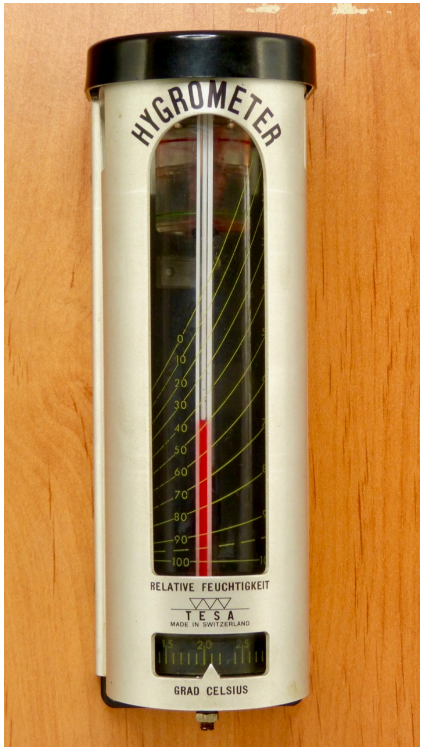
The Diffusion Hygrometer: A late invention of H. Greinacher

TESA [1]
(about 1960)



Rüeger [2]
(about 1960)

Jean-François LOUDE
jean-francois.loude@epfl.ch

UNIL | Université de Lausanne

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SPS - APS, Geneva, August 25, 2017 (rev.)

Abstract

The Diffusion Hygrometer: A late invention of H. Greinacher

The diffusion of gases, dry and moist, had been studied in 1874 by Louis Dufour, who observed a pressure difference across a porous wall separating moist air and a vessel containing either water or a desiccant. 70 years later, Heinrich Greinacher (1880–1974) claimed to have built the first Diffusion Hygrometer, proposed a theory and got a patent for it. Two different models were produced by firms of Lausanne, TESA and Rüeger. Eventually, they were a commercial failure. We found one exemplar of each maker in the collections of the Physics Museum at UNIL and have tested them. A comparison of the performances with the then currently available hygrometers will be made.

Physics Museum Web site:
https://museephysique.epfl.ch

Virtual visit (pdf):
https://documents.epfl.ch/users/l/lo/loude/www/Visite_MPL.pdf

I. HYGROMETRY JUST AFTER WWII [3]

Air moisture content is one of the 3 fundamental parameters describing the state of atmosphere:
— atmospheric pressure p_{atm},
— temperature T,
— water vapor partial pressure p_w, or the relative humidity RH

Satisfactory, easy to use instruments were available for the measurement of p_{atm} (*barometers*) and T (*thermometers*).

For the measurement of the moisture content of air, either outdoors or indoors, 3 types of instruments were in common use, none fully satisfactory:

— the *hair hygrometer*,

— several types of *psychrometers*,

— several types of *condensation (dew point) hygrometers*.

I.1. HAIR HYGROMETER

Before 1783: *Hygroscopes* based on the dimensional change of *hygroscopic* substances had already been built
Not calibrated!

1783: Horace-Bénédict de Saussure (1740-1799), at Geneva, publishes his « *Essais sur l'hygrométrie* » [4]

— Human hair is the best hygroscopic material for hygrometers

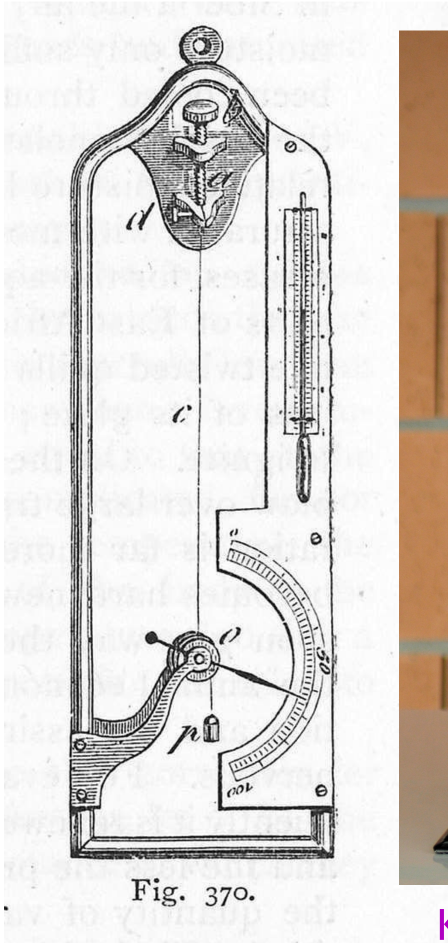
— Has beautiful instruments built by Jacques Paul
(see them at the *Musée d'histoire des sciences* of Geneva)

He makes hygrometry a quantitative science, by:

— doing extensive experiments on the vapor pressure of water at various temperatures

— publishing tables of water contents in grains per cubic foot at a number of temperatures and for various readings of his hygrometer [cf. Middleton, 1969]

EXAMPLES of HAIR HYGROMETERS:

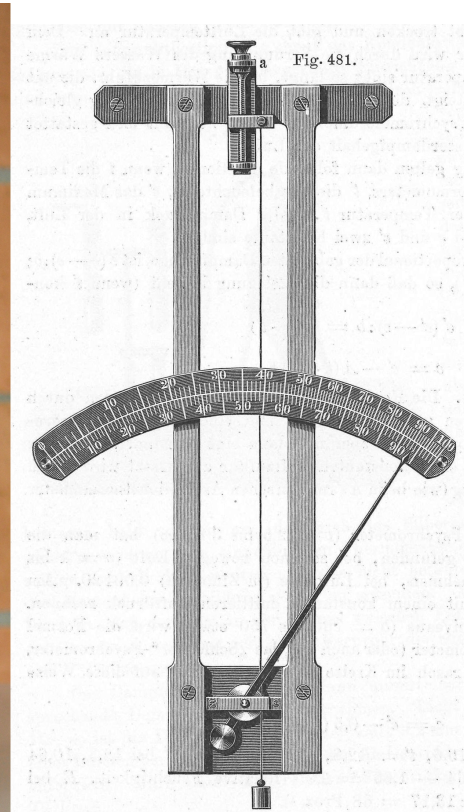


Hair Hygrometer

A. GANOT : Elementary Treatise on Physics experimental and applied 14th ed., 1893, P. 381, § 39

De Saussure-like (> 1783)

Koppe (1880-1920) [5]



Haarhygrometer von Saussure

MÜLLER-POUILLETs Physik (10. Aufl., 1907), Bd. III, S. 811, S. 248

Haenni & Cie AG (~ 1950) [6]

Simple, cheap, noiselesss, direct readout of *RH* (%), no attention needed, also recording models

Main drawback: low accuracy

Still manufactured today, still sold, still used!

