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Pregled metod merjenja vlažnosti zraka
A Review of Air Humidity Measurement Methods

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V prispevku je podan pregled stanja na področju merjenja vlažnosti zraka. Higrometri so razdeljeni po načelu delovanja. Opisane so njihove prednosti, pomanjkljivosti, metrološke značilnosti (merilno območje, merilna negotovost, odzivni čas), poglavitne konstrukcijske značilnosti in področje uporabe. Podane so tudi smeri razvoja higrometrov.

This paper presents a review of humidity measurements in air. Hygrometers are classified by the principle of operation. Their advantages, disadvantages, metrological properties (measuring range, uncertainty of measurements, response time), basic constructional properties and applications are described. Future development of hygrometers is also presented.

0. UVOD

Pri merjenju vlažnosti plinov in trdnih snovi poznamo več ko štirideset različnih postopkov in metod merjenja [1], [2]. Vsaka od merilnih metod ima določene prednosti, pa tudi pomanjkljivosti oziroma omejitve. Zato je treba pri izbiri higrometra za določen primer uporabe poznati njegove glavne merilno-tehnične, metrološke in funkcionalne značilnosti, kajti le tako se lahko odločimo za najustreznejšega.

Ta prispevek je dopolnitev objave [3], v kateri je podana le analiza merilne negotovosti pri določanju vlažnosti zraka po psihrometrski metodi.

Na podlagi pregleda dosegljive strokovne literature oziroma objavljenih referenčnih razprav je podan pregled stanja razvoja in uporabe sodobnih merilnih zaznaval in metod merjenja vlažnosti. Kakor je razvidno v nadaljevanju, so bili razviti številni postopki in metode za določanje veličin stanja, ki definiranjo vlažnost zraka.

Kljub temu, žal, še vedno ne obstaja higrometer, ki bi izpolnjeval vsa pričakovanja popolnega merilnika vlažnosti, kakor so: izredno velika merilna točnost oziroma majhna merilna negotovost, zadostna občutljivost, najmanjša histereza, ustrezna stabilnost, primerne dinamične značilnosti ter ponovljivost.

Poleg tega so pri izbiri ustreznega merilnika vlažnosti odločujoče tudi preprostost uporabe, vzdrževanja, cena in doba trajanja.

Razvoj nove generacije merilnikov vlažnosti je usmerjen predvsem v mikroprocesorsko zasnovana merilna zaznavala in merilne sisteme z možnostjo sprotnega ugotavljanja stanja vlažnega zraka oziroma prenosa vlage v plinih in trdnih snoveh.

0. INTRODUCTION

More than forty different methods for humidity and moisture measurements are known [1], [2]. Each of those methods has its advantages and disadvantages. In selecting a humidity sensor for a concrete example, their basic technical, metrological and functional properties must be known, for only then is it possible to select the most suitable hygrometer.

This work completes the article [3], which represented an analysis of uncertainty of measurement in psychrometric humidity measurements.

On the basis of the review of available technical literature or the published reference discussions, a review of development and use of contemporary humidity sensors and humidity measurement methods is given. Many methods for the determination of the values which define air humidity have been developed and some of them are presented.

Despite this, a hygrometer has still not been developed, which would fulfil all the conditions for an »ideal« humidity sensor, as: very high accuracy or low uncertainty of measurement, adequate sensibility, minimum hysteresis, appropriate stability, suitable dynamic characteristics and repeatability.

Moreover, in selecting a humidity sensor, the simplicity of use and maintenance, cost and life time are also decisive.

Development of a new generation of humidity sensors is oriented toward microprocessor humidity sensors and measuring systems for simultaneous determination of the condition of humid air and moisture transport in gases and solids.

1. VRSTE HIGROMETROV IN NJIHOVE ZNAČILNOSTI

1.1 Glavne definicije

Navedli bomo glavne definicije nekaterih veličin stanja vlažnega zraka, ki ga obravnavamo kot dvokomponentno zmes vodne pare in suhega zraka.

– *Vlažnost* x pomeni razmerje med maso vodne pare m_{vp} in suhega zraka m_{sz}:

$$x = \frac{m_{vp}}{m_{sz}} \quad (1).$$

– *Relativna vlažnost* φ je razmerje med delnim tlakom vodne pare v zraku p_{vp} in tlakom nasičenosti vodne pare p_{nas} pri temperaturi vlažnega zraka t_{vz}:

$$\varphi = \frac{p_{vp}}{p_{nas}(t_{vz})} \quad (2).$$

– *Temperatura rosišča* t_{ros} pomeni temperaturo, pri kateri se začne kondenzacija vodne pare, ko se vlažni zrak ohlaja pri konstantni vlažnosti in konstantnem tlaku.

Grafična povezava med omenjenimi veličinami je prikazana na sliki 1.

1. HUMIDITY SENSOR TYPES AND THEIR PROPERTIES

1.1 The basic definitions

A number of different ways of expressing air humidity are used. The commonest ones and their basic definitions are:

– *Humidity ratio* x is the ratio of the mass of water vapour m_{vp} to mass of dry air m_{sz}:

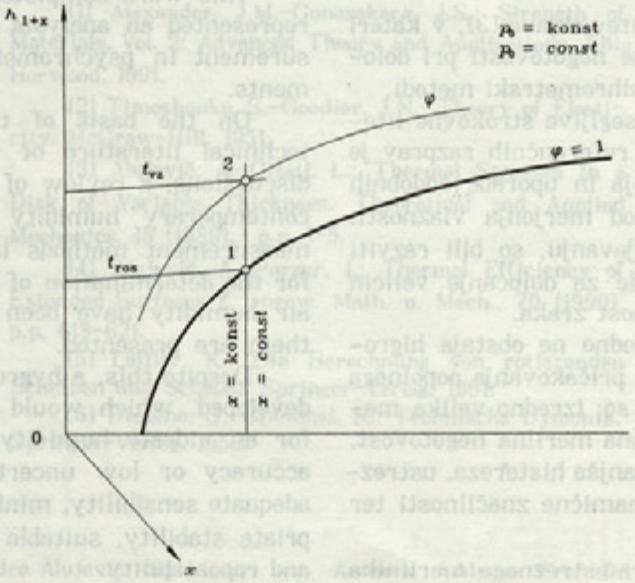
$$x = \frac{m_{vp}}{m_{sz}} \quad (1).$$

– *Relative humidity* φ is the ratio of the partial pressure of water vapour in the air p_{vp} to the saturation vapour pressure p_{nas} at the same air temperature t_{vz}:

$$\varphi = \frac{p_{vp}}{p_{nas}(t_{vz})} \quad (2).$$

– *Dew point temperature* t_{ros} is the temperature to which the humid air must be cooled at constant humidity and constant pressure to induce condensation.

Figure 1 shows their graphical comparison.



