Airflow rate calculation

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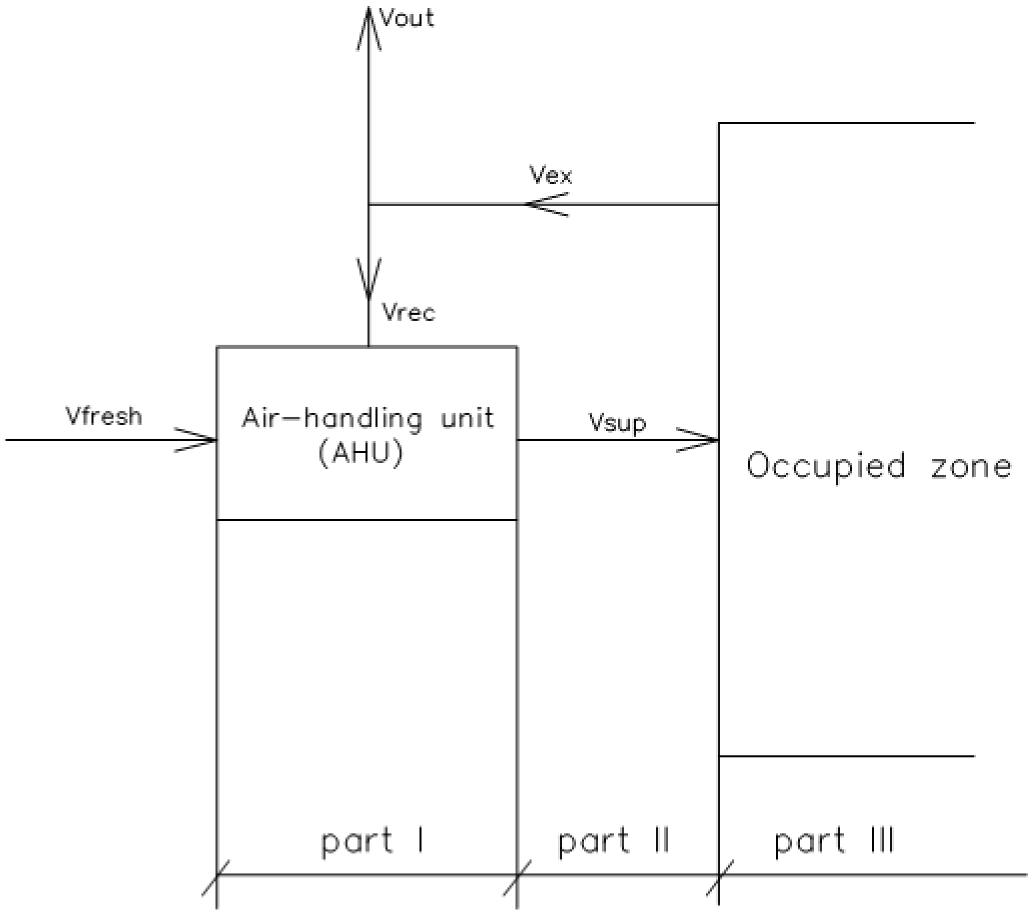
General aims

Generally, every ventilation system (or air-conditioning system) has three main parts. These are the followings:



In this figure:

V_{fresh} – is the airflow rate of fresh air from outside [m^3/h; m^3/s; l/h; l/s]

V_{sup} – is the airflow rate of supply air [m^3/h; m^3/s; l/h; l/s]

V_{ex} – is the airflow rate of exhausted air from the occupied zone [m^3/h; m^3/s; l/h; l/s]

V_{out} – is the airflow rate of threw air to outside space [m^3/h; m^3/s; l/h; l/s]

V_{rec} – is the airflow rate of re-circulated air in order to saving energy [m^3/h; m^3/s; l/h; l/s]

A most common unit of calculated airflow rate is [m^3/h], because when are calculating airflow rate, we usually get high numbers, e.g. 5000 [m^3/h], and if we change this number from [m^3/h] to [m^3/s] we will get much higher numbers, which is hard to treat in designing practice.
Now let's take a look at the main parts of an air-handling system.

