MEASUREMENT OF AIR HUMIDITY

1. Designations

A – psychrometric coefficient;
c_p – specific heat at constant pressure;
i – specific enthalpy;
H_m – millimetres of mercury;
m – mass;
M – kilomol mass;
p – pressure;
p_s – saturation pressure;
p_{ss}, p_{sm} – saturation pressure at dry and wet thermometer temperatures respectively;
q – heat related to 1 kg of medium;
R – gas constant;
r – heat of vaporisation of a liquid (water);
T – absolute temperature;
t – Temperature at ℃;
t_m – wet thermometer temperature for psychrometric measurement;
t_s – dry thermometer temperature for psychrometric measurement;
w – air velocity;
X – moisture content;
φ – relative humidity;
ρ – density;
ρ_p – absolute humidity;
τ – time;
Ψ – degree of saturation.

Indexing:

$\bullet g$ – gas (air);
$\bullet p$ – vapour (steam);
$\bullet r$ – dew point;
$\bullet w$ – liquid (water);
$\bullet s$ or $\bullet''$ – magnitudes corresponding to the saturation state (with the exception of temperature indexing for psychrometric measurements).

2. EVAPORATION PROCESS

To aid in understanding wet gas terminology, consider the example of producing pure steam by heating water isobarically until it evaporates. This process occurs in a cylinder enclosed by a frictionless, moving piston that exerts a constant pressure. Figure 1 illustrates the various stages of the process. Until the **saturation state** is reached, as represented in Fig. 1 by **bubble point** 2, heat input causes a temperature rise and only a slight increase in the volume of the pure liquid. The saturation state corresponds to point 2 on the evaporation curve in the p-T diagram (Fig. 2). With further heat input, the first vapour bubbles appear in the liquid. The system volume increases significantly upon the to appear of vapour (point 3), while the temperature remains constant, making the process isobaric-isothermal. The process is isobaric and isothermal.

A vapour in thermodynamic equilibrium with a liquid is known as a **saturated vapour**. If there are no liquid droplets present, it is referred to as a **dry saturated vapour** (point 4). A two-phase system that consists of dry saturated vapour and liquid with bubble point parameters is known as **wet saturated vapour** (as seen in point 3). The saturated state is defined as the point at which, upon increasing pressure, some of the vapour will condense, resulting in an increase in the mass of the liquid and a decrease in the mass of the vapour.

With enough heat input, the wet vapour reaches the state represented by point 4 on the T-q(τ) diagram, which is the **dew point**. At this point, all remaining liquid disappears. When cooling the vapour, the dew point corresponds to the state where the first liquid droplets appear in the gas. For a chemically homogeneous substance, the dew point temperature is equal to the **saturation point** temperature. On the p-T diagram, the saturation states from point 2 to point 4 are indicated by the points on the evaporation curve, which runs from the triple point to the critical point (refer to Fig. 2). It is evident that the temperature of the saturation state and the dew point are dependent on pressure, while the saturation pressure is dependent on temperature. Table 1 shows the temperature dependence of the saturation pressure of water vapour.

Further heat extraction leads to an increase in both the temperature and volume of the vapour. This increase in volume is due to the increase in temperature rather than an increase in gas mass, as seen in the saturated state transformation represented by section 2-4. The resulting steam is superheated. To convert a superheated vapour into a liquid, it must first be brought to a saturated state by either reducing its temperature or increasing its pressure (refer to Fig. 2 - section 6). This process can only occur if the temperature does not exceed the critical point temperature T_K.

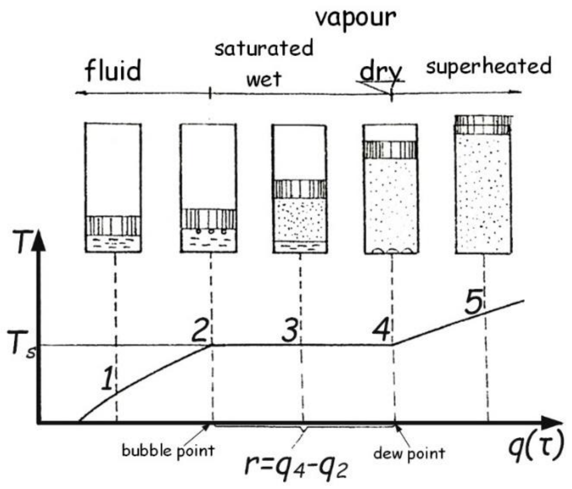


Fig. 1. Steam generation at constant pressure

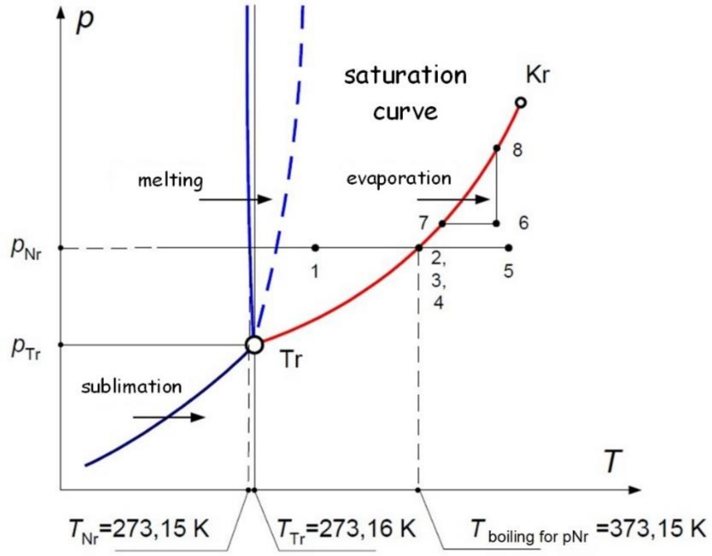


Fig. 2. Phase diagram in p - T coordinates. The dotted line shows the melting curve for a substance other than water

