Journal of Engineering and Applied Sciences 2 (11): 1613-1619, 2007
ISSN: 1816-949X

Simulation Analysis of Passive Solar Building Based on the Thermal Network Methods

[1]Djamel Beggas, [2]A.J. Wilson and [3]Jahid Zighiche
[1]Département d'Architecture, Université Badji Mokhtar, BP12 Annaba 23000, Algerie
[2]School of Architecture Bath University, BA2 7AY, UK
[3]Département de Genie Civil, Université Badji Mokhtar, BP12 Annaba 23000, Algerie

Abstract: The aim of this study is to present the modeling of passive solar building using the thermal networks methods for the thermal analysis the use of such modeling as an efficient computer formulation and analysis tools are especially suited to passive solar systems since they permit the analysis of system whose structure varies over time(e.g., due to the daily installation of windows or due to convection within building. etc.) and also permit hourly (or even more frequent) simulations of reasonably complex systems over an entire year the systems are divided into a number of nodes each of which has its own temperature, nodes can represent surface, air or internal parts of a surface and the number required to model a given building is a function of the variation of temperature distribution within the building and the accuracy required in the final result. The temperature of every node can be predicted at future time given the thermal properties or the structure and the variation in the boundary conditions which are usually outside air temperature and solar radiation. Thus, the thermal behavior of the building within its environment over a large period of time can be easily predicted and make possible to consider the effect of various parameters and construction variations over the thermal performance of the building. This gives designers in particular architects information about their passive systems at an early stage of the design process, in order to increase the possibility of producing a successful passive buildings, which can satisfy their occupants needs for space heating, cooling and lighting by natural means as far as possible and to reduce the peak cooling/heating power demands of a building, thus, reducing the size of the air conditioning/heating equipment and the period for which its required.

Key words: Passive solar buildings, thermal modeling, thermal Networks

INTRODUCTION

Passive solar design is one of the most economical uses of solar energy in buildings; particularly when incorporated in the design of new buildings where the climate is suited.

The interest of the thermal behavior of buildings need not be demonstrated. The fact that summer thermal comfort is now taken into account in the new French regulation.

Although most of the regions the Arab word offer an ideal climate for passive solar design a great amount of energy is wasted annually to heat or cool buildings. From an architect's point of view given such conditions, passive solar design should be an integral part of the architectural design process. However, to produce successful passive buildings, designers must have an accurate, simple and easy analytical tool to enhance the possibility of successful design.

Unfortunately, since passive solar techniques have become popular especially in Algeria, much has been written on the topic, most of which is descriptive, but relatively little has been done to surmount the problem of applying theory to practice, in particular to meet Architect's need in terms of providing simple and easy analytical tools. In order to contribute to the development of analytical tools, the modeling of passive solar building based the thermal network methods is presented with application to building.

Thermal network models have been used extensively in the analysis of passive solar buildings in recent year (Gilles *et al*., 202; Saulnier and Alexander, 1985; Maloney *et al*., 1982; Szokolay, 1980). Such models are especially suited for the analysis of passively solar heated/cooled building since they permit the analysis of the systems whose structure varies over times and also permit hourly or more frequent simulations of reasonably complex systems over an entire year.

Using the nodal method to analyze thermal networks the system is divided into a number of nodes each of which has its own temperature. Nodes can present surface, air or internal parts of the structure and

Corresponding Author: Djamel Beggas, Département d'Architecture, Université Badji Mokhtar BP12 Annaba 23000 Algerie

the number of nodes required to model a given building is a function of the variation of temperature distribution within the building and the accuracy required in the final result. The object of the thermal analysis is to predict the temperature of every node at future times given the thermal properties of the structure and the variations in the boundary conditions, which are usually outside air temperature and solar radiation. The procedure consists of writing an energy balance for each node, this usually involves heat transfer from other nodes and storage of energy if a node has thermal capacity.

HEAT BALANCE EQUATIONS

At each node a heat balance equation is written using an explicit or implicit formulation. Explicit methods have the advantage that future temperatures can be predicted at each time interval. This means that computation of each node's temperature requires little computational power and can be done using a hand calculator. The major disadvantage is that stability is a function of the time step used and the solution may require extremely short time intervals and consequently a large number of calculations for one day simulations.

