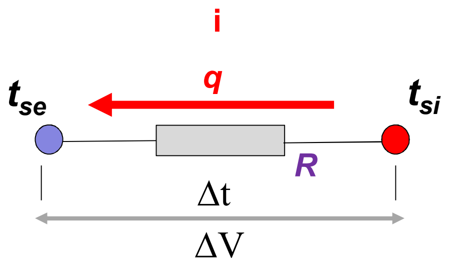
Peak power determination, simplified energy demand for heating, schematic of heating systems

Thermal conduction

Steady state conditions 1-D:

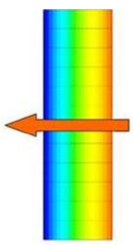


Single layer

$$q = S\frac{\lambda}{s}(t_{si} - t_{se})$$

$$R = \frac{s}{\lambda}$$

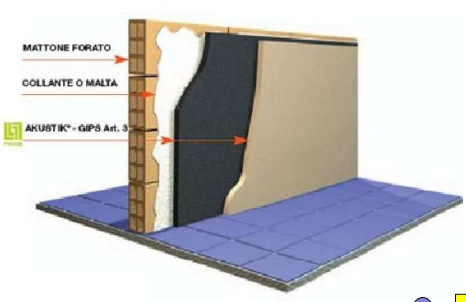
$[m^2\ K/W]$



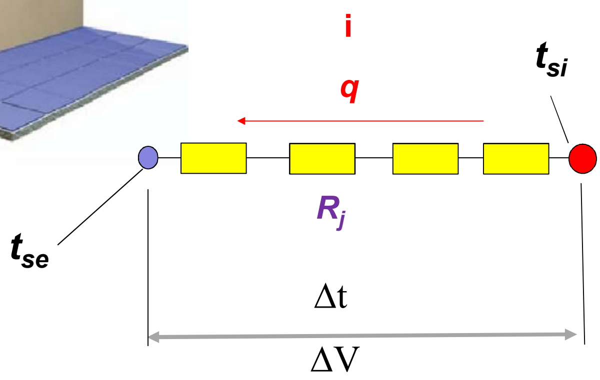
Thermal conduction

<u>Steady state conditions</u>: 1-D

multi-layer

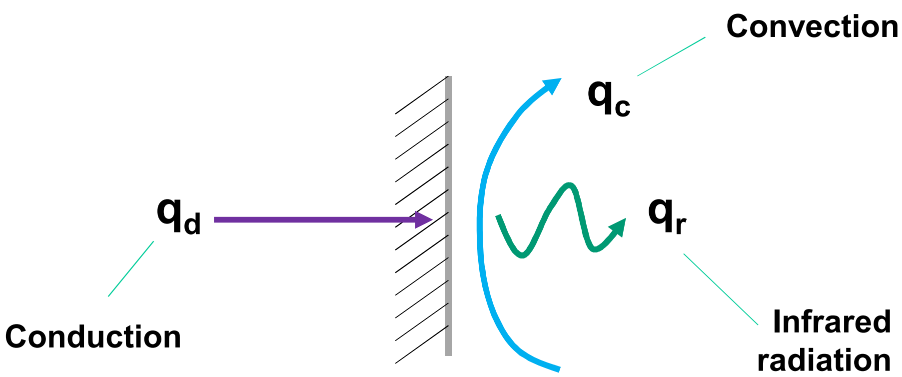


$$q = \frac{S\,(t_{si} - t_{se})}{\Sigma R_j}$$



Heat transfer on surfaces

Heat balance on a surface not considering the solar gains or other radiant loads (e.g. lighting)



Convection

A fluid flow at temperature t brushes against a solid surface at temperature t_s

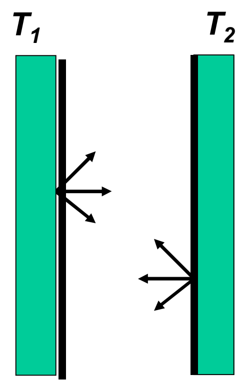
Heat flux:

$$q = h_c\ S\ (t_s - t) \qquad t_s > t$$

Coefficient of the convective heat transfer

h_c **[W/(m² K)]**

Infrared radiation



Plane, parallel, front facing surfaces at temperature, respectively, T_1 and T_2

$$q = \frac{\sigma_n S\ (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

σ_n**: Stephan-Boltzmann's constant**

5.76 x 10⁻⁸ W/(m² K⁴) $5.76 \times 10^{-8}\ W/(m^2 K^4)$

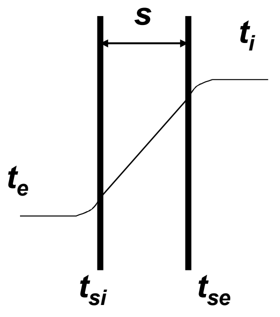
$\varepsilon_1, \varepsilon_2$ **: emissivity of the two surfaces. For usual finishing materials of walls**

$$\varepsilon_1 = \varepsilon_2 = 0.9 \quad \longrightarrow \quad 1 < \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 < 1.1$$

$$q = \sigma_n S\ (T_1^4 - T_2^4) = 4\ \sigma_n\ S\ T_m^3\ (T_1 - T_2) = h_r\ S\ (T_1 - T_2)$$

h_r **radiant heat transfer coefficient = 5.5 W/(m² K)**

Overall heat transfer on a surface



-Outdoor temperature and indoor temperature t_e and t_i

- Surface temperature t_{si} t_{se}

On the external surface the heat flux is:

- For convection with the external air
  $q = h_{ce}\ S\ (t_{se} - t_e)$
- For radiation:
  $q = h_{re}\ S\ (t_{se} - t_e)$
- overall:
  $q = (h_{re} + h_{ce})\ S\ (t_{se} - t_e)$

External overall heat transfer coefficient h_{se}

Similarly, on the inner surface of the layer the heat flux is:

$$q = (h_{ri} + h_{ci})\ S\ (t_{si} - t_i)$$

h_{si} Internal overall heat transfer coefficient

$$h_{si} = h_{ri} + h_{ci} = 1/R_{si}$$

$$h_{se} = h_{re} + h_{ce} = 1/R_{se}$$

U-value of a building element

$$q^* = \frac{\lambda}{s}(t_{si} - t_{se})$$

$$q^* = h_{si}\ (t_{si} - t_i)$$

$$q^* = h_{se}\ (t_{se} - t_e)$$

Trasmittance
U-value
[W/(m² K)]

$$U = \frac{1}{\frac{1}{h_{si}} + \Sigma R_j + \frac{1}{h_{se}}} = \frac{1}{R_{tot}}$$

$$R_{tot} = \frac{1}{h_{si}} + \Sigma R_j + \frac{1}{h_{se}}$$

$$R_{tot} = R_{si} + \Sigma R_j + R_{se}$$

For a multi-layer wall:

$$U = \frac{1}{\frac{1}{h_{si}} + \Sigma \frac{\lambda}{s} + \Sigma R + \frac{1}{h_{se}}}$$

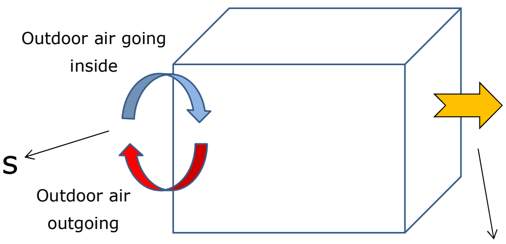
$$R_{tot} = \frac{1}{h_{si}} + \Sigma \frac{\lambda}{s} + \Sigma R + \frac{1}{h_{se}}$$

Italian law

L. 373 — L. 10/1991 — D.Lgs. N.192 — From 1/1/2021 nZEB

	1960	1970	1976	1991	2005	Today
Walls [W/(m² K)]	1,4	1,0	0,8	0,7	0,35	0,2
Windows [W/(m² K)]	5,7	2,8	2,4	2,4	2,2	1,7
Roof [W/(m² K)]	1,0	0,8	0,6	0,5	0,33	0,2
Floor [W/(m² K)]	0,8	0,8	0,7	0,6	0,33	0,2
Specific Energy [kWh/(m² year)]	230	200	170	120	60	15

Peak power calculation in heating



Ventilation losses q_V

Transmission losses (through the envelope) q_T

$$q_V = \dot{m}\, c_p\, (t_i - t_e)$$

$$q_V = \dot{V}\, \rho\, c_p\, (t_i - t_e)$$

H_V

$$q_V = H_V\, (t_i - t_e)$$

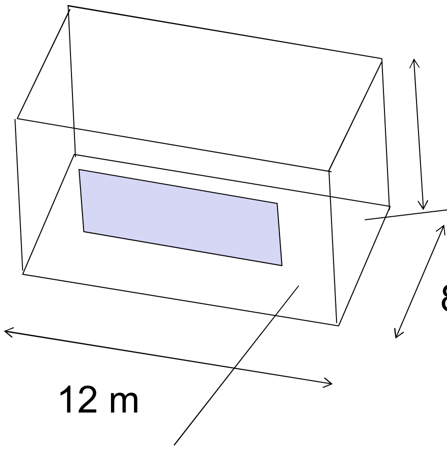
$$q_T = \Sigma_j\, U_j S_j\, (t_i - t_e)$$

H_T

$$q_T = H_T\, (t_i - t_e)$$

$$q = q_T + q_V$$

Example



$S_2 = 8 \times 3 = 24\ m^2$

$S_1 = 12 \times 3 = 36\ m^2$

$A_f = 12 \times 8 = 96\ m^2$

$V = 96 \times 3 = 288\ m^3$

$S/V = 60/288 = 0.21\ m^{-1}$

$S_{tot} = 24 + 36 = 60\ m^2$

$A_w = 96 \times (1/6)\ m^2 = 16\ m^2$

$S_{op} = 60 - 16 = 44\ m^2$

$U_{op} = 1\ W/(m^2\ K)$

$U_w = 6\ W/(m^2\ K)$

$H_T = 44 \times 1 + 6 \times 16 = 140\ W/K$

$n = 0.5\ h^{-1}$

$\dot{V} = n \times V = 0.5 \times 288 = 144\ m^3/h$

$$H_V = \frac{\dot{V} \times \rho \times c_p}{3600} = \frac{144 \times 1.2 \times 1007}{3600} = 48\ W/K$$

