Calculation of heat loss of buildings

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1 *Energy Balance of a Heated Space*

Energy balance is when the heat (or rate of heat over unit time) enters across a control volume is equal to the heat (or rate of heat over unit time) leaves across a same control volume.

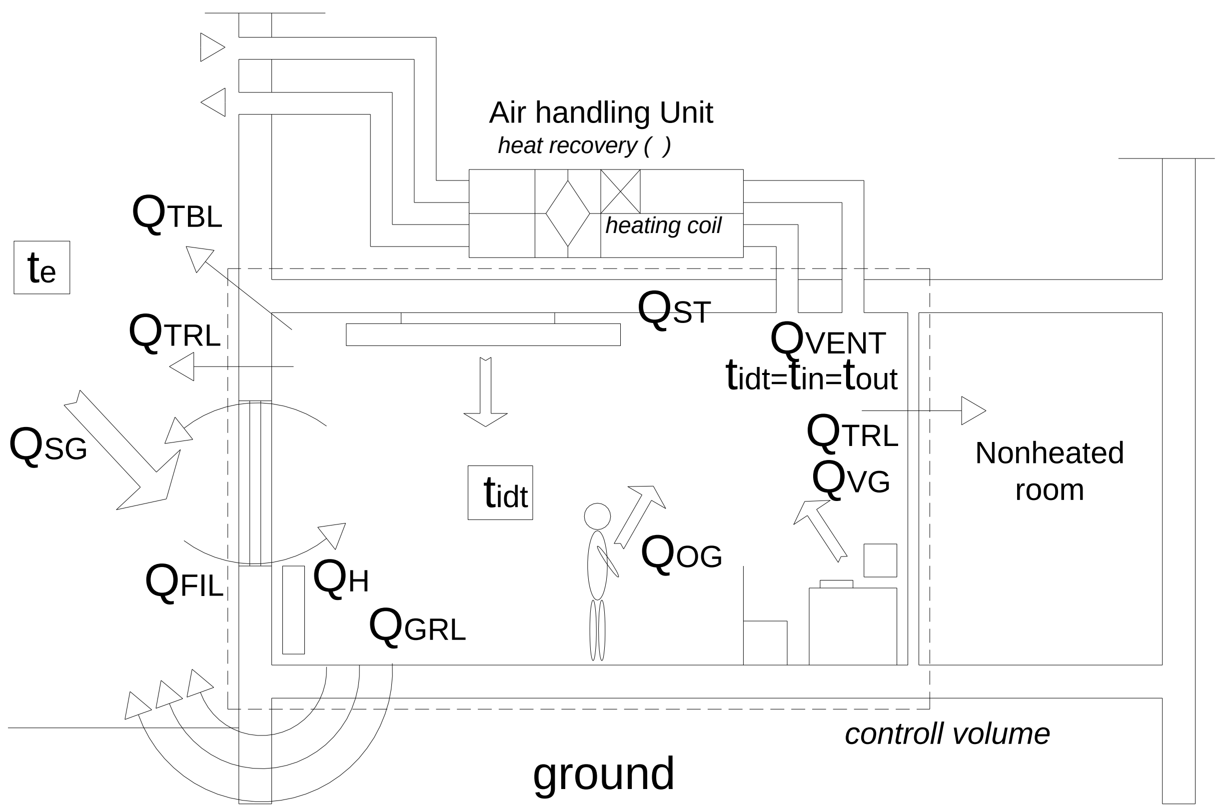
Through a given volume energy enters (called gains), and leaves (called losses) in unit time. Gains and losses are equal to each other.

$$Q_{gains}=Q_{losses}$$

Most of the losses are proportional to the internal and external temperature different. During winter period (when additional heat is required produces by heating) the internal temperature is always higher than the external one, thus

$$Q_{losses}\sim(t_{idt}-t_{edt}).$$

In the equation t_{idt} is the design temperature; t_e is the external temperature (for details see chapter 2. and 3.).



Energy balance of a heated space

Concerning gains internal and external ones are distinguished. Losses and gains with more details described by the following equation:

$$Q_{ext.gains}+Q_{int.gains}=Q_{FL}+Q_{FIL}+Q_{VENT}\pm Q_{ST}$$

Where

Q_{FL} – is **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. (Q_{TRL}),
- Additional heat loss due to **thermal bridge** effect (Q_{TBL}),
- **Ground loss**, which is heat loss of ground-coupled building elements, like ground floor and wall of a basement (Q_{GRL}).

