EXPERIMENTAL METHOD TO DETERMINE THE ENERGY ENVELOPE PERFORMANCE OF BUILDINGS

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ABSTRACT

In France, buildings represent 40% of the annual energy consumption. This sector represents an important stack to achieve the objective of reducing by 4 the greenhouse gas emissions by 2050. Knowledge of construction techniques and the use of equipments are the main keys to realize low energy buildings.

To achieve this aim, we monitored 24 experimental buildings. In order to evaluate these experimental buildings we compare the monitored energy performance to the predicted energy performance and explain the differences between both performances.

Therefore, we developed an in-situ method to determine the thermal envelope performance of buildings ($U_{building}$). The buildings are monitored in order to know the followings inputs:

- Occupancy rate;
- Heat supply;
- Solar supply;
- Ventilation and airflow losses
- Distributions losses

The method is based on the following equation which translates the energy balance of a building's envelope:

$$U_{building} * (T^{inside} - T^{outside}) = \sum Q^{supply} - \sum Q^{losses}$$

With

$U_{building}$: thermal performance envelope
Q^{supply} : energy supply of the building
Q^{losses} : energy supply of the building
T^{inside} : inside building's temperature
$T^{outside}$: outside building's temperature

The aim of this paper is to present the developed method and monitoring protocol. In order to validate the proposed experimental approach, we will present applications on different monitoring buildings in context of the project PREBAT (Research Program on Building's Evaluation).

INTRODUCTION

In France, buildings represent 40% of the annual energy consumption. This sector represents an important stack to achieve the objective of reducing by 4 the greenhouse gas emissions by 2050. Knowledge of construction techniques and the use of equipments are the main keys to realize low energy buildings.

To achieve this aim, we monitored 24 experimental buildings. In order to assess these experimental buildings we compare the monitored energy performance to the predicted energy performance, through the EBBE Method (energy balance of building's envelope) that helps us to explain the differences between both performances.

Therefore, we developed an in-situ method to determine the thermal losses of building's envelop ($U_{building}$). It is based on the energy balance equation of the building's envelop and on a monitoring protocol defined in order to be able to calculate each terms of the equation.

The aim of this paper is to present the EBBE (energy balance of building's envelope) method and the monitoring protocol. In order to test the proposed approach, we will present an application on a monitored building in context of the project CEBO (Research Program on Existing Building's Evaluation): the restaurant of the primary school of Langueux.

THE EBBE METHOD

The energy balance of the building envelop

The method is based on the equation 1 which translates the energy balance of a building.

$$Q^{heat\ supply} = Q^{envelop\ transmissions} + Q^{internal\ supply} + Q^{solar\ supply} + Q^{airflow\ losses} [\text{kWh}] \qquad \textbf{equation 1}$$

With

$Q^{heat\ supply}$: energy supply for heating the building
$Q^{internal\ supply}$: energy supply due to the internal gain : occupancy, electric appliance and lighting
$Q^{solar\ supply}$: energy supply due to solar gain
$Q^{airflow\ losses}$: energy losses due to airflow : ventilation and building air tightness

$Q^{envelop\ transmissions}$: energy loss by thermal transmissions through the buiding envelop

$$Q^{envelop\ transmissions} = U_{building} * (T^{inside} - T^{outside}) \quad [\text{kWh}] \quad \textbf{equation 2}$$

with

T^{inside} : inside temperature

$T^{outside}$: outside temperature

$U_{building}$ [W/m².K] thermal performance envelope, which expresses the building heat losses due to thermal transmission through the building's envelope.

We developed a method to determine each terms of the equation based on 3 tools that enable to resolve the energy balance of building. As it is shown on the following schedule, we have (cf. Figure 1):

- Tool n°1: Solar supply. This tool allows calculating the solar supply to the building during the considered period.
- Tool n°2: air flow losses. It permits to calculate the losses due to ventilation, opening windows and air tightness of the building.
- Tool n°3: Internal supply, for calculating the internal gain due to occupancy, lighting and equipment.
- Tool n°4: Energy balance of building's envelope. With the results of tools n°1, 2, 3 and the inputs known by the monitoring of the building, we are able to make the energy balance of building envelope and estimate the $U_{building}$.

