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Klaus Daniels, Dirk U. Hindrichs (eds.)
Plusminus 20°/40° Latitude – Sustainable Building Design in Tropical and Subtropical Regions
With contributions by Sonja Berthold, Klaus Daniels, M. Norbert Fisch, Ralph E. Hammann, Winfried Heusler, Haruyoshi Kibe, Ajay Shah, and Magdi Yacoub. 460 pp. with ca. 1100 ill., 230 x 297,5 mm, hard-cover, English
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When looking for appropriate building solutions in tropical and subtropical regions, the chief aims are saving energy and reducing pollutant emissions as much as possible. Natural ventilation, passive and active use of solar energy, the use of rainwater and the energy potential of the soil are the key issues here. Traditional urban and building structures, described in an exemplary way by local architects for a wide variety of locations, provide a stimulus for thinking about the many positive elements already developed by master builders of the past, alongside all the technical possibilities that exist today.

Natural ventilation of a building is made possible by its particular urban location, but also by the structure of the building itself as a result of internal thermal circulation and wind-induced pressures. Extensive planting, including planting within the building, further helps to improve the quality of urban spaces and structures.

In addition, the outer skin of a building is a key element in dealing with the requirements described here. For this reason, the façade systems including the glazing and the shading elements are considered in detail. The use of photothermic and photoelectric solar technologies is also examined extensively, along with the use of the energy potential of the soil, which to date has still not been taken into account in many regions of the world.

Important examples of realized objects show the interplay between the use of natural resources and the building technology that has been added on.

Dirk U. Hindrichs and his company Schüco International, working with chief technologist Winfried Heusler, have consistently shown the way forward for energy-optimized building envelopes since the mid-1990s. Schüco transforms buildings from energy consumers into energy generators by combining measures to save energy and harness solar power. The central concern here is the reduction of CO_2 pollution. Klaus Klaus Daniels was professor at the Eidgenössische Technische Hochschule in Zurich until he retired. The experience he accumulated in almost 40 years of work as a consulting engineer in the fields of aerophysics, building climatization and technology has been set down in numerous books.

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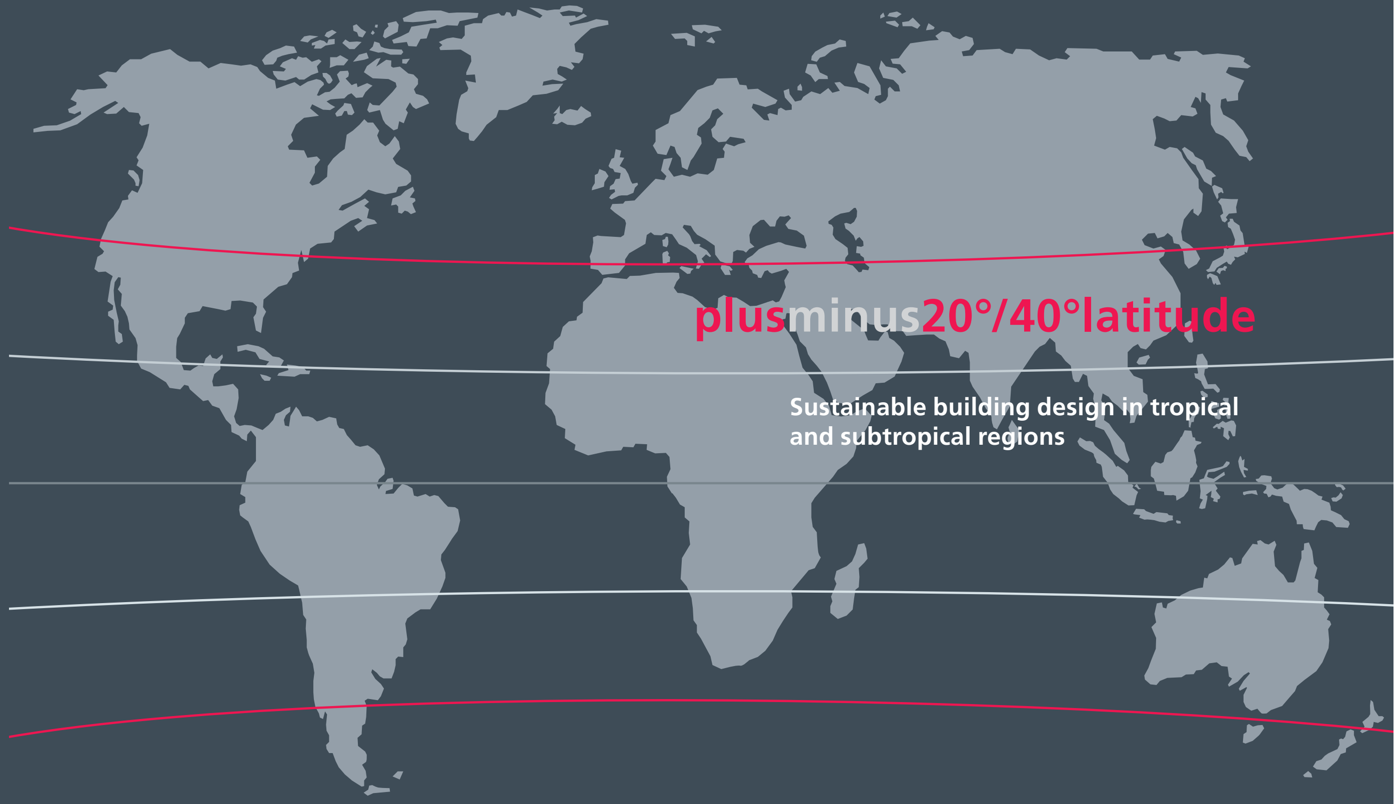

