STUDY OF PASSIVE CONCEPTS FOR SOLAR HEATING AND COOLING OF BUILDINGS

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TO LORD HARNATH

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S U M M A R Y

This thesis is a study of few passive concepts utilized in the architecture of the building to maintain thermally comfortable environment without using any active means of energy. Passive systems using Sun's radiation for heating and nocturnal or evaporative processes for cooling usually employ direct and indirect gain concepts for the former, while for the later use may be made of large radiative surfaces earth sheltered structures, earth tunnels etc. Some novel concepts have recently been proposed to minimize convection losses in the well known Trombe wall concept used for passive heating. Analytical models have been forwarded to predict the thermal performance of passive heating systems using these concepts in terms of forcing functions namely the solar radiation and the ambient temperature etc.

In passive heating systems using a Trombe wall, vents are usually provided for a quick removal of heat flux by the room air flowing within the sun space between the glazing and the blackened surface of the wall. During night time, however the vents and closed to stop the air circulation. Periodic theory has been applied to analyse such a passive heating system employing time dependent air flow rate to obtain explicit expressions for the relevant physical parameters.

In the indirect gain passive heating systems such as the one using Trombe wall concept, the heat gain is lower than the one obtained in the direct gain ceoncept to avoid fluctuations of temperature inside the living space. In the direct gain concept the storage may be provided in the floor. Three types of such storage media have been considered and their analysis provided. Sometimes it is desirable for a passive heating system to use a small fan or a blower to collect heat from solar energy collector. A new concept for roof integrated solar collectors has been proposed in which the roof acts as a solar collector and the pipe/duct are laid in between during its construction. A study of the system has been performed including the effect of a night insulation.

Direct gain concept has also been applied to study the physibility of heating the swimming pool in the arid and semi arid zones. Another prime requirement of a passive system is the reduction of heat flux coming into the room during summer season.

This is usually provided by providing overhangs over the walls and simultaneously making the roof/walls hollow and insulated. A new concept of variable resistivity wall has been forwarded to increase the effectiveness of a building in reducing the cooling load of the building in comparison to a simple cavity/insulated wall and its analysis and comparison with experiments has been performed.

Temperature deep inside earth remains constant throughout the year. A tunnel made at such a depth helps to cool or heat the air flowing through in summer and winter seasons respectively. Experiments have been cited in the literature to prove the validity of this concept. An analysis has been provided in the last chapter of this thesis to evaluate the performance of such earth air tunnel systems and comparison with the corresponding experimental data made to validate the developed theory.

PREFACE

The effects of the depletion of world energy resources have already been demonstrated by supply deficiencies arising from international trading factors. Recent price increase have shown that fuel costs permeate the whole economy. Thus, as the availability of fossil fuels becomes strained, the standard of living is likely to fall specially in the developed countries. The developing countries have to face more severe problem of simultaneously cont . their development programmes and cope up with the problem of increasing population. Increasing amount of energy are needed to improve agricultural production, turn the wheels of industry, provide goods and services throughout.

What is then the solution? One has to obviously turn his concentration towards such sources of energy, which are renewable in nature and are available in almost all the regions of the earth. One has to simultaneously devise methods of more efficient ways of utilising energy for various purposes.

One of the major uses of energy is for totally different purposes from manufacturing industry and transport. Energy in buildings is used for heating, ventilation, air conditioning, lighting, heating and cooling of water, as also for distributing water/air and running automatic controls, office machinery and communication systems. The pattern of energy consumption shows that residential houses consume about twice as much energy as other type of buildings. The scope for energy conservation in buildings does not simply mean turning off the lights and turning down the thermostate. A large amount of conventional energy that is used to keep the buildings thermally comfortable can be saved through proper building design and constraction. Ancient architcture all over the world, has many characteristics which led to thermal comforts in buildings[1]. The buildings were shaped and different parts of the buildings e.g. indoor spaces (like courtyards), doors, windows etc. located and oriented in such a way as to maintain a comfortable thermal environment inside the room. The art of maintaining natural comfort without expenditure of conventional energy is known as solar passive[2,3]. Sometimes one has to use fans and blowers to maintain proper ventilation and a particular rate of convection in a building, this necessitates electrical energy for operating these appliances. Due to the energy crises generated in 1973, there have been renewed interest in passive aspects of the building architecture. This led to the formal recognition of the passive heating and cooling of buildings as a distinct science. Since the sun played a dominant role in all such considerations, the science came to be known as the passive solar architecture. The conference and workshop on passive solar heating and cooling of buildings at Albuguerque in May 1976 marked the recogn:tion of the maturity of the science and arcituecture of solar passive houses. A definition was evolved during the above conference on passive systems, under the auspices of the Energy Research and Development Administration and the Los Alamos scientific laboratory.

