Lecture 2.
Energy Consumption of a Heated Space

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Fabric **L**oss **C**oefficient (FLC):

Fabric loss is transmission loss of opaque and transparent building elements or multilayer constructions. Fabric heat loss is heat transfer directly through the building element by convection and conduction. Typical building elements are windows, doors, floors and ceiling of the room etc. For ease of calculation, it is assumed that these losses are at a uniform rate through each surface. There are three main components of fabric losses:

- Transmission loss of single or multilayer planar building element, like internal and external partition walls, windows etc. Transmission loss is a surface loss, so its proportional to the external surface (*A*) and also proportional to the Overall Heat Loss Coefficient (*U*) and the temperature different of the internal and external area (t_i-t_e).
- Additional heat loss due to thermal bridge effect. This is proportional to the length of a thermal bridge, also proportional to the Thermal Bridge Loss Coefficient and the temperature different of the internal and external area.
- Ground loss, which is heat loss of ground-coupled building elements, like ground floor and wall of a basement. This is proportional to the length of a wall or ground section, also proportional to the Ground Loss Coefficient and the temperature different of the internal and external area.

  Thermal Bridge Loss and Ground Loss also called as linear losses, and it coefficient is linear loss coefficient (ψ). Also note that each loss is proportional to the temperature different at steady state:

$$\dot{Q}_{FL}[W] = \sum_{j=1}^{n} U_j \cdot A_j \cdot (t_i - t_e) + \sum_{k=1}^{m} \psi_k \cdot L_k \cdot (t_i - t_e) \qquad / : (t_i - t_e)$$

In the above equation $\dot{Q}_{FL}$ is the Fabric Loss by unit time (W), which divided by the overall temperature different (t_i-t_e):

$$\dot{q}_{FL}[W/K] = \sum_{j=1}^{n} U_j \cdot A_j + \sum_{k=1}^{m} \psi_k \cdot L_k \qquad / : V_h$$

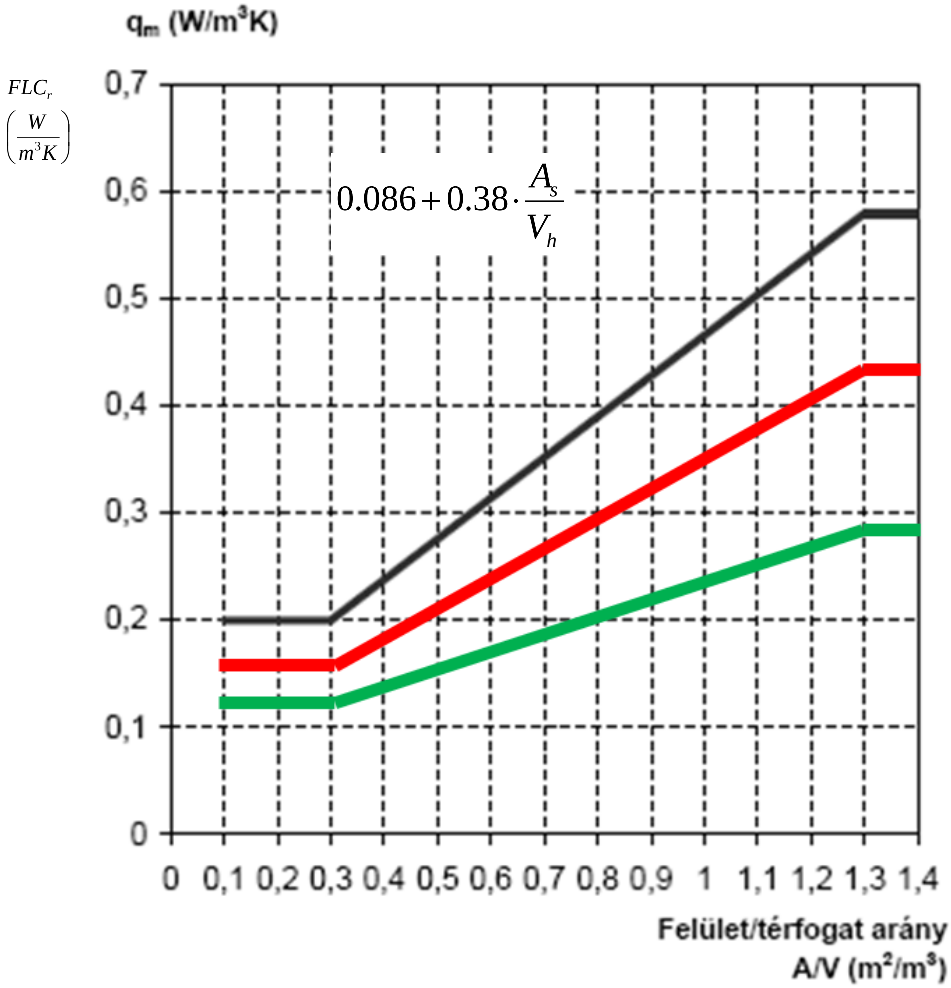
The above equation represents the Fabric Loss by unit time at unit temperature (W/K), which is the *fabric conductance*. If the above equation is divided by the net volume of the heated space (V_h), the Fabric Loss Coefficient (FLC) is defined:

