the direct heating of internal air, surfaces, and objects. The heat gain is proportional to the area of insolated internal surfaces. This mode of heat gain can be easily avoided by obstructing the passage of light.

Heat gain can also be caused by ventilation, which results when warm outside air flows into the building replacing the cooler interior air that escapes to the outside and by external air exchanging heat with the internal air. The rate of gain is dependent on the ventilation rate. Ventilation heat gain can be avoided by restricting the size of openings, especially during the heat of the day.

The other sources of heat gain are the inhabitants of the building themselves and household equipment such as electric lights and appliances. These sources, unlike the solar radiation, can contribute heat even at night.

Figure 4 illustrates these modes of heat gain.

Thermal Loss

The difference between diurnal and nocturnal heat losses in a building when not considering artificial cooling devices, is not marked as in the case of heat gain. Heat is lost by conduction through the walls, by exactly the same process that it is gained from the direct solar radiation once it has been absorbed by the surface, or through the roof by a combination of convection and conduction.

Ventilation is also another mode of heat loss which occurs when hot air escapes through an opening in the roof or a wall to be replaced by cooler air from outside. Nocturnal heat losses can be retarded by closing vents.

Evaporation from the surface of the building or from objects within the interior can produce a cooling effect on the building which acts as a source of heat loss. In hot arid climates, this can be a particularly effective cooling mechanism since the rate of evaporation in dry air is very high.

Figure 4 also shows the modes of heat loss.

Dynamic Thermal Equilibrium

At any particular time, the heat gained by the building can be expected to be balanced by the heat lost and an internal temperature distribution thus established. These temperatures are dependent on the outside (ambient) temperature and the ratio of the heat gained to the heat lost and can be adjusted by regulating the sources of heat gain and loss. For example, if one were to reduce to a minimum the heat losses of an insolated building, the internal temperature would rise, much as in the case of an automobile left in the sun with its windows closed. This is called greenhouse gain. On the other hand, a very cool internal temperature could be obtained by shading the insolated surface, obstructing direct penetration of solar radiation, enhancing a flow of cool air, using thick light-colored walls made of a low thermal-conductivity material, using high ceilings provided with roof ventilation, and providing sources of evaporation including possibly a roof pond and an internal fountain.

However, in fact, the temperature situation within a building changes slowly throughout the day for two important reasons. First, the solar radiation and external temperatures vary slowly, and the internal temperatures are constantly adjusting to the changing rates of heat gain and loss. Second, the mass of the building structure does not react instantaneously to external changes but has a thermal inertia requiring from many minutes to hours to adjust to a temperature change. The principle of thermal inertia can be used advantageously to provide dynamic heating and cooling of a building by selecting the wall material and its thickness such that the warmth of the day penetrates the building only after nightfall when it would be welcomed and is dissipated before morning.

Thus, it is seen that the microclimatic situation of a building is in a constant state of flux and that the equilibrium that is established is a dynamic one. When providing a comfortable microclimate, it is necessary to reduce the extreme fluctuations to within the range of human comfort by regulating the various parameters that govern heat gain and loss.

Before examining the systems and devices that have been developed to do this in the hot arid zones, it is first necessary to have an idea of the heat-regulating mechanism of the human body and the microclimatic conditions for human comfort.

Heat-regulating Mechanisms of the Human Body

As discussed earlier, the human body must maintain a fairly constant temperature over a considerable range of external air temperatures. The human body is subject to the same laws of physics as other objects, gaining and losing heat by the processes described above, namely: radiation through space; conduction between bodies and/or substances in contact; convection involving the transfer of heat from a warm body to a body of air above it, which then rises to be replaced by cooler air; and evaporation, which requires that the evaporating surface give up some heat. However, the human body is not simply a passive object warmed or cooled like metal or water. Its metabolic processes generate its own heat as well, similar to a heat-producing engine. Like any other engine, it burns fuel, in the form of food, and converts this into heat and work. As with an engine, work cannot be generated without producing some heat—even if unwanted—which must be dissipated just as for an automobile.

In a hot environment, the heat generated by the human body must be dissipated. Body heat regulation is essentially the maintenance of a balance between heat gains and losses. The body has an excellent heat-regulating mechanism, which under normal conditions can adjust its temperature to maintain the appropriate heat balance. Only when it is exposed to prolonged severe conditions do serious difficulties arise.