Thus

$$Q_{FL}=Q_{TRL}+Q_{TBL}+Q_{GRL}$$

Q_{FIL} – is a filtration loss, which is related to the air tightness of a building shell,
Q_{VENT} – is the energy loss due to mechanical ventilation,
Q_{ST} – Heat which is stored in the building mass. The stored heat is related to the heat capacity and density of the building shell.

External gain is more or less **a solar gain** thus $Q_{ext.gains}=Q_{SG}$

Internal gains are due to **lighting** (Q_{LG}), **occupancy** (Q_{OG}) and all other gains of electrical driven equipments which are called **various** (Q_{VG}). Also a heat which is loaded by the heating equipment can be considered as internal gain (Q_H). Thus the detailed energy balance equation can be written as

$$Q_{SG}+(Q_{LG}+Q_{OG}+Q_{VG}+Q_H)=(Q_{TRL}+Q_{TBL}+Q_{GRL})+Q_{FIL}+Q_{VENT}\pm Q_{ST}.$$

In a case of heating and also cooling (the equation above can be extended for summer case), the necessary heat emission is questioned, so the above equation can be expressed for Q_H

$$Q_H=(Q_{TRL}+Q_{TBL}+Q_{GRL})+Q_{FL}+Q_{VENT}-Q_{SG}-(Q_{LG}+Q_{OG}+Q_{VG}+Q_H)\pm Q_{ST}$$

Note that the above equation is not for sizing heat emitters but for the emitted heat to reach the thermal equilibrium at certain external and internal design temperatures. In the next chapters the above elements will be described with more details.

2 Internal design temperature

In country by country there are slightly difference between the recognize design temperatures for domestic and other rooms. Design temperatures is mainly depends on the activity in the room, but it should be chosen to ensure satisfactory comfort conditions. If there are significant differences between adjacent temperatures of rooms during the heat loss calculation this should also be considered.

	UK standard		Hungarian standard	
Room temperatures	***°C***	***°F***	***°C***	***°F***
Lounge	21	70	20	68
Dining Room	21	70	20	68
Bedsitting Room	21	70	20	68
Bedroom	18	65	20	68
Hall and Landing	16	60	20	68
Bathroom	22	72	24	75
Kitchen	18	65	20	68
WC	18	65	18	65

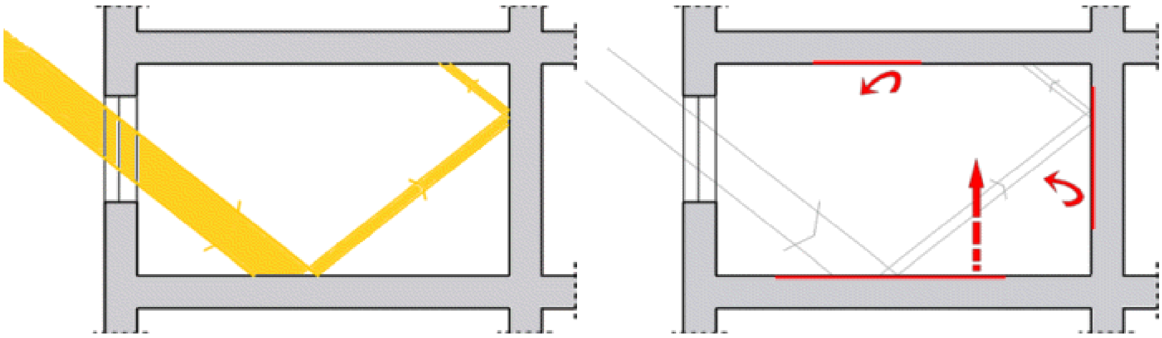
Standard domestic room temperatures

3 External design temperature

The external design temperature should allow for all but the most extreme conditions. This is the reason that different countries have different external design temperatures. Even in a certain country for different regions there are specific design temperatures. For instance in UK generally -1°C is normally chosen, but in further North of England and Scotland, - 3°C or even -5°C is chosen. Even in Hungary have differences in external design temperatures. It's varies between -12 .. -20 °C.

