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# Energy consumption in humidification process

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**Abstract**. The purpose of the air-conditioning system is to provide people in an air-conditioned room or facility with thermal-humidity comfort. For this purpose, the external air before entering into the room is processed for its treatment. These processes include, among others, humidification of the air. Too high a humidity level also does not benefit the building and its people. Humidification of the air can be realized as directly, then the steam or water mist injection takes place in the room, and indirectly, when the supply air to the room is humidified in the ventilation system. The energy consumption in the humidification process depends primarily on stream of humid air, methods of humidifying the air (water or steam), the type of energy carrier used to produce steam or secondary heating of humid air, range of relative humidity maintained, external humidity parameters. In the case where both the steam and the secondary heating use the same energy sources, the costs in both cases will be comparable. In this paper the calculation of energy demand in hourly and annual period as well as for water and steam humidifier unit have been calculated and presented in many tables and figures. The semidetached house were taken under consideration to analyzed the energy consumption for humidification process. The amount of energy needed to humid the air during the annual season varies from 127 to 545 kWh/ar, depending on the humidifier used and the pump power, while for steam humidification the amount of energy for humidification is less than 9421 kWh/a. As a result, water humidification should be considered more economical. The basic difference between water and steam humidification, as evidenced by the hx graphs is decrease in the air temperature during water humidification and need to reheat it. Taking into account the energy requirements in both cases is similar. The humidifying costs of the steam humidifiers are much higher than those of water humidification.

## 1. Introduction

The main goal of the air-conditioning system is to ensure thermal and humidity comfort of persons staying in an air-conditioned room or facility. For that purpose, before the external air is introduced to the room, it goes through processes which aim at treating it. Such processes include, inter alia, air humidification. During air humidification the content of air humidity is increased to the adequate level of relative humidity in particular thermal conditions. It is important to ensure a proper level of humidity in air-conditioned facilities due to human health and comfort, the course of technological processes, proper storage of goods and the presence of electrostatic charges in the room. Too dry air in industrial plants results in a significant growth of electrostatic charges in the machine operating environment. The decrease of relative humidity below 35% causes the creation of large electrostatic charges on the surfaces of dielectrics. Thus, discharge may take place in computer rooms, which results in the damage of memory and circuitries. Additionally, too large electrostatic radiation from computers and monitors may adversely affect humans [1]. It is essential to adopt an individual attitude to each facility when designing the air-conditioning system. The function of a building determines parameters of the supplied air, including relative humidity. The choice and maintaining of relative air humidity at a proper level ensures comfort of the environment intended for people and minimizes the adverse effect of the air on the quality of goods stored in a particular facility.

## 2. Characteristic features of the air humidification process

The air humidification process involves the increase of the humidity content in the air which is supplied to the room to the required level of relative humidity in the actual thermal conditions. In air-conditioning systems, the air may be humidified using two methods:

- adiabatic humidification,
- injection of vapour into the air.

The basic difference between the two methods from the thermal point of view is a slight increase of air temperature during water vapour humidification. Whereas, during water humidification, the air is significantly cooled [2]. Air humidification may take place:

- directly - then, the injection of water vapour or mist is performed in the room,
- indirectly - when the air blown into the room is humidified in the ventilation system.

The first method is used especially for large shop floors whereas indirect humidification is used for comfort [3].

### *2.1 Air humidification using water*

Air humidification using water is performed by spraying water in the stream of flowing air by applying nozzles (humidification chamber) or by the contact of the air with the wet surface of the chamber with a significant surface area (humidification chamber). In the first case, a heat (as a result of convection) and mass transfer between air and water takes place in the humidification chamber. Energy of heated air is used for water vaporization. A very important factor which has an influence on the intensity of the humidification process is the size of both phases' contact area due to a very short time of contact and a relative speed of drops and air [3]. The above-mentioned conditions are met by a humidification chamber in which two types of the change of state of water may be carried out: the polytropic and adiabatic processes.

- The polytropic process takes places when the temperature of water contacting the air is different from the temperature of the damp thermometer of that air. Applying such processes, we may both humidify and dry the air.
- The adiabatic process takes places when the temperature of water contacting the air is equal to the temperature of the humid air [1].

Presently, the most frequently chosen solution is a humidification chamber operating in the adiabatic cycle. During air humidification, with the increase of the humidity content, the air is cooled down. The adiabatic process is used also in humidification chamber when they are fed with circulating water which has the same temperature as the humid air [3].

