THE *PASSIVHAUS* STANDARD IN EUROPEAN WARM CLIMATES:
DESIGN GUIDELINES FOR COMFORTABLE LOW ENERGY HOMES

Part 3. Comfort, climate and passive strategies

Passive-On project

ieea

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Part 3. Comfort, climate and passive strategies

Edited and compiled by: Brian Ford, Rosa Schiano-Phan and Duan Zhongcheng, School of the Built Environment, University of Nottingham

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PARTNERS

Politecnico di Milano, Italy
Dipartimento di Energetica (e-ERG)
Piazza Leonardo da Vinci 32
20133 Milano
Andrew Pindar (Co-ordinator)
Lorenzo Pagliano

University of Nottingham, UK
School of the Built Environment
University Park
Nottingham NG7 2RD
Brian Ford
Rosa Schiano-Phan

AICIA, Spain
Asociación de Investigación y Cooperación Industrial de Andalucía
Escuela Superior de Ingenieros. Camino de los Descubrimientos s/n
E-41092, Sevilla
Servando Alvarez
Jose' Manuel Salmeron Lissen

ICE, France
International Conseil Energie
6 rue de Verdun
93450 Ile-Saint-Denis
Sophie Attali & Dominique Maigrot

Natural Works, Portugal
Projectos de Engenharia
Calcada Marques de Abrantes N48 2D
1200-719 Lisboa
Maria Malato Lerer
Guilherme Carrilho da Graca

INETI, Portugal
National Institute of Engineering Technology and Innovation I.P.
Estrada do Paço do Lumiar
1648-038 Lisboa
Helder Gonçalves
Luisa Brotas

MAIN SUBCONTRACTOR

Passivhaus Institut
Rheinstraße 44/46
D-64283 Darmstadt
Juergen Schneiders

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July 2007

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1 COMFORT MODELS

1.1 INTRODUCTION

Why are comfort models important to well-being and energy saving? Because they describe quantitatively (based on large surveys of people) in what range of conditions people will feel thermally comfortable in buildings, and because choosing too narrow a range of conditions can lead to unnecessary consumption of energy. And “avoiding unnecessary use of energy and ... safeguarding comfortable indoor climatic conditions (thermal comfort) in relation to the outside temperature” are among the stated goals of the Energy Performance of Buildings Directive (comma 16 of the preambule)

There are two prevailing comfort models (Fanger and Adaptive).
According to EN 15251 (2007) standard, acceptable comfort temperatures actually depend on the type of system used to provide summer comfort. If cooling is provided by an active system then indoor temperatures must respect those defined by the Fanger Model plus certain assumption of acceptability for different categories of buildings. Instead if summer comfort is provided by passive cooling strategies then the upper temperature limit is set by the Adaptive Model plus certain assumption of acceptability for different categories of buildings.

Generally the implementation of the Adaptive model indicates that indoor thermal comfort is achieved with a wider range of temperatures than does the implementation of the Fanger model. As said both models use statistical analysis of survey data to back up their claims in their respective areas of applicability.
In consequence in some situations it proves possible to maintain a building’s interior conditions within the Adaptive Comfort limits entirely by natural means. In these cases there is no energy use associated with achieving indoor summer comfort.

The implications are described by de Dear and Brager in “Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55”, Energy and Buildings 34 (2002) 549–561:
“If a building’s interior conditions were able to be maintained within the Adaptive Comfort limits entirely by natural means, then one could potentially save 100% of the cooling energy that would otherwise be used by an airconditioner to maintain conditions within the more narrow ASHRAE Standard 55 (based on Fanger model) comfort zone. If one were to apply the Adaptive Comfort to a mixed-mode building, however, the airconditioner might be used in a limited way to keep the more extreme temperatures from rising past the acceptability limits of the Adaptive Comfort Standard. In this case, the energy savings would be proportional to the difference between set-points defined by the upper limit of the Adaptive Comfort Standard, compared to typical setpoints used in an air-conditioned building. (…) Savings are likely to be much higher than indicated [note: in the article] since it is more common to find buildings operating at the center of the ASRHAE Standard 55 comfort zone (approximately 23°C) than at the upper end of 26°C.”

The present text explains the theory behind the two models and simple methods by which to determine year-round indexes of comfort based on the Fanger or the Adaptive models which can be used by architects and engineers in their endeavour to design successful passive and low energy buildings. The indexes serve to estimate how close to comfort conditions will be a certain specific house design.

1.2 THE SCIENTIFIC BACKGROUND

The thermal interaction between humans and the environment is highly complex such that it draws upon fields as wide as physiology (to study the internal processes by which we produce and respond to heat), psychology (our conscious feelings about the environment) and physics (the processes of heat transfer between humans and the environment). In addition, there are social and cultural factors which determine the way in which we react to the natural and built environment.

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We produce energy by metabolizing food and most of this energy takes the form of heat. The body produces this “metabolic heat” all the time, although more is produced when we are active. For the proper functioning of the organs of the body and particularly that of the brain, the temperature of the internal organs (the “deep-body” or “core” temperature) must be constant.

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Our impression of the warmth or cold of our environment from the skin sensors is integrated with the information about the core temperature on whether the overall effect is towards or away from the restoration of deep body equilibrium.

Psychophysics is the study of the relation between our sensations and the stimulus we receive from the physical world. Our feelings are not mapped on a one-to-one basis with the physical conditions which cause them; that is a particular stimulus gives rise to a range of sensation. In consequence we cannot say that a particular set of conditions will give rise to a particular sensation, only that there is a probability that a sensation will arise.

To the physicist, the human being is a heated object with variable surface characteristics, and which loses heat to the environment through three principal processes: convection, radiation and evaporation.
Normally heat loss by conduction is significantly smaller than heat loss by the other three processes and usually can be ignored though in certain circumstances, it too can become important.

The basic equation for energy balance of the human body is

$$H = W+S+K+C+R+E+E_{res}+C_{res}$$

Where H is the metabolic production, W is the work done and S is energy stored in the body (assumed zero over time). K, C and R are the heat losses (or gains) from skin (or clothing if covered) by conduction, convection and radiation. E is the heat loss from the skin by evaporation. E_{res} and C_{res} are the evaporative and convective heat exchanges through respiration. A further set of equations links the individual contributions of the energy balance equation to the metabolic rate, physical conditions of the skin, clothing levels and the environmental parameters (McIntyre, 1980; Parsons, 2002a).

As noted to ensure that the vital organs of the body work, the “deep-body” or “core” temperature of the body must kept close to 37°C. This occurs when for a given set of environmental conditions the S term of the energy balance equations is zero, i.e. the body does not accumulate energy. This condition is assumed in the Fanger model to equate with thermal comfort.

Though equation (1) provides a general understanding of physical comfort it is not directly helpful when designing buildings. Also importantly it only considers the purely physical aspects of comfort, not the physiological and psychological.

Two general approaches have been adopted when undertaking comfort surveys; the first looks at people in controlled laboratory environments, the second examines people in real buildings.

Both way experiments and surveys on thermal comfort, characterise a subject's feelings in terms of either “hotness”, or “coldness” or in terms of “comfort” and “desire for change”.

Generally surveys about feelings of hotness and coldness are measured on the seven point ASHRAE scale, (ASHRAE 55-2004 and ISO 7730), which offers a set of standard answers to the question: how do you feel at this time?

+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cold
-2	cool
-3	cold

Experiments using “comfort” or “desire for change” generally use either the three point McIntry scale of preference (for a warmer or cooler environment or no change), or a five point scale as used in the SCATs project. Both provide a set of standard responses to the question: how would do you prefer to be?

much cooler
a bit cooler
no change
a bit warmer
much warmer

1.3 THE FANGER MODEL AND LABORATORY STUDIES

Most scientific study of human thermal comfort has been undertaken in the controlled laboratory environment. Studies in the laboratory allow the of feelings hot or cold, comfort or desire for change to be recorded in relation to measured environmental variables (air temperature, humidity, airspeed, etc). By recording the response of a large number of people to different (precisely defined) environmental conditions it becomes possible to develop a statistical picture which links “comfort vote” (see last section) to the thermal conditions of the environment. In consequence it becomes possible, given the thermal conditions of an environment to predict the likely comfort vote of the future occupants, or alternatively to identify those conditions which maximise the comfort vote for the largest number of people.

There have been a number of attempts to present an index based on heat exchange theory which will specify the likely response to any given set of conditions and much research has been directed towards this goal.

This type of research has lead to the development of a number of indices. These include the revised Effective Temperature (ET) and its extended version, the Standard Effective Temperature (SET) both of which have been the basis of standards for the USA. However the most widely accepted comfort index is Fanger’s Predicted Mean Vote (PMV) (Fanger 1970). This index predicts the mean vote of a group of people on the ASHRAE scale when subject to a set of environmental variables. Together with the associated Probability of People Dissatisfied (PPD) index (see below) the PMV forms the basis of the EN/ISO7730 norm. The norm includes a computer program by which the two indices maybe calculated.

Fanger realized that the predicted vote was only the mean value to be expected from group of people and he extended the PMV to predict the proportion of any population (Probability of People Dissatisfied (PPD)) who will be dissatisfied with environment. Those who vote outside the central three scaling points on the ASHRAE scale (-1, 0, +1) were counted as dissatisfied. The PPD is defined in terms of the PMV and does provide any more information about the interaction between people and their environment than does the PMV.

The Fanger model is is based on steady-state heat flow theory and underpinned by measurements in which the subjects typically remain in any one particular condition for three hours.

1.3.1 Fanger PMV and PPD indexes

PMV and PPD are detailed in the following tables. From ISO 7730. 2005: “The PMV values given in the tables are calculated for a relative humidity of 50%. The influence of humidity on thermal sensation is small at moderate temperatures close to comfort and may usually be disregarded when determining the PMV value”

Index	**Predicted Mean Vote**	
Symbol	PMV	
Unit	[-]	
Definition	The PMV is an index that predicts the mean value of the votes of a large group of persons on the following 7-point thermal sensation scale: +3 hot +2 warm +1 slightly warm 0 neutral -1 slightly cold -2 cool -3 cold	ISO 7730:1994, revised 2005
Applies to	Global comfort 63%	

Determination	The *PMV* index is derived for steady-state conditions, but can be applied with good approximation during minor fluctuations of one or more of the variables, provided that time-weighted averages are applied. Measurement of the environmental parameters Measure the following parameters: - air temperature; - mean radiant temperature; - relative air velocity; - partial water vapour pressure, or relative humidity. In homogeneous environments these parameters should be measured at the abdomen level only. In heterogeneous environments they should be calculated as the average of the measured values at the head, abdomen and ankle levels. Estimation of the personal parameters Estimate the following parameters: - activity (metabolic rate); - clothing (thermal resistance). Determine the PMV index This can be done either : - from the equation given in ISO 7730 - which may be solved by iteration. - or using tables given in ISO 7730 for different combinations of activity, clothing level, operative temperature and relative air velocity. - or by direct measurement, using an integrating sensor	ISO 7730:1994
Validity conditions	The index shall be used only for values of PMV between -2 and +2 and when the six main parameters are within the following intervals.: The index shall be used only for values of PMV between -2 and +2 and when the six main parameters are within the following intervals.: - Activity between 0.8 and 4 met (46 to 232 W/m^2) - Clothing between 0 and 2 clo (0 m^2 K/W and 0,310 m^2 K/W - Air temperature t_a: 10 °C ≤ t_a ≤ 30 °C; - Radiant mean temperature t_{mr}: 10 °C ≤ t_{mr} ≤ 40 °C; Air velocity v_a: v_a ≤ 1 m/s; Water vapour partial pressure, p_a : 0 ≤ p_a ≤ 2700 Pa;	ISO 7730:1994, revised 2005
Recommended thermal comfort requirements	EN15251 recommends values of PMV comprised within the interval -0,5 to +0,5 for new buildings and renovations (category II) and within -0,7 to +0,7 for existing buildings (category III); ISO 7730:1994,(Annex D, informative) and ASHRAE 55-2004 recommend values of PMV comprised within the interval -0,5 to +0,5	EN 15251 – 2007; ISO 7730:1994, revised 2005; ASHRAE 55-2004

Index	**Predicted Percentage of Dissatisfied**	
Symbol	PPD	
Unit	[%]	
Definition	The *PPD* is an index that predicts the number of thermally dissatisfied persons among a large group of people. It is based on the PMV index (those who vote outside the central three scaling points on the ASHRAE scale (-1, 0, +1) are counted as dissatisfied) and it adds no information to it: it just presents the results in a different way.. It assumes the simplification that PPD is symmetric around a neutral PMV.	ISO 7730:1994; ASHRAE 55-2004
Applies to	Global comfort	

<table>
<tr>
<td>Determination</td>
<td>
Determination of the PPD index as a function of PMV
This can be determined either from the following equation:

$$PPD = 100 - 95 \cdot \exp(-0{,}033\,53 \cdot PMV^4 - 0{,}217\,9 \cdot PMV^2)$$

or found from the graph below.

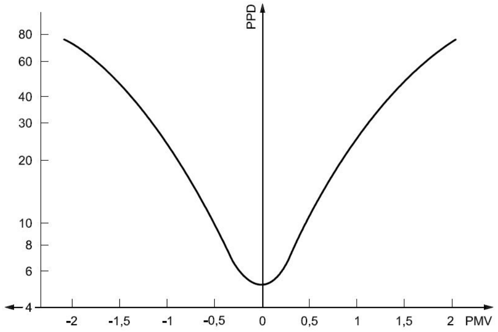
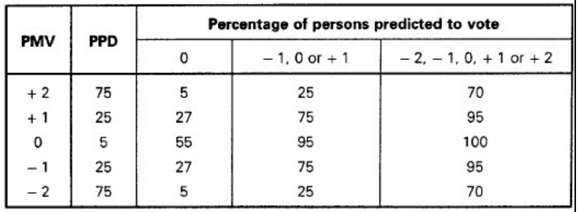


Figure 1 — Predicted percentage of dissatisfied (PPD) as a function of predicted mean vote (PMV)

Table 1 — Distribution of individual thermal sensation votes (based on experiments involving 1 300 subjects) for different values of mean vote



<table>
<tr><th rowspan="2">PMV</th><th rowspan="2">PPD</th><th colspan="3">Percentage of persons predicted to vote</th></tr>
<tr><th>0</th><th>– 1, 0 or + 1</th><th>– 2, – 1, 0, + 1 or + 2</th></tr>
<tr><td>+ 2</td><td>75</td><td>5</td><td>25</td><td>70</td></tr>
<tr><td>+ 1</td><td>25</td><td>27</td><td>75</td><td>95</td></tr>
<tr><td>0</td><td>5</td><td>55</td><td>95</td><td>100</td></tr>
<tr><td>– 1</td><td>25</td><td>27</td><td>75</td><td>95</td></tr>
<tr><td>– 2</td><td>75</td><td>5</td><td>25</td><td>70</td></tr>
</table>

Note that 5% of people are anyway dissatisfied (that is they vote outside the interval – 1 to +1) even when the mean vote is zero (neutral). The vertical scale is logarithmic
</td>
<td>ISO 7730:1994</td>
</tr>
</table>

Validity conditions	Same as PMV: The index shall be used only for values of PMV between -2 and +2 and when the six main parameters are within the following intervals.: - Activity between 0.8 and 4 met (46 to 232 W/m^2) - Clothing between 0 and 2 clo (0 m^2 K/W and 0,310 m^2 K/W - Air temperature t_a: 10 ℃ $\le t_a \le$ 30 ℃; - Radiant mean temperature t_{mr}: 10 ℃ $\le t_{mr} \le$ 40 ℃; Air velocity v_a: $v_a \le$ 1 m/s; Water vapour partial pressure, p_a : 0 $\le p_a \le$ 2700 Pa;	
Recommended thermal comfort requirements	EN15251 recommends values of PPD < 10 % for new buildings and renovations (category II) and < 15 % for existing buildings (category III); ISO 7730:1994,(Annex D, informative) and ASHRAE 55-2004 recommend values of PPD < 10 %	EN 15251 – 2007; ISO 7730:1994, revised 2005; ASHRAE 55-2004

1.3.2 Adjustment to take into account effect of air speed > 0.20 m/s

In addition to the recommendation for values of PMV and PPD to be adopted, and ISO 7730-2005 states that “
increased air velocity can be used to offset the warmth sensation caused by increased temperature.
Often, the air velocity is increased by opening of windows or use of fans to adapt to warmer environments. Under summer conditions, the temperature can be increased above the level allowed for comfort if a means is provided to also elevate the air velocity. The amount by which the temperature may be increased is shown in Figure 1.1. The combinations of air velocity and temperature defined by the lines in this figure result in the same total heat transfer from the skin. The reference point for these curves is 26 ℃ and 0,20 m/s of air velocity. The benefits that can be gained by increasing air velocity depend on clothing, activity, and the difference between the surface temperature of the clothing/skin and the air temperature. Figure 3.1 shows the air velocity that is required for typical summer clothing (0,5 clo) and sedentary activities (1,2 met) that correspond to summer comfort.”

