Measuring Building indoor temperature for energy performance assessment

Definitions proposal and uncertainties

Antoine CAUCHETEUX[1,2]

[1] Cerema, DLRCA 23 avenue de l'Amiral Chauvin BP 20069 49136 Les Ponts de Cé cedex, France

[2] LARIS, EA7315 université d'Angers, 62 avenue notre dame du Lac 49000 Angers, France

Abstract

In the physical framework, the problem of temperature definition is set. For the transmission heat exchange towards the external environment (or adjacent zones or ground), conduction and convection have to be considered. The definition of the (indoor) temperature depends on the convection phenomenon, while the conduction relates on surface temperature. In the handbook of heat transfer, it is define as a "characteristic fluid temperature". It could be "the temperature of the fluid far away from the surface, often identified as $T_{infinite}$". But in a building, lot of phenomenon disrupt the only convection transfer.

On the other hand, a pure statistical approach for average building temperature assessment from measurements is presented. The systematic uncertainty can be assessed by sampling theory. Many hypothesis should be made such as the way the sampling is made: with or without statistical stratification.

Two cases studies have been explored: a commercial occupied building in Angers and an unoccupied single house in Loughborough. It shows that the uncertainty from physical definition of the temperature and the sampling uncertainty have about the same order.

Keywords: building temperature measurement, uncertainty, building monitoring.

1 INTRODUCTION AND OBJECTIVES

In order to assess the Heat Transfer Coefficient (HTC) of a building, the physical framework describes heat flows occurring when considering heat balance of a building. Many of them depend on the indoor temperature: heat exchange with outdoor, ground, neighbouring buildings or ventilation. The problem that is discussed in this paper deals with the definition of the indoor temperature and its measurement.

In this paper we focus the problem to heat exchange through building fabric. The definition of the HTC is then:

$$HTC = \sum U_i A_i + \sum \psi_i L_i + \sum X_i \qquad (1)$$

where U_i are the heat transfer coefficients corresponding to the homogeneous surfaces A_i of the building. ψ_i, L_i, and X_i correspond to the thermal bridges. In the French regulation (RT 2005), a multiplication factor (between 0 and 1) could affect U_i in the case of wall in contact with a neighbouring building, an unheated room, … It gives:

$$HTC = \sum b_i U_i A_i + \sum b_i \psi_i L_i + \sum b_i X_i \qquad (2)$$

where $b_i = 1$ for each wall in contact with outdoor.

Most of the methods developed in the annex take into account the dwelling in its entirety, considering "the total volume V" of the dwelling – the volume protected by the HTC. In most of them, considering the heat flow by transmission (ϕ_{tr}), we'd like to define an equivalent temperature $T_{in\text{-}eq\text{-}building}$ to write:

$$HTC * \left(T_{in-eq-building} - T_{eq-out}\right) = \int U_{dS} * \left(T_{dS\,in} - T_{dS-out}\right) dS \qquad (2)$$

where $T_{in\text{-}eq\text{-}building}$ is the building or dwelling equivalent temperature, dS is a subsurface of envelop, U_{dS} is the transmission coefficient of dS (including convection), T_{dS} is the indoor characteristic fluid temperature and $T_{dS\text{-}out}$ is the outdoor characteristic temperature. If dS is small enough, it can be considered that the thermal bridges are included in the right hand term (even if it's not really true, it doesn't change the problem for temperature definition and measurement).

Assuming that T_{out} is constant (that have also to be discussed), it leads to

$$HTC * \left(T_{in-eq-building}\right) = \int U_{dS} * (T_{dS\,in}\,)\,dS \qquad (3)$$

Note that here the radiative exchanges are neglected. Indeed, first, in the indoor environment, it is assumed that the differences between wall temperatures are negligible for radiative exchange with respect to convection exchanges. Secondly, the air temperature definition is not affected by radiative exchange that could be treated in a second time.