$H_{tot} = H_T + H_V = 48 + 140 = 188\ W/K$

$P_{tot} = 188 \times (t_i - t_e) = 188 \times 25 = 4708\ W$

Due parametri Importanti:

- $P_{tot}/V = 4708/288 = 16.3\ W/m^3$
- $P_{tot}/A_f = 4708/96 = 49\ W/m^2$

Case 1.a

Case 1	**2 surfaces**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			144	m^3/h		**20**	**-5**	**25**
Stot	60	m^2		m	172.8	kg/h				
Stot/V	0.208333	m^{-1}			0.048	kg/s				
	S	U	HT	HV	PT	PV	Ptot	PV	PS	
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]	
Opaque	44	1	44							
Window	16	6	96							
Total	60		140	48	**3500**	**1208**	**4708**	**16.3**	**49.0**	
					74%	**26%**				

Case 2.a

Case 2	**2 surfaces + roof**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			144	m^3/h		**20**	**-5**	**25**
Stot	156	m^2		m	172.8	kg/h				
Stot/V	0.541667	m^{-1}			0.048	kg/s				
	S	U	HT	HV	PT	PV	Ptot	PV	PS	
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]	
Opaque	140	1	140							
Window	16	6	96							
Total	156		236	48	**5900**	**1208**	**7108**	**24.7**	**74.0**	
					83%	**17%**				

Case 3.a

Case 3	**2 surfaces**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			288	m^3/h		**20**	**-5**	**25**
Stot	60	m^2		m	345.6	kg/h				
Stot/V	0.208333	m^{-1}			0.096	kg/s				
	S	U	HT	HV	PT	PV	Ptot	PV	PS	
	$[m^2]$	$[W/(m^2\ K)]$	[W/K]	[W/K]	[W]	[W]	[W]	$[W/m^3]$	$[W/m^2]$	
Opaque	44	1	44							
Window	16	6	96							
Total	60		140	97	**3500**	**2417**	**5917**	**20.5**	**61.6**	
					59%	**41%**				

Case 4.a

Case 4	**2 surfaces + roof**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			288	m^3/h		**20**	**-5**	**25**
Stot	156	m^2		m	345.6	kg/h				
Stot/V	0.541667	m^{-1}			0.096	kg/s				
	S	U	HT	HV	PT	PV	Ptot	PV	PS	
	$[m^2]$	$[W/(m^2\ K)]$	[W/K]	[W/K]	[W]	[W]	[W]	$[W/m^3]$	$[W/m^2]$	
Opaque	140	1	140							
Window	16	6	96							
Total	156		236	97	**5900**	**2417**	**8317**	**28.9**	**86.6**	
					71%	**29%**				

Summary of cases «a»:

- **Outdoor temperature -5°C**
- **High U-values**

Case 1.a:
- **2 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
3.5	1.2	4.7	16	49
74%	26%			

Case 2.a:
- **3 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
5.9	1.2	7.1	25	74
85%	15%			

Case 3.a:
- **2 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
3.5	2.4	5.9	20	62
60%	40%			

Case 4.a:
- **3 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
5.9	2.4	8.3	29	87
70%	30%			

Case 1.b

Case 1.b	**2 surfaces**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m²		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m³			144	m³/h		**20**	**-15**	**35**
Stot	60	m²		m	172.8	kg/h				
Stot/V	0.208333	m⁻¹			0.048	kg/s				

	S [m²]	U [W/(m² K)]	HT [W/K]	HV [W/K]	PT [W]	PV [W]	Ptot [W]	PV [W/m³]	PS [W/m²]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	48	**4900**	**1692**	**6592**	**22.9**	**68.7**
					74%	**26%**			

	S [m²]	U [W/(m² K)]	HT [W/K]	HV [W/K]	PT [W]	PV [W]	Ptot [W]	PV [W/m³]	PS [W/m²]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	48	**3500**	**1208**	**4708**	**16.3**	**49.0**
					74%	**26%**			

Case 2.b

Case 2.b	2 surfaces + roof									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			144	m^3/h		**20**	**-15**	**35**
Stot	156	m^2		m	172.8	kg/h				
Stot/V	0.541667	m^{-1}			0.048	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	48	**8260**	**1692**	**9952**	**34.6**	**103.7**
					83%	**17%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	48	**5900**	**1208**	**7108**	**24.7**	**74.0**
					83%	**17%**			