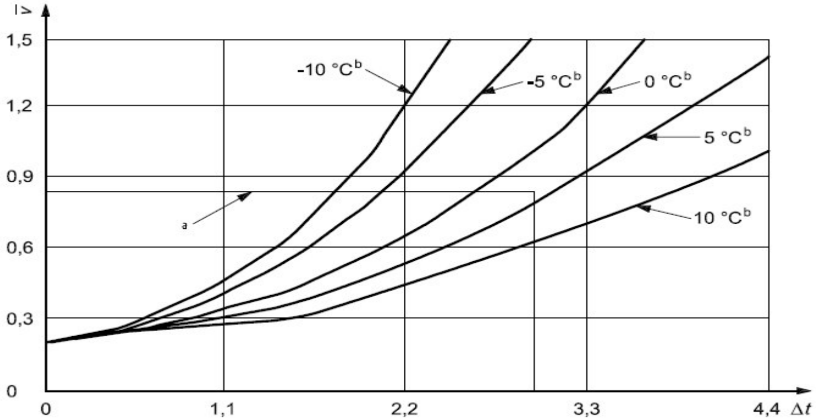


Fig. 1. 1 – Adaptation of indoor temperature by increasing air velocity, from the reference values T = 26 ℃ and v = 0,2 m/s. For light, primarily sedentary activity, Δt should be ≤ 3 ℃ by v < 0,82 m/s.

Δt rise in comfort temperature above 26 ℃

v mean air velocity, [m/s]

[a] Limits for light, primarily sedentary, activity.

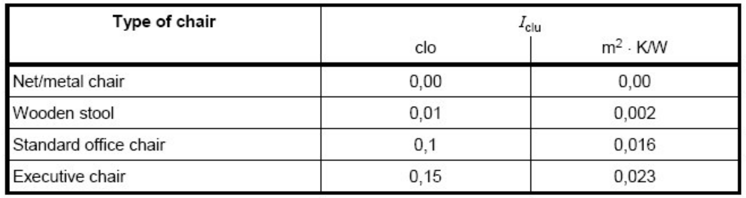
[b] $(t_r - t_a)$, ℃ (t_a, air temperature, ℃; t_r , mean radiant temperature, ℃).

Hence, if the pure PMV calculation and recommendation lead to a temperature of 26 ℃ at v = 0,2 m/s, the above means that with an air velocity of 0,82 m/s, temperature can be raised to 29 ℃ maintaining the same level of comfort

1.3.3 Adjustment to take into account insulation level of furniture

ISO 7730-2005 suggests (Annex C, informative), values of Thermal insulation for chairs. The values given in Table 1.1 may be added to individual garment insulation values or to the ensemble clothing values

Table 1. 1 – Thermal insulation values of different types of chairs, to be added to the clothing values in mainly sedentary working environments.



Type of chair	I_{clu}	
	clo	$m^2 \cdot K/W$
Net/metal chair	0,00	0,00
Wooden stool	0,01	0,002
Standard office chair	0,1	0,016
Executive chair	0,15	0,023

1.3.4 Critical issues connected to PMV-PPD indexes

Several authors have raised a number of issues with the PMV model:.

- the subjective data on which Fanger's model is based were obtained exclusively from climate chamber studies where a steady state heat exchange had been reached between subject and environment; in particular observations were made after the subjects had been subject to constant conditions for three hours.

- the value of clothing insulation used by the practitioner is obtained from tables in which clothing insulation is listed against descriptions of items or ensembles of clothing. The new version of ISO 7730 acknowledges that activity, ventilation, body movement reduce the insulation of clothing. Hence new (relatively complex) correlations are proposed to determine the insulation level as a function of air velocity relative to the person, walking speed and other variables
- metabolic rate is similarly obtained from tables which assign a certain metabolic rate to specified activities. Various authors (Baker and Standeven, 1995), Nicol and Humphreys (1973), and Fanger and Toftum (2002) have all suggested that the metabolic rate associated with a given activity may vary with temperature, rather than being a constant value.

For the building designer aiming to provide a comfortable indoor environment these characteristics of the Fanger model pose a number of problems.

- He/she must assume what clothing the occupants of the building will wear.

- He/she must know what activity they will be engaged in, which poses an additional problem for buildings where a number of activities are taking place in the same space.

- He/she must assume that conditions in the building approach those of the steady-state as achieved in the climate chamber.

All these factors tend to direct the designer towards a highly serviced building which provides closely controlled internal conditions appropriate to some assumed clothing level and activity.

Indeed, the method is difficult to apply to buildings with no mechanical air conditioning. The temperature in a free-running building will almost certainly change continually with time, particularly were occupants have some control over energy sinks and sources (for example the possibility to open windows). This intrinsically variable situation of free running buildings contrasts with the steady state conditions on which the PMV model was defined.

By examining data from a wide range of field studies conducted around the world (using the “ASHRAE database of field studies”) Humphreys showed that the range of temperatures that subjects found comfortable was much wider than predicted by the PMV (Humphreys (1976). In particular Humphreys calculated the comfort temperature predicted by the PMV equation from the recorded environmental variables in the database which he

then plotted against the comfort temperature derived from interviews to occupants.
The results were that PMV prediction was reasonably accurate for air-conditioned buildings, but inaccurate at predicting comfort temperatures as resulting from surveys of occupants of Naturally Ventilated buildings

Humphreys went on to show that comfort temperature as resulting from surveys of occupants of Naturally Ventilated Buildings showed a stronger relationship to outdoor temperatures than it did to the comfort temperature predicted by the PMV model. (Figure 1.2).

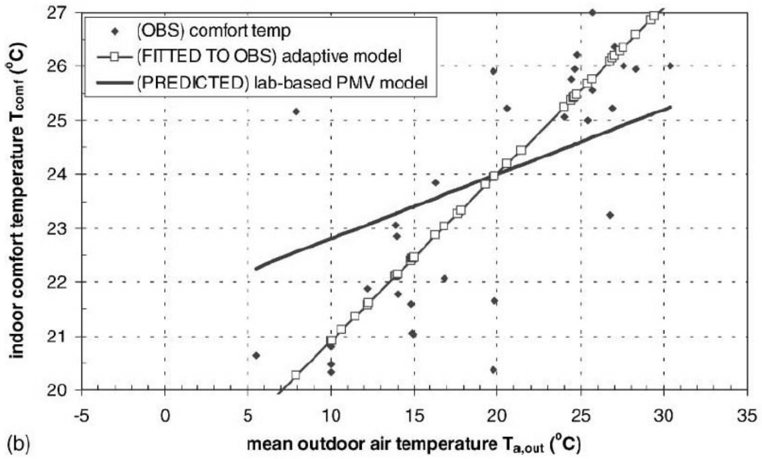


Fig. 1. 2 – Difference between predicted comfort temperatures with PMV calculations and comfort temperatures obtained from the ASHRAE database of field studies in naturally ventilated buildings.

ISO 7730-2005 incorporates these type of findings stating that “Extended acceptable environments may be applied for occupant-controlled, naturally conditioned, spaces in warm climate regions or during warm periods, where the thermal conditions of the space are regulated primarily by the occupants through the opening and closing of windows. Field experiments have shown that occupants of such buildings could accept higher temperatures than those predicted by the PMV. In such cases, the thermal conditions may be designed for higher PMV values than those given in Clause 6 and Annex A”

1.4 THE ADAPTIVE MODEL AND FIELD STUDIES

1.4.1 Description

The Adaptive Approach to thermal comfort has been developed from field-studies of people in daily life. While lacking the rigour of laboratory experiments, field studies have a more immediate relevance to ordinary living and working conditions. The adaptive method, unlike the heat-exchange method, does not require knowledge of the clothing insulation and the metabolic rate in order to establish the temperature required for thermal comfort. Rather it is a behavioural approach, and rests on the observation that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity.

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*.

They do this by making adjustments (adaptations) to their clothing, activity and posture, as well as to their thermal environment. The set of conceivable adaptive actions in response to warmth or coolness may be classified into five categories:

- regulating the rate of internal heat generation
- regulating the rate of body heat loss
- regulating the thermal environment
- selecting a different thermal environment
- modifying the body's physiological comfort conditions.

In fact ISO 7730-2005, after describing in detail the PMV-PPD method, states: "In determining the acceptable range of operative temperature according to this International Standard, a clothing insulation value that corresponds to the local clothing habits and climate shall be used. In warm or cold environments, there can often be an influence due to adaptation. Apart from clothing, other forms of adaptation, such as body posture and decreased activity, which are difficult to quantify, can result in the acceptance of higher indoor temperatures. People used to working and living in warm climates can more easily accept and maintain a higher work performance in hot environments than those living in colder climates...

EN 15251 (2007) gives more detailed guidance on how to use the Adaptive model (see below)

1.4.2 The relationship between comfort temperature and indoor temperature

In field surveys the comfort temperature is closely correlated to the mean indoor temperature measured over a number of days (or weeks). This was found to be the case in surveys conducted over a wide range of indoor climates (Figure 1.3a). A similar effect was found when data were collected in Pakistan (Nicol et la, 1999) and Europe (McCartney and Nicol, 2002) from the same group of subjects at monthly intervals throughout the year (Figure 1.3b). The variety of indoor temperatures, particularly in Pakistan, is remarkable. The data show a strong relationship of comfort temperature with indoor temperature.

Nicol and Humphreys suggested that this effect could be the result of feedback between the thermal sensation of subjects and their behaviour and that they consequently "adapted" to the climatic conditions in which the field study was conducted.

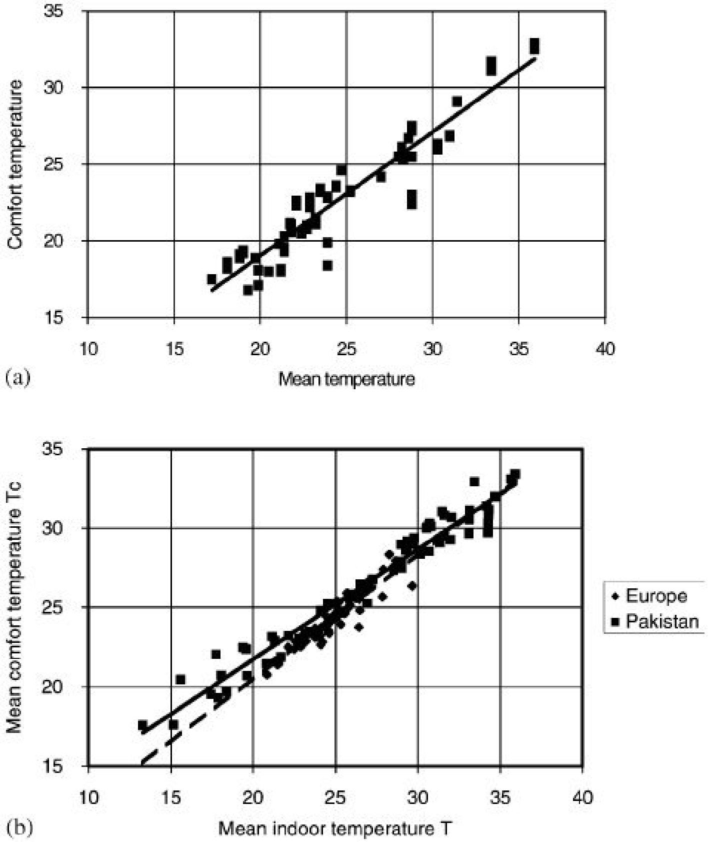


Fig. 1. 3 – The variation of comfort temperature with mean historic indoor temperature (a) from surveys throughout the world (from data presented in Humphreys (1976) and (b) from within a particular set of climates (Europe (dashed line) and Pakistan) but at different times of the year (from Nicol and Humphreys, Energy and Buildings 34, 2002)

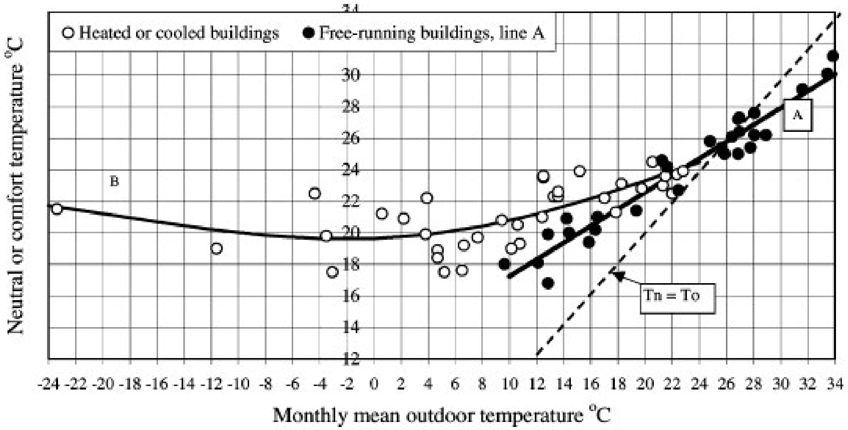


Fig. 1. 4 – The change in comfort temperature with monthly outdoor temperature. Each point represents the mean value for one survey. The buildings are divided between those that are climatised at the time of the survey and those that are free-running. Subsequent analysis of the ASHRAE database of comfort surveys (Humphreys and Nicol, 2000a) showed similar results (after Humphreys, 1978)

1.4.3 The relationship between comfort temperature and outdoor temperature

Humphreys (1978) took the indoor comfort temperature recorded in a number of surveys conducted world-wide and plotted them against the outdoor monthly mean temperature at the time of the survey. The results are shown in Figure 1.4 above. Humphreys found a clear division between the comfort temperature expressed by people in buildings which were free-running (neither heated nor cooled) at the time of the survey and the comfort temperature expressed by those in buildings that were climatized (heated or cooled) at the time of the survey. For free running buildings the observed comfort temperature proved to be almost linearly dependent on the past outdoor temperature. In climatized buildings the relationship is more complex.

1.4.4 The running mean outdoor temperature

The Adaptive model derives from surveys of people in real buildings a relationship between comfort indoor operative temperature and past outdoor temperatures. The relationship between indoor comfort and outdoor temperature has been expressed (e.g. in ASHRAE 55-2004) in terms of the monthly mean of the outdoor temperature. Important variations of outdoor temperature do however occur at much shorter than monthly intervals. Adaptive theory suggests that people respond on the basis of their thermal experience, with more recent experience being more important. A running mean of outdoor temperatures weighted according to their distance in the past may be used to characterise the response. The exponentially weighted running mean of the daily mean outdoor air temperature T_{rm} is such a series, and is calculated from the formula:

$$T_{rm} = (1-\alpha).\{T_{od-1} + \alpha.T_{od-2} + \alpha^2 T_{od-3}.....\} \qquad (1)$$

Where T_{od-1} is the outdoor daily mean temperature for the previous day, T_{od-2} is the outdoor daily mean temperature for the day before and so on. α is a constant between 0 and 1 which defines the speed at which the running mean responds to the outdoor temperature. The use of an infinite series would be impracticable were not equation (1) reducible to the form:

$$_{n}T_{rm} = (1-\alpha).T_{od-1} + \alpha._{n-1}T_{rm} \qquad (2)$$

Where $_{n}T_{rm}$ is the running mean temperature for day n and $_{n-1}T_{rm}$ for the previous day. So if the running mean has been calculated (or approximated) for one day, then it can be readily calculated for the next day, and so on.

The SCATs project which was undertaken in Europe has provided a value of α of 0,8 for this region. Such a value implies that the characteristic time subjects take to adjust fully to a change in the outdoor temperature is about a week.
The exponentially weighted running mean of the daily mean outdoor air temperature is used in EN 15251 (2007)

1.4.5 Application to offices

The section details the correlation between the inddor operative comfort temperature and running mean of the daily mean outdoor air temperature.

