Modelling Building Envelopes in order to assess and improve their Thermal Performance

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ABSTRACT

It is of significant importance, for the health of building residents and the protection of the natural environment, to attain conditions of thermal comfort within buildings and reduce their energy demands for cooling or heating. In order to set up a sustainable built environment and prevent the waste of natural resources, a serious consideration of several vital factors is essential. These factors mainly concern the outdoor environment, the envelope surfaces and the indoor environment of buildings. The aim of this study is to illustrate the fundamental steps of a modelling approach, which allows the efficient design of building envelopes at the very early stages. The fundamentals of this approach are related with electrical circuits and the equivalent thermal-network models. The assessment of various architectural building design decisions, is based on node temperatures and branch heat flows, of the thermal model.

1. INTRODUCTION

The building envelope is the intermediate barrier (separating boundary) between the outdoor and the indoor environment. Its purpose and function is primarily to control the internal physical environmental factors, such as, heat, light and sound. In addition, building envelope schemes are designed with respect to dissimilar requirements such as environmental, technological, socio-cultural, functional or aesthetic issues. Especially, the achievement of suitable indoor conditions with low energy demands is of significant importance for the well-being of inhabitants (Oral et al., 2004; Santamouris and Asimakopoulos, 1996).

In order to investigate the performance of building envelopes from a thermal point of view, it is clear that various central parameters must be considered. These individual predominant physical environmental parameters with respect to the indoor environment of buildings are (Lombard and Mathews, 1999; Mathews et al., 1997):

• The outdoor environmental parameters.

• The building envelope design parameters.

• The indoor environmental parameters.

The aim of this work is to reveal the most important parameters that have a profound effect on the thermal behaviour of building envelopes. The main concept of lumped thermal-network modelling and the nodal method are briefly presented (transient thermal analysis). Lumped thermal-network models are based on the fundamental principles of thermal circuits and the familiar analogies and equivalences between the thermal and electrical laws. Their utilization enables the suitable installation of buildings shells, at the very early stages of the design process (initial architectural design of buildings).

2. INFLUENTIAL PARAMETERS

The appropriate design of buildings is a complicated and multifaceted procedure that affects the indoor/outdoor environment, as well as the quality of our life. For that reason, several vital parameters that interfere and modify the thermal response of building envelopes must be taken into account, initially. These influential parameters, as shown in Figure 1, concern the outdoor environment, the building envelope design and the indoor environment of buildings. When thermal comfort conditions within buildings haven’t been fulfilled, it is important to adjust the values of building design parameters that lead to this unwanted state. On the other hand, the attainment of a sustainable indoor environment signifies the necessary building design decisions (Oral et al., 2004).

2.1 Outdoor environmental parameters

The external conditions, as well as the design parameters related to the built environment on the settlement unit scale, have a very profound effect on the thermal conditions within the building shell. Their consideration is always required, since they are beyond the control of the designer.

2.1.1 External conditions

This information mainly depends on the region and the
period of the investigation.

(i) *Ambient-air temperature*: The ambient-air temperatures $T_o$ and swings have an intense effect on the temperature field and energy demands of building envelopes. In addition, the temperature variations of the ground affect their thermal response and behaviour.

(ii) *Incident solar radiation*: The impact of solar radiation $Q_{sol}$ leads to increased values of the sol-air temperatures $T_s$. Mainly, the effect of solar radiation depends on the outdoor absorption coefficient $\alpha_s$ of opaque surfaces coatings and the properties of glazing surfaces (solar absorptivity $\alpha_s$, solar reflectivity $\rho_s$ and solar transmissivity $\tau_s$ of building envelope surfaces).

(iii) *Relative humidity*: The humidity of the outdoor environment has also a severe effect on the thermal response of building envelopes.

(iv) *Wind velocity and direction*: The velocity and direction of the wind on the outdoor environment affects considerably the horizontal and vertical surfaces. Thus, the wind modifies significantly the outdoor heat transfer coefficient $h_e$ values due to combined convection and radiation.

2.1.2 Design parameters on settlement unit scale

This information is related to the surrounding built environment.

(i) *Dimensions and orientation of external obstructions*: The dimensions and orientation of external obstacles affect fundamentally the intensity of external conditions.