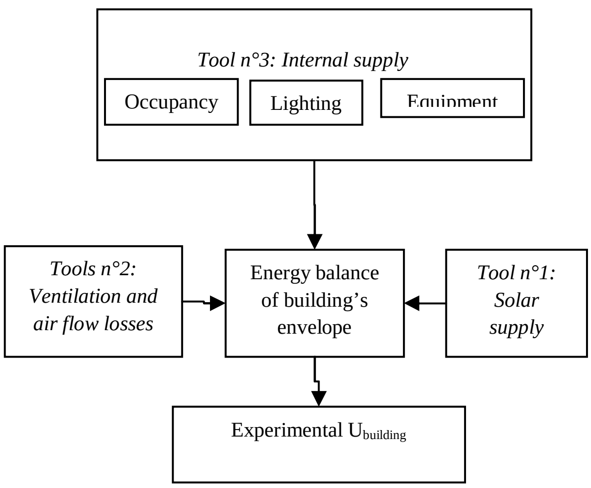

Figure 1. EBBE Tool structure

Tool 1 Solar energy supply

To determine the solar gain, we used the tool developed by J.A. Bouchet, CETE Méditerranée, for the project PREBAT (Research Program on Building's Evaluation). This tool calculates the solar energy supply for energy balance of building's envelope with the daily global irradiance of the place considered.

For each face of the building, the tool defined for each day of the year, the equivalent horizontal surface of the building for the direct and the diffuse radiation.

We usually do not have the measured global radiation. Therefore, the tools consider that the value of the global radiation is near to the average of the 10 last years. With the weather data of 40 cities in France, we are able to determine the solar gain for the place considered.

Tool 2 Airflows loss

The airflow loss is due to heat losses through ventilation $Q^{airflow\ losses}_{ventilation}$ and through the building's air tightness $Q^{airflow\ losses}_{tightness}$.

$$Q^{airflow\ losses} = Q^{airflow\ losses}_{ventilation} + Q^{airflow\ losses}_{tightness} \quad [\text{kWh}] \quad \textbf{equation 6}$$

To determine the airflow losses due to ventilation, we have to monitoring the inside and outside temperature and the electricity consumption of the ventilation extractors. We assume that the maximal electricity consumption is associated to maximal airflows according to the technical manual of the equipments. With these data, we are able to calculate the heat losses due to ventilation for each week according to the equation 7.

$$Q^{airflow\ losses}_{ventilation} = 0{,}34 * V_{ventilation} * (T^{inside} - T^{outside}) \quad [\text{kWh}] \quad \textbf{equation 7}$$

With

$V_{ventilation}$ [m^3/h] the airflow due to the ventilation extractors

T^{inside} [°C] the inside temperature inside

$T^{outside}$ [°C] the outside temperature

The calculation of heat loss due to building's air tightness is based on measured air tightness according to the protocol defined by the norm NF EN 13829. The airflows through the building envelope due to tightness, $V_{tightness}$, is then calculated with equation 8.

$$V_{tightness} = \dot{I}_4 * \frac{1}{(\frac{4}{50})^{2/3} * \frac{V_{heat}}{S}} * 2 * V_{heat} * e * \boldsymbol{\varepsilon} \quad [m^3/h]$$

equation 8

With

I_4 [m³/h.m²] the air tightness of the building measured

V_{heat} [m³] the heated volume of the building

S [m²] the inside surface of the building's envelope

ε height corrective coefficient, taking into account the augmentation of the wind speed with the height (cf. figure 4)

e the exposition coefficient, depends on the exposition of the building to the wind (cf. figure 5)