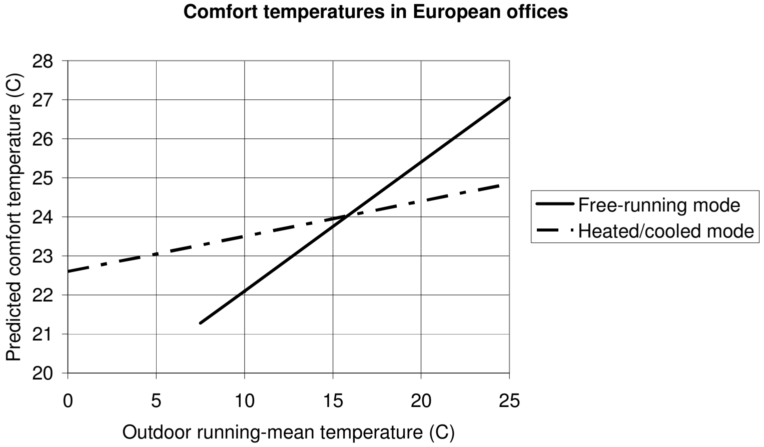


Fig. 1. 5 – optimal comfort temperatures for free running (continuous line) and heated and cooled (dashed line) buildings from the SCATs database (see equations 3 and 4)

Figure 1.5, plots comfort operative temperatures as a function of running mean outdoor temperature for free-running and for heated or cooled buildings as determined from the European SCATs project, from the analysis of interviews in real buildings. A well designed building is one in which indoor temperatures change only gradually in response to changes in the weather, and follow the plots of Figure 1.5.. The comfort temperatures are defined by the equations:

For free-running operation $T_{comf} = 0{,}33\ T_{rm} + 18{,}8$ (3)
For heated or cooled operation $T_{comf} = 0{,}09\ T_{rm} + 22{,}6$ (4)

Where T_{comf} is the estimated comfort temperature (^{o}C) for the particular mode of operation and T_{rm} is the exponentially-weighted running mean of the daily mean outdoor temperature with $\alpha = 0{,}8$.
Equation (4) has been included into EN 15251, approved in 2007.

1.4.6 Occupant control

Adaptation is assisted by the provision of control over the thermal environment. So where practicable, convenient and effective means of control should be provided to occupants to allow them adjust the thermal environment to their own requirements. This ‘adaptive opportunity’ may be provided in the summer, for instance, by fans or windows which can be opened and in the winter or by local temperature controls. A control band of ± 2K (or a bandof air velocity producing an equivalent effect) should be sufficient to accommodate the great majority of people (see below). Individual control is more effective in promoting comfort than is group-control.

1.4.7 Customary thermal environments and comfort

Comfort temperatures are not fixed, but are subject to gradual drift in response to changes in both outdoor and indoor temperature. A departure from the current comfort temperature, if suddenly imposed upon the occupants, is likely to provoke discomfort and complaint, while a similar change, occurring gradually over several days or longer, would be compensated by a gradual corresponding change in clothing, and would not provoke complaint. In particular:

Temperature drifts during a day. Field research has provided results which indicate the extent and rapidity with which people will adapt their clothing and therefore which temperature drifts are acceptable. The studies have found that in offices during the working day there is surprisingly little systematic clothing-adjustment in response to variations in temperature. As a consequence it is desirable that the temperature during office hours vary little from the customary temperature. Temperature drifts within ±1 K of the comfort temperature would attract little notice, while ±2 K would be likely to attract attention and cause some mild discomfort.

Temperature drifts over several days. The adjustments people make to clothing and their local environment (for example opening or closing windows) in response to day-on-day changes in temperature as the building responds to weather and seasonal changes, occur quite gradually, and take a week or so to complete. It is desirable therefore that the day-to-day change in mean indoor Operative temperature during office hours does not normally exceed about ± 1 K, nor does the cumulative change over a week exceed about ±3 K. These figures apply to sedentary or lightly active people.

Dress codes. The extent of seasonal variation in indoor temperature that is consistent with comfort depends on the extent to which the occupants wear cool clothing in summertime and warm clothing in wintertime. Some dress codes restrict this freedom, and have consequences for thermal design, for services provision, and consequently for energy consumption. Organisations that have dress codes should be made aware of this, and be encouraged to incorporate adequate seasonal flexibility.

1.4.8 Probable comfort temperatures in relation to climate.

During the summer months many buildings in Europe are free-running (i.e. not heated or cooled). The temperatures in such buildings will change according to the weather outdoors, as will the clothing of the occupants. Even in air-conditioned buildings the clothing has been found to change according to the weather. As a result the temperature people find comfortable indoors also changes with the weather. Comfort evaluation of homes meeting *Passivhaus* standard are proposed in the following chapter.

1.5 THE *PASSIVHAUS* PROPOSALS AND INDOOR COMFORT

Part 1 of the guidelines identifies a set of house designs for meeting the *Passivhaus* standard in the UK, France, Italy, Portugal and Spain. These designs are discussed in more detail in Part 2. These proposals were developed by careful modelling of the thermal behaviour of the homes via a simulation software (for example using Energy Plus or DYNBIL dynamic modelling environments). The models and associated software allow the building energy requirements, and indoor temperature (air and radiant temperature, whose weighted mean is the operative temperature) and humidity levels of the different spaces to be accurately predicted over time.

Buildings are modelled in respect of given set of climatic conditions. Most building dynamic modelling environments make use of climatic data files containing hourly records of climatic variables (for example: air temperature, wind speed and direction, insolation levels) for a full year, allowing indoor temperature and humidity levels to be predicted at hourly time intervals.

By comparing the modelled (predicted) indoor temperatures with the “Comfort temperature” defined by the two comfort models (Fanger and Adative) it is possibile to either:

- evaluate to what degree a proposed building provides Comfortable indoor conditions
- or progressively improve a building design in order to ensure that Comfort conditions are effectively achieved.

In naturally ventilated homes indoor temperatures in summer will vary over time such that at certain hours of the day Comfort conditions may be achieved, whereas at other times indoor temperatures may be above the temperatures defined by the Fanger or Adaptive models as comfortable. In order to evaluate the Comfort conditions over the year it is possibile to either:

- report the seasonal indoor temperatures and Comfort temperatures on a graph and qualitatively compare and establish whether Comfort temperatures are on the all achieved
- develop a “Comfort Index” which weighs and sums the difference between predicted indoor temperatures and neutral Comfort temperates at each hour of the day over the summer period

Three comfort indexes were used to evaluate the Comfort conditions of the homes reported in part 1. The Comfort Indexes sum the “distance” between the predicted room operative temperature and the neutral temperature (or band) at each hour over the entire year.
In the first index the neutral temperature is that defined by Fanger model and codified by the ASHRAE 55 standard, and includes a correction for air velocity and humidity. Both day and night time neutral comfort temperatures were determined by considering different metabolic rates and clothing levels.

In the second Comfort Index, the neutral Comfort temperature is defined on the basis of the Adaptive Models codified in the En 15251 standard which defines neutral Comfort temperature based on the running average of the external air temperature of the previous day.

The third Comfort Index, the neutral Comfort temperature is defined on the base of the monthly Adaptive Models reported in ASHRAE 55.
In all three cases the Comfort Index provides a value in terms of hours.
In particular:

FI (Fanger Index) =

$$\sum_{h=1}^{t}\left(1+\frac{\left|(T_{op})_h-(T_{fanger,\lim it})_d\right|}{\left|(T_{fanger})_d-(T_{fanger,\lim it})_d\right|}\right)_h \cdot h$$

AI1 (Adaptive Index 1) =

$$\sum_{h=1}^{t}\left(1+\frac{\left|(T_{op})_h-(T_{adaptive-ASHRAE55,\lim it})_d\right|}{\left|(T_{adaptive-ASHRAE55})_d-(T_{adaptive-ASHRAE55,\lim it})_d\right|}\right)_h \cdot h$$

AI2 (Adaptive Index 2) =

$$\sum_{h=1}^{t}\left(1+\frac{\left|(T_{op})_{h}-(T_{adaptive-prEN15251,\lim it})_{d}\right|}{\left|(T_{adaptive-prEN15251})_{d}-(T_{adaptive-prEN15251,\lim it})_{d}\right|}\right)_{h}\cdot h$$

Where $T_{fanger,limit}$ and $T_{adaptive,limit}$ are the upper limits of comfort range in °C. A low value of Comfort Index indicates a home in which temperatures exceed acceptable comfort temperatures for only a few hours a year. That is the lower the value of the Comfort Index the more comfortable the proposed home. In developing the homes presented in Parts 1 and 2 the design teams worked to two restraints:

- ensure heating and cooling demand were below 15 kWh/m^2/year
- ensure weighted average index Adaptive Index AI1 equaled, or was very close to zero (i.e. that homes were comfortable)

That is the proposed designs provide comfortable homes with a very low energy demand.

The Comfort Indexes determined from the analysis of proposed homes are reported in Parts 1 and 2.

2 CLIMATE CHARACTERIZATION

2.1 CLIMATIC SEVERITY INDEX

In order to calculate the heating and cooling demand of any given building, it is necessary to have trustworthy climatic data which represents its location. Although extreme climatic data is enough in maximum power calculations, it is different in the case when the target is to determine the total building energy demand. In this last case, it is necessary to have climatic data of the period which we are interested in, normally annual data. In this sense, climatic data from available databases have been used.

The climatic data coming from the databases, previously mentioned, present as disadvantage that building characteristics do not take part in the files generation, whereas the building and its surroundings modify external conditions.

In one research project [Markus et al 1984] a technique was developed which allows characterizing the hardness of any given climate on a building of known characteristics. This technique is carried out by means of the calculation of the Climatic Severity Index (CSI), a single number on a dimensionless scale which is specific for each building and location. The advantage of the Climatic Severity Index (CSI), in contrast to the simple degree day total, is that it takes in account more climatic variables (radiation, number of sun hours, etc.) and building characteristics.

The use of the Climatic Severity Index (CSI) allows the analysis of the influence on the building heating and cooling demand of possible modifications in the external climatic excitations. For this aim, it is necessary, on the one hand, to relate the Climatic Severity Index (CSI) to the heating and cooling demands and, on the other hand, to the climatic variables.

2.1.1 Determination

Two different winter climatic conditions could be considered identical if the heating demand is the same in a certain building. Then, we could say that both winter climatic conditions have the same Winter Climatic Severity (WCS).

The same definition is valid for cooling demand and the term used would be Summer Climatic Severity (SCS). It could happen that two different climatic conditions have equal Winter Climatic Severity (WCS) and different Summer Climatic Severity (SCS), and vice versa.

In the task of building components characterization, the heating and cooling demand have been obtained for 8 buildings in 18 locations. Taking the average value of heating demand and cooling demand from all the buildings in each location, one heating demand and one cooling demand have been assigned to each location. In order to standardize, all the heating demands and cooling demand values are divided by Madrid values. By this way, we get the Winter Climatic Severity (WCS) and Summer Climatic Severity (SCS) in each location, the values appear in the Table 1.

Table 2. 1 – Climatic Severity Indexes in European locations

Location	Winter Climatic Severity (WCS)	Summer Climatic Severity (SCS)
Germany (Dresden)	3.31	0.00
Germany (Braunschweig)	2.56	0.05
Germany (Freiburg)	2.14	0.10
United Kingdom (Brighton)	1.83	0.01
United Kingdom (Glasgow)	2.59	0.00
United Kingdom (London)	2.22	0.01
United Kingdom (Newcastle)	2.59	0.00
United Kingdom (Nottingham)	2.36	0.00
France (Agen)	1.44	0.19
France (Carcassonne)	1.24	0.37
Italy (Milan)	1.81	0.46
Italy (Rome)	0.83	1.19
Italy (Trapani)	0.32	1.87
Portugal (Lisbon)	0.37	1.05
Spain (Seville)	0.32	2.56
Spain (Madrid)	1.00	1.00
Spain (Granada)	0.81	1.11
Spain (Burgos)	1.96	0.05

2.1.2 Correlation

We have obtained correlations based on the degrees days and the relative daylight hours with the aim of extrapolating Climatic Severity Index (SCI) to other European locations which have weather data,

Winter Climatic Severity (WCS)

$$WCS = a \times HDD + b \times {}^{Wn}\!/_{WN} + c \times HDD^2 + d \times \left({}^{Wn}\!/_{WN}\right)^2 + e$$ where

HDD:
Average of heating degree days in base temperature 20 ºC for the months of January, February, March, April, May, October, November and December.

Wn / WN :
Ratio between measured daylight hours and maximum daylight hours for the months of January, February, March, April, May, October, November and December.

a	b	c	d	e
1.1408E-04	-5.8977E+00	1.4057E-07	5.0562E+00	1.5812E+00

The next Figure 1 shows a graph with one 45º line which represents simulations results in x-axis and results using the correlations of Winter Climatic Severity in y-axis. The buildings simulated are the standard houses in the partner countries of the Passive On project.

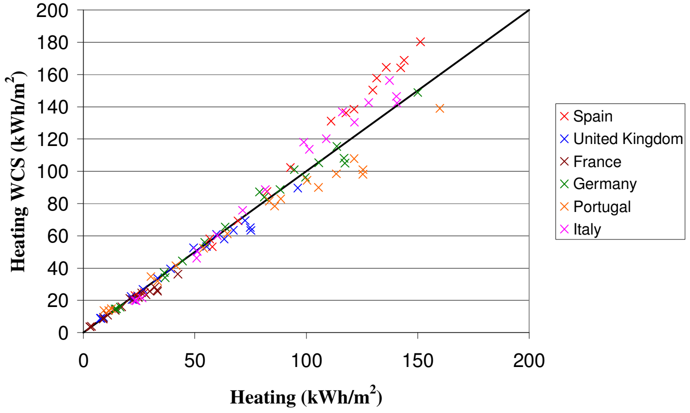


Fig. 2. 1 – Correlations of Winter Climatic Severity

Summer Climatic Severity (SCS)

$$SCS = a \times CDD + b \times {}^{Sn}\!/_{SN} + c \times CDD^2 + d \times \left({}^{Sn}\!/_{SN}\right)^2 + e$$ where

CDD:
Average of cooling degree days in base temperature 20 ºC for the months of June, July, August and September.

Sn / SN:
Ratio between measured daylight hours and maximum daylight hours for the months of June, July, August and September.

a	b	c	d	e
1.3679E-03	1.8050E+00	4.0014E-06	-2.1385E+00	-4.1027E-01

The next Figure 2 shows a graph with one 45º line which represents simulations results in x-axis and results using the correlations of Summer Climatic Severity in y-axis. The buildings simulated are the standard houses in the partner countries of the Passive On project.

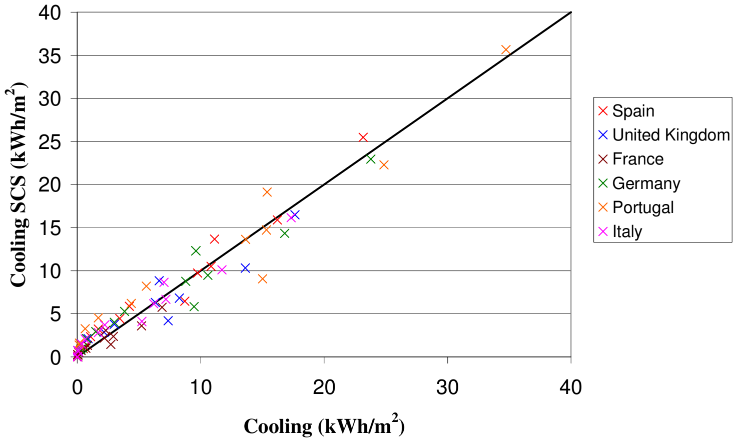


Fig. 2. 2 – Correlations of Summer Climatic Severity

2.1.3 Example

As application example, one building from United Kingdom is simulated with climatic data from Seville (Spain) and from London (United Kingdom) whereas the rest of parameters maintain the same values. The simulation results are the followings:

Heating Demand (Seville) = 14.80 kWh/m^2
Heating Demand (London) = 99.67 kWh/m^2

If we had applied the Winter Climatic Severity indexes from Table 1, the results would have been obtained through the next equation:

$$\frac{HD_1}{WCS_1} = \frac{HD_2}{WCS_2}$$

where

HD_1 and HD_2 Heating demand in locations 1 and 2 respectively.