Sl. 1. *Diagram h-x za vlažen zrak.*
Fig. 1. *Diagram h-x for humid air.*

Matematične povezave med njimi so take:

Their mathematical dependences are:

$$x = \frac{M_{vp}}{M_{sz}} \frac{\varphi \; p_{nas}(t_{vz})}{p_{vz} - \varphi \; p_{nas}(t_{vz})} \quad (3),$$

$$\varphi = \frac{x\, M_{sz}}{x\, M_{sz} + M_{vp}} \frac{p_{vz}}{p_{nas}(t_{vz})} \quad (4),$$

$$x = \frac{M_{vp}}{M_{sz}} \frac{p_{nas}(t_{ros})}{p_{vz} - p_{nas}(t_{ros})} \quad (4).$$

Pri tem pomenita M_{vp} molsko maso vodne pare in M_{sz} molsko maso suhega zraka. Algoritem za izračun tlaka nasičenosti v odvisnosti od temperature lahko povzamemo po priporočilih v [4].

1.2 **Razdelitev higrometrov**

Kakor smo že omenili v uvodu, obstaja veliko različnih načinov določanja vlažnosti zraka in s tem tudi veliko različnih vrst higrometrov. V tem prispevku bomo opisali predvsem tiste, ki se največ uporabljajo. Razdelili jih bomo po načelu delovanja. Vsaka skupina ima svoje posebnosti in značilnosti. Zato je nekatere njihove metrološke značilnosti (predvsem merilno negotovost) na splošno težko natančno primerjati med seboj.

1.2.1 *Težnostni higrometri*

Temelj delovanja je ločitev vodne pare in suhega zraka. S tehtanjem obeh komponent neposredno določimo vlažnost x (sl. 2).

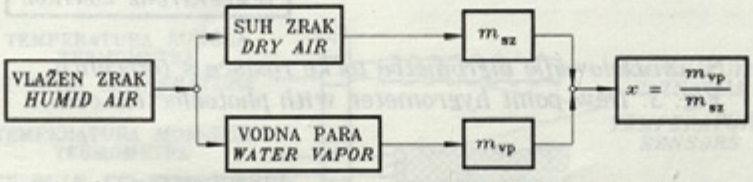
Where M_{vp} is the molecular weight of water vapour and M_{sz} is the molecular weight of dry air. The saturation vapour pressure and its dependence on temperature can be obtained from [4].

1.2 **Classification of hygrometers**

There are many different methods for humidity measurement and, because of that, many different hygrometers, too. In this article we will describe the hygrometers most often used. They will be classified according to the principle of operation. Every group has its characteristics, making it difficult for their metrological properties (especially the uncertainty of measurement) to be compared.

1.2.1 *Gravimetric hygrometers*

Operation of the gravimetric hygrometer is based on separation of the water vapour and the dry air. Humidity ratio x is determined directly by weighting (Fig. 2).



Sl. 2. *Določanje vlažnosti zraka s težnostnim higrometrom.*
Fig. 2. *Gravimetric hygrometer for air humidity measurement.*

Prednosti:
– imajo najboljše metrološke lastnosti,
– primerni so za umerjanje drugih higrometrov,
– imajo možnost računalniškega krmiljenja delovanja in obdelave rezultatov.

Pomanjkljivosti:
– niso primerni za merjenje dinamičnih sprememb vlažnosti,
– pri merjenju moramo vzpostaviti stacionarni tok vlažnega zraka,
– imajo veliko časovno zakasnitev (pri zelo majhnih vlažnostih tudi več deset ur),
– pri uporabi so zahtevni in zapleteni.

Metrološke značilnosti [5], [6]:
– merilno območje: za vlažnosti od 0,19 g/kg do 27 g/kg, kar ustreza območju $-35\,^{\circ}\mathrm{C} < t_{ros} < +30\,^{\circ}\mathrm{C}$;

Advantages:
– they have the best metrological properties,
– they are suitable for the calibration of other hygrometers,
– operation can be automated by computer.

Disadvantages:
– they are not suitable for measurement of dynamic changes in humidity,
– they require a constant humid air flow rate,
– they have a high time constant (several hours at low humidity),
– their use is demanding and complex.

Metrological properties [5], [6]:
– measuring range: from 0.19 g/kg to 27 g/kg for humidity, which corresponds to the range $-35\,^{\circ}\mathrm{C} < t_{ros} < +30\,^{\circ}\mathrm{C}$;

— merilna negotovost: od ±0,13 do ± 0,2% izmerka;

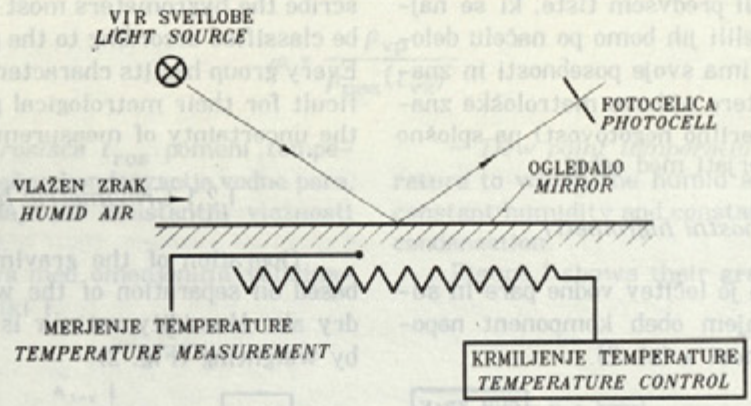
— odzivni čas: razmeroma zelo dolg (tudi več deset ur).

Konstrukcijske značilnosti in področje uporabe:

Kot primarni referenčni higrometer ga uporabljajo v ZDA [5], v Veliki Britaniji [6], na Japonskem [7], na Poljskem [8]. Primeren je samo za umerjanje drugih higrometrov.

1.2.2 *Higrometri točke rosišča*

Temelj delovanja je zniževanje površinske temperature ogledala, na katerem so ob določeni temperaturi (temperaturi rosišča) pojavi rosa oziroma srež. Iz t_{ros} lahko izračunamo vlažnost zraka. Shematični prikaz delovanja je na sliki 3.



Sl. 3. *Delovanje higrometra točke rosišča s fotocelico.*
Fig. 3. *Dew point hygrometer with photoelectric cell.*

Prednosti:

— so natančni — sekundarni standardni higrometri,

— ni jih treba umerjati, razen za najbolj natančne meritve,

— široko merilno območje,

— dobra ponovljivost in zanesljivost,

— dolga časovna stabilnost.

Pomanjkljivosti:

— potrebno je pravilno in periodično čiščenje ogledala,

— niso primerni za merjenje vlažnosti v plinih, ki bi lahko sami kondenzirali,

— potrebno je filtriranje zraka,

— potrebujejo večjo napajalno energijo od drugih higrometrov,

— so razmeroma dragi.

Metrološke značilnosti [9], [10]:

— merilno območje: za vlažnosti od 0,001 g/kg do stanja nasičenosti, od -75 °C do +90 °C temperature rosišča, do tlaka 15 MPa;

— uncertainty of measurement: from ±0.13% to ±0.2 % of result of measurement;

— response time: relatively long (up to several hours).