I. 2. PSYCHROMETERS [7]

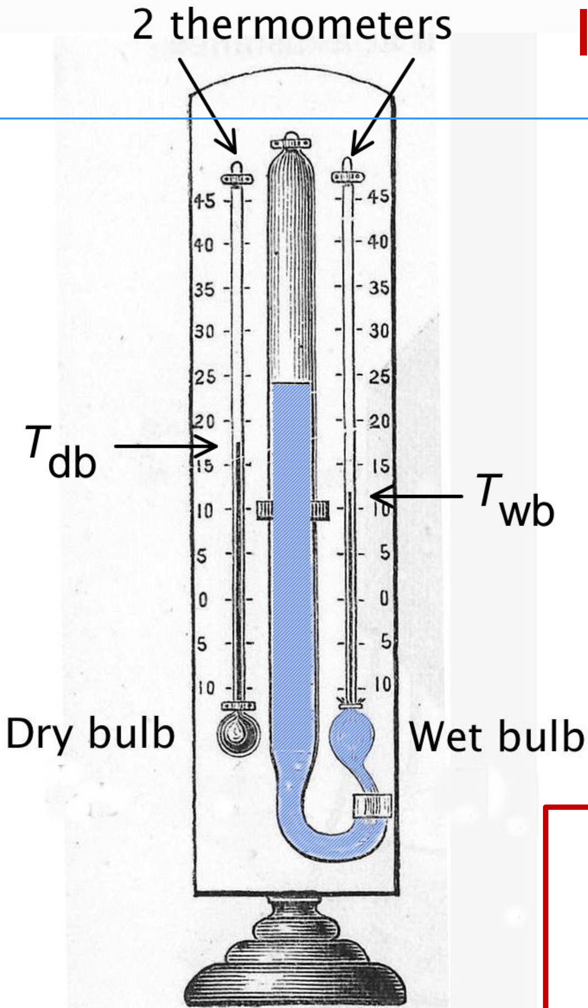
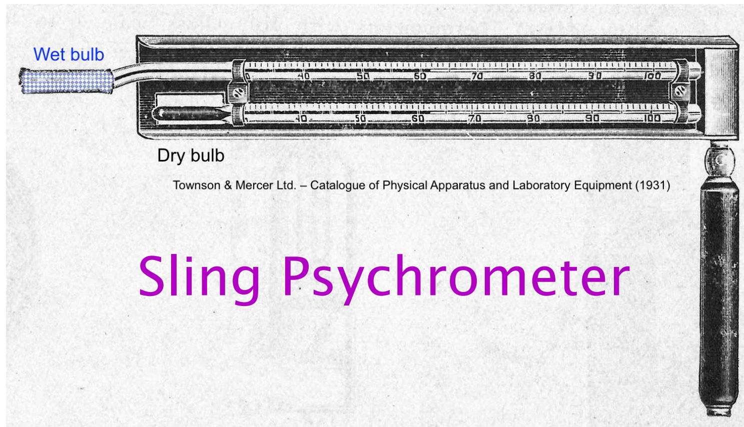


Fig. 369.

August Psychrometer

A. GANOT : Elementary Treatise
on Physics experimental and applied
14th ed., 1893

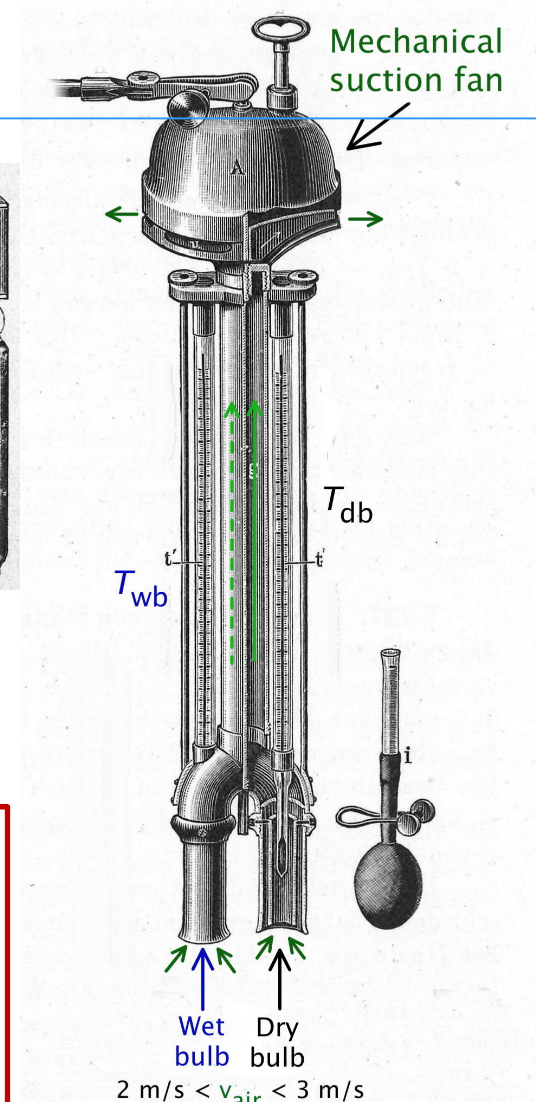


Sling Psychrometer

T_{db}, T_{wb}, $(T_{db}-T_{wb})$, p_{atm},
instrument constant

⬇

RH, T_{DP}, p_{ws}, …



MÜLLER-POUILLETs Physik (10. Aufl., 1907)
Bd. III, S. 811

1825: August's Psychrometer

1886: Aßmann's Aspiration Psychrometer

PSYCHROMETERS: How to calculate *RH*, p_{ws}, T_{DP} …

Semi-empirical formulas, tables, charts, mechanical devices [8]

Relative Humidity Table (wet/dry bulb method)

