Using the utilization factor concept for natural ventilation

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ABSTRACT

A well-known parameter in the calculation of solar gains for the heating requirements is the utilization factor concept. This parameter allows the assessment of the heating requirements diminishment due to the contribution of the solar gains, and it can be easily calculated as a function of the building inertia, and the ratio between solar gains to losses.

The present paper analyses the utilization factor equation in order to obtain the relations among all the involved variables. Thus, using the transfer function method, a new and realistic utilization factor equation is obtained. A comparison between both expressions is made, and the differences encountered are explained.

Taking account the usefulness of this concept for the calculation of the heating requirements, an effort has been made in order to use it for the calculation of the cooling requirements. In this case, we are interested in the calculation of the cooling requirements diminishment due to the contribution of the natural ventilation.

Finally, the paper shows the dependency of the utilization factor as a function of variables like the daily distribution of the heating or cooling requirements, the daily distribution of the solar gains or the natural ventilation contribution, the number of hours of solar gains or natural ventilation, etc.

1. INTRODUCTION

The present paper starts analysing the heat storage and heat restitution from a building component to its adjacent air. This will be very interesting for compare the different construction typologies that can be present in a given building.

Next we will define the utilization factor of a building component, and will evaluate it. This can be seen as an interim step to generalize the utilization factor of a space.

In order to do this, in addition, we will need the storage efficiency of a space. Thus, this ratio between the energy stored by the components of a space, and the energy used to diminish the cooling loads of the given space will be assessed.

Finally, the utilization factor of the space will be defined and characterized as a function of the thermal inertia of the building components that configure the space and the ratio between energy losses (ventilation loads) and energy requirements (cooling loads).

2. HEAT STORAGE IN A BUILDING COMPONENT

The heat storage in a space occurs in its components: walls, roofs and floors. Thus, as a previous step in the study of the utilization factor for a space, it is necessary to analyse the thermal performance of these components. This section tries to explain using an example the heat storage in a building component, and its relations with the components thermal properties.

Figure 1 shows a transversal section of an exterior wall. In this example we will suppose that the interior temperature is equal to 15ºC during 8 hours, and it is equal to 25ºC the rest of the day.

The interior film coefficient is taken equal to 2 W/m^2 ºC, or 4 W/m^2 ºC, depending on the driven forces: natural convection or forced con-

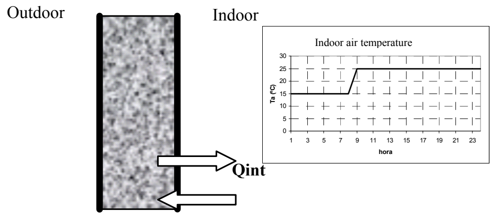

Figure 1: Exterior Wall Scheme and Interior Temperature.

vection respectively.

On the other hand, the exterior film coefficient is taken equal to 20 W/m^2 ºC, and the exterior air temperature is supposed to be constant and equal to 27ºC.

This set of hypothesis allows us to easily calculate the heat storage in the wall as a function of its thermal properties and its thickness.

Three different wall constructions have been analysed:

- two cases with a single layer, with thickness equal to 24 cm and 29 cm,
- and, one multilayer case with an interior insulation material.

The graphs of Figures 2, 3 and 4 show the heat storage and the interior wall temperatures for each case. In the heat storage graph, it can be seen that part of this heat storage is lost to the exterior, and the rest goes to the interior space.

The right graph shows the interior wall temperature against the wall thickness (from the interior to the exterior face). The maximum temperature is represented with a red line, and the minimum temperature with a blue one. The ability to store heat depends on the difference between the maximum and the minimum interior wall temperatures.

In Table 1, we have summarized the main results of these cases: the total heat storage, the flux to the interior space (useful), and the lost to the exterior.