Design properties and field of application:

The gravimetric hygrometers are currently used as the primary standard in the USA [5], in the Great Britain [6], in Japan [7], in Poland [8]. They are suitable only for the calibration of other hygrometers.

1.2.2 *Dew point hygrometers*

The principle of the dew point hygrometer operation is the following: A mirror in contact with circulating air, the humidity of which is to be measured, is slowly cooled down until dew (or frost) appears on the mirror surface. Humidity ratio is a function of the dew point temperature. The scheme of operation is shown in fig. 3.

Advantages:

— they are accurate - secondary standard,

— they need no calibration except for the most precise measurement,

— their operation range is very wide,

— they have good repeatability and reliability,

— high time stability.

Disadvantages:

— the mirror requires regular and periodic cleaning,

— they are not suitable for use with condensable gases,

— they require a filtered gas stream,

— they need more operational energy than other hygrometers,

— they are relatively expensive.

Metrological properties [9], [10]:

— measuring range: for humidity from 0.001 g/kg to saturation, from -75 °C to +90 °C for dew point temperature, up to 15 MPa pressure;

– merilna negotovost: od ±0,1 °C do ±0,5 °C temperature rosišča; v manjšem merilnem območju (od -20 °C do +25 °C t_{ros}) pa celo ± 0,05 °C;

– odzivni čas: od 1 s do 1 min v odvisnosti od temperature in vlažnosti zraka.

Konstrukcijske značilnosti in področje uporabe:

Ogledalo lahko hladimo na različne načine: termoelektrično (Peltierov učinek), termodinamično (Joule-Thomsonov učinek) [11], s tekočim dušikom [12]. Nastanek rose ali sreža lahko zaznavamo optično s fotocelico [9] ali električno [13]. Uporablja se kot sekundarni standardni higrometer, npr. v Franciji [9], na Japonskem [14].

1.2.3 *Psihrometri*

Načelo delovanja: psihrometer je sestavljen iz dveh temperaturnih zaznaval. Z enim merimo temperaturo zraka (temperatura suhega termometra t_s), z drugim pa tako imenovano temperaturo mokrega termometra t_m. To temperaturno stanje nastane zaradi hlajenja pri izhlapevanju vode s termometra, ki je obdan z vlažno krpico (sl. 4). Iz razlike temperatur in ob poznavanju tlaka okolice p_o ter psihrometrske konstante A lahko z uporabo psihrometrske enačbe določimo delni tlak vodne pare, potem pa še relativno vlažnost zraka:

– uncertainty of measurement: from ±0.1 °C to ±0.5 °C dew point temperature; for a limited measuring range (from -20 °C to +25 °C t_{ros}) even ± 0.05 °C;

– response time: from 1s to 1min, depending on temperature and air humidity.

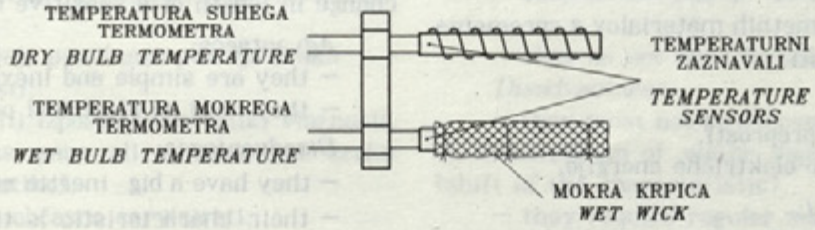
Design properties and field of application:

The mirror can be cooled in different ways: thermoelectrically (Peltier effect), thermodynamically (Joule-Thomson effect) [11], with liquid nitrogen [12]. Dew or frost appearance can be detected: optically with the photocell [9] or electrically [13]. They are used as the secondary standard in France [9], in Japan [14].

1.2.3 *Psychrometers*

The principle of operation: A psychrometer consists of two temperature sensors. One measures the ambient, dry bulb temperature t_s, the other measures the wet bulb temperature t_m. This thermometer is covered by a wick, which is wetted and the resulting evaporation cools it to the wet bulb temperature (Fig. 4). The partial pressure of the water vapour and relative humidity can be calculated from the temperature difference, air pressure p_o and psychrometric constant A by the help of the psychrometric equation:

$$p_{vp}(p_o, t_s, x) = p_{nas}(t_m) - A\, p_o\, (t_s - t_m) \qquad (6).$$



Sl. 4. *Shematičen prikaz temperaturnih merilnih zaznaval psihrometra.*
Fig. 4. *Schematic diagram of psychrometer temperature sensors.*

Prednosti:

– njihovo vzdrževanje je preprosto in poceni,

– imajo zadovoljivo merilno negotovost (posebej pri višjih temperaturah zraka),

– omogočajo neposredno merjenje relativne vlažnosti,

– z njihovo uporabo določimo tudi temperaturo zraka,

– teoretično so dobro opisani,

– imajo dolgo dobo trajanja.

Pomanjkljivosti:

– na krpici se nabira umazanija - potrebna je pravočasna zamenjava,

– na izhlapevanje vode vpliva umazanost krpice,

Advantages:

– their maintenance is simple and cheaps,

– a satisfactory uncertainty of measurement (especially at higher air temperatures),

– measurement of relative humidity is made directly,

– they measure air temperature,

– the theoretical basis is well established,

– they have a long life time.

Disadvantages:

– dirt collects on the wick – it requires timely exchange,

– the rate of evaporation from the wick depends on dirtiness of the wick,

— potrebno je prisilno gibanje zraka (sicer je merilna negotovost večja),

— niso primerni za merjenje vlažnosti v majhnih zaprtih prostorih,

— potrebno je pravilno polnjenje zbiralnika z destilirano vodo.

Metrološke značilnosti [3], [5], [15]:

— merilno območje: za relativne vlažnosti od 20 do 100 odstotkov, od -10 °C do +200 °C temperature zraka (zgornja meja je odvisna od $t_m < 99$ °C);

— merilna negotovost: pri običajnih izvedbah je od ±1 % do ±3 % relativne vlažnosti; s posebno konstrukcijsko izvedbo so dosegli celo ±0,25 odstotkov relativne vlažnosti [5];

— odzivni čas: približno od 1 min do 5 min.

Konstrukcijske značilnosti in področje uporabe:

Temperature lahko merimo z živosrebrnimi termometri, s termoelementi [2], [16] ali z uporovnimi zaznavali [17]. V ZDA ga uporabljajo kot sekundarni standardni higrometer [5], sicer pa se uporablja v meteorologiji, industriji, klimatizaciji [2].

1.2.4 *Mehanski higrometri*

Temelj delovanja je sprememba dolžine nekaterih naravnih ali umetnih materialov s spremembo relativne vlažnosti.