Dry Bulb	Wet Bulb depression (°C)														
(°C)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	18	20
2	99%+	84%	68%	52%	37%	22%	8%									
4	99%+	85%	70%	56%	42%	29%	26%	3%								
6	99%+	86%	73%	60%	47%	34%	22%	11%								
8	99%+	87%	75%	63%	51%	39%	28%	18%	7%							
10	99%+	88%	76%	65%	54%	44%	33%	23%	14%	4%						
12	99%+	89%	78%	67%	57%	47%	38%	29%	20%	11%	3%					
14	99%+	89%	79%	69%	60%	51%	42%	33%	25%	17%	9%					
16	99%+	90%	80%	71%	62%	54%	45%	37%	29%	22%	14%					
18	99%+	91%	81%	73%	64%	56%	48%	41%	33%	26%	19%	6%				
20	99%+	91%	82%	74%	66%	58%	51%	44%	37%	30%	24%	11%				
22	99%+	91%	83%	75%	68%	60%	53%	46%	40%	34%	27%	16%	5%			
24	99%+	92%	84%	76%	69%	62%	55%	49%	43%	37%	31%	20%	9%			
26	99%+	92%	85%	77%	70%	64%	57%	51%	45%	39%	34%	23%	14%	4%		
28	99%+	92%	85%	78%	72%	65%	59%	53%	47%	42%	37%	26%	17%	8%		
30	99%+	93%	86%	79%	73%	67%	61%	55%	49%	44%	39%	29%	20%	12%	4%	
32	99%+	93%	86%	80%	74%	68%	62%	56%	51%	46%	41%	32%	23%	15%	8%	1%
34	99%+	93%	87%	81%	75%	69%	63%	58%	53%	48%	43%	34%	26%	18%	11%	5%
36	99%+	93%	87%	81%	75%	70%	64%	59%	54%	50%	45%	36%	28%	21%	14%	8%
38	99%+	94%	88%	82%	76%	71%	65%	60%	56%	51%	47%	38%	31%	23%	17%	11%
40	99%+	94%	88%	82%	77%	72%	66%	62%	57%	52%	48%	40%	33%	26%	19%	13%
42	99%+	94%	88%	83%	77%	72%	67%	63%	58%	54%	50%	42%	34%	28%	21%	16%
44	99%+	94%	89%	82%	78%	73%	68%	64%	59%	55%	51%	43%	36%	29%	23%	18%

Haenni 1953

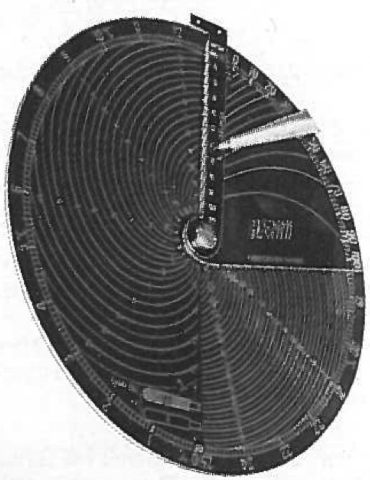
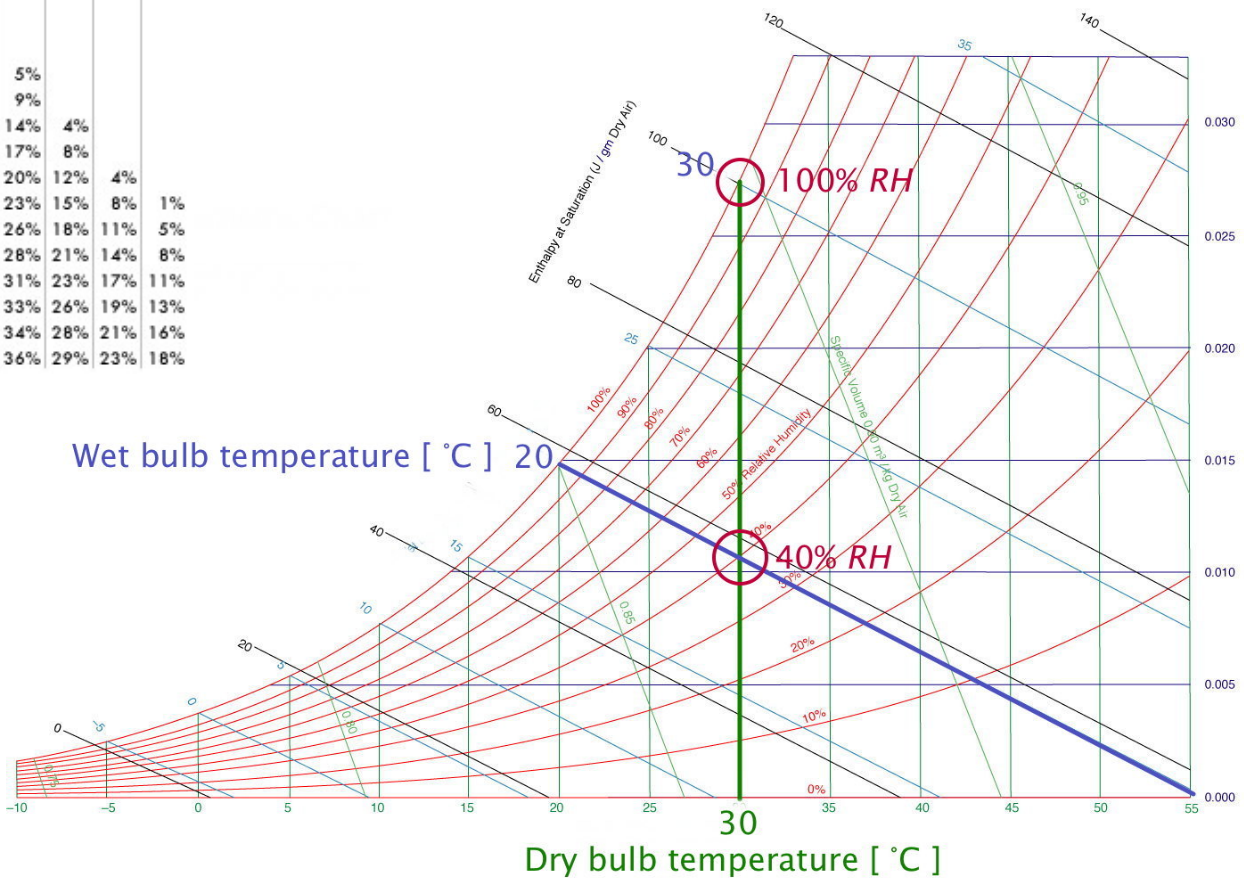