Table 1. Properties of humid air - dependence of water vapour pressure p_s in hPa on temperature t [°C]

t [^{0}C]	p_s [hPa]	t [^{0}C]	p_s [hPa]	t [^{0}C]	p_s [hPa]
-20	1,029	0	6,107	20	23,37
-19	1,133	1	6,566	21	24,86
-18	1,247	2	7,054	22	26,42
-17	1,369	3	7,575	23	28,08
-16	1,504	4	8,129	24	29,82
-15	1,651	5	8,719	25	31,66
-14	1,809	6	9,346	26	33,60
-13	1,981	7	10,012	27	35,63
-12	2,169	8	10,721	28	37,79
-11	2,373	9	11,473	29	40,04
-10	2,594	10	12,271	30	42,42
-9	2,833	11	13,118	31	44,91
-8	2,094	12	14,015	32	47,54
-7	3,376	13	14,967	33	50,29
-6	3,681	14	15,974	34	53,18
-5	4,010	15	17,041	35	56,22
-4	4,368	16	18,17	36	59,40
-3	4,754	17	19,36	37	62,74
-2	5,172	18	20,63	38	66,24
-1	5,621	19	21,96	39	69,91

Table 2. Basic components of dry air at sea level.

Type of gas	Kilomol mass [$kg \cdot kmol^{-1}$]	Volume fraction	Mass fraction
N_2	28,016	0,7803	0,7551
O_2	32,000	0,2099	0,2315
Ar	39,944	0,0094	0,0130
CO_2	44,003	0,0003	0,0004
Ne	20,179	0,0002	$1{,}4 \cdot 10^{-4}$
H_2	2,016	0,0001	$6{,}9 \cdot 10^{-6}$

Kilomol mass of dry air M_p=28.967 $kg \cdot kmol^{-1}$, gas constant R_p=287.03 $J \cdot kg^{-1} \cdot K^{-1}$.

3. PROPERTIES OF MOIST GASES

Moist gases are mixtures of dry gas and steam. If dry gas is mixed with superheated vapour (such as the superheated vapour represented by point 5 in Fig. 1 and 2), an **unsaturated moist gas** is obtained. When dry gas is mixed with saturated dry steam (point 4), a **saturated moist gas** is obtained. A **supersaturated moist gas** is a solution of wet saturated vapour (e.g. point 3) and dry gas, where liquid water may be present as liquid or ice mist.

When describing atmospheric moisture content, **dry air** is one of the components of the solution. Table 2 provides the composition of dry air at sea level.

When describing a moist gas, use the following agreement: the lower index '**p**' indicates quantities relating to vapour, the index '**g**' indicates quantities relating to dry gas (in the case of air), the index '**w**' indicates quantities relating to the condensed phase, i.e. aqueous liquid or ice mist, the index '**s**' indicates quantities relating to the saturated state. Quantities relating to moist gas will have no indicators.

According to Dalton's Law [5], the pressure of moist air is equal to the sum of the pressures of the components of dry gas p_g and vapour p_p

$$p = p_g + p_p. \tag{1}$$

The constituent pressure of the water vapour contained in a moist gas is generally so low that the vapour can be treated as a perfect gas. The error of such an approximation is generally not more than 2% in relative terms.

The component pressure of the vapour contained in the gas must not exceed the saturation pressure, otherwise condensation will occur, resulting in a loss of vapour. The saturation pressure (see Fig. 2 and Table 1) of the vapour increases with increasing temperature. However, it is obvious that it cannot exceed the total pressure of the moist gas p. Thus, the maximum component pressure of the vapour in the moist gas is:

$p_{p\,max}=p_s$ – when the vapour saturation pressure is less than the solution pressure($p_s < p$); this is the state we are generally dealing with;

$p_{p\,max}=p$ – when the vapour saturation pressure is greater than the solution pressure($p_s \geq p$). When the $p_{p\,max}$ value is reached, the solution contains no air and consists only of water vapour.

The actual water vapour content of a gas (air) is characterised by the absolute humidity (moisture) of the gas ρ_p, which is the ratio of the amount of vapour m_p to the volume of wet gas V

$$\rho_p = \frac{m_p}{V} = \frac{p_p}{R_p T} \tag{2}$$

which is the **density of the vapour at its constituent pressure p_p and wet gas temperature**. The absolute humidity is maximum and equal to the saturated dry vapour density

$$\rho_{p\ max} = \rho_p'' = \frac{p_s}{R_p T} \tag{3}$$

when the component vapour pressure equals the saturation pressure (p_p=p_s), the gas temperature becomes equal to the dew point.

However, the water vapour content of air is most often characterised by relative humidity. The **relative humidity** φ is the ratio of the absolute humidity ρ_p to the maximum absolute humidity ρ''_p for the same temperature. From the quoted relations (2) and (3), it can be defined as the ratio of the constituent vapour pressure p_p to its maximum pressure $p_{p\ max}$ at the same temperature

$$\varphi = \left(\frac{\rho_p}{\rho_p''}\right)_T = \left(\frac{p_p}{p_{p\ max}}\right)_T \qquad 0 \le \varphi \le 1 \tag{4}$$

It is important to note that both absolute humidity and relative humidity only describe the vapour content of a gas. They do not indicate the total water content, which can exist in both gaseous and condensed states as liquid or ice mist. The ratio of the total quantity of volatile vapour m_p and possibly condensed vapour m_w to the quantity of dry gas m_g

$$X = \frac{m_p + m_w}{m_g} \tag{5}$$

is called the **moisture content** (wetness). For a moist unsaturated gas, m_w=0 and therefore

$$X = \frac{m_p}{m_g} = \frac{\rho_p}{\rho_g} = \frac{M_p p_p}{M_g p_g} = \frac{M_p}{M_g}\frac{\varphi p_s}{p - \varphi p_s}, \tag{6}$$

while for a saturated gas (m_w=0, φ=1)

$$X'' = \frac{M_p}{M_g}\frac{p_s}{p - p_s}. \tag{7}$$

It is worth noting that the gravimetric water content X corresponds to the moisture content in 1 kg of dry gas, expressed in kg.

