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Built2Spec

Built to Specifications – Tools for the 21st Century Construction Site

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D2.1 State of the art of the next generation thermal self-inspection technique

Primary Author: ENSAN

Contributors: All WP2 Partners

1st Quality reviewer: Alain Sempey (UB)

2nd Quality reviewer: Tingting Vogt Wu (UB)

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Executive summary

This report focuses on describing the state of the arts of the self-inspection technique and introducing the methodology of thermal diagnostic of building. Each method is analysed in regard of benefits and disadvantages. The necessary instruments are presented.

This report firstly introduce the conventional methods of measuring thermal properties (steady-state techniques and transient method), most of them are implemented in the lab. However, the building envelop is usually with a large thickness and within unstable weather condition, those method should be improved in order to be applied on building envelop in situ.

Then a collection of surveys on building thermal diagnostic has been made. The diagnostic of building includes thermal qualitative diagnostic and thermal quantitative diagnostic. 9 kinds of quantitative methods are introduced in Section 4.2, including HFM method, IR thermography method, THz method, ultrasound method and so on.

Finally the numerical simulation models of heat transfer in building walls have been analysed.

This work can help to identify forthcoming technique developments and propose a low-cost, convenient, ergonomic, low time-consuming and reliability method for BUILT2SPEC program.

CONTENT

Abbreviations

Nomenclature

A	Absorbance	-
a	Diffusivity	$m^2 \cdot s^{-1}$
b	Effusivity	$J \cdot K^{-1} \cdot m^{-2} \cdot s^{-1/2}$
c	Specific heat capacity	$J \cdot K^{-1} \cdot kg^{-1}$
E	Energy	$W \cdot m^{-2}$
h	Heat transfer coefficient	$W \cdot K^{-1} \cdot m^{-2}$
I	Signal intensity	mW
k	Absorption coefficient	-
L	Thickness	m
q	Heat flux	$W \cdot m^{-2}$
Q	Heat flow	W
R	Thermal resistance	$K \cdot m^2 \cdot W^{-1}$
S	Area	m^2
T	Temperature	K
U	Thermal transmittance	$W \cdot K^{-1} \cdot m^{-2}$
v	wind velocity	$m \cdot s^{-1}$

Greek alphabet

λ	conductivity	$W.m^{-1}.K^{-1}$
ε	Emissivity	-
θ	Temperature (Laplace transform)	K
φ	Heat flux (Laplace transform)	$W.m^{-2}$
ρ	Density	$kg.m^{-3}$
σ	Stefan-Boltzmann constant	$W.K^{-4}.m^{-2}$

Subscript

air	air
t	output
0	input
r	radiant
s	surface
flu	fluid
i	indoor
o	outdoor
h	heating
c	cooling
m	maximum

1 Introduction

Problems of environmental degradation and energy crisis are becoming more and more obvious. Awareness of energy conservation and environment protection is growing and analytical works are into concrete actions. In the energy structure, building consumes the largest share comparing with industry, transport and others, and half of global electricity consumed, also responsible for approximately one-third of global carbon emissions [1-3]. According to the statistics of IEA (International Energy Agency) [4], shown in Fig.1, Buildings represent 35% (2010 edition) of total final energy consumption, bigger than industry (31%) and transport (30%). In terms of primary energy consumption, buildings represent around 40% in most IEA countries. And with population increasing and improving in economic development and living levels, the building consumption will rise sharply in the future and form additional pressure on the energy system. Energy demand in buildings rises by almost 50% between 2010 and 2050 in a business-as-usual scenario.

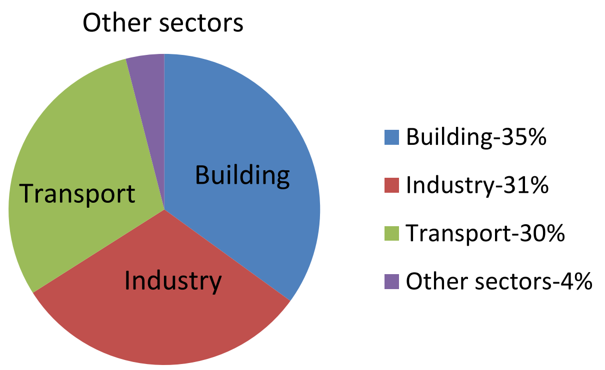


Fig.1 Final energy consumption

Energy consumption of building mainly includes climate controlling, water heating, applications, lighting and other installed equipment and so on. Climate controlling occupies nearly half of the consumption, which can be improved by rising the building energy efficiency. So improving the energy efficiency in buildings is of greatly importance. Methods and policies to encourage renovation and energy efficiency improvements are being implemented to improve the energy efficiency of both existing buildings and future buildings.

The building envelope plays a critical role in determining levels of comfort and building efficiency. Some energy-efficient building materials should be used for minimizing energy required for heating and cooling, decrease heat loses through the envelope. We need to detect the thermal characteristics of the materials. Research and development on the methodology for energy diagnostic in the building envelop is a hot topic and necessary trend.

The aim of this report is to Summarize and compare methodology for measuring thermal properties of solids, analyse and explore diagnostic method for thermal parameters of building in situ. And then propose a precise, fast, convenient, less-cost, and less instruments-method which could be wildly used in the future.

2 Thermal principles and parameters

As known to all, there are three forms of heat transfer: conduction, convection and radiation, all these should be considered in measurement of thermal properties.

For the thermal radiation, the calculation is based on the Stefan Boltzmann law, energy E is

$$E = \varepsilon\sigma T^4 \tag{1}$$

and heat flux q form body 1 to body 2 is given by:

$$\mathrm{q} = \varepsilon\sigma(T_1^4 - T_2^4) \tag{2}$$

For the convection heat transfer, the calculation is based on Newton's law,

$$\mathrm{q} = \mathrm{h}\left(T_s - T_{flu}\right) \tag{3}$$

Heat conduction is the mainly form of heat transfer in the measurement, the heat equation is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{\lambda} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{4}$$

Conduction can be divided into two kinds of heat transfer theories. One is steady state heat transfer, in which the temperature is independent on the time. Another is transient heat transfer, in which the temperature changes with the time changing.

The following parameters are normally used to represent the heat transfer ability of materials:

Thermal conductivity $\lambda = \frac{q}{gradT}$, also λ =L/R (5)

Thermal effusivity b= $\sqrt{\lambda\,\rho c}$ (6)

Thermal diffusivity $\alpha = \frac{\lambda}{\rho c}$ (7)

Thermal transmittance (U-value), the heat transfer is from air to air.

$$U = \frac{q}{T_i - T_o} \tag{8}$$

Thermal resistance (R), the heat transfer is from surface to surface.

$$R = \frac{T_{s\,i} - T_{s\,o}}{q} \;/\; R = \frac{L}{\lambda} \tag{9}$$

Generally, thermal transmittance (U-value) [5, 6] and thermal resistance (R-value) [7, 8] are usually measured for characterizing the thermal performance of wall of building.

3 Conventional Thermal metrology for solids

Many methodologies have been developed to measure the thermal transfer properties for the solids. Based on the heat transfer principles, these methods can be divided into two kinds: steady-state techniques where time does not intervene and transient (dynamic) techniques where time dependent [9], shown in Fig.2. In this part, some traditional and common methods are introduced, which mainly implement in the laboratory.

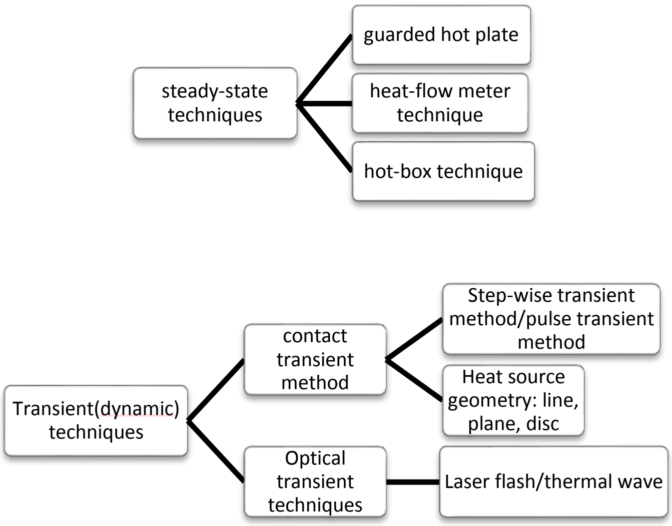


Fig 2 Conventional Thermal metrologies for solids

3.1 Steady-state techniques

Steady-state techniques are the earliest group of measurement techniques. This measurement is based on the steady state heat transporting, establishing a temperature gradient over a known thickness of a sample to control the heat flow from one side to the other. A one-dimensional flow approach has been employed most frequently, but also other geometrical arrangements are used. The thermal conductivity is simply determined by measuring the temperature gradient and the heat flow through the sample. These methods are primarily suitable for analysing materials with low or average thermal conductivities at moderate temperatures [9].

Although these techniques are simple in theory, they are difficult to experimentally implement since it is not easy:

- To establish a permanent regime.
- To obtain a unidirectional flow in the wall.
- To measure the flow and temperature accurately.
- Maintain constant in time and uniform convection coefficient h at the sample surface.

Three steady-state measurement techniques are most commonly used: the guarded hot plate, heat-flow meter technique and hot-box technique.

3.1.1 The guarded hot plate method

In 1920, Van Dusen provided detailed information on the design and theory of operation of the apparatus for the guarded hot plate. In 1945, this method was formally adopted as a standard and designated ASTM Test Method C 177 [10], and it also has become a standard: ISO 8302: 1991.

Fig.3 is a diagram of a similar version of the NVS 200mm guarded hot plate apparatus.

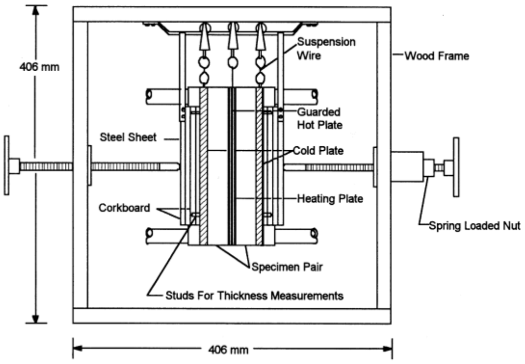


Fig.3 Schematic of NBS 200 MM guarded hot plate apparatus (1928 version)

The apparatus is consisting of a flat electrically heated copper plate and two flat water-cooled cold plates, suspended from the framing by thin wires.

The heated plate actually consisted of two plates enclosing a heater grid wound around fiberboard and insulated from the metal plates by sheets of micanite. Two nearly identical specimens were placed on each side of the heating plate. The cold plates were maintained at constant temperature by circulation of either water or brine through the plates.

Heat was supplied electrically at a known rate to the heated plate, and a constant temperature difference was maintained between the hot and cold plates. The temperature differences of the surfaces were measured by means of thermocouples. Additional details of the apparatus are available ASTM 2000a.

So a one-dimensional heat flow through a pair of specimens is established. Based on the Fourier's heat conduction equation for one dimensional heat flow, the heat conduction is:

$$\lambda = \frac{QL}{2S(T_h - T_c)} \quad (10)$$

This method formed a standard reference method and can measure large sample thickness.

However, some disadvantages are proposed: requires for a large size samples 50 x 50 cm^2; not suitable for $\lambda > 1$ W/mK; Need to provide Pressure monitoring device; No measuring the conductivity in the plate; Experience not involving the capacitive effect of the material, the method does not achieve the thermal capacity; Time of establishment of the steady regime is too long.

Industrial instruments have been manufactured based on this principle. For instance, Fig 4. is the product of NETZSCH GHP 456 for measuring thermal conductivity with the guarded hot plate method applied.

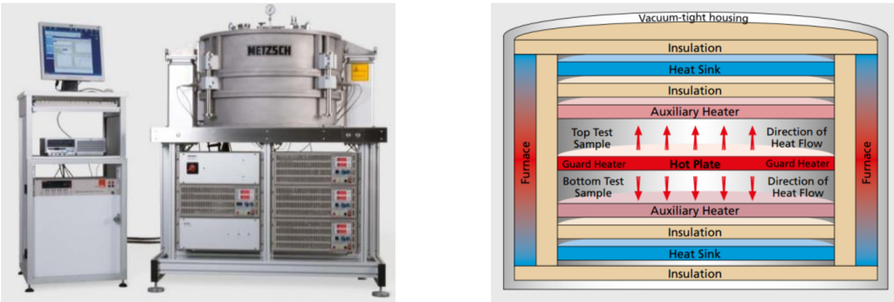


Fig.4 Instrument of NETZSCH and its principle based on guarded hot plate principle

3.1.2 Heat-flow meter technique

Fig.5 shows the simplified diagram of heat-flow meter technique [9], a square sample with a well-defined thickness is inserted between the hot plate and cold plate. The heat flow through the sample is measured with heat flow sensors after a fixed temperature gradient is established. The calculated equation for λ is same with the guarded hot plate method

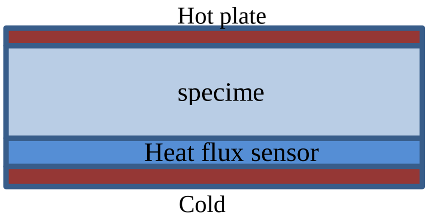


Fig.5 Simplified diagram of heat-flow meter technique

Fig.6 is the measuring instrument of NETZSCH HFM 436 Lambda.

