5. AN INTRODUCTION TO BUILDING PHYSICS

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ABSTRACT

This chapter places the System Identification Competition in a broader context of evaluating the thermal performances of building components. It gives a global context for identification techniques in relation to the thermal performances of building components. Basic information is provided about the various processes involved in heat transfer in building components as well as the commonly used formulas to express these heat flow processes. The key parameters in which the building sector is interested are given with an explanation for these priorities. Moreover, thermal testing in general and dynamic testing specifically is situated in this overall context and finally the role and importance of the System Identification Competition is explained.

5.1 INTRODUCTION

This chapter is aimed as an introduction to building physics for people without a background in this field as well as for people with a limited involvement in building physics. The major aims of this chapter are:

- to provide a basic knowledge of the different aspects involved in heat transfer in building components and in thermal testing;
- to indicate the key parameters the building sector is interested in to derive from thermal testing as well as a motivation for it;
- to act as guidance for correctly understanding the objectives of the competition.

5.2 THERMAL CHARACTERISTICS OF BUILDING COMPONENTS

5.2.1 Physical context

Heat transfer in opaque building components is a combination of convective, radiative and conductive processes.

- at the inner surface of a component there is convective heat exchange between the air and the inner surface and radiative heat exchange between the surrounding surfaces and the inner surface;
- inside the materials, the process is a combination of conduction through the solid phase and a combination of radiation, conduction and convection in the air cavities;
- for air layers inside a component, it is also a combination of conduction, radiation and convection (the latter if the air layer becomes larger than a few millimetres);
- at the outer surface, it is a combination of radiation and convection.

For the temperature levels normally observed in building applications, the different heat exchange processes are in most cases expressed as a linear function of temperature difference. The heat flow through homogeneous building materials is then given by:

$$q = \frac{T_1 - T_2}{d/l} \qquad (\mathrm{W/\,m^2}) \qquad (5.1)$$

where :

T_1 and T_2 are temperatures at both sides of the layer (K)
d = thickness of the layer (m)
λ = thermal conductivity of the material (W/mK)

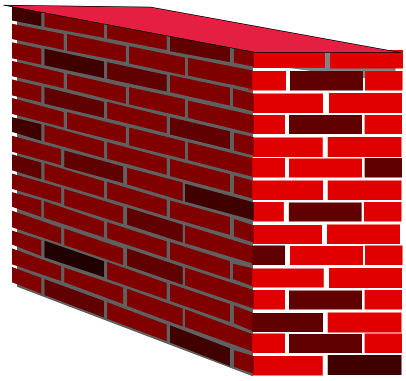

Fig. 1. Opaque elements

The heat exchange at the inner and outer surface is normally by the following simplified expressions :

$$q_i = \frac{T_{rs} - T_{io}}{R_i} \qquad \text{and} \qquad q_e = \frac{T_{eo} - T_e}{R_e} \qquad (5.2)$$

where :

R_i and R_e : internal and external surface resistance (combined effect of convective and radiative exchange)
T_{rs} = dry resultant temperature at the inside (more or less the average of the air and radiant temperature)
T_e = outside air temperature

For standard calculations, the surface resistances are fixed values.

R_e = 0.04 m^2K/W and R_i = 0.13 or 0.16 m^2K/W (depending on the situation)

These fixed values are very rough simplifications of the physical reality. Table 5.1 gives typical values for the thermal conductivity of various building materials. One observes a very large variation in the thermal conductance.

Material	λ (W/mK)	ρ (kg/m^3)	c (J/kgK)
Aluminium	203	~2700	~880
Concrete	2	~2300	~840
Wood	0.1...0.2	~600	~1900
Mineral	0.02...0.06	~100	~840

wool			

Table 5.1 Thermal conductance, density and specific heat for typical building materials

Another important characteristic of a building material is its thermal capacitance. It indicates the ability of the material to store heat. It is described by the specific capacity of the material c (J/kgK) and the density ρ (kg/m^3). With respect to the specific capacitance, it is useful to mention that this value is for most common building materials between 1000 and 2000 J/kgK.