The metabolic processes of the living human body continuously generate heat. Even at complete rest, an important quantity of heat is produced. This basal heat production amounts to 73 kcal/h (290 Btu/h) for an average adult male. For a short time he can increase this rate eightfold through violent exercise, although over 24 hours the average heat production would not amount to more than 130% of the basal rate for sedentary work and 300% for heavy manual labor.[11]

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[11] Douglas H. K. Lee. *Physiological Objectives in Hot Weather Housing: An Introduction to Hot Weather Housing Design* (Washington, D.C.: Government Printing Office, 1953).

Table 3. Heat gain and loss processes for the human body

Mechanism	Gain Process	Loss Process
Metabolism	Basal heat production Digestion Activity Muscle tensing and shivering in response to cold	
Radiation	From solar radiation—direct and reflected From radiation by radiators	To surrounding air
Conduction	From air above skin temperature (increased by air movement) From warmer bodies in contact	To air below skin temperature To cooler bodies in contact
Evaporation		From respiratory tract From skin covered with perspiration or applied water

Table 3 shows the modes of heat gain and loss between the human body and its surroundings for the metabolic activities and three mechanisms of physical heat exchange, namely, radiation, conduction, and evaporation.

Air movement has a significant influence on the heat transfer between the skin and air and will increase the transfer rate in whichever direction it is proceeding, i.e., either to or from the body. Air movement increases the rate of heat loss by evaporation. For continued heat loss, the evaporated water vapor must be free to move away from the site of evaporation. Thus the difference between the vapor pressure at the skin surface and that of the surrounding air controls the ease with which evaporation cools the skin. The vapor pressure at the skin surface results largely from the extent to which a water film covers the skin, which may vary from less than 10% of the skin area on a cool, dry day, to 100% when the skin is bathed in perspiration.

The consequences of heat stress can be important. When the human body has difficulty losing heat, the blood vessels of the skin dilate, allowing much more blood to circulate and cooling by heat loss through any of the processes discussed above. But this increase in blood-vessel volume may exceed the body's ability to provide a corresponding amount of blood. To compensate, other blood vessels in the internal organs may receive less blood, although this still may not yield sufficient blood. During such a relative blood shortage, the brain, located at the highest part of the body, may be deprived of an adequate supply. Brain tissue is most sensitive to the shortage of oxygen and quickly produces the characteristic symptoms of "heat exhaustion": lassitude, headache, nausea, dizziness, uneasiness, and ultimately fainting. However, a wide range of lesser disturbances probably interfere with efficiency without resulting in total exhaustion. In addition, the human body has a remarkable sweating capability. With moderately hard work under hot dry conditions, a man can produce about 1.5 liters (3 pt) of perspiration per hour. Although he probably would not keep this up for more than two or three hours, he could lose as much as 8 liters (4 gal) in one day, which must be compensated for by drinking water. Eight liters is a large quantity of water for the body to handle, and even at lower sweating rates there probably will be periods when water loss exceeds supply. Then the already precarious blood supply is depleted still further and the risk of heat exhaustion is increased. Further indirect consequences of heat stress are lowered alimentary activity due to the insufficient blood supply, discomfort from hot and moist skin, the risk of skin disturbances when moist skin is chafed, possible salt deficiencies due to sweat loss, and perhaps urinary stones from reduced urine flow.[12]

Thus it is important to avoid conditions that stress human heat-regulatory processes until they interfere with normal body functions or health. A permanent state of human comfort need not be guaranteed, but there is a range of microclimatic conditions that can be maintained with an effort that is more than recovered by the saving in human efficiency. Securing this degree of climatic improvement should be the aim of tropical architecture.

Measurement of Conditions of Human Comfort

A convenient standard for thermal comfort is required. Analysis shows that a variety of factors can be involved in situations of discomfort. For example, temperature alone does not determine discomfort. In Athens, 32 °C (90 °F) is quite bearable, but it is generally intolerable in Bahrain. The difference is due entirely to the relative humidity of the atmosphere. In Bahrain the air is very humid and perspiration evaporates slowly, decreasing the body's ability to lose heat. In Athens, with its dry air, the evaporation rate is high and perspiration evaporates quickly, lowering body temperature.

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12. Ibid.