Then the questions discussed are:

- Which temperature has to be taken into account and measured (for HTC identification)?
- What are the error made by simplification in the method (number of nodes)
- What are the error made by measurement regarding to the temperature definition

2 Physical approach

2.1 Back to fundamentals

For the transmission heat exchange through building fabric, conduction and convection have to be considered. The definition of the (indoor) temperature depends on the convection phenomenon, while the conduction depends on surface temperature. In the "handbook of heat transfer" (Rohsenow et al 1998), the indoor air temperature is defined as a "characteristic fluid temperature". It could be "the temperature of the fluid far away from the surface, often identified as $T_{infinite}$.

In a building, many phenomenon disrupt the "only" convection phenomenon and then the "fluid" temperature. Then the "characteristic fluid temperature" has to be the temperature of the fluid far away enough from the surface but still realistic for convection exchanges. The question is true for all subsurface dS of the building envelop. Buildings are made of many rooms, the first obvious conclusion is that characteristic air temperature of heat exchange has to be taken in the room where the wall is.

Then equation 3 can be write:

$$U_{eq.building} * S_{building} * \left(T_{in-eq-building}\right) = \sum_i^{room} U_i S_i T_{eq-i} \qquad (4)$$

where HTC = $U_{eq.building} * S_{building}$ and

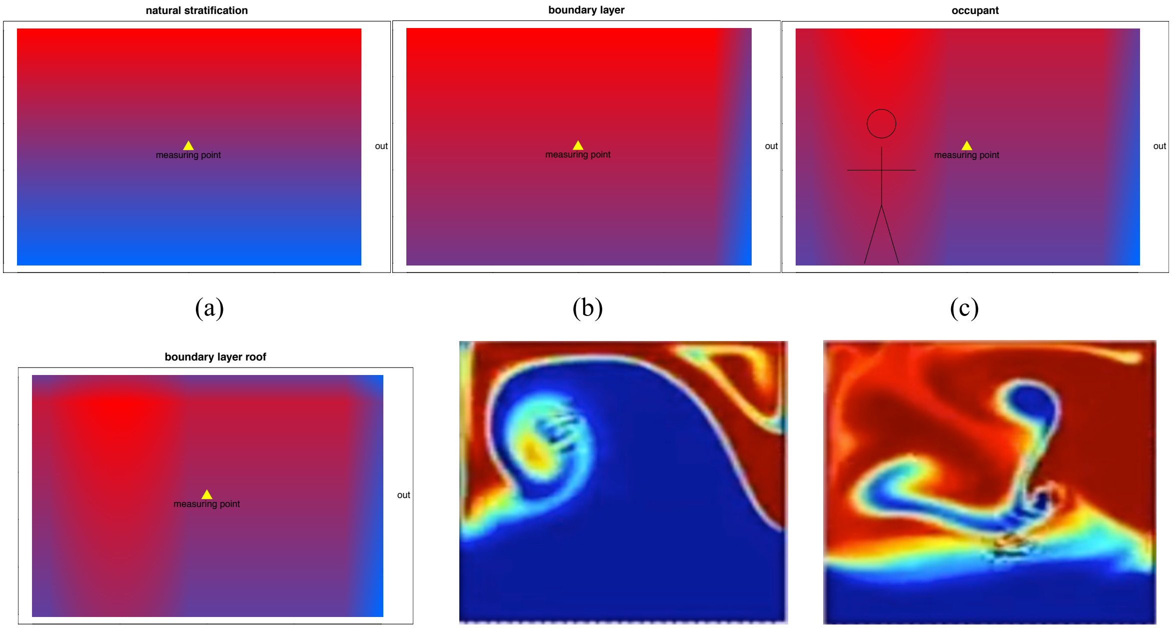
$$U_i * S_i * \left(T_{eq-i}\right) = \int_{room} U_{dS} * (T_{dS\,in}\,)dS \qquad (5)$$

Let's now consider phenomenon that disrupt room temperature repartition under convection:

- Natural stratification: in the absence of forced air movements, warm air rises, then air temperature is higher with height. (Fig 1-a).
- Heat exchange: along the wall where heat exchange occurs, there's a boundary layer, where temperature is lower (if temperature on the other side of the wall is lower). (Fig 1-b). The same phenomenon occurs on the ceiling if in touch with the roof (fig 1-d).
- Occupant can create heat island everywhere in the room. (Fig 1-c).
- When heating occurs, there could be a heat island in the room. For example, in Loughborough case, heaters stand in front of windows, the boundary layer could partially warm. (Fig 1-e,f) and all temperature distribution in the room could be disrupt. It mainly increases the stratification effect.

Now assuming that fabrics are homogeneous enough, we can write:

$$\int_{room} U_{dS} * (T_{dS\,in}\,)dS = U_{wall} * \int T_{dS\,in\,wall} dS + U_{windows} * \int T_{dS\,in\,windows} dS + U_{ceilling} * \int T_{dS\,in\,ceiling} dS + U_{floor} * \int T_{dS\,in\,floor} dS \qquad (7)$$



(a) (b) (c)

(d) (e) (f)

Figure 1 : air temperatures repartition in a room under many physical phenomenon (e and f from Youtube2018)

2.2 Cases study

2.2.1 Examples of temperature variability in a room

In order to observe temperature dispersion in a building, a building (A), located in Angers, has been monitored. It is a tertiary sector building built in 2011/2012 [caucheteux 2017]. One office and a meeting room have been monitored with about 20 sensors during 2 months (January and February 2015).

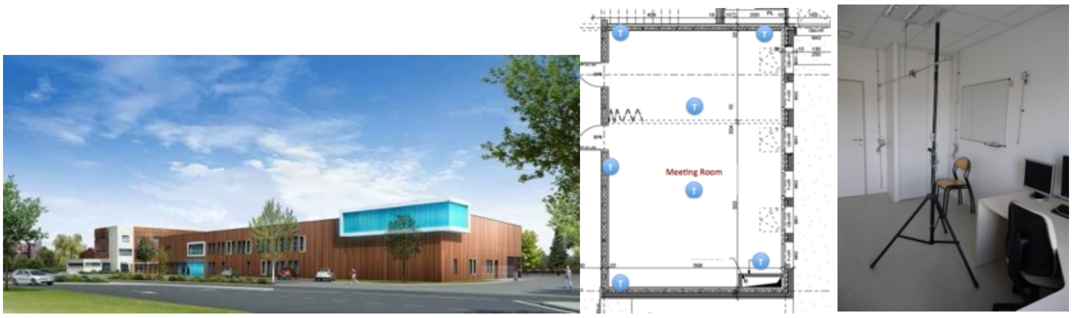


Figure 2 : 3D view of the studied building, temperature monitoring map of the meeting room and picture of the monitored office

The meeting room is approximately 50 m^2, is located on the ground floor and is east-facing. The sensors were positionned in the four corners of the room, on two poles in the centre of the room, and on a wall at the entrance to the room. At each location, measurements were made at 20 cm, 90 cm, 160 cm and 240 cm height. The second room is a 12 m2 office, facing north and unoccupied during the measurement period. The measurement principles are equivalent. The time step is 5 minutes.

In another building (B), built in the years 1975 and un-refurbished, 2 offices (occupied and unoccupied) of about 20 square meters have also been monitored with 20 to 30 sensors during 2 months in winter 2010-2011.

For each sensor, the average temperature of the 2 months has been computed. The standard deviation of the averages temperatures has then been computed for each room: it corresponds to the systematic standard error (table 1).