$$FLC[\frac{W}{m^3 K}] = \frac{1}{V_h} \sum_{j=1}^{n} U_j \cdot A_j + \frac{1}{V_h} \sum_{k=1}^{m} \psi_k \cdot L_k$$

Fabric Loss Coefficient is the Energy loss of a heated space by unit time, at unit temperature and of the heated volume of the building (W/m^3K). Fabric loss coefficient only depends on the thermal quality of the building shell.

Requirements for Fabric Loss Coefficient (FLCr):

In order to improve thermal behavior of the building shell Fabric Loss Coefficient (FLSr) is maximized. Note that sometimes utilized external gain (direct and indirect gains by energy collecting building elements: window, trombe wall, mass wall, solar space, transparent insulation etc.) also included in the FLC calculation. Because fabric loss is not independent from the shape and volume of the building often the required value is not a constant but a function of a heated area pro heated volume:



Filtration **L**oss **C**oefficient (FILC):

Ventilation and infiltration both bring outside air into the building, forcing out the air that was inside the building. In winter time, the cold outside air replaces the warm inside air. To keep the temperature inside at standard value, the heating system must raise the temperature of the outside air temperature. This heating of ventilation and infiltration increases the heat loss of the building.

With these air changes, it is necessary to calculate the energy required to heat the volume of air by the temperature difference. (*Air changes per hour is a measure of how many times the air within a defined space (normally a room or house) is replaced.)*

In Hungary an average ACH value is required. For examples: residential buildings: ACH=0.5 1/h, office buildings: ACH=0.8 1/h, educational buildings: ACH=0.9 1/h . For public buildings CR 1752 standards sets the minimum required ventilation rate.

$$\dot{Q}_{FIL}[W] = \dot{m} \cdot c_p \cdot (t_i - t_e) = V_h \cdot ACH \cdot \left(\frac{c_p \cdot \rho}{3600} \right) \cdot (t_i - t_e)$$

$$\dot{Q}_{FIL}[W] = V_h \cdot ACH \cdot \left(\frac{1.05 \cdot 1.2}{3.6} \right) \cdot (t_i - t_e) = 0.35 \cdot V_h \cdot ACH \cdot (t_i - t_e) \qquad / : (t_i - t_e)$$

$\dot{q}_{FIL}[W/K] = 0.35 \cdot V_h \cdot ACH \qquad / : V_h$ which is a filtration conductance. Filtration Loss Coefficient is represented by the following equation:

$$FILC[W/m^3K] = 0.35 \cdot ACH$$

Typical ACH values:

Building	**'Leaky' building**	**Moderately 'tight' building**	**Airtight, low energy buildings**
Office Type 1: naturally ventilated, 100 – 3000 m^2	0,90	0,30	0,10
Office Type 2: naturally ventilated, 500–4000 m^2	0,70	0,25	0,12
Office Type 3: air conditioned, 2000–8000m^2	0,60	0,20	0,10
Office Type 4: air conditioned HQ-type building, 4000–20000 m^2	0,65	0,25	0,12
Factories, warehouses, halls	0,65	0,25	0,12
Schools	0,70	0,25	0,12
Hospitals and Health Care buildings	0,60	0,25	0,12
Hotels	0,85	0,30	0,15
Dwellings – 1 storey	1,15	0,40	0,20
Dwellings – 2 storeys	1,00	0,35	0,17
Apartments – 1 to 5 storeys	1,00	0,50	0,25
Apartments – 6 to 10 storeys	1,60	0,55	0,27

Total Heat **L**oss **C**oefficient (TLC):