Implicit methods of solutions result in a series of simultaneous equations describing the whole network with the future temperatures at each node being the unknowns. As there is one equation for each unknown temperatures simultaneous solutions of the equations results in the calculations of all unknown temperatures. This method requires the ability to solve a large number of simultaneous equations and store the matrix of coefficients at each time step. Thus greater computational capacity is required but the solution is inherently stable.

In the most complex formulation each node will have thermal capacity and there will be conduction or convection and radiation to other nodes. Solar radiation may fall on a node or there may be environmental plant which passes heat to or from the nodes.

For each the energy balance may be written:

$$\text{Heat}_{\text{in}}^{t} - \text{Heat}_{\text{out}}^{t} = \text{Change in stored enegy}^{t}$$

Where the superscript t refers to the time over which the energy flow occurs.

For a single node heat transfer (ϕ) may be conduction, convection or radiation and the equations describing the heat transfer are:

Conduction: In the Hypothesis of mono-dimensional transfers, the heat conduction may be written, in the form references (Gilles *et al*., 2002; Saulnier and Alexandre, 1985; Balemans, 1987).

$$\frac{d^2T(x,t)}{dx^2} = \frac{1}{a}\frac{dT(x,t)}{dt} \qquad (1)$$

In a no homogenous two layers case with low thickness (Δx_n), the conduction equation in discrete form is written as:

$$\frac{T(x+(\Delta x_1),t)-T(x,t)}{R_1} - \frac{T(x+(\Delta x_2),t)-T(x,t)}{R_{21}} = \frac{(dt(x,t))}{dt} \qquad (2)$$

The layers are characterized by their Resistance, R and its thermal capacity C:

$$R = \frac{\Delta x}{\lambda} \text{ and } C = \rho C_m \Delta x_n S \text{ Or } C = \rho C_m V$$

For a single node heat transfer ϕ to other nodes the equation describing the heat transfer by conduction is:

$$\phi_{cond} = \frac{A\lambda\Delta T}{x} \text{ Or } \phi_{cond} = \frac{A\Delta T}{R}$$

Convection: The convective heat flow exchange between a wall surface at temperature T and an air volume at temperature T_a can be expressed with Newton equation reference (Balemans, 1987):

$$\phi_{conv} = h_c A(T - T_a)$$

For convective resistance is:

$$R = \frac{1}{h_r}$$

The convective heat transfer coefficient h_c depends on the thermal proprieties of the fluid and the state and the geometry of the flow. For natural convection which is our case the CIBS (1980) recommended the following values:

Inside building:

Walls to air	3.0 W/m²K
Ceiling to air	4.5
Floor to air	1.5

Outside building: For surfaces the value of h_c is a function of the wind speed across the surface and the expression commonly used (CIBS, 1980) is:
h_c = 5.8 +4.1 v where v is the air speed across the surface [m sec^{-1}].

Three standard conditions are defined for external convective coefficient:

Severe v	= 9.0 m sec^{-1}, exposed site, 5th floor suburbs, 9th floor city.
Normal v	= 3.0 m $sec^{-}{}_{1}$, up to 4th floor suburbs, country, 4-8th floor city.
Sheltered v	= 1.0 m sec^{-1} up to 3rd floor city.

And the heat flow by Convection can be expressed by:

$$\phi_{conv} = \frac{A\Delta T}{R_{conv}}$$

Long wave radiation: The external surfaces of the walls exchange LW radiation with the sky and the external environment. The heat flow can be written in a linear form reference (Allard *et al.*, 1986):

$$\phi_{rad}^{ext} = h_{pc} A(T - T_c) + h_{ranp} A(T - T_{ext})$$

If we represent the sky by means of a half-sphere and the external environment by a horizontal plane, the radiative heat transfer coefficients are, respectively:

$$h_{rvc} = 4\varepsilon\sigma \frac{1+\cos\beta}{2}\left(\frac{T+T_c}{2}\right)^3$$

$$h_{renv} = 4\varepsilon\sigma \frac{1+\cos\beta}{2}\left(\frac{T+T_c}{2}\right)^3$$