To obtain cleaner air, specialized non-absorbable ceramic beds are used and silver ions are added to supplying water; such ions get into bacterium cell structures, curb their development and prevent bacteria from spreading in the humidification and ventilation system.

### *2.2 Air humidification using vapour*

Vapour humidifiers are alternative to water humidifiers. Their task is to introduce dry water vapour which does not contain condensate from the existing vapour source to the air in such an amount as to ensure the required air humidity. Water vapour may be produced in its own vapour generator or taken from the technological water vapour system existing in a particular facility. The process takes place through the direct introduction of vapour to the ventilation duct or vapour humidification section which is a part of the air-conditioning unit by using vapour lances. Water vapour introduced into the air displays the following features: it is dry, saturated vapour with the temperature of 105 - 110°C or slightly overheated with the overpressure of approx. 200 kPa, when it is fed from the central source of vapour feeding, or below 30 kPa, when it is produced in an individual generator. Moreover, it must be clean and odourless. Vapour humidifiers may be divided into:

1) air humidifiers with its own vapour generator - vapour is produced by bringing water to the boil, i.e. thanks to power connection. Vapour which has been created in this way is absorbed by the ambient air. In this group, there are three humidifiers:
   - electrode humidifiers,
   - resistance humidifiers,
   - humidifiers with a heat exchanger fed with hot water with the temperature of above 115°C,
   - humidifiers fed with gas.
2) air humidifiers fed with foreign vapour - used in facilities equipped with the technological vapour system [3].

*2.3 Water quality in the process of air humidification*

The quality of water used for humidification in air humidifiers, apart from humidification chamber, is very important. Purified and filtrated water should be used, otherwise minerals or micro-organisms contained in water may get to the air – table 1.

**Table 1.** Recommendations concerning the reaction (action) to be triggered when a particular number of nonpathogenic bacteria is exceeded in water used for air humidification [4].

| | Typical facilities | Special facilities | Recommendations / actions |
|---|---|---|---|
| | Number of nonpathogenic bacteria [CFU/ml of water] | | |
| **Upper limit** | 10000 | 1000 | Check water for the presence of pathogenic bacteria |
| **Warning state** | 1000 | 100 | Check and clean the system |

To additionally secure the purity of the water humidification process, ultraviolet lamps are used in humidification chambers and drop separators are covered with an antibacterial layer [3].When a great stream of water mass which is not able to totally evaporate is supplied to the air with the initial state “1”, then, the air will reach the state “2” and its relative humidity will be less than 100%. – figure 1.

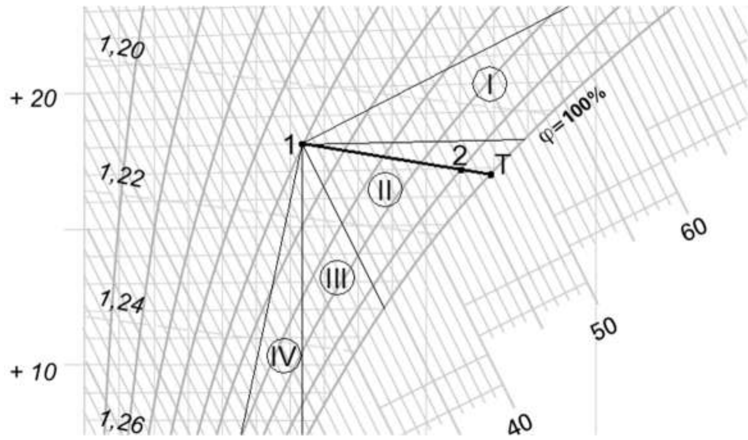


**Figure 1.** Scope of the possible change of state of air after the direct contact with water having various temperatures on hx diagram[6].

The change of state of air which may result from the contact of the air with water go in various directions. The area may be divided into 4 sectors. The location of the course of the change in particular sectors depends on the temperature of humidification water – table 2 [5].