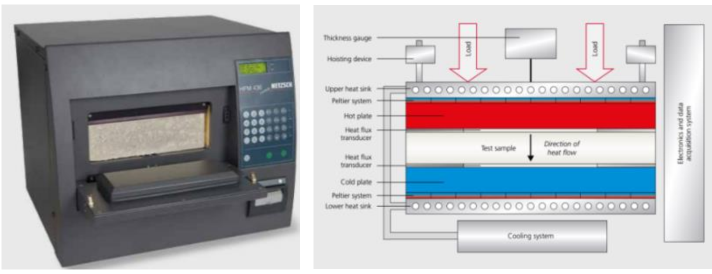


Fig.6 Instrument of NETZSCH and its principle based on HFM

This method is usually applied to test the insulation parameters of building envelopes in situ because of its lightweight components and easily matching. However, the main disadvantage is that the large errors between the testing results and given values.

3.1.3 Hot-box technique

The hot box technique is usually used measuring the overall thermal resistance or thermal transmittance (heat transfer from air to air), and it was applied in the papers [11-13], experimental method is shown in Fig.7.

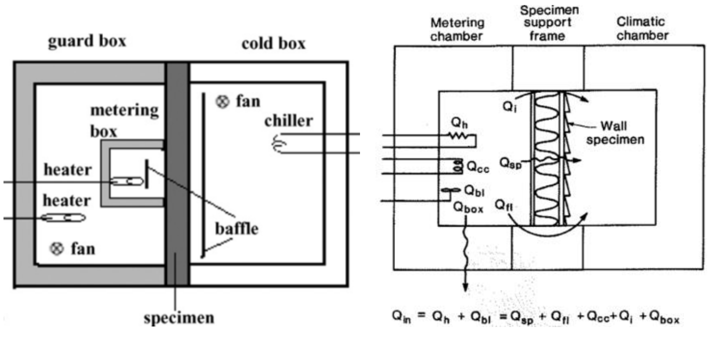


Fig.7 Schemes of hot box technique

A large specimen is placed between a hot and a cold chamber operating at fixed temperatures, humidity and air flow conditions. In the Fig.7 (a), a guarded metering box is attached to the central section of the specimen. Temperature sensors are placed at positions approximately opposite those in the specimen to obtain the corresponding air temperatures. Testing is performed establishing and maintaining a desired steady temperature difference across a test panel for a period of time so that constant heat flow and steady temperature are ensured. When air temperatures across the metering box wall are maintained the same, the heat interchange between the metering box and the guard box is zero. At this time, the heat flow (dc-power) is measured. This is a measure of heat in the metering box through a known area of the panel.

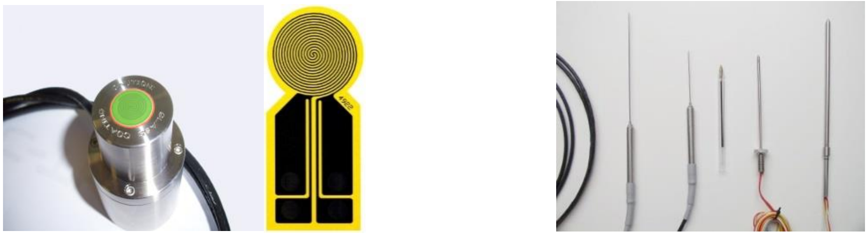
In the Fig.7 (b), the outer walls of the hot chamber are made with very thick insulation to minimize conduction losses and the power flow through those walls is measured for a range of hot chamber and laboratory temperatures, using the calibration panels.

3.2 Transient (dynamic) measurement techniques

Transient methods are based on the generation of dynamic temperature filed inside the sample. The temperature of the body is stabilized and uniform, the measurement is to test the temperature–time response by sending a signal to create heat in the body. The signal is in the form of a heat pulse or a step-wise heat flux. Generally, these techniques are divided into two categories according to measurement apparatus: contact transient method and optical transient techniques.

3.2.1 Contact transient method

In the contact transient method, the heat signal is contact with the body. Heat source and thermometer are placed inside the specimen. The dynamic temperature filed is generated by the passage of the electrical current through a line or plane electrical resistance. Signal is Heat pulse or heat flux in the form of step-wise. The geometries of heat source are line, plane and disc, shown in Fig.8. the signal can be step-wise or pulse. This method is wildly used because it is simple and easily realized.



a b

Fig 8 Heating sources a. disc; b. needle probe

Kubicar and Bohac [14] reviewed several transient method of measuring thermal physical parameters. Table 1 shows a summary of common contact transient measurement techniques. More details are analysed in this paper: mathematical model, experiment arrangement, and sensitivity.

Table 1 Common contact transient measurement techniques

Heat source geometry	**Way of heat generation**	**Heat source thermometer conFiguration**	**Measured parameter**	**Name of method**
Line source	Step-wise	Thermometer united with heat source	Thermal conductivity,	Hot Wire Method
Plane source	pulse	Thermometer apart form heat source	Thermal conductivity, thermal diffusivity, specific heat	Pulse Transient Method
Plane source	Step-wise	Thermometer apart from heat source	Thermal conductivity, thermal diffusivity, specific heat	Step-wise Transient Method
Plane source	Step-wise	Thermometer united with heat source	A combination of thermal conductivity and thermal diffusivity	Hot Plate Transient Method
Disc	Step-wise	Thermometer united with heat source	Thermal conductivity, thermal diffusivity, specific heat	Hot Disc Transient
Concentric circles	Step-wise	Thermometer united with heat source	Thermal conductivity, thermal diffusivity, specific heat	Gustafsson Probe

For example, in 2000, Kubicar and Bohac [15] made a measurement with a planar heat source producing a constant heat in the form of the stepwise function.

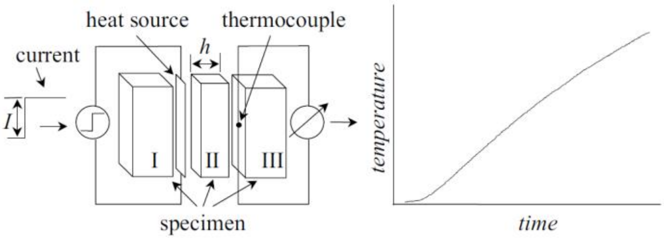


Fig.9 The principle of the step-wise transient method [15]

As shown in Fig.9, the specimen is cut into three pieces. The dynamic temperature field is generated by the passage of the electrical current through a planar electrical resistance made of thin metallic foil. The response of the temperature is measured by a thermocouple. Both the thermocouple and the heat source are placed between the cut surfaces of the specimen.

The model of the method is:

$$T(F,h) = \frac{qh}{c\rho a} \times \left[\frac{1}{2}\left(\frac{F}{\pi}\right)^{1/2} exp\left(-\frac{1}{4F}\right) - \frac{1}{2} erfc\left(\frac{1}{2\sqrt{F}}\right)\right] \qquad (11)$$

$$erfc(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x exp(-\delta^2)\, d\delta, F = a\bar{t}/h^2 \qquad (12)$$

The step-wise transient method gives all three thermophysical parameters within a single measurement. This method need to consider the boundary conditions. There is contact thermal resistance between the heat source and the specimen, also between the thermocouple and the specimen due to the metallic foil having a real thickness. In the model, the body is unlimited, and in real set up the specimen surfaces might influence the measurement. So it needs to apply a correction function.

M. J. Assael [16] applied the transient hot-wire technique for thermal conductivity measurements based on a full theoretical model with equations solved by finite-element method applied to the exact geometry.

Silas E. Gustafsson [17] applied the pulse transient method to measure thermal conductivity and thermal diffusivity. The method is based on a procedure by which a string of square pulses, via an accoupled circuit, is applied to the hot strip

3.2.2 Optical transient techniques

These methods are more advanced, more expensive and requires on the equipment. It can directly measure the thermal diffusivity. The heat source signal is energy pulse (Laser flash) or thermal waves. The most widely used optical transient technique is the laser flash method.

The flash method was first approved and described by W. J. PARKER at al. [18] in 1960 for measuring the thermal diffusivity, heat capacity, and thermal conductivity. It has become the main technique for measuring thermal diffusivity of solids.

A laser or a flash lamp is applied on one surface of the specimen, the fixed thermocouple or IR camera is used to measure the temperature of rear surface. The thermal diffusivity can be calculated with the temperature-time response curve and the thickness of the sample.

The temperature response for the flash is:

$$T(x,t) = \frac{Q}{\rho cL}\left[1 + 2\sum_{n=1}^{\infty} cos\frac{n\pi x}{L}\cdot\frac{\sin(n\pi l/L)}{n\pi l/L} exp\left(-\frac{n^2\pi^2}{L^2}at\right)\right] \quad (13)$$

Define *l:* T(x,0)=Q/ρcl (0<x<*l*);   T(x,0)=0 (*l* <x<L)

For opaque materials, *l* is very small.

At the rear face:

$$T(L,t) = \frac{Q}{\rho cL}\left[1 + 2\sum_{n=1}^{\infty} -1\, exp\left(-\frac{n^2\pi^2}{L^2}at\right)\right] \; (x = L) \quad (14)$$

The maximum temperature of the rear face is:

$$T_m = \frac{Q}{\rho cL} \quad (15)$$

Define V as:

$$V(L,t) = \frac{T(L,t)}{T_m} \quad (16)$$

$$V = 1 + \sum_{n=1}^{\infty}(-1)^n \exp(-n^2\omega) \quad \omega = \pi^2 at/L^2$$

And this equation is plot in Fig. 10:

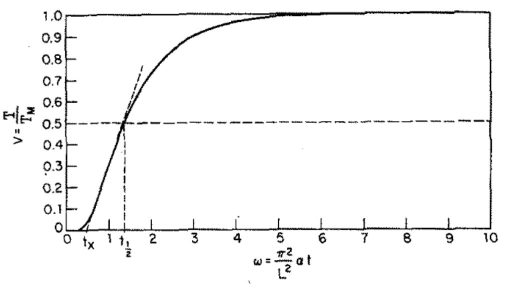


Fig. 10 Dimensionless plot of rear surface temperature history

T1/2 is the time required for the back surface to reach half of the maximum temperature rise.

$$a = 1.38L^2/\pi^2 t_{1/2} \quad (17)$$

Four major error sources are responsible for the measurement uncertainties of the method:

- The radiative and convective heat loss from the sample.
- The inhomogeneity of the incident heat flux.
- The length and shape of the pulse.
- The effects of non-linearity.

The following assumptions are generally used:

- Consistency of the radiative flux absorbed across the sample surface;
- Uniform temperature equal to the room temperature at t = 0;
- Convective exchange coefficient identical on all sides.

Fig. 11 is the instrument NETZSCH LFA 427/457, which used for laser flash measurement.

Fig.11 *Instrument of NETZSCH and its principle based on Flash method*

The flash method is not suitable for measuring thermal properties of building in situ because walls are often semi-transparent to the radiations of the flash lamp and always with a large thickness, which leads it need a large time for the rear face to response for the pulse.

This technique has undergone many changes in pace of technological development of instrumentation (lasers, calculation tools, measuring devices,) as well as the development of models with one or two dimensional or that better reflect the reality of the transfer of heat within the material. Many methods have been proposed for measuring thermal properties of insulating materials or building envelop in situ based on the flash method. These improved flash methods will be described in the following sections.

4 Thermal diagnostic of building envelop in situ

For new buildings, though the performance of walls have been pre-calculated , once built, the characteristics of walls can be changed because of the management of construction, humidity, materials difference, the properties of walls should be re-test. For some old buildings, there is no thermal statistics saved. To improve the energy efficiency of existing old building, it is necessary to measure the thermal properties of walls in situ for thermal renovation during a program of old building optimization. So it is essential to estimate the thermal properties of building envelop in situ.

The diagnostics of building in situ includes thermal qualitative diagnostic and thermal quantitative diagnostic.

4.1 Thermal qualitative diagnostic of building in situ

IR thermography is a very popular non-destructive method for building qualitative diagnostics and has been widely used. IR thermography can be a powerful tool for fast and accurate building qualitative diagnostics, such as the detection of thermal bridging or excessive heat loss areas, air leakages, missing or damaged thermal insulation in the building's elements, sources of moisture, the location of building components, as well as the monitoring for the preservation of historical buildings and monuments. Thermal irregularities, voids, air leakage, moisture intrusion and the buildings structure produce different models of superficial temperature that have characteristic shapes in a thermal image [19].

It can be used quickly survey the entire building and spot heat losses or gains through the envelop and substantiate proposals using the IR images as a proof of a problem or support other data and information collected. For the IR thermography inspecting, the influence of solar radiation and wind should be considered.

For example in Fig 12 [20], an outdoor thermograph of the structural component during winter is taken, thermal bridges appear as light coloured areas because the heat losses from the indoor heated space cause a temperature increase.

An IR inspection around a window or a door frame can easily pinpoint the leaking areas. Cold air infiltration around the door frame appears in the dark colour in Fig 12 right.