Inside the building, there are several methods, which evaluate, in a more or less approximate way, radiatives exchanges between surfaces (Allard *et al.*,1986; Gilles *et al.*, 2002). We retain a linear equation expressing the radiative flow between a wall and all the others walls:

$$\phi_{rad}^{int} = h_r A(T - T_m)$$

The value of h_r depends on the mean temperature of the walls T_m:

$$h_{r = 4\varepsilon\sigma T_m^3}$$

are: 5.70 for T = 20°C (293°K)h_r Typical values of 4.61 For T = 0°C (273°K)

The radiative resistance is:

$$R_{rad} = \frac{1}{h_r}$$

And the heat flow by radiation can be expressed by:

$$\phi_{rad} = \frac{A\Delta T}{R_{rad}}$$

The similarity of the equations of these three modes in that heat transfer is directly proportional to a simple temperature difference for a given area leads to the description of heat flow by conduction, convection or radiations between nodes in the form:

$$\phi = K_{nt}\,\Delta T$$

Where, K_{ni} is the thermal conductance between the nodes n and i.

The units of conductance are W/°C or J/s°C and it can be thought of as the heat flow per unit temperature difference per second.

As a result of heat flow to the node, the node may change in the temperature. This change is determined by the thermal capacity associated with the node, thus for a heat flow ϕ (J/s) into a node for a time t seconds the energy balance may be written as:

$$\phi = V\rho C \frac{T_{t-}T_0}{t}$$

Where, V is the volume associated with node, ρ is the density of the surrounding material, C is the specific heat, T_t is the temperature of the node after t seconds and T_0 this equation may be written :

$$\phi = C_n (T_t - T_0)$$

Where, C_n is the capacitance of node n which has the same units as conductance W/°C.

In addition to heat transfer between nodes solar energy may cause heat transfer to a node. This will obviously depend on whether the node is seen by the sun and its magnitude will depend on the presence of attenuating surfaces such as windows witch reduce the solar input.

Typical values of solar input on any passive element, which is represented by node for the Algerian climate, are given in (Capderou, 1983).

EXAMPLES

Consider a three internal node system (1), (2) and (3) with another node (a) to represent the outside air temperature. The most complex heat exchange pattern may be represented by a network shown in Fig. 1.

The temperature T_1, T2 and T_3 can represent the node temperature at the time t or at the time t+? where ? is the time step employed in the simulation.

If they are the temperature at the time t it assumed that they are all known and an explicit from of the heat balance equation results with the only unknown temperature being T_1 at time t+?. As has been already noted the implicit formulation is to be preferred and the energy balance for node 1 may be written as follows.

$$K_{12}(T_2-T_1)+K_{13}(T_3-T_1)+K_{1a}(T_a-T_1)+Q_{s1}= C_1(T_1-T_1^t)$$

Or

$$T_1(K_{12}+K_{13}+K_{1a}+C_1)+T_2(-K_{12})+T_3(-K_{13}) =T_1^t (C_1)+T_a(K_{1a})+Q_{s1}$$

Where, Ta is the air temperature and Qs1 is the solar radiation absorbed by the node 1 during a time interval ∂.

In this form the unknown nodal temperature and the known solar radiation and the air temperature are at the time t+∂. The only superscript variable T^t is the known node temperature at the time t. similar equations may be written for the others nodes:

$$T_1(-K_{12})+T_2(K_{21}+K_{23}+K_{2a}+C_2)+T_3(-K_{23}) = T_2^t(C_2)+T_a(K_{2a})+Q_{s2}$$

$$T_1(-K_{31})+T_2(-K_{32})+T_3(K_{31}+K_{32}+K_{3a}+C_3) = T_3^t(C_3)+T_a(K_{3a})+Q_{s3}$$

These nodal equations may be rewritten:

$$B_{11}T_1 + B_{12}T_2 + B_{13}T_3 = D_1$$
$$B_{21}T_1 + B_{22}T_2 + B_{23}T_3 = D_2$$
$$B_{31}T_1 + B_{32}T_2 + B_{33}T_3 = D_3$$

Where:

$B_{ni} = C_n + \sum K_{ni} + K_{na}$ for n = i

$B_{ni} = -k_{ni}$ for n not equal to i

$D_n = C_nT_n + K_{na}T_a + Q_{sn}$

These equations may be solved for the unknown nodal temperatures using standard procedures for solving simultaneous equations.

