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The Effect of Wind on Energy Consumption in Buildings

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The discussion focuses on four mechanisms of building heat exchange with the surrounding environment and their effects on overall energy consumption.

1. Air infiltration and exfiltration is treated in terms of pressure distributions and gradients and the resulting mass transfer at building surfaces.

2. Surface heat transmission is affected by turbulent mixing of air close to the building surface; the various mechanisms causing this turbulent mixing are discussed.

3. Air circulation around buildings strongly affects the effectiveness of air-conditioning cooling towers, and the improper location of ventilation inlets and exhausts can reduce thermal efficiencies of cooling equipment and can increase fan power requirements.

4. Wind is a primary determinant of human thermal comfort in outdoor environments, and the traditional architectural response for building entrances and passageways has been enclosure. Some results of studies of human comfort in urban outdoor surroundings are reported.

The relative importance of the combinations of these effects for various building types is presented and discussed.

INTRODUCTION

The environment around a building affects its energy consumption, primarily by influencing its requirement for space heating and cooling. The environmental variables influencing the amount of energy needed for heating and cooling are outside temperature, humidity, shading and wind.

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Wind influences building energy consumption in four ways:

(1) air infiltration and exfiltration;
(2) surface heat transmission;
(3) mechanical systems efficiency;
(4) necessity for enclosing outdoor space.

Air infiltration and exfiltration

Air movement is an important cause of energy loss, particulary in residential buildings, where infiltration commonly causes between 30 and 75% of the total heat load in winter [1].

Wind affects the air pressure distribution on building surfaces, which controls the heat loss and gain by mass transfer through apertures in the walls and roof. The pressure distribution depends on the following.

(1) The aerodynamics of the building in relation to its surroundings. This determines the velocity/pressure field around the entire building. Essentially, there is an increase in pressure on the windward side of a building and a decrease in zones where flow has accelerated (the corners of the windward side of the building and the ridge of the roof) or separated (to leeward of the building). (See Fig. 1).

(2) The aerodynamic effects of surface features. The geometry of wall and roof architectural features controls the local pressure patterns. This is particularly impor-

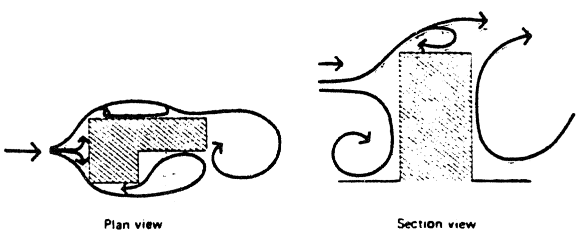

Fig. 1. Sample schematic of air flow around buildings.

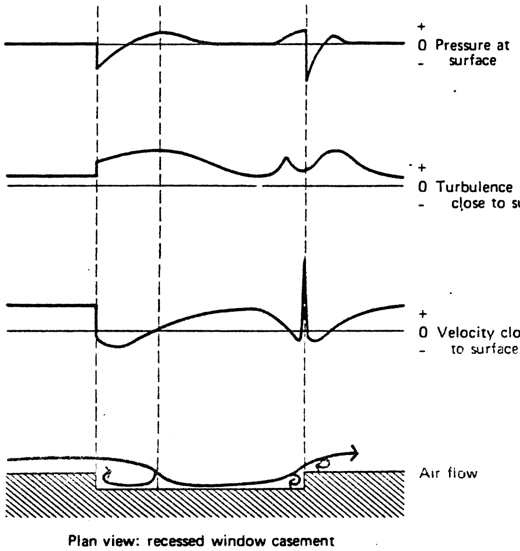

Fig. 2. Characteristics of air flow across a building surface near a recessed window casement.

tant around window and door casements, in which the local air pressure next to a crack may be significantly different from the overall pressure on that part of the building (Fig. 2).

(3) The local surface pressure on high-rise building surface with mullions shows wide variations from the overall pressure coefficient of the same surface without mullions [2]. Near the corners of buildings with mullions, local negative pressures can be more than five times the value for the same corner on a smooth-surfaced building.

Heat loss by infiltration is proportional to the amount of flow through the openings in the wall. This is related to pressure and incident velocity as follows:

Microscopic pores: laminar flow, pore diameter <0.01 in.

$$q \propto \Delta P \propto u^2$$

where q is the volumetric heat flow, ΔP is the pressure difference between interior and exterior, and u is the exterior wind speed.