A simple analysis from the comparison of the heat storage graphs and the table above shows that:

- The total heat storage is higher in the single layer cases,
- The maximum heat storage occurs during the first hour, and decreases slower in the single layer than in the multi layer. This is a consequence of the higher thermal inertia in the first two cases.
- The lost to the exterior is lower in a multi layer wall due to the interior layer of insulation material.

Analysing the interior wall temperatures we can see:

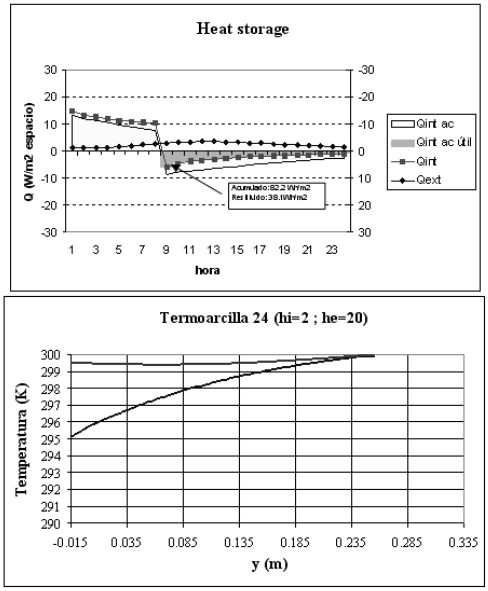

Figure 2: Heat Storage in a Single Layer Wall with a Thickness of 24 cm.

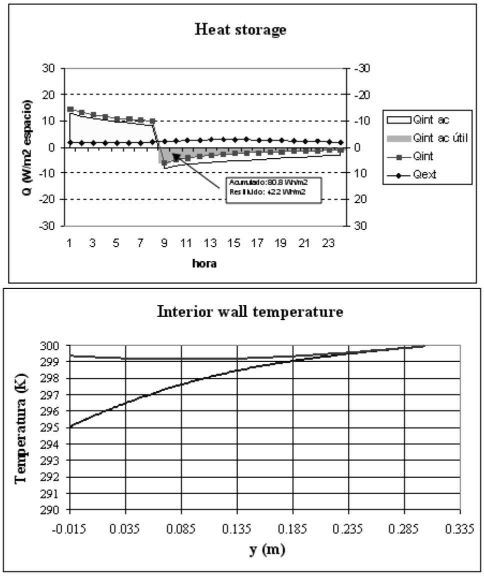

Figure 3: Heat Storage in a Single Layer Wall with a Thickness of 29 cm.

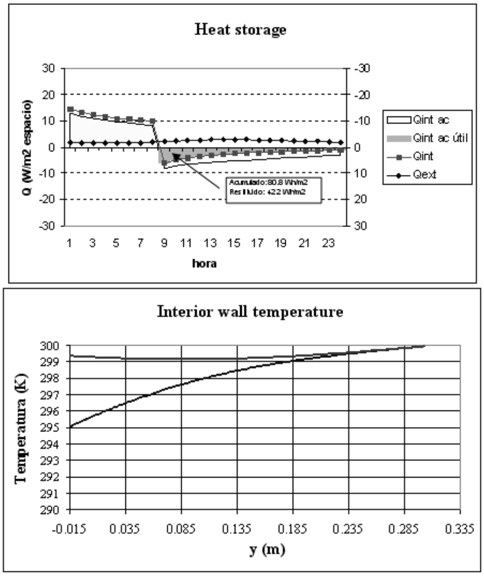

Figure 4: Heat Storage in a Multi-Layer Wall.

Table 1: Heat Storage Comparison.

	Single Layer 24 cm	Single Layer 29 cm	Multi Layer
Total Heat Storage (Wh/m^2)	82.2	80.8	68.5
To the Interior Space (Wh/m^2)	38.1	42.2	37.6
Lost to the exterior (Wh/m^2)	44.1	38.6	30.9

- In a single layer wall is found a maximum thickness that is useful for the purpose of heat storage. This maximum thickness depends on the wall thermal properties and on the excitations: interior and exterior air temperatures, and interior and exterior film coefficients. In this example, it can be seen that this maximum thickness is around 23.5 cm. Then a higher thickness is not useful, and the total heat storage can not be increased with a thickness higher than that maximum.
- In a multi layer wall, only the layers from the insulation material to the interior space are able to store heat. This can be seen in the interior temperature graph, where the presence of the interior insulation material provokes a high discontinuity of the distribution of the interior temperature.