It should be noted that what whichever method of solution used the initial nodal temperature at time zero

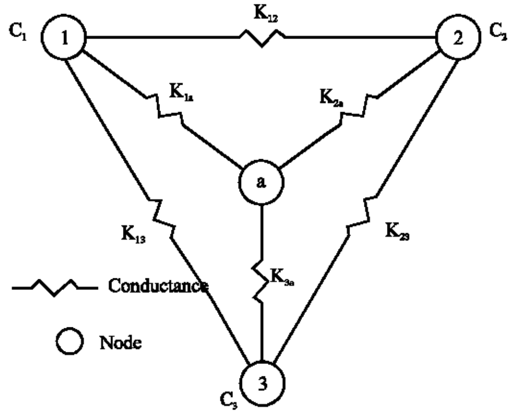

Fig. 1: Network repressentating the heat exchange between three internal nodes (1, 2, 3) and an outside air temperature node (a)

must be guessed. This initial guess will not be correct and it is necessary to simulate the model with the same daily repetition of the air temperature and solar radiation until the temperature of each node returns at the same value at the same time in each day's simulation. At this point the building is in the thermal harmony with the environment and the live simulation with varying conditions may be preceded.

SIMULATIONS PROCEDURE (APPLICATION EXAMPLE OF THERMAL NETWORK TO BUILDING)

Most Architects fin it difficult to use models developed using the thermal network, as they have to design the network which represents the solar systems. This requires more knowledge of the thermal network technique and heat transfer principles, than most architects have.

In order to overcome this lack we have used a default system, so the model designs the network of the building using these defaults systems from the input data supplied by the user.

The building network is viewed as being composed of sub networks corresponding to the solar system used. For the complex case of a house Fig. 2 with three types of solar systems (conservatory, window and trombe wall) four sub networks are created by the model for the purpose of the simulations as shown in Fig. (2) and (3) shown the transformation of the house into four sub networks and each sub network is detailed separately according to the heat exchange Fig. 4 to 7.

Sub network one: This represents the heat flow from inside the house to the out side (non south fabric and

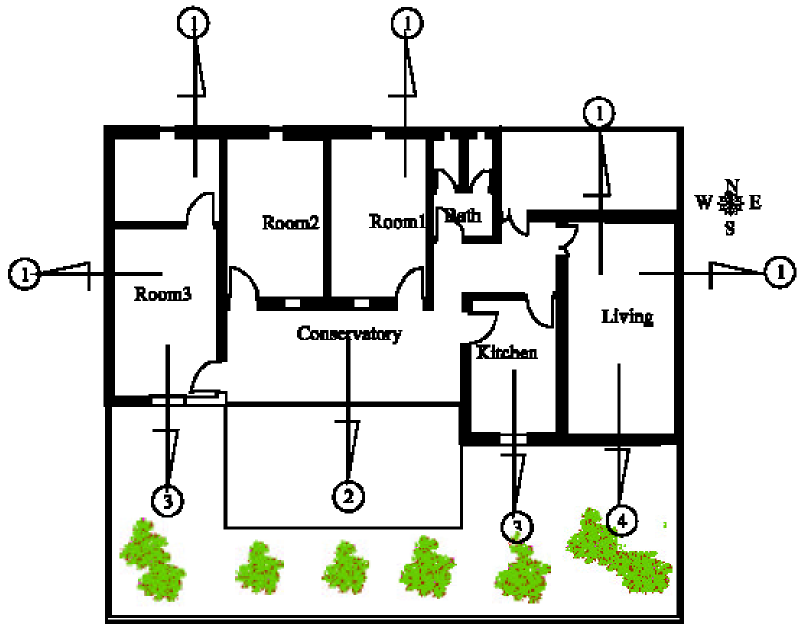

Fig. 2: View of the house to be transformed on sub network showing the possible heat exchange: 1 thought non south fabric, 2 thought consevatory, 3 throught windows and 4 throught trombe wall