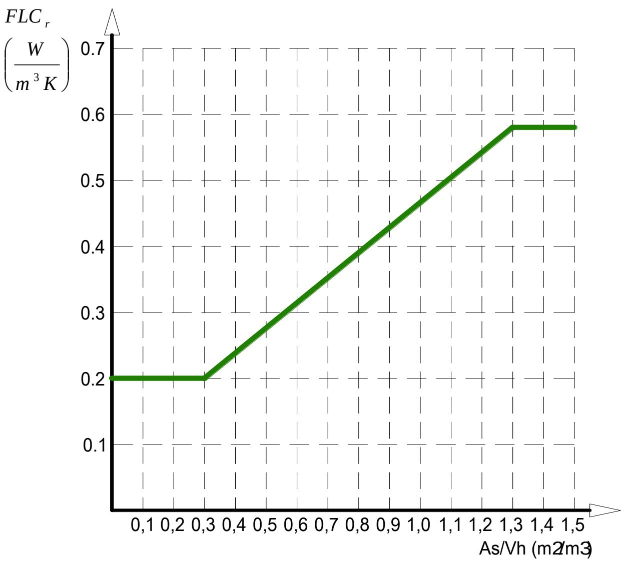
In heat total loss coefficient fabric losses (transmission loss, thermal bridge and ground loss are included) and filtration loss are concerned:

TLC = FLC + FILC thus

$$\mathrm{TLC}[\frac{\mathrm{W}}{\mathrm{m}^3 K}] = \frac{1}{V_h}\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{U_j} \cdot \mathrm{A_j} + \frac{1}{V_h}\sum_{\mathrm{k=1}}^{\mathrm{m}} \psi_{\mathrm{k}} \cdot \mathrm{L_k} + 0.35 \cdot \mathrm{ACH}$$

Note that in the above equation if we define an average filtration for the heating session TLC is independent from all the internal and external circumstances. Only depends on the thermal behavior and the air tightness of the building shell.

Example 1.



A., Estimate the Total Loss Coefficient for a following simplified (one zone model) building, if the Fabric Loss is just fulfills the requirement. For estimating the required Fabric Loss Coefficient, use the following diagram. The average Air Change during the heating period is 0.5/h. The building is a 10mx10mx3m rectangle.

B., Estimate the heat loss of a unit cubic, and the total heat loss, if the building shell fulfils the energetic requirement. The internal average temperature is 20°C, the external design temperature is -15°C,

A., External surface: A_s=2·10m·10m+4·10m·3m=320m^2

Heated volume: V_h=300m^3

A_s/ V_h=320/300=1.067m^2/m^3

0.3≤A_s/ V_h≤1.3 thus $FLS_r = 0.086 + 0.38 \cdot \frac{A_s}{V_h} = 0.086 + 0.38 \cdot 1.067 = 0.497 \frac{W}{m^3 K}$

TLC = FLC_r + FILC = FLC_r+ 0.35·ACH = 0.497 + 0.35·0.5 =

=0.497 + 0.175 = 0.666 W/m^{3}K

B., $\dot{\mathrm{q}} = \mathrm{TLC} \cdot (\mathrm{t_i} - \mathrm{t_e}) = 0.666 \frac{W}{m^3 K} \cdot 35°C = 23.3 \frac{W}{m^3}$

$\dot{\mathrm{Q}} = \dot{q} \cdot V_h = 23.3 \frac{W}{m^3} \cdot 300 m^3 = 6990 W$

Heating **D**egree **H**our (HDh)

In the previous chapter Total Loss Coefficient (TLC) was defined. TLC represents the thermal loss behavior of the building shell including fabric and filtration loss. If TLC is multiplied by the net heated volume of the Building Loss Factor is defined, which is a sum of the Envelop Conductance ($\dot{q}_{FL}$ (W/K)) and Filtration Conductance $\dot{q}_{FIL}$ (W/K), it defines the total heat loss of a building at 1K temperature different:

$$\mathrm{BLF} = \dot{q}_{FL} + \dot{q}_{FIL} = \sum_{j=1}^{n} U_j \cdot A_j + \sum_{k=1}^{m} \psi_k \cdot L_k + 0.35 \cdot V_h \cdot \mathrm{ACH}\ (\mathrm{W/K})$$

or

$$\mathrm{BLF} = \mathrm{TLC} \cdot V_h\ (\mathrm{W/K})$$

Note that Building Loss Factor includes thermal and geometrical behavior of the building. It's also independent from the internal and external thermal circumstances.
The total fabric loss and filtration loss equation is the following:

$$\dot{Q} = \dot{q}_{FL} + \dot{q}_{FIL} = \sum_{j=1}^{n} U_j \cdot A_j \cdot (t_i - t_e) + \sum_{k=1}^{m} \psi_k \cdot L_k \cdot (t_i - t_e) + 0.35 \cdot V_h \cdot \mathrm{ACH} \cdot (t_i - t_e)\ (\mathrm{W})$$