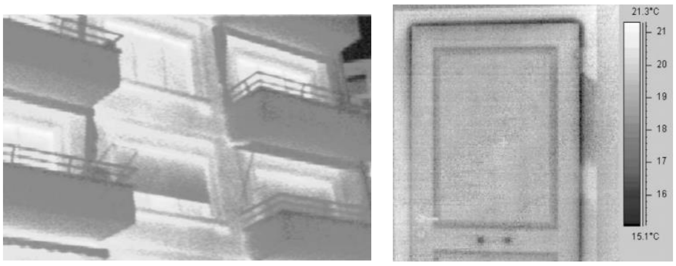


Fig 12: left: Thermography of a building façade illustrating missing wall thermal insulation and thermal bridges; right: thermograph of an exterior door viewed-Air leakage through door

Another research [21] investigates and identifies the location of thermal bridging by integrating infrared imaging into the LEED certification process as a qualitative test method. As this study shows, the introduction of infrared imaging as a means of analysing and improving the energy efficiency of building envelopes can result in an enhanced LEED rating system. Thermal irregularities, voids, air leakage, moisture intrusion and the buildings structure produce different models of superficial temperature that have characteristic shapes in a thermal image.

In this paper [22], some results of thermographic surveys conducted before and after the earthquake are presented by infrared technology, the damages occurred after the earthquake were analysed.

In the European program Built2Spec, the report [23] shows the state of the art and common practice for thermal performance assessment in the UK. The development of building thermography is described in this report. In the report [24], the author describe how the building thermal survey methods are done together with the benefits and disadvantages of each survey in the UK, including street view thermal image surveys, aerial thermal image surveys, typical compliance survey, TI Compliance survey, heat flux assessment, co-heating test method.

4.2 Thermal quantitative diagnostic of building in situ

Most of methods introduced in Section 3 are not suited to measure thermal properties of building walls in situ, which is insulating materials with low density and with a large thickness. These methods are difficult to implement for the following reasons:

1. Walls are often semi-transparent to the radiations of the flash lamp, and it needs a long time for the rear face to response from the pulse due to the large thickness of the wall, and also need a low frequency heat signal as heating source.

2. The measurement device is difficult to be applied to the thick walls in situ; The thermal conductivity of the heating source is higher than that of walls, the longitudinal heat transfer in the heat source leads to a large estimation error; The size of the samples is large, and the measurement is easily affected by thermal bridges, such as beams and pillars. The experimental conditions are not as easy to be controlled as in the lab.

3. It is difficult to measure precisely and ensure the sensitivity. Measurement error and system error caused experimental data noise, which influences the calculation results by the inverse-numerical model. So a precise numerical model should be proposed.

Many improved methods have been proposed base on all these techniques described in preceding section. Non-destructive method and destructive method are two common measurements in situ. The destructive method is to directly survey of the fabric layers with direct measure of their thickness, it is invasive. The non-destructive method is usually based on measuring the temperature gradient or a temperature-time response in the wall.

Desogus and Mura [7] applied both non-destructive technique and destructive sampling method to test the wall physical characteristics, the differences between the results of the two methods are so small. The non-destructive method, such as heat flowmeter method, is not invasive but requires the heat-flow rate measurement of inside building surfaces and temperatures of both inside and outside surface. Measurement with the use of a heat-flux meter is strongly affected by environmental conditions. The destructive method requires coring of the building envelope and very simple measurements, but it is very invasive. Moreover, the recognition of in situ construction materials is quite difficult. In most cases it is not possible to evaluate the density and moisture content of each layer, thus attributing thermal conductivity or resistance values may cause deterministic and non-systematic errors that cannot be easily quantified. Totally, the non-destructive method is more wildly used.

Based on the heat transfer theory, the main non-destructive methods can be generally divided into steady state method and transient method, as introduced in part 3 of this report. While if IR cameras are applied in the measurement, it can also be called Infrared Thermography Passive method or Infrared Thermography active method based on the IR measuring principles. In this field, infrared thermal technique-ITT has not been fully investigated yet, even if it has been used for more than 30 years in the building sector. Infrared thermal technique becomes more and more widely used because of its advantages: non-contact measurement; fast implementation; non-destructive, 2D mapping and temporal changes in temperature; high temperatures possible. For the infrared thermography passive method, there is no artificial heating or cooling is applied in the measurement, it highlights temperature differences between the environment and the studied object. While an artificial thermal signal is required to observe any response on envelops in the Infrared Thermography active method.

The following text will introduce several researches on thermal quantitative measurement of building in situ.

4.2.1 Measurements based on HFM

The heat flowmeter method-HFM is a kind of steady state method and is in detail described in standers ISO 9869:1994. Based on this standers, measurements are proposed to measure the thermal properties of building envelop, such as, (total) thermal resistance, thermal transmittance.

Ahmad and Maslehuddin [25] in 2014 applied the HFM to measure the thermal transmittance and thermal resistance of hollow reinforced precast concrete walls. Thermal performance of two exterior walls of a building was determined in situ. The instrumented building and the test room walls are shown in Fig. 13

Fig. 13 The instrumented building and the test room walls

According to the standards, the thermal transmittance is based on the simultaneous measurement of the time averaged heat flux and the differential air temperature, while the thermal resistance is based on the simultaneous measurement of the time averaged heat flux and differential wall surface temperature.

The in situ thermal resistance (surface to surface) was calculated using the following equation:

$$R = \frac{\sum_{j=1}^{m}(T_{s\,oj} - T_{s\,ij})}{\sum_{j=1}^{m} q_j} \tag{18}$$

The in situ thermal transmittance (air to air) was calculated using the following equation:

$$U = \frac{\sum_{j=1}^{m} q_j}{\sum_{j=1}^{m} (T_{oj} - T_{ij})} \quad (19)$$

Thus work involved the in situ measurement of thermal parameters, such as inside and outside air temperature, inside and outside surface temperature of exterior walls, and the heat flux through the exterior walls surface. The main instruments are heat flux sensors, air temperature sensors and thermocouples. An air conditioner is installed to control the air temperature inside.

The trial was last for a period of about two months in the summer and obtained three sets of data. The results indicate that the thermal transmittance depends on the wall orientation and local weather conditions, which nearly have no effect on the thermal resistance. The results also show that a measurement period of six days is sufficient to obtain in situ thermal performance properties of reinforced precast concrete walls.

Peng and Wu [26] introduced a method for measuring thermal resistance of buildings by recording the heat flux and surface temperatures of walls. A chamber was tested in situ. The air-conditioning unit is equipped for cooling to keep temperature and humidity constant. Heat flux sensors were applied to measure the temperature and heat flux. The climate outside was recorded in real time by means of three pyranometers, a pyrheliometer, and a small meteorograph station. 30 thermopairs and 6 heat flux meters were arranged in the room. Fig. 14 shows the details of the experiment.

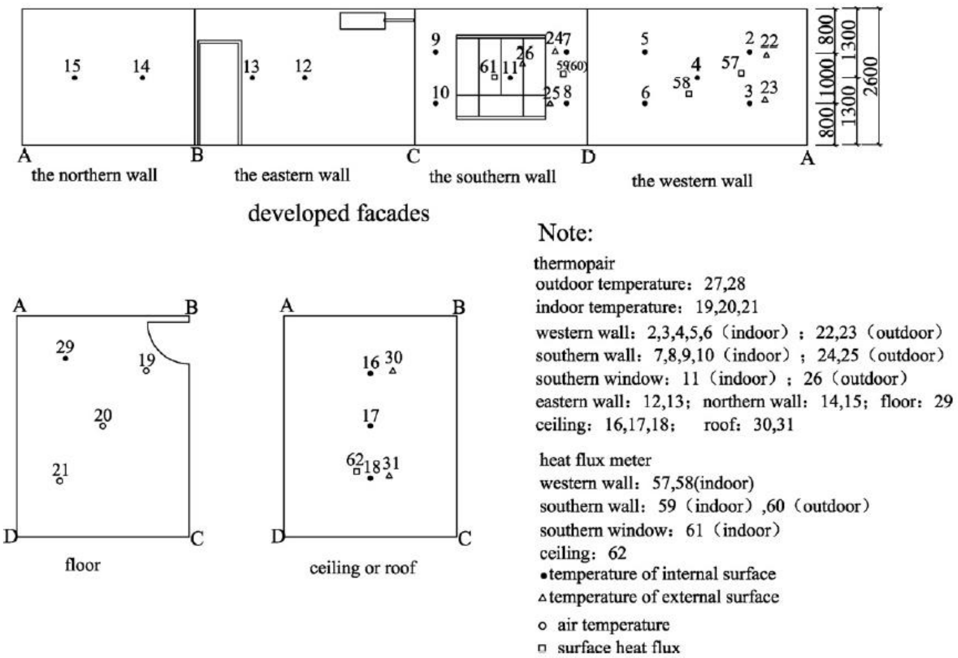


Fig.14 Detail placement for measuring

To calculate the total thermal resistance in situ, this paper also proposed three analysis methods: the synthetic temperature method, the surface temperature method and the frequency response method.

In the synthetic temperature method, the R-value is evaluated using the mean of temperatures and heat flow rates in a period of temperature wave, for example 1 day, instead of using the immediate data. And the outdoor synthetic temperatures To, which including the influence of solar radiation, are used in the equation.

$$R = \frac{\overline{To} - \overline{Ti}}{\bar{q}} \tag{20}$$

$\overline{To}$ is the mean outdoor synthetic temperature Tsa in 24h, and $\overline{Ti}$ is the mean indoor temperature Ti in 24h and $\bar{q}$ is the mean heat flux in 24h.

In the surface temperature method, the R value is the sum of R_0 (resistance between two surfaces), heat transfer coefficients of both inside and outside air film convection.

$$R = \frac{1}{h_i} + R_0 + \frac{1}{h_o} \tag{21}$$

$$R_0 = \frac{\overline{\theta o} - \overline{\theta \imath}}{\bar{q}} \tag{22}$$

Where $\overline{\theta o}$ and $\overline{\theta \imath}$ are the average surface temperature of outside and inside.

In the frequency responses method, the R-value is evaluated by the product of v_0 and h_i or by the quotient of v_0 and h_i:

$$R = R_i v_0 = \frac{v_0}{h_i} \tag{23}$$

v_0 is the 0th order of the frequency responses of heat conduction, calculated by the thermoelectricity analogy method (TEAM) [27]. R_i is the resistance of heat diffusion on the inner surface of buildings. h_i is the coefficient of heat transfer of the inside air film of buildings.

The differences between the results of the three methods are so small that any of them could be used to evaluate the in situ R-value of buildings. The frequency response method is better than the other two methods to evaluate the in situ R-value of buildings.

Desogus and Mura [7] implemented a similar measurement on two chambers. The results show that the R value measurement with a (temperature difference between cold chamber and warm chamber) equal to or higher than 10ºC is the most reliable method since it is affected by the smallest error (9%).

In another research [5], four cubicles (2.4 x 2.4 x 2.4 m) with different insulation materials were measured. The structure of the four cubicles of this study was made of four mortar pillars with reinforcing bars, one in each edge of the cubicle. The base consists of a mortar base of 3 x 3 m with crushed stones and reinforcing bars. The walls consist of perforated bricks (29 x 14 x7.5 cm) (Fig. 15) with an insulating material (depending on the cubicle) on the external side and plaster on the internal side. The external finish was done with hollow bricks (Fig. 15) and a cement mortar finish. Between the perforated bricks and the hollow bricks there is an air chamber of 5 cm. The roof was done using concrete precast beams and 5 cm of concrete slab.

Fig 15 Cubicle studied in the research

Table 2 The experimental results were listed in table.

Comparison between experimental and theoretical wall thermal transmittances for the selected periods of two weeks with pervasive fog in winter 08–09.

		Average temperature difference (°C)[a]	Average heat flux (W/m^2)	Λ_{exp} (W/m^{2}K)	σ of Λ_{exp} (W/m^{2}K)	Λ_{theo} (W/m^{2}K)	Difference
Last week of December 08	Reference	13.87	−20.69	1.49	0.060	2.02	26%
	PUR	18.53	−6.62	0.36	0.039	0.33	−7%
	MW	16.00	−7.47	0.47	0.047	0.52	10%
Week in the middle of January 09	Reference	16.30	−23.03	1.42	0.092	2.02	30%
	PUR	20.88	−7.05	0.34	0.042	0.33	−1%
	MW	20.26	−9.89	0.49	0.066	0.52	6%

The uncertainty of the experimental thermal transmittance is a function of the temperature difference between external and internal walls. Applying the standard method for determining uncertainty propagation, for temperature differences in the range 16–208°C, the calculated uncertainty is in the range 20–15%.

Generally, the disadvantage of this measurement is that the experimental period lasts too long and it needs a steady and regular ambient during the measurement.

4.2.2 Measurements based on hot box method

T. Nussbaumer, K. Ghazi Wakili [8] detected the thermal performance of vacuum-insulation panels applied to walls and made comparisons were made with conventional insulation and also with vented vacuum panels. Steady-state conditions and stepwise are applied.

The thermal transmittance measurements were carried out using a guarded hot-box apparatus complying with the international standard ISO 8990, as shown in Fig 16, the metering zone was surrounded by a guard zone held at a stable temperature. The wall system was incorporated in a surround panel made of an insulation material of known thermal properties and was fully encompassed by the metering area on the warm side. The total surface resistance was determined based on these values and the heat flux through the specimen.