"Passive systems use the sun's radiation for heating and natural processes for cooling; heat distribution is accomplished by convection, radiation and conduction. Non renewable energy used for movement of insulation, diurnal transfer of water from one space to another, movement of dampers or valves, etc. must be so small in amount that coefficient of performance of the system, defined as the ratio of the useful heating or cooling accomplished by renewable energy sources or sinks to the non-renewable energy consumed, is greater than 50 to 1". This definition is consistent with the intent of the solar heating and cooling Act of 1974, which includes the process of radiation, convection and evaporation in its definition of solar cooling. When both heating and cooling can be accomplished with negligible consumption of nonrenewable energy, then the system may indeed be called "passive".

Design of the buildings based on solar architecture makes use of which briefly be summarized as follows:

1. Direct and Indirect Gain Concepts

Direct sunlight admitted through a window or a glass wall facing south (in Northern hemisphere) heats up the walls, floors and objects (consequently, the air) in the room. The temperature fluctuations in the room by this method, however, can be rather large ($10^{0}C$) and depends on the degree of variation of available solar radiation. To reduce these oscillations, a part of solar energy is stored in the form of heat during sunshine hours and released inside the room during off sunshine periods.

The storage of energy is usually done in a concrete wall between the southern glazing and the living space. This concept has been patented by Trombe[4,5]. For summer operations, the glazing is removed and the wall covered with a reflecting insulating panel during the day and left bare at night. The concrete wall can sometimes be substituted by drums full of water stacked one above the other. In this case, for a given area of the south wall, the total heat input into the building through a thermal storage wall is much less (about half) than the corresponding amount in the indirect gain configuration. However, the heat enters the living space at a fairly uniform rate, reducing the temperature swings. Further, there is a time lag between the maximum solar radiation outside and the maximum heat input into the building. Thus by proper design, the heat entering the building can be matched to the heat loss by the building.

2. Solarium

An integration or the direct gain and indirect gain concepts provides a pleasant sunspace in addition to a living space maintained at thermally comfortable temperatures. The living space has a thermal storage on the south side; attached to the south wall on the otherside is the space enclosed by glass. The glass enclosure, called sunspace, receives the heat by direct gain, while the living space receives the heat by indirect gain through the thermal storage wall. The sunspace, may be used for recreation or growth of plants.

3. Earth-sheltered Structures

About 4 meters inside the ground, the temperature remains constant throughout the year[6]. Earth sheltered buildings, therefore, automatically provide thermal comforts. The deeper one goes, the better it is from the thermal point of view, but more expensive it becomes from the structural angle. Hence at a depth easily obtainable, the roof may be insulated by synthetic insulators in the normal manner. The additional heating when needed may be supplied by means of direct gain through windows near the roof, projecting above the ground. When cooling is needed, one can suck outside air through underground ducts where the temperature is low. If necessary, ducts may be cooled by evaporation.

4. Earth Air Tunnels

Since temperature of the ground, a few meters below the surface, is almost constant throughout the year; hence air passed through a tunnel at a depth of few meters will get cooled in summer and heated in winter. Strayer has given a chart which indicates heating/cooling by passing the air through a tunnel. The cooling can be enhanced by keeping tunnel surface wet. Sinha et al[7] presented a theoretical and experimental analysis of cooling technique using an underground pipe. The theoretical analysis of these authors is based on dividing the pipe into elements along the length and analysing each element separately. Author has developed a simple analysis leading to closed expression for the air temperature at the outlet of the pipe enabling one to evaluate the performance of dry and wet tunnels for any climate.

5. Swimming Pools

Direct heating of swimming pools by solar radiation in the mild winters of tropical dry climates is an interesting possibility to make swimming possible, in winter months, where it is closed or to save energy, where swimming pool water is heated by conventional fuels. There are some papers on solar heating of swimming pools[8], recently Govaer and Zarmi[9] presented a method for evaluating the thermal performance of a directly solar heated swimming pool, which may be open or covered. Author has forwarded a periodic analysis for an open and closed swimming pools. The analysis besides all other parameters, is able to predict the losses through ground.