Cracks and larger openings: orifice flow, crack diameter >0.01 in.

$$q \propto (\Delta P)^{1/2} \propto u$$

Experimental tracer-gas measurements by Dick [3, 4] showed that air changes in closed unoccupied townhouses were directly proportional to the average approach velocity. This could be taken to imply that the significant infiltration in houses occurs through crack- or

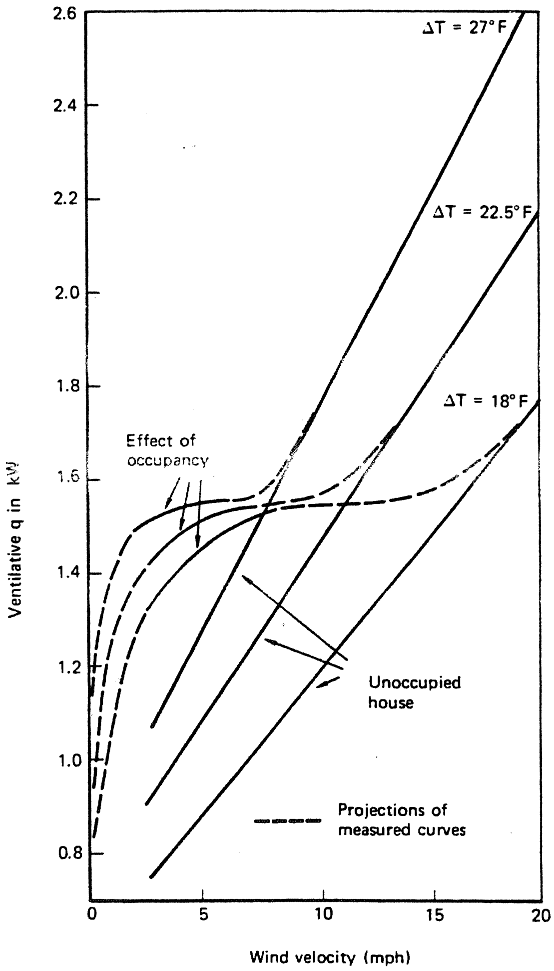

Fig. 3. Ventilative heat loss for a closed and occupied house of floor area 1000 ft^2. (Source: Dick and Thomas [5].)

larger-sized openings, although the resolution of the data may not warrant this conclusion.

The situation may be complicated by other factors such as human comfort perception. Measurements made in occupied houses in a cold environment [5] (see Fig. 3) show a large ventilation rate at low wind speeds due to opened windows. As wind velocity increases, occupants begin to close windows and doors, causing the incremental infiltration rate to decrease. Dick and Thomas' data suggest that these occupants sensed an acceptable rate of ventilative heat loss and took steps to curtail heat loss above that rate.

In 1974 and 1975, members of the Princeton study group at Twin Rivers, New Jersey, performed wind tunnel and full-scale infiltration tests on a row of two-storey townhouses [1]. The average winter air infiltration measured in these houses was about one-third of the total heating energy requirements during the winter.

Models of the same buildings were tested in a wind tunnel to determine the effects on infiltration of the orientation of the building and of shelter by surrounding objects. The measured pressure distributions of the various faces of the townhouses were converted into infiltration rates by a simple mathematical model.

The tests showed the rate of infiltration was strongly influenced by the direction of the wind approacing the house and by the position of the individual houses in the townhouse row. Infiltration commonly varied by more than 50% between houses of different orientation. Shelter by landscape elements such as trees and fences also cut infiltration rates. For example, a 5 ft high solid fence to windward of a house reduced infiltration by 30% in the wind tunnel models. Higher reductions occurred for combinations of trees and fences.

Subsequent full-scale tests were made to test these results. A row of experimental trees (25 ft high eastern white pine Christmas trees) was planted to windward of one of the townhouses. Measurements were made in external winds ranging from 5 to 22 miles per hour. The results are currently being analysed, but findings to data have supported the wind tunnel result that significant reductions are obtained from shelter (conversation with George Mattingly*).