Prednosti:

— so poceni in preprosti,

— ne potrebujejo električne energije,

Pomanjkljivosti:

— imajo veliko vztrajnost in veliko histerezo,

— njihove značilnosti se spreminjajo s časom,

— imajo nelinearni izhod,

— imajo veliko merilno negotovost.

Metrološke značilnosti [2], [10]:

— merilno območje: od 0 do 100 odstotkov relativne vlažnosti, od -10 °C do +100 °C temperature zraka;

— merilna negotovost: ±5% relativne vlažnosti;

— odzivni čas: od 5 min do 20 min.

Konstrukcijske značilnosti in področje uporabe:

Izdelani so lahko iz človeških las [18], sintetičnih vlaken [10], bambusovega papirja [19]. Uporabljajo se za manj natančne meritve, npr. v meteorologiji, tekstilni industriji.

— they require forced gas stream (otherwise the uncertainty of measurement is greater),

— they are not suitable for humidity measurements in small, closed chambers,

— the reservoir requires regular filling with distilled water.

Metrological properties [3], [5], [15];

— measuring range: from 20 % to 100 % for relative humidity, from -10 °C to +200 °C for air temperature (upper limit depends on $t_m < 99$ °C);

— uncertainty of measurement: normally from ±1 % to ±3 % of the relative humidity, in special cases even ±0.25 % of the relative humidity [5];

— response time: approximately from 1 min to 5 min.

Design properties and field of application:

Temperatures can be measured by mercury-in glass thermometers, by thermocouples [2], [16] or by platinum resistance sensors [17]. They are the secondary standard hygrometers in the USA [5]. The psychrometers are widley used in meteorology, in industry, in air-conditioning engineering [2].

1.2.4 *Mechanical hygrometers*

Mechanical humidity sensors depend on the change in length of a sensitive material.

Advantages:

— they are simple and inexpensive,

— they need no electrical power.

Disadvantages:

— they have a big inertia and hysteresis,

— their characteristic is time dependent,

— they give a nonlinear output,

— they have a considerable uncertainty of measurement.

Metrological properties [2], [10]:

— measuring range: from 0 % to 100 % for relative humidity, from -10 °C to +100 °C for air temperature;

— uncertainty of measurement: ±5 % relative humidity;

— response time: from 5 min to 20 min.

Design properties and field of application:

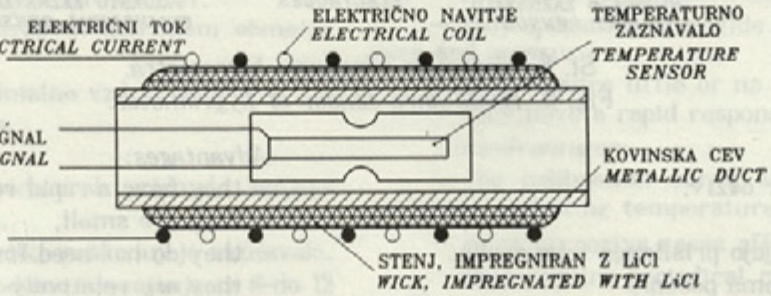
They can be made of human hair [18], synthetic thread [10], bamboo paper [19]. They are suitable for non-exacting applications such as humidity measurements in meteorology and in textile manufacture.

1.2.5 *Higrometri točke rosišča z litijevim kloridom (Dunmorejevi higrometri)*

Načelo delovanja: nad nasičeno raztopino soli je pri isti temperaturi delni tlak vodne pare nižji od tlaka nasičenosti nad površino čiste vode. Zato pride do vsrkavanja vodne pare v nasičeno raztopino soli, ki se ji zaradi tega spremeni električna upornost. Če raztopino segrevamo, se absorpcija zmanjšuje in pri določeni temperaturi ustavi (prenehanje spreminjanja električne upornosti raztopine). Iz te temperature lahko ob poznavanju temperature zraka določimo temperaturo rosišča. Higrometer je shematično prikazan na sliki 5.

1.2.5 *Lithium chloride dew point hygrometers (Dunmore – type hygrometers)*

The principle of operation: At the same temperature, the partial pressure of water vapour over the saturated salt solution is lower than over pure liquid water. When unsaturated humid air is in contact with the surface of the solution, water vapour is absorbed in saturated salt solution, which changes its electrical resistance. During heating the saturated salt solution, absorption becomes lower and lower and at certain temperature stops (electrical resistance becomes constant). Dew point temperature can be deduced from drying and ambient temperature. The hygrometer is shown schematically in fig. 5.



Sl. 5. *Higrometer točke rosišča z litijevim kloridom.*
Fig. 5. *Lithium chloride dew point hygrometer.*

Prednosti:
– namesto hlajenja, kakor pri higrometrih točke rosišča, se uporablja gretje,
– so majhni, preprosti, robustni,
– ne dodajajo vlage zraku niti je ne odvzemajo iz zraka,
– ne potrebujejo prisilnega gibanja zraka.

Pomanjkljivosti:
– ne smejo biti izpostavljeni veliki vlažnosti, kondenzaciji vodne pare ali umazanemu zraku (premik karakteristike),
– treba jih je občasno servisirati,
– uporabni so samo za določene pline - nevarnost kemične reakcije,
– niso primerni za merjenje majhnih relativnih vlažnosti,
– imajo počasen odziv pri nizkih temperaturah.

Metrološke značilnosti [1], [2], [10]:
– merilno območje: od relativne vlažnosti 20% do 100%, od -20 °C do + 100 °C temperature zraka, do tlaka 1 MPa;
– merilna negotovost: od ±0,5 °C do ±1 °C temperature rosišča;
– odzivni čas: okrog 3 min.

Konstrukcijske značilnosti in področje uporabe:
Kot nasičena raztopina je najprimernejša vodna raztopina litijevega klorida $LiCl \cdot H_2O$ [20]. Uporablja se v klimatizaciji, procesih sušenja itd.

Advantages:
– instead of cooling (dew point hygrometer), they use heating,
– they are small, simple and robust,
– they do not add or take humidity from the air,
– they do not need forced air flow.

Disadvantages:
– they must not be exposed to high humidity, to condensation of water vapour or to dirty air (shift of the characteristic),
– they require regular servicing,
– they are suitable only for certain gases - danger of chemical reaction,
– they cannot measure very low humidity,
– they have long response time at low temperatures.

Metrological properties [1], [2], [10]:
– measuring range: from 20% to 100% for relative humidity, from -20 °C to +100 °C for air temperature, up to 1 MPa pressure;
– uncertainty of measurement: from ± 0.5 °C to ±1 °C of dew point temperature;
– response time: approximately 3 min.