I. *AHU* stands for Air Handling Unit, where we can change the physical parameters of supplied air, like air temperature, air humidity, pressure, velocity, and so on. The way of changing these parameters are heating, cooling, heat exchange, air humidification, air drying, mixing of exhausted air with fresh air, reduction of air contamination by air filters, etc. When we are going to design an air-conditioning system, it is very important to select the right Air Handling Unit. The basic of this is the calculated air flow rate of supply air, which will be the main subject of this lesson.

II. *Air duct system*, where we can make transport air from the Air Handling Unit to the occupied zone of ventilated spaces. When we design an air-conditioning system, we have to calculate the main dimensions of air ducts (diameter, side dimensions, length, etc.), and have to choose the suitable heat insulation to reduce heat loss and avoid condensation on duct surface.

III. *The occupied zone of ventilated space*, which can be comfort type (e.g. classrooms, offices, family houses, etc.) or industrial type (e.g. a factory hall).

Based on the continuity equation, which is actually the conservation of mass, can be written:

$$V_{ex} = V_{out} + V_{rec}$$

and

$$V_{sup} = V_{fresh} + V_{rec}$$

If $V_{fresh} = 0$, the air handling system only operates with re-circulated air. It is not allowed due to standard CR 1752, because some fresh air in the occupied zone is required.
If $V_{fresh} \neq 0$, the air handling system operates both fresh air and re-circulated air.
If you are going to design an air-conditioning system, one of the first and most important steps is calculation of airflow rate of supply air (V_{sup}).
We can calculate the airflow rate of supply air in two cases. The first one is continuous ventilation, when the airflow is continuous in the system, and it is never zero, the fan always operates. The other one is periodic ventilation, where airflow rate in the system is occasionally zero, but it is not always true. The operating hours depend on the type of building, occupied zone and other requirements given by operators and owners.

The primary duty of the airflow rate of supply air is to remove some kinds of loads from the occupied zones. These loads can be the followings: *heat load*, *humidity load* and *load of pollutants*.

<u>Calculating airflow rate of supply air in case of heat load</u>

The heat balance in the occupied zone of ventilated spaces usually is different in winter and in summer conditions.

The resultant heat load in winter:

$$\sum \dot{\boldsymbol{Q}}_{\boldsymbol{winter}} = -\dot{Q}_{tr} \pm \dot{Q}_{techn} + \dot{Q}_{people} + \dot{Q}_{gain} + \dot{Q}_{light} \;\; [W; kW]$$

where

Q_{tr} – is the transmission heat loss between the occupied zone and the outdoor environment, which is always negative [W, kW]. This value depends on the temperature difference between the occupied zone and the outdoor space, because the bigger this temperature difference, the higher the transmission heat loss. Besides, this type of heat loss depends on the building's structure, its material, and so on.

Q_{techn} – is the heat load from technological processes, which can be both positive and negative. Positive heat load is e.g. heat load of machines in a factory, negative is e.g. an ice-cream counter in a supermarket [W, kW]

Q_{people} – is the load of people, which usually depends on the activity level, e.g. sedentary occupation vs. significant moving, closing insulation, health condition, age, etc. [W, kW]

Q_{gain} – is something internal heat gain, which can come from built-in heating, e.g. floor heating, radiator or fireplace, etc. [W, kW]

Q_{light} – is heat load from lighting [W, kW].

The resultant heat load in summer is:

$$\sum \dot{\boldsymbol{Q}}_{\boldsymbol{summer}} = +\dot{Q}_{tranzient} \pm \dot{Q}_{techn} + \dot{Q}_{people} + \dot{Q}_{gain} + \dot{Q}_{light} \;\; [W; kW]$$

where

$Q_{transient}$– is the transient (time dependent) heat load in summer, e.g. from sunlight [W, kW]. It depends on time, because in summer exterior temperature significantly changes during a day period.