The use of sufficiently irradiated outside walls of a building as a collector surface is generally advantageous. A mass storage wall, (Trombewall) is usually made of concrete or brick. The surface of the mass wall faces south (in the Northern hemisphere), it is blackened and glazed to reduce the convective and radiative losses. This concept of a mass storage wall has the advantage of simplicity and even if the outside surface is near the room temperature, it acts as a heating source from the inside, by preventing heat flow from the room to the outside through this part of the room. Disadvantges compared to a storage in the interior of building are the higher losses during periods with insufficient or no radiation and that only those rooms which lie behind a storage wall can be warmed directly. Correspondingly, outside wall storage will preferrably be complemented by a system with internal storage. Because of its very low working temperature and the possibility of utilizing periods with low irradiation intensities, outside wall storage systems are capable of furnishing a large part of the total heating demand of a building. There exist several modifications of this system, in that the heat capacity of the wall is increased by insertion of volumes with water heat storage materials or by the application of mechanisms which improve the heat transfer to the storage or to the space to be heated[10] with another construction method the solar absorber and the heat storage are separated by thermal insulation[11]. The heat transfer from the solar absorber, a normal solar collector, to the storage wall which acts as the room heating surface is made by circulating liquid or by circulating air. There are real passive systems and others with pumps or blowers which improve the heat transfer and render its control possible. To minimize the outside losses the author has studied 4 special designs which offer the possibility of high efficiency and simple construction have been evaluated from the point of view of thermal operational behaviour. The most important requirement is that the transparency of the structure covering the solar absorber should be as high as possible and that simultaneously its heat transfer coefficient to the outside should be as small as possible. Various variations of systems incorporating the opposing requirements of high transparency for the solar radiation and low losses from the storage to outside have been studied by the author.

Indoor temperature fluctuations and the phase lag between the maxima/minima of incoming heat flux and the solar radiation are controlled by the wall thickness. The knowledge of phase lag and oscillations in the incoming heat flux are important from the point of view of building design for thermal comforts. The heat output of a masonary wall can be regulated by the addition of thermo-circulation vents, of roughly equal size, at the top and bottom of a masonary wall. An analytical study of such a system has been performed earlier[11]. But these authors assumed constant flow rate of air, which effects the human comfort as well as decreases the efficiency of the system. Moreover with natural circulation of air, it is not possible to maintain constant flow rate in view of the changing temperature of the walls surface. Author has studied the performance of a Trombe wall with vents taking the flow rate of air as time dependent. It is observed that for heating purposes the air flow should be restricted to sunshine hours only.

One of the basic requirement of any solar heating system is low cost per unit useful energy. Keeping this in mind many designs of solar energy collectors have been proposed. The heated air/water may be used for purposes such as agricultural drying, space heating and domestic pruposes etc. Among the various concepts for inexpensive air heaters used for space heating, an interesting one is roof integrated system, in which the south facing wall or roof of a building are used as collectors of solar energy. This concept of a solar heating collectors integrated with a building (roof or southwall) consists of a blackened glazed south wall or roof of the room; with hollow pipes laid in it. The sun's energy is collected by the blackened surface and gets conducted in the wall/roof; a part of it is transferred to the air/water flowing through the pipes. An analysis has been developed to study the performance of such a system. The effect of a movable insulation have been incorporated in the analysis.

The maxima of outdoor thermal conditions occur at the noon time, when the ambient temperature is also high. The ambient temperature being low around the period of mid night, it is desirable to get the maximum heat flux around these hours i.e., create a phase lag between the outdoor and indoor conditions. This is usually done by taking a thick south wall. Thick wall, however, increases the cost of construction and makes the economics of the system unattractive.

A new concept of introducing a gap of variable resistance has been forwarded in this thesis. Such a concept help to create a relatively larger phase difference with smaller wall thickness. The concept has been studied for cooling purposes. The author has developed an analysis to study the thermal performance of such a wall and carried out numerical calculations, (essentially for cooling purposes), to explicitly show the advantage of such a concept.

The whole work has been presented in the following seven chapters. A brief discussion about each of them is as follows:

CHAPTER I

In this chapter analytical models have been forwarded to predict the thermal performance of passive heating systems, which have been suggested by Bahr and Piwecki[12]. They proposed two systems of Trombe wall type of storage wall for minimising thermal losses from the storage to the ambient.

Out of the proposed two systems, one consisted of a set of thermal diodes, (heat flow only in one direction), with a suitable liquid, whose outside surfaces are painted black and doubly glazed. Solar radiation, absorbed on the black surface is converted in to heat, a part of it is lost to the surrounding and a part is transferred to the liquid. The liquid in turn gets heated and is vapourised The vapour thus formed gets condensed in the portion of the tube lying inside the storage vessel. The storage medium considered here is a column of water which has a layer of mineral wool on the front side. Behind the storage is the brick wall, with an air gap of 1cm which receives heat from the storage and acts as the room heating surface.

The second category of heating systems combine collection and storage in a single unit. Coloured water acts both as the storage and collection medium. The various systems, used to suppress convection effects, such as a honey comb structures with square horizontal channels, a set of inclined transparent sheets and four vertical transparent sheets. In the experimental installation Bahr and Piwecki[12] have insulated the side as well the back of the wall by a layer of plastic foam. The heat flux through this insulation to atmosphere, may be regarded as the heat which, in the real case will flow from the brick

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wall into the room behind it, replacing other heat losses from this room. From a rough calculation it is found that these heat flows are nearly the same when the brick wall temperature is 22^{0}C and the room temperature is 20^{0}C with the mean ambient temperature of 2^{0}C[12]. No theoretical model, however, exists to evaluate such systems. In this chapter, the author has developed thermal models for such systems to enable one to study their performance for any climatological data. Based on periodic solutions of the heat conduction equation explicit expressions have been obtained for wall temperature in various cases. Numerical calculations corresponding to the parameters of Bahr and Piwecki show that the theoretical and experimental results are in fairly good agreement.