Height of the building	0 - 10 m	>10 – 30 m	> 30 m
ε height corrective coefficient	1,0	1,2	1,5

Figure 2. Height corrective coefficient in function of the height of the building

Type of exposition	Without protection from the wind (building in windy area)	Moderate protection from the wind (building protected by trees or other buildings)	High protection from wind (small buildings in downtown
e exposition coefficient	0,05	0,03	0,02

Figure 3. The exposition coefficient in function of the exposition of the building to the wind

Knowing the outside and inside temperature, we can calculate the energy loss due to the air tightness of the building.

$$Q_{tightness}^{airflow\ losses} = 0{,}34 * V_{tightness} * (T^{inside} - T^{outside}) \quad [kWh]$$

equation 9

With

$V_{tightness}$ [m³/h] the airflow due to the tightness of the building

T^{inside} [°C] the inside temperature inside

$T^{outside}$ [°C] the outside temperature

The studied period is during winter and we consider that the occupants do not open the windows. We do not have any energy loss due to opening windows.

Tool 3: internal energy supply

The internal energy supply is due to occupancy $Q_{occupancy}^{internal\ supply}$, lighting $Q_{equipment}^{internal\ supply}$ and electric appliance gain $Q_{lighting}^{internal\ supply}$.

$$Q^{internal\ supply} = Q_{occupancy}^{internal\ supply} + Q_{equipment}^{internal\ supply} + Q_{lighting}^{internal\ supply} \quad [kWh]$$

equation 3

The internal gain due to occupancy is calculated from the occupancy rate per hour with the metabolism energy production according to the activity Met [W/m²] (cf. Table 1) and with a correction for children. We consider that the corporal area is 1,8 m² for adults and 1 m² for children.

The internal energy supply due to occupancy $Q_{occupancy}^{internal\ supply}$ is given by the following equation:

$$Q_{occupancy}^{internal\ supply} = Met * S * t \quad [kWh]$$

equation 4

With

S [m²] the corporal area of the occupant

t [h] the time of occupancy

Met [W/m²] the metabolism energy production

Activity	**Metabolism energy production**	
	[W/m²]	[Met[1]]
Rest, be lying	46	0.8
Rest, be sit	58	1.0
Sedentary activity (work desk, at home, school, laboratory)	70	1.2
Slight activity, standing up (Purchasing, laboratory, slight industry)	93	1.6
Moderate activity, standing up (sale, housework , work on machines)	116	2.0
Walking with 2km/h speed	110	1.9

Figure 4. The metabolism energy production (NF EN ISO 7730, 2006)

[1] The unit of the metabolism energy production is the met. One met corresponds to the metabolism of one person at rest and valued 58.2 W/m² per corporal unit surface, knowing that the rate of corporal surface is 1.8 m² for pa person.

The internal gain due to electric appliance is calculated from the number in use per hour with their electric power (cf. table 2). We assume the electric appliance is only in use when building is occupied.

$$Q^{internal\,supply}_{equipment} = \sum_{i=1}^{N} t_i * P_i \quad [\text{kWh}] \quad \textbf{equation 5}$$

With

N the number of appliance

t_i [h] the time of use of appliance n°i

P_i [Wh] the heat energy due to the use of appliance n°i

The heat energy due to the use during one hour is given in the table for several types of equipments and function of the state of use.

Equipment	State of use	Heat energy [Wh]
Central processing unit	ON	47
	Sleep mode	20
	OFF	2.8
Screen	ON	21
	Sleep mode	1.7
	OFF	1.7
Printer	ON	52
	Sleep mode	17.5
	OFF	0
Photocopier	ON	153
	Sleep mode	25
	OFF	0
fax	ON	25
	Sleep mode	5
	OFF	0
Electric range	ON	1150
Induction range	ON	588
Vitroceramic range	ON	999
Oven	ON	1331
Small Oven	ON	898
Microwave	ON	913
kettle	ON	1200
coffepot	ON	800

Figure 5. Heat energy due to the use of equipment during one hour

To assess the internal gain due to lighting $Q^{internal\,supply}_{lighting}$, we assume that 100% of the electricity consumption of a light is dissipated in internal gain. Therefore, we can deduce the energy supply due to lighting for each week of the concerned period by monitoring the electricity consumption per hour of lighting.