Calculating transmission heat loss:

$$Q_{tr} = U \cdot A \cdot \Delta t$$

where

U – is the heat transfer factor between the occupied zone and the outdoor space [W/m^{2}K]

A – is the surface of heat transfer, e.g. wall surface, window surface, etc. [m^2]

Δt – is the temperature difference between the occupied zone's air and outdoor' air [°C, or K]

Calculating technological heat load

$$Q_{techn} = \eta \cdot f \cdot q_{techn} \ [W, kW]$$

where

η – is the efficiency of the machine, which loads indoor air with heat [-]

f – is the operation factor, which shows machine's operating hours during a period (e.g. it operates only 5 hours from 8 during a day)

q_{tech} – is the specific heat load of the technological machine [W/piece]

Heat load of people

Naturally, the heat load of people can be different in summer and in winter conditions. People's heat load generally can be calculated as:

$$\dot{Q}_p = n_p \cdot \dot{\mathrm{q}}_{1\mathrm{p}} \ [\mathrm{W, kW}]$$

where

n_p – number of people in the occupied zone,

q_{1p} – one person's specific heat load [W/person; kW/person]

People's specific heat load in winter is about 120 [W/person], while in summer it is about 150 [W/person].

Heat load of lighting

$$Q_{light} = A \cdot f \cdot q_{light} \ [W, kW]$$

f – is the operating time factor, which shows the operating time of lighting during a period (e.g. it operates 5 hours from 8 a day)

q_{light} – is the specific heat load of lighting [W/m^2]

A – is the basic area of the ventilated space [m^2]

Transient heat load in summer

The transient heat load depends on the sunlight, the shielding of buildings, the position of buildings, e.g. North, South, West, etc., part of the day, structure of the building and material.

Based on the above, ***airflow rate of supply air can be calculated in summer***:

$$\dot{V}_{sup,summer} = \frac{\sum \dot{Q}_{summer}}{\rho_{sup} \cdot \Delta h} = \frac{\sum \dot{Q}_{summer}}{\rho_{sup} \cdot c_p \cdot \Delta t}.$$

In the numerator we can find the load of the ventilated space, while in the denominator is the driving force of the ventilation. The calculated airflow rate can pick up the load of the indoor environment.

In the formula:

ρ_{sup} – is the average density of supply air [kg/m^3]

$\Delta h = h_{sup} - h_{ex}$, if $h_{sup} > h_{ex}$, mainly in winter, it is the specific enthalpy difference between supply- and exhausted [kJ/kg]

$\Delta h = h_{ex} - h_{sup}$, if $h_{ex} > h_{sup}$, mainly in summer, it is the specific enthalpy difference between supply- and exhausted [kJ/kg]

$\Delta t = t_{sup} - t_{ex}$, if $t_{sup} > t_{ex}$, mainly in winter, it is the temperature difference between supply- and exhausted [°C, vagy K]

$\Delta t = t_{ex} - t_{sup}$, if $t_{ex} > t_{sup}$, mainly in summer, it is the temperature difference between supply- and exhausted [°C, or K]

c_p – is the average specific heat capacity on a constant pressure [kJ/kgK]

The average air density can be calculated by using the universal gas law and Boyle-Mariotte law.

As far as we know, the *universal gas law* can be described with the following formula, assuming that the air is ideal gas:

$$\frac{p_0}{T_0 \cdot \rho_0} = \frac{p_1}{T_1 \cdot \rho_1},$$

where index 0 and 1 mean two different states of air.

The *Boyle-Mariotte* law is written as:

$$\frac{p}{\rho} = R_s \cdot T,$$

where

R_s – is the specific gas constant of air [J/kgK]

The specific gas constant of air is:

$$R_s = \frac{R_u}{M_{air}}$$

where

R_u – universal gas constant, which is 8314 [J/kmolK]

M_{air} – is the mole mass of air [kg/kmol]

Based on the above, the *average air density* can be written:

$$\rho_{sup} = \rho_0 \cdot \frac{T_0}{T_0 + t_{sup}}$$

where

T_0 – is the air temperature on physical normal state, which is 273 [K]

ρ_0 – is the air density on physical normal state [kg/m^3]

The ***airflow rate of supply air in winter state is***:

$$\dot{V}_{sup,winter} = \frac{\sum \dot{Q}_{winter}}{\rho_{sup} \cdot \Delta h} = \frac{\sum \dot{Q}_{winter}}{\rho_{sup} \cdot c_p \cdot \Delta t}.$$

In most cases, the calculated airflow rate is higher in summer state, than in winter, because average heat load is higher in summer compared to winter. As a result, when we design a ventilation system, we have to choose air handling unit for airflow rate of supply air calculated by summer state heat load. We usually supervise the system for winter state.