Fig. 620

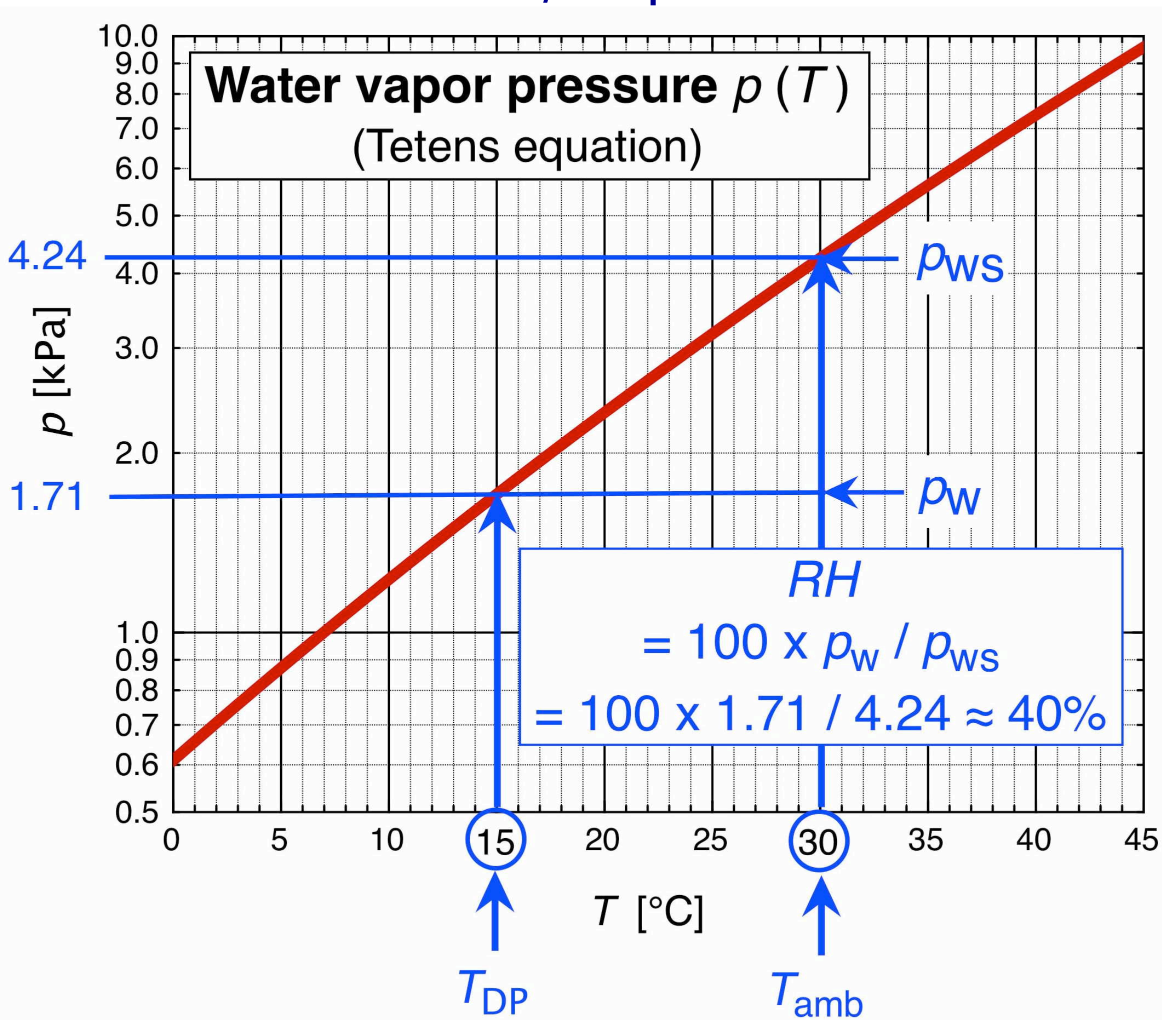
Psychrometric Chart (Sea level)
based on data from
Carrier Corp. Cat. No. 794-001 (1975)



I.3. CONDENSATION HYGROMETERS

Measurement of the temperature (Dew Point T_{DP})
at which a slowly cooled mirror is tarnished by droplets of water

Firm theoretical/empirical foundation [9]:



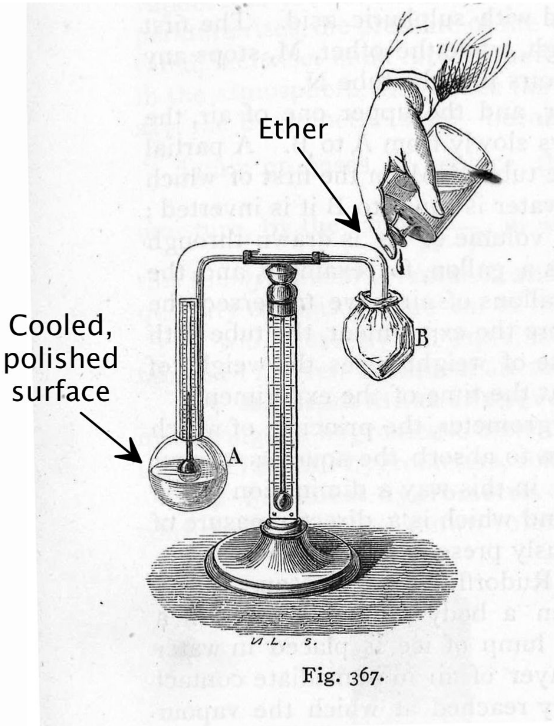
Example:

T_{DP} = 15 °C
=> Water vapor pressure
p_w = 1.71 kPa

T_{amb} = 30 °C
=> Saturation water pressure
p_{ws} = 4.24 kPa

=> Relative humidity
$RH = 100 \times p_w / p_{ws}$
≈ 40 %

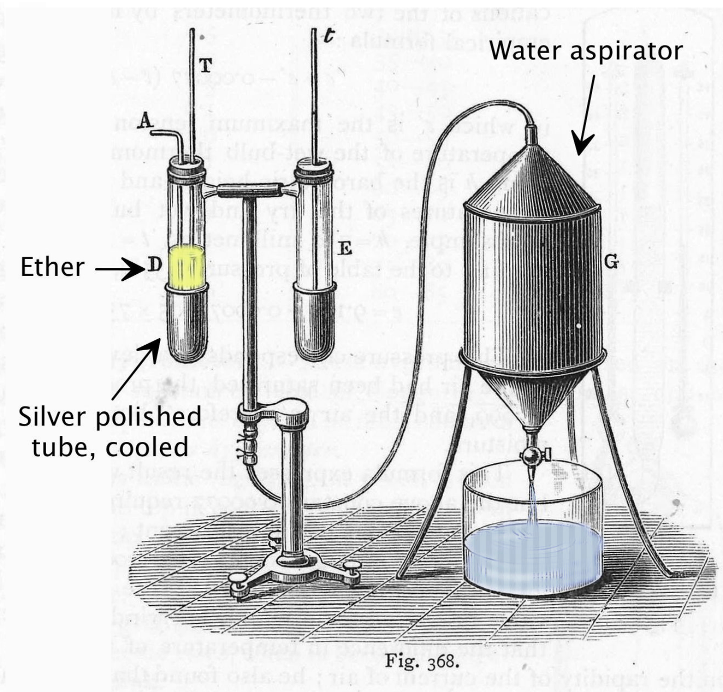
EXAMPLES of DEW POINT HYGROMETERS [10]



Daniell Dew-Point Hygrometer

A. GANOT : Elementary Treatise on Physics experimental and applied
14th ed., 1893, P. 378, § 396

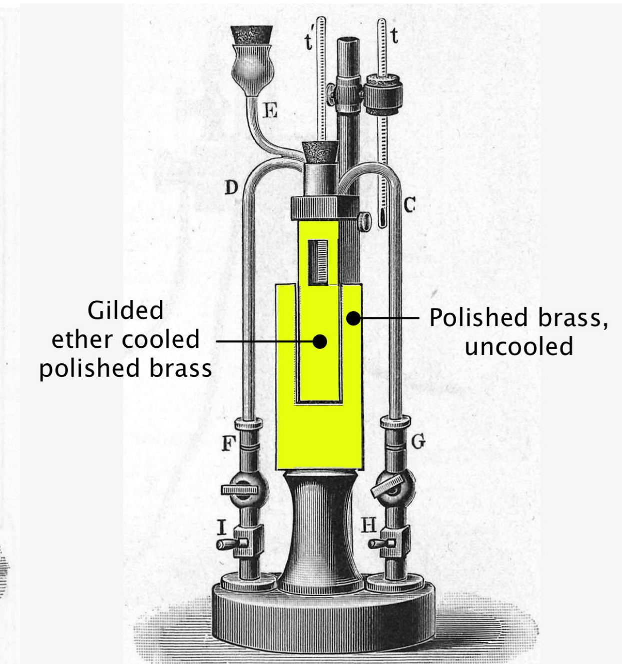
1819 : Daniell



Regnault Dew-Point Hygrometer

A. GANOT : Elementary Treatise on Physics experimental and applied
14th ed., 1893, P. 379, § 396

1845 : Regnault



Use remote viewing to avoid operator's body heat and moist breath disturbing effects!

Alluard Hygrometer

O.D. CHWOLSON: Lehrbuch der Physik (Übersetzt von E. Berg)
Bd. III, S. 777
(Braunschweig: Friedr. Vieweg & Sohn A.G. 1905)

1878 : Alluard

The most accurate hygrometer type !
But smelly (ether cooling!), telescope observation,
time consuming operation, needs a skilled operator

Modern mirror condensation hygrometers automated
by Peltier cooling, opto-electronics, solid-state electronics

II. Louis DUFOUR

1832: Born at Montreux

Studies physics at Lausanne, then at Paris

1855: Physics prof. at the Academy of Lausanne

1867: Declines an invitation to the Poly of Zurich

1878: Forced to retire by a physical illness

1892: Death in Lausanne

Successor : Henri Dufour (no kin)

22 years of research:

— Very modest laboratory; one student-assistant

— Studies heat related problems

(delays in the freezing of water when cooled, in the boiling when heated; the “Foehn” problem [11]; …)

L. DUFOUR: Diffusion of gases and vapours (1874–1875)

His last experimental work

Studies the diffusion of gases and vapours, especially moist air, through porous walls (clay, marmor, diverse forms of carbon, etc.)

Many experiments, described in words (and numeric tables) only, no figures, no graphs

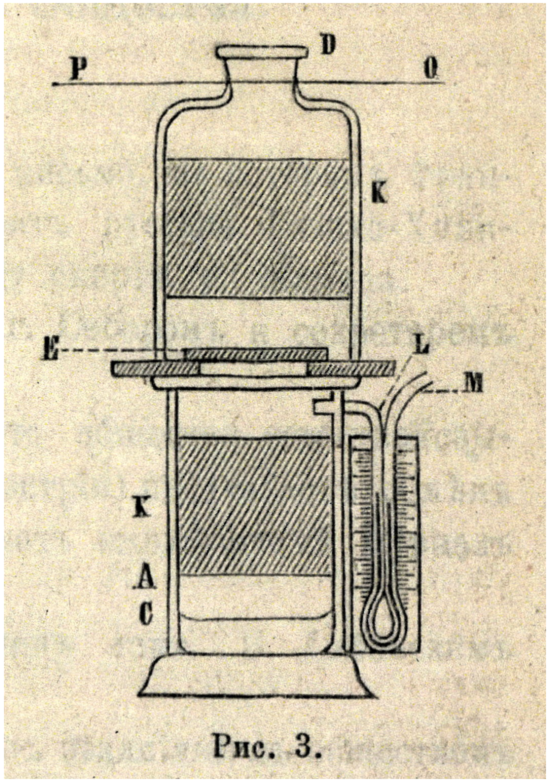
Main result:

Difference of pressure Δp between the *moist atmosphere* of the laboratory and a vessel containing either a *desiccant* ($\Delta p < 0$) or *water* ($\Delta p > 0$)

Dufour calls the phenomenon "Hygrometric Diffusion"

Stopped by illness, he doesn't provides a theory, neither does he build an hygrometer