Tool 4: EBBE: Resolving the energy balance of the envelop

With tools n°1, 2 and 3 we can calculate:

- $Q^{internal\ \ supply}$: energy supply due to the occupancy, the equipments and the use of lighting
- $Q^{solar\,supply}$: energy supply due to solar gain
- $Q^{airflow\,losses}$: energy losses due to ventilation and building's air tightness airflow

Monitoring the inside and outside temperature, we can choose an experimental value of the thermal envelope performance $U_{building}$ to make the energy balance of building's envelope.

$$Q^{heat\,supply}_{calculated} = U_{building} * (T^{inside} - T^{outside}) + Q^{internal\,supply} + Q^{solar\,supply} + Q^{airflow\,losses} \quad [\text{kWh}] \quad \textbf{equation 10}$$

With the inputs known by the monitoring of the building, we can calculate the rate of energy supply for heating the building $Q^{heat\,supply}_{measured}$.

We can compare the difference between measured and calculated energy supply for heating for a thermal performance envelope $U_{building}$.

$$\delta = \frac{\left|Q^{heat\,supply}_{calculated} - Q^{heat\,supply}_{measured}\right|}{Q^{heat\,supply}_{measured}} \quad [\%] \quad \textbf{equation 11}$$

The difference is calculated for each week of the considered period. We can choose a thermal performance envelope $U_{building}$ when the difference is minimized between the values calculated and measured.

The monitoring protocol

The monitoring protocol has to be defined in order to retrieve the necessary inputs to resolve the equations of the EBBE method.

- the internal gain : number of electric power, occupation rate and hours, lighting consumption
- heat supply of heating system : heat supply monitoring
- solar gain : global horizontal radiance
- airflow losses : building's air tightness according norm NF EN 13829,
- ventilation : electric consumption of the extractors
- In-and outdoor air temperature for the heat losses calculation due to airflow and for resolving the heat balance equation

Frequency of measuring has to be hourly.

APPLICATION

Monitored building

The case studied is on the restaurant of a primary school based in the city of Langueux, France. The building was built in 1987 and its area is 713 m². It is composed with 2 rooms for receiving the children and a part for prepare the cooking. The heat system is a gas boiler with fin-type radiator. Three single extractors maintain the ventilation of the locals.

Thanks to the monitored protocol, a calorimeter was installed to follow the energy supply for heating the building by the boiler. Electric counters were put in to follow the electric consumption of lighting and the three ventilation extractors. Several thermometer in different rooms enable to follow the inside temperature. The time step of each measure is one hour.

The monitoring was made for 14 weeks, from the 4th of January 2010 to the 11th of April 2010.

Tool 1 Solar energy supply

With the solar inputs measured, we calculated the solar energy supply for energy balance of building's envelope with the daily global irradiance of the place considered.

Tool 2 Airflow Losses

We measured the tightness of the building, based on the protocol defined by the norm NF EN 13829. The result was a tightness of I_4 = 2.5 $m^3/h.m^2$ for a building envelop of 1232 m² and a volume of 2053 m^3. The airflow through the building envelop calculated with tool n° 2 is about 350 m3/h.

Tool 3 Internal energy supply

The restaurant is occupied by 350 children and 15 adults on Monday, Tuesday, Thursday and Friday. They eat from 12:00 to 14:00. 7 people work for prepare the cooking and wash the room from 10:00 to 12:00 and from 14:00 to 16:00.

On Wednesday, we just have 73 people in the restaurant for eating. During holidays, we don't have any occupation of the building.