	Sd (°C)
Meeting room, building A	0.9
Office building A	0.34
Occupied office building B	0.28
Unoccupied office building B	0.34

Table 1 : Standard deviation of average temperature in the rooms

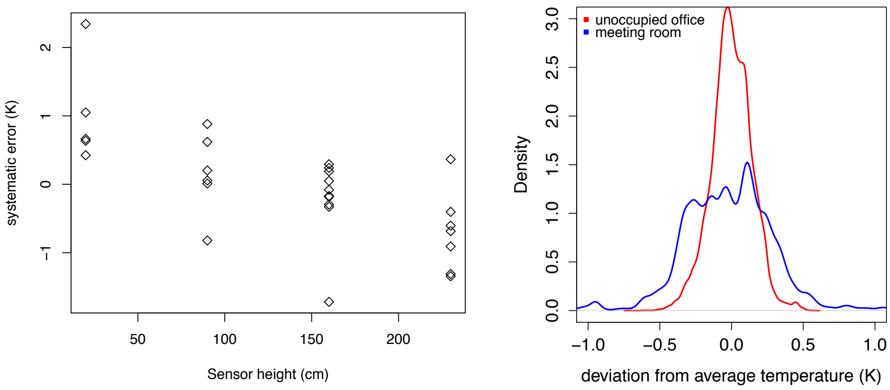


Figure 3 : Systematic standard sensor error depending on their height for the meeting room (left) and probability distribution for the office and meeting room in building A (right).

Figure 3 shows the systematic deviation from the average, for each sensor in the meeting room depending of their height. Stratification (in the aeraulic sense) is observed within the room: the higher the sensor, the greater the measured temperature.

2.2.2 Equivalent temperature (or characteristic average temperature) vs building average temperature, Loughborough case

Relevant information about temperature repartition in the room requires a lot of measurements in a single room. In many cases there is at best one measuring point a room. There are two main cases for sensor location:

- the middle of the room for unoccupied building like Loughborough,
- along the wall, often at the opposite of external wall for occupied building.

In both cases, the following **assumption** can be made:

- By taking the temperature at a middle height (1.8 m), errors made regarding stratification offsets one another, considering heat exchange through vertical walls and windows and for thermal bridges (assuming they are homogeneously distributed with height)
- Sensor location is far enough from the boundary layer and still realistic,
- Missing room heat island's has no major influence on exchanges,
- For exchange through the ceiling, temperature is under evaluated,
- For exchange through the floor, temperature is over evaluated,
- When heating occurs, temperature is under evaluated.

In this part, the aim is to assess error made by taking an average building temperature instead of a characteristic temperature for each part of the building fabric. It is assumed that the measured temperature is characteristic for all convection heat transfer in the room. It is applied to Loughborough case.

Considering first flows through vertical walls, and assuming that fabrics are homogeneous enough, we can write, from Eq. 4 and Eq. 7:

$$U_{eq.building\ wall} * S_{building\ wall} * (T_{in-eq-building-wall}) = \sum_i^{room} T_{meas-i}(U_{i-wall}S_{i-wall} + U_{i-win}S_{i-win}) \quad (8)$$

In Eq.8 all U and S are computed from theoretical values (from Beizaee et all (2015)) and Eq. 1, not considering thermal bridges (no information about it). The equivalent temperature can then be computed.

In another way, the average temperature of the building can be computed:

$$\overline{T_{meas}} = \frac{\sum T_{meas-i}}{n} \quad (9)$$

with n the number of sensors.

Then the average flows ($U*S*(T_{in} - T_{out})$) are computed using both definition of temperature, for the 1 month monitoring, taking the average temperatures during the month. Then error is assessed with:

$$error_{heat\ flow} = 100 * \frac{\phi_{average} - \phi_{equi}}{\phi_{equi}} \quad (10)$$

And the $error_{temperature}$ made on equivalent temperature:

$$error_{temperature} = \overline{T_{meas}} - T_{in-eq-building-wall} \quad (11)$$

For roof flow, instead of taking the average value of the entire dwelling, the temperature of the first floor rooms are taken, and ground rooms for ground flow. For ground flow, it is considered a constant ground temperature of about 12 °C. For now taking into account the heaters, we first identify when heater is hot enough to affect characteristic temperature: its surface temperature is greater than 40°C. Then for all those cases, temperature is increased (in absence of more information, from 1 to 5 K). Table 2 shows the error in all cases.