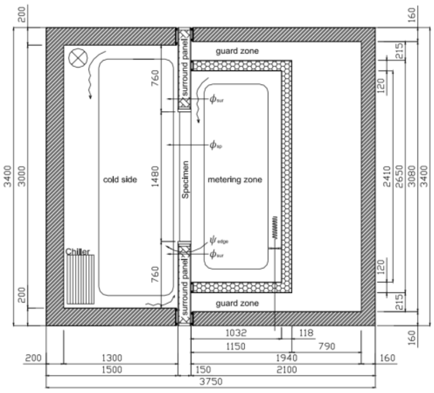


Fig 16 Schematic vertical cross-section of guarded hot-box apparatus (dimensions in mm).

4.2.3 Measurement of infrared thermography technique

Albatici and Tonelli [28] proposed a faster and less invasive method to measure thermal transmittance (U-value) of walls in 2010. It is a kind of steady state method. Convection (due to air temperature and speed) and irradiation (due to the temperature of the surfaces positioned near and around the element) are considered in this method. Fig. 17 shows the principles of heat transfer.

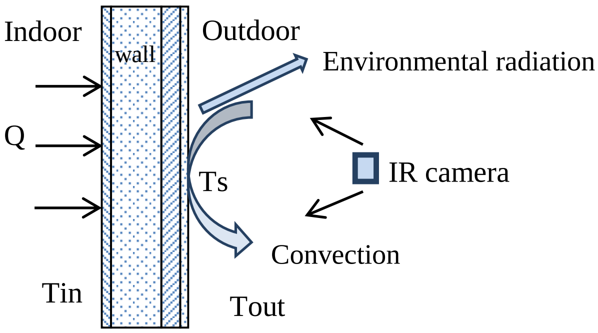


Fig. 17 Principles of heat transfer

The total heat flux can be:

$$Q = Qconvect + Qradiant \quad (24)$$

The sensible heat flux for convection is:

$$Qconvect = 3.8045v(Ts - Tair) \quad (25)$$

The Stefan–Boltzman Law for grey body radiation:

$$Qradiant = \varepsilon\sigma T^4 \quad (26)$$

The transmittance is:

$$U = \frac{5.67\varepsilon\left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right] + 3{,}8054v(T_s - T_o)}{T_i - T_o} \tag{27}$$

ε here is the emissivity on the entire spectrum calculated as:

$$\varepsilon = 1 - \frac{T_r^4 - T_o^4}{T_s^4 - T_o^4} \tag{28}$$

Soldering iron is positioned near the surface, and then a thermographical image is suddenly taken to measure the radiant temperature of the source and of its reflected image visible on the element surface. The test results are shown in Fig.18, the source (soldering iron) T_s=140 ºC, the apparent source temperature reflected by the wall T_r=30 ºC, the outdoor temperature T_o=20 ºC.

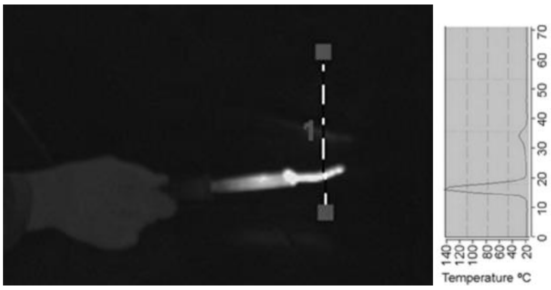


Fig. 18 Thermal image of the soldering iron with the radiance temperature profile on the right end part

Usually following equipment is needed: an IR camera to take infrared thermal images of building both outside and inside, a hot-wire anemometer to measure wind speed, a soldering iron to measure ε.

3 cases are studied to measure U value with ITT method and HFM method, in one case, the value higher of 59% compared to the theoretic one with HFM. And with ITT method, value higher of 31% compared to the calculated one.

The advantages of this method are:

- Global thermographic image is taken and all the detected element surfaces are considered so that anomalous thermal behaviour can be rejected (local thermal bridges, areas with high moisture and so on).
- The procedure is sufficiently fast, a medium size building can be analysed in situ in about 2–3 h (plus 15 h of data handling in office).

The main limits are:

- The measurement can be done only during evening so as to avoid direct solar radiation.
- Wind speed must be lower than 1m/s (best condition is lower than 0.2 m/s) in order to avoid convective phenomena out of control.

- The building elements must have stored a sufficient amount of heat during previous days in order to have a dispersed thermal power significantly measurable, the meteorological situation must have been fair (clear sky, possibly sunny and non-rainy or windy).
- The difference between inner and outer temperature during the measurement must be of at least 10–15 ◦C in order to allow a measurable heat exchange through the element.

This method was later developed by Fokaides and Kalogirou [29]. Their approach is a little different because of its calibration procedure and determination of the coefficient convective transfer. The notional U-Values were obtained according to EN ISO 6946: 199,778. To complete the calculating of the transmittance for the tested wall, temperatures interior and exterior are measured.

$$U = \frac{4\varepsilon\sigma T_s^3(T_s - T_r) + h(T_s - T_i)}{T_i - T_o} \quad (29)$$

The measurement was performed from the inside of the building. The reflective ambient temperature (T_r) is evaluated by a crumpled sheet-smoothed aluminium. The emissivity of the wall is evaluated by correction using a piece of black tape known emissivity, it is showed in Fig. 19.

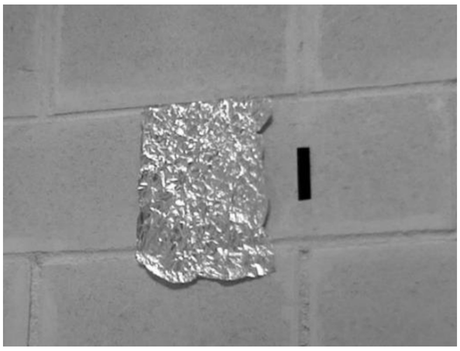


Fig.19 Arrangement for determination of reflected temperature and emissivity

This ITT method is applied to measure five dwellings in Cyprus. Results are shown in Table 2, the percentage absolute deviation between the notional and the measured U-values for IR thermography are in the range of 10–20%. It is noted that the tests were conducted on the walls, roofs and for different types of glazing (single, double, treaties). The results of the estimated U-values for heating and cooling period obtained by IR thermography are given in Table 3.

Table 3 Notional and measured U-values in winter and summer

Building element	Notional *U*-Values EN ISO 6946:1997 and EN 673	Estimated *U*-Values IR thermography	
		Winter	Summer
Wall	2.1	2.35	2.32
Roof	1.52	1.71	1.74
Glazing	2.7	3.03	3.01
Wall	1.39	1.56	1.58
Roof	3.33	3.74	3.75
Glazing	5.8	6.67	6.83
Wall	0.42	0.47	0.52
Roof	3.33	3.53	3.57
Glazing	1.6	1.94	1.89
Wall	1.39	1.39	1.38
Roof	0.56	0.89	0.93
Glazing	1.6	1.93	1.98
Wall	1.39	1.52	1.66
Roof	0.55	0.59	0.53
Glazing	2.7	2.94	2.99

A sensitivity analysis is made in this paper, the thermal emissivity and the reflective ambient temperature have a significant impact on the measured temperature.

The test is implemented indoor. Indoor measurement is better than test outdoor because the reflected temperature is more stable than external exposed outdoor, shown in the Fig.20, and the test can be conduct both in summer and winter.

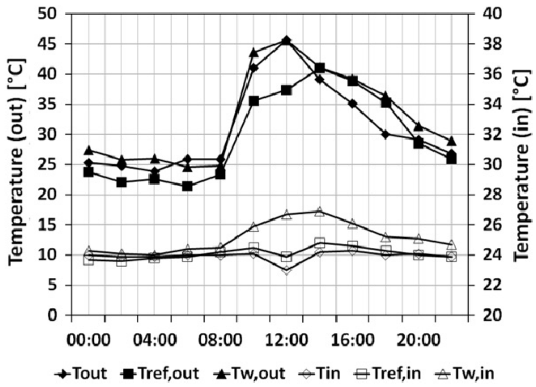


Fig.20 Ambient reflected, ambient and wall temperature – outdoor (primary axis –left) and ambient reflected, ambient and wall temperature – indoor (secondary axis– right).

It is believed in this paper that IR thermography results are more correct due to the fact that the method considers also radiation effects such as radiative temperature and the emittance of the actual surfaces, which are ignored by the other methods.

The application of infrared thermography in non-destructive evaluation has been introduced by Xavier Maldague [30-32], it has been widely employed for qualitative evaluations for building diagnostics, meanwhile, the IR thermography technology also has a large potentiality for the evaluation of the thermal characteristics of the building envelope. The advantages of IR thermography applying on building diagnostic are mainly:

1, Remote sensing, non-direct contact between the sensor and the object, non-instructive; convenient;

2, The ability of performing real-time surface measurements, speediness and safety of the process

3, Large monitoring capacity, the IR cameras are capable of monitoring the temperature at many different points within the scene simultaneously;

4, Results relatively easy to interpret (image format);

5, Global thermographic is taken so that anomalous thermal behaviour can be rejected (local thermal bridges, areas with high moisture and so on);

6, Fast inspection rate;

However, it also exists several disadvantages of IR camera used for building diagnostic:

1, Only limited to a certain depth of the target to subsurface defect detection;

2, The target's emissivity and the reflective temperature have to be known for the calibration and accurate results;

3, Current industry standard cameras have ±2% accuracy or worse in temperature measurement, or advanced models can reach up to ±1% accuracy, while either of them is not as accurate as contact methods.

4, The interpretation of the images requires considerable experience, intuition and judgment

The author in paper [33] made a review of state-of-the-art literature and research regarding the IR thermography for building diagnostic. Two approaches for thermographic inspections, namely passive and active thermography. The active one includes active pulsed thermography, active step-heating thermography, active lockin thermography and active vibro thermography, as shown in Fig 21[34].

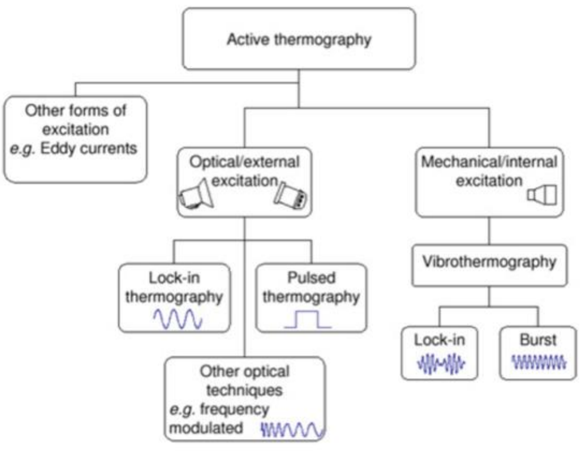


Fig 21 Approaches of active thermography

Fundamentals of IRT and the thermographic process for building diagnostics are presented in [33]. While IRT is a useful tool, there is still a great prospect for the development of more advanced and accurate approaches. Advantages and restrictions of IRT also have been described in the review.

Giuliano and Luca [35] implemented an in situ measurement for the U-value of the envelope element with IR camera.

The basic equipment consists of an infrared camera with a spectral sensitivity of 7.8 µm to 14 µm (infrared thermal wavelength range) in order to take infrared thermal images of the building and a cardboard box coated with aluminium for the measurement of the reflected apparent temperature (Figure 22).

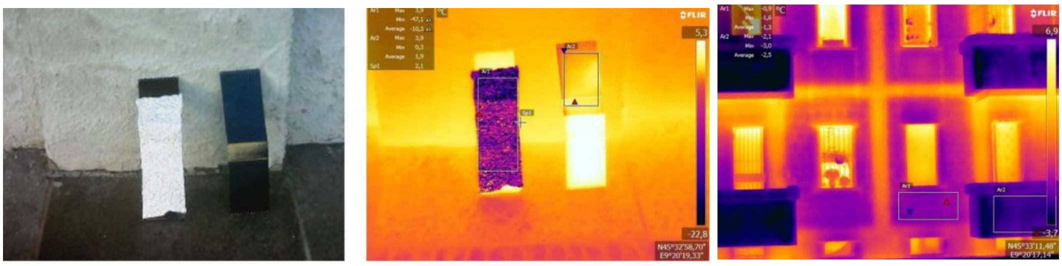


Fig 22 (left and middle) Visible image and thermogram of the cardboard box coated with aluminium; (right) Graphic definition of the areas of the wall to evaluate the average temperatures to be considered.