30 percent of the adult population have a sedentary activity and 70% gave a slight activity. The entire population of children has a slight activity. The following rate gives the internal energy supply due to occupancy during a week.

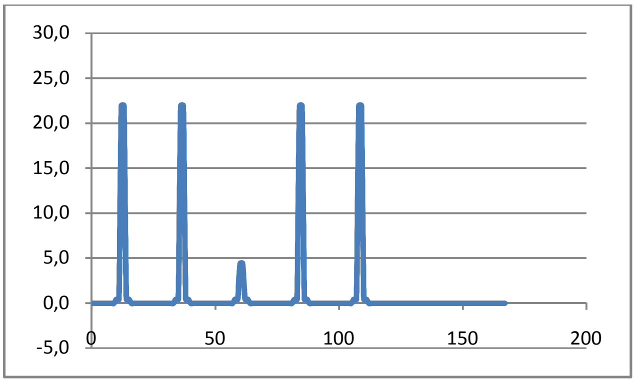

Figure 6. Internal energy supply [kWh] due to occupancy during a week (168 hours)

During one worked week, the internal energy supply due to occupancy is about 193 kWh.

The equipments in the building are:

- 1 central processing
- 1 screen
- 1 fax
- 1 oven
- 1 microwave
- 1 kettle
- 1 coffeepot
- The following table gives the state of use during occupation and inoccupation of the building.

	Occupation			Inoccupation		
Equipment	ON	Sleep mode	OFF	ON	Sleep mode	OFF
Central processing	80%	20%	-	-	-	100%
Screen	80%	20%	-	-	-	100%
Fax	10%	90%	-	-	100%	
Oven	60%	-	40%	-	-	100%
Microwave	60%	-	40%	-	-	100%
Kettle	40%	-	60%	-	-	100%
coffeepot	2%	-	95%	-	-	100%

Figure 7. State of use of equipment during occupation and inoccupation

According to the occupancy rate, established previously, this is the rate of energy supply due to equipment during one week.

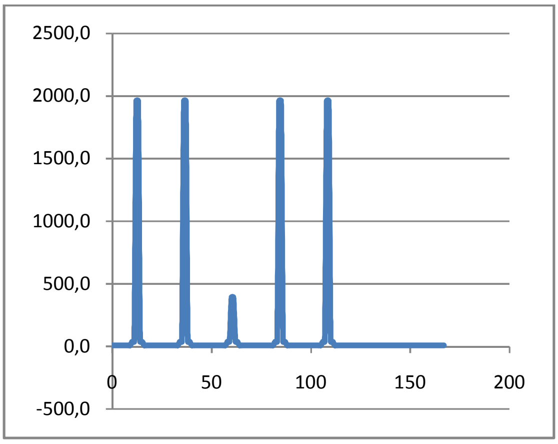

Figure 8. Internal energy supply due to equipment [Wh] during a week (168hours)

During one worked week, the total internal energy supply due to equipment is about 53 kWh.

Tool 4 Energy Balance of the envelope

In order to make the energy balance of the envelope, we measured the energy supply for heat the building during 14 weeks.

RESULTS

The following table shows the energy balance of building's envelope for the restaurant of the primary school in Langueux for a thermal performance envelope of $U_{building}$ = 0,8 W/m².K. just 3 weeks are shown instead of the 14 weeks of study.

Week	Solar energy supply	Energy supply due to lighting	Energy supply due to occupants and equipments	Airflow loss due to ventilation	Airflow loss due to air tightness of the envelope	Energy loss through envelope transmissions [kW	Heat supply calculated for $U_{building}$ = 0,8 W/m².K	Heat supply measured
1	147	51,1	252	-759	-693	-4590	-5592	-7450
2	157	47,5	252	-737	-658,7	-4360	-5300	-5190
3	184	51,8	252	-585	-557	-3692	-4348	-3900

Figure 9. Energy balance of building's envelope for the restaurant of the primary school for $U_{building}$ = 0,8 W/m².K