WCS_1 and WCS_2 Winter Climatic Severity in locations 1 and 2 respectively.

Applying the last relation, the London's heating demand, obtained from Seville's heating demand, would be:

$$\frac{HD_1}{2.22} = \frac{14.80\ kWh/m^2}{0.32}$$

$$HD_1 = 102.68\ kWh/m^2$$

To sum up, the Climatic Severity Index procedure allows extrapolating results from one climate to another one with sufficient approximation and it is a powerful tool for mapping tasks.

2.2 HEATING ENERGY SAVING WHEN THE INSULATION LEVEL INCREASE

The objective of this approach is to find the relation between the insulation level increase and its effect on the heating energy savings. For this aim the insulation level of a particular component (i.e. Wall) is modified whereas the rest of the components maintain their original values. A high number of cases are run on the AICIA's Dynamic Thermal Modelling (DTM) software. This allows the determination of the influence of different U-values on the buildings energy demand as well as the estimation of some trends.

Thus, the approach is divided in the following four sections:

1. Energy savings in external walls due to the insulation increase.
2. Energy savings in roofs due to the insulation increase.
3. Energy savings in floors due to the insulation increase.
4. Energy savings in windows due to the insulation increase.

2.2.1 Important study parameters

The influence of the insulation level increase on the heating demand saving has been analysed by means of the next parameters:

1. Climate. All the European climates have been taken in account through the Winter Climate Severity (WCS) and the climate extrapolations have been made of simulations results from Seville, Granada, Madrid, Burgos and Dresden. This is justified because all the WCS indexes are between Seville's WCS and Dresden's WCS.
2. Architecture. The buildings simulated are nineteen: fourteen from Spain, one from Germany, Italy, United Kingdom, Portugal and France.
3. Orientation. All the buildings have been rotated eight times, each 45º. That is, all the building component elements have been simulated in different building orientations (N, NE, E, SE, S, SW, W and NW).
4. Component. (External Walls, Roofs, Floors and Windows). Five sufficiently representative elements have been selected per component in each building.
5. Insulation level. The insulation level is modified by means of three U-values.

To sum up, the total number of simulations run on AICIA's Dynamic Thermal Modelling (DTM) has been 45600 cases (5 locations × 19 buildings × 8 orientations × 4 components × 5 elements × 3 insulation levels)

The analysis of the simulations results has allowed us to arrive at important conclusions to obtain the relation between insulation level increases and heating demand savings. These conclusions are the followings:

1. A frequency distribution exists of heating demand savings in function of the location, orientation and insulation level. Figure 2.3 gives an example of this frequency distribution in walls and the Table 2.2 shows the corresponding average, maximum and minimum values, typical deviation and the 90 and 10 percentile.

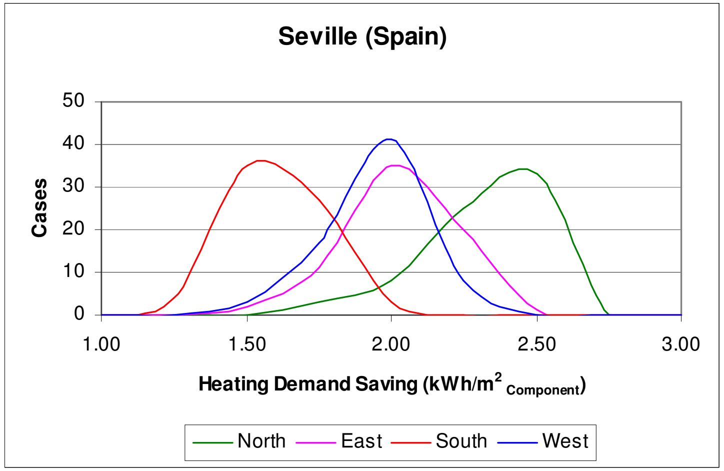


Fig. 2. 3 – Frequency distribution in heating demand saving on walls (ΔU = 0.09 W/m2K)

Table 2. 2 – Heating demand saving on walls (ΔU = 0.09 W/m2K)

$kWh/m^2_{Component}$	North	East	South	West
90 Percentile	2.40	2.08	1.10	2.02
10 Percentile	1.90	1.68	1.28	1.65
Average	2.19	1.90	1.48	1.84
Typical Deviation	0.194	0.177	0.161	0.179

2. The heating demand saving is directly proportional to the insulation level, therefore the ratio heating demand saving / insulation level only depends on the climate and orientation. Tables 2.3, 2.4 and 2.5 show these ratios for three insulation levels in Seville (Spain), regarding this data, it is clear that the ratio heating demand saving / insulation level data does not depend on the insulation level.

Table 2. 3 – Ratio heating demand saving / insulation level on walls (ΔU = 0.09 W/m²K)

Dimensionless	North	East	South	West
90 Percentile	26.64	23.10	18.85	22.46
10 Percentile	21.15	18.67	14.27	18.36
Average	24.32	21.12	16.46	20.44
Typical Deviation	2.15	1.97	1.79	1.98

Table 2. 4 – Ratio heating demand saving / insulation level on walls (ΔU = 0.12 W/m²K)

Dimensionless	North	East	South	West
90 Percentile	26.51	23.03	18.76	22.31
10 Percentile	21.30	18.59	14.33	18.44
Average	24.15	21.00	16.43	20.34
Typical Deviation	2.13	1.88	1.72	1.88

Table 2. 5 – Ratio heating demand saving / insulation level on walls (ΔU = 0.21 W/m²K)

Dimensionless	North	East	South	West
90 Percentile	26.56	23.06	18.82	22.36
10 Percentile	21.08	18.60	14.31	18.36
Average	24.22	21.05	16.44	20.39
Typical Deviation	2.14	1.92	1.75	1.92

2.2.2 Proposed correlations

Taking in account the last deductions, one correlation could be found to get the ratio heating demand saving / insulation level in function of the orientation and climate.

2.2.2.1 Independent variables

The independent variables are the orientation and the climate but both of them can be represented by the external excitation (temperature and radiation) since the solar radiation on vertical surface include the orientation effect.

Thus, the external excitation of a building component element is

$$q = A \cdot h_{CR} \cdot \left(T_{SA} - T_{ES}\right)$$

where,

A = Area of the building component element

h_{CR} = Convective/radiant coefficient

$$h_{CR} = h_C + h_R$$

h_C = Convective coefficient

h_R = Radiant coefficient

T_{ES} = External surface temperature

T_{SA} = Sun/air temperature

$$T_{SA} = \frac{\alpha \cdot I}{h_{CR}} + T_{eq}$$

α = Absorptivity

I = Incident solar radiation on the building component element

The solar incident radiation on a building element depends on the type of component (walls, floors, roofs or windows) to which it belongs. According to the component building position, the global solar radiation is calculated following the next procedures:

- On walls and windows: Global solar radiation is equal to the sum of direct solar vertical radiation in accordance with the orientation, diffuse solar radiation and reflected solar radiation.

- On roofs: Global solar radiation is equal to the sum of direct solar horizontal radiation and diffuse solar radiation.

- On floors: Global solar radiation is equal to 0.

T_{EQ} = Equivalent temperature

$$T_{EQ} = \frac{h_C \cdot T_A + h_R \cdot T_R}{h_C + h_R}$$

T_A = Air temperature

T_R = Radiant temperature

The sun-air temperature, previously defined, can be used to obtain the Modified Heating Degree Days (MHDD) whose calculation is similar to the known Heating Degree Days (HDD) but replacing the air temperature with the sun-air temperature.

Modified Heating Degree Days (MHDD) are calculated in base temperature 20 ºC for the months of January, February, March, April, May, October, November and December. This parameter includes more information than the traditional Heating Degree Days (HDD) since the orientation, the external radiation and the average radiant temperature are taken in account.

2.2.2.2 Correlations

The simulations results have been used to obtain two groups of correlations, one corresponding to conduction in walls, roofs, floors and windows and the second to radiation in windows. In conduction in walls, roofs, floors and windows, the functional dependency is the following:

$$\frac{\Delta D}{A \cdot \Delta U} = \text{f (Climate, Orientation)}$$

where

ΔD = Heating demand saving (kWh)
ΔU = Increase of insulation level (W/m^2 K)
A = Area of the building component element (m^2)

Meanwhile, in the case of radiation in windows, that dependency is the next one:

$$\frac{\Delta D}{A \cdot \Delta g} = \text{f (Climate, Orientation)}$$

where

ΔD = Heating demand saving (kWh)
Δg = Increase of solar factor (dimensionless)
A = Area of the building component element (m^2)

The correlation type is linear, leading to the next expressions:

- Conduction in walls, roofs, floors and windows

$$\frac{\Delta D}{A \cdot \Delta U} = a \cdot MHDD$$

where

$MHDD$ = "Modified Heating Degree Days"
a = Proportionality constant. Its values are the followings:

Table 2. 6 – Constants of the correlations for conduction in walls, floors, roofs and windows

	a (kwh/(W/K × DD))
90 Percentile	0.835
10 Percentile	0.651
Average	0.754

Radiation in windows

$$\frac{\Delta D}{A \cdot \Delta g} = a \cdot RG$$

Where

GR = Global radiation (W/m^2)
a = Proportionality constant. Its values are the followings:

Table 2. 7 – Constants of the correlations for radiation in windows

	a (kwh/(W/K × DD))
90 Percentile	0.705
10 Percentile	0.355
Average	0.536

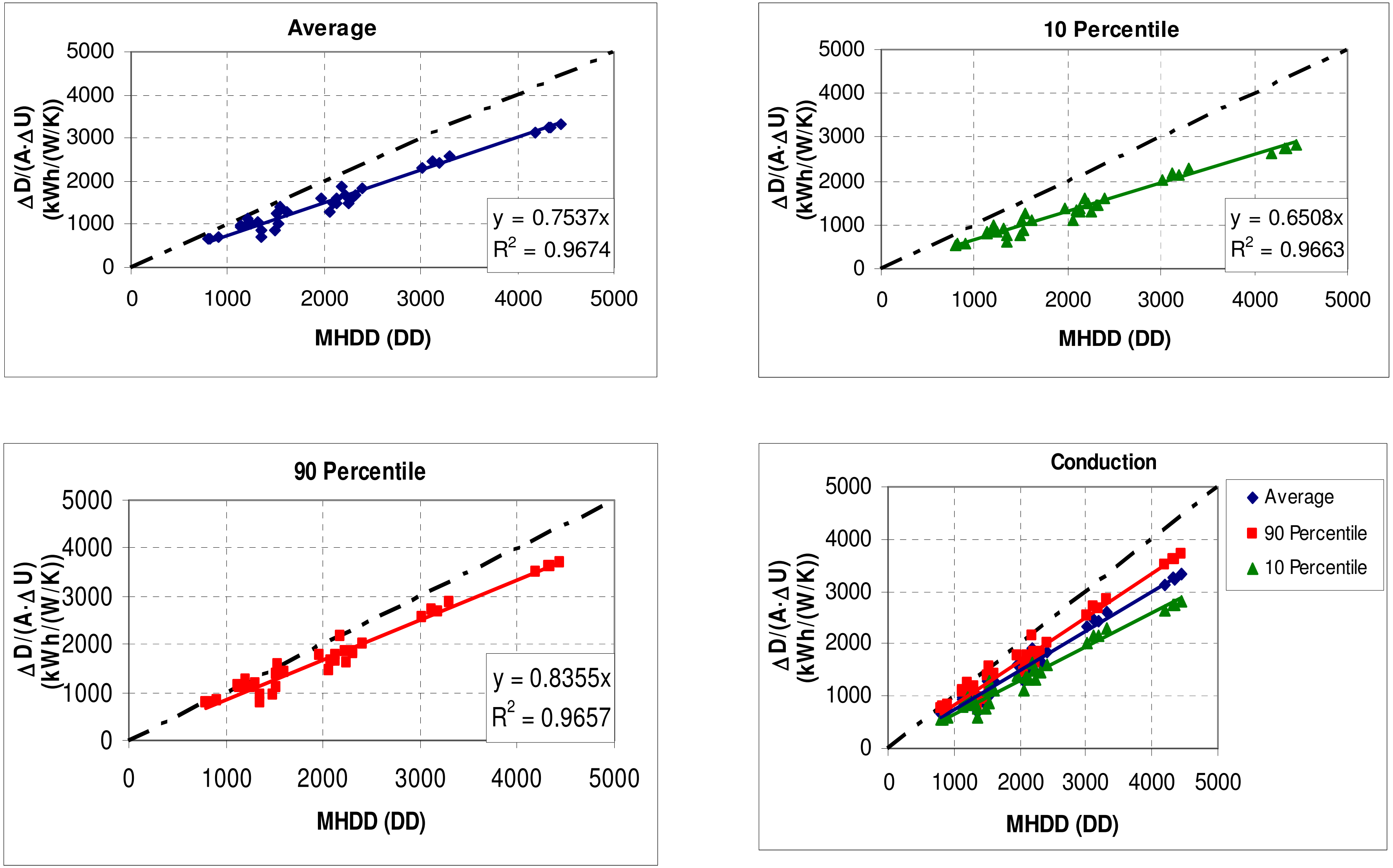


Fig. 2. 4 – Correlations for conduction in walls, floors, roofs and windows

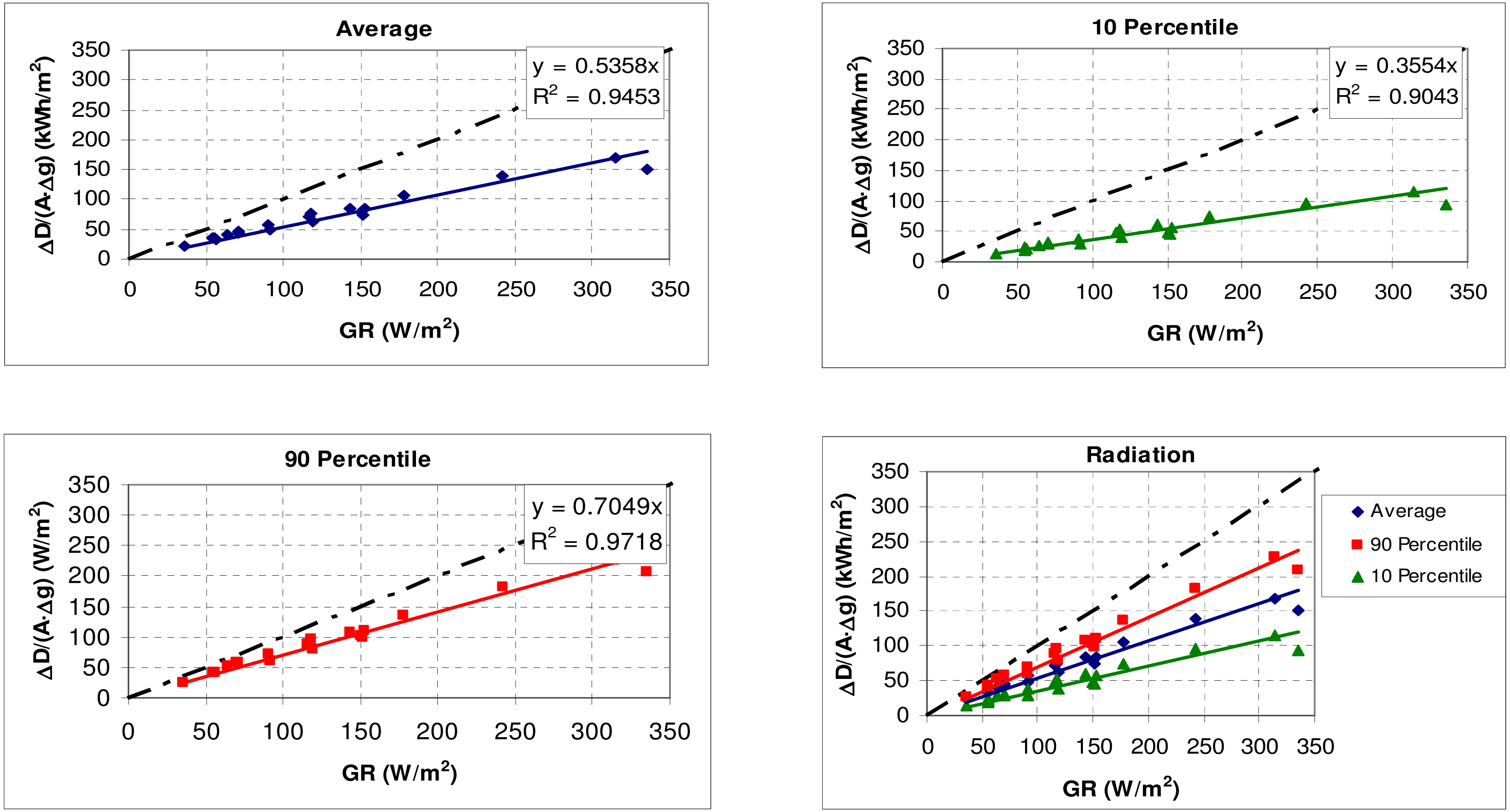


Fig. 2. 5 – Correlations for radiation in windows

3 PASSIVE STRATEGIES

3.1 GENERAL BUILDING SHAPE/TYPOLOGY

3.1.1 Description

General building shape, or typology, is defined by all the external walls that separate indoor spaces from outdoor. In single dwellings, we can distinguish, in a qualitative form, between detached, semi-detached and terraced houses. The difference is the way of joining the different residential units in each case; thus, detached houses does not have any party walls, semi-detached houses only have one party-wall and finally, terraced houses are joined making a row, so each house has two or more party walls. Quantitatively we can distinguish between the different typologies using a parameter called “compactness” – or characteristic length. Compactness is the ratio between the total treated volume of the dwelling and the heat loss surface area. Typically, for dwellings with the same total treated volume, this parameter takes low values for detached houses, low-medium for semi-detached houses and, medium-high in terraced houses. Minimum compactness values are around 0.8m and maximum around 2.2m.