4 External gain

External gain is or solar gain (also known as solar heat gain or passive solar gain) which refers to the increase in temperature in a space, object or structure that results from solar radiation. The amount of solar gain increases with the strength of the sun, and with the ability of any intervening material to transmit or resist the radiation. Objects struck by sunlight absorb the short-wave radiation from the light and reradiate the heat at longer infrared wavelengths. Where there is a material or substance (such as glass) between the sun and the objects struck that is more transparent to the shorter wavelengths than the longer, then when the sun is shining the net result is an increase in temperature - solar gain. This effect, the greenhouse effect, so called due to the solar gain that is experienced behind the glass of a greenhouse, has since become well known in the context of global warming.



Greenhouse effect due to irradiation

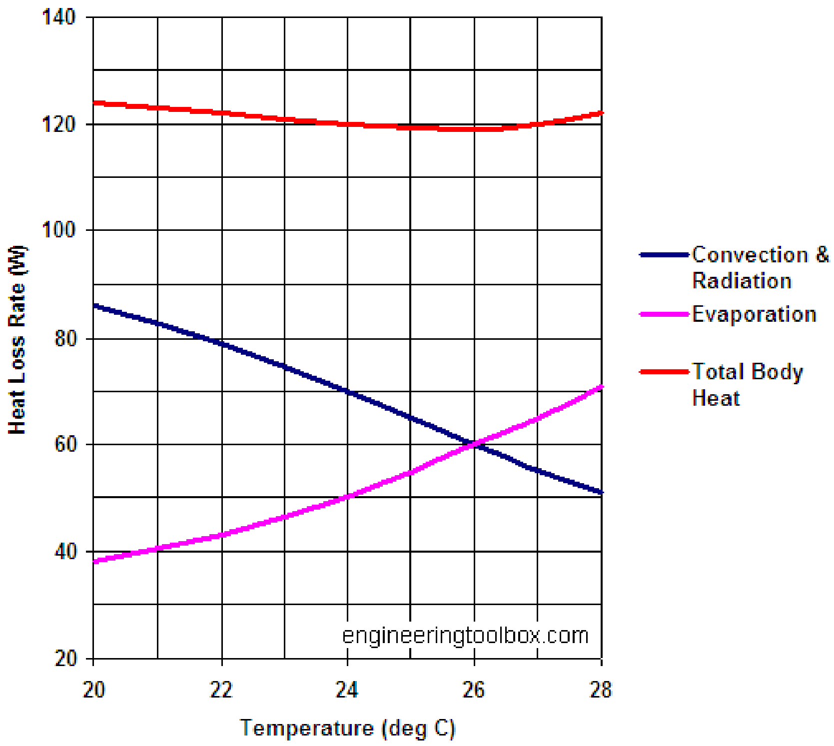
5 *Internal gains*

Inside buildings people, technical equipment, artificial lighting, and even warm goods give off heat. High occupancy levels and great number of technical devices cause high internal loads especially in office buildings. The conditions are easily calculated using specific office building occupancy schedules. Residential buildings are more variable in occupancy and technical equipment. The internal heat gains remain generally remain lower and therefore much less significant than in office buildings, schools etc.

Heat production of the occupancy (Q_{OG}) is mainly depends on its activity and the ambient temperature and humidity:

Degree of Activity	Typical Application	Average Metabolic rate - male adult (*W*)	Room Dry Bulb Temperature (*°C*)											
			28		27		26		24		22		20	
			Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.
Seated at rest	Cinema, theatre, school	100	50	50	55	45	60	40	67	33	72	28	79	21
Seated, very light work	Computer working	120	50	70	55	65	60	60	70	50	78	42	84	36
Office work	Hotel reception, cashier	130	50	80	56	74	60	70	70	60	78	52	86	44
Standing, walking slowly	Laboratory work	130	50	80	56	74	60	70	70	60	78	52	86	44
Walking, seated		150	53	97	58	92	64	86	76	74	84	66	90	60
Moderate work	Servant, hair dresser	160	55	105	60	100	68	92	80	80	90	70	98	62
Light bench	Mechanical production	220	55	165	52	158	70	150	85	135	100	120	115	105

work														
Moderate Dancing	Party	250	62	188	70	180	78	172	94	156	110	140	125	125
Fast walking	Mountain walking	300	80	220	88	212	96	204	110	190	130	170	145	155
Heavy work	Athletics	430	132	298	138	292	144	286	154	276	170	260	188	242