(ii) *Solar radiation reflectivity of surrounding surfaces*: The values of reflectivity of the surrounding surfaces affect intensely the quantities of radiation absorbed, reflected or transmitted by the building envelope.

(iii) *Soil cover and nature of the ground (plantcovered and groups of trees)*: Similarly, the soil cover and nature of the ground modifies the solar energy result.

2.2 Building envelope design parameters

The design parameters related to the built environment on the element scale and the building scale, have an extensive effect on the thermal performance of buildings. Their consideration is necessary, since building envelopes are the intermediate limit and barrier between the outdoor and indoor environment.

2.2.1 Design parameters on element scale

These parameters concern the opaque and transparent or semitransparent elements of the building envelope.

(i) *Configuration of construction surfaces*: The position and distribution of materials (masonry and insulation) have an effect on the dynamic thermal characteristics of building envelopes, and their thermal behaviour.

(ii) *Geometrical properties*: The area $A$ of horizontal and vertical surfaces (such as walls, floors, ceilings, roofs or glazing systems), as well as the thickness $d$ of material elements, affect the overall thermal resistance $R$ and capacitance $C$ of the building envelope.

(iii) *Thermo-physical properties*: Thermal conductivity $\lambda$, density $\rho$ and specific heat $c_p$ of materials also affect the thermal resistance $R$ and thermal capacitance $C$ of building envelopes.

(iv) *Properties of coatings*: The solar absorptivity $\alpha_s$, reflectivity $\rho_s$ and transmissivity $\tau_s$ of building façade coatings modify the solar energy distribution.

(v) *Additional features*: These features are related with

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Figure 1: Parameters with an influence on the thermal performance of building envelopes.
low-\(\varepsilon\) coating films, shading devices, air gaps, double-skin facade schemes, PV-cells etc. Their employment can upgrade adequately the indoor environment.

2.2.2 Design parameters on building envelope scale
These parameters are related with the:
(i) Building orientation: The orientation of buildings and glazing surfaces affect directly the solar gains and losses.
(ii) Building aspect ratio B.A.R.: The building aspect ratio refers to the analogy between the length and the width of the building. The B.A.R. values illustrate the shape and form of the building shell.
(iii) Glazing ratio GR: Glazing opening systems ranging from typical windows to extended glazed surfaces have become a common feature of building architecture, allowing natural light into the building, visual communication with outdoors and a reduced wall load on the supporting structure. From an energy point of view, buildings take advantage of glass property to trap solar energy, due to the non-gray characteristic of glass. This allows the propagation of sun rays through the building, whether in the form of visible light or of infrared energy (heat). The utilization of glazing systems is associated with:
- Passage of energy through the building.
- Natural ventilation.
- Infiltration.
- Natural lighting.
- Daylight visual comfort level.
- View and visual communication.
- Reduction of wall loads.
(iv) Plant covered roof or wall surfaces: The contribution of horizontal or vertical plant covered surfaces on the thermal performance of buildings is essential. Their exploitation reduces the impact of solar radiation. Thus, plants absorb a momentous fraction of solar radiation for their growth and biological functions.

2.3 Indoor environmental parameters
The design parameters on the zone scale have a very profound effect on the thermal conditions within the building shell.

2.3.1 Design parameters on building zone scale
As a rule, these parameters are related with the HVAC unit. Hence, these factors are:
(i) Operation schedule period of the HVAC unit.
(ii) Plant capacity of the heating/cooling unit.
(iii) Form of ventilation (natural, forced or combined).
(iv) Rate of air changes ACH. (ventilation-infiltration).

2.3.2 Internal conditions (thermal mass)
These parameters concern:
(i) Human presence and activities.
(ii) Building function.
(iii) Furniture and electric equipment.

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**Figure 2: A classification of building thermal analysis methods.**

- Response factor methods
- Finite-difference methods
- Lumped network methods (i.e., thermal-network model)
3. MODELLING BUILDING ENVELOPES

The modelling of building envelopes necessitates the understanding of the physical problem of heat transfer. Additionally, the utilisation of a method is required in order to solve the thermal model and conduct the transient thermal analysis.