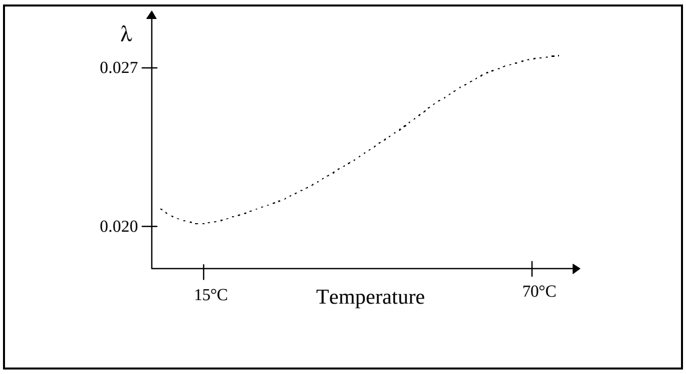

Figure 5.2 : Variation of the λ-value of polyurethane as function of temperature

The thermal conductivity λ is not really a constant value, e.g. it can vary as function of the temperature. This is illustrated in figure 5.2, which shows a typical dependency for the variation of λ for a material such as polyurethane. It is important to note that the construction industry is strongly interested in many applications of the thermal conductivity of building materials (λ-value) but only marginally interested in the density and specific heat of the material. Therefore, very detailed testing procedures for the determination of the λ-value exist and a lot of testing is done.

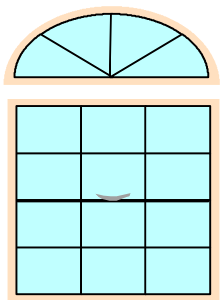

Figure 5.3 Transparent components

The λ-value of thermal insulation materials, must be determined with an accuracy of the order of a few percent: e.g. an insulation material with a λ-value of 0.030 W/mK is from a commercial point of view substantially different from a material with a λ-value of 0.025 W/mK.

In the case of transparent components (e.g. double glazing), the heat exchange phenomena as described, occur as well as reflection, absorption and transmission of the short wave radiation.

For glazing components, the key features for the building sector are the U-value (see 5.2.2) and the solar gain and visual transmittance characteristics.

5.2.2 U-value and thermal resistance

The thermal characteristics of building materials and components (the combination of different materials to form a wall, a roof, etc.) are needed for various applications:

- for calculating the thermal insulation level of buildings and the normalised energy demand;
- for predicting the thermal comfort in summer and winter time;
- for evaluating the risk of condensation and mould growth problems.

In the past, and even today, the most interest goes into the first application. Many countries have standardised procedures for the calculation of the overall thermal insulation level and the normalised energy demand of the building during the heating season.

For the heating demand in winter time, one can show that the transmission losses are primarily determined by the steady state building characteristics of the different components and not that much by the thermal capacitance (the dynamic characteristics). In case of the determination of the normalised energy demand of the building (as described in prEN 832), the dynamical characteristics are considered for estimating how useful the solar gains are, but the way the thermal capacitance is taking into account is rather rough. In the framework of CEN, the thermal mass of the building interferes in the estimation of the usefulness of internal and solar gains. This is illustrated in figure 5.4 where the assumed efficiency (η) of the total gains is a function of the so-called GLR (Gain-Loss Ratio, the total monthly gains divided by the total monthly transmission and ventilation losses; see also prEN 832). A lower efficiency is found for lightweight buildings.

Figure 5.4 Gain-Loss Ratio

In practice, the key characteristic of a building component is the U-value. The U-value is the parameter which describes the performance of the component for transporting heat from inside to outside in steady state conditions.

The U-value is calculated as (the formula given here is a somewhat simplified expression):

$$U = \frac{1}{R_T} = \frac{1}{R_i + \sum \frac{d}{l} + \sum R_j + R_e} \qquad (5.3)$$

where R_T : thermal resistance from environment to environment
R_i and R_e : internal and external surface resistance
$\Sigma(d/\lambda)$ = sum of the different layer resistances
ΣR_j = sum of different air layers and non-homogeneous layers resistances

The heat exchange between two environments can be described as:

$$q = U.A.\,(T_{rs} - T_e) \quad \text{(W)} \qquad (5.4)$$

where :
A : surface of the element (m^2)
T_{rs} = dry resultant temperature at the inside (more or less the average of the air and radiant temperature)
T_e = outside air temperature

As far as the issue of thermal bridges is concerned, standards and evaluation procedures exist in several countries as well as at CEN level. In nearly all cases, these calculations are done in steady-state which means that there is only very limited interest in the dynamic characteristics of the component.