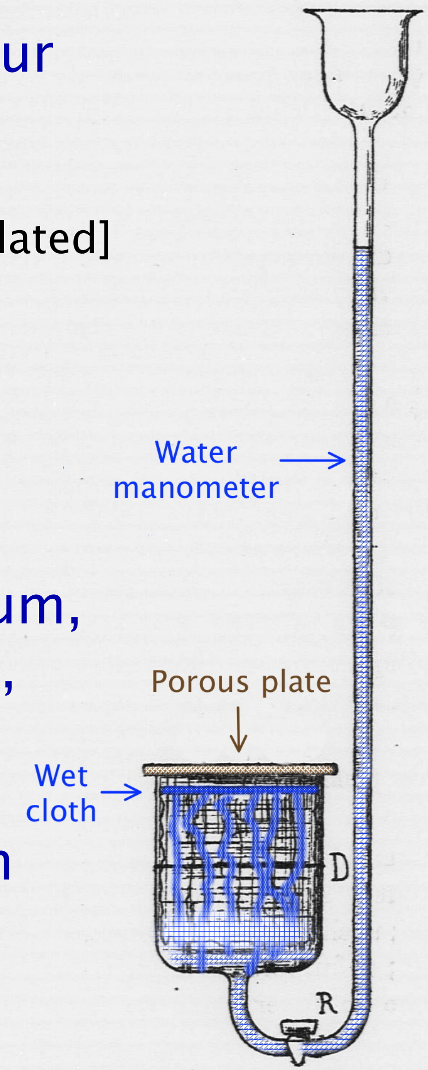
August Kundt (1877) compares existing theories of diffusion with the experimental results of Dufour, of Merget (1874), Violle and others



Schidlowsky (1886) Fig. 3

F. Schidlowsky (1886), in Russia, repeats the experiments of Dufour and is reported to have built the first Diffusion Hygrometer
[original paper (22 pages !) not yet translated]

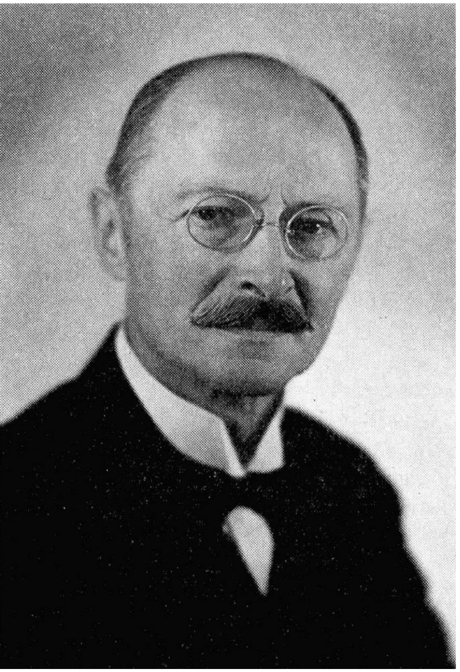
A. Jouveneau (1896), in Belgium, gives a very short description, of a Diffusion Hygrometer, along with a drawing.
No dimensions, no calibration



Hygromètre à diffusion
A. Jouveneau, 1896

Then nothing until 1944 !

III. Heinrich GREINACHER: life and work



1880: Born in St Gall

Studies physics at Zurich, Geneva and Berlin

1907: P.D., then prof. at the University of Zurich

1924: Prof. at the University of Bern

1952: Retirement

1974: Death

Work : mainly on electrotechnology, radioactivity and instrumentation for nuclear particle detection

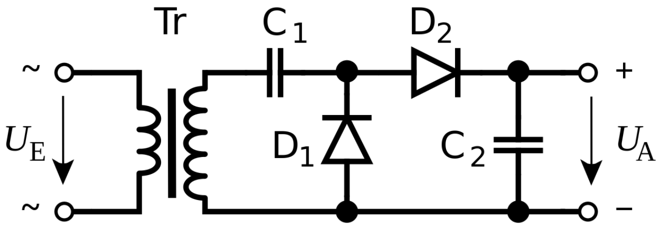
Remembered above all for:

— his Voltage Doubler (1914),

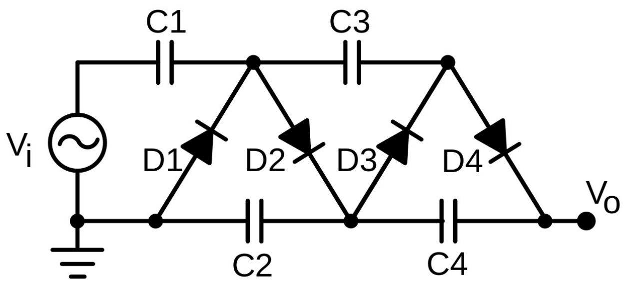
— his Cascade Voltage Multiplier (1920),

— his pioneering studies of the Magnetron (1921)

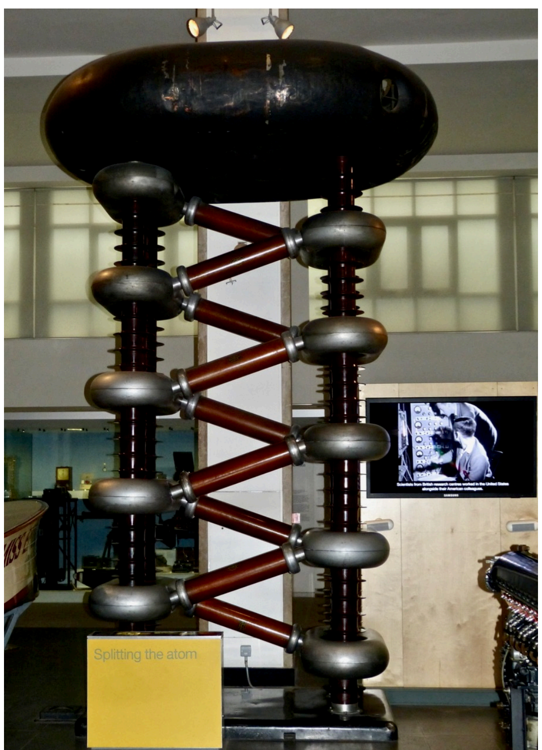
H. GREINACHER: His inventions



Voltage Doubler (1914):
AC-to-DC Converter



Greinacher Cascade Multiplier
(CH and DE patents 1920):
AC-to-DC Converter



1932: Cockroft and Walton at the Cavendish Laboratory rediscover the Cascade Voltage Multiplier and use it to build a particle accelerator

The Greinacher voltage multiplier became known as the Cockroft–Walton voltage multiplier…