The factors that have been identified as standard for thermal comfort within buildings are: air temperature, air humidity, rate of air movement, level of radiation, and rate of heat production by the bodies of people in the building. Extensive studies have established representative physiological scales that take into account all of these variables. An index used in the United States, and which with one limitation appears to provide an adequate measure of environmental warmth, is *effective temperature*. This takes into account temperature, humidity, and airspeed, but not radiation. Introduced by Houghton and Yaglou, this measure of heat sensation is defined as the temperature of saturated motionless air that would produce the same sensation of heat or cold as the combination of temperature, humidity, and air motion under consideration. An improvement on this measurement by Vernon and Warner uses the temperature given by the *globe thermometer* instead of the dry-bulb air temperature and thus includes an approximation of the radiation component. This standard is known as the *corrected effective temperature* and is the most useful scale of thermal sensation now available for the Tropics.

The effective temperature scale is in fact a physiological temperature scale. To establish it, a large number of people were exposed to wide ranges of temperature, humidity, and airspeed, and their sensations recorded. Later it was determined that the physiologically objective reactions of the subjects, such as pulse and perspiration rates, were in agreement with this effective temperature scale. However, it must not be assumed that this scale can be indiscriminately applied throughout the world with equal accuracy. Its American originators were the first to point out the limitations imposed by the fact that the scale was established from experiments on American subjects wearing clothing of American style and material. To establish an accurate, effective temperature scale for, say, Pakistan, a complete investigation using Pakistani subjects and clothing would be necessary.

The physical parameters to be measured and the instruments needed are shown in table 4.

Measurements made using a globe thermometer include the heating effects of infrared radiation emitted by warm flooring, roofing, and walls. The dry-bulb thermometer of a whirling psychrometer permits a nearly accurate evaluation of the basic air temperature; its speed through the air is sufficient to eliminate radiation effects. The Kata thermometer is superior to the usual type of vane anemometer. It indicates the sum of the effects of variable draughts to which a vane anemometer is not sensitive but which are physiologically important.

Table 4. Parameters to be measured for establishing an effective temperature scale and the corresponding instruments required

Parameter	Instrument
Air temperature	Silvered thermometer or whirling (dry-bulb) psychrometer
Air temperature including approximation of radiant heat contribution	Globe thermometer
Air humidity	Whirling wet-bulb psychrometer
Air movement	Kata thermometer

It also records velocities lower than most anemometers, and it needs no calibration.

Table 5 gives some examples of effective temperatures for different combinations of air temperature, relative humidity, and airspeed. For optimal comfort in air-conditioned buildings, the recommended range of effective temperatures is 22.2–23.3 °C (72–74 °F), corresponding to dry-bulb temperatures of 25.6–26.7 °C (78–80 °F), at 50% relative humidity.

Such physiological scales are useful when comparing the relative comfort of different sites. It should be remembered, however, that buildings can reduce the free wind speed. Studies in London have shown that wind speed at street level is generally about one-third of the unimpeded wind speed.

To subjectively compare human reactions to various conditions of heat, humidity, and airspeed, several microclimatic comfort sensation scales have been established. An example of such a scale and instructions for its use are given in Appendix 2.

At the London School of Hygiene and Tropical Medicine, a group of 32 students were asked to record their sensations of comfort under precise air-temperature, humidity, and airspeed conditions. They included approximately equal numbers of students from Great Britain and the United States, and from tropical countries. A summary of the student responses at 22.2 °C (72 °F) dry-bulb temperature, 16.1 °C (61 °F) wet-bulb temperature, 56% relative humidity, and 0.25–0.38 m/s (50–75 ft/min) airspeeds is given in table 6. Although this is a preliminary, and by no means conclusive, experiment with only a small number of subjects, it indicates some fundamental difference between people from tropical and temperate countries with regard to comfort sensation.

Table 5. Examples of effective temperatures for different combinations of air temperature, relative humidity, and airspeed

Shaded Dry Bulb Temperature	Relative Humidity (%)	Effective Temperature at Airspeeds of: 0.1 cm/s (0.33 ft/s)	0.5 cm/s (1.64 ft/s)	22.5 m/s (73.8 ft/s)	Effective Temperature Difference for Airspeed Increase from 0.1 to 22.5 m/s (0.33 to 73.8 ft/s)
40.6 (105)	75	36.7 (98)	36.7 (98)	36.1 (97)	−0.6 C° (−1 F°)
	40	32.8 (91)	32.2 (90)	31.4 (88.5)	−1.4 C° (−2.5 F°)
	20	30.6 (87)	30.0 (86)	29.2 (84.5)	−1.4 C° (−2.5 F°)
35 (95)	90	33.9 (93)	33.3 (92)	32.2 (90)	−1.7 C° (−3 F°)
	75	31.7 (89)	31.4 (88.5)	30.0 (86)	−1.7 C° (−3 F°)
	40	28.9 (84)	28.3 (83)	26.9 (80.5)	−2.0 C° (−3.5 F°)
29.4 (85)	90	28.6 (83.5)	27.7 (82)	25.6 (78)	−3.0 C° (−5.5 F°)
	75	27.2 (81)	26.7 (80)	24.4 (76)	−2.8 C° (−5 F°)
	40	24.4 (76)	23.9 (75)	22.2 (72)	−2.4 C° (−4 F°)

Note: All absolute temperatures are in °C (°F).