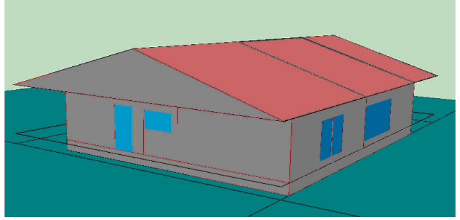
3.1.2 Relevance in *Passivhaus* design

A dwelling with a correct shape, in terms of energy efficiency, will be a house with a high compactness. For winter, a high compactness is functional due to the fact that exposed surface area is low and so the heat losses are. Moreover, we can take advantage to design a dwelling with medium-high compactness in summertime, because the cooling demand will be reduced. A high compactness could be sacrificed sometimes in order to have a higher surface oriented to the south, in this situation an intermediate solution can be adopted with medium compactness.

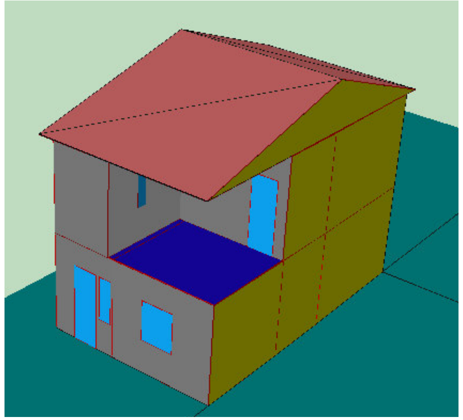
3.1.3 Reference to the regional solutions/Climatic applicability

In general, it is desirable to design buildings with high compactness. The more compactness, the lower heating demand.

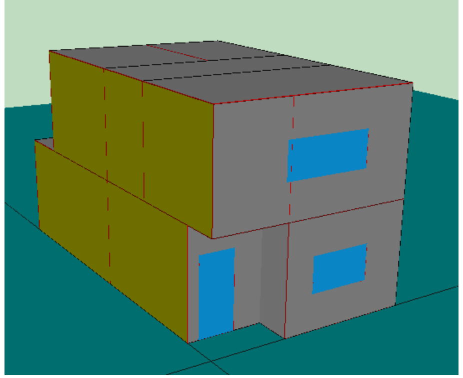
In Mediterranean climates, it is convenient to sacrifice higher compactness in order to increase south oriented glazing area – see Spanish *Passivhaus* description.



Treated floor area: 157 m^2
Total treated volume (TV): 310 m^3
Heat loss surface area (A): 250 m^2
Compactness (TV/A): 1.24 m



Treated floor area: 84 m^2
Total treated volume (TV): 210 m^3
Heat loss surface area (A): 160 m^2
Compactness (TV/A): 1.31 m



Treated floor area: 110 m^2
Total treated volume (TV): 330 m^3
Heat loss surface area (A): 194 m^2
Compactness (TV/A): 1.70 m

Fig. 3. 1 – Examples of low, medium and high compactness of buildings

3.2 ORIENTATION

3.2.1 Description

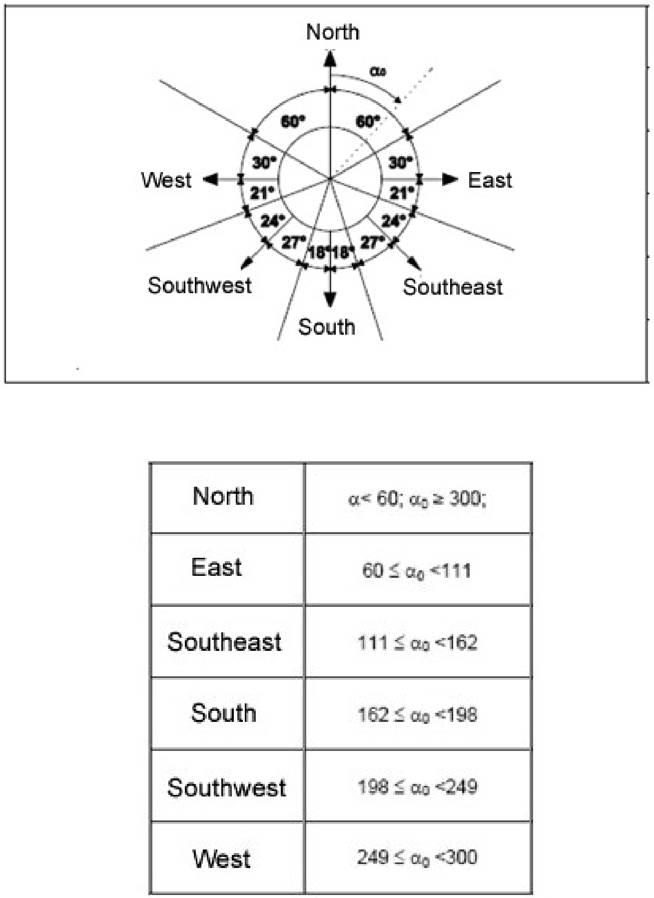
Orientation is a parameter defined for each one of the external walls of the building. Quantitatively, the orientation must be obtained from the angle between the normal to the wall and the north direction. However, in general we can talk about orientation in a qualitative way using the cardinal points: North, South, East and West and its secondary directions. The quantitative description allows us to assign each rank of angles with an orientation. For example if the angle of the normal to one façade and the north (α_0) is 75º, this façade can be considered East oriented. The difference between façades with different orientation is the level of solar radiation that impinges on each façade. Below, we show a compass card with different orientations and their corresponding rank of angles.

3.2.2 Relevance in *Passivhaus* design

A dwelling with a correct orientation should have a high level of heat loss area oriented to the south; this will contribute to increase heat gains due to solar radiation, it is mandatory in this case to design south walls with a high percentage of glazing. In summer this measure requires a well designed system of solar control because in other case the building or at least the adjacent zone will be overheated. Overhangs are good systems to obtain a good solar control in south oriented walls. East and west orientation are avoided because the level of radiation in these ones is very low in winter, also, in summer, solar control is much more complicated than in south orientation. Typically, the percentage of glazing surface related to floor area should be around 20% to the south, and 5% to the north.

3.2.3 Reference to the regional solutions/Climatic applicability

A good orientation of the building is a goal in all climates. This objective can not always be reached due to external constraints like the urban layout. In these cases other measures have to be used in order to neutralize as much as possible, the effect of inadequate orientation.



North	$\alpha < 60$; $\alpha_0 \geq 300$;
East	$60 \leq \alpha_0 < 111$
Southeast	$111 \leq \alpha_0 < 162$
South	$162 \leq \alpha_0 < 198$
Southwest	$198 \leq \alpha_0 < 249$
West	$249 \leq \alpha_0 < 300$

Fig. 3. 2 – Orientations

3.3 SHADING

3.3.1 Description

Shading avoids solar radiation to impinge on external walls of buildings. We can distinguish between three kinds of shading: own shading due to the building surfaces over themselves, shading due to near obstacles like overhangs or Venetian blinds, and shading due to far obstacles like other buildings in the surroundings.

3.3.2 Relevance in *Passivhaus* design

Solar shading devices have to be designed in a selective way, thus they should allow radiation to reach the building in winter and at the same time, and they block the radiation in summer. This devices must be designed taking into account the own shading and the shading due to far obstacles that exist in the present or can exists in the future.

3.3.3 Reference to the regional solutions/Climatic applicability

Shadings should be used to reduce solar heat gains during summer, thus these devices are applicable in locations with medium to high Summer Climatic Severity (see Chapter 2).

In geometry, the stereographic projection is a certain mapping that projects a sphere onto a plane. Intuitively, it gives a planar picture of the sphere. Stereographic projection finds use in several areas; we use it particularly for the calculation of solar access and sky opening.

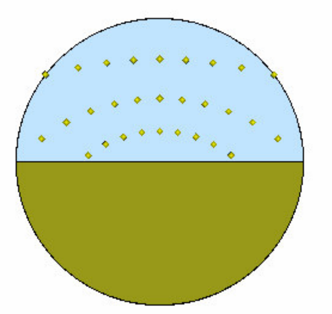


Fig. 3. 3 – Stereographic projection of a south facing window without any kind of solar control system.

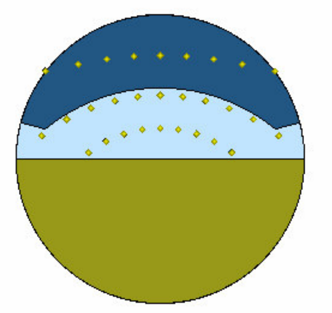


Fig. 3. 4 – Stereographic projection of a south facing window with an overhang.

3.4 BUFFER ZONES

3.4.1 Description

A ‘buffer’ space is a free-running intermediate space between inside and outside providing thermal (and sometimes acoustic) protection to the interior. This thermal buffering not only reduces heat loss from the interior, but can also preheat ventilation supply air, and can also be a source of direct solar heat gain. The buffer space often takes the form of an entrance lobby, store, access stair or greenhouse/ conservatory /glazed balcony. Where buffer zones have a southerly aspect, the outer layer is normally glazed to enhance solar gains in winter. Shading is necessary to reduce solar gain and risk of overheating in summer. Buffer zones are ‘transitional’ spaces ie they are only occupied very briefly, and can therefore be allowed to vary in temperature much more widely than an occupied space which is expected to meet accepted thermal comfort criteria most of the time. Conservatories can act as buffer zones, but residents will often want to extend the period of use by heating them (clearly a negative result). Used wisely, however, conservatories can be a significant thermal benefit (even in southern Europe).

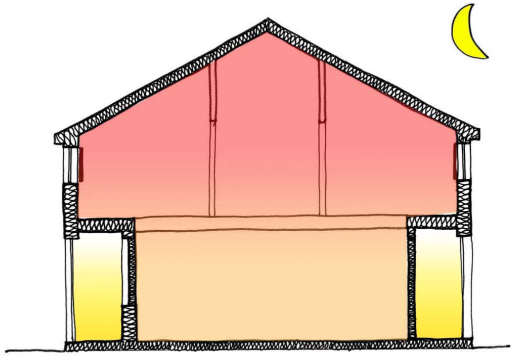


Fig. 3. 5 – Buffer zones (yellow) in winter night time help minimising heat losses

3.4.2 Relevance in *Passivhaus* design

Automatic vent opening devices are incorporated in both buffer zones located at ground level. These devices control natural ventilation in response to the balance between internal and external conditions. This automatic control can be overridden by the occupants.

3.4.3 Reference to the regional solutions/Climatic applicability

In northern Europe an unheated buffer space can be used to reduce infiltration heat losses in winter, to potentially pre-heat ventilation supply air to the living spaces and improve the effective U-value of the external envelope. Studies of attached sunspaces in the UK have demonstrated significant potential thermal benefits in winter. In summer the potential risk of overheating arising from such spaces can be minimised by shading or opening up both layers.

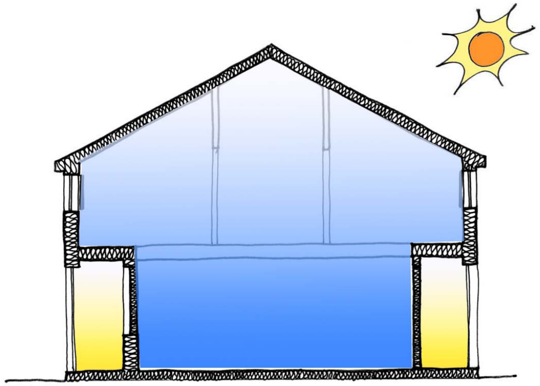


Fig. 3. 3 – Buffer zones in summer daytime help sheltering from the outdoor heat

3.5 THERMAL MASS

3.5.1 Description

Thermal mass is the term used to describe materials of high thermal capacitance ie materials which can absorb and store large quantities of heat (expressed in Joules/kg). Materials within a building which have a high thermal capacitance can provide a 'flywheel' effect, smoothing out the variation in temperature within the building, and reducing the swing in temperature on a diurnal and (potentially) longer term basis. Thermal mass may be in the form of masonry walls, exposed concrete soffits to intermediate floors, or possibly embedded phase change materials. In the most general sense, it is any mass that absorbs and holds heat.

3.5.2 Relevance in *Passivhaus* design

Thermal mass, coupled to the interior of the building, can be of considerable advantage both in the summer and winter. In summer it can be used to limit the upper daytime temperature and thereby reduce the need for cooling. This effect can be enhanced by coupling the high capacitance material with night time convection to pre-cool the thermal mass for the following day. In residential buildings, however, this could sometimes prove difficult due to limitations in the use of space. Nevertheless, night time purging is applicable by use of automated vent devices, secure high level openings and a design that promotes air movement. By this process, internal temperatures can be held significantly below external ambient temperatures during the summer. Equally, in winter, mass can absorb heat gains which build up during the day, for release into the space at night. This can potentially reduce heating demand.

3.5.3 Reference to the regional solutions/Climatic applicability

The proposed UK *Passivhaus* incorporates thermal mass primarily in the intermediate floor slabs, but also in the 'party' walls. An alternative would be to use plasterboard with encapsulated PCM in ground and first floor ceilings. The cooling effect of thermal mass coupled with night time ventilation works best in locations where there is an appreciable diurnal variation.

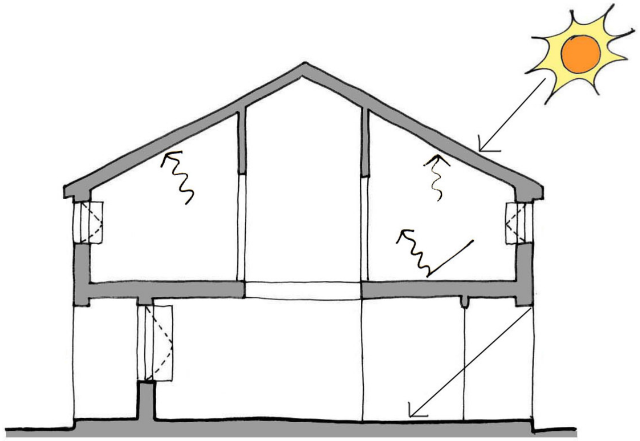


Fig. 3. 4 – Heat storing effect of thermal mass during the day

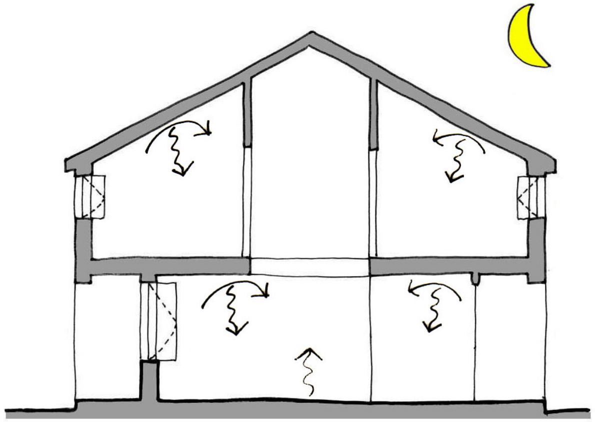


Fig. 3. 5 – Heat stored in the mass is released at night

3.6 PASSIVE COOLING

3.6.1 Description

A number of different approaches to passive cooling have been successfully adopted in housing in southern Europe and the USA, including night ventilation; night sky radiation; evaporative cooling, and ground cooling.