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Sustainable building design in tropical and subtropical regions

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Contents

8.
Building structures

8.1
Principles of building structure and enclosure

The enclosure of a building, the so-called building envelope or façade, has to respond to aesthetic as well as structural and physical goals. In a structural sense one has to distinguish generally between the load-bearing and non-load-bearing walls of a building:

- Load-bearing walls take up all the forces acting upon a building, both vertically and horizontally. They transfer those forces into the foundation or the supporting soil.
- By lateral stabilization, cross-bracing walls contribute to the structural concept of the building as well and thus are also considered load-bearing walls.
- Non-load-bearing walls are generally resisting only their own weight or forces out of wind, which are transferred typically to a primary structure, generally made out of steel or reinforced concrete in today's buildings.

The building materials that are mostly used in tropical and subtropical climates include wood, clay (adobe), brick, and concrete (Figure 8.1). Wood is used mainly in climate regions that are characterized by large diurnal temperature swings and significant seasonal temperature differences. Earthen construction is used traditionally in hot-arid climates of the Middle East and Africa. In more moderate climate zones, the material brick, often combined with timber construction is common. Concrete as a building material was first used for the construction of the domed hall of the Pantheon in Rome, built 118 to 126 AD, a temple of bearing masonry. Since the end of the 19th century, reinforced concrete has been used as a primary structural material in buildings. This composite material of steel and concrete is considered today one of the most important load-bearing materials in the world of architecture due to its versatile capability to transfer tensile forces via the embedded steel and the concrete's resistance to compressive forces (Figures 8.2 to 8.4)

As early as in a conceptual phase of a project, the main structural material should be defined. To successfully achieve a cost-effective building, ordering principles of the structure are important to consider, independently of the building being a load-bearing wall or post-and-beam construction. As a result, clear spans of the structural system have great consequences on initial cost. In the case of a load-bearing wall structure, cost increases exponentially with clear span.

Figure 8.1
Typical traditional buildings
in Sharjah (UAE)

The physical demands on a building envelope range from protection against heat loss or gain to humidity control, acoustics, fire protection, and the resistance against driving rain. Building envelopes can be designed as single- or multi-layered assemblies. The structural and physical properties of single-layered or monolithic constructions are solely defined by the material property and its thickness. Consequently, in those wall types just one material must be able to satisfy several multi-functional demands. In a multi-layered envelope construction, on the other hand, the diverse materials of the individual layers can be brought to optimization in order to respond to specific functional requirements.

Besides the composition of the building envelope in general, its constructive design and its interrelationship with the structure – i.e., connections, joints, and energy and sound bridging – play a more or less decisive role. In addition, the design of the constructive connection between building façade and interior partitions plays an important role with regard to lateral transfer of sound.

Not only do the demands on building envelopes vary according to different climatic conditions, such as the quality of outside air and noise levels, but optimized solutions also need to consider the variation of those parameters during the course of a day or year. Expenditures for mechanical and electrical equipment and their cost of operation in buildings, such as electrical lighting, ventilation, and heating/cooling, can be minimized by building enclosure systems, that do the following:

- minimize the influences of external climatic conditions on internal comfort conditions (i.e. reduce the impact of exterior weather conditions on the building interior),
- soften the variations of local weather conditions by leveling off their peaks.

Figure 8.2
Reinforced concrete frame
construction in the Middle East;
Beirut (Lebanon) 2006

Figure 8.3

Figure 8.3 and 8.4
Reinforced concrete frame
construction in the Middle East;
construction boom in Dubai
(UAE) 2006

8.2
Protection against driving rain and humidity

Especially in tropical and subtropical regions, poor protective measures against driving rain and/or humidity lead not only to uncomfortable conditions for users but also to consequential damage of the building structure.