<u>Calculating airflow rate in case of humidity load</u>

The resultant humidity load usually comes from two different sources. One of them is the human occupation, and the other is some kind of water surface, e.g. a swimming pool, or a fountain in a supermarket.

$$\sum \dot{\boldsymbol{m}}_{\boldsymbol{vapour}} = n_p \cdot \dot{m}_{1p} + A_{water} \cdot \beta \cdot (p_{vapour,saturation} - p_{vapour}).$$

where

m_{1p} – is the humidity load of one person [g/h,person; kg/h,person]

A_{water} – is the free surface of evaporating water [m^2]

β –is the evaporating factor, which depends on the liquid’s material

$p_{vapour,saturation}$– is the saturation pressure of vapour [Pa]

p_{vapour} – is the partial vapour pressure [Pa]

An average adult person's humidity load in winter state is about 50 [g/h,person], while in summer it is about 65 [g/h,person] due to standard CR 1752. It actually consists of sweating and evaporation.

Based on the above, ***the calculated airflow rate of supply air in summer is***:

$$\dot{\boldsymbol{V}}_{\boldsymbol{sup,summer}} = \frac{\sum \dot{m}_{vapour,summer}}{\rho_{sup} \cdot (x_{ex} - x_{Sup})}$$

where

x_{ex} – is the humidity ratio of exhausted air [g/kg; kg/kg]

x_{sup} – is the humidity ratio of supply air [g/kg; kg/kg]

The ***airflow rate of supply air in winter is***:

$$\dot{\boldsymbol{V}}_{\boldsymbol{sup,winter}} = \frac{\sum \dot{m}_{vapour,winter}}{\rho_{sup} \cdot (x_{ex} - x_{Sup})}$$

In most cases, this value is higher in summer than in winter due to the bigger number of summer's humidity load.

<u>Calculation of airflow rate of supply air in case of load of pollutants</u>

The primary pollutant load is the human occupation and activity, because people produce CO_2 gas. The secondary load of pollutants can be technology processes, like painting, chemical processes, elements of the building, furniture, smell, virus, bacterium, different dusts, etc. Each pollutants have mass/volume flow rate [kg/s, or m^3/s], which depends on the length of time of polluting, the type of pollutants, and so on. E.g. if the primary source is CO_2, the calculation method of airflow rate is:

$$\dot{V}_{sup} = \frac{\dot{K}_{CO2}}{k_{perm} - k_{sup}}$$

k_{perm} – is the permissible pollutant concentration [g/m^3; kg/m^3]

k_{sup} – is the pollutant concentration of supply air [g/m^3; kg/m^3]

This formula is also given in standard CR 1752, and you can find concentration values for several types of pollutants in this standard.

When you design an air-conditioning system, you should calculate airflow rate of supply air for each loads, and the highest one has to be chosen to select the air handling unit.

When the heat load is the significant in the ventilated space, the airflow rate has to be calculated by using it (e.g. computer rooms).

In a swimming pool e.g. the significant load is humidity; therefore airflow rate is calculated by using this load. If the load of pollutants is significant, it is recommended to calculate airflow rate with it, e.g. factory halls, or closed rooms with crowd of people, because they breath-out lot of CO_2.

<u>Exercise</u>

Volume of the room is 600 [m^3] and the interior heat load is 12 [kW]. The transmission heat loss in winter is 9 [kW], the average heat load in summer is 6 [kW]. The height of the ventilated space is 5 [m]. In this room, the average required air temperature and relative humidity are 22 [°C] and 50 [%] in winter condition, while in summer these values are 24 [°C] and 50 [%]. Calculate the required airflow rate of supply air, if permissible temperature difference between supply- and exhausted air is 6 [K]-t. Let us suppose that airflow rate in this ventilation system is constant (it is continuous ventilation).