Case 3.b

Case 3.b	2 surfaces									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			288	m^3/h		**20**	**-15**	**35**
Stot	60	m^2		m	345.6	kg/h				
Stot/V	0.208333	m^{-1}			0.096	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	97	**4900**	**3384**	**8284**	**28.8**	**86.3**
					59%	**41%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	97	**3500**	**2417**	**5917**	**20.5**	**61.6**
					59%	**41%**			

Case 4.b

Case 4.b	2 surfaces + roof									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		ti	te	Dt
Af	96	m²		n	1	1/h		[°C]	[°C]	
V	288	m³			288	m³/h		20	-15	35
Stot	156	m²		m	345.6	kg/h				
Stot/V	0.541667	m^{-1}			0.096	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m²]	[W/(m² K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m³]	[W/m²]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	97	**8260**	**3384**	**11644**	**40.4**	**121.3**
					71%	**29%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m²]	[W/(m² K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m³]	[W/m²]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	97	**5900**	**2417**	**8317**	**28.9**	**86.6**
					71%	**29%**			

Summary of cases «b»:

- **Outdoor temperature -15°C**
- **High U-values**

Case 1.b:
- **2 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
4.9	1.7	6.6	23	69
75%	25%			

Case 2.b:
- **3 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
8.3	1.7	10.0	35	105
85%	15%			

Case 3.b:
- **2 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
4.9	3.4	8.3	29	87
60%	40%			

Case 4.b:
- **3 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
8.3	3.4	11.7	40	121
70%	30%			

Case 1.c

Case 1.c	**2 surfaces**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			144	m^3/h		**20**	**-5**	**25**
Stot	60	m^2		m	172.8	kg/h				
Stot/V	0.208333	m^{-1}			0.048	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	44	0.2	8.8						
Window	16	2	32						
Total	60		40.8	48	**1020**	**1208**	**2228**	**7.7**	**23.2**
					46%	**54%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	48	**3500**	**1208**	**4708**	**16.3**	**49.0**
					74%	**26%**			

Case 2.c

Case 2.c	**2 surfaces + roof**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			144	m^3/h		**20**	**-5**	**25**
Stot	156	m^2		m	172.8	kg/h				
Stot/V	0.541667	m^{-1}			0.048	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	0.2	28						
Window	16	2	32						
Total	156		60	48	**1500**	**1208**	**2708**	**9.4**	**28.2**
					55%	**45%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	48	**5900**	**1208**	**7108**	**24.7**	**74.0**
					83%	**17%**			

Case 3.c

Case 3.c	**2 surfaces**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			288	m^3/h		**20**	**-5**	**25**
Stot	60	m^2		m	345.6	kg/h				
Stot/V	0.208333	m^{-1}			0.096	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	44	0.2	8.8						
Window	16	2	32						
Total	60		40.8	97	**1020**	**2417**	**3437**	**11.9**	**35.8**
					30%	**70%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	97	**3500**	**2417**	**5917**	**20.5**	**61.6**
					59%	**41%**			

Case 4.c

Case 4.c	**2 surfaces + roof**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			288	m^3/h		**20**	**-5**	**25**
Stot	156	m^2		m	345.6	kg/h				
Stot/V	0.541667	m^{-1}			0.096	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	0.2	28						
Window	16	2	32						
Total	156		60	97	**1500**	**2417**	**3917**	**13.6**	**40.8**
					38%	**62%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	97	**5900**	**2417**	**8317**	**28.9**	**86.6**
					71%	**29%**			

Summary of cases «c»:

- **Outdoor temperature -5°C**
- **Low U-values**

Case 1.c:
- **2 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.0	1.2	2.2	8	23
45%	55%			

Case 2.c:
- **3 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.5	1.2	2.7	10	28
55%	45%			

Case 3.c:
- **2 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.0	2.4	3.4	12	36
30%	70%			

Case 4.c:
- **3 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.5	2.4	3.9	14	41
40%	60%			

Case 1.d

Case 1.d	**2 surfaces**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m²		**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m³			144	m³/h		**20**	**-15**	**35**
Stot	60	m²		m	172.8	kg/h				
Stot/V	0.208333	m⁻¹			0.048	kg/s				
	S	U	HT	HV	PT	PV	Ptot	PV	PS	
	[m²]	[W/(m² K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m³]	[W/m²]	
Opaque	44	0.15	6.6							
Window	16	1.5	24							
Total	60		30.6	48	**1071**	**1692**	**2763**	**9.6**	**28.8**	
					39%	**61%**				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m²]	[W/(m² K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m³]	[W/m²]
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	48	**4900**	**1692**	**6592**	**22.9**	**68.7**
					74%	**26%**			