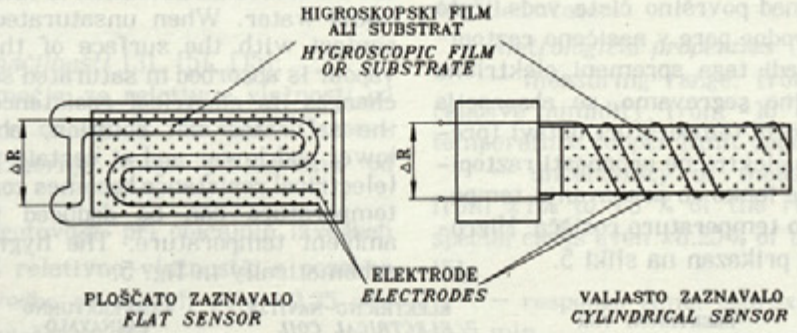
Design properties and field of application:
The most suitable saturated salt solution is the water solution of lithium chloride $LiCL \cdot H_2O$ [20]. It is used in air-conditioning, in drier control etc.

1.2.6 *Električno sorpcijski higrometri*

Temelj delovanja je spreminjanje električne upornosti higroskopnega materiala v odvisnosti od spreminjanja relativne vlažnosti (sl. 6).

1.2.6. *Electrical Sorption Hygrometers*

The principle of operation: The electrical resistance of a hygroscopic material is a function of relative humidity of the ambient air (Fig. 6).



Sl. 6. *Uporovno zaznavalo higrometra.*
Fig. 6. *Resistance sensor of hygrometer.*

Prednosti:
– imajo hiter odziv,
– so majhni,
– ne potrebujejo prisilnega toka zraka,
– so razmeroma poceni.

Pomanjkljivosti:
– imajo razmeroma veliko histerezo,
– sčasoma se njihova karakteristika spreminja (rok uporabe do štiri leta),
– karakteristika se jim spremeni ob stiku z nasičenim zrakom ali vodo.

Metrološke značilnosti [21], [22]:
– merilno območje: od 30 % do 90 % relativne vlažnosti od -30 °C do +120 °C temperature zraka;
– merilna negotovost: od ±2 % do ± 4 % relativne vlažnosti;
– odzivni čas: od 1 s do 15 s.

Konstrukcijske značilnosti in področje uporabe:

Zaznavala so lahko iz litijevega klorida [1], polimera [21], kalijevega metafosfata [22]. Uporablja se za merjenje vlažnosti v majhnih zaprtih prostorih, npr. pri preučevanju mikroklimatskih razmer oblečenega človeka, za manj zahtevna merjenja vlažnosti v industriji ipd.

1.2.7 *Higrometri na podlagi spremembe električne impendance*

Temelj delovanja je sprememba električne upornosti in kapacitivnosti materiala s spremembo relativne vlažnosti zraka. Shematični prikaz higrometra je na sliki 7.

Prednosti:
– so razmeroma stabilni,
– imajo majhno histerezo,
– njihovi temperaturni koeficienti so majhni,
– so zanesljivi,

Advantages:
– they have a rapid response,
– they are small,
– they do not need forced air flow,
– they are relatively inexpensive.

Disadvantages:
– their hysteresis is relatively high,
– their characteristic changes with time (life-time aproximately four years),
– the calibrations show drifts at accidental contact with saturated air or water immersion.

Metrological properties [21], [22]:
– measuring range: from 30 % to 90 % for relative humidity, from -30 °C to +120 °C for air temperature;
– uncertainty of measurement: from ±2 % to ±4 % of relative humidity;
– response time: from 1s to 15s.

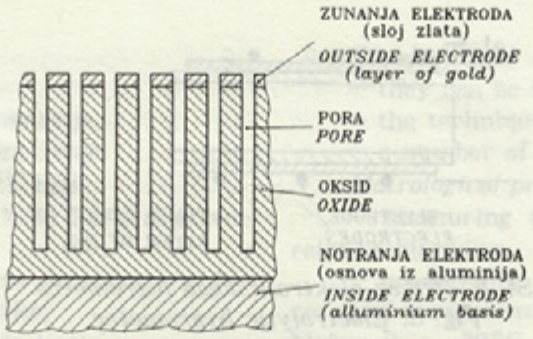
Design properties and field of application:

Sensors can be made of lithium chloride [1], polymer [21] or potassium metaphosphate [22]. They are used for humidity measurement in a small closed space such as in the study of microclimatic conditions in human clothing; and for non-exacting humidity measurements in industry.

1.2.7 *Electrical impedance hygrometers*

The principle of operation: A change in electrical resistance and capacitance occurs with changes in relative humidity. This is schematically shown in fig. 7.

Advantages:
– they are relatively stable,
– they have low hysteresis,
– they have low temperature coefficients,
– they are reliable,



Sl. 7. *Prikaz sestave higrometra iz aluminijevega oksida.*
Fig. 7. *Structure of aluminium oxide hygrometer.*

– niso odvisni od hitrosti zraka,
– so izredno občutljivi za vlažnost,
– uporabni so v širokem merilnem območju temperatur in tlakov,
– potrebujejo minimalno vzdrževanje,
– se hitro odzivajo.

Pomanjkljivosti:
– pri višjih temperaturah pride do večjega premika karakteristike,
– korozivni plini lahko poškodujejo zaznavalo,
– potrebno je periodično umerjanje za 6 do 12 mesecev,
–imajo omejeno dobo trajanja.

Metrološke značilnosti [2]:
– merilno območje: od 0% do 100% relativne vlažnosti, od -110 °C do +100 °C temperture rosišča, od tlaka 0,7 do 34 MPa;
– merilna negotovost: od ±1% do ±2% relativne vlažnosti;
– odzivni čas: od 1 s do 2 min.

Konstrukcijske značilnosti in področje uporabe:

Za zaznavalo uporabljajo različne materiale: najpogosteje aluminijev oksid [1], [23], ki ga že zamenjuje silicij [2], organski polimeri [2], [24], ogljik [1], keramika [2], kobaltov oksid [10]. Uporabljajo se za merjenje vlažnosti v klimatizacijski tehniki, sušilnih procesih, industriji.

1.2.8 *Elektrolitski higrometri*

Načelo delovanja: med dvema elektrodama je nameščen fosforjev pentoksid P_2O_5 (sl. 8), ki z vsrkano vodno paro dela fosforjevo kislino, le-ta pa se z elektrolizo razgradi v kisik in vodik. Tok, ki ob elektrolizi teče skozi zaznavalo, je merilo za vlažnost zraka.

Prednosti:
– primerni so za majhne vlažnosti,
– primerni so za nepretrgane meritve (vsa absorbirana vodna para se z elektrolizo takoj razgradi - sprotno sušenje P_2O_5),
– nimajo histereze,
– ne potrebujejo umerjanja.

– they are flow independent,
– they have high sensitivity for humidity,
– they operate over a wide range of temperature and pressure,
– they require little or no maintenance,
– they have a rapid response.

Disandvantages:
– the calibration curve shows slow drifts at higher operating temperatures,
– some corrosive gases affect the probe,
– they require periodical calibration every 6 to 12 months,
– they have a limited life time.