Figure 8.5 depicts the various forms of impacts of rain or humidity on building envelopes. Various causes can lead to water damage in building assemblies:

- faulty or missing protection against driving rain in façades by omitting cornices or canopies, mainly on the windward side,
- water mist as a consequence of car traffic,
- rain water that enters masonry wall construction through faulty gutters or sealing,
- improper protection against water back splash at plinths on balconies and canopies,
- condensation occurring on the inside of exterior building components,
- condensation occurring inside exterior building assemblies.

Strains on external walls are mainly a result of rain and the coexistence of wind. The rainwater is either able to enter the wall through cracks, joints, or faulty caulking by the pressure of the wind, or it can be absorbed by the wall assembly by capillary reaction. Protection of a wall assembly against water absorption and its capabilities to evaporate moisture in the case of driving rain can be achieved by proper constructive measures and the selection of adequate materials and surface qualities. The connections of an outside wall, such as outside and inside corners, plinths, and sills, need to be executed in such a way that they not only are watertight against the interior of the building but also provide proper measures to conduct water away from the building in a controlled manner. Drainage has to be provided without the forming of water-collecting "depots", which may lead over time to water streaks.

Humid air will lead to condensation in or on building assemblies when it encounters surfaces whose temperature is below the dew point of the temperature of the humid outside air.

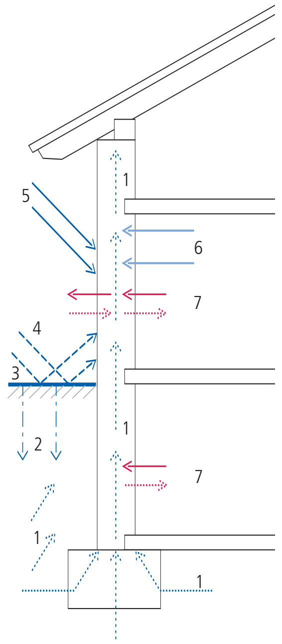


Figure 8.5
Humidity impact on exterior building components

1 Humidity of the soil, dissolved minerals
2 Seeping water, dissolved minerals
3 Surface water
4 Driving rain
5 Rain
6 Condensate and hygroscopic humidity
7 Vapor diffusion

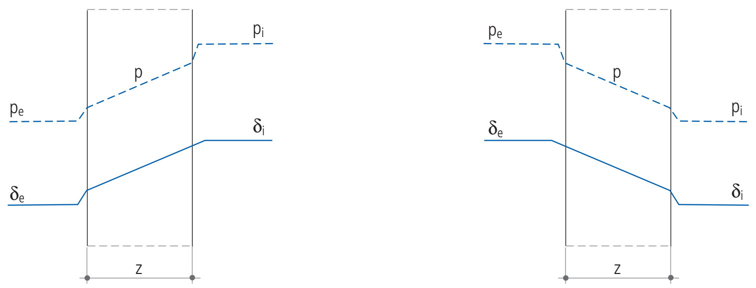
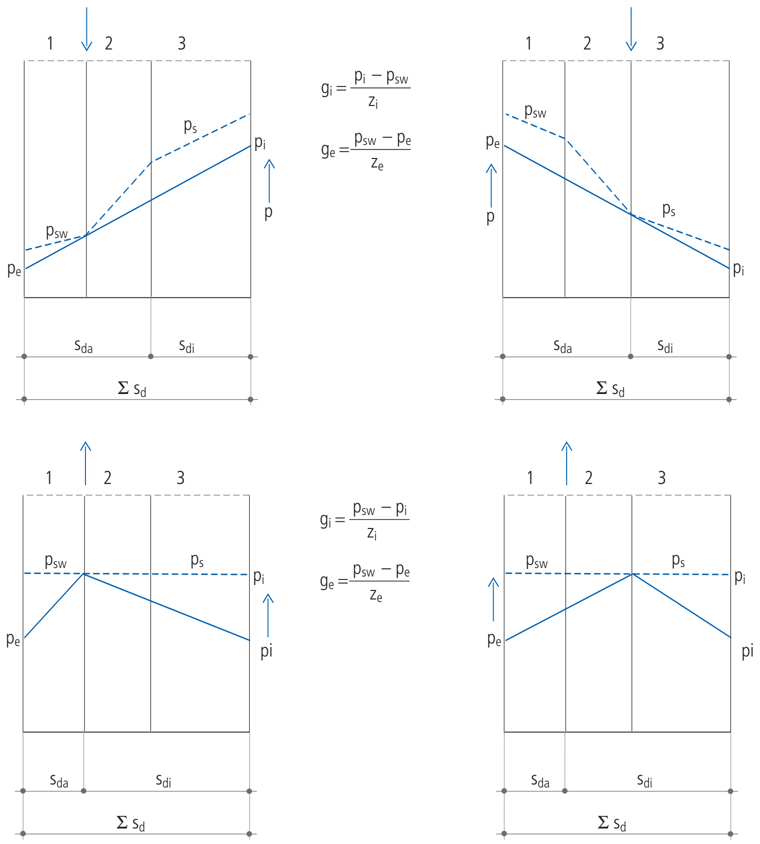