3.1 Thermal analysis

3.1.1 Tasks of thermal analysis

The thermal analysis process involves three main tasks (Cengel, 1998; Incropera and DeWitt, 1996):

- First of all, to build the model.
- Secondly, to apply the loads.
- At last, to obtain the solutions and review the results.

3.1.2 Analysing thermal phenomena

A thermal analysis aims to determine the related quantities in a building system or structure component. More specifically, these thermal quantities concern the:

- Temperatures (temperature field).
- Heat flows (gains or losses).
- Thermal gradients.
- Thermal fluxes.

Thermal simulations are necessary for the appropriate design of building envelopes. Their use aims to improve the indoor conditions and reduce the energy demands.

3.1.3 Methods of thermal analysis

In Figure 2 the fundamental methods of thermal analysis are illustrated. These methods are (Tuomaala and Vuolle, 2000):

- Steady-state thermal analysis: In this sort of analysis the temperatures and heat flows under steady-state loading conditions, are determined.
- Transient thermal analysis: On the contrary, this analysis leads to the assessment of thermal quantities, under conditions that vary over a short or long period of time.

3.2 Thermal-network models

Thermal-network models are derived and based on the well-known analogies and equivalences between the thermal and electrical laws. Consequently, node voltages $V$ and branch currents $I$ correspond to temperatures $T$ and heat flows $Q$, respectively.

Thermal models are always lumped, while a one-dimensional heat flow simplification is considered. Transverse heat flows from one part of a surface to another part of the same surface are assumed negligible. Therefore, thermal models can be easily used and analyse the combined processes of conduction, convection and radiation through the building envelopes, under specific environmental conditions and forcing functions (Calahan, 1968; Kuo and Magnuson, 1969).

The solution of the thermal problem employs a one-dimensional lumped thermal-network model, in which several distributed thermal resistances and capacitances are connected to each other via a finite number of nodes. In Figure 3a, b the three-dimensional and one-dimensional representation of a section layer, are illustrated respectively. As seen in Figure 3a, the three-dimensional model comprises six resistances and a lumped capacitance. On the other hand, as seen in Figure 3b, the one dimensional model (in $x$-axis) consists of two resistances $R$ and a lumped capacitance $C$ at the mid-node. Hence, this model is designated as $RCR$ model. The values of the circuit elements are determined on the basis of the geometrical and thermo-physical properties of the corresponding materials.

Figure 3. Thermal-network model of a section layer: (a) three-dimensional representation and (b) one-dimensional representation in $x$-axes ($RCR$ model).

For the period of the transient analysis, the accuracy is related on the number of nodes/sections of the lumped model. Consequently, the thermal model encloses all the essential features that illustrate the discrete problem and its number of nodes is generally large enough to ensure a desirable precision (Lombard et al., 1999; Mathews et al., 1997; Kontoleon and Bikas, 2002; Hensen and Nakhi, 1994).
3.3 Nodal method
The differential equations describing the dynamic behaviour of thermal circuits can be discretised leading to a set of algebraic equations with time-dependent coefficients and driving sources. As a result, the thermal model can be analysed numerically by employing the non-linear nodal approach. During the solution procedure the dynamic behaviour of the thermal-network model is assessed in discrete time steps $\Delta t$, while a preliminary five-day period is used for the simulation in order to eliminate the effect of initial conditions after the steady-state analysis at $t = 0$. A brief description of the mathematical formulation and the solution procedure has been presented in another study (Kontoleon and Bikas, 2002).

4. CONCLUSIONS
The aim of this study was to present the fundamental steps of a modelling approach, which can lead to an adequate design of building envelopes, at the very early stages. The modelling scheme is based on electrical circuits, while the nodal method is employed. These models have been proved to be flexible and precise from past experience. The above methodology allows the consideration of several vital parameters that contribute during the period of the transient analysis. As it is pointed out, these parameters concern the outdoor environment, the envelope structure and the indoor environment of buildings zones. Consequently, the thermal model can attain conditions of thermal comfort within buildings and reduce the energy demands for cooling or heating. In addition, their use can prevent the waste of natural resources. All these aspects can essentially lead to a sustainable building environment. This is very crucial, since during the last decades the environmental changes are leading to undesirable conditions and disasters. Therefore, the worrying environmental threats and predictions must change our attitude and way of living.

REFERENCES