Solution:

Resultant head load in winter is:

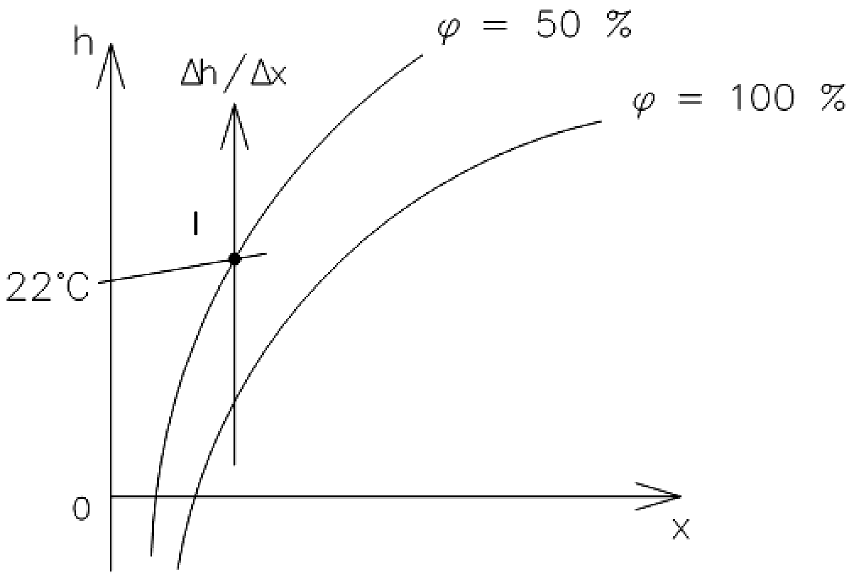
$$\sum \dot{Q}_{winter} = \dot{Q}_{tr} + \dot{Q}_{techn} = -9 + 12 = 3\ [kW].$$

Resultant humidity load in winter is given by the designer or operators:

$$\sum \dot{m}_{vapour,winter} = 0.$$

The indicator can be calculated in winter condition as:

$$\frac{\Delta h}{\Delta x_{winter}} = \frac{\sum \dot{Q}_{winter}}{\sum \dot{m}_{vapour,winter}} = \frac{3}{0} \rightarrow +\infty.$$



Resultant heat load in summer is:

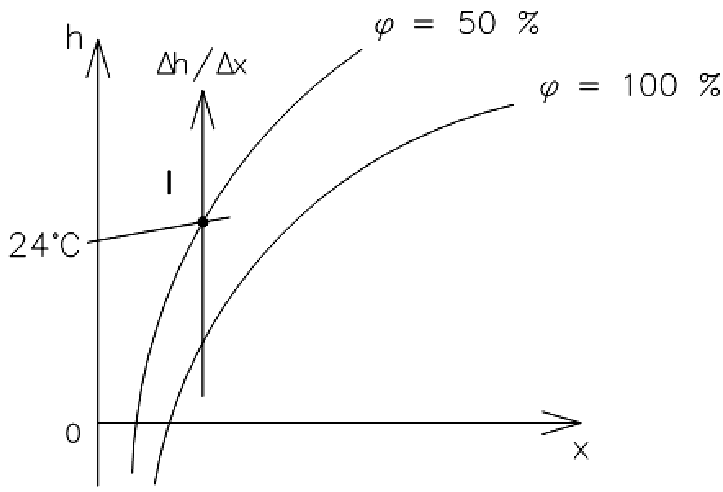
$$\sum \dot{Q}_{summer} = \dot{Q}_{gain} + \dot{Q}_{techn} = 6 + 12 = 18\ [kW].$$

Resultant humidity load in summer is given by the designer or operators:

$$\sum \dot{m}_{vapour,summer} = 0.$$

Based on the above, the indicator in summer state is:

$$\frac{\Delta h}{\Delta x_{summer}} = \frac{\sum \dot{Q}_{summer}}{\sum \dot{m}_{vapour,summer}} = \frac{18}{0} \rightarrow +\infty.$$



As summer heat load is higher, than the winter value, we will calculate the required supply airflow rate using summer condition.