5.2.3 Capacitance - dynamical aspects

As indicated in 5.2.2, in practice one is mainly interested in the U-value and, for thermal bridge problems, in the conductances of the different materials. However, there is an increased interest in the dynamic performances of the components, the main reason being the growing concern for the thermal performances of buildings in summer time: overheating problems and/or the energy need for active cooling.

Therefore, dynamic simulations are becoming more important and for these types of calculations, the ρ and c-values of the different materials are needed.

Does this means that these values have to be identified with great accuracy? Not really, and this for several reasons:

- the density of the different building materials is in most cases very well known and in any case extremely easy to measure with a reasonable accuracy;
- the specific heat of building materials does not vary so much.

In practice, the tabulated values found in many handbooks and standards are sufficient for practical calculations and precise measurements of these parameters is nearly never done. A fundamental change in attitude is not at all to be expected.

5.3 THERMAL MEASUREMENTS

5.3.1 Steady-state testing

In the past and even today, the majority of the thermal tests on building materials and components are done in steady state conditions, which means no variation over time and therefore no information on the dynamical characteristics of the material and component.
The commonly used tests can be splitted up in 2 groups :

- measurements of the surface to surface thermal resistance on homogeneous and rather small samples: guarded hot plate and heat flux meter method;
- measurements of the overall U-value on rather large samples which don't have to be homogeneous: hot box methods.

Guarded hot plate and heat flux meter methods

The determination of the λ-value of building materials, especially thermal insulating materials, is a standard procedure and probably each day hundreds of measurements are done in Europe, as well as for official testing reports. Most countries have national standards, furthermore ISO (International Standardisation Organization) standards exist and also CEN (European Standardisation Organization) is preparing standards.
Two types of tests are in practice applied (guarded hot plate and heat flux method approach) with a number of common characteristics:

– the test specimen is placed between a hot (e.g. 20°C) and a cold plate (e.g. 0°C). The temperature difference is in most cases of the order of 20K;
– the specimen thickness is normally in the range of 30 to100 mm (depending on equipment characteristics) and both surfaces of the specimen must fulfil severe flatness requirements;
– the dimensions of the specimen vary between 0.5 x 0.5 m^2 up to 1 x 1 m^2;
– the pre-conditioning of the samples (drying, ageing, etc.) are in most cases very well described;
– steady-state conditions at both sides of the component (no temperature variation);
– very accurate measurement of the surface temperatures at hot and cold side of the specimen (T_h and T_c);
– measurement of the heat flow density (q) through the specimen;
– calculation of the λ-value as :

$$l = \frac{q}{T_h - T_c} \tag{5.5}$$

The way the heat flow through the specimen is measured is the fundamental difference between the two approaches:

- guarded hot plate test (see figure 5.5)
  The heating plate is split up in a central zone and a guard. The aim is that both plates are heated in such way that the difference between the temperatures of both plates is close to zero. In that case one can assume that the heat flow through the central plate is one dimensional. Often two identical samples are used.
  The power is directly measured by recording the electrical power.

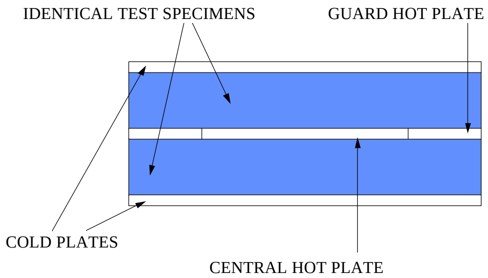

Figure 5.5 Guarded hot plate

- heat flux meter method (see figure 5.6)
  This method makes use of calibrated heat flux meters. The test specimen is placed between a hot and cold plate and the heat flux density is measured in the central area of the specimen. It is not necessary to make use of 2 identical samples.