Surface heat transmission

Wind flow around a building causes forced convection heat transfer from and to the walls and roof, resulting in increased energy consumption. The convective heat transfer is caused by the turbulent mixing of air close to the wall due to:

(1) the turbulence generated in the wall boundary layer itself,

(2) the wind-flow patterns around the building,

(3) the turbulence inherent in the wind stream.

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The method most often used for determining the effect of wind on heat losses takes into account only the first mechanism, that of boundary-layer turbulent mixing. It is based on the "Reynolds analogy", which assumes that, for a turbulent boundary layer in air flows parallel to a plane boundary, the thermal transfer mechanism is the same as the momentum transfer mechanism. The heat losses can then be expressed in the form [6]

$$\mathrm{Nu} = \frac{1}{2}\,\mathrm{Re}\,C_f$$

or

$$\frac{h_c x}{k} = \frac{1}{2}\,\frac{ux}{\nu}\,C_f$$

where Nu = Nusselt number
Re = Reynolds' number
h_c = convective transfer coefficient
k = conductivity
u = wind velocity
ν = kinematic viscosity
x = length from leading edge
C_f = surface drag coefficient

The surface drag coefficient is proportional to velocity: $C_f \propto u^{-1/n}$, where $2 \leqslant n \leqslant 5$, depending on the turbulence of the low. For a given fluid of fixed conductivity and viscosity, therefore, the surface convection coefficient will be proportional to the velocity raised to an exponent between 0.5 and 0.8.

Surface convection is only a part of heat transmission through and from a surface. The overall heat transfer depends as well on radiation from the outside surface, the conductance of the wall, and the interior surface coefficients of radiation and convection.

The total heat transfer q is

$$q = UA\Delta T \tag{1}$$

where A is the area, ΔT is the temperature difference between interior and exterior air, and U, the wall coefficient of transmission, is given by

$$\frac{1}{U} = R_i + R_w + \frac{R_r R_c}{R_r + R_c} \tag{2}$$

where R_i, R_w, R_r and R_c are the resistances of interior surface, wall, exterior surface radiation, and exterior surface convection, respectively.

The external wind affects only the value of R_c. This means that U varies with wind velo-

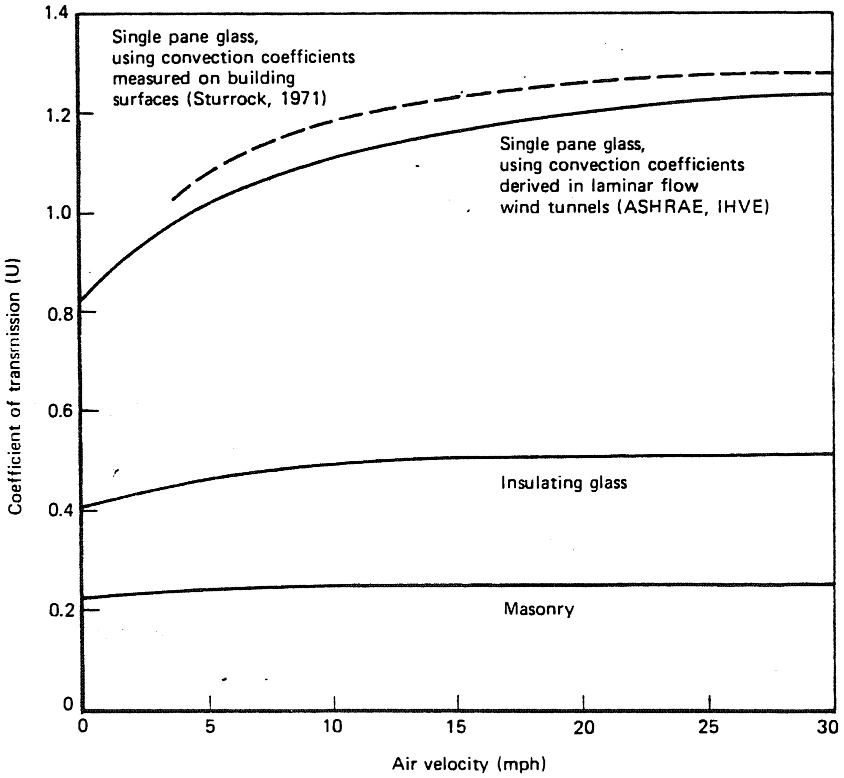

Fig. 4. Effect of air velocity on surface heat transmission.

city*, as shown in Fig. 4. The effect of wind on heat transmission is clearly only significant for poorly insulated materials, such as single-pane glass. A rougher material such as masonry with a higher surface drag coefficient may have twice the convection coefficient of glass but, since the wall resistance of masonry is much greater, the overall variation in surface heat transfer with wind velocity is minimal.