3. UTILIZATION FACTOR OF A BUILDING COMPONENT

The utilization factor of a building component can be defined as the relation between the decrease of heat load in a space, and the fraction of heat store by the component that goes to the space. Thus, if we want to characterise the utilization factor, a previous analysis of the dependencies of the heat fluxes mentioned above, it's necessary.

In order to study the way that the stored heat goes to the interior space, we will use the example of Figure 5.

The excitation is in this case a triangle with a peak value of interior temperature equal to 1ºC. In this example, we will not consider the heat lost to the exterior. Thus, an exterior film coefficient of 0 is used.

It can be easily demonstrated that for this case, and assuming capacity system behaviour, the heat flux to the interior space can be calculated as a function of the main time constant (τ).

The problem equations are:

$$\begin{cases} M\ Cp\ \dfrac{d\,T(t)}{d\,t} = h\ A\left(T(t) - T_s(t)\right) \\ h\ A\left(T(t) - T_e\right) = \dot{m} c_p \left(T_s(\mathrm{t}) - T_e\right) \end{cases}$$

where:

M: is the building component mass,

C_p: is the building component specific heat,

T(t): is the building component temperature as a function of time,

$\dot{m}$: is the air flux due to the ventilation system,

c_p: is the air specific heat,

T_e: is the input air temperature (triangle of the figure above),

T_s: is the output air temperature.

Solving this problem we get:

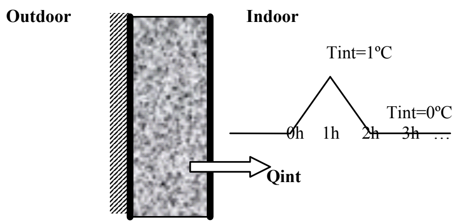

Figure 5: Stored heat flux to the interior space.

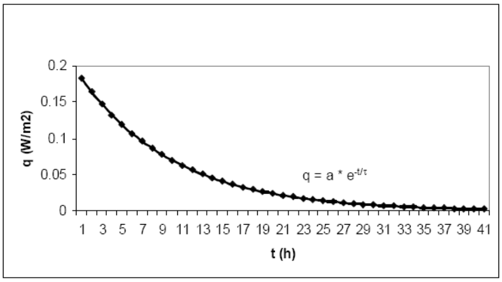

Figure 6: Heat flux to the interior space against the time.

$$T_k(t) = C1 + C2 \exp\left(-\frac{\dot{m}_k\, cp}{M_k Cp_k} \frac{h_k A_k}{h_k A_k + \dot{m}_k cp} t \right)$$

Where *C1* and *C2* are constants and can be fixed using the initial conditions:

$$\begin{cases} t = 0 & T(0) = C1 + C2 \\ t = \infty & T(\infty) = C1 \end{cases}$$

then:

$$\begin{Bmatrix} C1 = T(\infty) = T_e \\ C2 = T(0) - T_e \end{Bmatrix}$$

and finally, the output air temperature can be calculated from:

$$T_k(t) = T_e + (T_k\,(0) - T_e) \exp\left(-\frac{\dot{m}_k\, cp}{M_k\, Cp_k} \frac{h_k A_k}{h_k A_k + \dot{m}_k cp} t \right)$$

Where $\tau = \dfrac{(\mathrm{h_k\ A_k + m_k\ cp})\mathrm{M_k Cp_k}}{\mathrm{h_k\ A_k\ m_k\ cp}}$ is the main time constant of the building component.