Case 2.d

Case 2.d	**2 surfaces + roof**								
Length	12	m							
Width	8	m							
Height	3	m	cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2	**n**	**0.5**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3		144	m^3/h		**20**	**-15**	**35**
Stot	156	m^2	m	172.8	kg/h				
Stot/V	0.541667	m^{-1}		0.048	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	$[m^2]$	$[W/(m^2 K)]$	[W/K]	[W/K]	[W]	[W]	[W]	$[W/m^3]$	$[W/m^2]$
Opaque	140	0.15	21						
Window	16	1.5	24						
Total	156		45	48	**1575**	**1692**	**3267**	**11.3**	**34.0**
					48%	**52%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	$[m^2]$	$[W/(m^2 K)]$	[W/K]	[W/K]	[W]	[W]	[W]	$[W/m^3]$	$[W/m^2]$
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	48	**8260**	**1692**	**9952**	**34.6**	**103.7**
					83%	**17%**			

Case 3.d

Case 3.d	**2 surfaces**								
Length	12	m							
Width	8	m							
Height	3	m	cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2	**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3		288	m^3/h		**20**	**-15**	**35**
Stot	60	m^2	m	345.6	kg/h				
Stot/V	0.208333	m^{-1}		0.096	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	$[m^2]$	$[W/(m^2 K)]$	[W/K]	[W/K]	[W]	[W]	[W]	$[W/m^3]$	$[W/m^2]$
Opaque	44	0.15	6.6						
Window	16	1.5	24						
Total	60		30.6	97	**1071**	**3384**	**4455**	**15.5**	**46.4**
					24%	**76%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	$[m^2]$	$[W/(m^2 K)]$	[W/K]	[W/K]	[W]	[W]	[W]	$[W/m^3]$	$[W/m^2]$
Opaque	44	1	44						
Window	16	6	96						
Total	60		140	97	**4900**	**3384**	**8284**	**28.8**	**86.3**
					59%	**41%**			

Case 4.d

Case 4.d	**2 surfaces + roof**									
Length	12	m								
Width	8	m								
Height	3	m		cp	1007	J/(kg K)		**ti**	**te**	**Dt**
Af	96	m^2		**n**	**1**	**1/h**		**[°C]**	**[°C]**	
V	288	m^3			288	m^3/h		**20**	**-15**	**35**
Stot	156	m^2		m	345.6	kg/h				
Stot/V	0.541667	m^{-1}			0.096	kg/s				

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	0.15	21						
Window	16	1.5	24						
Total	156		45	97	**1575**	**3384**	**4959**	**17.2**	**51.7**
					32%	**68%**			

	S	U	HT	HV	PT	PV	Ptot	PV	PS
	[m^2]	[W/(m^2 K)]	[W/K]	[W/K]	[W]	[W]	[W]	[W/m^3]	[W/m^2]
Opaque	140	1	140						
Window	16	6	96						
Total	156		236	97	**8260**	**3384**	**11644**	**40.4**	**121.3**
					71%	**29%**			

Summary of cases «d»:

- **Outdoor temperature -15°C**
- **Low U-values**

Case 1.d:

- **2 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.1	1.7	2.8	10	30
40%	60%			

Case 2.d:

- **3 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.6	1.7	3.3	12	35
50%	50%			

Case 3.d:

- **2 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.1	3.4	4.5	16	47
25%	75%			

Case 4.d:

- **3 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.6	3.4	5.0	18	52
30%	70%			

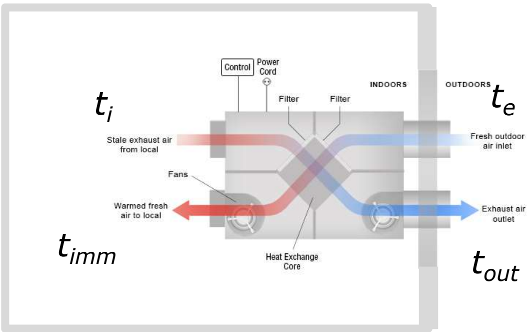
Heat recovery on ventilation

Overall heat loss:

$$q_V = \dot{m}\, c_p \quad (t_i - t_e)$$

$$\varepsilon = \frac{\text{Heat recovery}}{\text{Overall heat loss}}$$

$$\varepsilon = \frac{\dot{m}\, c_p \quad (t_{imm} - t_e)}{\dot{m}\, c_p \quad (t_i - t_e)}$$

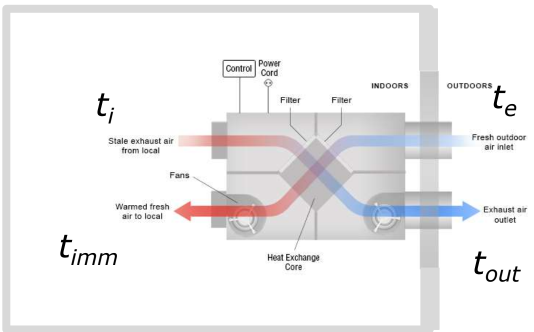


$$\varepsilon = \frac{(t_{imm} - t_e)}{(t_i - t_e)}$$

Ventilation loss:

$$q_V = \dot{m}\, c_p\, (t_i - t_{imm})$$

$$\varepsilon = \frac{(t_{imm} - t_e)}{(t_i - t_e)}$$



$$\varepsilon = \frac{(-t_i + t_{imm} + \ t_i - t_e)}{(t_i - t_e)} = \frac{(t_{imm} - t_i) + (t_i - t_e)}{(t_i - t_e)} = \frac{(t_{imm} - t_i)}{(t_i - t_e)} + 1$$

$$(t_i - t_{imm}) = (1 - \varepsilon\,)\ \ (t_i - t_e)$$

H_V

$$q_V = \dot{m}\, c_p\, (t_i - t_{imm}) = \dot{m}\, c_p\, (1 - \varepsilon\,)\, (t_i - t_e)$$