Use of Fig. 4 will give reasonable approximations for the heat loss from a flat surface at zero incidence (parallel air flow) in a steady air stream with low-intensity isotropic turbulence. Actually, real wind flows around building surfaces are considerably more complex.

The shape of the building and its orientation to the wind strongly influence the wind velocities and flow characteristics in its vicinity. The wind-flow pattern along each wall will be different (see Fig. 1). On windward faces the flow will accelerate toward the corners; on the leeward side the flow pattern will be determined by the separation eddy. For these conditions, with strong pressure gradients and separated flows, the Reynolds analogy does not apply. On the windward face, the impinging flow causes more heat transfer [9]; on the lee side mean velocities will be lower and it would be expected that there would be less heat transfer. However, at certain locations of the lee side, such as flow re-attachment areas, turbulent fluctuations can be very large. Instantaneous high turbulent fluctuations close to the wall surface (even then there is a very small mean velocity) may produce mixing that will exceed the flat plate steady flow case.

In addition to the overall aerodynamics of the building, small-scale architectural features affect the airflow. Protrusions from the surface, such as mullions and window frames, increase turbulent mixing and hence heat loss (see Fig. 2).

The nature of the approaching wind flow itself will affect the flow pattern around a building. Buildings are situated in the earth's

*The term $R_r R_c/(R_r + R_c)$ is referred to as the "surface resistance" shown in the ASHRAE Handbook [8], Chap. 20, Table 1, for moving air is the surface convection resistance only. In determining U-values, surface radiation resistance should also be considered.

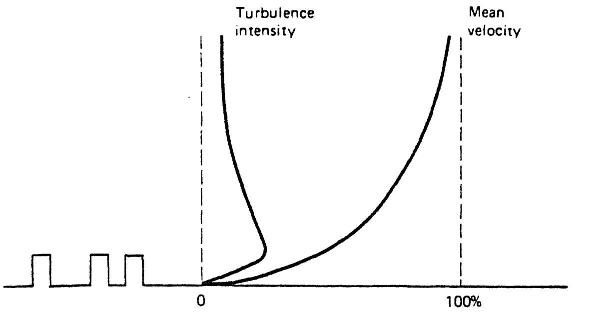

Fig. 5. Velocity and turbulence intensity profiles in the atmosphere, scaled to the gradient wind velocity at the top of the boundary layer. (Source: Counihan [10].)

boundary layer, whose wind velocity and turbulent intensity distribution vary according to the upwind topograph (see Fig. 5).

The high turbulent intensities of the atmospheric boundary layer will be superimposed on the turbulent structure of the wall boundary layer and will increase the amount of turbulent mixing and hence heat transfer at the wall surface.

It would appear that, because of the windflow effects around the building and the nature of the wind itself, the convective heat losses from an actual building would be higher than that predicted by using the Reynolds analogy for parallel flow on a flat plate. Unfortunately, little work has been done to examine the heat loss relationships for actual building shapes immersed in the earth's boundary layer. Sturrock's measurements [9] of convective losses for simple building shapes in the wind tunnel are approximately 50% higher than those given by the parallel flow flat-plate formula. A surface forced convection coefficient 50% higher for single-pane glass would result in the *U*-values shown by the broken line in Fig. 4.

It can be seen that the variation in overall surface heat transmission between high velocities (30 mile/h) and very low velocities (3 mile/h) is of the order of 30% for single-pane glass. A typical office block in the San Francisco area loses approximately 20% of its heat through surface heat transmission; under the new design rules this may increase to 30%.* Thus, one might expect the wind to cause 10% of the total heat transfer to the environment. Practically, however, the designer cannot reduce the wind speed or turbulence by more than perhaps 60%. The resulting reduction of the building's total heat load becomes very small of the order of 3%.