**Table 2.** Characteristic features of the change of state of air in the water humidifier during humidification [6].

| Process direction | Water temperature | Temperature difference | Enthalpy difference | Humidity difference | Process type |
|---|---|---|---|---|---|
| Sector I | $t_B>t_w>t_1$ | $\Delta t> 0$ | $\Delta i> 0$ | $\Delta x> 0$ | heating and humidification |
| $t_1$ = idem | $t_w = t_1$ | $\Delta t = 0$ | $\Delta i> 0$ | $\Delta x> 0$ | isothermal humidification |
| Sector II | $t_1>t_w> t_{mo1}$ | $\Delta t< 0$ | $\Delta i> 0$ | $\Delta x> 0$ | cooling and humidification |
| $i_1$ = idem | $t_w = t_{mo1}$ | $\Delta t< 0$ | $\Delta i = 0$ | $\Delta x> 0$ | adiabatic humidification |
| Sector III | $t_{mo1}>t_w> t_{R1}$ | $\Delta t< 0$ | $\Delta i< 0$ | $\Delta x> 0$ | cooling and humidification |
| $x_1$ = idem | $t_w = t_{R1}$ | $\Delta t< 0$ | $\Delta i< 0$ | $\Delta x = 0$ | cooling at x=const. |
| Sector IV | $t_{R1}>t_w>t_A$ | $\Delta t< 0$ | $\Delta i< 0$ | $\Delta x< 0$ | cooling and dehydration |

The adiabatic process takes place in such devices as humidifiers with the humidification chamber or nozzle water humidifiers. Presently, it is used for air humidification in the season. Due to the risk entailed by the influence of water on the quality of the treated air, frequently, other devices are used instead of this kind of humidifiers.The humidification efficiency for the adiabatic process is expressed by the following dependence [8]:

$$\eta = \frac{t_1 - t_2}{t_1 - t_T} \tag{1}$$

$$\eta = \frac{x_2 - x_1}{x_T - x_1} \tag{2}$$

The humidification efficiency of the humidification chamber depends on many factors; the most important ones include:

- speed of the air flow,
- arrangement and number of humidification nozzles,
- number of rows of nozzles and distances between them,
- water pressure in front of the nozzles,
- type and diameter of nozzle outlets,
- humidification intensity of one plane of nozzles,
- total length of the humidification chamber [7].

Exemplar values of the humidification efficiency $\eta_{max}$for the adiabatic process were presented in the table 3.A very important parameter connected with air humidification process is a degree of humidification B which affects the amount of water necessary to humidify the treated air. The amount of water which is necessary to humidify the air may be determined on the basis of:

$$M_W = W \cdot B\ [kg/s] \tag{3}$$

$$W = V_W \cdot \rho \cdot (X_2 - X_1)\ [kg/s] \tag{4}$$

where:

$V_W$ - stream of ventilation air [$m^3/s$], ρ - air thickness [$kg/m^3$], $X_1$ – humidity content in the external air under the computational conditions [g/kg], $X_2$ – humidity content in the blown air [g/kg].

**Table 3.** Maximum values of the humidification efficiency for the adiabatic humidification processes in the humidification chamber [8].

| Number of rows of nozzles | Direction of spraying water relative to the direction of the air flow | $\eta_{max}$ |
|---|---|---|
| 1 | co-current | 0.65 |
| 1 | counter-current | 0.80 |
| 2 | co-current and counter-current | 0.85 |
| 2 | two counter-current | 0.95 |
| 3 | one co-current and two counter-current | 0.99 |

B - humidification factor depending on the structure of the humidification chamber, the following values are assumed most frequently:

- counter-current chambers: B = 2.5 ÷ 4,
- co-current chambers: B = 3.5 ÷ 5.

*2.4 Vapour humidification*

The process takes place through the direct introduction of water vapour to the treated air. During this process the humidity content rises and the temperature of the air is slightly increased. The balance of heat and humidity is presented as a direction of the change of state of air according to the following formula:

$$\varepsilon = \frac{\Delta i}{\Delta x} = \frac{i_2 - i_1}{x_2 - x_1} = i_{pw} \tag{5}$$

where:

$\varepsilon$ – direction coefficient of air state [kJ/kg],$i_1$ – enthalpy of the air in the initial state [kJ/kg], $i_2$ – enthalpy of the air in the final state [kJ/kg],$i_{pw}$ – enthalpy of water vapour [kJ/kg],$x_1$ – humidity content in the initial state [g/kg],$x_2$ – humidity content in the final state [g/kg].

## 3. Demand for energy for air humidification

Energy consumption in the humidification process depends mainly on:

- stream of humidified air,
- method of air (water or vapour) humidification,
- type of energy carrier used to produce water vapour or reheat the humidified air,
- scope of maintained relative humidity,
- humidity parameters of the external air.