Cases 1 - 2: **n = 0.5 Vol./h**

$$H_V = n \dot{V} \rho c_p / 3600 = 48 \text{ W/K}$$

Cases 3 - 4: **n = 1.0 Vol./h**

$$H_V = n \dot{V} \rho c_p / 3600 = 96 \text{ W/K}$$

Heat recovery (ε = 75%):

Cases 1.e – 2.e – 1.f – 2.f:

n = 0.5 Vol./h

$$H_V = (1-\varepsilon)\, n \dot{V} \rho c_p / 3600 = 12 \text{ W/K}$$

Cases 3.e – 4.e – 3.f – 4.f:

n = 1.0 Vol./h

$$H_V = (1-\varepsilon)\, n \dot{V} \rho c_p / 3600 = 24 \text{ W/K}$$

Summary of cases «e»:

- **Outdoor temperature -5°C**
- **Low U-values, heat recovery unit (ε = 75%)**

Case 1.e:

- **2 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.0	0.3	1.3	5	14
75%	25%			

Case 2.e:

- **3 surfaces**
- **n = 0.5 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.5	0.3	1.8	7	19
85%	15%			

Case 3.e:

- **2 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.0	0.6	1.6	6	17
65%	35%			

Case 4.e:

- **3 surfaces**
- **n = 1.0 ACH**

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.5	0.6	2.1	8	22
70%	30%			

Summary of cases «f»:

- **Outdoor temperature -15°C**
- **Low U-values, heat recovery unit (ε = 75%)**

Case 1.f:
- 2 surfaces
- n = 0.5 ACH

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.1	0.4	1.5	6	16
70%	30%			

Case 2.f:
- 3 surfaces
- n = 0.5 ACH

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.6	0.4	2.0	7	21
80%	20%			

Case 3.f:
- 2 surfaces
- n = 1.0 ACH

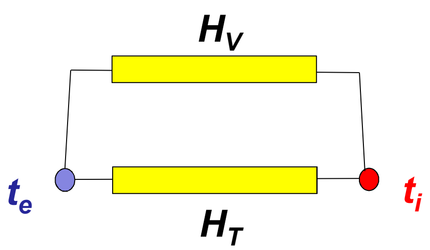
PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.1	0.8	1.9	7	20
55%	45%			

Case 4.f:
- 3 surfaces
- n = 1.0 ACH

PT [kW]	PV [kW]	Ptot [kW]	PV [W/m³]	PS [W/m²]
1.6	0.8	2.4	9	26
65%	35%			

Energy demand with a simplified method

Steady state model can be used for determining the energy demand of the building, due to the use of the temperature difference between inside and outside.



In a simplified way, it is possible to assume that the energy demand is related to Degree Days (DD), or to average monthly temperature:

$$Q_{heating} = DD \cdot (H_T + H_V) \cdot 24 / 1000$$

Very rough estimation of the heating energy demand [kWh].

Main simplifications: no effects of solar radiation and/or internal gains, no building capacitance

Simplified energy demand in the examples

Usually the energy demand of buildings is referred to the floor area (A_f). This way it is possible to compare different buildings.

The following hypotheses have been chosen:

For the climate with te = -5°C we consider 2500 DD

For the climate with te = -15°C we consider 4000 DD

For costs we consider 0.08 €/kWh of thermal energy

Simplified energy demand in the examples

	Case 1.a	Case 2.a	Case 3.a	Case 4.a
Htot	188	284	237	333
Energy [MWh]	11.3	17.1	14.2	20.0
Specific energy [kWh/(m² year)]	118	178	148	208
Cost [€]	904 €	1,365 €	1,136 €	1,597 €

	Case 1.b	Case 2.b	Case 3.b	Case 4.b
Htot	188	284	237	333
Energy [MWh]	18.1	27.3	22.7	31.9
Specific energy [kWh/(m² year)]	188	284	237	333
Cost [€]	1,446 €	2,184 €	1,818 €	2,555 €

	Case 1.c	Case 2.c	Case 3.c	Case 4.c
Htot	89	108	137	157
Energy [MWh]	5.3	6.5	8.2	9.4
Specific energy [kWh/(m² year)]	56	68	86	98
Cost [€]	428 €	520 €	660 €	752 €

	Case 1.d	Case 2.d	Case 3.d	Case 4.d
Htot	79	93	127	142
Energy [MWh]	7.6	9.0	12.2	13.6
Specific energy [kWh/(m² year)]	79	93	127	142
Cost [€]	606 €	717 €	977 €	1,088 €