The results presented show that it is possible to use sufficiently reliable infrared diagnostics to make evaluations on energy performance (U-values) of existing buildings, as long as some appropriate precautions are taken. The proposed methodology does not allow the determination of a single value of transmittance but rather a range within which the value is likely to lie,

Larbi Youcef and Feuille [36] applied passive infrared thermography for the in situ quantitative diagnosis of insulated building walls. Estimated the different modelling unknown parameters and compared them. An experimental test bench was used in real conditions to examine a multi-layered wall, shown in Fig.23

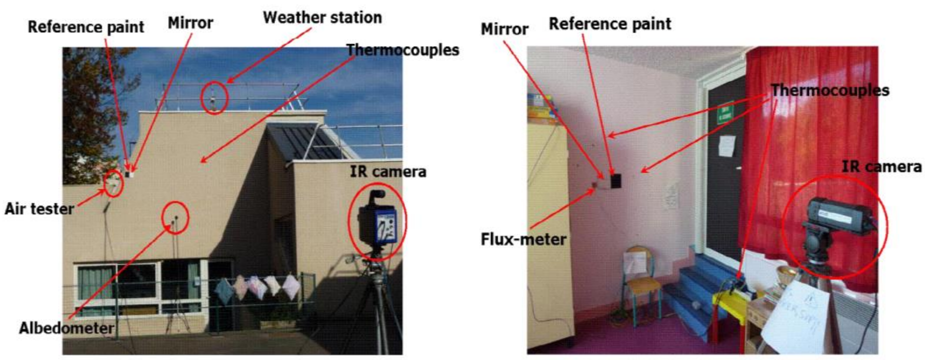


Fig.23 Instruments for inside and outside of wall in situ

The atmospheric parameters (temperature, pressure, relative humidity, vertical and horizontal solar heat flux) acquired form a weather station. The indoor and outdoor wall temperatures are measured by means of infrared cameras and thermocouples. The period of the test lasts about 8 days.

The measured parameters are associated with heat transfer numerical modelling (finite elements or finite differences) in order to estimate the insulation properties of the wall. A schematic view of the wall structure and heat exchanges is presented in Fig.24 the inverse problem is used in this model and the minimizing issue is solved by the least-squares sense or Levenberg-Marquardt algorithm. The unknown parameters are the exterior and interior heat exchange coefficient values, the absorption factor of the wall surface and the thermal conductivity (or thickness).

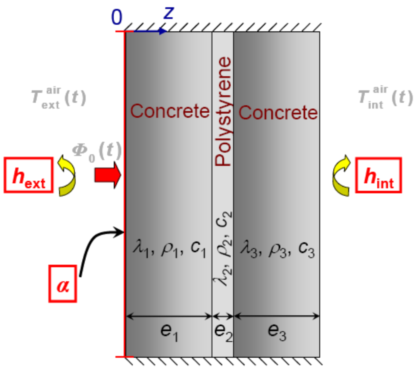


Fig.24 Scheme of wall structure and heat exchanges

The results firstly showed that it was possible to estimate either the thickness or the thermal conductivity of the insulating layer by analysing the measurement data obtained from this method.

It was also confirmed that the greatest sensitivity to parameters to estimate was obtained by considering the temperature gradient between interior and exterior wall surface temperature, instead of considering only interior or exterior surface temperatures. It is possible to obtain a very good estimated (lower than ± 0.5°C error with the measured temperature gradients).

The main limit of this measurement is that the structure of wall and thickness of each layer should be known, which is difficult for some old buildings.

In this study of Monchau et al [37], passive infrared thermography measurements on a multi-layered wall (PANISSE platform) are analysed. A set of parameters is measured continuously: outside and inside air temperatures and humidities, surface wall temperatures. A fluxmetric method is used to measure the thermal resistance of the wall. Infrared temperature measurements are compared after correction with numerical simulation results.

The differences between infrared camera and thermocouple temperature measurements for three regions of the façade are plotted in Fig 25 (left). There is a satisfactory agreement between thermocouple and infrared camera measurements excepted for some cloudy and sunny alternating short periods.

The exterior wall surface temperature measured by IR thermography is compared with the temperature calculated with modelling, as shown in Fig 25 (right). The unknown parameters which determine the thermal resistance of the wall in the finite modelling can be estimated based on this temperatures difference.

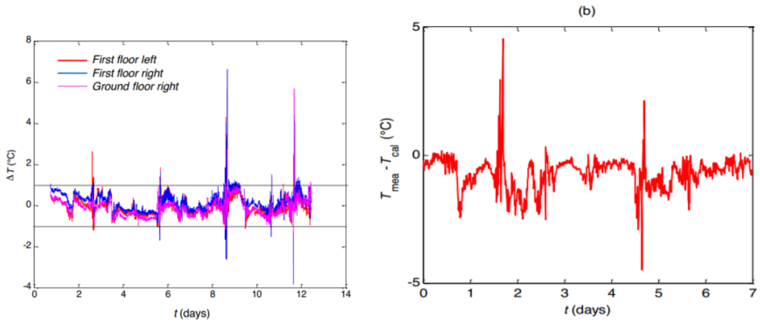


Fig 25 left: Temperature differences between thermocouple and corrected infrared measurements ;right: Measured and calculated temperatures differences Tmea-Tcal

Defects of void inside the wall are quantitative detected by Ch. Maierhofer and A. Brink [38] based on an active impulse thermography method, both experimental results and numerical simulations are presented in this paper.

The experimental set-up is shown in Fig.26 1 (left). It consists of a thermal heating unit, an infrared camera and a computer system which enables digital data recording in real time. The thermal heating unit contains three infrared radiators having a power of 2400 W. The specimen was built as demonstrated in Fig. 26 (right), having a size of 1.5x1.5x0.5 m^3 with eight voids inside.

Fig.26 (Left) Experimental set-up; (Right) Concrete test specimen with voids (units are in cm)

The numerical simulation is based on finite differences and the differential equation of Fourier. Simulations were performed with three different heating times (300, 900, and 2700 s) for voids in concrete having a size of 20·20·10 cm^3 at depths between 1 and 10 cm. Fig. 27 left shows the calculated difference curves at heating times of 2700s. The axis y is temperature difference between defect point and reference point. For the different temperature difference curves, t_{max} is plotted as a function of defect depth in the Fig. 27 right.

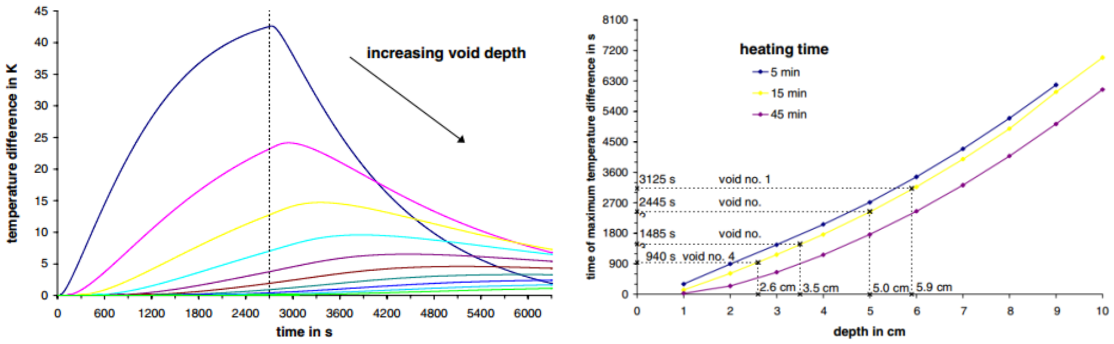


Fig 27 (left)Temperature difference as a function of time for polystyrene blocks calculated for defect depth from 1 to 10 cm and heating times of 2700 s; (right) time of maximum temperature difference for different depths.

P.D. Pastuszak [39, 40] applied the active infrared thermography as a viable non-destructive evaluation tool for testing of composite materials. The present study emphasized the ability of the pulsed thermography to detect, locate and evaluate of the delamination (artificial and developed during the tests) within GFRP cylindrical panels with different stacking sequences and subjected to an axial compression. The set-up is shown in Fig 28.

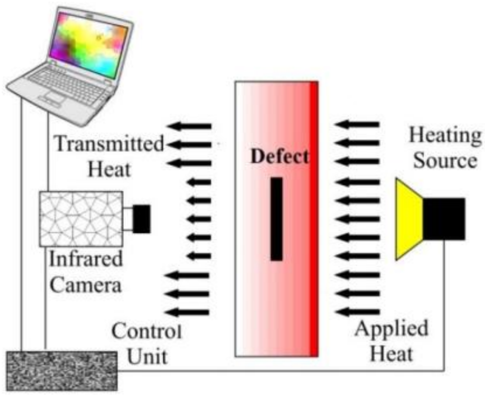
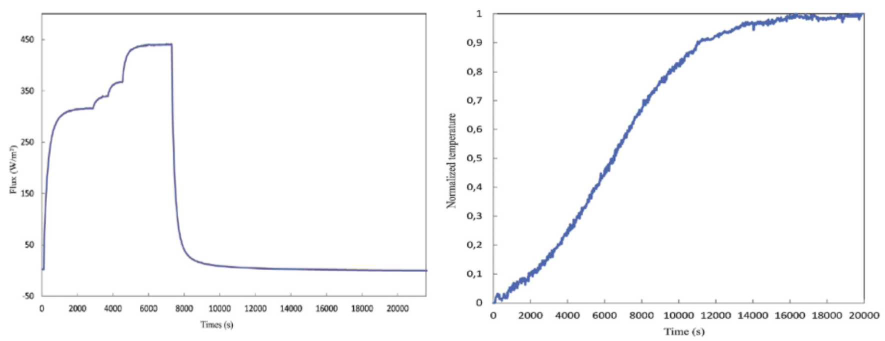


Fig 28 *Principle of the pulsed thermography*

A signal source is required to produce a heat flow on one side of the wall. The source can be lamp, heating element and natural signal, the signal can be step wise or pause.

Chaffar and Chauchois [41] installed a heating resistance outside the wall to produce the heat flux, as Fig. 29 shown.



a b

Fig. 29 a. The entering heat flux for in situ. b. normalized temperature for in situ.

In paper [42], Defer tested the building by studying the natural thermal signals. The values of flux density and surface temperature are recorded for 150h, as shown in Fig.30.

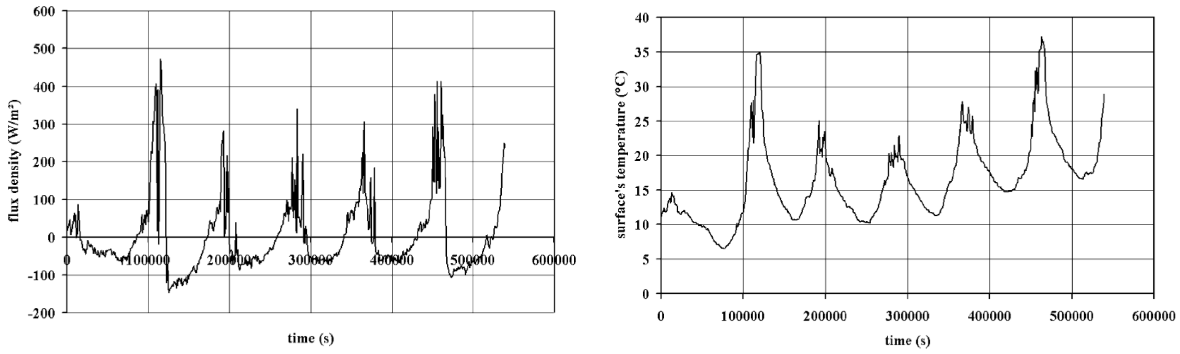


Fig. 30 a. Flux density of natural thermal signals b. temperature response of outer surface of wall

Here we make a simulation by Matlab as following: a step-wise heat signal applied on the wall, the temperature of rear face is simulated, as shown in Fig.31, T_{front} is the temperature of the entering heat flux surface of wall, and the T_{rear} is the response temperature of the opposite surface, q is the entering heat flux.

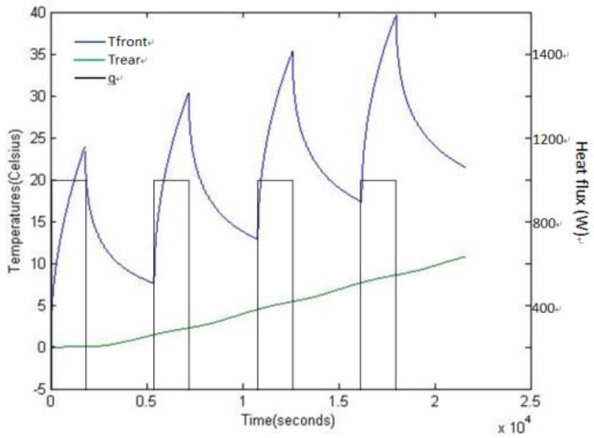


Fig. 31 The temperature-time response to the step-wise heat flux.

4.2.4 Transient/dynamic methodology

The dynamic methodology is establishing a dynamic temperature filed inside the wall, as described in section 3.2. The thermal parameters are evaluated by recording the temperature–time response. Normally a numerical model of heat transfer and inverse method are used in this methodology.

Derbal and Defer [43] applied a sandwiched structure for simultaneous determination of thermal conductivity and volumetric heat capacity of a construction material without any control of boundary conditions. The material to be characterized is placed between two layers of materials with known thermos-physical properties, shown in Fig 32. Thermocouple probes are placed at the different interfaces and record the variations in temperature when the whole multilayer is subjected to stimulation by heat resistance.