This equation can be separated by two variables: Building dependent variable (BLF) and thermal circumstance variable (t_i-t_e):

$$\dot{Q} = \mathrm{BLF} \cdot (t_i - t_e)\ (\mathrm{W})$$

If the energy loss is to be calculated for a certain period, the above equation should be multiplied by that certain time period ($\Delta\tau$). Concerning SI unit it's one second (s):

$$Q = \mathrm{BLF} \cdot (t_i - t_e) \cdot \Delta\tau\ (\mathrm{J})$$

The product of temperature different and time has an integrating property. By extending time its value is getting bigger and bigger. Instead of applying SI unit in the equation above, time is 1h, than it has a unit W·h. Dividing it by 1000 the unit becomes kW·h:

$$Q = \frac{\mathrm{BLF} \cdot (t_i - t_e) \cdot 1 \cdot h}{1000}\ (\frac{\mathrm{kW}}{\mathrm{h}})$$

Based on the above equation a Heating Degree Hour can be defined, by leaving Building Loss Factor (which holds the building properties)

$$\mathrm{HDh}_{ti} = (t_i - \bar{t}_{e,h}) \cdot 1 \cdot h \quad (\mathrm{h} \cdot {}^\circ\mathrm{C}, \mathrm{h} \cdot \mathrm{K})$$

The external temperature is the average temperature during the investigated hour ($\bar{t}_{e,h}$). In order to define HDh the internal temperature should be set. The unit of Degree Hours is h·°C or h·°C. The energy consumption of a building shell for one hour can be calculated based on the Heating Degree Hour:

$$Q = \frac{\mathrm{BLF} \cdot (t_i - \bar{t}_{e,h}) \cdot 1 \cdot h}{1000} = \mathrm{BLF} \cdot \frac{(t_i - \bar{t}_{e,h}) \cdot 1 \cdot h}{1000} = \frac{\mathrm{BLF} \cdot \mathrm{HDh}_{ti}}{1000}\ (\frac{\mathrm{kW}}{\mathrm{h}})$$

Heating Degree Hours is used in estimating the energy consumption for heating. The t_i index of HDh indicates that HDh is only represented at given internal temperature.

Heating **D**egree **D**ay (HDD)

If degree hours is summarized for one day Heating Degree Day is calculated:

$$\mathrm{HDD} = \sum_{24h} \mathrm{DH_{ti}} = \sum_{24\mathrm{h}} \left(t_i - \bar{t}_{e,h}\right) \cdot 1 \cdot h \quad (\mathrm{h \cdot °C, h \cdot K})$$

Heating degree day also can be calculated based on the daily average external temperature:

$$\mathrm{HDD} = \sum_{24h} \mathrm{HDh_{ti}} = \left(t_i - \bar{t}_{e,24h}\right) \cdot 24 \cdot h \quad (\mathrm{h \cdot °C, h \cdot K})$$

To get the same unit (h°C) the equation is multiplied by 24. Instead of h°C, Day°C can be used as unit. Change rate is 24: 1 Day°C = 24 h°C = 24 hK.

Degree **D**ay for a **H**eating **S**ession (**H**eating **D**egree **D**ays - H_{ti})

If the number of hours when the heating system is on is known, Degree Days or Degree Hours can be defined for estimating heat required for the whole session:

$$\mathrm{H_{ti}} = \sum_{hh} \mathrm{HDh_{ti}} = \sum_{hh} \left(t_i - \bar{t}_{e,h}\right) \cdot h \quad (\mathrm{h \cdot °C, h \cdot K})$$

or

$$\mathrm{H_{ti}} = \sum_{hh} \mathrm{HDD_{ti}} = \sum_{hd} \left(t_i - \bar{t}_{e,24h}\right) \cdot Day \quad (\mathrm{Day \cdot °C, Day \cdot K})$$

Heating degree day (H_{ti}) is a measurement designed to reflect the demand for energy needed to heat building. It is derived from measurements of outside air temperature. The heating requirements for a given structure at a specific location are considered to be directly proportional to the number of H_{ti} at that location. A similar measurement, cooling degree day' (CDD), reflects the amount of energy used to cool a home or business.