Water humidification is regarded as the cheapest methods of humidification in air conditioning in energy terms. That is the case on condition that the air is not subject to reheating or a cheap heat source is used to heat water. Energy consumption is lower and, thus, operational (including humidification) costs concerning the change of state of air are smaller when the air-conditioning system operates properly. The most important factors are: maintaining optimal air parameters, adjusting the system working time to actual requirements of the users or to the technological process and keeping the air-conditioning system clean [9].

*3.1. Hourly demand for energy for humidification*

The following initial data was assumed according to figure 2:

a) the facility for which the calculations were made is located in the city of Lublin.
b) external air parameters:
    - temperature: $T_z$ = -20°C,
    - relative humidity: $\varphi_z$ = 100%,
    - enthalpy: $i_z$ = -18.4 kJ/kg,

- humidity content: $x_z$ = 0.8 g/kg.

c) internal air parameters:
- temperature: $T_p$ = 20°C,
- relative humidity: $\varphi_p$ = 50%.

d) technological parameters:
- total heat gains: $Q_c$ = 28.7 kW,
- sensible heat gains: $Q_j$ = 18.6 kW,
- humidity gains: W = 9.8 kg/h,
- number of persons staying in the room: N = 120 persons.
- $V_w = 10050[m^3/h] = 2{,}792\ [m^3/s]$

Establishing hourly demand for energy for humidification

a) Amount of water necessary for humidification in the water humidifier (the humidification chamber) $M_W = W \cdot B\ [kg/s]$ and $W = V_W \cdot \rho \cdot (X_2 - X_1)\ [kg/s]$.
where: $V_w$ – stream of ventilation air, $V_w$ = 2.792 $m^3$/s,ρ - air thickness, ρ = 1.2 kg/$m^3$, $X_1$ – humidity content in the external air, $X_1$ = 0.8 g/kg,$X_2$ – humidity content in the blown air, $X_2$ = 6.3 g/kg,B - humidification factor, B was assumed to be 3.5.
Thus $W = 2{,}792 \cdot 1{,}2 \cdot (6.3 - 0.8) = 18.425\ [g/s] = 0.0184\ [kg/s]$
and $M_W = 0.0184 \cdot 3.5 = 0.0645\ [kg/s] = 232.16\ [kg/h]$

b) Humidification efficiency

$$W = V_w \cdot \rho \cdot (X_2 - X_1)\ [kg/s] \quad (6)$$

where: $V_w$ – stream of ventilation air, $V_w$ = 2.792 $m^3$/s,ρ - air thickness, ρ = 1.2 kg/$m^3$, $X_1$ – humidity content in the external air,$X_1$ = 0.8 g/kg,$X_2$ – humidity content in the blown air, $X_2$ = 6.3 g/kg.

In table 4 has been presented the electric power of humidifier.

**Table 4.** Hourly demand for energy for humidification depending on the type of vapour humidifier.

| **Type of vapour humidifier** | **Power rating of humidifier [kW]** |
|---|---|
| Electrode humidifier | 50.0 |
| Resistance humidifier (double unit) | 22.3 |
| Gas humidifier | 73.0 |

### *3.2. Seasonal demand for energy for humidification*

*3.2.1. Water humidification.* Amount of energy necessary for humidification in the season:

$$E_{naw} = P_{naw} \cdot \Sigma[(1 - \eta_W) \cdot (X_2 - X_{śr})/(X_2 - X_1) \cdot t_W]\ [kWh/\mathrm{a}] \quad (7)$$

where: $P_{naw}$ – power of water humidifier (pump) for computational conditions [kW], $\eta_W$ – humidity recovery efficiency in a given month [-], $X_1$ – humidity content in the external air under the computational conditions [g/kg], $X_2$ – humidity content in the blown air [g/kg], $X_{śr}$ – average humidity content in the external air in a given month [g/kg], $t_W$ –working time during a given month [h].