Metrological properties [2]:
– measuring range: from 0 % to 100 % for relative humidity, from -110 °C to +100 °C for dew point temperature, from pressure 0.7 to 34 MPa;
– uncertainty of measurement: from ±1% to ±2 % of relative humidity;
– response time: from 1s to 2min.

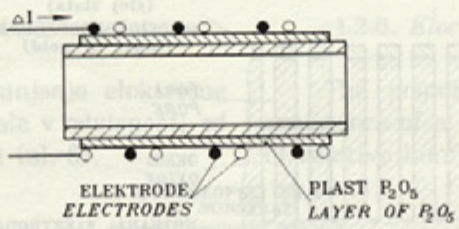
Design properties and field of application:

This hygrometer can be made of different materials: the one most often used is aluminium oxide [1], [23] - which is slowly being replaced by silicon [2] - organic polymers [2], [24], carbon [1], ceramic [2], cobalt oxide [10]. They are used for humidity measurements in air-conditioning engineering, in drier processes, in industry.

1.2.8 *Electrolytic hygrometers*

The principle of operation: Between two electrodes, phosphorus pentoxide P_2O_5 (Fig. 8), which forms phosphoric acid on absorbing water vapour, is placed. Electrolysis takes place and oxygen and hydrogen are evolved from the electrodes. The resultant electric current depends on ambient air humidity.

Advantages:
– they have low limits of detection,
– they are suitable for continuous measurements (the absorbed water vapor is decomposed by electrolysis - simultaneous drying of P_2O_5),
– they have no hysteresis,
– they do not require calibration.



Sl. 8. *Prikaz elektrolitskega higrometra.*
Fig. 8. *Electrolytic hygrometer.*

Pomanjkljivosti:
– potrebujejo konstanten tok zelo čistega zraka,
– ker je P_2O_5 zelo reaktiven, je omejeno področje plinov, v katerem lahko merimo vlažnost,
– potrebna je pravilna obnovitev celice,
– ob potopitvi v vodo je celica uničena.

Metrološke značilnosti [2], [25]:
– merilno območje: za vlažnosti od 0,001 g/kg do 3 g/kg, do tlaka 40 MPa;
– merilna negotovost: od ±2% do ±5% izmerka.
– Odzivni čas: od 1 s do nekaj min.

Konstrukcijske značilnosti in področje uporabe:
Namenjeni so za merjenje majhnih vlažnosti v kemični industriji, za laboratorijsko merjenje itn.

1.2.9 *Spektroskopski higrometri*

Temelj delovanja je vsrkavanje infrardeče svetlobe v zraku, ki je odvisna od vlažnosti zraka (sl. 9).

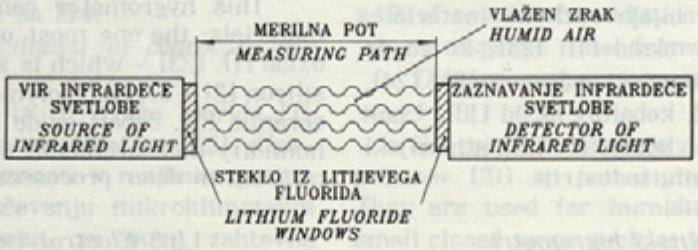
Disadvantages:
– they require a constant pure air flow rate,
– the P_2O_5 is highly reactive, which limits the range of gases with which it can be used,
– the cell requires regular regeneration,
– the cell is destroyed by accidental water immersion.

Metrological properties [2], [25]:
– measuring range: from 0.001 g/kg to 3 g/kg for humidity ratio, up to 40 MPa pressure;
– uncertainty of measurement: from ±2% to ±5% of the result of measurement;
– response time: from 1s to few min.

Design properties and field of application:
They are suitable for low humidity measurements in chemical industry, for laboratory measurements etc.

1.2.9 *Spectroscopic hygrometers*

The principle of operation: Certain wavelengths of infrared radiation are absorbed selectively by water vapour (Fig. 9).



Sl. 9. *Shema infrardečega higrometra.*
Fig. 9. *Scheme of infrared hygrometer.*

Prednosti:
– imajo preprosto konstrukcijo,
– so lahki, majhni,
– občutljivi so tudi na majhno količino vodne pare v zraku,
– merimo lahko pri poljubni temperaturi,
– uporabljamo jih v širokem območju tlakov,
– omogočajo merjenje profila vlažnosti,
– omogočajo merjenje v zelo korozivnih plinih,
– primerni so za merjenje v zaprtih prostorih,
– imajo hiter časovni odziv.

Advantages:
– their design is simple,
– they are light and small,
– they have low limits of detection,
– they can measure at any temperature,
– they have a wide pressure working range,
– they can measure the humidity profile,
– they can be used with highly corrosive gases,
– they are suitable for measurements in closed chambers,
– they have a rapid response.

Pomanjkljivosti:
– so razmeroma dragi,
– potrebno je občasno umerjanje,
- več plinov lahko moti merjenje.
Metrološke značilnosti [2], [13]:
– merilno območje: od 0 % do 100 % relativne vlažnosti;
– merilna negotovost: za temperature ledišča nad -30 °C je ±2% izmerka;
– odzivni čas: od 0,001 s do 1 min.
Konstrukcijske značilnosti in področje uporabe:
Za natančno merjenje je treba zagotoviti konstanten vir infrardeče svetlobe. Uporabljajo se v meteorologiji, merilnih laboratorijih, tobačni in papirni industriji ipd.

1.2.10 *Drugi higrometri*

Za merjenje vlažnosti zraka se uporablja še več različnih vrst higrometrov. Naj jih nekaj naštejemo:
– pnevmatični mostovni higrometer [5],
– piezoelektrični sorpcijski higrometer [2],
– mikrovalovni higrometer [5].
Vlažnost zraka lahko določimo tudi zaradi:
– merjenja toplotne prevodnosti zraka [10],
– merjenja toplote, ki se sprošča ob vsrkanju vodne pare v ustrezno trdno telo [10],
– spremembe barve soli s spremembo relativne vlažnosti [10],
– merjenja hitrosti zvoka v zraku [26],
– merjenja kondenzacijske toplote [10],
– zaznavanja vlažnosti s kemično reakcijo [10] itn.

1.3 **Merilna točnost higrometrov**

V literaturi so merilne negotovosti higrometrov podane na različne načine. Ker jih glede na razpoložljive podatke ni mogoče natančno preračunati na skupni imenovalec, smo na sliki 10 prikazali njihove približne vrednosti. Kljub temu pa lahko tako dokaj dobro ocenimo področje uporabe posameznih vrst higrometrov. Merilne negotovosti smo prikazali v odstotkih izmerka glede na temperaturo rosišča (ledišča), ki jo lahko za določeno temperaturo zraka preračunamo v relativno vlažnost (npr. pri temperaturi zraka 100 °C in temperaturi rosišča 50 °C je relativna vlažnost 55 %).
Za višje temperature zraka (t_{zr} > 100 °C) so uporabni naslednji higrometri: higrometri točke rosišča, psihometri, električni sorpcijski higrometri, spektroskopski higrometri.