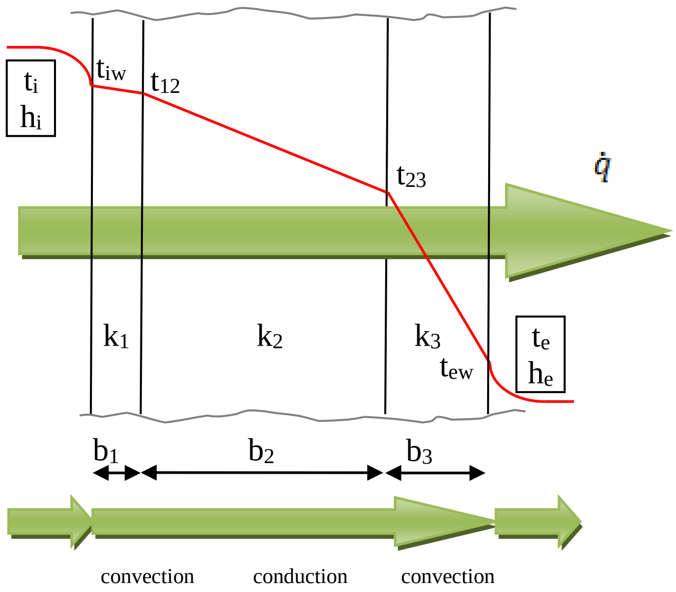


Body Heat Generated at moderate activity- seated, very light work (computer working)

The lighting gain can be calculated by the following formula:

$Q_{lighting} = \Sigma\, p \cdot A$
where p [W/m^2] – the specific electric power demand of lighting:
Low visual demand: 5 W/m^2 (such functions and rooms would be: storages, WC, machinery rooms,etc.)
Intermediate visual demand: 10 W/m^2, (such functions and rooms would be: reception, restaurant, hall, mall, corridors, etc.)
Mediate visual demand: (15 W/m^2, such functions and rooms would be: offices, kitchen, pay-desk, etc.)
High visual demand: (20 W/m^2, such functions and rooms would be: exhibition rooms, cosmetics, etc.)
A [m^2]: sum of floor areas of the rooms having similar visual demand.

There are several other electrical equipments like computer, copy machine, cooker etc. These equipments are called as various (Q_{VG}).



Transmission loss of single or multilayer planar building element means conduction and convection. In steady state (constant temperatures of the boundaries) heat flux is constant from and to the boundaries and also constant at each layers.

Slab consisting of three layers of thickness b_1, b_2 and b_3, having thermal conductivities k_1, k_2 and k_3, transmitting heat by convection between air at temperature t_i, t_e with heat transfer coefficient h_1, h_2. In the steady state, per unit area of slab the heat flux is

$$\dot{q} = h_i(t_i - t_{iw}) = \frac{k_1}{b_1}(t_{iw} - t_{12}) = \frac{k_2}{b_2}(t_{12} - t_{23}) = h_e(t_{ew} - t_e) = const. \left[\frac{W}{m^2}\right]$$

then

$$t_i - t_{iw} = \dot{q}\frac{1}{h_i}, t_{iw} - t_{12} = \dot{q}\frac{b_1}{k_1}, t_{12} - t_{23} = \dot{q}\frac{b_2}{k_2}, t_{23} - t_{ew} = \dot{q}\frac{b_3}{k_3}, t_{ew} - t_e = \dot{q}\frac{1}{h_e}$$

$$\sum \Delta t : t_i - t_e = \dot{q}\left(\frac{1}{h_i} + \frac{b_1}{k_1} + \frac{b_2}{k_2} + \frac{b_3}{k_3} + \frac{1}{h_e}\right).$$

Reordering to the heat flux

$$\dot{q} = \frac{t_i - t_e}{\frac{1}{h_i} + \frac{b_1}{k_1} + \frac{b_2}{k_2} + \frac{b_3}{k_3} + \frac{1}{h_e}}.$$

In general:

$$\dot{q} = \frac{t_i - t_e}{\frac{1}{h_i} + \sum_{j=1}^{n}\frac{b_j}{k_j} + \frac{1}{h_e}}$$