The moisture content of a gas can also be characterized by the gravimetric saturation degree ψ which is the ratio of the gravimetric water content X to the saturated gas gravimetric water content X'' at the same temperature T

$$\psi = \left(\frac{X}{X''}\right)_T. \tag{8}$$

It is worth noting that, unlike relative humidity ϕ, the gravimetric saturation degree ψ can be greater than 1 - this for a supersaturated gas.

For an unsaturated gas, from relations (6) and (7), the following is obtained

$$\psi = \varphi \frac{p - p_s}{p - \varphi p_s}. \tag{9}$$

In general, the saturation pressure of the vapour contained in the gas p_s is much less than the pressure of the moist gas p, i.e. $p_s \ll p$, giving $\psi \approx \phi$.

It is evident that the gas constant can be represented as soon as the gravimetric water content X of an unsaturated gas is introduced into the description

$$R = \frac{R_g + X \cdot R_p}{1 + X} = \frac{R_g}{1 - \left(1 - \frac{R_g}{R_p}\right) \cdot \frac{\varphi \cdot p_s}{p}}. \tag{10}$$

The density of a moist gas is equal to the sum of the densities of the components at their component pressures

$$\rho = \rho_g + \rho_p = \left(\frac{p_g}{R_g} + \frac{p_p}{R_p}\right) \cdot \frac{1}{T} = \frac{p_g}{R_g \cdot T}(1 + X). \tag{11}$$

When describing a moist gas, specific volumes refer to a fixed quantity of dry gas. The volume of 1+X kg of moist gas, i.e. 1 kg of dry gas is equal to

$$v_{1+X} = R_g \cdot \frac{T}{p_g} = R_g \left(\frac{R_g}{R_p} + X\right) \cdot \frac{T}{p} \tag{12}$$

The enthalpy of 1+X kg of moist unsaturated or saturated ($X \leq X''$) vapour gas with a heat of vaporisation r in a reference state at T_0 is

$$i_{1+X} = c_{pg}(T - T_0) + X\left[c_{pp}(T - T_0) + r\right]. \tag{13}$$

For air and water vapour, after assuming M_p=18,015 kg·kmol^{-1}, M_g=28,967 kg·kmol^{-1}, R_p=461,52 J·kg^{-1}·K^{-1}, R_g=287,03 J·kg^{-1}·K^{-1}, c_{pg}=1,005 kJ·kg^{-1}·K^{-1}, r=2501 kJ·kg^{-1} przy T_0=273,15 K, c_{pp}=1,88 kJ·kg^{-1}·K^{-1}, respectively, are obtained:

- gravimetric water content of air:

$$X = 0.622 \frac{\varphi p_s}{p - \varphi p_s} \tag{14}$$

- gravimetric water content of saturated air:

$$X = 0.622 \frac{p_s}{p - p_s} \tag{15}$$

- gas constant of moist air:

$$R = 461.5 \frac{0.622 + X}{1 + X} = \frac{287.03}{1 - 0.378 \cdot \frac{\varphi \cdot p_s}{p}} \frac{J}{kg \cdot K} \tag{16}$$

- specific volume of 1+X kg of moist air:

$$v_{1+X} = 461.5 \cdot (0.622 + X) \cdot \frac{T}{p \cdot (1 + X)} \frac{m^3}{kg} \tag{17}$$

- enthalpy of 1+X kg of moist air:

$$i_{1+X} = 1.005 \cdot t + X(1.88 \cdot t + 2501) \frac{1}{(1 + X)} \frac{kJ}{kg} \tag{18}$$

4. CHART OF COORDINATES i_{1+X}-X FOR WET AIR

Calculations and considerations related to humid air can be conveniently interpreted using the Mollier diagram, which is a graph made in the enthalpy-gravimetric water content system, i.e. the i_{1+X}-X graph (Fig. 3). This diagram is provided in the literature for a humid air pressure of p=1000hPa≈750 Tr or p=1 Kg·cm^{-2} =735.56 Tr and can be successfully applied over a range of pressures differing by ± 3% from these values.

The enthalpy i in this diagram is calculated for a mixture of 1 kg of dry air and X kg of vapour, as shown by the following formula based on the assumption that the enthalpy is calculated with respect to temperature 0°C (i_0=0; compare with (13))

$$i = c_{\mathrm{pg}} \cdot t + X\left(r + c_{\mathrm{pp}} \cdot t\right), \tag{19}$$

where c_{pg} and c_{pp} are the specific heats, respectively, at constant pressure p (hence the unfortunate overlap of index designations) of dry gas and steam, and r is the heat of vaporisation of water at temperature 0°C. As a reminder, it can be explained that the enthalpy i represents, in this case, the heat to be supplied by 1+X kg of moist air to heat it from 0°C to temperature t: factor one is the heat of heating 1 kg of dry air, factor two is the heat of evaporation at 0°C X kg of water and heating the resulting vapour.

To enhance readability and prevent the characteristic lines from appearing too dense, the coordinate axes of the Mollier diagram i_{1+X}-X are angled at 135°. The graph includes a grid of abscissa X=const and ordinate i=const coordinate lines, as well as isotherms t=const and lines of constant relative humidity φ=const. The isotherms are straight lines, assuming constant values of specific heats, while the lines φ=const are curves. The air saturation line is the most characteristic line, denoted by φ=1. The area below this line is where supersaturated air, or haze, occurs, causing moisture to condense out of the air. Conversely, the area above the φ=1 line is where unsaturated air is found.

The slope of the isotherms in the unsaturated air zone, i.e. above the saturation line, can be calculated by determining the derivative of

$$\left(\frac{\partial i_{1+X}}{\partial X}\right)_t = r + c_{\mathrm{pp}} \cdot t\,. \tag{20}$$

This slope is variable and temperature-dependent. The lower the temperature, the smaller the slope of the isotherm.