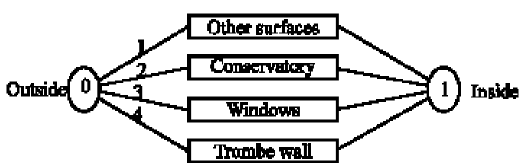

Fig. 3: Representation of the four possible subnetwork corresponding to the house in Fig. 2

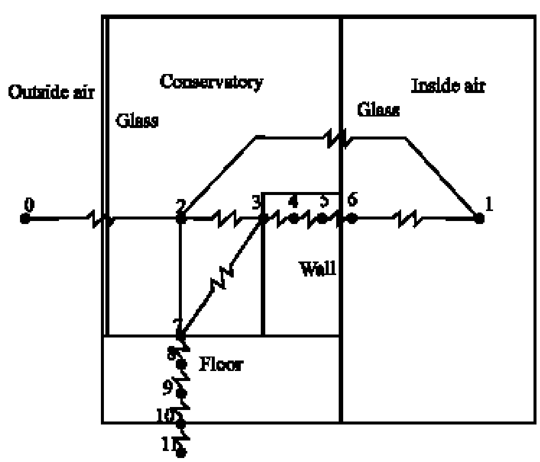

Fig. 5: Sub network two representing the heat exchange throught the consevatory

ventilation). The number of nodes which represent the internal air temperature depends upon comfort requirement of the different spaces, as the intention is to maintain a uniform temperature throughout the building, then the internal temperature of the whole building could reasonably be represented by a single node (0) and the outside air temperature by the single node (1). This sub network is shown in Fig. (4). The conductance between Node 0 and node 1 K_{01} is equal to the UA factor of non south fabric plus ventilation loss (NV/3).

Sub network two: Thermal network representing the modeling of the heat flow thought the conservatory Fig. (5).

Where:Node 2 represents inside conservatory air temperature.

Nodes 3, 4, 5 and 6 represent the wall between the inside and the conservatory.

Nodes 7, 8, 9 and 10 represent the conservatory floor.

Each conductance between these nodes is calculated according to the mode of heat transfer between the nodes.

Sub network three: Thermal network representing the modeling of the heat flow through the window Fig (6).

Where: Nodes 12, 13, 14 and 15 represents the south wall.

Nodes 16, 17, 18 and 19 each represents the floor.

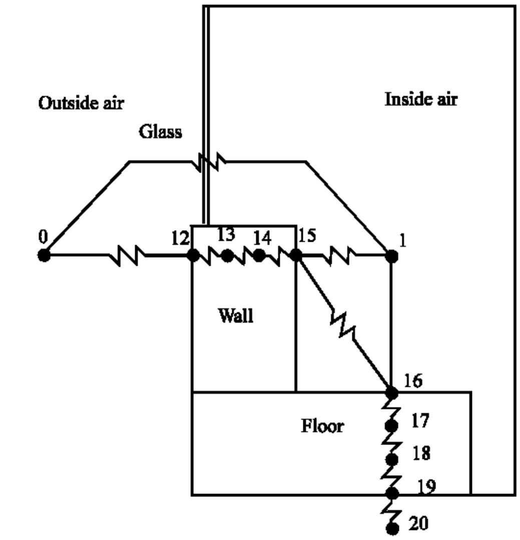

Fig. 6: Sub network three representing the heat exchange trought a window

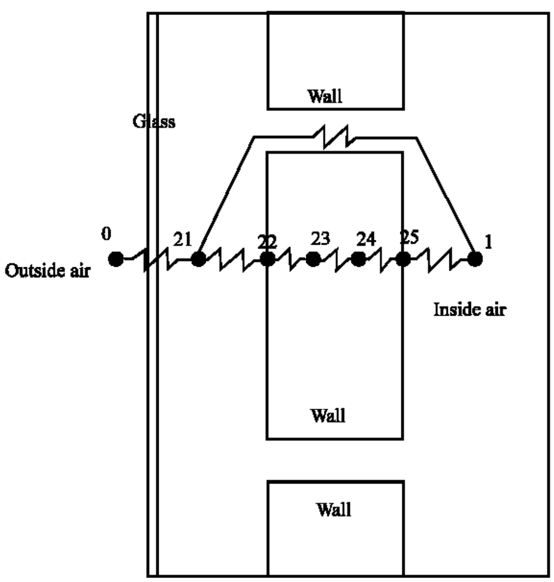

Fig. 7: Sub net work four representing the heat exchange trought a trombe wall

Sub network four: the thermal network representing the heat flow through the tombe wall Fig. (7)

Where: Node 21 represents the trombe wall air gap. Nodes 22, 23, 24 and 25 represent the trombe wall.