4. HEAT STORAGE IN A SPACE. STORAGE EFFICIENCY

Once, the heat storage in building components has been studied, we will focus on the analysis of the heat storage in a space.

An analogous process to that described above has been followed calculating a new time constant. In this case, it is convenient to look for the relation between the space time constant and those time constants of each building components.

In a space with ‘n’ building components able to stored heat, the heat flux to the space can be expressed as follows: (The total heat storage has been divided into two periods):

$$Q_{0\to t} = M_1\ Cp_1\ (T_1(0) - T_1(t)) + M_2\ Cp_2\ (T_2(0) - T_2(t)) + \ldots + M_n\ Cp_n\ (T_n(0) - T_n(t))$$

$$Q_{t\to\infty} = M_1\ Cp_1\ (T_1(t) - T_e) + M_2\ Cp_2\ (T_2(t) - T_e) + \ldots + M_n\ Cp_n\ (T_n(t) - T_e)$$

And then, the total heat storage is:

$$Q_{0\to\infty} = Q_{\max} = M_1\ Cp_1\ (T_1(0) - T_e) + M_2\ Cp_2\ (T_2(0) - T_e) + \ldots + M_n\ Cp_n\ (T_n(0) - T_e)$$

4.1 Storage efficiency

We can define the storage efficiency (SE) as the relation between the stored heat during a certain period and the maximum possible:

$$SE = \frac{Q_{0\to \mathrm{t}}}{Q_{\max}}$$

and then:

$$SE = 1 - \frac{Q_{t\to\infty}}{\mathrm{Q_{max}}}$$

or:

$$SE = 1 - \frac{M_1\ Cp_1\ (T_1(t) - T_e) + M_2\ Cp_2\ (T_2(t) - T_e) + \ldots + M_n Cp_n (T_n(t) - T_e)}{M_1\ Cp_1\ (T_1(0) - T_e) + M_2\ Cp_2\ (T_2(0) - T_e) + \ldots + M_n Cp_n (T_n(0) - T_e)}$$

Assuming the same initial temperature:

$$SE = 1 - \frac{M_1\ Cp_1\ (T_1(t) - T_e) + M_2\ Cp_2\ (T_2(t) - T_e) + \ldots + M_n Cp_n (T_n(t) - T_e)}{\sum_{i=1}^{n} M_i\ Cp_i\ (T\ (0) - T_e)}$$

$$SE = 1 - \frac{M_1 Cp_1}{\sum_{i=1}^{n} M_i Cp_i} \frac{(T_1(t) - T_e)}{(T\ (0) - T_e)} - \frac{M_2 Cp_2}{\sum_{i=1}^{n} M_i Cp_i} \frac{(T_2(t) - T_e)}{(T\ (0) - T_e)} - \ldots - \frac{M_n Cp_n}{\sum_{i=1}^{n} M_i Cp_i} \frac{(T_2(t) - T_e)}{(T\ (0) - T_e)}$$

then:

$$1-SE=\frac{1}{\sum_{i=1}^{n} M_i Cp_i}\left(M_1 Cp_1 \exp\left(-\frac{t}{\tau_1}\right)+M_2 Cp_2 \exp\left(-\frac{t}{\tau_2}\right)+\ldots\right.$$

$$\left.\ldots+M_n Cp_n \exp\left(-\frac{t}{\tau_n}\right)\right)$$

If $-\frac{t}{\tau_k}$ is a low figure, it can be assumed that:

$$\exp\left(-\frac{t}{\tau_n}\right)\cong 1-\frac{t}{\tau_n}$$

Finally:

$$\boxed{1-SE=\exp\left(\frac{-t}{\tau}\right)}$$

where:

$$\frac{1}{\tau}=\frac{M_1\ \ Cp_1}{\sum_{i=1}^{n} M_i\ \ Cp_i}\frac{1}{\tau_1}+\frac{M_2\ \ Cp_2}{\sum_{i=1}^{n} M_i\ \ Cp_i}\frac{1}{\tau_2}+$$

$$\ldots+\frac{M_n\ \ Cp_n}{\sum_{i=1}^{n} M_i\ \ Cp_i}\frac{1}{\tau_n}$$

5. UTILIZATION FACTOR OF A SPACE

The utilization factor for heating purposes is a well-known parameter. This utilization factor is defined as the relation between the decreased of the heating requirements due to solar radiation load and that solar radiation load.