	Error on heat flow	Error on temperature (K)
Vertical walls	1 to 6 %	0.1 to 0.7 K
Roof	5.5%	0.6 K
Floor	-3.8%	-0.4 K

Table 2 : Error made by considering average temperature of the building in Loughborough case, considering that measured temperatures are realistic for convection exchange.

3 MEASUREMENT UNCERTAINTY FOR AVERAGE BUILDING TEMPERATURE: PURE STATISTICAL APPROACH

In this part we want to consider the average temperature of the building, which is defined as the average of temperatures (T) of each elementary volume (dv) of the building, at a time t.

$$T_{bui}(t) = \frac{\int T(t)dv}{V_{bui}} \quad (12)$$

It is obvious that we never dispose of all the temperature of each elementary volume of the building, then the assessment of the average temperature faces a problem of statistical inference, i.e.: how to estimate the average of a population (of elementary volumes) by measuring a sample of that population. One would also like to estimate the uncertainty of the estimate of this average by sampling. Statistical theory solved this problem a long time ago.

It is required to know the average temperature of a building at each time t ($T_{bui}(t)$) and its uncertainty, by measuring a sample of temperatures ($Ti(t)$) at a number *n of points i* in this building. Each point represents a volume dv of the building.

It is a question of sampling. Two approaches are possible:

- The building as a whole can first be considered, with an infinite number of possible measurement points (for each dv).
- It is also possible to sample by stratification (in the statistical sense), i.e. we will sample taking into account homogeneous sub-populations, each representing, for example, one room in a building.

3.1 Estimation of the average temperature T_{bui} in the case of sampling without stratification

The focus now turns to systematic component of variance. It is considered that if the quantity of interest is computed with enough measurements, random type variability will be compensated: for example a daily heat balance with sub hourly time step.

First, considering the building as a whole, it is assumed that the (infinite) population of temperatures (T) of each elementary volume dv follows a normal distribution of standard deviation σ_{pop} (unknown) with average T_{bui}. T_{bui} being the average temperature of the building over the period under consideration. The theory of statistical inference states that the average building temperature can be approximated by the sample mean of the temperatures measured:

$$T_{bui}(t) = T_{bui\text{-}sam}(t) = \frac{\sum_{i=1}^{n} T_i(t)}{n} \qquad (13)$$

The uncertainty of this estimate can be assessed. The main assumption is a random positioning of the sensors (that is often not really true but in fact improve the results).

Rigorously, when the sample is less than 30, it is shown that the variable T (Eq.14) follows Student's distribution with (n-1) degrees of freedom.

$$T = \frac{T_{bui-sam} - T_{bui}}{\sigma_{sam} \,/ \sqrt{(n-1)}} \qquad (14)$$

With $T_{bui\text{-}sam}$ the average of measured temperature, T_{bui} the real building average temperature (unknow), $\sigma_{sam}$the measured temperature standard deviation, and n the number of measurements.

Student's law tends to a standard normal distribution when the degree of freedom k tends towards infinity. It can then be approximated by a normal distribution with standard deviation k/(k-2). Then in all cases, T_{bui} can be estimated by $T_{bui\text{-}sam}$ with an uncertainty $\frac{n-1}{n-3}\frac{\sigma_{sam}}{\sqrt{(n-1)}}$, following a normal distribution.

This method is a simple one, making it possible to assess the uncertainty on a case-by-case basis. However, it seems that the accuracy of this uncertainty could be improved by taking into account the fact that each room of the building has its own heating setpoint and thermal behaviour. This method also allows to assess the average temperature and its uncertainty in a room, when many measurements are available.