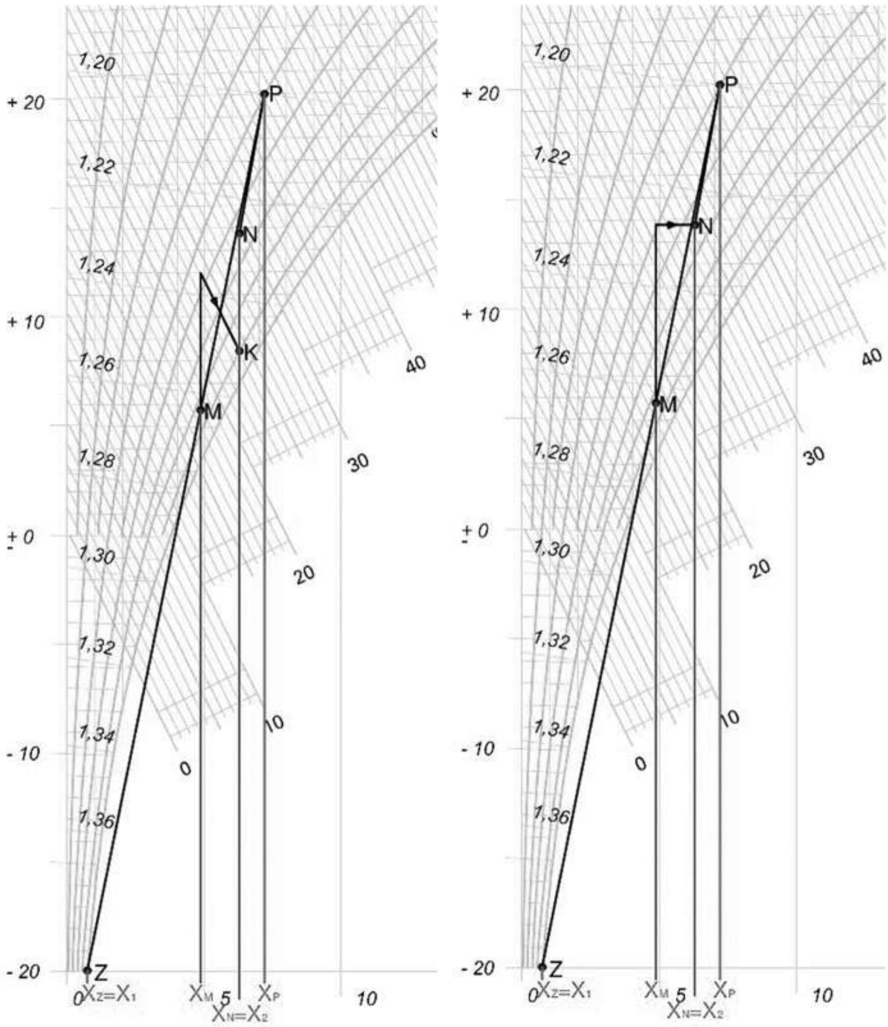


**Figure2.** Course of the change of state of humid air on the i - x chart for water humidification (on the left) and vapour humidification (on the right) [own study].

Average monthly humidity content is presented in table 5.

**Table 5.** Average humidity content in the external air throughout a year.

| Month | Average monthly humidity content $X_{av}$ [g/kg] |
|---|---|
| January | 2.48 |
| February | 3.31 |
| March | 3.27 |
| April | 5.01 |
| May | 6.71 |
| June | 9.11 |
| July | 9.39 |
| August | 10.1 |
| September | 8.52 |
| October | 5.38 |
| November | 4.17 |
| December | 3.19 |

Humidification efficiency counted for the computational conditions:

$$\eta_W = (X_M - X_1)/(X_2 - X_1) \quad (8)$$

where:
$X_M$ – humidity content in the air mixture, $X_M$ = 4.9 g/kg (value from the chart),$X_1$ - humidity content in the external air, $X_1$ = 0.8 g/kg,$X_2$ – humidity content in the blown air, $X_2$ = 6.3 g/kg.
Thus

$$\eta_W = \frac{(4.9 - 0.8)}{(6.3 - 0.8)} = 0.75$$

Energy for seasonal humidification is counted only for months which meet the following condition:

$$X_2 > X_{\text{av}} \quad (9)$$

$X_2$ = 6.3 g/kg $\rightarrow$ energy necessary for humidification in the season was calculated for the following months: from January to April and from October to December.
Amount of energy necessary for humidification in the season is

$$E_{naw} = P_{naw} \cdot 363.65\ [kWh/a]$$

Values of $P_{naw}$ are collected in table 6.