At the intersection with the line φ=1, the isotherms break down and have a different slope in the supersaturated air zone. They can be determined by differentiating the following formula for the enthalpy of supersaturated air containing condensed water of mass m_w

$$i = c_{pg} \cdot t + X'' \cdot \left(r + c_{pp} \cdot t\right) + X_w \cdot c_{pw} \cdot t, \tag{21}$$

where c_{pw} is the specific heat of water, the gravimetric water content X'' is at the same time the amount of water vapour corresponding to the saturation state, and X_w=m_w/m_g, i.e. is the amount of condensed water per 1 kg of dry air. The derivative of this function after X will be equal to

$$\left(\frac{\partial i_{1+X}}{\partial X}\right)_t = c_{\mathrm{pw}} \cdot t\,, \tag{22}$$

as X'' depends only on temperature and has a constant value; only X_w can change. The isotherms in the supersaturated air region are therefore also straight lines and follow a course similar to that of the constant enthalpy line. The t>0°C isotherms run slightly smoother in relation to these, and the t<0°C isotherms run slightly steeper. At the bottom of the graph, a line indicating the dependence of saturation pressure on moisture content is usually additionally given.

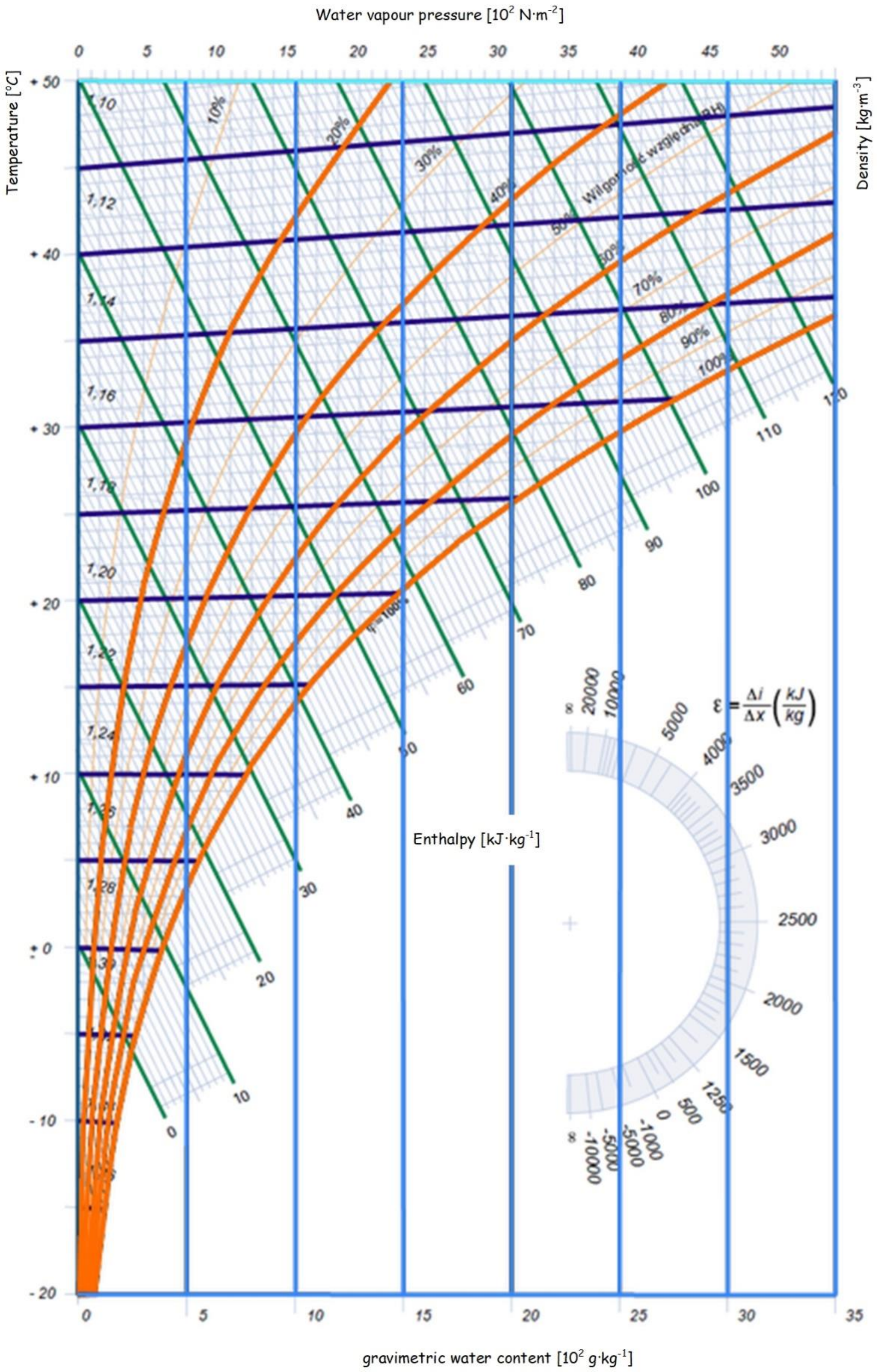


Fig. 3. Graph with i_{1+X}-X coordinates (Mollier) for moist air.

Examples of using the Mollier diagram.

1. Given a given humid air temperature t_1, it is possible to determine for this temperature the saturation pressure p_s and the gravimetric saturation degree of air X'', i.e. the number defining the maximum water vapour content. This is illustrated in Figure 4 - from the point of intersection of the isotherm t_1 with the line $\varphi=1$ (point 2), a vertical line is drawn corresponding to the constant water content characterised by the X coordinate. The point of intersection with the 'pressure' line 3 determines the saturation pressure p_s and the point of intersection with the abscissa axis X the gravimetric water content degree of the saturated air.