CHAPTER II

The analysis and the performance of a Trombe wall with and without vents has been studied earlier[11]. However, the analysis forwarded so far assumes a constant value of the air flow rate in the sunspace. For any practical purposes, the air flow rate has to be varying i.e. a time dependent function. The author has modified the previous analysis to take into account the effect of variable flow rates. A corresponding analysis assuming a night insulation has also been developed and numerical calculations performed to establish the advantages of Trombe wall type of system with and without insulation and with the varying flow rates for passive heating of buildings.

CHAPTER III

It is sometimes desirable to design a building using direct gain concept for better thermal efficiencies and for providing natural lighting. To avoid fluctuations of temperature, inside the living space in the direct gain concept, storage is provided usually in the floor.

This chapter presents a comparative study of three typical systems, for such a storage of thermal energy, three types of flooring has been considered (i) concrete (ii) water contained in drums and (iii) concrete and water contained in drums. Using periodic solutions of the concerning balance equations, exact expressions have been developed for the temperature of the air inside the room. The numerical results show that water stored in drums provides the best storage effects. The concrete thickness above the ground should be kept minimum for better storage effects.

CHAPTER IV

A new concept for roof integrated solar air heating system has been proposed. The system consists of a wooden box filled with sand, the upper surface of the sand is usually fixed by mixing sodium silicate sprayed with black board paint and suitably glazed. A plastic tubing is usually placed inside the sand at the desired depth. Air, flowing through the tube, gets heated, the amount of collected heat depending upon the depth at which the tube is placed. The thermal performance of the system can be improved by the use of a night insulation over the glazing. The periodic theory has been applied to get explicit expressions for the outlet air temperature and the useful heat gain for both the cases namely (i) no night insulation is used and (ii) night insulation is used. The effect of parameters like mass flow rates and depth of heat required on the thermal performance of the system has been studied in detail. The results of this study on a solar sand air heater helps to optimise the parameters of a roof or a vertical wall of a house, used as a solar energy collector and in which pipes are inside the wall/roof within its material.

CHAPTER V

In this chapter an analysis has been developed to evaluate the thermal performance of a swimming pool which is receiving direct solar radiation. The swimming pool may be opened or covered with a glazing provided with a window for ventillation. Numerical calculations have been performed corresponding to the variation of solar intensity and ambient temperature of average yearly variation of 1967-76 for Israel's coastal plain at Betdagan (at 30^0)[9]. The analysis shows that a closed swimming pool taking advantage of the green house effect can extend the usability of the swimming pool from 4 months (for open pools) to 10 months in a typical and climatic zones where the average ambient temperatures can go as low as 10^0C. The analysis also helps to calculate heat losses to the ground.

CHAPTER VI

This chapter deals with the analysis of a variable resistivity wall employed passive for cooling. The system consists of an air gap in between a south wall and a plywood board covering the wall, the circulation can either be natural or forced. The board is painted light yellow, so as to absorb minimum solar radiation. As in the Northern hemisphere, there is a maximum solar radiation on the south wall, which is checked by the cover, and a portion of the heat conducted is taken away by the flowing air, thereby reducing the thermal flux entering the room. The concept of variable resistivity helps to bring the same delay in phase with a thin concrete wall as is otherwise provided by a much thicker structure.

CHAPTER VII.

Air passed through a tunnel, constructed at a depth where the earth temperature remains constant throughout the year, gets cooled in summer and heated in winter[6]. Sinha et al[7] presented a theoretical and experimental analysis of cooling technique using an underground pipe. In this chapter a simple analysis is developed for such an earth/air tunnel system leading to close form expressions for air temperature at the outlet of the pipe enabling one to evaluate the performance of dry and wet tunnels for any climate. Numerical calculations have been performed corresponding to the experimental set up of Sinha et al and found that our expressions predict the outlet temperature fairly accurately. The analysis is able to take into account the effect of parameters like length of the tunnel, flow velocity, cross sectional area and moisture on the tunnel's surface. A quantitative study about the influence of various parameters on the thermal performance of earth air tunnels is made corresponding to the meteorological data of the year 1974 at New Delhi. The results of the study show that it is desirable to have two separate tunnels; one built under a glazed blackened ground surface and the other under a surface provided with trees, shrubs, grass and other type of plants which are periodically watered. The former provides heating during winter and later provides adequate cooling during summer.

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