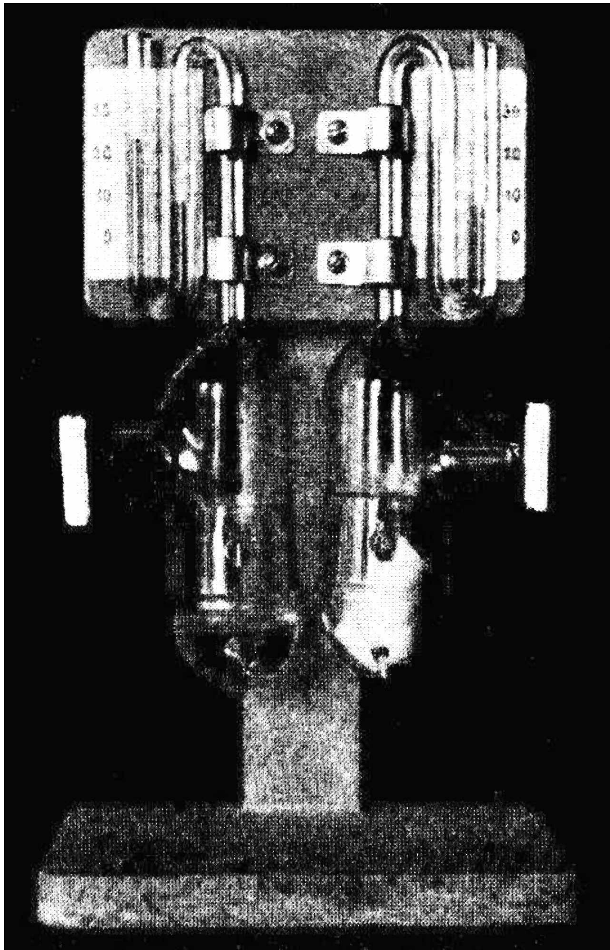
Philips particle accelerator (1937)
at the Science Museum in London

© J.-F. Loude, 2012

H. GREINACHER: his Diffusion Hygrometer

Also *Director of the Meteorological Observatory* at Bern.
That could explain why, near the end of his active life, he became, 70 years after Dufour, suddenly interested in instruments to measure the atmosphere moisture content

First paper: H.P.A. (1944), followed by
7 more until 1954, after his retirement.
He cites the works of L. Dufour, as well
as the theoretical considerations of Kundt
Brief mention of Schidlowsky, none of Jouveneau

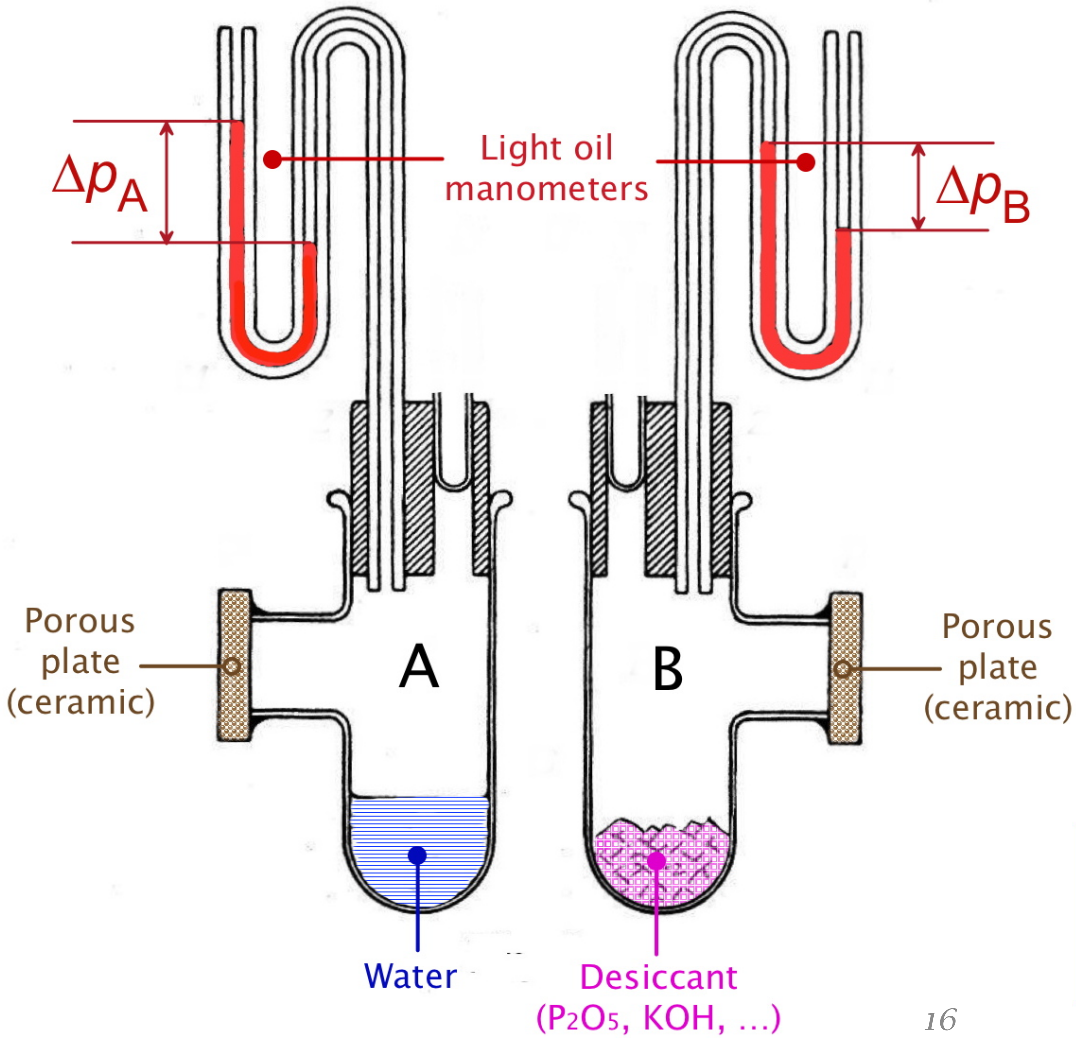


First prototype of the Double Diffusion Hygrometer (Bern, 1944)

In 1944, he got 2 patents
for his invention:
a Swiss one, and a British one

GREINACHER's Double Diffusion Hygrometer (1944)

Device at $T = T_{amb}$,
in moist atmosphere
($RH > 0$, partial water pressure p)