Mechanical systems efficiency

Wind controls the circulation around structures, influencing the location and effectiveness of ventilation inlets and exhausts and/or air-conditioning cooling towers. Failure of cooling tower systems to perform to specifications during wind is apparently a common problem.**

Wind influences the energy requirements of mechanical systems in two major ways:

it can cause inadvertent exhaust recycling, reducing thermal efficiency of cooling equipment and heat pumps;

the pressure gradients it induces affect the fan power requirements for exhausts, inlets and cooling towers.

Attempts to avoid these problems have led designers to space exhausts and inlets far apart, increasing ductwork and pumping costs. Knowledge of wind influences might be used to advantage to allow designers to minimize the distance between inlets and exhausts, thereby reducing pumping costs and the amount of materials invested in ductwork, and increasing the feasibility of waste energy retrieval equipment.

There does not appear to be published literature on the magnitude of wind-induced mechanical inefficiencies, although these can be serious. In San Francisco there are examples of cooling towers on high-rise buildings that lose 70% of their cooling capacity during the daily 20 - 30 mile/h sea breeze.** It is estimated that typical wind influence on the mechanical systems of high-rise office buildings causes energy losses of the order of 5% of the building's total energy consumption.*

Necessity for enclosure: climate of the building's environment

The spaces around buildings may be used for human activities if their climates are comfortable for people engaged in those activities. Because many shopping plazas,

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**Conversation with Bert Stubblefield, Buonaccorsi and Associates, San Francisco, Calif. (U.S.A.).

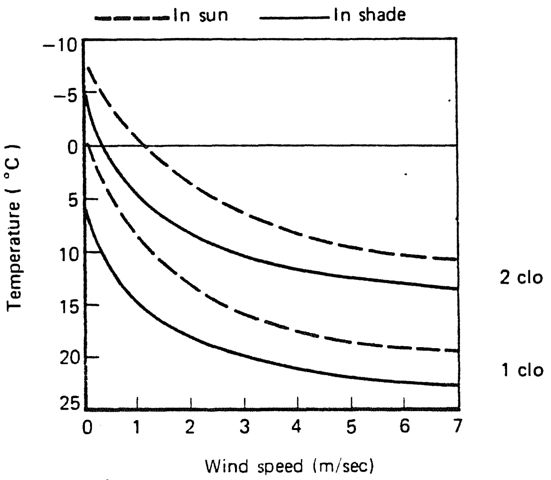

Fig. 6. Comfort curves for the thermal equilibrium of a pedestrian walking at 2.5 mile/h in an outdoor environment. The "clo" is a unit of clothing insulation, where 1 clo is taken to be typical light clothing (office dress).

passageways and building entrances have been found to be uncomfortable due to excessive windiness or poorly-controlled climate, architects have been tending to enclose them as indoor lobbies and malls, either remedially or as part of the initial design [11]. Appropriate climatic design of such outdoor spaces and their surrounding buildings could in some cases obviate the need for these enclosures, thus saving the energy costs of materials, construction, heating, air conditioning, lighting and maintenance of indoor spaces.

Successful design of outdoor spaces depends on knowledge of the local climate that will exist in a planned outdoor space, and on knowledge of whether that climate will be comfortable for people engaged in the activities that are planned for that space (*i.e.* seated activities require warmer and more controlled climates than pedestrian activities, where people generate more metabolic heat and are free to move to maintain their comfort).

Considerable interest is developing in the study of civilian comfort in urban outdoor surroundings. British research on comfort in cold climates [12, 13] is noteworthy and begins to explore the design implications of the comfort criteria it established. Figure 6 is an example of thermal equilibrium curves that show comfortable outdoor conditions in varying temperature, wind and sun [14]. Two clothing levels are given. The metabolic rate is fixed.

Comfort in hot indoor environments has been widely studied for many years. This information is being applied toward an outdoor design model by Herrington and Vittum [15].

In the climatic design of unenclosed spaces, the factors to be adjusted are the following.

Hot climates: promote wind ventilation; block sun from the inhabitated areas; use surfaces with high thermal admittance.

Cold climates: block wind; expose the inhabited spaces to sun.

Outdoor design accommodating both hot and cold seasons is very possible and there are many examples of this in the world's traditional architecture.