From the Mollier diagram (Fig. 3), for isotherm t_1=22.5°C (half the distance between isotherms 20 and 25°C), $p_{s1} \approx 2600$ Pa and $X'' \approx 0.0174$ are obtained. For comparison - the value of saturation pressure at 22.5°C calculated from the data in Table 1 brings p_{s1}=2721 Pa.

2. At a given temperature t and relative humidity φ, or temperature t and moisture content X, the dew point temperature tr and the component pressure of the water vapour contained in the air pp can be read off the graph. The data pairs (t, φ) or (t,X) uniquely determine the position of a point on the Mollier diagram. The intersection of the vertical line drawn from this point (Figure 4, e.g. point 1) with the line φ=1 (point 5) determines the dew point temperature t_r - this is the temperature of the isotherm passing through the intersection point; $t_r=t_5$. It is worth noting that, from a physical point of view, the process 1 - 5 corresponds to the cooling of the air - isotherms with lower and lower temperature values are intersected - at constant moisture content ($X=X_1$=idem), until the first dewdrops appear at φ=1. As the temperature decreases, the relative humidity φ increases along the section 1- 5. The component pressure is determined by the next intersection point - in Fig. 4 this is point 6.

For example, for t_1=22.5°C and X_1 = 0.010 (φ= 0.5), the following is obtained from the Mollier diagram: t≈13.8°C, $p_{p1} \approx 1240$ Pa. The heat given off when cooling 1+X kg (i.e. 1,010 kg in the case) of moist air, corresponding to the enthalpy difference i_{1+X} (for state 1 it is about 48.5 kJ/kg, for state 5 about 39 kJ/kg), is about 9.5 kJ/kg.

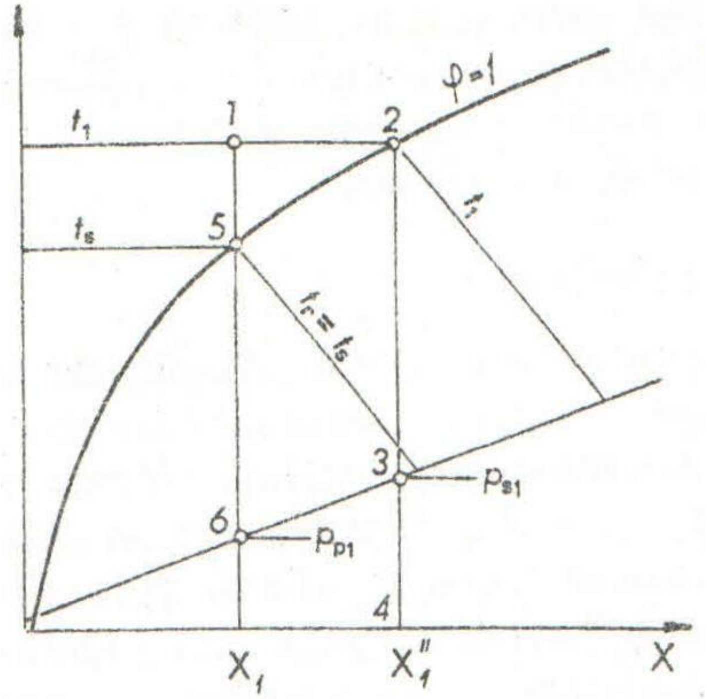


Fig. 4. Method of reading the saturation pressure p_s and the gravimetric saturation degree X'' of saturated air from the Mollier diagram for a given temperature t_1 and the dew point temperature t_r and the component pressure of the vapour p_p contained in the air for data (t,X) or (t,φ)

3. Having the results of psychrometric measurements in the form of dry thermometer temperatures t_s and wet thermometer temperatures t_m, it is possible to determine the approximate value of relative humidity φ, as shown in Fig. 5. The relative humidity φ is defined by point 3 of the intersection of isotherm t_s with the extension of isotherm tm from the fog region (section 1 - 2 extended to point 3).

From the Mollier diagram for t_s=t_1=22.5°C and t_w=15.0°C, the relative humidity value $\varphi\approx0.4$ is obtained.

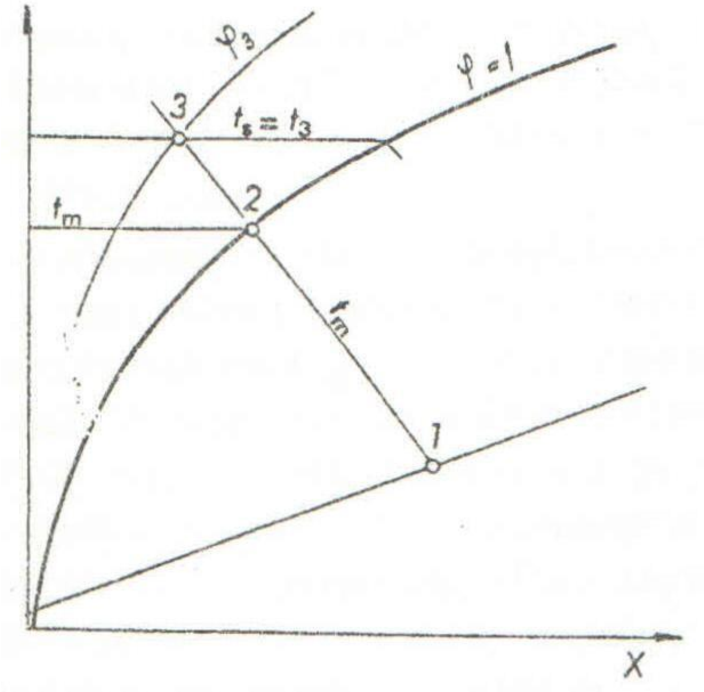


Fig. 5. Using the Mollier diagram to determine relative humidity φ from psychrometric measurements in the form of wet t_m and dry t_s thermometer temperatures.

