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THERMAL INSULATION IN BUILDINGS

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1. INTRODUCTION

The usefulness of thermal insulating materials for making buildings more comfortable has been recognized since the time of primitive man. Typical examples of applications range from the insulating effect of the snow of an Eskimo's igloo to the shade-cooling relief offered by a thatched roof in the tropics.

The purpose of this paper is to review and discuss from the viewpoint of the engineer the presently used thermal design procedures including practical limitations, the environmental and applications factors that influence the performance of a thermal design and some current research problems that involve insulated constructions. Also, the benefits of insulated constructions and their importance to a nation will be mentioned.

2. DESIGN PROCEDURES

The engineer and architect must produce a thermal design for a building shell that is compatible with the structural, architectural, mechanical and electrical designs of the building. Sometimes the requirement for compatibility restricts the designer in regard to dimensions and space available for insulation and must be recognized from the start. Also, a predetermined cost limitation may become a primary consideration in the production of a thermal design.

The usual thermal design approach is to view the building shell as an insulating envelope whose walls, roof, and floor retard the flow of heat into or out of the building and provide a protective barrier from the elements. The thermal resistance of each building component or element to the flow of heat is determined using published or measured coefficients of thermal conductivity and conductance for candidate building materials and insulations, and selected dimensions of the components. Several alternative designs are usually possible and heating and cooling loads for the building should be calculated for each design. Loads can then be compared and used as the basis for selecting the best design for the building, rather than using a comparison of individual coefficients of heat transmission, or U-values, because the total load includes infiltration and ventilation losses which can vary with the individual thermal design. The calculation procedures for a single design are given in detail in reference [1] and are well known to engineers responsible for the design or sizing of mechanical equipment for heating or cooling.

The currently used design procedure is largely based on a steady-state heat transfer concept. The thermal coefficients for insulation and building materials as used by the designer are given in materials specifications that are based on steady-state test methods. The procedure thus presumes static or steady thermal conditions when in fact the thermal behavior of a building in use is quite dynamic. Outdoor temperatures rise and fall each day and the response of the building, depending upon its ability to store heat, lags the weather so that a truly steady-state heat flow situation rarely exists in a building. A suitable, simple design procedure that more closely matches the dynamic character of buildings would allow the engineer to more closely predict the thermal performance and loads of a building.

The design procedure sometimes demands as much art as science because considerable latitude for judgement and experience is evident in the procedure. Two general design solutions for providing a desirable indoor environment can be used. The more usual practice is to provide temperature and humidity control by using heating, ventilating and air-conditioning equipment in whatever quantity is necessary, sometimes at large operating costs. Alternatively one can design the building shell to greatly retard the flow of heat. The latter solution is preferred not only because the lowered costs for heating and air-conditioning more than offset the additional cost of insulation but because a well-insulated building provides a more comfortable and more easily controlled indoor environment. A typical example of the utilization of well-insulated building shells is in the application of electric heating and cooling. However, the principles of good thermal design are applicable regardless of the source of energy for heating and cooling be it electric, gas, oil, coal, or atomic energy.

3. ENVIRONMENTAL FACTORS

The engineer must carefully assess both the indoor and outdoor environments for their bearing upon his thermal design.

Indoor temperature and relative humidity are most important factors. For example, too little insulating effect in a construction in winter could produce indoor surface temperatures that are below the dewpoint of the indoor air resulting in the formation of surface condensation. A typical case is condensation on single glass windows in cold climates. The typical solutions for this case are to lower the indoor dewpoint, or to increase the interior glass surface temperature by raising the indoor temperature or by using double or triple glass windows.