Table 6. Summary of the comfort sensation of two groups of students exposed to 22.2 °C (72 °F) dry-bulb temperature, 16.1 °C (61 °F) wet-bulb temperature, 56% relative humidity, and 0.25–0.28 m/s (50–75 ft/min) airspeeds

Comfort Sensation	Students from Temperate Zone (%)	Students from Tropical Zone (%)
Comfortable temperature	36	7
Too warm	14	0
Too stuffy	30	0
Comfortably cool	7	36
Comfortably dry	0	31
Air fresh	30	50

Table 7. The values for the ambient and most appreciated air-conditioning temperatures and humidities in four tropical cities

	Dry Bulb Temperature	Wet Bulb Temperature	Dew Point	Relative Humidity	Effective Temperature
Ambient conditions:					
Delhi, India	43.3 (110)	24.4 (76)	16.1 (61)	21%	30.4 (86.8)
Abadan, Iran	46.1 (115)	26.7 (80)	19.4 (67)	22%	31.9 (89.5)
Bombay, India	32.2 (90)	27.7 (82)	26.7 (80)	72%	29.0 (84.2)
Lagos, Nigeria	35.0 (95)	28.3 (83)	27.8 (82)	62%	30.2 (86.3)
Most desired conditions	25.6 (78)	19.4 (67)	15.6 (60)	55%	22.5 (72.5)

Note: All temperatures are in °C (°F).

Table 8. Comparison of outdoor and indoor temperature and humidity conditions provided by a continuous airspeed of 0.3 m/s (60 ft/min) over a wet surface

Location	Dry Bulb Temperature	Wet Bulb Temperature	Dew Point	Relative Humidity	Effective Temperature
Outside	43.3 (110)	24.4 (76)	16.1 (61)	21%	29.5 (85.2)
Inside	32.2 (90)	26.1 (79)	24.4 (76)	65%	27.2 (81.0)

Note: All temperatures are in °C (°F).

Table 7 shows values for air-conditioning that were found to be generally favored by the occupants of buildings in tropical countries. The airspeed was taken to be 0.3 m/s (60 ft/min) in these effective temperature calculations.

Table 8 shows that it may not be necessary to use powered air-conditioning, an expensive expedient in places where ambient conditions are hot and dry, as in Delhi or Lahore. The inside effective temperature can be reduced using only evaporation in such climates, merely by ensuring a continuous air speed of 0.3 m/s (60 ft/min) over a continuously wet surface. Thus a reduction in effective temperature of 2.3 C° (4.2 F°) can be achieved.

With this understanding of the physical principles affecting human comfort, it is now possible to examine the applications of scientific concepts to architectural design and town planning in hot arid regions.

Before the advent of modern mechanical means for obtaining thermal comfort, people in the hot arid and warm humid zones were forced to devise ways to cool their houses with only natural sources of energy and physical phenomena. Generally, these solutions have been found to be much more in harmony with the human physiological functions than such modern means as electrically powered desert coolers and air-conditioners.

This situation is unchanged for the majority of people in the industrially developing countries, where the conventional energy sources of the industrialized world are not readily available at affordable prices. There is a clear need to further develop the traditional systems based on natural resources. Before inventing or proposing new mechanical solutions, traditional solutions in vernacular architecture should be evaluated, and then adopted or modified and developed to make them compatible with modern requirements. This process should be based on modern developments in the physical and human sciences, including the fields of materials technology, physics, aerodynamics, thermodynamics, meteorology, and physiology.

Architectural Design for a Comfortable Microclimate

In designing and planning for the hot arid and warm humid zones, two of the main problems confronting the architect are to ensure protection against heat and provide adequate cooling. The Earth's major source of heat and light, the sun, also creates the secondary climatic elements of wind and humidity that affect physiological comfort. These are caused by the configuration and nature of the local surface, such as the mountains, plains, oceans, deserts, and forests. The interplay between this astronomical source of energy with the effects it causes and the landscape creates the microclimate, which is the concern of the science of meteorology.