Figure 8.6
Vapor diffusion through exterior building component
cold-dry region (left)
hot-humid (right)

δ Temperature
P Partial pressure of water vapor



$$g_i = \frac{p_i - p_{sw}}{z_i} \qquad g_e = \frac{p_{sw} - p_e}{z_e}$$

$$g_i = \frac{p_{sw} - p_i}{z_i} \qquad g_e = \frac{p_{sw} - p_e}{z_e}$$

Figure 8.7
Vapor diffusion with condensate formation inside of building component (upper)

Vapor diffusion with evaporation (lower)

cold-dry region (left)
hot-humid (right)

Term	Symbol	Unit
Partial pressure of water vapor	p	Pa
Relative humidity	φ	1
Mass related humidity content	u	kg/kg
Water vapor diffusion coefficient	D	m^2/h
Water vapor diffusion density	g	$kg/(m^2 \cdot h)$
Water vapor transmission rate	Z	$m^2 \cdot h \cdot Pa/kg$
Thickness of air-layer equivalent to water vapor diffusion	s_d	m

Table 8.1
Humidity control technology, terms, symbols, units

Figure 8.8
Water vapor retarder applied to the outside of a building envelope, bituminous coating on concrete, Dubai (UAE)

Figure 8.9
Water vapor retarder applied to the outside of a building envelope, detailed view, Dubai (UAE)

Condensation on surfaces of building envelopes

Poorly insulated building envelopes are subject to the formation of condensate:

- on the inside, when humid interior air meets the inner surface of an outside wall under low exterior temperature conditions,
- on the outside, when humid exterior ambient air meets the outside surface of a mechanically cooled building.

Condensate forms also on very well insulated building envelopes:

- on the outside, under clear sky conditions and low outside temperatures.

Condensation inside of building envelope assemblies

Differences in humidity levels between interior space and the exterior are equalized relatively rapidly by water vapor diffusion depending upon the water vapor characteristics of the building envelope design. Porous materials, depending upon their physical and chemical characteristics, absorb more or less humidity in the form of water vapor from the surrounding inside or outside air. **Figures 8.6** and **8.7** show diagrams concerning water vapor diffusion, condensation levels, and evaporation of water vapor for outside walls. In case of condensation of absorbed water vapor in capillary cavities, the water moves according to the laws of capillary physics. It is critical that the formation of condensate inside of building envelopes must not compromise their functionality. This is particularly the case if:

- the materials of the envelope assembly that come into contact with the condensate become damaged – i.e., by corrosion or mildew,
- the water that forms inside the assembly due to condensation cannot be given off to the outside during cycles of evaporation.

In Middle Eastern construction, a common method of avoiding problems of condensation consists of the application of a layer of asphalt as a water vapor retarder on the exterior of concrete walls (**Figures 8.8, 8.9**)

8.3
Insulation of outside walls and roofs

8.3.1 Single-layer envelopes

With the help of the thermal simulation software TRNSYS, various opaque exterior walls and roofs in tropical and subtropical regions were analyzed and graded with regard to their energy demands for cooling, and, if necessary, heating. During the dynamic calculations, the cooling and heating demand in kWh/m^2 during the course of a year is calculated in hourly steps for a base case building as a reference. The influence of an enclosed building construction on energy demand is shown here proportionally and graded.