We are really concerned with the rate of heat transfer between the two sides of the composite slab rather than the process between surfaces. It is convenient to define an overall heat transfer coefficient (U-value), given by

$$\dot{q} = U(t_i - t_e) \quad (\frac{W}{m^2 \cdot K})$$

thus

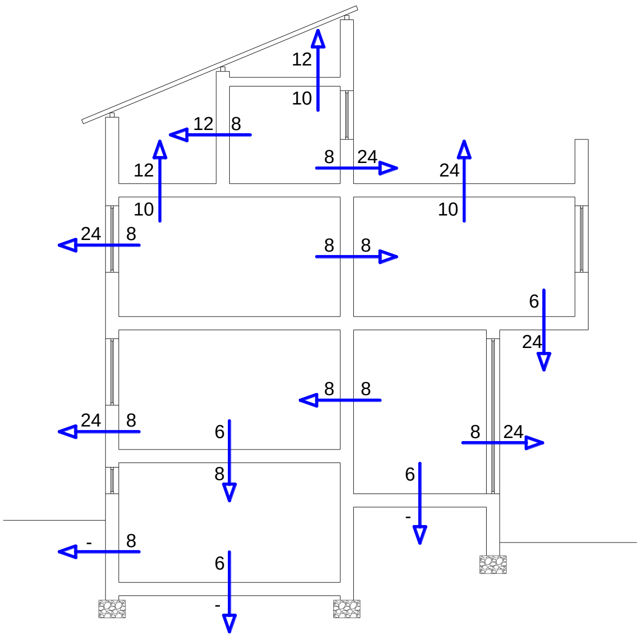
$$U = \frac{1}{\frac{1}{h_i} + \sum_{j=1}^{n} \frac{b_j}{k_j} + \frac{1}{h_e}} \quad (\frac{W}{m^2 \cdot K}).$$

The transmission heat flow rate is proportionate to the U value, the temperature difference between the indoor and outdoor air (t_{idt}-t_e) and the area (A) of the surface:

$$\dot{Q} = U \cdot A \cdot (t_{idt} - t_{edt}) \quad (W)$$

The U-value measures how well a building component, e.g. a wall, roof or a window, keeps heat inside a building. For those living in a warm climate the U-value is also relevant as it is an indicator of how long the inside of the building can be kept cold. The technical explanation of the U-value U-value physically describes how much thermal energy in Watts [W] is transported through a building component with the size of 1 square meter [m²] at a temperature difference of 1 Kelvin [K] (=1ºC). Thus the unit for U-values is W/(m²K).
Different national standards set as the minimum requirements for U-values.

Internal and external surface convection (h) are estimated by approximate values. (See figure at left hand side).



Surface convection coefficients (h) for different cases

7 Additional loss due to thermal bridges (Q_{TBL})

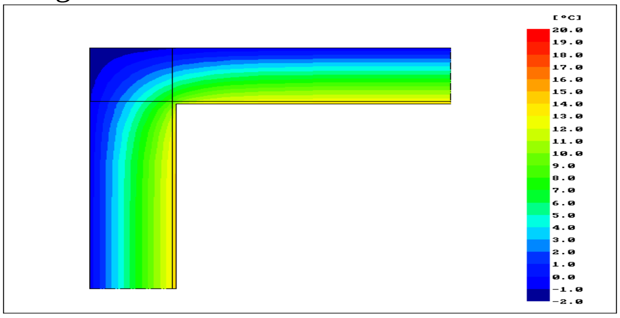
A thermal bridge is a component, or assembly of components, in a building envelope through which heat is transferred at a substantially higher rate than through the surrounding envelope area, also temperature is substantially different from surrounding envelop area.

To simplify the calculation of the extra heat losses due to the thermal bridge effect, the concept of linear heat loss coefficient (ψ) was implemented. This refers to the extra heat losses along a unit length of a thermal bridge, at a unit temperature difference and in a unit time. It is measured in W/mK, where l is the length of the edge (corner, joint, column, window perimeter). Thus the additional heat loss is expressed by

$$\dot{Q}_{TBL} = l \times \Psi(t_{idt} - t_{edt})(W)$$

equation.

There are several ways of estimating overall heat loss of external wall including thermal bridges:



- *Linear heat loss coefficients are collected in structural details handbooks.*
- *Simplified methods*
- *Simulation tools (KOBRA, THERM)*

The additional heat loss due to thermal bridges can be considered in the overall het transfer coefficient by expressing the fabric losses in one equation:

$$Q_{FL} = AU_e(t_{idt} - t_e dt) = Q_{TRL} + \sum_j Q_{TBL_j} = AU\ (t_{idt} - t_e) + \sum_j l_j \Psi_j (t_{idt} - t_e)$$

reordering the equation for the equivalent (or fabric loss) overall heat transfer coefficient:

$$U_e = U\ + \frac{\sum_j l_j \Psi_j}{A},$$

$$U_e = U\ + \frac{U}{U}\frac{\sum_j l_j \Psi_j}{A} = U \cdot \left(1 + \frac{\sum_j l_j \Psi_j}{A \cdot U}\right)$$