However, the built environment produces changes in the microclimate. The configuration of buildings, their orientations, and their arrangement in space create a specific microclimate for each site. To this must be added the building materials, surface textures and colors of exposed surfaces of the buildings, and the design of open spaces, such as streets, courtyards, gardens, and squares. These man-made elements interact with the natural microclimate to determine the factors affecting comfort in the built environment: light, heat, wind, and humidity.

There is no doubt that certain configurations create better microclimates than others. For each site, there is an optimum arrangement in space that the designer should seek and use as a standard of reference in the process of deciding upon a certain design. Where it can be avoided, it is inappropriate and irresponsible to implement a design that adds even one degree of temperature or reduces air movement by one centimeter per second, if this would negatively affect thermal comfort. This obviously includes defective designs which require energy-intensive mechanical means for their rectification.

Building Materials

The materials surrounding the occupants of a building are of prime importance for protection against heat and cold. Great care must be taken in the choice of the wall and roof materials and their thicknesses with respect to their physical properties, such as thermal conductivity, resistivity and transmission, and optical reflectivity.

Considering an external wall exposed to a high outside air temperature and a lower inside air temperature (see fig. 1), the rate of heat flow transmitted through the wall from the outside air to the inside air is proportional to the air temperature difference, area of the wall, and rate of global heat transmittance that can be determined from an analysis of the components of the total resistance to heat flow.[1] The

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[1] If the wall is of thickness L, area A, and exposed to an outside air temperature T_1 and an inside air temperature T_2, with T_1 greater than T_2, the rate of heat flow, Q, transmitted through the wall can be calculated using the formula:

$$Q = UA(T_1 - T_2) \tag{9}$$

where Q is given in kcal/h and U is the rate of global heat transmittance.

total resistance is composed of the resistance to heat flow through the material, the interfacial resistance at the external surface, and the interfacial resistance at the internal surfaces.[2] Since the interfacial resistances are determined primarily by temperature conditions over which the builder has little control, his principal effect on the heat transmittance is on changing the resistance to heat flow through the wall material.[3] To reduce the heat transmission from one side of a wall to the other, the thermal transmittance must be reduced as much as possible by either increasing the thickness of the wall or using materials of lower thermal conductivity and therefore of higher resistance. Often walls composed of several materials, as shown in figure 2, are used to provide the desired thermal and aesthetic wall characteristics.[4] Coefficients of thermal transmittance for a variety of wall materials and of combinations of such materials are provided in Appendix 3. These coefficients are given in the practical units commonly used: kcal/hm^{2}C° and Btu/hft^{2}F°.[5]

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2. Representing these resistances by R_M, R_1, and R_2, respectively, the total resistance is

$$R = R_M + R_1 + R_2. \tag{10}$$

3. Using eq. (8) of fn. 10, eq. (10) gives the following expression for the rate of global heat transmittance:

$$\frac{1}{U} = \frac{L}{k} + \frac{M_1}{M_1} + \frac{M_1}{M_2}, \tag{11}$$

where R_M is obtained from eq. (4) of fn. 6, M_1 is a constant for the external surface which was empirically found to be 18 kcal/hm^{2}C° (3.69 Btu/hft^{2}F°), and M_2 is a constant for the internal surface which was empirically found to be 7 kcal/hm^{2}C° (1.4 Btu/hft^{2}F°).

4. If the wall is composed of n different materials of thickness $L_1, L_2, \ldots,$ and L_n that have, respectively, the thermal conductivities $k_1, k_2, \ldots,$ and k_n, the formula for heat transmission becomes

$$\frac{1}{U} = \left(\frac{L_1}{k_1} + \frac{L_2}{k_2} + \ldots + \frac{L_n}{k_n} + \frac{1}{M_1} + \frac{1}{M_2}\right). \tag{12}$$

5. Two examples demonstrate how this information is used.

Example 1 (see fig. 1): an external brick wall of thickness 0.11 m (4.3 inch) and thermal conductivity 0.6 kcal/hmC° (0.12 Btu/hft^{2}F°) gives

$$\frac{1}{U} = \frac{0.11\ \text{m}}{0.6\ \text{kcal/hmC°}} + \frac{1}{7\ \text{kcal/hm}^2\text{C°}} + \frac{1}{18\ \text{kcal/hm}^2\text{C°}} = 0.382\,\frac{\text{hm}^2\text{C°}}{\text{kcal}}$$

resulting in

$$U = 2.62\ \text{kcal/hm}^2\text{C° } (0.537\ \text{Btu/hft}^2\text{F°}).$$

In hot arid climates, the coefficient of thermal transmittance should be about 1.1 kcal/hm^{2}C° (0.225 Btu/hft^{2}F°) for an outer wall to have an appropriate thermal resistance. Table 9 lists the thicknesses of walls composed of various construction materials needed to achieve coefficients of approximately 1.1 kcal/hm^{2}C° (0.225 Btu/hft^{2}F°).