The question of how much insulation should be used faces the engineer for each design. Economic and dimensional considerations aside, the bare minimum should always be sufficient to prevent surface condensation. However, use of minimal amounts of insulation sometimes produces uncomfortable rooms because cold walls, ceilings, or floors promote cold drafts and increase the amount of heat transferred by thermal radiation from occupants to the cold building surfaces even though the air temperature at or near the thermostat is maintained at the design value. The maximum amount of insulation that can be used is usually controlled by the practical limitations of the dimensions and thicknesses of the construction. A guide for design with a view toward comfort of the occupant is that the amount of insulation used be sufficient to restrict the average difference in temperature between the indoor air and the surface of exposed walls, ceiling, and floor areas, figured at the selected indoor and outdoor design temperature conditions. The suggested average difference in temperature should not exceed from 5 to 10 degrees F, the lower the better. This average value usually cannot be achieved for windows in cold climates, so that the percentage of glass area must be controlled or draperies or window coverings must be used to maintain comfort if large areas of glass are involved. The suggested design guide will usually prove to be economically justifiable.

A water vapor pressure difference usually exists between the interior and exterior of a building. This pressure difference causes water vapor to migrate following a path of least resistance from the highest to the lowest pressure. Since most building materials are permeable to water vapor one means by which vapor may enter the construction is by the process of diffusion of vapor through the building materials. In winter, if water vapor permeates the construction, condensation and accumulation of water or frost on cold areas can occur. However, widespread use of vapor barriers such as paint films or membranes which often are an integral part of the insulation, has largely controlled the accumulation of concealed condensation via this process. A second, and much faster, means for water vapor to enter a construction is by its transport in air flows into the construction via avenues opened by cracks under baseboards, passages in walls between a crawl space and an attic space, openings around pipes, ducts, electrical fixtures, trap doors, etc. Natural convection forces arising from indoor-outdoor temperature differences, or wind forces, promote large flows of air if even small passages exist. Large amounts of moisture can be transported to cold regions by this means, often leading to excessive condensation and accumulation of moisture. For example, 100 cubic feet of air at 70° F and 35 percent relative humidity will release about 150 grains of moisture if its temperature is lowered to 20° F. A one-square inch passage through a ceiling at a light fixture can allow, into an attic overhead, an air flow of more than one cubic foot per minute, which in one month can deliver to the attic as much as 9 pounds (over one gallon) of water condensable at 20° F. Much can be done by the designer and applicator to alleviate this source of damage by requiring simple stuffing and taping of holes to block convection air paths.

The susceptibility of the design of the insulated construction to water ingress is very important. Water staining of painted surfaces, dripping from ceilings, and similar damage poses the problem as to whether the source of the moisture is from an accumulation of condensate originating from indoors or from an exterior roof or wall rain leak, or water from leaking pipes. Outdoor conditions of wind-driven rain, solar-heating and night-time cooling, freezing and thawing, etc., are forces that help deteriorate outdoor surfaces allowing ingress of rain or melt water that wets insulation and damages other building materials. Ideally, in winter, water vapor that does enter the building shell from indoors should be free to pass outdoors without condensing and at the same time the outdoor surface should prevent rain or blowing snow from entering the construction.

The effects of possible improper application of insulation and building materials on the performance of the thermal design should be evaluated. For example, storage of insulation in the open where it can get wet and subsequent use of the wet insulation between a vapor barrier material and built-up roofing greatly reduces insulating value and ultimately deteriorates the roofing. Installation of insulating materials with the vapor barrier on the cold side instead of the winter-warm side of heated buildings invites accumulations of moisture. Gaps, tears, fishmouth shaped apertures at the edges of insulation that allow convection of air within the construction should be assessed. An inspection should be made at the site during construction to assure that insulation and building materials are installed according to specification or manufacturers recommendations.