4. Figure 6 illustrates the desiccation process of moist air, with the initial parameters defined by section 1, through its cooling and the associated vapour condensation. The cooling (section 1 - 3) proceeds at a constant moisture content (X=idem) first in the unsaturated air region (1-2) and then in the mist region (2-3) until the assumed minimum temperature t_3 is reached. At constant gravimetric water content X, the individual points of section 2-3 correspond to supersaturated states. Section 3-4 illustrates the condensation of moisture at constant temperature - the degree of moisture decreases. After isobaric heating of the air from dew point 4 to point 5, corresponding to the initial temperature (t_5=t_1), air with lower humidity is obtained. As a result of dehumidification, ΔX=X_1-X_5=X_3-X_4 kg of moisture per kilogram of dry air has condensed and the relative humidity has decreased by $\Delta\varphi = \varphi_1 - \varphi_5$.

Let φ_1=0.4 at t_1=35°C, and let the lower cooling temperature be t_3=10°C. The following values can be read off from the Mollier diagram: X_1=0.015, X_4=X_5=0.008, φ_5= 0.23. With such drying, ΔX=0.015-0.008=0.007 kg of water per kilogram of dry air will condense and the relative humidity will decrease from 40% to 23%.

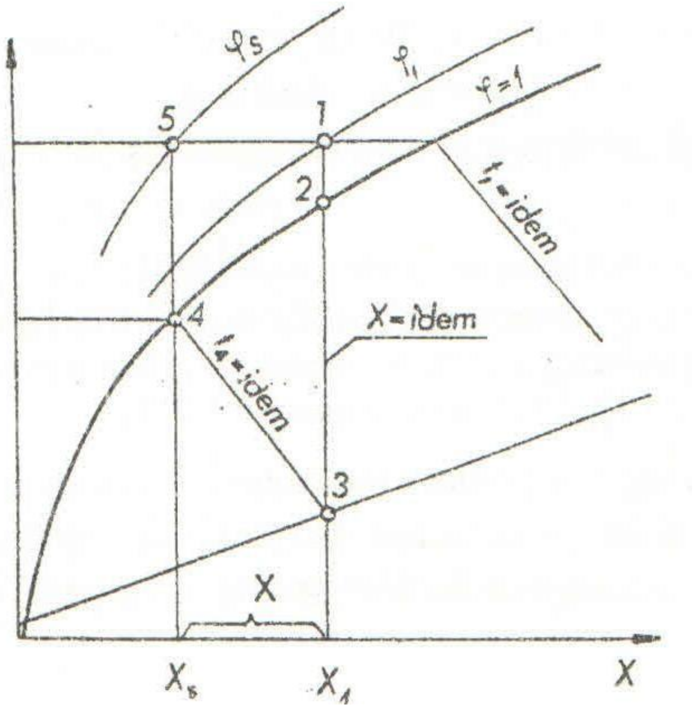


Fig. 6. Illustration of the drying process of moist air with initial parameters defined by the position of point 1 by cooling it (1- 3) and then heating it (4-5)

5. HIGROMETERS

Humidity meters or hygrometers are instruments used to measure air humidity. They use various physical phenomena during construction to obtain information about the humidity of a medium, either directly or indirectly. The adopted measurement principle allows for the distinction of different types of humidity meters:

- gravimetric hygrometers - measure the amount of water in a gas by determining the difference in mass of a hygroscopic substance before and after absorbing moisture from the air.

- thermometric hygrometers - humidity is determined by measuring temperature. Instruments of this type are called psychrometers and will be discussed in more detail in the next paragraph.

- dew point hygrometers - determine the dew point temperature of a given atmosphere, from which the humidity is calculated. The measurement involves observing the polished surface of a cooled metal, with the appearance of moisture droplets indicating that the dew point has been reached. Cooling is typically achieved through the evaporation of an ether aerosol from the opposite surface.

- hygroscopic hygrometers - use changes in the mechanical properties of materials under the influence of humidity changes. This group includes popular hair hygrometers, which are based on changes in the length of defatted human or animal hair, as well as some synthetic fibres under the influence of air humidity changes. The deformations of the hair are transferred by a lever to a pointer giving the relative humidity directly on the scale.

- electrical hygrometers - include capacitive instruments, which measure changes in the capacitance of a capacitor, and instruments that indirectly measure changes in the thermal conductivity of air. The latter case is a little misleadingly named 'electrical', but the alternative term 'automatic' also fails to capture the essence of the measurement. Hygrometers that operate on the principle of changing air's thermal conductivity with humidity changes have an electrical circuit in the form of a Wheatstone bridge. Two branches of the bridge are located in chambers containing dry air and air with the humidity being tested.

In addition to the aforementioned groups, it is worth mentioning spectrometric methods. Infrared technology has been rapidly developing recently. However, these instruments are not among the most affordable and are generally used for the global analysis of a medium's composition, after removing moisture. Hair hygrometers and psychrometers remain the most popular instruments for applications. Hair hygrometers have a simple design and provide a direct indication of the quantity being measured. However, their accuracy is low, and it is necessary to periodically check the accuracy of the readings by comparing them with other hygrometers and adjusting them accordingly. As a result, the field of more accurate laboratory measurements is dominated by psychrometers.

6. THE PRINCIPLE OF PSYCHROMETERS

Psychrometers operate based on adiabatic saturation, which is the process of a gas becoming saturated with moisture through adiabatic evaporation. This concept will be explained using the example of air flow with a relative humidity less than 100% over the surface of a liquid in a thermally insulated container (see Figure 7). Initially, we assume that there is no flow. It is a well-known fact that the moisture content of the air is dependent on the distance from the surface of the water. At the surface, the moisture content will be at its maximum of 100%. As the distance from the surface increases, the relative humidity decreases. If the air above the liquid surface is exchanged, for instance, by flow, the equilibrium must be restored by replenishing the moisture in the introduced mass of air above the liquid surface.