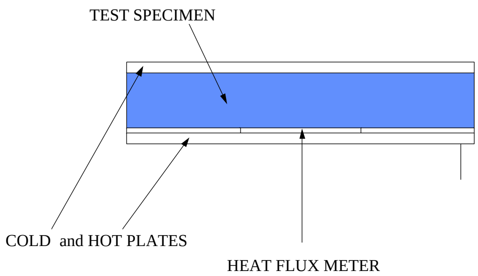

Figure 5.6 Heat flux meter

Hot box testing

Whereas the two previously described tests are primarily aimed for testing homogeneous layers of materials with a limited thickness and size, hot box tests can be done on whole wall and roof components, with sizes up to several m^2. Some of the key characteristics are:

- steady state testing (all temperatures constant during the test);
- the surface resistances are included in the test results, and therefore much attention is given to a very precise definition of the boundary condition, e.g. the air flow pattern at the hot side of the component and the wind velocity and direction at the cold side of the component;
- standards exist in most countries, at ISO level (ISO 8990) and in preparation at CEN level;

5.3.2 Dynamic testing

Over the last 10 years, an increased interest in dynamic testing and simulation has been noticed. Some of the reasons for this tendency are the following:

– more emphasis on issues as summer comfort, cooling issues, etc., which require information on dynamic characteristics of materials and components;

- more interest in the energetic performance of components under real weather conditions : real weather conditions automatically mean variations in time and therefore a dynamic behaviour;
- Increased calculation possibilities of computer hardware and software.

This increased interest has resulted in more research work on developing reliable procedures for evaluating building components in-situ (in a real building) as well as in outdoor test cells (with the real outside climate).

Component testing in situ

The in-situ measurement of the thermal resistance and U-value of building components is since the end of the seventies investigated by different researchers. In the eighties, ISO prepared (and adopted?) a standard for the in-situ measurement of the thermal transmittance and resistance of building components (ISO 9869).
In relation to the EC Building Products Directive (1988), the EC DG III has given a mandate to CEN for preparing a standard for the in situ measurement of the thermal resistance of building components. This work is prepared by CEN TC89 WG8 (convenor Prof. F. De Ponte) and the proposed standard is now in public enquiry.

Some important characteristics of the proposed standard are :
- no possibility to measure directly the U-value. The reason is that the surface resistance's R_i and R_e can substantially differ from the values given in 5.2.1. Therefore, the draft standard only allows to measure the surface to surface thermal resistance. The U-value can afterwards be calculated by adding the standard values for the surface resistance's.
- The standard allows to make use of the averaging method but give preference to a dynamic identification method. With respect to these identification methods, a number of requirements have to be fulfilled. A series of 4 different tests are included in the standard and the user must prove that his method can meet the requirements specified in the standard:

    ⇒ Test 1 : noiseless data sets with different length and conditions have to be tested. Its objective is to reveal shortcomings in the transient model used for the building element in relation with transient test conditions. Furthermore to reveal problems with insufficient information contained in the data sets.
    ⇒ Test 2 : data sets as in test 1 are to be applied, but perturbed with an independent random signal (noise). Its objective is to reveal shortcomings in the method to produce a reliable surface-to surface thermal resistance value and to produce reliable estimate of the confidence interval in case of noisy data.
    ⇒ Test 3 : data sets as in test 1 are to be applied but input data are shifted by a fixed quantity. Its objective is to verify that a systematic error on measured temperatures or density of heat flow rate is not affecting the accuracy of the results far more than in a measurement under steady-state conditions.
    ⇒ Test 4 : data sets as in test 1, but the building element performs with mass transfer and/or linear temperature dependent properties. Its objective is to reveal shortcomings in the method to produce a reliable surface-to surface thermal resistance confidence intervals in such cases.

It is important to stress that the error analysis has received a high priority in this CEN work and that it considers different types of error sources:

- errors related to the measurement equipment (accuracy voltmeters, temperature sensors, heat flux sensors, etc.)
- errors related to the disturbance of the heat flow pattern by installing the sensors;
- errors related to the analysis of the data

Test cell experiments

The in-situ measurements allow to identify the thermal performances of the component on which heat flux sensors are installed. One of the important assumptions is that the heat flow is one-dimensional. This procedure is not applicable to more complex components nor to components which combine various sub-components (e.g. a window, a combination of balcony and wall). For these type of components, testing in outdoor test cells is an attractive solution.