Data on the reference building:

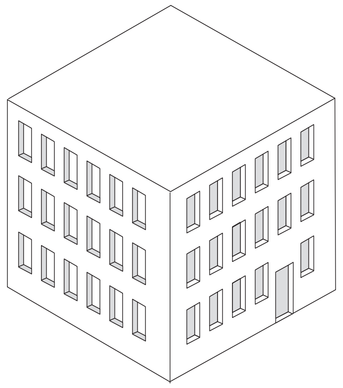
Gross building volume	1,130 m^3
Net building volume	882 m^3
Net usable space	294 m^2
Building footprint	103 m^2
Wall total gross area	385 m^2
Roof total gross area	103 m^2
Window: exterior surface ratio depending on orientation	25 %
Surface: volume ratio	0.52

Building systems parameters:

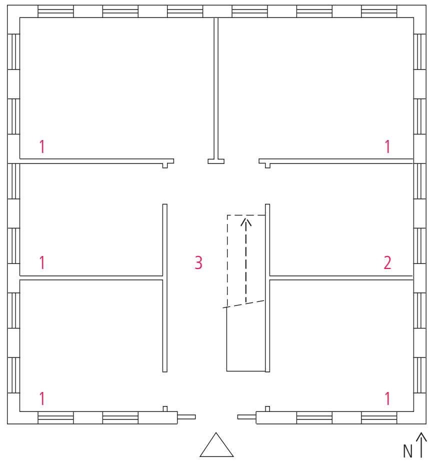
Heating setpoint	20 °C
Cooling setpoint	26 °C

In case of outside temperatures of > 29 °C,
Sliding increases
cooling setpoint definition according to DIN 1946

Opaque building components – starting scenario
The simulation uses today's typical exterior wall and roof assembly of a building in Ahmedabad, India (**Figures 8.11, 8.12**). With regard to the energy demand for heating and cooling, this typical wall is compared with a wall construction insulated by a layer of 40-mm polystyrol foam.



Isometric façades, south-west



Ground plan

Figure 8.10
Reference building used in simulation

1 Office
2 Bathroom
3 Hallway

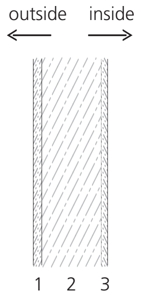


Figure 8.11
Wall assembly, single-layer/solid
U = 1.50 $\text{W/m}^2\text{K}$

1 Cement plaster/stucco,	37 mm
2 Masonry,	239 mm
3 Cement plaster/stucco,	24 mm

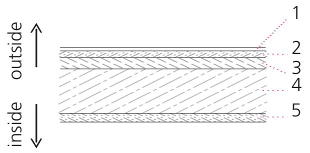


Figure 8.12
Roof assembly

1 Ceramic tile	12 mm
2 Mortar bed	12 mm
3 Masonry	83 mm
4 Concrete slab	150 mm
5 Cement plaster/stucco	24 mm

In the tropical climate of hot-humid and hot-arid regions, which are characterized by annual average air temperatures of > 25 °C, the energy consumption for cooling drops only insignificantly after the addition of the 40-mm-thick insulation. In a subtropical climate on the other hand, where average yearly temperature ranges below 20 °C, energy savings for cooling cannot be achieved, yet the energy used for heating is decreased significantly.

The chosen insulation improves the U-value $[\text{W/m}^2\text{K}]$ (rate of heat loss, in 1 s through 1 m^2 of a building surface, when the difference between the air temperature on either side is 1 K) of the perimeter wall assembly, which reduces transmission heat loss, or gain. The insulation reduces the energy consumption used for heating in the cool period very effectively, yet it is only marginally able to contribute to energy savings for cooling under high outside temperatures.

Orientation
In this chapter the influence of building orientation on the effectiveness of insulation of exterior wall surfaces will be analyzed.

As shown in **Figures 8.16** to **8.18**, the effect of insulation of a roof surface with regard to reductions of energy use for heating and cooling is more effective than the different wall orientations – only savings in the case of heating are worth mentioning.

The analysis of the influence of insulation thickness shows that most savings for heating and cooling are achieved for thicknesses of up to 40 mm. Beyond this dimension, reductions in energy use for cooling are insignificant, but reduced energy levels for heating still can be expected to be significant.

The insulation of opaque exterior wall surfaces reduces the energy used for heating up to 25 %, but for cooling energy, on the other hand, reduction is only up to 6 %. The use of insulation in subtropical climates is recommended in light of savings for a heating case and to improve comfort by increasing the surface temperatures of exterior walls in the winter time. In hot-humid and hot-arid zones, it is necessary to carefully consider additional initial cost for added insulation and the expected savings for cooling.