Replenishment involves the evaporation of water, which causes a decrease in temperature due to the thermal insulation of the tank. This process will continue as long as the air requires replenishment to reach 100% moisture content. The process will only stop when the blown air reaches the dew point, which is the temperature at which the air has a relative humidity of 100%. This phenomenon is a common occurrence in everyday life. For example, blowing air on a sweaty body can provide a cooling effect.

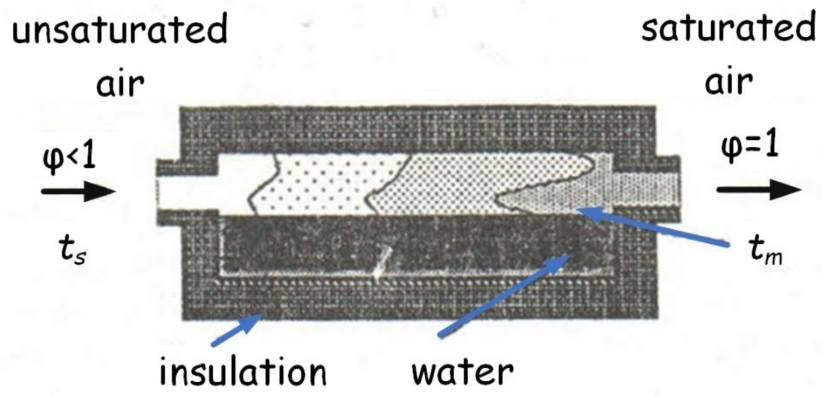
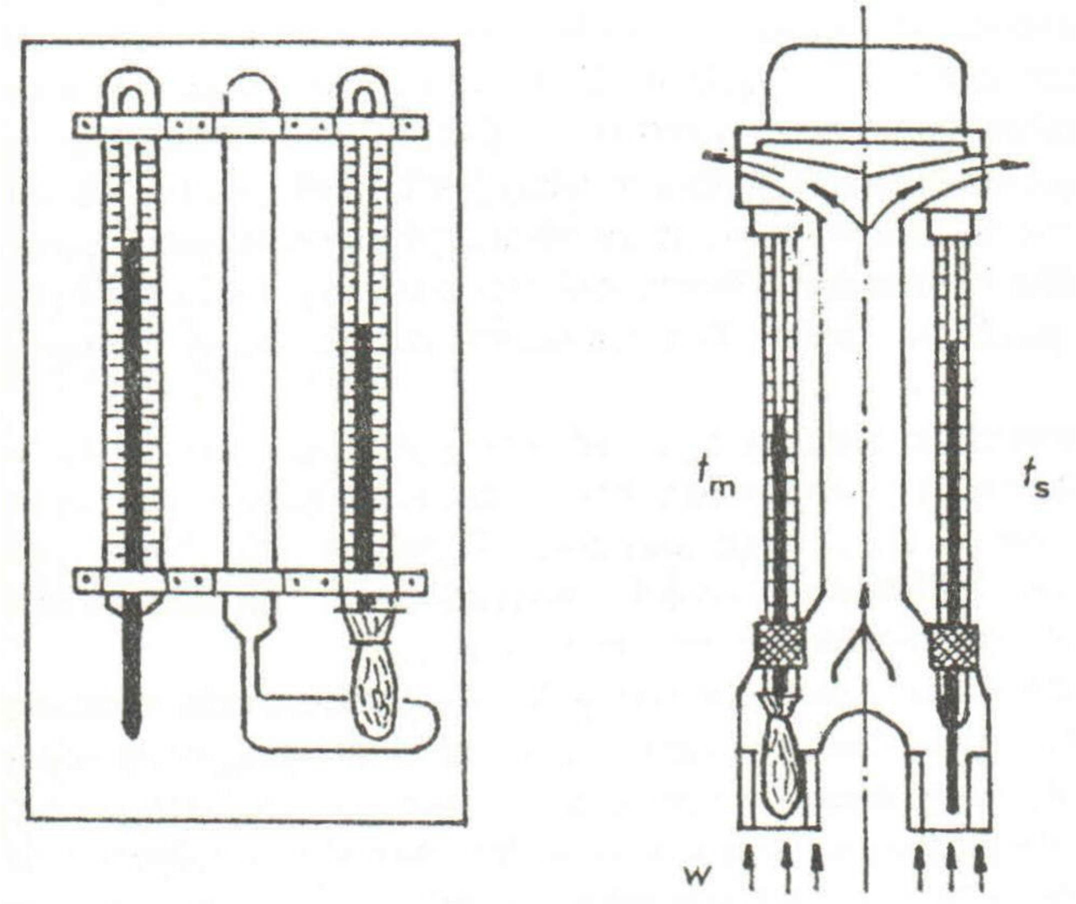


Fig. 7. Illustration of the adiabatic gas saturation process with moisture (psychrometer principle)



a) b)

Fig. 8. Psychrometers: a) August's; b) Assmann's.

Psychrometric measurements utilise the phenomenon of 'adiabatic' water evaporation from materials such as gauze that is saturated with it. The purpose of using gauze, cotton wool or other fabric is to maximise the evaporation surface area. Each psychrometer consists of two identical, highly accurate mercury thermometers. One thermometer's mercury reservoir is circulated directly through the air, which is known as a dry thermometer. The reservoir of the second thermometer containing mercury is covered with a gauze or batiste shirt. The lower part of the thermometer, which does not come into contact with the reservoir, is either submerged in the reservoir of distilled water or moistened with distilled water just before taking the measurement. This type of thermometer is referred to as a wet thermometer.

In the August psychrometer (Figure 8.a), the airflow around the thermometer is natural and therefore random, but also relatively slow. This can result in measurement errors of up to several per cent, primarily due to insufficient cooling of the wet thermometer.