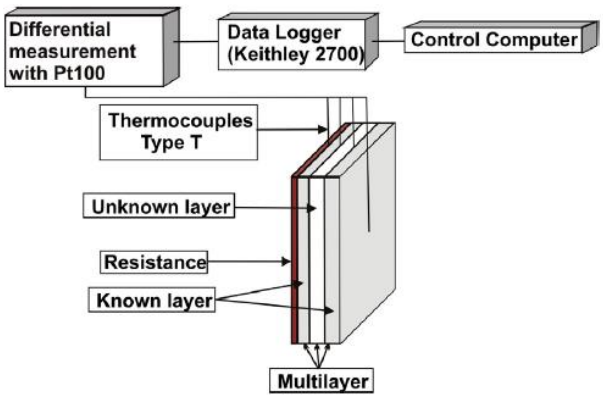


Fig. 32 Experimental set up

Four multilayer set ups have been tested. The four multilayers are pileups of respectively: 3 successive PVC layers, PVC/EPS/PVC layers, PVC/Plaster/PVC layers, PVC/Concrete/PVC. And it is also proposed to apply the method in situ.

Parameter estimation is completed with the LMA optimization algorithm and the inverse method, a finite difference theory is applied in the numerical model, as Fig. 33 shown.

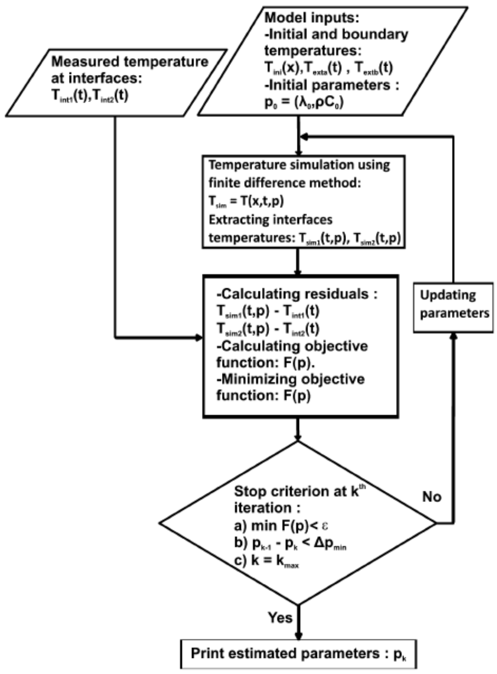


Fig.33 Parametric estimation by inverse method diagram

Chaffar and Chauchois [41] proposed a method to measure thermal characteristics of a wall in situ by applying a heat flux and studying the response in terms of the temperature recorded by infrared thermography on the opposite surface, shown in Fig. 34. The thermal conductivity and volumetric heat can be estimated with the signals of flux and temperatures of rear face by finite differences numerical model and inverse method.

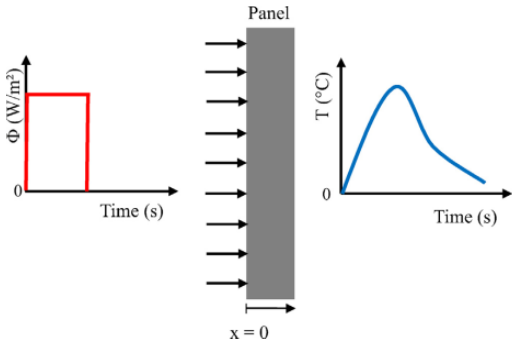


Fig. 34 Scheme of the measurement

The experimental design is illustrated in Fig.35, a reinforced concrete shell of 15cm thickness was studied in summer, a flat heating resistance and the insulating plate installed on the outside surface of the wall 10h before the trail in order to obtain a steady state. The fluxmeter are installed outside to test the heat flux. The IR camera records the rear face temperature, the heating time is 120min, and the data acquisition lasts 22h.

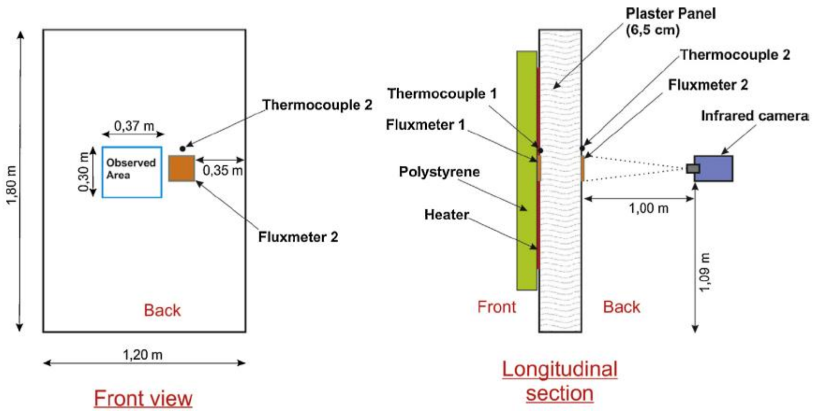


Fig. 35 Scheme of the experiment

The results in situ appear to be identified and satisfied relatively close to the reference values, this method is of validity. However, this method is connected and kind of inconvenient.

Wiecek and Poksiska [44] carried out a detection of architectural monuments with a lamp using for providing a step wise signal and IR camera measures the temperature at the same side, see in Fig 36. This idea and measurement are widely used for many other researches.

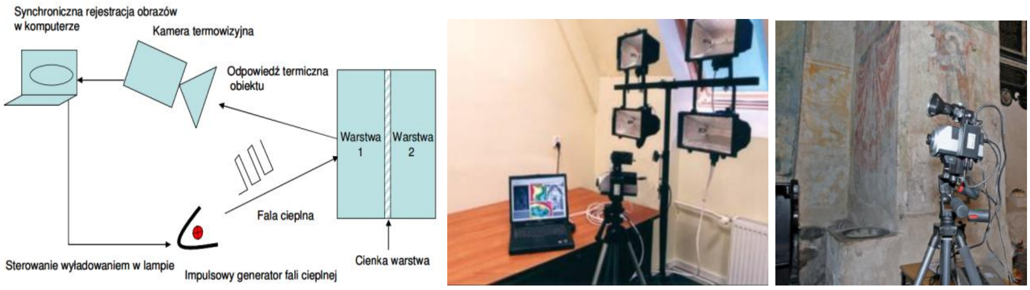


Fig 36 Experimental scheme and instruments

4.2.5 A knowledge base with combination of visible and infrared imagery

Ribaric and Marcetic [45] proposed another technique with infrared thermography: the flash method. The originality of the approach lies on the combination of visible and infrared imagery and the introduction of a base knowledge, the objective of merging a lot of data is to enable the rapid diagnosis (a few minutes depending on the author) of a building:

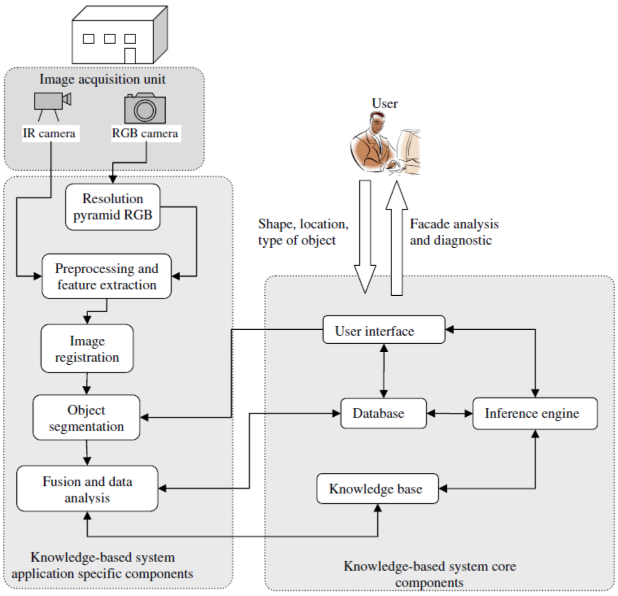


Fig.37 The architecture of the proposed knowledge-based system

The architecture of the system is represented by two main subsystems: application-specific and knowledge-based system-core components. The application-specific components are: image acquisition and pre-processing, the resolution pyramid, feature extraction, image registration and data fusion. The knowledge-based system core components are: the database, the knowledge base, the inference engine and the user-friendly interface. Basic knowledge creation contains mainly databases and sets of instructions (rules, syntax,), which are all being accessible through a user interface.

Experimentally, two images of the same wall are acquired simultaneously. The external temperature, the acquisition distance, a subjective estimate of the speed and direction of wind, the power and the exposure to sunlight, are also identified.

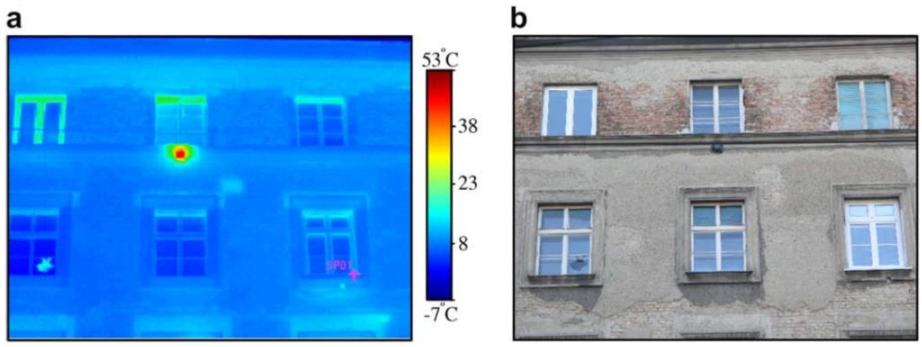


*Fig.38 (a)IR image (320*240 pixels); (b)interpolated RGB image (320*240 pixels)*

The visible and infrared sensors are with different sizes (number of pixels), so firstly a digital processing is performed to reduce the size of the visible image to be the same as in the infrared. Subsequently, the conventional image processing (filters, thresholding, edge detection, segmentation…) is applied in order to merge the two types of information:

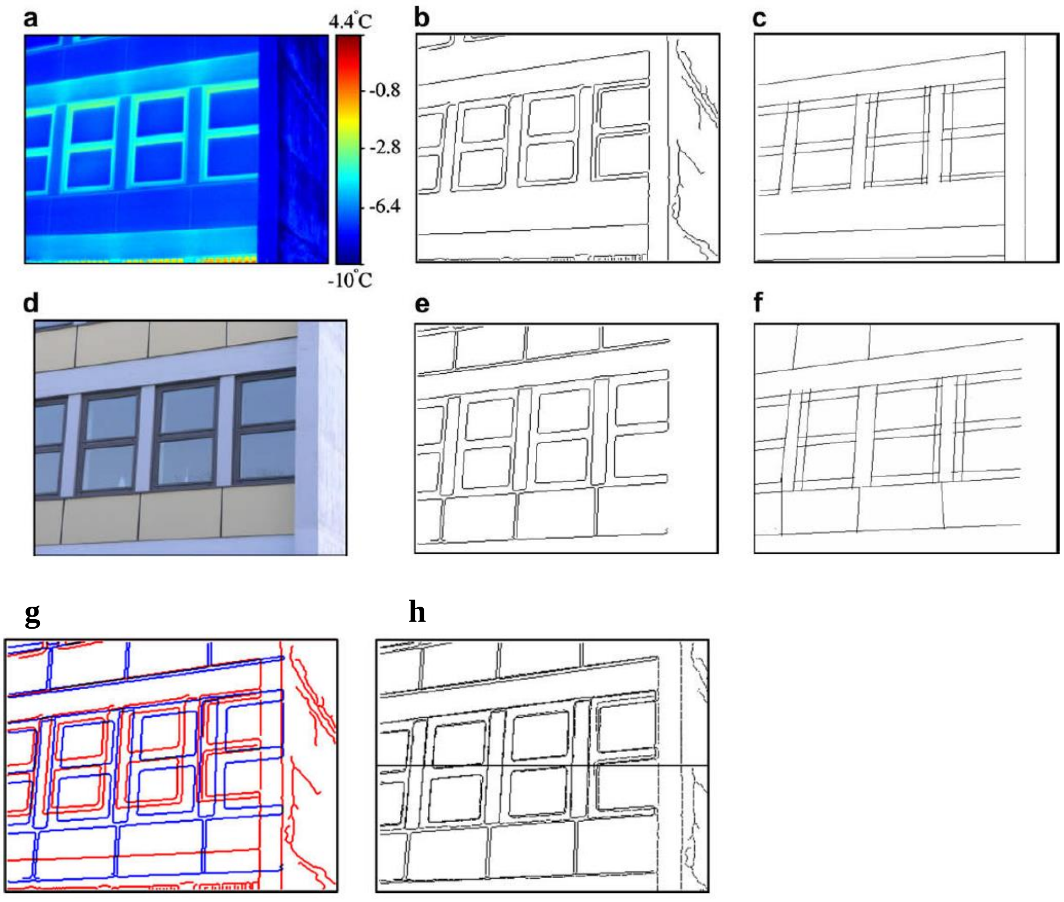


Fig.39 Process of pre-processing and feature extraction (a) original IR image; (b) IR edge image obtained by applying the Canny operator; (c) IR line segment image (d) interpolated RGB image (e)RGBedge image (f) RGB line segment image; and experimental results of image registration method (g) oberlap of edge images before registration(red edge elements are from the IR image and the blue edge elements are from the visual RGB image); (h) registered IR to RGB edge image

When the visible and infrared information is merged, it can identify various elements (doors, windows…) and make up the resulting image, which based on a segmentation operation. Thereafter, the operator can recognize and mark the different openings and singularities on visual image through a conventional graphical user interface. This information is directly merged with the infrared image through correspondence treatments visible/infrared established in the previous steps:

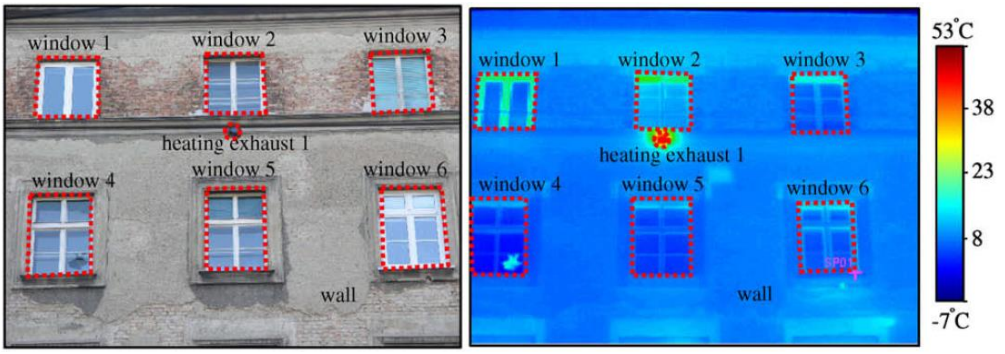


Fig.40 RGB visual image with marked and labelled structural components after the object segmentation (left) and corresponding IR image segmentation (right)

After the combination, the author deals with the measurement data with the knowledge base to get the rule number. For instance, Fig.41 shows the relationship between outdoor-to-indoor temperature difference and its values.