In 1985, the European Commission launched the PASSYS project. It had as major objective to set up a European wide network for testing the thermal and solar performances of building components. The PASSYS project was followed up by the PASLINK and COMPASS projects. In 1994, the PASLINK EEIG (European Economic Interest Grouping) was created aiming to set up and maintain a strong link between the different organisations involved.

The different activities have resulted in

- 14 test centres in 11 countries and a total of 39 test cells;
- standard test procedures;
- a quality control scheme for operating the test centres;
- a whole concept for combining testing activities with simulation work.

The analysis of the collected data is performed by making use of identification methods. In the quality manuals, the aim is to come to a performance approach, which means that there are in principle no strict requirements with respect to the method used for the analysis but that a method can only be applied if certain commonly agreed criteria are fulfilled.

5.4 NEEDS FROM PRACTICE

With respect to data for opaque building components, it is clear that industry, architects, building consultants and constructors are essentially interested in the steady state characteristics: λ – and U-values. Differences and uncertainties on test results of more than 5 to 10 % in the λ and U-value are in many cases considered as unacceptable.

As far as λ– and U-values are derived from measurements, the major requirements of industry are :

- to obtain accurate results;
- to obtain correct information on the total uncertainty of the results (no underestimation of the confidence intervals and combination of the different types of errors and uncertainties);
- to have test methods which are cost effective (limited test duration, limited labour and testing costs);

- to have procedures which as much as possible refer to standardised methods (preferably CEN methods);
- to have λ- and U-values which give identical values when derived from steady-state tests and from dynamic testing.

In case of transparent components, the steady state characteristics of the energetic and visual properties are also of great interest.

It cannot be stressed too much that the choice of the testing strategy and the analysis of the test results should essentially focus on deriving the steady state performances (most probable value of λ and U and the related confidence interval) from information on the dynamic characteristics with a much lower priority.

5.5 STEPS IN THE COMPETITION IN RELATION TO OVERALL CONCEPT

Research on energy savings in buildings can be divided in to three major areas:
1) building components,
2) test cells and unoccupied buildings in real climate and
3) occupied buildings.

Three competitions are planned along this line. The global aims of the different competitions are to set-up a comparison between alternative techniques and to clarify particular problems of system identification applied to the thermal performance of buildings. It helps to clarify the conflicting claims among many researchers who use and analyse building energy performance data and to foster contact among these persons and their institutions.

The aims of the competition are intended also:
- to improve the quality of data analysis in general;
- to improve confidence in the existing methods;
- to extend the level of difficulty by involving solar radiation and real data series.

The specific aims of the first competition are to assess through estimation and prediction, the thermal properties of building components and no solar radiation involved. Five different cases were provided for estimation and prediction. Three cases have been designed with wall components in order to test parameter estimation methods. Prediction tests are also included.

The second competition is concerned with wall components and solar radiation. Four different cases are provided for estimation and prediction. Three of these cases have been designed with wall components in order to test parameter estimation methods and include different degrees of difficulty. Prediction tests are included on experimental data. Some of the dependent variable values will be withheld from the data set in this case.

A third competition will be devoted to one-zone and real building cases.

5.6 CONCLUSIONS

Energy efficiency and environmental protection has received increased attention over the last years. Buildings are important energy consumers and therefore their energy demand receives substantial interest. One of the options is to reduce the transmission losses of the buildings by better insulating the different building components. Another approach is making better use of solar and internal gains.

In practice, there is no doubt that the thermal conductivity of building materials (λ-value) and of components (U-value) are key data in this context. Information on the thermal capacitance, although important in the overall policy, is not an area of large interest and should therefore not receive the same level of attention as the steady-state characteristics. The major reasons are that on the one hand capacitance data are for most applications sufficiently well known from literature and that on the other hand a larger uncertainty on these data is less critical.

Another important aspect is the confidence interval on the identified test results. It is essential that these intervals are reliable or at least not underestimating the confidence intervals.

The System Identification Competition is in this context an important event. It contributes to the development of improved quality procedures and it also indicates important trends in the present state-of-the-art.

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