Night Ventilation. Throughout Europe, a relatively large diurnal swing in air temperature is experienced in Summer, with night time temperatures dropping well below the ‘neutral’ temperature. This cool air can be drawn into the house to flush out any residual heat from the day and to pre-cool the internal fabric for the following day. The coupling of the air flow path with well distributed high thermal capacitance materials is vital. Automatic vent openings to regulate both the air flow rate and the temperature inside the building is also vital, both to promote adequate cooling and to avoid over cooling.

Night Sky Radiation. The clear night sky can provide a potential heat sink by radiation from the relatively warm surface of the roof of the dwelling, to the extreme cold of outer space. (Space has a temperature which equates to Absolute Zero -273K). With well insulated roofs, a technique has to be found to couple the cooling potential with the interior of the dwelling. A range of techniques for exploiting night sky radiation, including irrigated roofs and roof-ponds, are described in book ‘Roof Cooling’ by Simos Yannas, but to date have rarely been applied to housing in Europe.

Evaporation. The cooling potential of evaporating water has been exploited throughout southern Europe, the Middle East and northern India for many centuries. As a general rule, a reduction in supply air temperature of 70-80% of the dry bulb/ wet bulb depression can be achieved. This of course varies from only a few degrees when the air is relatively humid to as much as 10 to 12oC when the air is relatively dry. The upper limit for the application of direct evaporative cooling is considered to be a wet bulb temperature of 24oC (Ref Givoni). As with convective cooling, control of the rate of evaporation and the air flow through ventilation openings is vital to optimize performance and to avoid over-humidification.

Ground Cooling

The temperature of the Earth 3-4m below ground level is generally stable, and has been found to be equal to the annual mean air temperature for the location (anywhere in the world), varying perhaps by ±2oC according to the season. The earth is therefore a huge source of low grade heat, which can be used for either heating or cooling. For example, the annual average air temperature for central England is about 12oC. By introducing air to the dwelling through a network of buried pipes, it can be either pre-cooled in summer or pre-heated in winter. This source of heating and cooling can also be exploited by circulating water though pipes in the ground and then exchange heat through a heat pump to either increase or decrease the temperature according to the season. As a source of cooling, this is not as useful in Seville where the average annual temperature is ??. The Climate Maps provide in Chapter 5 provide an indication of the applicability of different measures by reference to the ‘Climate Severity index’.

3.6.2 Relevance in *Passivhaus* design

Passive cooling, where appropriate, can provide substantial energy savings and reductions not only in CO2 emissions but also in other harmful refrigerants. It also avoids the need of mechanical systems.

3.6.3 Reference to the regional solutions/Climatic applicability

In northern Europe, careful design of the building envelope (thermal properties, orientation, solar shading) can often remove the need for additional cooling in summer. In southern Europe, this may also be the case, but with climate change and with expectations of a high quality internal environment throughout the year, the opportunity of additional cooling needs to be considered. In most situations, the exploitation of ambient heat sinks by passive cooling techniques will meet any residual cooling requirements. Certainly they should be considered and assessed before any decision is made to include a mechanical back-up (with attendant environmental and maintenance implications).

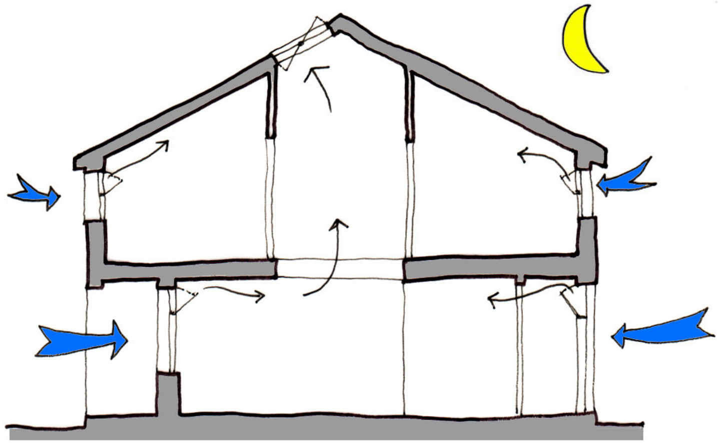


Fig. 3. 6 – Night-time cooling

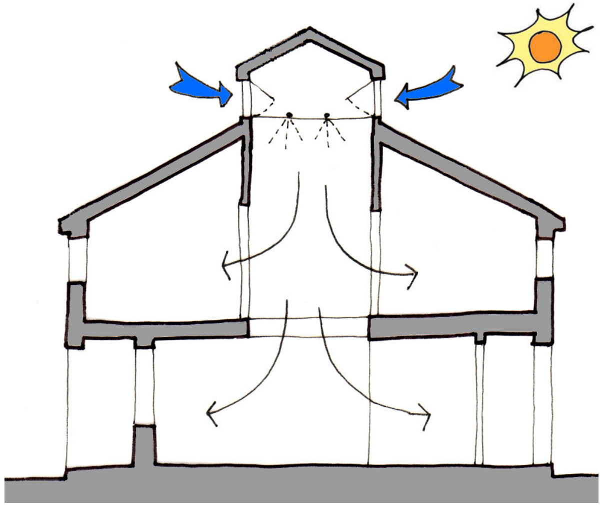


Fig. 3. 11 – Evaporative cooling

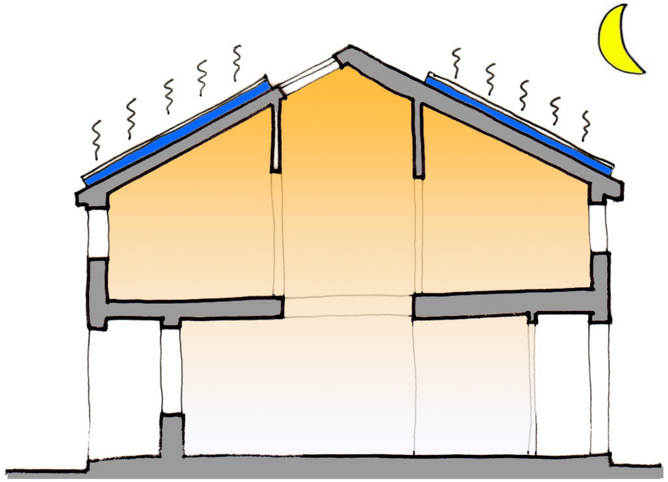


Fig. 3. 10 – Radiative cooling

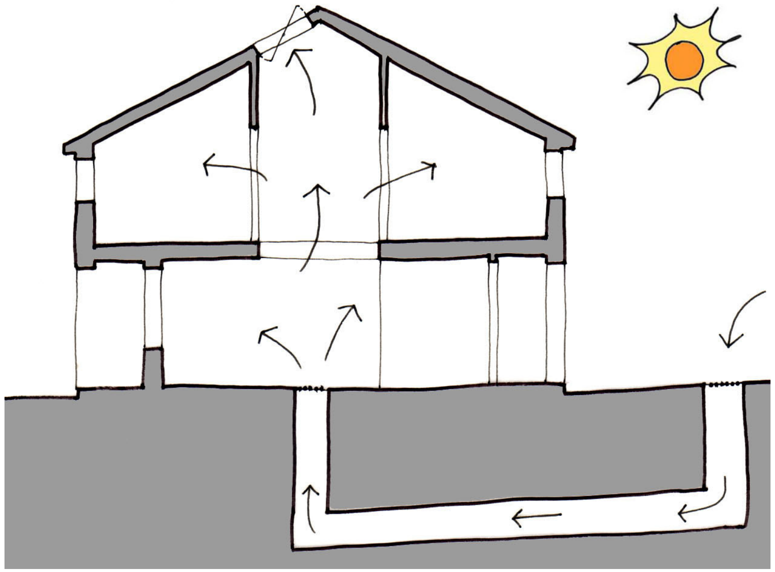


Fig. 3. 12 – Ground cooling

3.7 NATURAL VENTILATION

3.7.1 Description

The amount of ventilation required varies according to the season. In order to provide for our physiological needs and to maintain internal air quality, a minimum of 8-10 litres per person per second is required. This is the basis of the minimum ventilation rate required in winter. In summer, when ventilation may also be required to help remove internal heat gains, much larger ventilation rates are needed (typically 80-100 litres per person per second).

Infiltration can contribute to the minimum fresh air requirement, but it is generally recognized that uncontrolled infiltration should be minimized to avoid unwanted heat loss in winter and heat gains in summer. Airtightness standards in construction vary enormously throughout Europe, but legislation is pushing house builders to achieve greater airtightness. The choice between mechanical and natural ventilation for housing depends on the climate characteristics, the airtightness which can be achieved, and the value of heat recovery and occupant preferences.

Natural ventilation is driven by either wind or thermal forces (or a combination of both). Wind driven ventilation is induced by the pressure differences arising due to the change in momentum when the air is deflected (increasing speed and pressure) or when the air speed is reduced. Typically a difference in wind pressure arises between the windward and the leeward sides of a building, and this pressure difference can drive air through the building to achieve simple cross ventilation. Thermal buoyancy occurs when pressure differences arising from differences in temperature between inside and outside of the building create a flow of air between inside and outside. These pressure differences give rise to a flow which is normally from low level to high level, through openings provided to exploit this. There are three factors which determine the rate of air movement due to thermal buoyancy: the *pressure difference* (arising from the difference between the average temperature within the building and the outside temperature); the *area of openings* in the building (at high and low level), and the *height difference* between the openings. Steady state expressions which allow the calculation of air flow rates arising from both wind and buoyancy forces can be found in references in the appendix. The sizing of vent openings and the specification of vent actuators needs to be carefully considered to achieve a successful natural ventilation solution.

3.7.2 Relevance in *Passivhaus* design

Natural Ventilation can be used very effectively to provide fresh air and improve comfort and igienic conditions for occupants. Despite the variability and difficult of control of the natural driving forces, natural ventilation can reduce energy consumption, capital and running costs of mechanical and electrical plants as well as space for their installation.

3.7.3 Reference to the regional solutions/Climatic applicability

Natural Ventilation by stack effect is very effective in northern European climates where there usually is a greater temperature difference between the indoor and outdoor environments, both in summer and winter. Climates where there is a strong diurnal variation are suitable for the employment of thermal mass and night time ventilation. For more hot and humid climates, cross ventilation and shading have the advantage of reduce solar gains and improve the perception of coolth by increasing air movement.

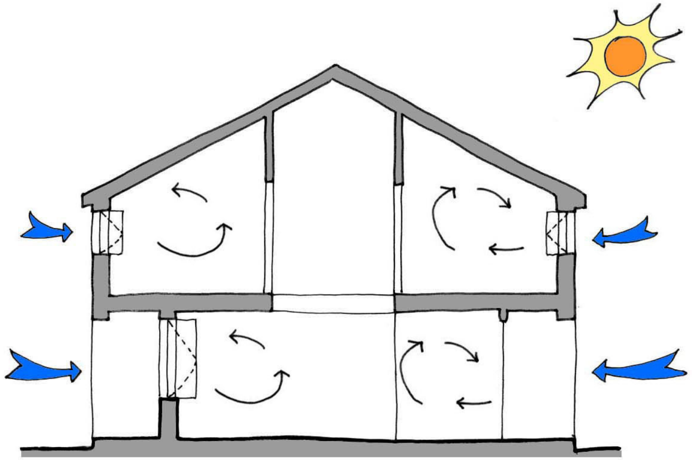


Fig. 3. 13 – Single sided ventilation

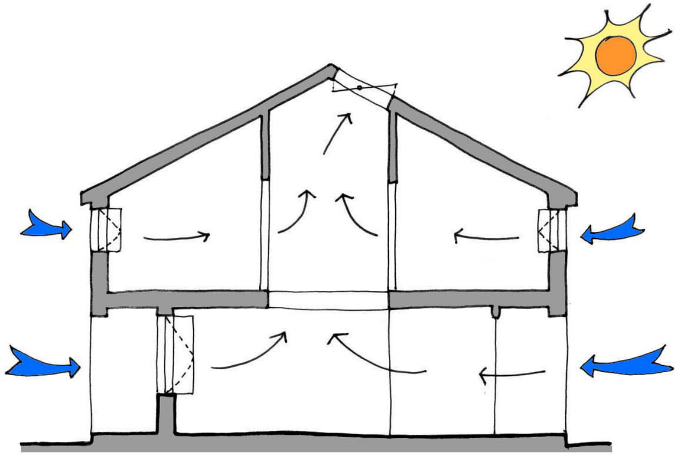


Fig. 3. 15 - Stack ventilation

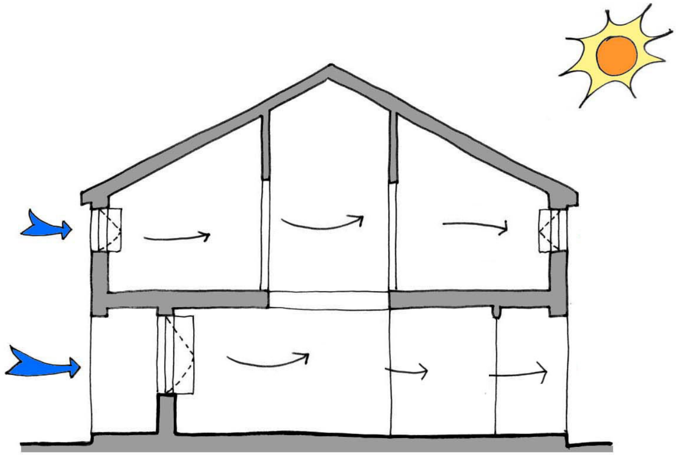


Fig. 3. 14 Cross ventialtion

3.8 PRIMARY ENERGY AND CO2

3.8.1 Description

The primary energy sources are those that can be obtained directly from nature, for example: solar or wind energy, or after an extractive process like, petroleum, natural gas or coal.

Energy consumption of a building can be expressed in terms of equivalent consumption in primary energy – Tons of Oil Equivalent - or in terms of CO_2 emissions. The factors that allow us to make this change of units depend on the energy sources and the way of generating energy in each country.

3.8.2 Relevance in *Passivhaus* design

A passive dwelling may use conventional energy systems only as a support to passive conditioning systems or measures. The conventional systems used must have high performance level, in the sense that they should have low levels of emissions and low levels of primary energy consumption. The goal is to use a system with a high energy rating, in the references it is possible to find European directives in relation to the energy labelling of heating and cooling systems for domestic use.

3.8.3 Reference to the regional solutions/Climatic applicability

The best systems in order to reduce CO_2 emissions can be very different for those one that minimize the primary energy consumption due to the “energy mix” in each location. In the upper box we can see the reference values in Spain. For example in Spain a heating or cooling system with a high energy rating could be a direct expansion heat pump with an A-label

Table 3. 1 – Primary energy

Kind of energy	ETP primary energy /MWh $_e$ energy
Electricity	0,224
Storage electricity based systems	0,174
Fuel and GLP	0,093
Natural Gas	0,087
Coal	0,086

Table 3. 2 – CO_2 emissions

Thermal energy	Emissions
Natural Gas	204 gr CO_2/kWh $_t$
GLP	244 gr CO_2/kWh $_t$
Coal	347 gr CO_2/kWh $_t$
Biomass	Neutral
Bio-fuels	Neutral
Electricity	649 gr CO_2/kWh $_e$
Solar Photovoltaic	0
Storage electricity based systems	517gr CO_2/kWh $_e$

3.9 GROUND INSULATION

3.9.1 Description

Two to three meters deep, the ground already has a temperature which is only slightly above the annual average air temperature during the whole year. The same is true below floor slabs: Diurnal, but even annual changes in temperature occur mainly near the boundary. During the heating period, heat losses through building elements adjacent to the ground are always lower than those of comparably insulated walls or roofs. Nevertheless, they can be further reduced by thermal insulation.