4. RESEARCH PROBLEMS INVOLVING THERMAL INSULATION

All insulations will produce the insulating value expected of them if they are properly installed and maintained in a dry condition. There are available to the designer materials specifications, methods of test, and products of good quality so that the basic technology of proper definition of insulations and of means to assure quality materials has been developed. Practically all problems involving insulation can be classified as problems that deal with components of construction and buildings where several building materials are combined and used simultaneously rather than problems of individual materials. For example, design procedures are needed that simultaneously account for the transient nature of heat transfer as well as air and moisture transfer, and allow a designer to be able to predict the performance of his design for a variety of exposure conditions. A standard method of measurement that simultaneously includes determination of heat flow, moisture flow and accumulation, air flow, wetting from rain, and expansion and contraction has not been developed. Some efforts along these lines are currently being pursued at the National Bureau of Standards. Performance specifications that are based on the transient nature or periodic behavior of a building or construction rather than steady-state tests on individual materials need to be developed. For example, recently a laboratory method of measurement for insulated flat roofs containing moisture was developed at the NBS [2], and 73 designs were evaluated. From this work, a proposed test specification and criteria for roofs that should dry out in place and recover insulating value, if wetted, was developed. The self-drying principle appears practicable and may save the high cost involved in complete replacement of wet insulation and roofing. The performances of designs produced using such criteria need to be checked in the field on full-size roofs to confirm the principle and allow a performance specification to be written that is based on both laboratory data and full-scale field experience.

Improved in-situ methods to measure the performance of a building and its elements in respect to heat flow, moisture content, expansions and contractions, deteriorations, cracking, corrosion, mechanical systems performance, and acoustical behavior, need to be developed and used to provide a basis for characterization and definition of a realistic performance standard and for evaluating the engineering behavior of a building. The Building Research Division is presently in the planning stages for one such endeavor.

Other technical problems and their solutions useful to the designer have been completed or are being considered. For example, the problem of outdoor columns on high rise buildings expanding when heated by the sun and contracting when cooled which produces differential movements in respect to the constant temperature inside columns. An analytical solution, programable in a computer, was prepared at NBS [3], that provides, for the first time, a means to predict temperatures within the outdoor column which must be known quantitatively before an evaluation of potential movement can be made. Also, a study is under way to help make the design decision as to just where in the thickness of an exposed building wall the insulation can best be located. It may be advantageous in terms of peak air-conditioning cooling loads to place insulation outboard of a masonry wall rather than at the usual inboard location. The large heat capacity of the masonry wall should stabilize the indoor air temperature and the masonry would not be subjected to daily and seasonal temperature extremes and to weather and water, all of which contribute to deterioration.

A need exists to critically evaluate the total indoor environment. Factors other than temperature and relative humidity affect indoor environment. Generally, criteria for indoor environmental conditions are needed and stem from human needs for well-being and comfort, but necessarily involve auxiliary criteria for operational equipment, systems, and functions of the building. Optimal human comfort and performance depends upon an integrated system that provides temperature and humidity conditions, light, air, desirable acoustics, communication, and transportation, for which performance standards are needed. Thermal insulation will probably play an important role in the development of such standards.

5. BENEFITS OF THERMAL INSULATION

Much has been written about savings in fuel or energy for heating or cooling for a fully insulated house as compared with a similar but uninsulated house. It is not difficult to show a reduction in heat transfer of over 50 percent. Thus, though the initial cost of insulation requires an outlay of money the investment rapidly pays for itself in fuel or energy savings and becomes very worth-while for the consumer. An interesting example of the impact of the economics of this is illustrated by what was done in 1957 in Great Britain [4]. Because Britain must import much fuel, energy costs are high. Huge national savings were estimated to be forthcoming by restricting the loss of heat and thus a law was passed making it mandatory to provide insulation in the roofs of all new industrial construction. The importance of this concept was rather forcibly brought home during this past unusually severe winter in England during which the electrical capacity of the country was overburdened through the use of supplementary electrical heaters, etc., to the point where several power plants had to be temporarily shut down.

Perhaps as important as monetary economy is the improvement of the indoor environment and comfort conditions that can be achieved by the use of insulation. This aspect is difficult to assess in terms of dollar benefits. First the problem of controlling temperature and relative humidity becomes simpler because the magnitude and fluctuations of the loads are reduced. Secondly, the differences in temperature from floor to ceiling and throughout the room are reduced and uncomfortable sensations experienced because of cold walls and drafts can largely be eliminated.

On a national basis, energy conserved by the use of insulation will help to conserve our fossil fuel reserves which have been predicted to have finite life-times, and to restrict entry of their products of combustion into the country's atmosphere.

6. REFERENCES

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