Heating degree days are defined relative to a *base* temperature - the outside temperature above which a building needs no heating. The most appropriate base temperature for any particular building depends on the temperature that the building is heated to, and the nature of the building (including the heat-generating occupants and equipment within it).

For calculations relating to any particular building, HDD should be selected with the most appropriate base temperature for that building. However, for historical reasons HDD are often made available with base temperatures of 20°C , or 24°C - base temperatures that are approximately appropriate for a good proportion of buildings.

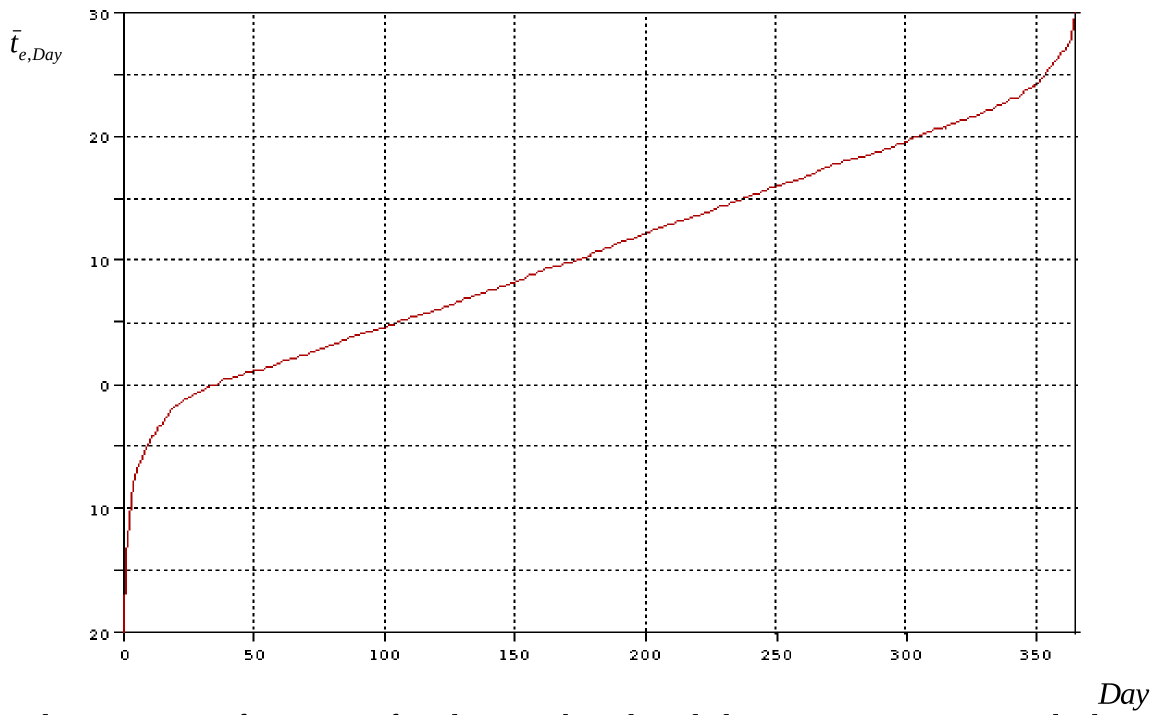
There are a number of ways in which HDD can be calculated: the more detailed a record of temperature data, the more accurate the HDD that can be calculated. HDD are often calculated using simple approximation methods that use daily temperature readings instead of more detailed temperature records such as half-hourly readings. One popular approximation method is to take the average temperature on any given day, and subtract it from the base temperature. If the value is less than or equal to zero, that day has zero HDD. But if the value is positive, that number represents the number of HDD on that day.

H_{ti} can be added over periods of time to provide a rough estimate of seasonal heating requirements.