Airflow rate in our ventilation system must be constant according to requirements given by the designer or operators. Therefore airflow rate of supply air in summer condition equals with winter value:

$$\dot{V}_{sup} = \frac{\sum \dot{Q}_{summer}}{\rho_{sup} \cdot \Delta h} = \frac{\sum \dot{Q}_{summer}}{\rho_{sup} \cdot c_p \cdot \Delta t}.$$

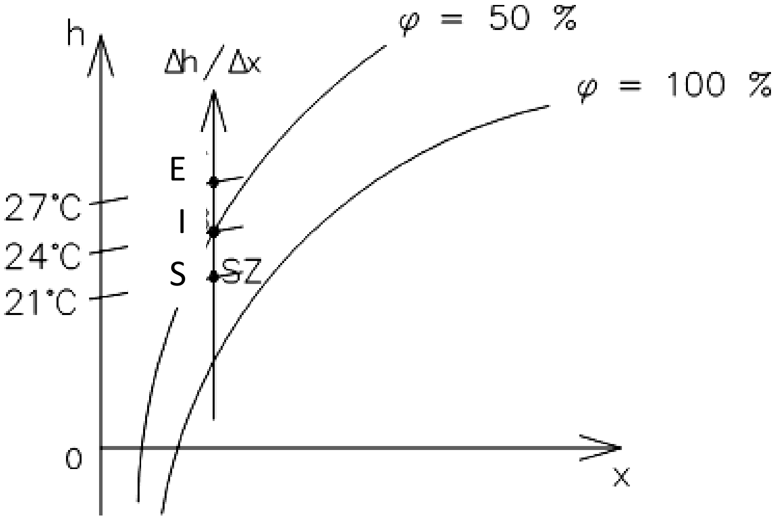
As far as we know, the allowable temperature difference in summer condition is given 6 [K], therefore we can write:

$$\dot{V}_{sup} = \frac{\sum \dot{Q}_{summer}}{\rho_{sup} \cdot c_p \cdot \Delta t_{max}}.$$

$$\Delta t_{max} = t_{ex} - t_{Sup}$$

because in summer $t_{Sup} < t_{ex}$.

Let us suppose that interior air state (I) is at the middle of section joined supply (S) and exhausted (E) air states:



Expressed with equation:

$$t_I - t_S = \frac{\Delta t_{max}}{2} = t_E - t_I.$$

From this equation we can calculate the supply air temperature, which is:

$$t_S = t_I - \frac{\Delta t_{max}}{2} = 24 - \frac{6}{2} = 21 \ [°C].$$

Supply air density is:

$$\rho_{sup} = \rho_0 \cdot \frac{T_0}{T_0 + t_s} = 1{,}293 \cdot \frac{273}{273 + 21} = 1{,}2 \left[\frac{kg}{m^3}\right].$$

Based on the above, the airflow rate of supply air is:

$$\dot{\boldsymbol{V}}_{\boldsymbol{sup}} = \frac{18\ [kW]}{1{,}2 \left[\frac{kg}{m^3}\right] \cdot 1 \left[\frac{kJ}{kgK}\right] \cdot 6\ [K]} = 2{,}5 \left[\frac{m^3}{s}\right] = \mathbf{9000} \left[\frac{\boldsymbol{m^3}}{\boldsymbol{h}}\right].$$

Considering the requirement for continuous ventilation, airflow rates in summer and winter are equal:

$$\frac{\sum \dot{Q}_{summer}}{\rho_{sup} \cdot c_p \cdot \Delta t_{max}} = \frac{\sum \dot{Q}_{winter}}{\rho_{sup} \cdot c_p \cdot \Delta t'}.$$

From this equation we can express Δt', which is the temperature difference between supply- and exhaust air in winter:

$$\Delta t' \approx \frac{\Delta t_{max}}{6} = \frac{6}{6} = 1\ [K].$$

Rounding of the calculated airflow rate:

If e.g.V_{sup} = 2320 [m^3/h], then the rounded value will be 2350 [m^3/h].

If e.g.V_{sup} = 7267 [m^3/h], then the rounded value will be 7300 [m^3/h].