It is also possible to enclose spaces without heating or cooling them. The Galleria in Milan and Wright's Marin Civic Center are examples of large common malls that admit sunlight through glass roofs and are cooled through natural ventilation by thermal and wind-induced convection.

COMBINED EFFECT OF WIND ON VARIOUS TYPES OF BUILDINGS

The total effect of wind on heat transfer tends to depend on the type of building.

Office buildings

(1) Infiltration is often negligible on office buildings with sealed windows; it is controlled more by the operation of the mechanical ventilation system than by the exterior wind.

(2) The fraction of total energy cost attributable to aerodynamic influences on surface transmission will approach 10% in large-scale office buildings of conventional design. This depends primarily on the area of glass, and also on the surface-to-volume ratio of the building. The designer is unlikely to be able to influence more than 3% of the building's total energy consumption by applying wind-control devices to the facade.

(3) Mechanical systems dominate the energy requirements of office buildings. Wind-induced inefficiencies might be of the order of 5% of total energy requirements, as mentioned above; there is room for research on this and on ways of designing wind-efficient inlet and exhaust systems.

(4) Although office towers commonly

produce very windy surroundings, their architects generally do not have the choice of whether exterior space should be enclosed. The unusual Ford Foundation Building in New York is perhaps the most interesting example of this choice is an office building.

Residential low-rise

(1) Infiltration studies on residences have been described above. Townhouse units with openable windows commonly lose more than 30% of their total winter heating load to infiltration, which is highly responsive to wind action (Fig. 3).

(2) Approximately one-third of the total winter heat loss from residences is *via* surface transmission from walls and roof, and another one-third from windows. The effect of wind on wall and roof surface transmission is negligible, but wind can double the heat transmitted through single-pane windows.

(3) Wind effect on efficiency of mechanical systems is generally unimportant in residential-scale buildings.

(4) Effective landscaping and house design could, in many cases, make outdoor spaces more livable and eliminate the need to enclose and heat them. Similarly, houses in hot climates designed to use the wind for natural ventilation save all the substantial energy needed for air conditioning.

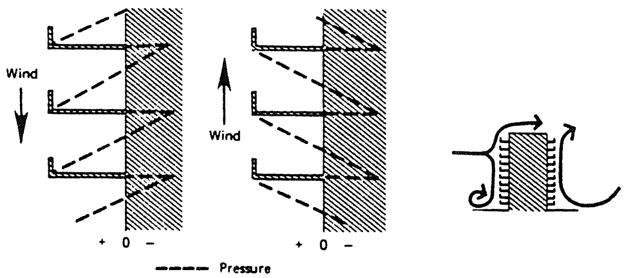

Fig. 7. Pressure distribution on the face of a building with balconies.

Residential high-rise

(1) Infiltration and exfiltration due to wind cause the primary heat loss from residential high-rise units with openable windows and doors to balconies. Fig. 7 is a schematic diagram of pressure distribution on the face of a high-rise apartment block with balconies; the inset shows the flow pattern around the entire building. It can be seen that the positive and negative local pressures at the top and bottom of the balcony space exceed the total pressure, and that this can cause substantial air leakage through the joints of sliding doors and windows.

(2) Surface transmission heat losses from residential high-rises should be the same as for office buildings, except that the areas of glass are generally less.

(3) Mechanical systems efficiency is probably affected by wind to a degree similar to that for office buildings.

(4) The issue of whether outdoor spaces should be enclosed generally does not apply to this type of construction.

Commercial

(1) Infiltration, (2) surface transmission, (3) mechanical systems — with the many different types of commercial buildings, these facotrs are too variable to discuss specifically (4) the questions of whether to enclose a space and whether to control its climate depend partly on wind. The tendency toward enclosure in shipping center design has important energy implications. Examples are given by Penwarden and Wise [11].

CONCLUSION

Some information has been presented, giving a feel for the wind effects on heating and cooling loads and their relative importance.

Existing research is sparse and there is much room for research on wind effects. Particular examples are:

infiltration on houses *versus* siting and landscaping;

infiltration on high-rise residential blocks,

wind effect on the mechanical systems of tall buildings;

better climatic design of outdoor spaces and indoor spaces without energy-consuming climate control.

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