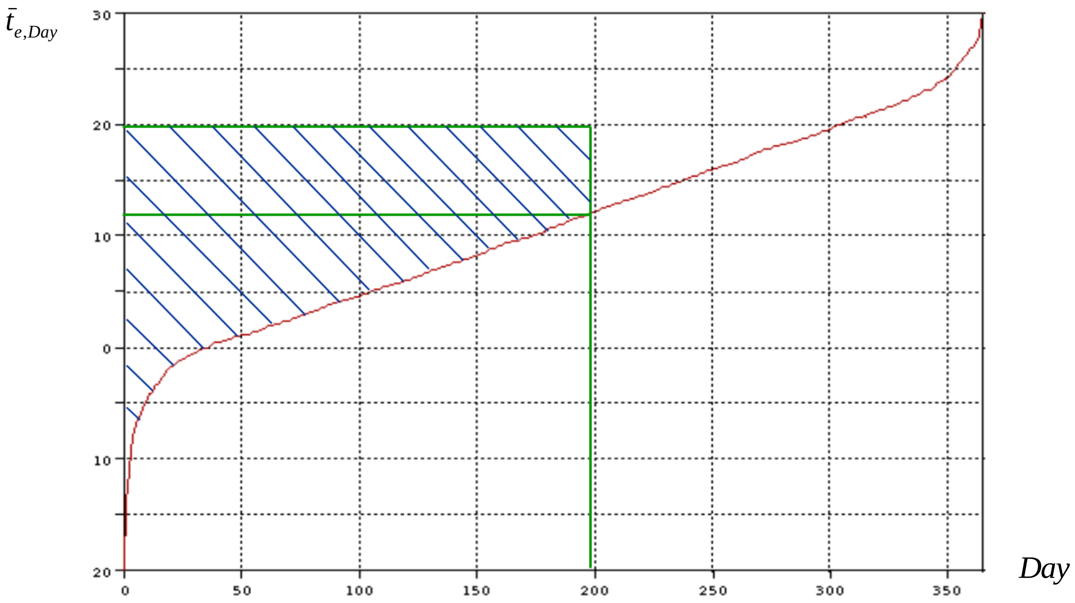
Calculations using H_{ti} have several problems. Heat requirements are not perfectly linear with temperature, and heavily insulated buildings have a lower "balance point". The amount of heating and cooling required depends on several factors besides outdoor temperature: How well insulated a particular building is, the amount of solar radiation reaching the interior of a house, the number of electrical appliances running (e.g. computers raise their surrounding temperature) the amount of wind outside, and individuals' opinions about what constitutes a comfortable indoor temperature. Another important factor is the amount of relative humidity indoors; this is important in determining how comfortable an individual will be. Other variables such as wind speed, precipitation, cloud cover, heat index, and snow cover can also alter a building's thermal response.
Another problem with HDD is that care needs to be taken if they are to be used to compare climates internationally, because of the different baseline temperatures used as standard in different countries and the use of the Fahrenheit scale in the US and the Celsius scale almost everywhere else. This is further compounded by the use of different approximation methods in different countries.

External temperature distribution, frequency and Degree Day

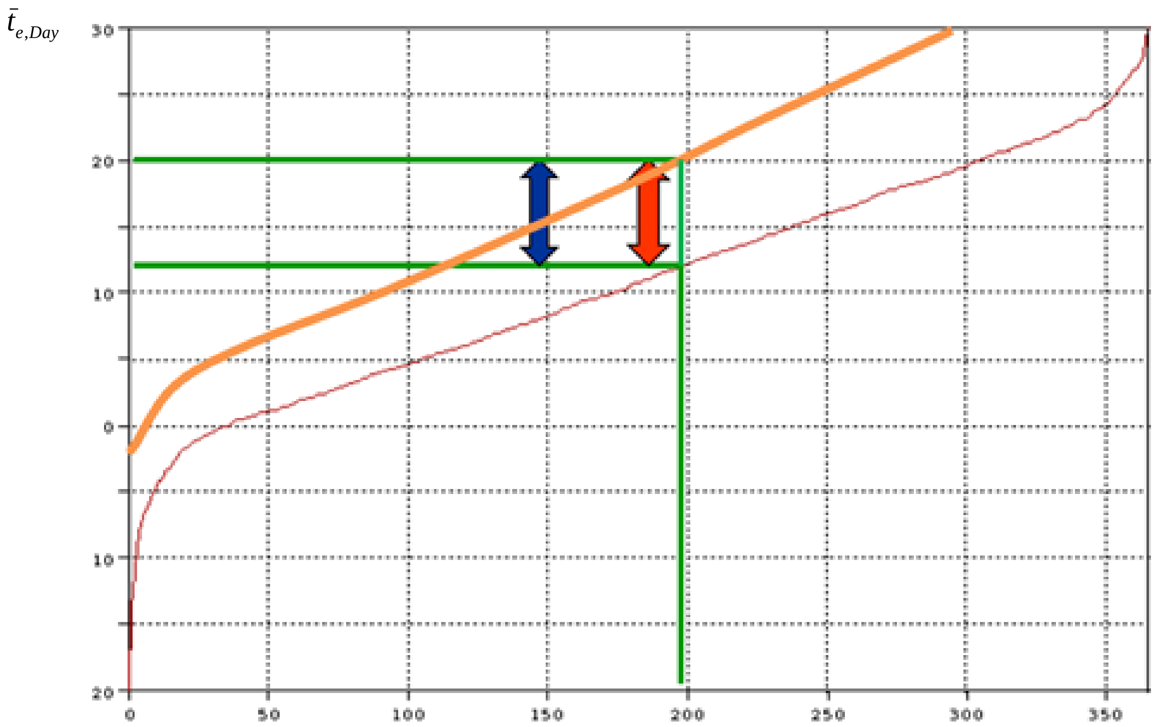
External temperature frequency is the number of external daily average temperatures of a year.