	Case 1.e	Case 2.e	Case 3.e	Case 4.e
Htot	53	72	65	84
Energy [MWh]	3.2	4.3	3.9	5.1
Specific energy [kWh/(m² year)]	33	45	41	53
Cost [€]	254 €	346 €	312 €	404 €

	Case 1.f	Case 2.f	Case 3.f	Case 4.f
Htot	43	57	55	69
Energy [MWh]	4.1	5.5	5.3	6.6
Specific energy [kWh/(m² year)]	43	57	55	69
Cost [€]	328 €	438 €	421 €	531 €

Lessons learnt from the examples

The peak load depends on:

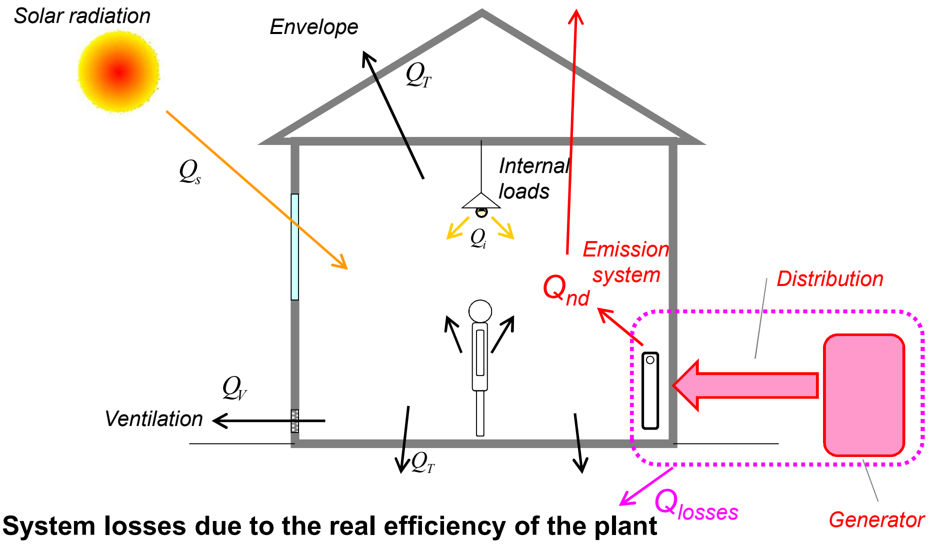
- **the level of insulation (U-value)**
- **the amount of ventilation (flow rate)**
- **the climate**
- **the presence of a heat recovery unit**

The energy demand depends on the same parameters.

The energy demand for residential buildings is expressed as kWh/(m² year)

How can we define the energy levels?

Ideal energy required by the plant to keep an indoor temperature over the season. The plant is considered to have 100% efficiency



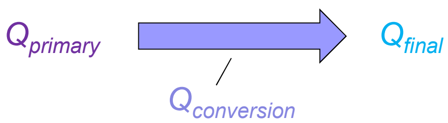
System losses due to the real efficiency of the plant (emission system, distribution system, generator)

Final energy, energy consumption, on-site energy: net energy demand added the losses of the system

Net energy damand + losses of the system = **Final energy, Energy consumption, Site energy, Energy use**

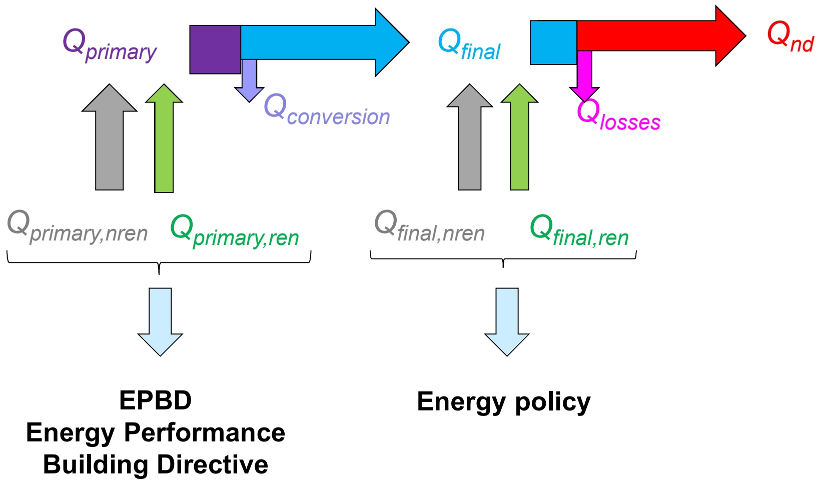
$$Q_{final} = Q_{nd} + Q_{losses}$$

The cost we have evaluated does not take into account the efficiency of the system and hence its losses.