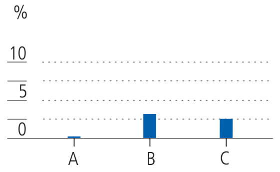


Figure 8.13
Hot-humid region

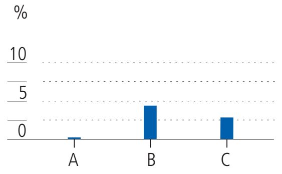


Figure 8.14
Hot-arid region

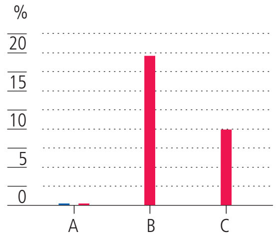


Figure 8.15
Mixed warm-humid region

Savings in annual energy demand in % through use of insulation

A Wall/roof, non-insulated
B Wall, 40 mm insulation
C Roof, 40 mm insulation

🟦 Cooling
🟥 Heating

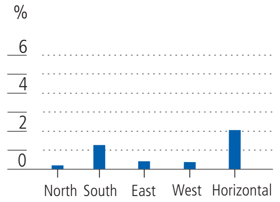


Figure 8.16
Hot-humid region

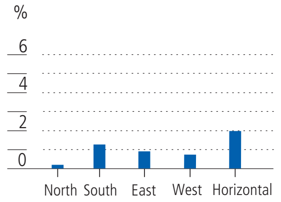


Figure 8.17
Hot-arid region

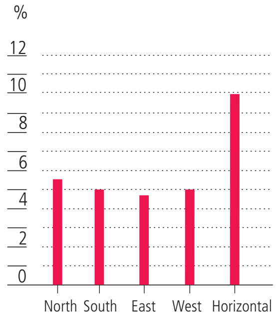


Figure 8.18
Mixed warm-humid region

Savings in an energy demand as a function of orientation

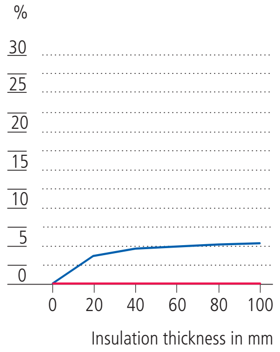
🟦 Cooling
🟥 Heating

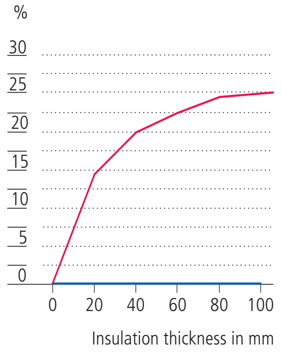
Savings in annual energy demand in % as a function of insulation thicknesses

— Cooling
— Heating

Figure 8.19
Hot-arid region

Figure 8.20
Mixed warm-humid region (right)





8.3.2 Cavity walls

Exterior cavity walls composed of a solid interior and exterior layer made of concrete or masonry will be analyzed with regard to energy use for cooling and heating compared with the single-layer base case wall.

Cavity walls will be compared both in their ventilated and non-ventilated form. Ventilation of masonry cavity walls is achieved by vertical joints left open in the zone of the base of the wall and the parapet. The ventilation of the roof is achieved by open joints, where wall and roof meet.

Savings potentials for cooling will increase – similar to the insulation of exterior wall surfaces – with an increase in annual average temperature of the respective building location. Energy savings related to cooling in the case of a cavity wall are small. Energy usage for heating can be decreased by approximately 8 % by utilizing a non-ventilated cavity wall. When comparing ventilated with non-ventilated cavity walls or roof assemblies, it can be said that a ventilated assembly design results in only insignificant energy savings. After the analysis of the efficiency of ventilated cavity walls, they will be compared with non-insulated and insulated monolithic walls.

It can be noted that the energy consumption increases linearly with an increase in the U-value. When comparing U-values, the ventilated cavity wall reduces energy consumption slightly better than the monolithic and insulated wall, yet the resulting increases in space for the additional thickness of a cavity wall need to be considered.

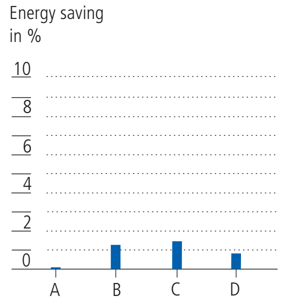


Figure 8.21
Hot-humid region

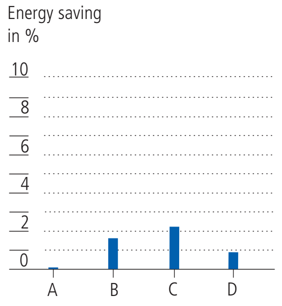


Figure 8.22
Hot-arid region

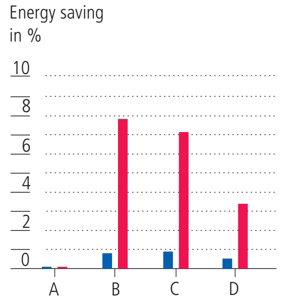
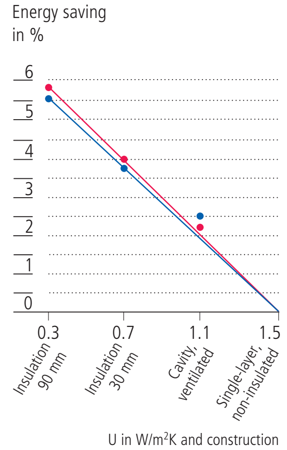