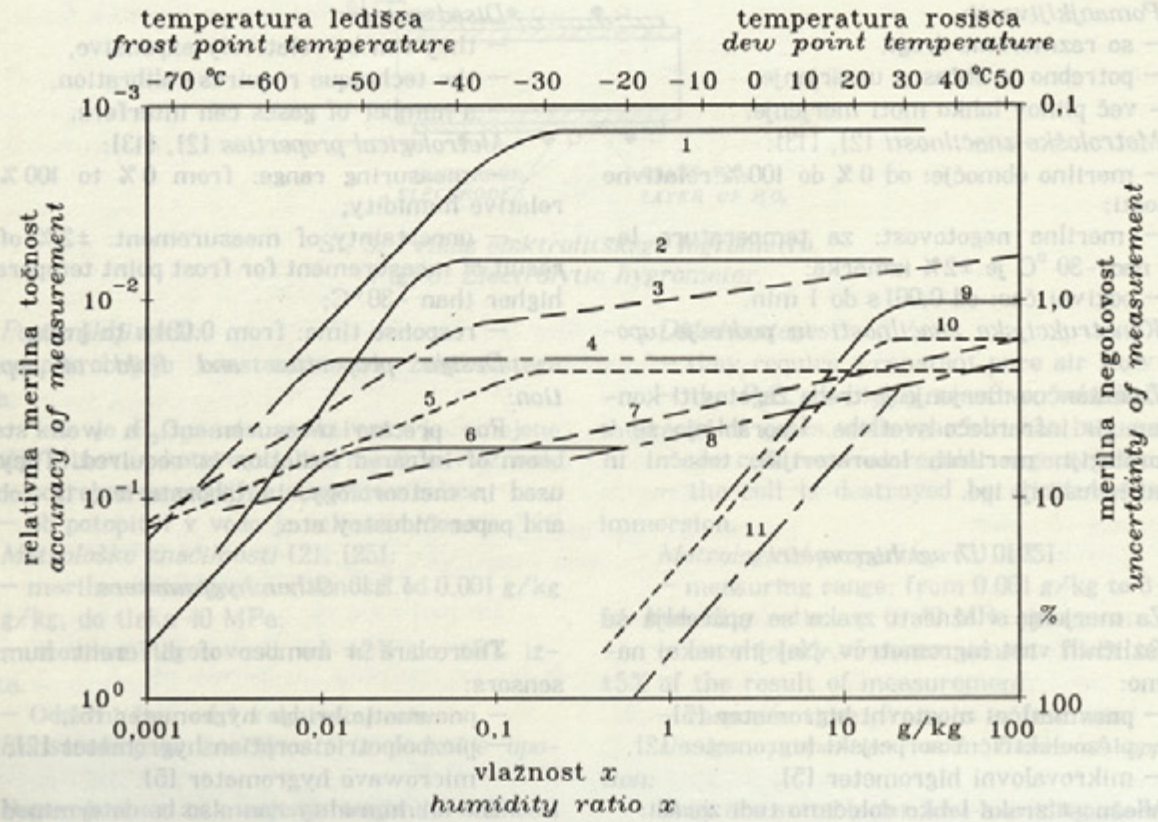
Disadvantage:
– they can be relatively expensive,
– the technique requires calibration,
– a number of gases can interfere.
Metrological properties [2], [13]:
– measuring range: from 0 % to 100 % for relative humidity;
– uncertainty of measurement: ±2 % of the result of measurement for frost point temperature higher than -30 °C;
– response time: from 0.001 s to 1 min.
Design properties and field of application:
For precise measurement, a well stabled beam of infrared radiation is required. They are used in meteorology, in laboratories, in tobacco and paper industry etc.

1.2.10 *Other hygrometers*

There are a number of different humidity sensors:
– pneumatic bridge hygrometer [5],
– piezoelectric sorption hygrometer [2],
– microwave hygrometer [5].
The air humidity can also be determined by:
– measuring thermal conductivity of air [10],
– measuring the heat of adsorption [10],
– color change of salts with changes in relative humidity [10],
– measuring the speed of sound in air [26],
– measuring the heat of condensation [10],
– detecting humidity by a chemical reaction [10] etc.

1.3 **Accuracy of the humidity measurements**

In the literature, the accuracy of the humidity measurements is presented in different ways. Without knowing all the necessary data, they cannot be adequately compared. Because of that, fig. 10 shows their approximate values. In spite of that, this way is suitable for determination of field of application for different hygrometers. The uncertainty of measurement is presented in percents of result of measurement with regard to dew (frost) point temperature. Relative humidity can be determined from dew (frost) point and air temperature (e.g. at air temperature 100 °C and dew point temperature 50 °C, relative humidity is 55 %).
The following hygrometers are suitable for high temperature (t_{zr} > 100 °C) humidity measurements: dew point hygrometers, psychrometers, electrical sorption hygrometers, spectroscopic hygrometers.



Sl. 10. *Praktično dosegljive merilne točnosti različnih higrometrov.*

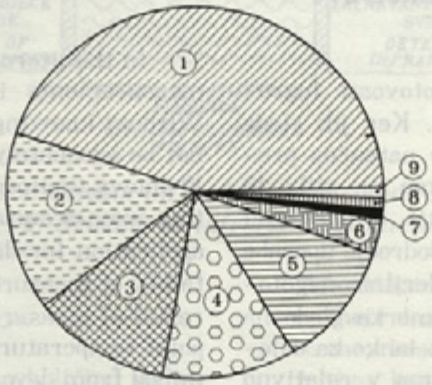
1 – težnostni, 2 – pnevmatični mostovni, 3 – temperature rosišča, 4 – elektrolitični, 5 – iz aluminijevega oksida, 6 – piezokristal, 7 – spektroskopski, 8 – iz litijevega klorida, 9 – psihrometer, 10 – uporovni, 11 – mehanski

Fig. 10. *Practically achievable accuracy of measurements for different hygrometers.*

1 – gravimetric, 2 – pneumatic bridge, 3 – dew point temperature, 4 – electrolytic, 5 – aluminium oxide, 6 – piezocrystall, 7 –spectroscopic, 8 – lithium chloride, 9 – psychrometer, 10 – resistance, 11 – mechanical

Na sliki 11 podajamo še pregled higrometrov, ki so jih leta 1980 najpogosteje uporabljali v Veliki Britaniji [27].

Fig. 11 shows a review of hygrometers used in the Great Britain in 1980 [27].