We varied the thermal performance envelope $U_{building}$ from 0,75 W/m².K to 1,1 W/m².K and the following table give the difference δ between the energy supply for heat calculated and measured.

week	Difference δ between the energy supply for heat calculated and measured [%]							
	$U_{building}$ = 0,75 W/m².K	$U_{building}$ = 0,8 W/m².K	$U_{building}$ = 0,85 W/m².K	$U_{building}$ = 0,9 W/m².K	$U_{building}$ = 0,95 W/m².K	$U_{building}$ = 0,1 W/m².K	$U_{building}$ = 1,05 W/m².K	$U_{building}$ = 1,1 W/m².K
1	35	32	28	25	22	18	15	11
2	12	7	3	2	7	11	16	21
3	4	1%	6	11	17	22	27	33
4	20	16	12	8	3	1	5	10
5	13	8	3	2	6	11	16	21
6	19	14	10	5	1	4	8	12
7	6	12	17	23	28	34	39	45
8	19	14	10	5	1	4	8	13
9	4	10	16	22	28	34	40	46
10	18	25	32	39	46	53	59	66
11	6	0	6	12	19	25	31	37
12	20	15	10	4	1	7	12	18
13	6	0	6	12	18	24	30	36
14	1	8	14	21	28	35	42	49

Figure 10. Energy supply for heat measured and calculated for different values of thermal performance envelope $U_{building}$

The following table gives the minimum, maximum, average and the relative scatter for the difference δ between the energy supply for heat calculated and measured for a thermal performance envelope $U_{building}$ from 0,75 to 1,1 W/m².K.

	Difference δ between the energy supply for heat calculated and measured [%]

	$U_{building}$ = 0,75 W/m².K	$U_{building}$ = 0,8 W/m².K	$U_{building}$ = 0,85 W/m².K	$U_{building}$ = 0,9 W/m².K	$U_{building}$ = 0,95 W/m².K	$U_{building}$ = 0,1 W/m².K	$U_{building}$ = 1,05 W/m².K	$U_{building}$ = 1,1 W/m².K
min	1%	0%	3%	2%	1%	1%	5%	10 %
avrg	13 %	12 %	12 %	14 %	16 %	20 %	25 %	30 %
max	35 %	32 %	32 %	39 %	46 %	53 %	59 %	66 %
rel. scat ter	9%	9%	9%	11 %	14 %	15 %	16 %	17 %

Figure 11. Minimum, maximum, average and relative scatter of the difference between the energy supply for heat measured and calculated for different values of thermal performance envelope $U_{building}$

According to this table, we can see that the difference δ between the energy supply for heat calculated and measured, has the smaller average for a thermal performance envelope $U_{building}$ between 0,8 and 0,85 W/m².K

DISCUSSION

The figure 12 shows the comparison between the energy supply for heat measured with the monitoring protocol $Q_{measured}^{heat\ supply}$ and the energy supply for heat calculated with the EBBE method $Q_{calculated}^{heat\ supply}$, for different thermal performance envelope $U_{building}$.

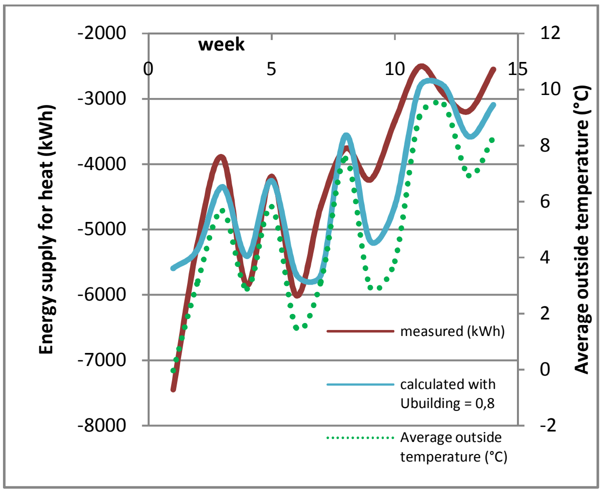

Figure 12. Comparison between the energy supply for heat calculated and measured for a thermal performance envelope Ubuilding = 0,8W/m².K