Daily temperature frequency of Budapest is based on daily average temperature calculation.

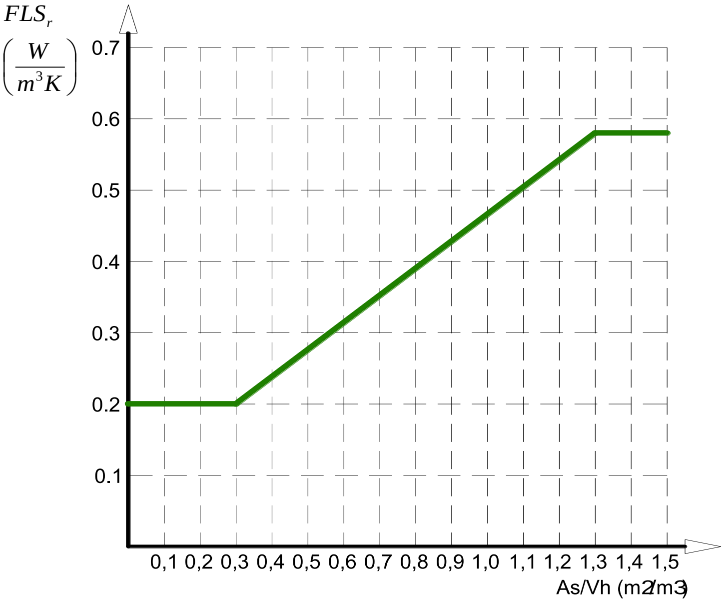


Area of Degree Hours or Degree Days at 20°C internal and 8°C internal balance point temperature different.



Balance point temperature

Example 2.



A., Estimate the net energy consumption for a heating session for a following simplified (one zone model) building. The average Air Change during the heating period is 0.5/h. The building is a 30mx20mx4m rectangle. HDD(20°C)=72kKh. The Fabric Loss is just fulfills the requirement. For estimating the required Fabric Loss Coefficient, use the following diagram.

A., External surface: A_s=2·30m·20m+2·20m·4m+2·30m·4m =1600m^2

Heated volume: V_h=20m·30m·4m= 2400m^3

A_s/ V_h=1600/2400=0.667m^2/m^3

0.3≤A_s/ V_h≤1.3 thus $FLS_r = 0.086 + 0.38 \cdot \frac{A_s}{V_h} = 0.086 + 0.38 \cdot 0.667 = 0.339 \frac{W}{m^3 K}$

TLC = FLC_r + FILC = FLC_r+ 0.35·ACH = 0.339 + 0.35·0.5 =
=0.339 + 0.175 = 0.514 W/m^{3}K

BLF=TLC·V_h=0.514 W/m^{3}K·2400 m^3=1234.4W/K

$$Q = \text{BLF} \cdot HDD \ (\text{kWh}) = 1234.4 (\text{W/K}) \cdot 72 (kKh) = 88876 \text{kWh}$$

The net energy consumption of a heating session is always expressed for each net heated floor area thus:

$$\frac{Q}{A} = \frac{88876 \text{kWh}}{20m \cdot 30m} \ (\frac{\text{kWh}}{\text{m}^2}) = 133{,}315 \frac{\text{kWh}}{\text{m}^2}$$