$$Utilization\ \ Factor=\frac{Decreased\ \ of\ \ heating\ \ requirements\ \ due\ \ to\ \ radiation}{Solar\ \ radiation\ \ load}$$

This parameter depends on the thermal inertia and on the relation between the solar radiation load and the heating requirements without that radiation.

In this paper, we present a new definition: utilization factor of a space for cooling purposes. This utilization factor is defined as the relation between the decreased of the cooling requirements due to ventilation and the losses by ventilation.

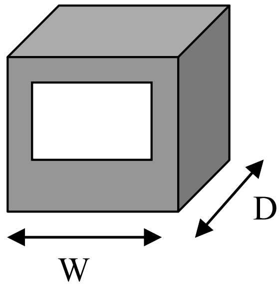

Figure 7: Building space scheme.

$$Utilization\ \ Factor=\frac{Decreased\ \ of\ \ cooling\ \ requirements\ \ due\ \ to\ \ ventilation}{Loses\ \ by\ \ ventilation}$$

As in the original utilization factor, this parameter depends on the thermal inertia and also on the relation between the losses by ventilation and the cooling requirements without that ventilation.

In order to find out the dependencies of the utilization factor, we have carried out a huge number of simulations using the thermal building simulation program developed by the Thermal Group of the University of Seville.

The simulated cases have been composed by different buildings in different situations by changing:

- the building orientation,
- the aspect ratio between width to depth,
- the space area,
- the number of exterior surfaces,
- and the percentage of window area of the façade.

The graph of Figure 7 represents a scheme of the building space.

The obtained results from the simulations have been presented in terms of utilization factors against the relation between the losses by ventilation and the cooling requirements without that ventilation.

6. CONCLUSIONS

This study has allowed us to express the following conclusions:

- The orientation of the external building façade has a big influence on the utilization factor. We have found increased values in the

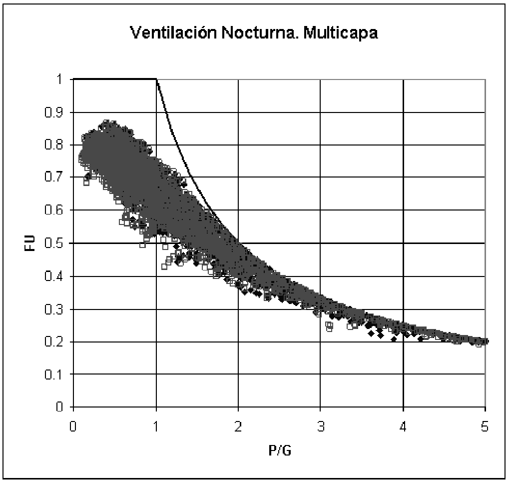

Figure 8: Example of the obtained results of utilization factors.

following order: south, east, west and north orientation.

There are two reasons explaining this different behaviour by orientation: on one hand, the total amount of cooling requirement depends on the orientation, and on the other hand, the hourly distribution of this cooling requirement is also different.

- For each orientation a more or less concentrated distribution of utilization factors is found, except for south orientation that shows a higher range of values.
- Another parameter affecting the range of values is the width to depth aspect ratio. Increasing values of the aspect ratio lead to higher range of utilization factors.
- An increased of the space area has the opposite effect.
- When there are two or more exterior facades, the losses to the exterior are higher, and in consequence, the utilization factor is lower.
- Finally, the ratio between the losses by ventilation and the cooling requirements without that ventilation decreased with an increased of the percentage of window area of the façade. For this reason, the utilization factor is higher in these cases.