A final network can be created using the combination of the above sub network, depending on the number of the solar system used in the same building. For each node a heat balance equation is written, which results in simultaneous equations that can be solved for the unknown nodes temperatures.

CONCLUSION

The interest of the thermal network methods in developing directly accurate and simplified models is highlighted. This model when used for detailed passive solar heating simulation; provides a great deal of information about temperature changes in a building and requires no more technical expertise to use. Thus and for design purpose, significant information can be draw like:

- The extent to which the solar elements used in the design of new buildings have reduced the monthly auxiliary heating requirement during the peak power demand and how this varies as various design parameters are changed.
- Does the building overheat in summer or in sunny spells in winter?

Using the thermal network model enables designer especially architects to investigate the effect of changes in building parameters on the thermal performance of the building accurately, simply and in more details at an early stage of the design process.

However, further, research is recommender to analyze multizone buildings where different space temperatures are required.

NOMENCLATURE

α	Thermal diffusivity (m^2s^{-1})
A	Surface (m^2)
B	Matrix factor
C	Thermal capacity ($J\,K^{-1}$)
C_m	Specific heat ($Jkg^{-1}\,K^{-1}$)
D	Matrix factor
h_c	Convective heat transfer coefficient ($W\,m^{-2}K^{-1}$)
h_r	Radiative heat transfer coefficient ($W\,m^{-2}K^{-1}$)
K	Thermal conductance ($W\,K^{-1}$)or($W\,C^{-1}$)
Q_{si}	Solar radiation falls on node i Wh^{-1}
T	Temperature (K^{-1})
R	Thermal resistance ($KW^{-1}m^{-2}$)
x	Thickness (m)
V	Volume (m^3)

GREEK LETTERS

β	Wall slope (°)
ΔT	Temperature difference (K^{-1})
Δx	Elementary Thickness (m)
ε	Wall emissivity factor
λ	Thermal conductivity ($W\,m^{-1}K^{-1}$)
ρ	Density (kgm^{-3})

σ Stephan-Boltzman constant $(Wm^{-2}K^{-4})$
ϕ Heat flow (W)
ϕ_{cond} Heat flow by conduction(W)
ϕ_{conv} Heat flow by convection(W)
ϕ_{rad} Heat flow by radiation(W)

REFERENCES

Allard, F., C. Inard and A. Roldan, 1986. Etude comparative de différentes methods de modélisation des echanges radiatifs de courtes et grandes longueurs d'ondes dans une cellule d'habitations, Annales de l'Institut Technique du Batiment et des travaux publics 442: 31-60.

Capderou M., 1983. Atlas Solaire de L'Algerie, Office des Publication Universitaire (O.P.U), Alger.

CIBS guide A3: 'Thermal properties of building structures' 1980.

Gilles Fraisse *et al.*, 2002. Development of a simplified and accurate building model based on electrical analogy, Energy and building Elsevier Edition. 34: 1017-1031.

Ir.L. Balemans., 1987. Review of correlations for convective heat transfer from flat surfaces in air. Chaleur et Climats 590.

Maloney J., T. Wang, B. Chen and J. Thorp, 1982. 'Thermal Network Prediction of Daily Temperature Fluctuations in Direct Gain Room'. Solar Energy, Vol 29 No. 3, 207-223.

Saulnier, J.B. and A. Alexandre, 1985. La modélisation thermique par méthode nodale: ses principes, ses succès et ses limites, Revue Générale de Thermique 280: 363-372.

Shrae, A., 1997. ASHRAE Handbook. Fundamentals American Society of Heating, Refrigerating and Air-Conditioning Engineers, (1997), Atlanta, GA.

Szzokolay' S.V., 1980. Environmental Science Handbook for Architects and Builders'. Construction Press.