3.2 Estimation of the average temperature T_{bui} in the case of sampling with stratification

The variance of the building average temperature (σ_{bui}) can be decomposed in the variance due to the location of sensor whitin a room (σ_{loc}) and the variance due to the different temperatures of rooms (σ_{room}):

$$\sigma_{bui}^2 = \sigma_{room}^2 + \sigma_{loc}^2 \qquad (15)$$

σ_{room} can be estimated by the standard deviation of the measurement's sample ($\sigma_{sam\text{-}room}$). It is shown that the quantity Q (Eq.16) follows Student's distribution with n-1 degrees of freedom:

$$Q = (T_{bui}\text{-}T_{bui\text{-}sam}) \frac{\sqrt{n*(N_{bui}-1)}}{\sigma_{sam-room}*\sqrt{(N_{bui}-n)}} \qquad (16)$$

Where $\sigma_{sam\text{-}room}$ is the standard deviation of the sample measured, N_{bui} is the number of rooms in the building and n the number of rooms where there is at least one measurement.

Student's law approaches a standard normal distribution when the degree of freedom k tends towards infinity. It can then be approximated by a standard normal distribution with standard deviation k/(k-2). Then the component due to rooms can be approximated by a normal distribution with standard deviation $\frac{n-1}{n-3}\sqrt{\frac{N_{bui}-n}{n*(N_{bui}-1)}}\,\sigma_{sam-room}$.

The component due to the location can be approximated by a normal distribution with standard deviation $\frac{n'-1}{n'-3}\frac{\sigma_{sam-loc}}{\sqrt{n'}}$. with n' the number of measurement in a room and $\sigma_{sam\text{-}loc}$ the standard deviation of the sample in the room.

Then T_{bui} can be approximated by a normal distribution centred on $T_{bui-sam}$ and with standard deviation σ_{bui}:

$$\sigma_{bui} = \sqrt{\left(\frac{n-1}{n-3}\right)^2 * \frac{N_{bui}-n}{n*(N_{bui}-1)} * \sigma_{sam-room}^2 + \left(\frac{n'-1}{n'-3}\right)^2 \frac{\sigma_{loc}^2}{n'}} \qquad (17)$$

3.3 Case study

The average building temperature estimator is the average of the temperatures measured. Uncertainty is evaluated by the methods described in previous part. There are two possible hypothesis: considering the samples with and without stratification.

The table 3 shows the systematic standard deviations considering many measuring plans for building A. In examples 3 and 4, the value of the uncertainty of measurement in a room corresponds to realistic values observed in the meeting room and in the unoccupied office. Obviously, the more sensors available, the more reduced is uncertainty.

	uncertainty
Ex 1 : n=12	0.38
Ex 2 : n = 26	0.23
Ex 3 : n = 12 + 10	0.33
Ex 4 : n=26 + 10	0.13

Table 3 : Systematic standard deviation for the average temperature of the building for different numbers of sensors, Ex 1 and 2 without considering stratification, ex 3 and 4 add 10 sensors in order to assess sensor's location uncertainty in a room.

4 Conclusion

Finally, by comparing the approach and cases study, the uncertainty due to sampling is about of the same order than the error made by the definition of the temperature (in the Loughborough case around 0.5 K).

As it is easier to compute sampling uncertainty (by standard deviation of the data), in the absence of precise knowledge, one may over-evaluate the uncertainty by multiply the sampling uncertainty by the square root of 2.

For example, in the case of Loughborough, the 9 sensors have a systematic standard deviation of 1.96 K. The error made by the definition of the temperature is around 0.5 K: that is not an uncertainty but an error. The equivalent building temperature may then have a standard systematic uncertainty of:

$$\sigma = \frac{9-1}{9-3}\frac{1.96}{\sqrt{9-1}} * \sqrt{2} = 1.3\ K$$

The method has to be extended to

- Temperature to be measured for ventilation flows,
- Outdoor temperature measurement.

The problem of radiation exchanges, however, takes a more important part and has to be further considered.

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