These tables do not contain data for mud-brick walls. However, experiment has proved that mud brick is most appropriate for achieving thermal comfort in addition to being widely available to all segments of the population.

In 1964, six small experimental buildings were built on the grounds of the Cairo Building Research Centre, using different materials. They were used to evaluate cost, local availability, and thermal comfort. Two modes of these six represented extremes. One was built entirely of mud brick with the 50-cm (20-inch) thick walls and roof in the shape of a combined dome and vault. The other was built of 10-cm (4-inch) thick prefabricated concrete panels for both the walls and the roof. Plans and sections of these buildings are given in figures 5 and 6, respectively.

These models were examined on a day in March when external air temperature varied from 12 °C (53.6 °F) at 6 A.M. to 28 °C (82.4 °F) at 2 P.M. and back to 12 °C (53.6 °F) at 4 A.M.[6] As shown in figure 7, the air-temperature fluctuation inside the mud-brick model did not exceed 2 C° (3.6 F°) during the 24-hour period, varying from 21–23 °C (69.8–73.4 °F), which is within the comfort zone. However, the maximum air temperature inside the prefabricated model reached 36 °C (97 °F), or 13 C° (23 F°) higher than in the mud-brick model and 9 C° (16 F°) higher than the outdoor air temperature. It fell within the comfort

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Example 2 (see fig. 2): the same brick wall with inside and outside layers of plaster of paris with 0.6 kcal/hmC° (0.12 Btu/hft^{2}F°) thermal conductivity and 2-cm (0.8-inch) thickness on both sides gives

$$\frac{1}{U} = \frac{0.11\ \text{m}}{0.6\ \text{kcal/hmC°}} + \frac{0.04\ \text{m}}{0.6\ \text{kcal/hmC°}} + \frac{1}{7\ \text{kcal/hm}^2\text{C°}}$$

$$+ \frac{1}{18\ \text{kcal/hm}^2\text{C°}} = 0.448\,\frac{\text{hm}^2\text{C°}}{\text{kcal}}$$

resulting in

$$U = 2.23\ \text{kcal/hm}^2\text{C° } (0.457\ \text{Btu/hft}^2\text{F°}).$$

[6] Omar El-Farouk, John Norton, Wendy Etchells, Jocelyn Levaux, Allan Cain, and Farroukh Afshar, *Climate Study—Traditional Houses*. Third World Studies (London: Architectural Association School of Architecture, 1974). (Measurements made 25 March to 10 May 1973.)

Table 9. Thicknesses of walls of different material that give coefficients of thermal transmittance of approximately 1.1 kcal/hm^{2}C° (0.225 Btu/hft^{2}F°)

Wall Material	Wall Thickness		Thermal Transmittance	
	(in m)	(in in)	(in kcal/ hm^{2}C°)	(in Btu/ hft^{2}F°)
Hollow brick block	0.30	12	1.10	0.225
Double-wall brick with holes and 8-cm cavity	2 × 0.12	2 × 4.7	1.12	0.229
Brick wall with holes	0.38	15	1.03	0.211
Sand-lime brick	0.51	20	1.25	0.256
Hollow block sand-lime brick	0.51	20	1.16	0.238
Lime	0.51	20	1.10–1.35	0.225–0.277
Concrete	1.00	39	1.20	0.246

zone for only one hour in the morning (9–10 A.M.) and between 8:40 P.M. and 12:20 A.M., as recorded in figure 8. The contrast can be explained by the fact that concrete has a thermal conductivity of 0.9, while that of mud brick is 0.34, and that the mud-brick wall is five times thicker than the prefabricated panels. Thus, the mud-brick wall has a thermal resistance more than 13 times greater than the prefabricated concrete wall. Unfortunately, these models were not evaluated for the salient dates of the equinoxes and solstices, which would have provided complete information, especially about the lag effect and heat storage.