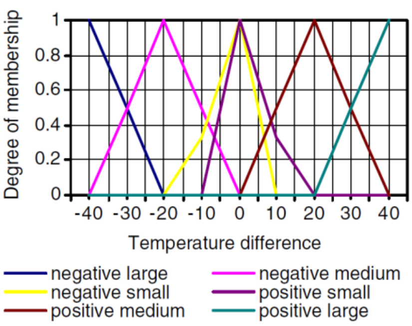


Fig 41 relationship between outdoor-to-indoor temperature difference and its values

The authors state that this operation is fast, intuitive and does not require training for the operator. Further information on the structure of the wall can be added and indicated by means of the database.

In this experiment, the available information is a visible image, a thermal image, knowledge of the structure and a good idea of vesting conditions. These data can be exploited to extract profiles of temperatures or histograms, which are for statistical treatment and also estimating sets of parameters relevant with the diagnosis of a building (heat losses, variations of temperature between the inside and outside …). Finally, it becomes possible to assign coefficients of thermal performance and analyse specific to each building. The authors indicate that this approach allows a non-destructive fast and intuitive diagnosis method and taking into a wide range of parameters.

The authors also plan to implement the automatic segmentation of visual and infrared images in order to find all the structural components without user intervention. The system will be tested on a large visual and infrared image pair database, collected over a long period of time and in different environmental conditions.

However, this methodology is not accuracy enough to quantify thermal parameters of wall.

4.2.6 Terahertz radiation method

Terahertz (THz) radiation is an electromagnetic radiation with frequency range from 0.1 (or 0.3) to 10 THz (wavelength from 3mm to 3um) [46], which is lying between the microwave and infrared regions of the spectrum, as shown in Fig.42.

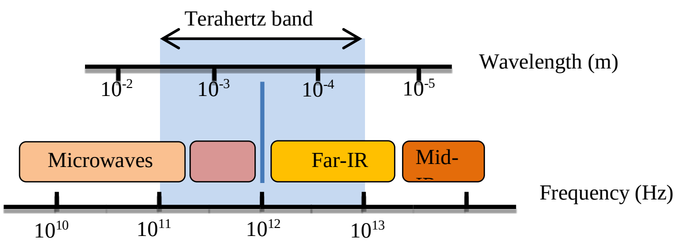


Fig.42 THz band in electromagnetic spectrum

More and more attentions are paid to the study of THz technology in the last two decades due to its a few remarkable properties, and it has been widely applied to the many potentialities in fields of safety inspection, nondestructive evaluation, atmospheric physics, biology, military applications, ecology and medicine [47]. One of the key points of development now is non-destructive testing (NDT). THz can offer a non-invasive, non-contact, non-ionizing method of assessing, which could overcome some of the short-comings of other non-destructive techniques such as x-rays, ultrasound and thermographic techniques. On one hand, THz radiation could have the unique ability to penetrate composites and identify defects such as voids, delamination, mechanical damage, or heat damage [48-50]. On the other hand, THz can be used to analyse structure of materials, for example insulating polymer foams, and characterize properties of materials [51-54].

The advantages for THz NDT applied on building diagnosis are: 1. THz radiation is with a high transparency for non-polarized, it has a rapidly penetration in insulating materials. 2. THz radiation causes no safety issues for operators or walls. 3. The absorbance coefficient of THz wave against water is highly obvious. The amount of water and degradation of wood or concrete due to water diffusion can be evaluated on the basis of high absorption properties of THz wave. Based on this property, water can be used as the enhancement for finding small cracks in concrete. Moreover, THz NDT technology can also be combined with other NDT methods to improve the accuracy and efficiency [13]. The best accuracy and reliability of results is still achieved with a combination of various NDT methods. Many researches have been made on diagnostic building envelop with Terahertz radiation [53-56].

In reference [53], the authors proposed that Terahertz (THz) spectroscopy and imaging can be used to analyse different types of thermal building insulation materials. The absorption coefficients of polymer foams are calculated, showing an inverse relationship with thermal conductivity. In addition, manufacturing imperfections and internal structures within the foams are clearly visualized with THz amplitude imaging. THz has a big potential to detect the thermal performance of wall as a non-destructive method.

Fig. 43a shows the absorption coefficients of the most used thermal insulating polymer foams in the frequency range between 1.35 THz and 5.0 THz. In Fig. 1b we present the relationship between the thermal conductivity and THz absorption coefficient of polymer foams. One can notice that the thermal conductivity is inversely proportional to the absorption coefficient given at all three selected THz frequencies. Fig. 1b also shows that the THz absorption coefficient varies the most for Bakelite foam which has the highest thermal conductivity, whereas for EPS foam the value of αis almost unchanged for all three selected THz frequencies.

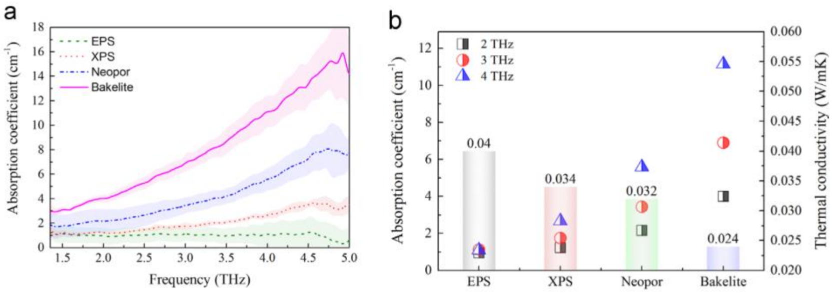


Fig 43 (a)Absorption coefficient of a variety of thermal insulating polymer foams in the frequency range between 1.35 THz and 5.0 THz; (b) relation between absorption coefficient at selected THz frequencies and the thermal conductivity of polymer foams;

Generally, Terahertz spectroscopy is studied in both pulsed modes and continuous wave (CW), and mainly fall into two categories: pulsed Terahertz domain spectroscopy (THz-TDS) and CW THz imaging system [57]. CW THz method affords a more compact, simple, fast and relatively low-cost system since it does not require a pump probe system and it does not require a time delay scan. The CW THz method presented in this paper only yields intensity data and does not provide any depth (frequency-domain or time-domain information about the subject) when a fixed-frequency source and a single detector are used.

Based on the measured intensity input and output data, the absorbance of building material can be calculated according to Beer-Lambert Law equation (1).

$$A = -log10(\frac{I_t}{I_0}) = kL \qquad (30)$$

Where I_0 is the intensity of input signal; I_t is the intensity of output signal; A is the absorption; k is absorption coefficient; L is the optical path length (cm).

For multilayer samples, the overall absorption is the sum of absorption of each layer, Eq (2).

$$A = \mathrm{A1} + \mathrm{A2} + \cdots + \mathrm{An} = -log10\left(\frac{It}{I_0}\right) = k1L1 + k2L2 + \cdots + knLn \qquad (31)$$

According to equation (2), the order of material layers makes no influence on the overall absorption.

If materials of building can be characterized by the absorption coefficient of a fixed THz, especially for heavy materials, such as concrete, that will be a rapid way for thermal detecting of building wall. THz radiation has a large potential to be used as a NDT tool.

4.2.7 Microwave Subsurface Imaging Technology

This reference [58] present a microwave subsurface imaging technology using antenna arrays for detecting invisible damage inside concrete and software focusing was developed in this. Numerical simulation and experiments were implemented in this study. Four conclusions were obtained according to the simulation and experiment analysis:

1. The imaging reconstruction algorithm using the bifocusing numerical operator developed in this study resulted in uniformed focusing intensity. A resolution in the order of the wavelength in the dielectric medium (concrete in this study) was achieved by focusing both the transmitting and receiving arrays;

2. The prototype slot antenna array consisting of 838 transmitting and 838 receiving antennas designed and fabricated in this study achieved the goal of high radiation and low mutual coupling;

3. The microwave imaging system consisting of the antenna array integrated with the imaging reconstruction algorithm is capable of detecting air voids and steel inside concrete; and 4. The effectiveness of simulation using CST Microwave Studio was experimentally verified. The simulation demonstrated that the image resolution can be improved by increasing the illuminating frequency.

4.2.8 Ultrasound method

The termultrasonicsis generally used to indicate the study and application of high-frequency sound waves (ultrasound), which are above the human hearing range (20 kHz). Recently, ultrasonic waves were exploited for non-destructive evaluation [59-63].

The ultrasonic method is based on the property of sound waves to travel inside solid materials. A beam of ultrasonic energy is launched inside the material by exciting, with a high-voltage pulse, a piezo-electric crystal contained in a transducer in contact with the material; such transducer is called transmitter probe. Three basic types of stress waves are created: longitudinal, shear and surface waves. Generally, the propagation is the fastest for longitudinal waves and the slowest for surface waves. A local variation of material characteristics (acoustical impedance) affects the energy transmission; thus, the amount of energy that arrives at the receiver probe gives information about the material, or structure, characteristics (density, stiffness, porosity).

Measurements can be performed in three modes: direct, semi-direct, and indirect transmission. Details were described in reference [59]. Measurements were carried out by Meola and Maio [59].

4.2.9 Electric-type geophysical methods

Electric-type geophysical methods were introduced in the reference [59]. The geophysical study basically consists of application and integration of electric-type geophysical methods: self-potential and geoelectrics. Basic principles and experimental tests were presented in paper [59].

5 Numerical simulation model of heat transfer in building walls

5.1 The average methodology

The average methods applied to the thermal analysis of building in situ allow the application of steady-state equations. The capabilities and limitations of the linear regression method based in averages were studied for the analysis of wall in situ. However these methods are valid provided that some hypotheses are accomplished, particularly the following:

1, The thermal properties of the material and the heat transfer coefficients are constant over the range of temperature fluctuations during the test.

2, The change of amount of heat stored in the element is negligible when compared to the amount of heat going through the element

The authors [64] make the identification of the optimum minimum integration period and identification of the maximum accuracy obtained using average methods amongst the considered options.

Reference [65] reports the application of multiple regression using daily averages to the energy performance analysis of 10 single family houses located different European countries.

Reference [66] proposed a pseudodynamic analysis tool based in multiple regression using daily averages to estimate the energy performance parameters of dwellings

5.2 Finite differences method based on heat equation

With heat transfer in one dimension, as shown in the Fig.44, the author [43] discretizes the spatial field by the axial pitch.

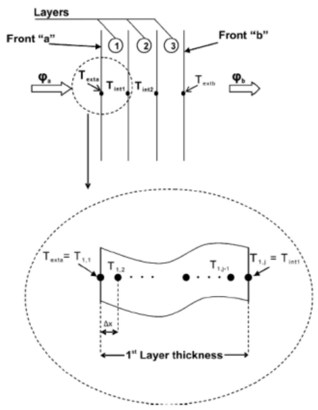


Fig. 44 Configuration of the tested multilayer and detailed discretization

Based on the heat transfer equation:

$$\frac{\partial T(x,t)}{\partial t} = a \cdot \frac{\partial^2 T(x,t)}{\partial x^2} \quad (32)$$

The one dimensional finite differences formulation is:

$$\left.\frac{\partial^2 T}{\partial x^2}\right|_{i,n+1} = \frac{T_{i-1}^{n+1} - 2T_i^{n+1} + T_{i+1}^{n+1}}{(\Delta x)^2} + 0[(\Delta x)^2] \quad (33)$$

Where $T(x,t) = T(i\Delta x, n\Delta t) = T_i^n$

Many researches have been made based on the numerical simulation of finite differences and the differential equation of Fourier [41, 38].