Before the week n°1, the building was not heated during 2 weeks because of the Christmas holidays. This period was very cold, and the building has a high thermal inertia. The energy supply for heat supply was important during the week n°1. The EBBE method doesn't take into account these phenomena of thermal inertia. Therefore we should to not take into account the week n°1 to choose the thermal performance envelope $U_{building}$.

In addition, during weeks n°7, 8, 11, 12, 13 and 14, as we can see and the figure 10, the average outside temperature is higher than 7°C. During these periods, the occupants use the windows and the EBBE method does not take into account the inherent airflows. Therefore, we should not consider these weeks for choosing the thermal performance envelope $U_{building}$.

Eliminating weeks n°1, 7, 8, 11, 12, 13, 14, we calculated the new difference δ between the energy supply for heat calculated and measured for different thermal performance envelope $U_{building}$ from 0,75 to 1,1 W/m².K.. The following table gives the minimum, maximum, average and the relative scatter for the difference δ between the energy supply for heat calculated and measured for a thermal performance envelope $U_{building}$ from 0,75 to 1,1 W/m².K.

	Difference δ between the energy supply for heat calculated and measured [%]							
	$U_{building}$ = 0,75 W/m².K	$U_{building}$ = 0,8 W/m².K	$U_{building}$ = 0,85 W/m².K	$U_{building}$ = 0,9 W/m².K	$U_{building}$ = 0,95 W/m².K	$U_{building}$ = 0,1 W/m².K	$U_{building}$ = 1,05 W/m².K	$U_{building}$ = 1,1 W/m².K
min	4%	1%	3%	2%	1%	1%	5%	10 %
avrg	13 %	12 %	12 %	13 %	15 %	19 %	25 %	30 %
max	20 %	25 %	32 %	39 %	46 %	53 %	59 %	66 %
rel. scat ter	7%	8%	10 %	13 %	16 %	18 %	19 %	20 %

Figure 13. Minimum, maximum and average of the difference between the energy supply for heat measured and calculated for different values of thermal performance envelope $U_{building}$

According to this table, we can suggest a new value of thermal performance envelope $U_{building}$ between 0,8 and 0,85 W/m².K.

Moreover, Thanks to the works of [David E.Claridge], it has been shown that infiltrations due to tightness $Q_{tightness}^{airflow\ losses}$ lead to a smaller change in the energy load than is customarily calculated. Changes as small as 20 percent of the calculated value were observed. Taking into account this possibility, we calculated the thermal performance envelope with airflows calculated reduced by 20 percent.

With this new consideration, we calculated the difference δ between the energy supply for heat calculated and measured lead to a thermal performance envelope of 0.85 and 0.9 W/m².K.

By the standard method of adding the theoretical thermal performance of each wall of the building, we calculated a thermal performance envelope $U_{building}$ of 1,0 W/m².K. We can consider that the EBBE method on this building, gives a good approximation of the theoretical results.

CONCLUSION

With the EBBE method, we defined a protocol of monitoring building and achieve to determine an experimental thermal performance envelope on the case of a building. A significant discrepancy is observed between the calculated and measured results.

The modelling of the opening of windows by the occupant has to be developed. Our protocol of monitoring building does not integrate devices to record the opening of windows by the occupants. This measure could be added for several locals of the buildings. Another possibility is to submit to the occupants to a questionnaire and elaborate a pattern of opening windows by the occupants.

A study on the uncertainty on the measure of the monitoring has to be done, in order to appreciate the results of the EBBE method. This method has also to be tested on larger amount of buildings. We planned to do it on 24 experimental building with high energy performance.

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