The Assmann psychrometer (Figure 8.b) uses thermometer reservoirs placed in corresponding sleeves through which air flows. The air movement is forced by a spring-driven fan. Assmann's psychrometers are easy to operate, comfortable to use, and highly accurate. They can be used not only to measure relative air humidity but also to check and calibrate less accurate humidity meters.

When measuring humidity with a psychrometer, the phenomenon of adiabatic saturation occurs in the layer of air surrounding the wet thermometer cup. This establishes the saturated state of the air with water vapour. The wet thermometer's bulb temperature is lowered due to the evaporation of water from the wetted tee. Therefore, it will show a lower temperature than a dry thermometer. The process of water evaporation continues until the saturation vapour pressure around the wet bulb of the thermometer equals the component pressure of water vapour in the humid air under test. The difference between the readings of the dry thermometer and the wet thermometer is known as the psychrometric difference. This difference is greater when the air is drier because more water needs to be added and more heat is required to evaporate it.

Based on the known temperatures indicated by the dry and wet thermometers, which provide the psychrometric temperature difference, it is possible to determine the relative humidity of the air either by consulting the appropriate tables attached to each instrument or by plotting i_{1-X}-X.

The relative humidity of the air can also be determined using the relationship

$$\varphi = \frac{p_p}{p_{ss}} = \frac{p_{sm} - A(t_s - t_m) \cdot p}{p_{ss}}, \tag{23}$$

where: p_p - component vapour pressure in the tested air, p_{sm} - vapour saturation pressure at the wet bulb temperature t_m , p_{ss} - vapour saturation pressure at the dry bulb temperature t_s , p - atmospheric pressure in hPa, A - psychrometric coefficient depending on the air flow velocity near the wet bulb, defined by the following empirical formula

$$A = \left(65 + \frac{6.75}{w}\right) \cdot 10^{-5} K^{-1}\,. \tag{24}$$

In the last relationship w is precisely the airflow velocity and is:

- for August's psychrometer w=0.4÷0.5 $\mathrm{m \cdot s^{-1}}$;
- for Assmann's psychrometer w≈2,5 $\mathrm{m \cdot s^{-1}}$.

The following values of constants can therefore be assumed:

- for August's psychrometer A ≈ $80 \cdot 10^{-5}$ $\mathrm{K^{-1}}$;
- for Assmann's psychrometer A ≈ $67{,}7 \cdot 10^{-5}$ $\mathrm{K^{-1}}$.

7. PROCEDURE FOR CARRYING OUT THE MEASUREMENTS

The aim: to measure the relative humidity of the air.

Instruments:

- Assmann's psychrometer;
- mercury barometer.

Measurement procedure:

1. Read the atmospheric pressure on the barometer.
2. Moisten the gauze shirt on the tank of the wet thermometer with distilled water using a pipette.
3. Screw on the spring that drives the psychrometer fan.
4. Start the fan.

5. Once the thermometers are set, read the temperature indicated by the wet thermometer t_m and the dry thermometer t_s.

Preparation of results:

1. 1. Convert the pressure values read from the barometer to hPa

$$p = 1{,}333 \cdot H_m[1 - (\beta - \alpha) \cdot t]\ hPa, \tag{25}$$

where Hm - height of the mercury in millimetres as read from the barometer, β-α = 0.000182 K^{-1} - relative (to glass) coefficient of volumetric expansion of mercury, $t = t_s$ - ambient temperature.

2. Read from Table 1 the vapour saturation pressures p_{ss} and p_{sm} at dry thermometer temperature t_s and dew point t_r, respectively. As can easily be seen, the vapour saturation pressure at dew point is equal to the component vapour pressure in moist air at dry thermometer temperature: p_{sr}=p_{ps}.
3. 3. Determine the relative humidity of the air from the formula (pressure in Pa):

$$\varphi = \frac{p_{sm} - 6.76 \cdot 10^{-6}(t_s - t_m) \cdot p}{p_{ss}}. \tag{26}$$

4. 4. Calculate from the values obtained:

a) gravimetric water content of unsaturated air X at dry thermometer temperature using (14) (p_s=p_{ss}, p_p=φp=p_{sr});

b) the gravimetric water content of the saturated air at dry thermometer temperature X'' from the formula (15);

c) gravimetric saturation degree ψ - (8);

d) the gas constant of moist air R - (16);

e) specific volume of moist air v_{1+X} - (17);

f) specific enthalpy of moist air i_{1+X} - (18).

5. Read from the chart i_{1+X}-X (Molliera):

a) saturation pressure p_{ss} and p_{sm} (p_{sm}=p_{ps} cf. point 2);

b) relative humidity φ;

c) gravimetric water content X;

d) specific enthalpy of moist air i_{1+X}.

6. Compare the results of the calculations in step 4 and the readings in step 5 in a table.
7. Calculate the mass of water contained in 1 m3 of moist air.

8. SAMPLE REVIEW QUESTIONS

1. Give a definition of saturated steam, dry saturated steam and wet saturated steam.
2. What is the dew point?
3. Characterise the evaporation process using a diagram p - T.
4. Discuss the quantities that characterise the moisture content of air.
5. How are the parameters of humid air calculated using the relationships for solutions of perfect gases?
6. Discuss Molière's diagram.

7. State how to determine saturation pressure, partial pressure, and relative humidity from a Molière diagram.
8. What are hygrometers and how do we classify them?
9. Discuss the principle of psychrometers based on the phenomenon of adiabatic evaporation.
10. State how relative humidity is measured using an Assmann psychrometer.

LITERATURA

[1] Warren H. Giedt Thermophysics. Van Nostrand Reinhold Company, New York, 1971.

[2] B. V. Karlekar Thermodynamics for Engineers. Prentice Hall Inc., New York, 1987.

[3] Bogumił Staniszewski Termodynamika. PWN, Warszawa, 1986.

[4] Jan Szargut Termodynamika. PWN, Warszawa, 1985.

[5] Stefan Wiśniewski Termodynamika techniczna. WNT, Warszawa, 1987.