In summer, insulation against the ground is generally disadvantageous in European climates: Heat flow to the cooler ground will reduce the indoor temperatures. Minor improvements of indoor summer temperatures by insulation are possible if the floor slab is insulated near the boundary, where the ground temperature can rise above the desired indoor temperature during summer.

3.9.2 Relevance in *Passivhaus* design

Depending on the climate and the general building properties, insulation of the floor slab or the basement can be necessary, useful or counterproductive. It the ground temperatures are low enough, insulation against the ground in indispensable to achieve *Passivhaus* standard. However, the insulation is usually thinner than in building elements adjacent to ambient air. In climates such as the lowlands of southern Italy or of the Iberian Peninsula, where heating energy demand can already be minimised by other means, insulation of the floor slab and the basement can be omitted, using the ground as a heat sink in summer.

3.9.3 Reference to the regional solutions/Climatic applicability

Insulation can be placed below the floor slab if the material can resist pressure and humidity, such as foam glas or extruded polystyrene. By this construction, the insulation layers of the floor slab and the exterior walls can be directly connected and thermal bridges along the boundary of the floor slab can be avoided.

It is also possible to install the insulation above the floor slab. Cold basements can also be realised by installing the insulation in the ceiling of the basement. Then, any staircase between the basement and the interior of the thermal envelope needs to be carefully designed because it can create excessive heat losses.

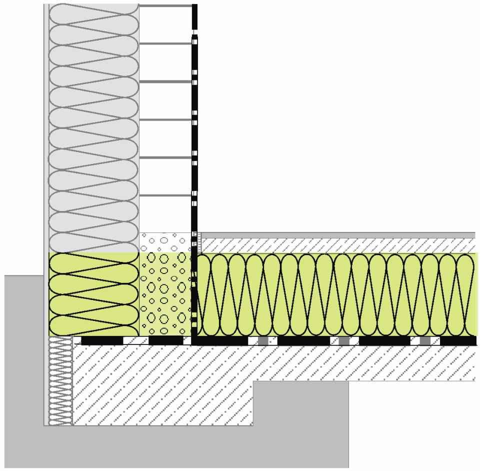


Fig. 3. 16 – Insulation above the floor slab. The load-bearing wall is placed on a layer of porous concrete to reduce the thermal bridge effect

Fig. 3. 17 – Foamglas and XPS being installed under the floor slab of a five-storey office building

3.10 WALL INSULATION

3.10.1 Description

Insulation of the walls reduces the average heat flow through the wall construction. The effect is characterised by the U-value, given in $W/(m^2K)$, which signifies the heat flow through 1 square meter of wall area at a constant temperature difference of 1 K (= 1 °C). Although there are variations in the heat flow due to the constantly changing boundary conditions, the U-value represents the average heat flow through the wall very well. Good insulation of walls limits the heat losses in wintertime and increases the interior surface temperatures, thus increasing thermal comfort and reducing the risk of damages due to excess humidity. Thermal insulation works symmetrically: During hot periods in summer, it reduces the heat flow from the outside to the inside, including the heat generated by solar radiation on the exterior surface.

3.10.2 Relevance in *Passivhaus* design

*Passivhaus*s require an uncompromising reduction of the useful energy demand. This includes minimising heat transmission through the opaque building envelope. Sufficient wall insulation is therefore indispensable for the reduction of heating energy demand in winter. Well-insulated walls also help to reduce the amount of heat that is transferred into the building during summerly heat waves. They support both night ventilation strategies and energy efficient active cooling concepts whenever the interior temperature drops below the daily average of the exterior surface temperature.

3.10.3 Reference to the regional solutions/Climatic applicability

Depending on the climatic conditions and the building project, the required level of insulation may vary. As a rough guidance, U-values will only be above 0.3 $W/(m^2K)$ in very mild climates such as in southern Italy or Spain, whereas values of 0.15 $W/(m^2K)$ or below can be required in France.

Fig. 3. 18 – 40 cm gable wall compound insulation system in a *Passivhaus* in Hannover

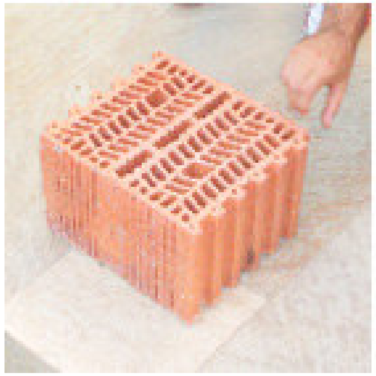


Fig. 3. 19 – Porous ceramics brick as used in a passively cooled project in Seville

3.11 ROOF INSULATION

3.11.1 Description

Similarly to the walls, an insulated roof reduces the heat transfer through the roof construction in both directions, during winter and summer. Especially during summertime, roofs are generally more exposed to solar radiation than walls, due to their nearly horizontal orientation and to reduced shading from surrounding buildings. Uninsulated roofs contribute significantly to excessive summer temperatures in buildings.

3.11.2 Relevance in *Passivhaus* design

Good insulation of the roof is necessary to reduce winter heating energy demand. Concerning the insulation thickness, there are usually less constructive constraints in the roof than in the walls. Therefore, roof insulation is typically dimensioned thicker than wall insulation. Well-insulated roofs are also a good solution for reducing the summer heat load.

3.11.3 Reference to the regional solutions/Climatic applicability

Insulation in inclined roofs can be applied between roof rafters or on top of the rafters below the tiles. For concrete roofs, exterior insulation above the concrete is useful. With modern, water-resistant insulation materials, the lifespan of the main waterproofing layer can be increased by installing it between the insulation and the concrete.

Again, the best insulation thickness depends on the climate and the specific requirements of the building. In a *Passivhaus*, a typical U-value of the roof will be below 0.3 W/(m^{2}K) in mild, southern European climates, and down to 0.1 W/(m^{2}K) in central Europe

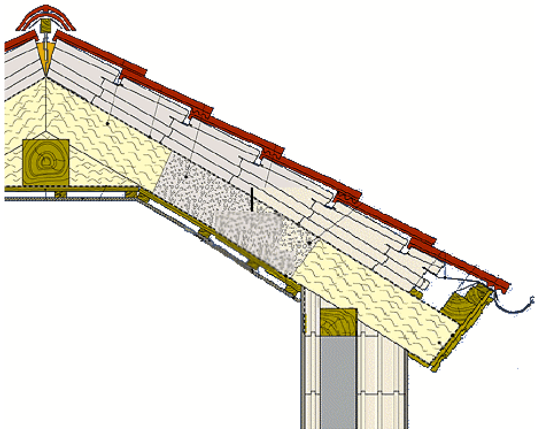


Fig. 3. 20 – Inclined roof with insulation between and above the rafters

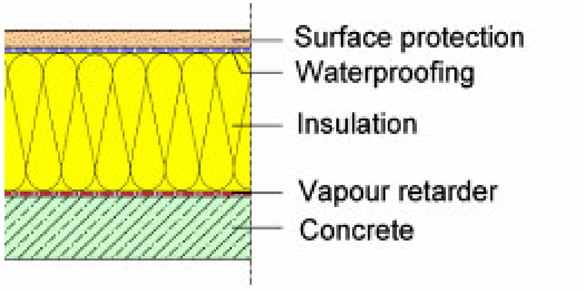


Fig. 3. 21 – Highly insulated concrete roof construction

3.12 INFILTRATION AND AIR TIGHTNESS

3.12.1 Description

Leaky building envelopes cause a large number of problems, particularly in cooler climates or during cooler periods. Airflows from the inside to the outside through cracks and gaps result in a high risk of condensation in the construction. Infiltration results in a lake of cold air, which makes the inhabitants, feel uncomfortable, too. Cold air infiltration also increases the temperature differences between different storeys of a building. Finally, using cracks in the building shell for ventilation purposes does not provide sufficient air change unless the envelope is so leaky that drafts and discomfort occur frequently.

3.12.2 Relevance in *Passivhaus* design

In many climates, *Passivhaus*s require a mechanical, supply and exhaust air ventilation system with heat recovery. In this case, excellent airtightness of the building envelope is required. If the envelope is not sufficiently airtight, the airflows will not follow the intended paths, the heat recovery will not work properly, and elevated energy consumption will result.

In very mild climates, it is possible to build *Passivhaus*s without heat recovery systems. In such a case, if no ventilation system is present, airtightness is not quite as important. On the contrary, very airtight buildings without ventilation systems run the risk of bad indoor air quality and excess humidity.

3.12.3 Reference to the regional solutions/Climatic applicability

Good airtightness is mainly achieved by appropriate design. It is necessary that one single airtight layer is running around the whole building. Internal plaster, plywood board, hardboard, particle board and OSB; PE foils and other durably stabilized plastic foils; bituminous felt (reinforced) and tear-proof (reinforced) building paper are all suitable materials for constructing an airtight envelope. All building element junctions need to be constructed such that no leakages occur, too.

Airtightness can be tested by means of the so-called blower door test. In this procedure, a ventilator is placed in an exterior door or window which creates a pressure difference of 50 Pa. The corresponding air change rate of the building (n50, expressed in ach^{-1}) indicates the level of airtightness.

Fig. 3. 22 – The sealing tape, on which plaster can be applied, will then link the interior plaster and the window

Fig. 3. 23 – Blower door installed for a pressurization test

3.13 THERMAL BRIDGES

3.13.1 Description

Heat transfer by transmission does not only occur in the regular building elements like walls or roof, but also at corners, edges, junctions etc. Places where the regular heat flow through a building element is disturbed, especially those where it is higher than in the regular construction, are called thermal bridges. Concrete beams that penetrate an insulated wall are a good example.

3.13.2 Relevance in *Passivhaus* design

In order to make good thermal insulation effective, it is necessary to pay attention to the reduction of thermal bridge effects. By following a few simple design rules, it is possible to eliminate the thermal bridge effects:

Do not interrupt the insulating layer.

At junctions of building elements, the insulating layers have to join at full width.

If interrupting the insulating layer is unavoidable, use a material with the highest possible thermal resistance.

Thermal bridges also result in reduced temperatures of interior surfaces in winter, thus increasing the risk of mould formation.

3.13.3 Reference to the regional solutions/Climatic applicability

Thermal-bridge-free construction does not only improve the quality of the thermal envelope, it also makes thermal bridge calculations obsolete, provided that heat losses are calculated using exterior dimensions of the building.

Window installation is an exception: Thermal bridge effects can be minimized here by installing the window in the insulating layer, not in the load-bearing wall (see lower figure), and by covering part of the frame with insulation. However, due to the change in thickness of the insulation layer, there is normally a thermal bridge left at the junction of the window and the wall.

Reduction or avoidance of thermal bridges is generally a cost-efficient means of reducing transmission losses or transmission heat load, respectively.

Fig. 3. 24 – Thermal bridges formed by concrete pillars and beams, in this case slightly reduced by two-hole hollow bricks

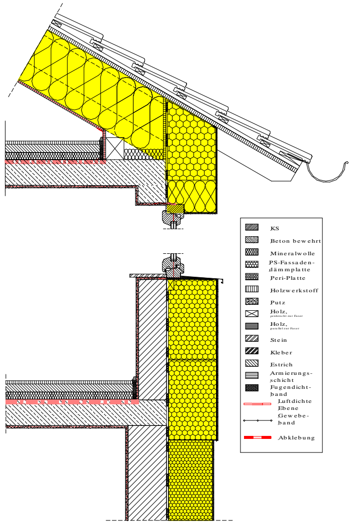


Fig. 3. 25 – Construction example without thermal bridges

3.14 HEATING SYSTEM

3.14.1 Description

Heating system energy performance is a function of the efficiency of the four major constituent components. In particular the global seasonal efficiency (ηg) of a heating system is defined as:

$$\eta_g=\eta_e\cdot\eta_c\cdot\eta_d\cdot\eta_p$$

where ηp ηe ηc ηd = average seasonal efficiency for production (generation), emission, control and distribution respectively.

Overall the heating system's energy efficiency is increased by improving the performance of the individual components. However, the potential energy savings offered by single components might not be realised or anyway reduced if they are incompatible with each other. Two principle strategies of improving the heating system's energy efficiency are:

Improving seasonal efficiency of production
Used with low temperature distribution system the seasonal efficiency of condensing boilers can arrive at 105% (with respect to fuel LHV) which is close to the nominal boiler efficiency. Even when used with standard radiators system (with design temperatures of 80°C) seasonal efficiencies of above 90% can be achieved. These represent potential savings of in the region of 10 – 25% with respect to the seasonal efficiencies offered by traditional three star boilers.

Ground sources heat pumps have COP's in the region of 4.5 to 5, which considering the average efficiency of electricity generation of 39% , leads to overall system efficiencies of 195% (with respect to fuel LHV). However the overall system efficiency (electricity generation + heat pump) of air sourced heat pumps with COP's of 2 to 2.5 is around 80 to 100% and thus no better or often worse than a condensing boiler.

Improving seasonal efficiency of emission
Much of building energy loss is associated with the need to adequately ventilate indoor spaces. Reducing indoor air temperature reduces energy loss due to ventilation.

Since room operating temperature is a weighted function of air and surface radiant temperatures, increasing increasing surface radiant temperatures allows air temperatures to be reduced without affecting indoor comfort. Using floor, wall or ceiling radiant heating systems provide effective and cost effective means by which this can be achieved.

When used with condensing boilers low temperature radiant panels provide maximum efficiency.

3.14.2 Relevance in *Passivhaus* design

Condensing boilers, ground sourced heating pumps and radiant panels are highly efficient solutions. However to a degree the heating system can be considered as an add-on component detached from the building; applicable to any construction in any locality.

Homes built to the *Passivhaus* standard in central Europe adopt a much more holistic approach. Here heat demand is reduced by removing infiltration of cold air through the building shell. This in turn requires an active ventilation system be introduced in order to guarantee occupants fresh air. Using an active ventilation system allows for heat recovery from the outgoing exhaust air which again reduces heat demand. If the home is insulated so as to reduce residual heat demand to 10W/m^2, heating can be provided by poste-heating the incoming ventilation air with a low powered heat pump. Alternatively, infiltration can still be reduced whilst providing fresh air by natural ventilation via automatically controlled vents and trickle ventilators.

In this solution the heating system and building are intricately combined, For example increasing the impermeability of the building shell would render the heating system impracticable. Matching the heating system and building in this way reduces construction costs whilst keeping heating demand below 15 kWh/m^2/yr.

3.15 SUBSOIL HEAT EXCHANGERS

3.15.1 Description

The ground behaves as an extremely large thermal mass whose temperature fluctuates little during the course of the year and the change of the seasons. Below roughly 1 m the temperature of the ground assumes a almost constant value equal to the average air temperature over the year, which in Europe depending on locality means 10 – 20℃. Thus the ground temperature can be significantly above (in winter) or significantly below (in summer) the local outside air temperature. The difference between ground and local air temperature provides the potential for heating or cooling a building with very little energy input.

This cooling and heating potential is usually accessed by installing a sub soil heat exchanger under or close to the building. The deeper the heat exchanger, the larger the active temperature difference, and the greater the cooling or heating potential. However excavation costs increase with depth and thus most heat exchangers are buried at between 1.5 and 3m. Most systems are usually constructed in smooth-walled, rigid or semi-rigid plastic or metal pipes of 100 to 450 mm diameter.

There are basically three configurations;
Open system - Outside air is drawn through a screened intake into tubing roughly 30m in length and then passes directly into the home.

Closed loop system – A portion of air from inside the home or structure is blown through a U-shaped loop(s) of typically 30 to 150m of tube(s) where it is moderated to near earth temperature before returning to be distributed via ductwork throughout the home. The closed loop system is usually more effective than the open system since it cools and re-cools the same air.

Combination system - This can be crafted with unidirectional check valve dampers to allow either closed or open operation depending on the season and/or fresh air ventilation requirements. Such a design, even in closed loop mode, can draw a quantity of fresh air when an air pressure drop is created in the house by a fireplace chimney draft or attic fan.
In general using larger diameter tubes allows the length of tubing to be reduced.

A small scale underground heat exchanger can deliver heating and cooling in the same specific price range of the common primary energy sources (oil, gas, biomass…). Larger underground heat exchangers for room cooling and backup cooling can save the investment costs of a conventional system (by complete substitution of the conventional cooling system) or reduce the investment costs (if the power of the conventional cooling systems is reduced).