Figure 8.23
Mixed warm-humid region

Savings in annual energy demand in % for ventilated and non-ventilated cavity and non-cavity wall and roof assemblies

A	Wall/roof, single-layer
B	Wall, cavity
C	Wall, cavity and ventilated
D	Roof, cavity and ventilated

🟦 Cooling
🟥 Heating



Figures 8.24 and 8.25
Savings in annual energy demand in % for ventilated, insulated, and non-insulated exterior cavity wall assemblies in different climate regions

● Hot-humid region
● Hot-arid region
● Mixed warm-humid region

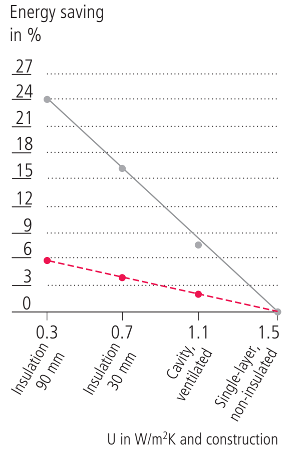


Figure 8.25

8.4
Surface coloration of exterior walls and roofs

For a standard construction, the influence of color of the exterior surface will be analyzed (solar absorption of surfaces). **Figures 8.26** and **8.27** show buildings with different surface colorations.

Surface temperature can be approximated as T_s, the solar-air temperature, by the equation:

$$T_s = T_a + aI / a$$

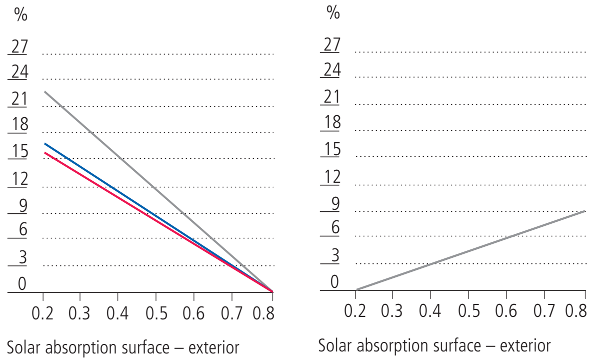
Where:

T_a = Exterior air temperature [°C]
I = Solar radiation [W/m^2]
a = Absorption coefficient [>0<1]
a = External heat transmission

White, glossy surface coloration reduces the energy consumption for cooling significantly, up to 16 – 23 %. Heating energy consumption only increases up to 9 % when using light surfaces. Therefore surface color is a significant factor in all climate regions when energy savings are of importance. **Figure 8.30** depicts this clearly.

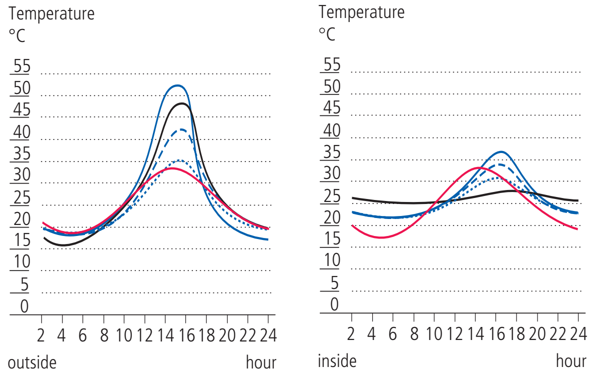
Figure 8.26
White, glossy roof:
solar absorption: 0.2
Exterior wall color light brown,
solar absorption: 0.6
(Sangath, Vastu-Shilpa
Foundation, Ahmedabad)

Figure 8.27
Dark glass façade:
Solar absorption: 0.75
Light exterior wall colors,
solar absorption: 0.3 – 0.4
(office building in Dubai,
UAE)



Figures 8.28 (left)/29 (right)
Savings in annual cooling energy demand in % (left) and heating energy demand (right) for various solar absorption coefficients in different climatic regions

— Hot-humid region
— Hot-arid region
— Mixed warm-humid region



Figures 8.30 (left)/31 (right)
Exterior and interior surface temperatures for a 10 cm concrete wall with various solar reflectivity. West façade, Cairo/July

— Outside temperature
— Absorption coefficient = 0.9
– – Absorption coefficient = 0.6
- - - Absorption coefficient = 0.3
— Black and insulation

8.5
Thermal storage in building mass

Thermal storage in a building may be decisive for the reduction of cooling loads (heat gain in building) and the reduction of temperature increases. Heat gain in buildings is evident when the heat load is a result of solar incidence or when room temperatures change. In these cases the momentary loads are so changed by the storing elements that the heat gain time function changes into a cooling load time function. For calculating cooling loads, thermal storage may be approached in several ways (storage factors in the room, storage factors in external walls).