Sl. 11. *Pregled higrometrov v praktični rabi.*

1 – mehanski (45 %), 2 – psihrometri (15 %), 3 – Al_2O_3 (12 %), 4 – elektrolitski (11 %), 5 – uporovni (11 %), 6 – LiCl (3 %), 7 – spektroskopski (1 %), 8 – temperatura rosišča (1 %), 9 – drugi (1 %)

Fig. 11. *Distribution of hygrometer types used in practice.*

1 – mechanical (45 %), 2 – psyhrometers (15 %), 3 – Al_2O_3 (12 %), 4 – electrolytic (11 %), 5 – resistance (11 %), 6 – LiCl (3 %), 7 – spectroscopic (1 %), 8 – dew point temperature (1 %), 9 – other (1 %)

Zanimivo je, da so v osemdesetih letih še vedno največ uporabljali (kljub številnim pomanjkljivostim glede histereze, merilne negotovosti, vztrajnosti) mehanske higrometre. Sedaj se je to razmerje že precej nagnilo na stran električnih higrometrov (kapacitivni, uporovni), ki jih bodo tudi v prihodnosti največ uporabljali.

Vse prej omenjene higrometre lahko uporabljamo tudi za merjenje vlažnosti v drugih plinih, in ne samo v zraku. Pri tem je treba upoštevati, da nekateri plini kemično reagirajo z določenimi higrometri in da imajo nekateri higrometri drugačno odzivno karakteristiko.

Prav tako kakor za merjenje vlažnosti v plinih obstaja tudi za merjenje vlažnosti v trdnih snoveh več različnih zaznaval, katerih delovanje temelji na [13], [28]:

– spremembi električne prevodnosti materiala s spremembo količine vlage,
– spremembi električne kapacitivnosti materiala s spremembo količine vlage,
– vsrkavanju mikrovalovnega sevanja,
– odboju infrardeče svetlobe,
– zaviranju nevtronov itn.

2. SMERI RAZVOJA HIGROMETROV

Upoštevajoč smeri razvoja sodobnih higrometrov je mogoče ugotoviti naslednje:

– merilna zaznavala za vlažnost postajajo vse bolj »inteligentna«,
– v večino sodobnih zaznaval je vključen mikroprocesor,
– v uporabi bo vedno več merilnih sistemov s frekvenčnim izhodnim signalom,
– vedno bolj se bo uporabljal prenos signalov po sistemu vstavljenega programa z uporabo optičnih vodnikov.
– merilna negotovost komercialno dostopnih merilnih sistemov za merjenje relativne vlažnosti zraka je manjša od ±1 %.

Metode, pri katerih merimo vlažnost s posrednim načinom, bodo počasi izgubljale svoj pomen, posebej pri merjenju vlažnosti zraka v ceveh, kanalih, zbiralnikih. Z razvojem mikroprocesorske tehnologije in odkritjem novih materialov zaznavala postajajo vse manjša in cenejša. Pri tem imajo velike razvojne možnosti spektroskopski in mikrovalovni higrometri. Vedno bolj uveljavljajo tudi higrometre, ki imajo frekvenčni izhod – s tem sta izboljšani zanesljivost in natančnost merjenja. Tudi pri merjenju vlažnosti bo pri prenosu ultravijolične in infrardeče svetlobe prišlo do vedno večje uporabe optičnih vodnikov. Ta zaznavala bodo imela na koncu optičnih vodnikov material, ki bo reagiral z vodno paro; s tem se bo spreminjal njegov

It is interesting that mechanical hygrometers (despite many disadvantages such as hysteresis, uncertainty of measurements, inertia) were used the most at that time. Now they are steadily being replaced by electrical hygrometers (capacity, resistance), which will be prefered in the future.

All the above mentioned hygrometers can be used for humidity measurements in other gases, not just in air. It must be considered that some gases can react chemically with certain hygrometers and that some hygrometers can have different response characteristics.

As in humidity measurements in gases, there are many different sensors for measurement in solids and liquids. Their principle of operation is based on [13], [28]:

– a change in electrical conductance of material with changes in moisture,
– a change in electrical capacitance of material with changes in moisture,
– absorption of microwave radiation,
– reflection of infrared light,
– obstruction of neutrons etc.

2. FUTURE DEVELOPMENT OF HYGROMETERS

Taking into account the current tendencies of development of hygrometers, it can be concluded that:

– humidity sensors are becoming more and more »intelligent«,
– most up-to-date sensors have a built-in microprocessor,
– in the future, more and more measurement systems with frequency output signals will be used,
– in the future, fibre-optics based sensors with in-line transmitted signals will be used,
– uncertainty of measurement of commercially available humidity sensors is less than ±1 %.

The use of the off-line humidity measurements will slowly decrease, particularly in humidity measurements in ducts, pipe lines, tanks. With microprocessor development and new materials, sensors are becoming smaller and low-priced. Spectroscopic and microwave hygrometers have a bright future in this area. Hygrometers with frequency related output signals - improvement in reliability and accuracy of measurement - will be used increasingly. With ultraviolet and infrared light transmission in humidity measurements, fibre-optics will be used more and more often. At one end of an optical fibre will be a material, which reacts with water vapour. Because of that, it will change its reflective index, changing the absorption of infrared light. A device

lomni količnik, kar se bo kazalo v vsrkanju infrardeče svetlobe. Takšno zaznavalo bo preprosto in robustno, z njim bomo lahko merili vlažnost v razmerah, kjer je bilo to do sedaj zelo drago, nedostopno in nevarno (npr. eksplozijske komore).

3. SKLEP

V tem prispevku smo podali pregled stanja, kar zadeva razvoj in uporabo merilne opreme za merjenje vlažnosti zraka.

Ugotovimo lahko, da je v vsakdanji industrijski uporabi še veliko mehanskih higrometrov in psihrometrov (sl. 11). Predvsem zaradi preproste zgradbe, nizke cene in merilne točnosti, zadovoljive za industrijsko uporabo, bodo imeli še nekaj časa pomembno vlogo. Glede merilne dinamike pa je njihov odgovor, žal, preskromen.

Razvoj novih proizvodnih tehnologij v mikroelektroniki prinaša tudi kar zadeva razvoj merilnih sistemov za merjenja vlažnosti nove rešitve.

Merilno-tehnične značilnosti sodobnih merilnih zaznaval in sistemov se pomembneje izboljšujejo predvsem z vidika merilne točnosti, ponovljivosti, odzivnosti, stabilnosti, občutljivosti in lezenja.

using this technology will be robust and simple and will probably allow the measurement of humidity in conditions where measurement is now extremely expensive, not feasible or dangerous (e.g. explosion chambers).

3. CONCLUSION

A review of development of humidity measurements systems and their use is presented in this paper.

It can be concluded that mechanical hygrometers and psychrometers are often used in everyday practice in industry (Fig. 11). They have a simple structure, a low price and satisfactory uncertainty of measurements. Because of that they will also often be used in the future. But their dynamic characteristics are, unfortunately moderate.

The rapid development in microelectronic technology has made it possible to manufacture new humidity measurement sensors.

The metrological properties of contemporary humidity sensors and systems have been significantly improved in terms of uncertainty, accuracy and repeatability of measurements, the response, stability, sensibility and drift.

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