**Table 6.** Amount of energy necessary for humidification in the season.

| Type of water humidifier | Humidifier power [kW] | Energy for humidification in the season [kWh/a] |
|---|---|---|
| Humidification chamber | 0.42 | 152.7 |
| High-pressure water humidifier | 1.50 | 545.5 |
| Low-pressure water humidifier | 0.35 | 127.3 |

*3.2.2. Vapour humidification.* Amount of energy necessary for humidification in the winter season:

$$E_{naw} = h_p \cdot V_w \cdot \rho[(X_2 - X_{śr})/1000] \cdot \Sigma[(1 - \eta_W) \cdot (X_2 - X_{śr})/(X_2 - X_1) \cdot t_W]\ [kWh/a] \quad (10)$$

where: $h_p$ – enthalpy of vapour [kJ/kg],$V_w$ - stream of ventilation air [$m^3$/s],$\rho$ - air thickness [kg/$m^3$],$X_1$ – humidity content in the external air under the computational conditions [g/kg],$X_2$ – humidity content in the blown air [g/kg],$X_{śr}$ – humidity content in the external air in a given month [g/kg], $\eta_W$ – humidity recovery efficiency in a given month [-],$t_w$ – humidifier working time during a given month [h].
Humidification efficiency counted for the computational conditions

$$\eta_W = \frac{(4.9 - 0.8)}{(6.3 - 0.8)} = 0.75$$

where: $X_M$ – humidity content in the air mixture, $X_M$ = 4.9 g/kg (value from the chart),$X_1$ - humidity content in the external air, $X_1$ = 0.8 g/kg,$X_2$ – humidity content in the blown air, $X_2$ = 6.3 g/kg.
Enthalpy of vapour

$$h_p = c_{pp} \cdot \theta_p + r\ [kJ/kg] \quad (11)$$

where:
$c_{pp}$ – thermal capacity of vapour, $c_{pp}$ = 1.84 kJ/kg;$\theta_p$ – temperature of vapour, usually $\theta_p$ = 105 ÷ 110°C, r - heat of vaporization, r = 2501 kJ/kg.
Amount of energy necessary for humidification in the season

$$h_p = 1{,}84 \cdot 105 + 2501 = 2698.4\ [kJ/kg]$$

Constant value:$ST = h_p \cdot V_w \cdot \rho \cdot (1 - \eta_w)/[(X_2 - X_1)/1000]\ [kW]$
Thus, $E_{naw} = 9420.83\ [kWh/a]$

*3.2.3. Comparison of costs of air humidification.* A method of air humidification and devices used for the humidification process have a direct influence on the consumption of energy and underlying costs. Water humidification is regarded as more economical because the energy of flowing air is used for vaporizing water. In case of vapour humidifiers, the energy consumption and, thus, humidification costs, are several times higher. It is possible, however, to reduce such costs by using thermal energy instead of electric energy to heat water [10]. Then, the costs of vapour humidification are comparable to the costs incurred when using water humidification. The comparison of costs depending on the method of air humidification and used humidifier was presented in the table7.

**Table 7.** Comparison of air humidification costs

| Type of humidifier | | Annual energy [kWh/a] | Annual cost* [PLN] | Cost of water treatment* [PLN] | Total cost [PLN] |
|---|---|---|---|---|---|
| Vapour | Gas | 9421 | 1120** | - | 1120 |
| | Resistance | 9421 | 5653 | - | 5653 |
| | Electrode | 9421 | 5653 | - | 5653 |
| Water | Low-pressure | 127.3 | 76.37 | 1145 | 1221 |
| | High-pressure | 545.5 | 327.3 | 1145 | 1472 |
| | Chamber | 152.7 | 91.64 | 1145 | 1237 |

*assuming that the cost of 1kWh of electric energy is PLN 0.60.
**assuming that the cost of 1kWh of natural gas is 0.11890 PLN/kWh

## 4. Summary

Air humidification is one of the elementary processes of ventilation air treatment, having an influence on users of the air-conditioned facility. Each humidification devices has advantages and disadvantages, so it is essential to individually approach each facility and choose the device which, under particular conditions, will ensure safety and comfort of people staying in such facilities and a proper course of technological processes. A very important aspect is also an amount of energy necessary for the air humidification process, especially now, when we are striving for the minimization of energy consumption of buildings and all its systems. As shown in the computational examples in chapter 6 of this study, a necessary amount of energy for humidification in the season in case of water humidification fluctuates between 127 ÷ 545 kWh/year depending on the water humidifier used and the power of its pomp system, whereas the amount of energy for humidification in case of vapour humidification is almost 9421 kWh/year. Therefore, water humidification should be regarded as more economical. The fundamental difference between water and vapour humidification, as displayed in the i - x charts, is a fall of air temperature during water humidification and the necessity to reheat it. Taking into account the demand for energy, it will be similar in both cases. The costs of air humidification when using vapour humidifiers are significantly higher than using water humidification. They may be, however, effectively reduced by using thermal energy instead of electric one for water vapour production.

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