The room, as a unit, absorbs radiant heat at the interior surrounding walls, through windows (diffuse and direct solar incidence), (artificial) lighting, occupants, machines, etc., all of which have an effect. How far radiant heat penetrates walls or building storage components depends on the wall layout and the duration of the radiation, thus causing an increase in surface temperatures. The surfaces are in a constant state of reciprocal radiation exchange. Depending upon air and surface temperatures, a convective heat transfer is effected from the surfaces to the air and vice versa. For variable room temperatures, a rise in temperature triggers a reduction in the cooling load due to thermal storage. A fall in room temperature triggers an increase in the cooling load due to heat release. Of particular interest here is the heat backflow, i.e. convective heat transfer and heat absorption occurring at the same wall.

Transmissions of external temperature fluctuations through the building envelope
External surfaces of building envelopes show higher or lower temperatures not only as a function of ambient air temperature, intensity of solar radiation (if applicable influenced by external shading devices) and the radiation physics of the envelope itself, but also dependent on their own thermal properties. Additionally, the transmission of external temperature fluctuations through a building envelope is not only a function of its U-value, but also of the capacity of the wall to store heat.

Dampening and delaying effects can be observed, which are a result of the wall being capable of absorbing energy (heat) in times of higher temperatures, and releasing it if temperatures decrease.

By dampening the heat transmission from the outside to the interior of a space, the resulting internal energy gains are reduced.

Heat exchange between a building element and a surrounding air volume is dependent on temperature differential, the timing of temperature changes, coefficient of heat penetration b, or thermal effusivity, into the building element and of the thermal transmission coefficient a between room air temperature and building component surface. The heat penetration b can be calculated as follows:

$$b = \sqrt{a \times r \times c}$$

Where:

b = thermal penetration coefficient Wh$^{1/2}$ m^{2}K
a = thermal conductivity W/mK
r = density kg/m^3
c = specific heat storage capacity Wh/kgK

The temperature transmission depends, on the one hand, on the temperature differences between room air and building element surface, and on the other on the air movement on the element surface.

The time between the exterior temperature maximum and the maximum on the inside of a space is called thermal lag F (Phi) and is given in hours (h). If a significant thermal lag exists, external daily heat loads are delayed and take effect on the inside of a space only after lower external temperatures are present. This is especially effective in climatic regions with great diurnal temperature differences. Large thermal lag is a result of high R-values (1/L) (inverse of the U-value (R = 1/U)) of the exterior wall assembly and of a high thermal penetration coefficient (b) of the building material. Very light exterior walls show a thermal lag of less than three hours, while heavy walls achieve values of approximately 12 hours.

The difference between the daily minimal and maximal external surface temperatures, mainly as a result of insolation, is called external temperature amplitude (Δqa). As a result of the above-described building element properties, greater or lesser temperature amplitudes on the inside of the envelope ensue (Δqi).

The relationship between the two temperature amplitudes is called temperature amplitude dampening Q (Theta):

$$Q = \Delta qa / \Delta qi = qa\ max - qa\ min / qi\ max - qi\ min$$

The reciprocal value of amplitude dampening is called the temperature-amplitude relationship (TAV):

$n = \Delta qi / \Delta qa$.

Its values (between 0 and 1) are to be as low as possible – in temperate regions below 0.25 and in hot regions below 0.1 Under this condition, a thermal lag between six and eight hours is sufficient, since in this case the greatest thermal stress occurs during nighttime hours. At that time, lower outside air temperatures allow for natural ventilation and cooling of interior spaces by opening windows.

In single-layered, opaque constructions, the TAV increases proportionally to the values of the thermal lag. In multi-layered assemblies, even reversed scenarios can develop. Analysis of the interdependencies of temperature-amplitude dampening, the thermal lag of building material properties, and wall assembly types results in the following conclusions:

- Concurrent conditions of small amplitude dampening and thermal lag will be present both in well-insulated assemblies without thermal storage capacity and in walls with inferior insulation qualities but significant storage capacity.
- Simultaneous conditions of a large degree of amplitude dampening and thermal lag can be achieved in homogeneous walls made of materials with good insulation and good storage capability.
- Optimal amplitude dampening is achieved in multi-layered assemblies with external insulation. For this scenario, thermal lag plays a smaller role, albeit a heavy interior wall material is advantageous.