Where the equation in the parenthesis represents the correcting factor of thermal bridge effect:

$$\chi = 1 + \frac{\sum_j l_j \Psi_j}{A \cdot U}$$

The correcting factor for additional heat loss of thermal bridges (χ) can be identified by a following table as a simplified method. In the table χ depends on type of the building shell:

Correction factor for thermal bridges of the building shell Type of the building shell			Correction factor of thermal bridge effect χ
External wall	**With insulation**	High loss	0,15
		Medium loss	0,20
		Low loss	0,30
	Without insulation	High loss	0,25
		Medium loss	0,30
		Low loss	0,40
Flat roof		High loss	0,10
		Medium loss	0,15
		Low loss	0,20
Timber roofing		High loss	0,10
		Medium loss	0,15
		Low loss	0,20
Ceiling			0,10
Arcade ceiling			0,10
Basement ceiling	**With insulation**		0,20
	Without insulation		0,10
Partition wall			0,05

From the above table three main thermal bridge classes are extinguished: low, medium and high rate of heat loss. The classes depend on the relative length of thermal bridges. Relative length values are identified in the following table:

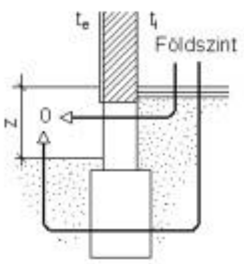
Type of the building shell	Relative length of the thermal bridge (fm/m^2)		
	Thermal bridge class		
	Low loss	Medium loss	High loss
External wall	< 0,8	0,8 – 1,0	> 1,0
Flat roof	< 0,2	0,2 – 0,3	> 0,3
Other	< 0,4	0,4 – 0,5	> 0,5

8 *Ground losses (Q_{GRL})*

Ground loss is also considered as linear loss, thus for heat loss through the ground is estimated by the linear loss equation:

$$\dot{Q}_{GRL} = l \times \Psi_{GRL}(t_{idt} - t_{edt})(W)$$

In this equation ψ is the linear ground loss coefficient, which can be also estimated by using computer simulation tools, or the following table can be used for ground floor or walls by the ground. There are two main dependencies: The resistance of the multilayer construction and the relative elevation (which is relative to the ground level around the building).



Elevation different relative to the external ground level	Thermal resistence of floor (considere area 1,5m from the external wall) $R = \frac{d}{\lambda}(m^2K/W)$							
z (m)	Non insulated	0,20- -0,35	0,40- -0,55	0,60- -0,75	0,80- -1,00	1,05- -1,50	1,55- -2,00	2,05- -3,00
-6,00	0	0	0	0	0	0	0	0
-6,00...-4,05	0,20	0,20	0,15	0,15	0,15	0,15	0,15	0,15
-4,00...-2,55	0,40	0,40	0,35	0,35	0,35	0,35	0,30	0,30
-2,50...-1,85	0,60	0,55	0,55	0,50	0,50	0,50	0,45	0,40
-1,80...-1,25	0,80	0,70	0,70	0,65	0,60	0,60	0,55	0,45
-1,20...-0,75	1,00	0,90	0,85	0,80	0,75	0,70	0,65	0,55
-0,70...-0,45	1,20	1,05	1,00	0,95	0,90	0,80	0,75	0,65
-0,40...-0,25	1,40	1,20	1,10	1,05	1,00	0,90	0,80	0,70
-0,20...+0,20	1,75	1,45	1,35	1,25	1,15	1,05	0,95	0,85
0,25....0,40	2,10	1,70	1,55	1,45	1,30	1,20	1,05	0,95
0,45....1,00	2,35	1,90	1,70	1,55	1,45	1,30	1,15	1,00
1,05....1,50	2,55	2,05	1,85	1,70	1,55	1,40	1,25	1,10