3.15.2 Relevance in *Passivhaus* design

In well insulted homes, acceptable indoor comfort temperatures can be achieved in summer exclusively with sub soil heat exchangers. In winter they can reduce heating loads significantly by preheating ventilation air, but some form of poste heater will still be required to bring the incoming air temperature (in the region of 14℃) up to room temperature.
Their use in context of *Passivhaus* development is consolidated. The photo on the bottom right shows the incoming and outgoing piping of a closed loop sub soil heat exchanger of an apartment block restructured to the *Passivhaus* standard in Hannover, Germany.

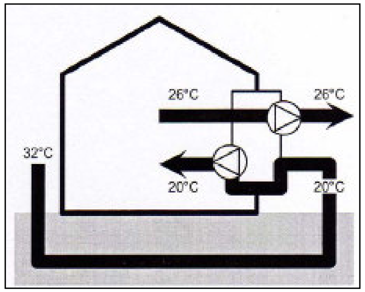


Fig. 3. 26 – Subsoil heat exchanger

Fig. 3. 27 – Closed loop sub soil heat exchanger

3.16 APPLIANCES AND LIGHTING

3.16.1 Description

Home appliances and lighting in the average European home typically consume in the region of 3000 - 4000 kWh/year of electricity (for example average household electricity use in Italy is 3500 kWh/year). Considered in relation to the size of an average house or apartment (roughly 100 m^2) this equates to a unit consumption of between 30 – 40 kWh/m^2/year.

However translated into primary energy, (70 - 100 kWh/m^2/year), energy demand for home appliances is similar to the primary energy demand for heating in standard new buildings in central, northern and parts of southern Europe. Thus energy demand for lighting and home appliances is important and should not be overlooked.

By adopting the best technologies currently available on the market average household consumption could be reduced cost effectively by about 35 to 40% though saving potentials of some specific end uses can be much higher. Several tools are available to help consumers (including designers) identify the most efficient appliances on the market:

The European Union introduced the household energy labelling scheme in 1995. Over time the label has been extended to cover 7 household appliance categories (refrigerators and freezers, dishwashers, electrical ovens, washing machines, tumble dryers, dishwashers and air conditioners) as well as household light sources. The energy label identifies the energy efficiency of a product on a 7 point scale from A to G, with A being the most efficient and the G the most inefficient.

So successful has the label been in transforming the cold appliance (refrigerator) market, that the A+ and A++ energy classes were added to the cold appliance energy label in 2003. A Class A++ refrigerator consumes only 30% of the average market model in 1995 (i.e. those refrigerators rated Class C).

Many other household appliances such as computers, printers and home electronics (for example TV's and VCR's) are covered by the Energy Star rating scheme. First developed in the US, the EU reached an agreement to use Energy Star in Europe in 2000. The Energy Star is an endorsement label which simply indicates whether a product is energy efficient, (whereas in comparison the EU energy label grades performance).
Other that these, there are a number of national schemes such as the Nordic Swan energy label operated in Scandinavia or the German Blue Angel programme.

3.16.2 Relevance in *Passivhaus* design

As the heating and cooling demand of buildings and homes is reduced so the relative importance of energy demand by household appliances and lighting grows. An appliance primary energy demand of 70 kWh/m^2/year is 4 higher than heating demand required for homes meeting the *Passivhaus* standard.

The *Passivhaus* standard permits a total primary energy demand (for all building services) of 120 kWh/m^2/year, which is not actually that restrictive. However it makes little sense to work hard to reduce heating and cooling demand and then use inefficient household appliances.

Though it is true that inefficient appliances help reduce heating loads in winter, this is a very inefficient way to heat a house. Also internal gains from inefficient appliances increase summer cooling loads and overall the net balance energy balance is usually negative.

Before considering energy efficient products designers should really look at alternative completely passive ways to provide building and home services. For example using a washing line to dry clothes (rather than a tumble dryer) requires no energy. A well insulated pantry is a traditional but energy efficient way to store food.

Fig. 3. 28 – Drying clothes by washing line

3.17 HEAT RECOVERY SYSTEMS

3.17.1 Description

A heat recovery ventilator (HRV) can help make mechanical ventilation more cost effective by reclaiming energy from exhaust airflows. HRVs use heat exchangers to heat or cool incoming fresh air, recapturing 60 to 80 percent of the conditioned temperatures that would otherwise be lost. Models that exchange moisture between the two air streams are referred to as Energy Recovery Ventilators (ERVs). ERVs are especially recommended in climates where cooling loads place strong demands on HVAC systems. However ERVs are not dehumidifiers. They transfer moisture from the humid air stream (incoming outdoor air in the summer) to the exhaust air stream. But, the dessicant wheels used in many ERVs become saturated fairly quickly and the moisture transfer mechanism becomes less effective with successive hot, humid periods.

In some cases, although some window or wall mounted units are available, HRVs and ERVs are most often designed as ducted whole-house systems. At the heart of the HRV is the heat exchanger in which incoming and outgoing airflows pass through different sides of thermally conducting plates (but are not mixed), allowing conditioned exhaust air to raise or lower the temperature of incoming fresh air. Heat exchangers can be one of two types; cross flow or inverse flow. Cross flow heat exchangers have an efficiency of around 60% and are often used in series in order to obtain combined efficiencies of around 80%, Inverse flow heat exchangers can on the other hand potentially achieve efficiencies of 95%.

After passing through the heat exchanger, the warmed or cooled air may be sent to the HVAC air handler, or directly to various rooms. Stale air from return ducts pre-conditions the incoming flow before exiting.

In a typical system configuration air is supplied to the living room, bedrooms and removed from the kitchen and bathroom.

3.17.2 Relevance in *Passivhaus* design

The heat recover system is an essential part of the central European *Passivhaus,* and allows homes to be built without conventional heating systems. As example the system installed in the *Passivhaus* in Darmstadt-Kranichestein recovers between 3.000 to 4.000 kWh/year thermal energy. By using a low powered (200-300 W) electronically commuted DC motors, energy consumption by the ventilators is limited to 200 – 400 kWh/year. Thus the final the ratio between absorbed and recovered energy is 1:10.

In the coldest months heat recovery may be insufficient to bring the incoming air to the required temperature. Thus the heat recover systems is often combined with a small powered heat pump (300- 500 W) to provide poste heating on incoming air.

Though central to the central European *Passivhaus,* heat (and cold) recovery systems also represents a viable solution for Mediterranean passive design as the Italian *Passivhaus* detailed in these guidelines shows. In warm climates the heat recover system is used to pre-cool incoming warm air. By installing a reversible heat pump this cooled incoming air can be further cooled to provide

3.17.3 Reference to the regional solutions/Climatic applicability

ERVs allow the exchange of moisture to control humidity. This can be especially valuable in climates with very cold winters. If indoor relative humidity tends to be too low, what available moisture there is in the indoor exhaust air stream can be transferred to incoming outdoor air.

Alternatively in climates which are cooling dominated, it can be critical to dry out incoming air so that mildew or mold do not develop in ductwork.

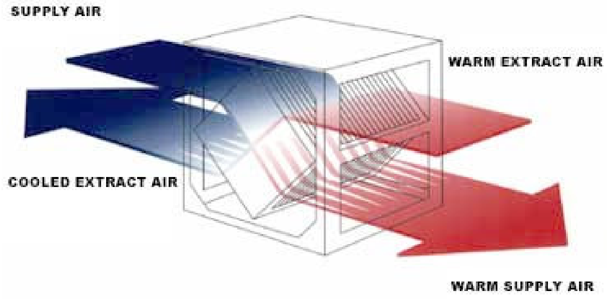


Fig. 3. 29 – Energy recovery ventilator

3.18 HEAT LOSSES OF WINDOWS

3.18.1 Description

Heat losses through windows are proportional to their U-value. In general it is convenient to diminish the heat losses, this implies a reduction in the U-value of the windows in all the orientations.

3.18.2 Relevance in *Passivhaus* design

Improve the insulation of the window areas has a tremendous effect for heating but null in general for cooling. In severe climates (high Winter Climate Severity as defined in chapter 2) it is recommendable to decrease the U-value of the window; but in moderate climates it is not so clear as the lower U-value is, the lower the radiation that passing through the window is. This is important because when we diminish the U-value, the heat losses decrease too, and as result the heating energy demand is lower; however, in the other hand, the radiation passing through the window is lower too and consequently the heating energy demand is higher.

The improvement on the thermal insulation performance of windows is achieved through a combination of:

Increasing number of panes.- up to triple glazing or quadrupled-glazed windows.
Different types of low emissivity coatings.- can be soft coatings that are used in sealed glazing units or hard coatings that can also be used in single panes.
Vacuum windows.- Heat transfer is reduced through evacuation of the inter-pane space to a pressure of about 0.01 Pa.
Aerogel.- Aerogel is an interesting material, having a silicate cell structure, with cell sizes less than the mean free path length. This result in a extremely low value of the material's thermal conductivity (lower than that of the air). However, it is expensive and not completely transparent.

Examples of the U-values for the center of windows illustrate the improvements that can be made (The Energy Book, 1996).

- Single glazing. 5.7 W/m^{2}K.
- Double glazing. 2.8 W/m^{2}K.
- Triple glazing. 1.9 W/m^{2}K.
- Sealed triple glazing unit with low-emission coating. 1.4 W/m^{2}K.
- Sealed triple glazing unit with low-emission coating and argon filling. 1.2 W/m^{2}K .
- Sealed triple glazing unit with two low-emission coatings and argon filling.- 0.8 W/m^{2}K.
- Vacuum window (high vacuum). 0.5 W/m^{2}K.
- 20 mm Aerogel window (low vacuum). 0.3 W/m^{2}K.

Window replacement with others of lower U value presents important advantages except for the reduction of the solar heat transmission. Change simple glazing for double or low emissive glazing, shows an important improvement that is especially important in cold climates, and in north directions.

Additional advantages are associated with the reduced condensation and window back – draught risk, increased radiant temperature during the winter period and reduced infiltration rates.

3.19 GLAZING AND SOLAR ENERGY

3.19.1 Description

The energy of the sun gets into the buildings as radiation through the windows. The radiation is measured in W per square meter of glazing surface and is very important due to:

- This radiation can diminish the heating demand
- This radiation can increase the cooling demand

As one consequence is positive and the other one negative, it is necessary to make a good design based on taking the benefits of solar radiation in winter and protect against the negative effects during summer in order to avoid overheating.

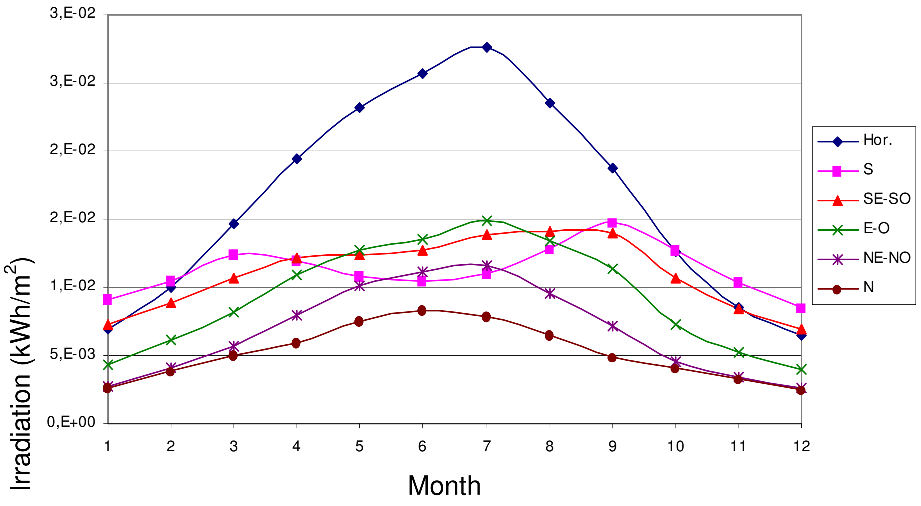


Fig. 3. 30 – Solar Irradiation for different orientations

3.19.2 Relevance in *Passivhaus* design

The quantity of radiation impinging in each façade is different; it depends on the orientation of the façade. Thus, it is very interesting to know the distribution of radiation in order to analyse how we can use it. The graph shows the quantity of radiation in all the orientations during the whole year. Although this graph has been done for a particular location the tendencies of curves are valid for all the locations. The first thing that we can mention is that radiation in the south is the maximum during winter and it is very low –near NE/NW- during summer. This means that during winter we can reduce the heating demand using high south-oriented glazing surface, during the summer we only have to protect this glazing are using shadings, and in any case the solar radiation in this surface will be lower than E/W or SE/SW.

3.19.3 Reference to the regional solutions/Climatic applicability

It is convenient to design buildings with a high percentage of south-oriented windows –the building with a better improving opportunity have a glazing surface to the south between a 75% and a 100% of the total glazing surface- protected in summer with movable shadings or horizontal overhangs –see component description: “shading”. The optimum glazing surface for mild winters like Seville is equal to 30% of the total surface of the building. In locations with more severe winter like Granada this optimum does not exist but it is recommended a glazing surface between a 15% and a 30% of the total surface.

3.20 PHASE CHANGE MATERIALS (PCM)

3.20.1 Description

Systems that use Phase Change Materials (PCM) can be used to store energy. All substances store energy when their temperature change, but when a phase change is produced in a substance the energy stored is higher, also heat storage and its recovery occurs isothermally, which makes them ideal for space heating /cooling applications. For example, if we assume an ice mass of 1 kg at -10ºC, and we lead this mass to 0ºC, the absorbed heat will be 42.3 kJ (specific heat * ΔT). In order to change the state of this mass from ice to water, the needed absorbed heat would be 2501 kJ. This means, that the heat storaged by the water during its phase change is 60 times higher than the heat storaged in order to increase its temperature in 10ºC. The next properties are required for PCM useful for construction systems:

- To have a life cycle according to their cost.
- To have a high specific heat.
- To be chemically stable.
- Not to be toxic, corrosive, or inflammable.
- Densities of solid and liquid state should be similar.

3.20.2 Relevance in *Passivhaus* design

The application of PCMs in building can have two different goals. First, using natural heat that is solar energy for heating or night cold for cooling. Second, using manmade heat or cold sources. In any case, storage of heat or cold is necessary to match availability and demand with respect to time and also with respect to power. Basically three different ways to use PCMs for heating and cooling of buildings are:

- PCMs in building walls;
- PCMs in other building components other than walls; and
- PCMs in heat and cold storage units.

The first two are passive systems, where the heat or cold stored is automatically released when indoor or outdoor temperature rises or falls beyond the melting point. The third one is active system, where the stored heat or cold is in containment thermally separated from the building by insulation. Therefore, the heat or cold is used only on demand not automatically. Depending on where and how the PCM is integrated, PCMs with different melting points are applied. Currently, there is a lack of commercial PCMs in the lower temperature range that is between 5 and 25ºC. Especially between 15 and 20ºC available products show too low enthalpies. Most important PCMs are in the range of 22–25ºC, as almost everybody agrees that this is the range for building passive heating and cooling.

3.21 COLOUR OF EXTERIOR SURFACES

3.21.1 Description

Colour of exterior surfaces determines the quantity of radiation that will be absorbed by that surface. It is feasible to use different colours in each façade, orientation or roof. This strategy is only useful for decreasing the cooling demand, thus, is not useful at all to decrease the heating demand. The aesthetic criteria can be a constraint to this technique.

3.21.2 Relevance in *Passivhaus* design

In order to diminish the cooling demand using this strategy it is necessary to apply light colours to those façades with more incident radiation during summer. This technique should be considered in buildings with high area of opaque surfaces to the east or west, can be interesting in roofs of buildings with 1 or 2 storeys. Also, it is necessary to take into account that this measure has a negative effect for the heating demand; this will be higher because the heat gains due to solar radiation will decrease. As a consequence, when for aesthetical reasons the colour of all the external façades has to be the same, and all of them will be painted in a light colour, the orientations SE, S and SW will be worst during winter. In this case, the usefulness of the measure has to be evaluated in an annual basis, and only should be applied in those locations with dominant summer; this is high Summer Climatic Severity (see chapter 2).

3.21.3 Reference to the regional solutions/Climatic applicability

In climates with light summers (Summer Climate Severity as described in chapter 2) it is recommended to use this measure painting E and/or W façades with light colours only if winter is not severe (Winter Climate Severity as described in chapter 2 lower than 0.4). Also, it is possible to apply this measure in the roofs of less than two storey buildings located in the same climatic zone.