5.3 Autoregressive models with exogenous (ARX)

Autoregressive models with exogenous (ARX) are widely used for parameters identification of walls. The authors [67] use measured data and an ARX model for identifying the thermal parameters of wall under real weather conditions. The physical parameters are the U-value, the dynamic solar energy transmittance and the effective heat capacity. The ARX model is obtained by deduction from a thermal network, Fig 45. The novelty of this model is to recover the physical parameters without using the final value theorem.

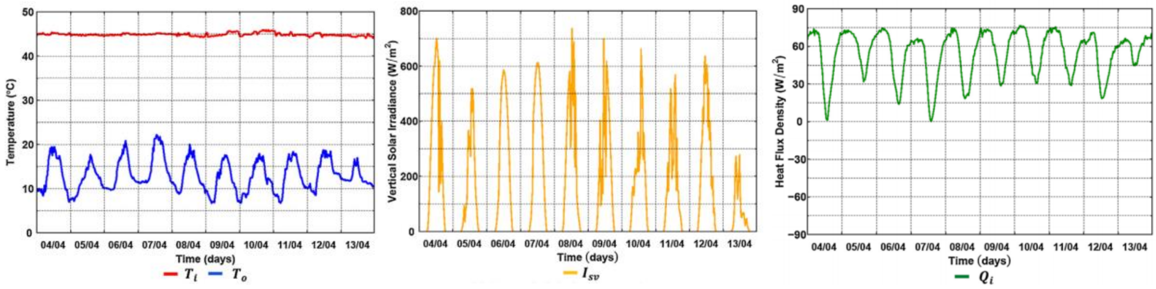


Fig 45 Measured data (left) indoor and outdoor temperature; (middle) vertical global solar irradiance; (right) inside heat flux density.

Thermal network with 3 nodes (shown in Fig 46) and state-space model are used for deducting heat transfer numerical model. Where R_k is thermal resistances, q_k is heat rates, b_k is temperatures sources, and nodes is to connect thermal capacities and heat sources.

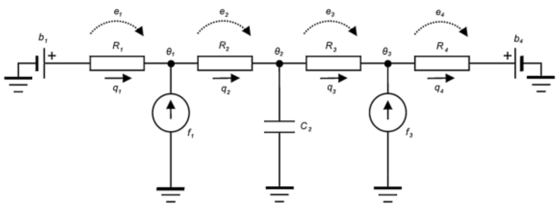


Fig 46 Thermal network using Ghiaus notation [55]: wall represented by 3 nodes

The U-value and the effective heat capacity of the wall can be recovered, the structure of the state space model and the chain of transformations should be known.

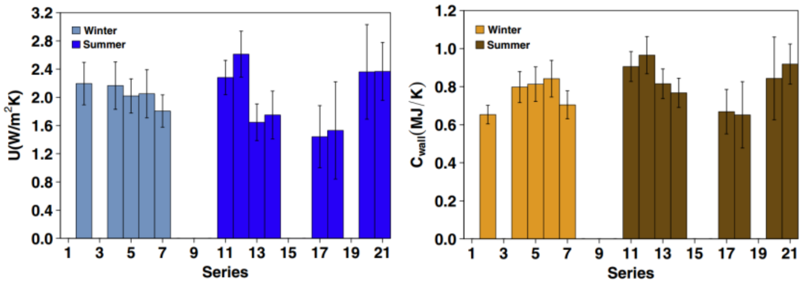


Fig 47 *Results of U-value and Effective heat capacity*

5.4 Dynamic nonlinear models

Recent studies have shown the flexibility and usefulness of dynamic nonlinear models, particularly for dealing with problems related to warm sunny weather [69]. Nonlinear models have been successfully applied to such cases as ventilated photovoltaic modules [70], solar chimneys and also for taking into account the boundary conditions in a test cell in sunny weather [71]. Models including time-dependent parameters have also been applied successfully for finding the characteristic parameters of a wall before and after energy refurbishment [72].

An experimental [73] test was carried out in a hottemperature climate for nine months. This study aims at proposing a dynamic method improving the regression averages method for estimation of parameters which describe the thermal behaviour of the wall. One-state and two-state models were used to analyse. Solar irradiance and long-wave radiation balance terms are added in the heat balance equation besides modelling of wind speed effect to achieve a complete description of the relevant phenomena which affect the thermal dynamics of the wall. The method is applied using different frequency data samples looking for the best to study this wall. The U value obtained characterising the wall is consistent with the one given by the regression averages method.

5.5 Inverse method

Fig. 48 shows the general principle of measurement for solid thermal characterization with inverse theory.

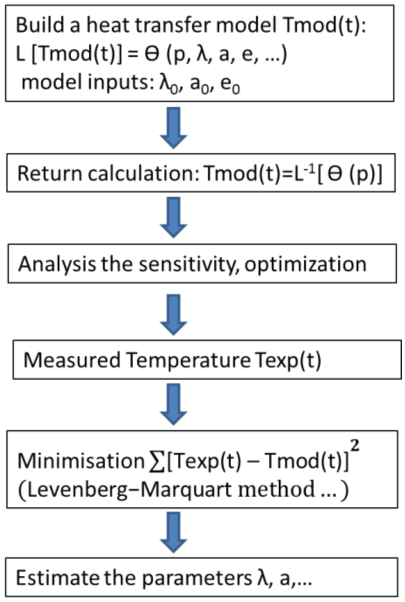


Fig.48 Principles of measurement for thermal parameters with inverse method.

The main idea of this method is to obtain the value of Measured Temperature Texp(t) and Temperature output of model Tmod(t)=f(q, λ, a, e…) to estimate λ and a by using inverse method. The unknown parameters can be obtained by minimizing the difference between the simulation results and experimental results. The minimizing issue is solved by the least-squares sense or Levenberg-Marquardt algorithm.

5.6 Thermal quadrupoles

For transient heat conduction in homogeneous and isotropic solid materials, the heat equation is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{\lambda} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{34}$$

And for 1D heat transfer without internal heat source in a one-layer slab, as presented in Fig. 49 (left), the heat equation is:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a}\frac{\partial T}{\partial t}\left(T = T_0 \; for \; t = 0\right) \tag{35}$$

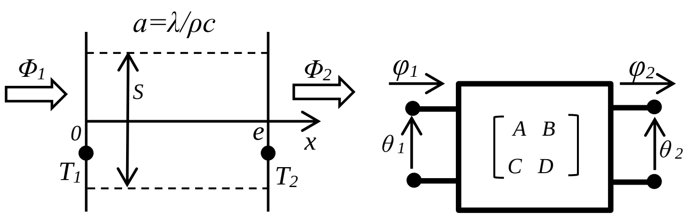


Fig 49 (left) Geometry for a 1D transient transfer in one-layer slab. (right) Matrix representation for a 1D transient transfer in one-layer slab

The heat flux at any location x inside the slab is defined for any cross section S as:

$$\Phi = -\lambda S \frac{\partial T}{\partial x} \tag{36}$$

Apply Laplace transform to both temperature and flux, $\theta(x,p)=L(T(x,t))$; $\varphi(x,p)=L(\Phi\ (x,t))$, and consider the Laplace transforms θ_1 and θ_2 as the front(x=0) and rear(x=e) face temperatures, respectively, φ_1 and φ_2 as the corresponding heat fluxes, shown in Fig.38 (right) [74,75].

$$\begin{bmatrix}\theta_1\\ \varphi_1\end{bmatrix} = \begin{bmatrix}A & B\\ C & D\end{bmatrix}\begin{bmatrix}\theta_2\\ \varphi_2\end{bmatrix} = M\begin{bmatrix}\theta_2\\ \varphi_2\end{bmatrix} \tag{37}$$

Where $A = D = \cosh\,(e\sqrt{p/a})\ ; B = \dfrac{1}{\lambda\sqrt{p/a}}\sinh(e\sqrt{p/a})\ ; C = \lambda\sqrt{p/a}\,\sinh(e\sqrt{p/a})$;

The matrix M with four coefficients A, B, C, D completely characterizes the system.

For multilayer wall, the global transfer matrix M_{eq} can be obtained by the matrices from each layer of medium M_1, M_2...M_n and two transfer coefficients h_i, h_o for inside and outside surface of the wall.

$$\begin{bmatrix}\theta_1\\ \varphi_1\end{bmatrix} = H_{ins}\cdot M_1\cdot M_2 \ldots\cdot M_n\cdot H_{out}\begin{bmatrix}\theta_{n+1}\\ \varphi_{n+1}\end{bmatrix} = M_{eq}\begin{bmatrix}\theta_{n+1}\\ \varphi_{n+1}\end{bmatrix}$$

(38)

$$H_i = \begin{bmatrix}1 & 1/h_i\\ 0 & 1\end{bmatrix}, H_o = \begin{bmatrix}1 & 1/h_o\\ 0 & 1\end{bmatrix}$$

T. WU [76] has applied the model above to estimate the contact effusivity and diffusivity on building walls.

Fig.50 shows the scheme of set up in situ. The signal is generated by the thermal flux. Fluxes and temperatures of both the inner and outer surfaces are available by integrated heat flowmeters.

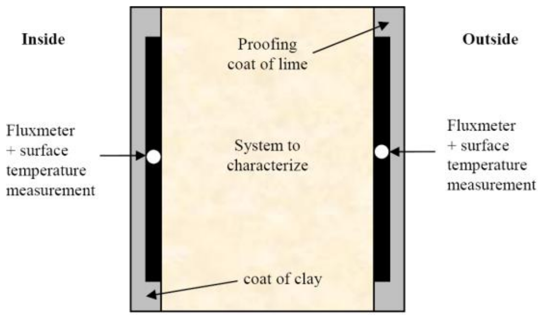


Fig.50 Scheme of instruments

The author improved the quadrupoles numerical model as:

$$\Sigma\phi(f) = H_1\,(f)\,\Delta\theta \qquad \Delta\phi(f) = H_3\,(f)\,\Sigma\theta\,(f) \tag{39}$$

Where H_1 and H_3 are defined from thermal parameters. The sensitivity was studied and confirmed that the function H_1 is well-suited to estimating the resistance while H3 can be used to identify the capacity.

Fig.40 presents the compare of modulus of the H_1 function between theoretical data and experimental results, the experimental value match very well with the theoretical value, where H_1 function is related to thermal resistance of wall.

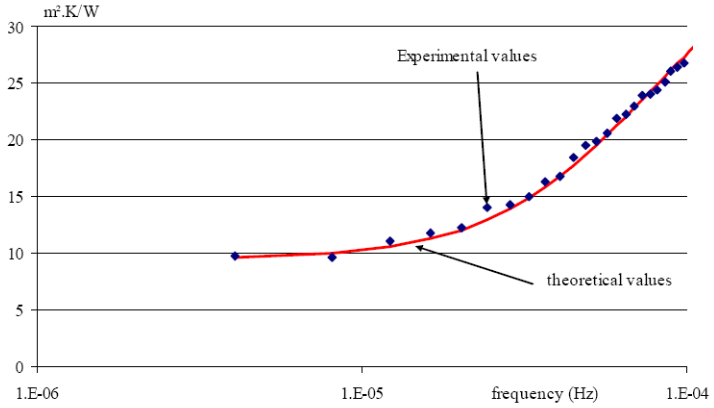


Fig.40 Theoretical and experimental modulus of the H1 function

6 Conclusion

This report firstly introduced the basic methods of measuring thermal properties, including steady state methods and transient methods, most of them are implemented in the lab and already became the standards. In order to apply methods for measuring thermal parameters of building envelop in situ, many improved measurement have been proposed.

The study on measuring thermal parameters of building envelop in situ is not too much, and still now there is no standard or wildly used measurement for the building in situ, thus this research is of great importance.

The wall is usually with a large thickness which makes it a long time to detect, and with insulation materials which is semi-transparent for some measurements (flash method). Some apparatus are difficult to be implemented for the high buildings.

For the steady state method, it is not easy to keep the experimental conditions constant, and obtaining the results from the time average data is also not precise enough, this method usually takes a very long time. The transient technology is preferred as the in situ measurement. The thermal parameters can be estimated by the temperature-time response and heat flux through the wall.

The application of IR thermography makes the measurement non-destructive, non-contact and fast, more information can be obtained during the detecting. As the signal source, the natural signals are convenient but need a long time to measure, while the heating element takes a shorter time but is inconvenient for high buildings.

A precise numerical model and correctly applying the inverse method is essential to estimate the thermal parameters. Sensitivity should be analysed in each measurement to ensure the accuracy of the estimation.

THz radiation has a potential to detect the thermal performance of building walls.

The trend of measurement for building in situ is non-destructive, precise, fast, simple, less-cost, less instruments. We can focused on a principle that a signal source produce a heat flow on one side of the wall and measuring the temperature variation on the opposite of the wall by non-contact measurement using an infrared camera. From the heat flux and measured temperature of the rear face, the thermal properties of the wall can be estimated by inverse method based on a numerical modelling of heat transfer in the wall. The identification of the thermal conductivity and thermal diffusivity of the wall will be achieved by optimizing the grouping of parameters that minimizes the difference between the measured normalized temperature and the simulated normalized temperature. At the same time, this method can be combined with THz radiation method to provide the added information of thermal performance of building envelops.

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