Elevation relative to the ground level [m]	Linear heat loss coefficient of a wall by the ground								
	0,30… 0,39	0,40… 0,49	0,50... 0,64	0,65… 0,79	0,80… 0,99	1,00… 1,19	1,20… 1,49	1,50… 1,79	1,80… 2,20
…- 6,00	1,20	1,40	1,65	1,85	2,05	2,25	2,45	2,65	2,80
- 6,00…- 5,05	1,10	1,30	1,50	1,70	1,90	2,05	2,25	2,45	2,65
- 5,00…- 4,05	0,95	1,15	1,35	1,50	1,65	1,90	2,05	2,25	2,45
- 4,05…- 3,05	0,85	1,00	1,15	1,30	1,45	1,65	1,85	2,00	2,20
- 3,00…- 2,05	0,70	0,85	1,00	1,15	1,30	1,45	1,65	1,80	2,00
- 2,00…- 1,55	0,55	0,70	0,85	1,00	1,15	1,30	1,45	1,65	1,80
-1,50…- 1,05	0,45	0,60	0,70	0,85	1,00	1,10	1,25	1,40	1,55
- 1,00…- 0,75	0,35	0,45	0,55	0,65	0,75	0,90	1,00	1,15	1,30
- 0,70…- 0,45	0,30	0,35	0,40	0,50	0,60	0,65	0,80	0,90	1,05
- 0,40…- 0,25	0,15	0,20	0,30	0,35	0,40	0,50	0,55	0,65	0,74
- 0,25 -…	0,10	0,10	0,15	0,20	0,25	0,30	0,35	0,45	0,45

9 *Filtration loss(Q_{FIL}), Ventilation loss(Q_{VENT})*

Definition of air changes (ACH):

Air changes per hour is a measure of how many times the air within a defined space (normally a room or house) is replaced. Air changes in a confined space are important for a variety of reasons, mainly though, we need fresh air to live. Without sufficient fresh air exchange, moisture is trapped in a room/home/building, molds can feed, and other allergens and excessive dangerous gases (e.g. Carbon monoxide, Carbon Dioxide, urea formaldehyde), can remain in the home.

Number of 'air changes per hour' were less of a problem before 'air sealing' came into play, because construction practices and products were not geared to energy efficiency. With a new focus on energy efficiency, and reducing dependence on fossil fuels, consumers try to seal their homes from air transfer in and out of their homes in winter and summer.

The importance of fresh air intake cannot be understated. An air change does not represent a complete change of all air in the enclosure or structure unless it can be considered plug flow. The actual percentage of an enclosure's air which is exchanged in a period depends on the airflow efficiency of the enclosure and the methods used to ventilate it.

air changes per hour (1/h)	
Lounge	1
Dining Room	2
Bedsitting Room	1
Bedroom	0.5
Hall and Landing	1.5
Bathroom	2
Kitchen	2
WC	1.5

For example in the UK there are recognised Air Changes for each room (see right). Where the rooms have not been draught proofed, the number of air changes should be increased.
With these air changes, it is necessary to calculate the energy required to heat the volume of air by the temperature difference.
In Hungary an average and required ACH value is considered. For examples: residential buildings: ACH=0.5 1/h, office buildings: ACH=0.8 1/h, educational buildings: ACH=0.9 1/h

$$\dot{V} = ACH \cdot V \ (m^3/h) = \frac{ACH \cdot V}{3600} \ (m^3/s)$$

Energy required for air exchange:

The energy and power required for heating up the infiltration air is governed by the second law of thermo dynamics:

$$\dot{Q}_{FIL} = \dot{m} \cdot c \cdot \left(t_{idt} - t_{edt}\right) (W)$$

where m is the mass flow rate, c is the specific heat of the moist air. By using the definition of ACH the above equation becomes

$$\dot{Q}_{FIL} = \frac{ACH \cdot V}{3600} \cdot c \cdot \rho \cdot \left(t_{idt} - t_{edt}\right) (W)$$

If we consider the specific heat of the air (c=1.05kJ/kg·K) and the density of the air (ρ=1.2kg/m^3), the above equation can be simplified:

$$\dot{Q}_{FIL} = 0.35 \cdot ACH \cdot V \cdot (t_{idt} - t_{edt})\,(W)$$

The ventilation loss equation is similar to the filtration loss equation. The only different when there is heat recovery is applied in the air handling unit. In this case part of the heat of the leaving air is transferred to the incoming air. The efficiency of the heat recovery is represented by η which is the ratio of the total heat content of the leaving air and the recovered heat.

$$\dot{Q}_{VENT} = 0.35 \cdot ACH \cdot V \cdot (1-\eta) \cdot (t_{idt} - t_{edt})\,(W)$$