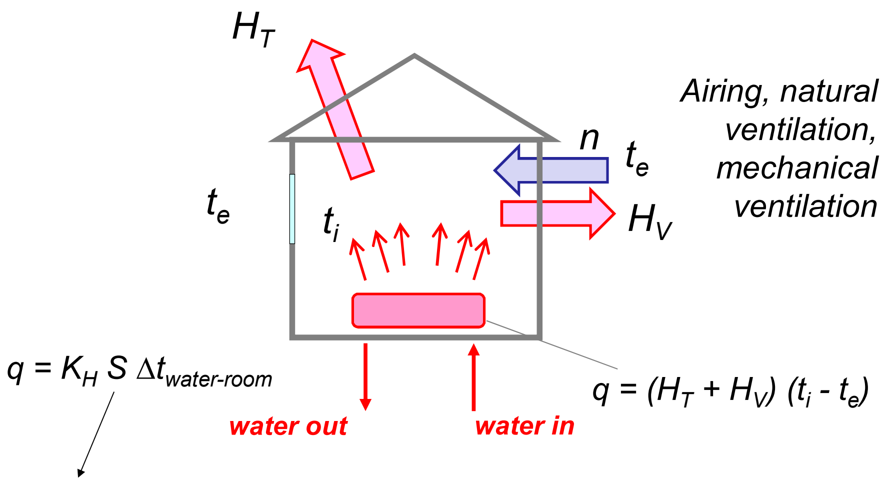
Final energy + conversion losses = **Primary energy Source energy**

$$Q_{primary} = Q_{final} + Q_{conversion}$$



Types of HVAC systems

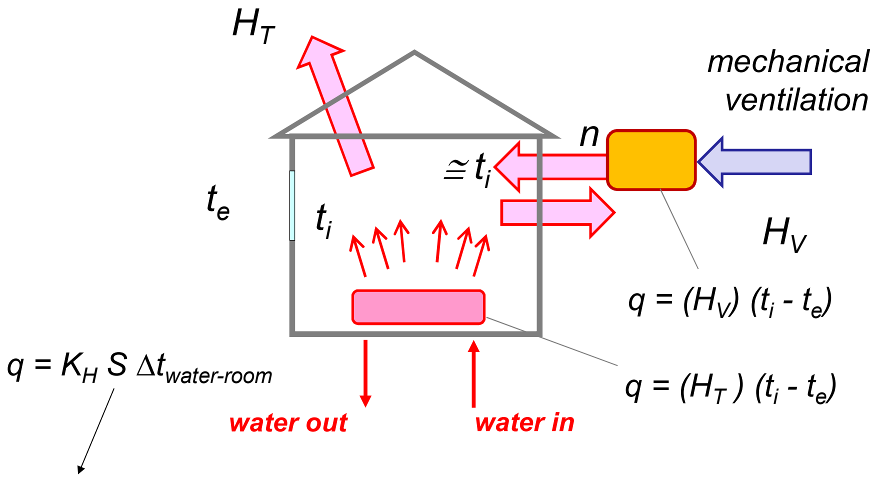
1. Water based heating



- Type and size of the emission system
- Average water temperature in the emission system

Types of HVAC systems

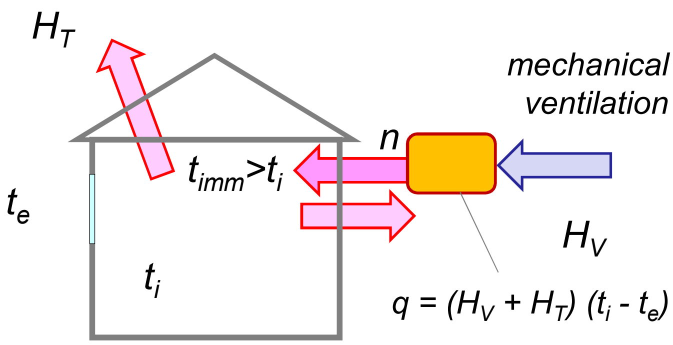
2. Air and water based heating



- Type and size of the emission system
- Average water temperature in the emission system

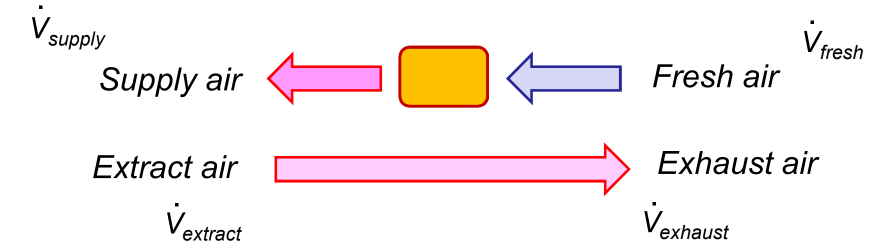
Types of HVAC systems

3. Full air heating



The air enters the room with higher temperature (t_{imm}) than t_i. Depending on the flow rate and t_{imm}, there are 2 possible solutions.

1) No recirculation: $\dot{V}_{fresh} = \dot{V}_{supply} \cong \dot{V}_{exhaust}$



2.) With recirculation: $\dot{V}_{fresh} < \dot{V}_{supply} \cong \dot{V}_{extract}$