10 Estimating total heat loss of buildings

When the task is to determine the size of the emitter of specific rooms internal and external gains are neglected. If the gains were considered the system would be underestimated. So finally the energy balance equation becomes:

$$Q_H = (Q_{TRL} + Q_{TBL} + Q_{GRL}) + Q_{FL}$$

When the boiler size of a building is to be determined, heat losses are summarized, but two additional parts appears:

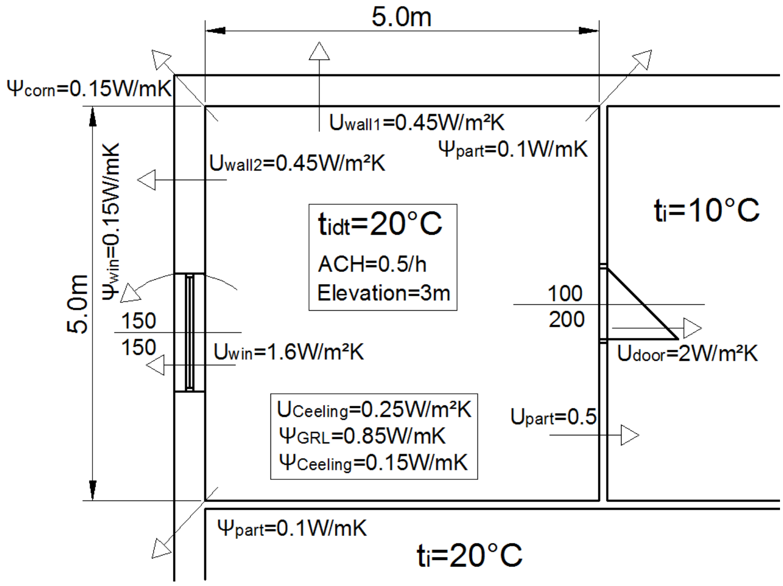
$$Q_{Boiler} = \sum Q_H + Q_{VENT} + Q_{DHW}$$

In the above equation Q_{VENT} is energy required for the ventilation system and Q_{DHW} is the energy required for producing domestic hot water.

Example 1.: Estimate the U-value for a multilayer wall:

	h	d	lambda	R
inner s	8			0,125
plaster		0,015	0,85	0,018
brick		0,380	0,18	2,111
plaster		0,015	0,85	0,018
outler s	24			0,042
Sum				2,3131
U				0,4323

Example 2.: Estimate the heat loss of a room!



ti(°C)=	20						
te(°C)=	-15						
Floor elevation (m)	0						
1. Transmission Loss	**Q=U*A*dt**			**2006**		**2017**	
	A (m2)	A-Aopening	dt(°C)	U (W/m2K)	Q (W)	U (W/m2K)	Q (W)
Wall 1	5*3=15	15	35	0,45	236,3	0,24	126,0
Window	1.5*1.5=2.25	2,25	35	1,60	126,0	1,00	78,8
Wall 2	5*3=15	12,75	35	0,45	200,8	0,24	107,1
Ceeling	5*5=25	25	35	0,25	218,8	0,17	148,8
Floor	(linear loss)	0	35	0,00	0,0	0,00	0,0
inner door	1*2	2	10	2,00	40,0	2,00	40,0
partition wall	5*3=15	13	10	0,50	65,0	0,26	33,8
Sum of transmission losses (W)					**886,8**		**534,4**
2. Linear Losses:	**Q=L*Pszi*dt**			**2006**		**2017**	
	L(m)	Pszi(W/mK)	dt(°C)		Q (W)		Q (W)
Partition wall 1	3	0,1	35		10,5	0,05	5,3
Partition wall 2	3	0,1	35		10,5	0,05	5,3
Wall corner	3	0,15	35		15,8	0,075	7,9
Window perimeter	6	0,15	35		31,5	0,075	15,8
Ceeling	10	0,15	35		52,5	0,075	26,3
Floor (ground loss)	10	0,85	35		297,5	0,425	148,8
Sum of linear losses(W)					**418,3**		**209,1**
Fabric losses(W): 1+2					***1305,1***		***743,5***
3. Filtration loss	**Q=0,35*ACH*V*dt**						
	ACH (1/h)	V (m3)	dt (°C)		Q (W)		Q (W)
Room	0,5	75	35		**459,4**	0,125	**114,8**
Total loss (including fabric and filtration losses) (W)					**1764,4**		**858,4**
Q/V(W/m3)					***23,5***		***11,4***
Q/A(W/m2)					***70,6***		***34,3***