Theory as given by Greinacher:

p_s saturation water pressure at T

Vessel A:

$$\Delta p_A = K\,(p_s - p) \qquad 0 < K < 1$$

K instrument constant, depending on the properties of the porous plate

Device in dry atmosphere:

$$p = 0 \;\Longrightarrow\; K = {}^{\Delta p_A}/_{p_s}$$

Vessel B (ideal desiccant):

$$\Delta p_B = K \cdot p$$

$$\Delta p_A + \Delta p_B = K \cdot p_s$$

$$100\,\frac{\Delta p_B}{(\Delta p_A + \Delta p_B)} = \frac{p}{p_s} = RH$$

GREINACHER's Diffusion Hygrometer evolution

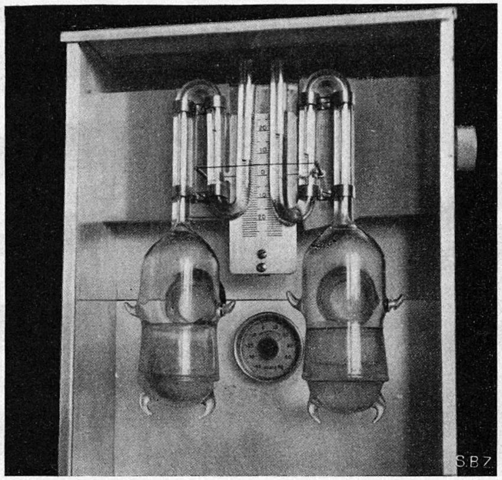
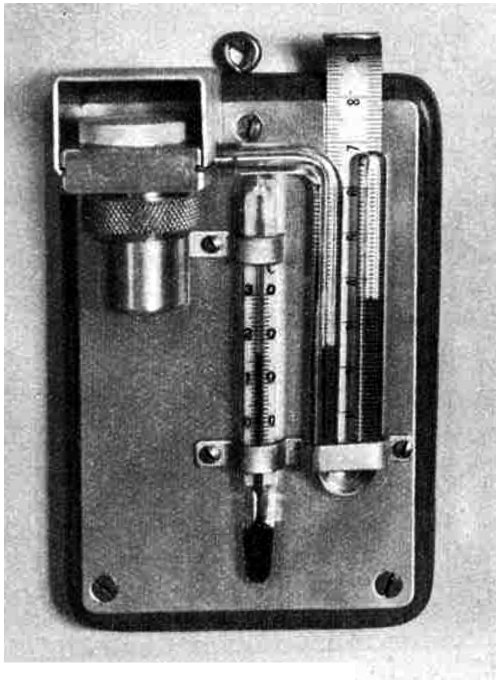
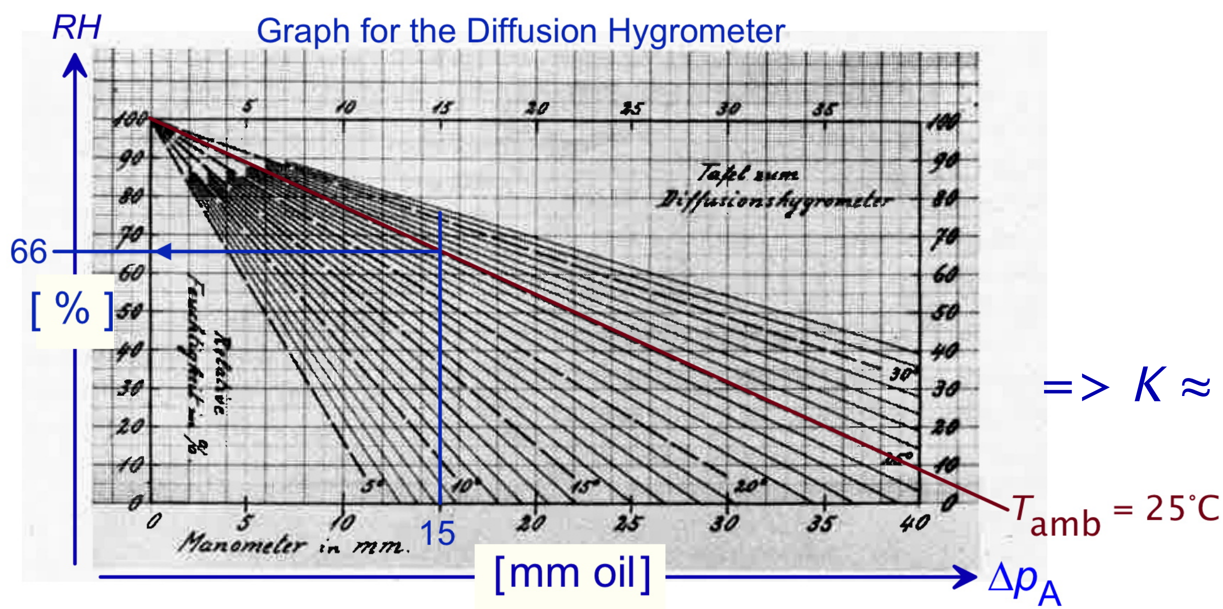


Bild 2. Zweiteiliger Apparat mit Flüssigkeitsmanometern

Bern 1946
Thermometer
in the same box,
porous plates at
the rear, protected
from drafts

Bern 1949
Drastic simplification
Only one water-filled vessel !
Thermometer needed
RH (T_{amb}, *K*) provided by graph



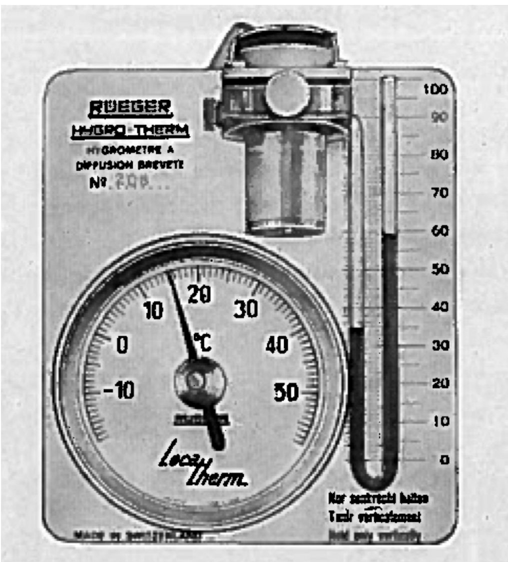


=> $K \approx 0.12$

IV.1. Commercial Diffusion Hygrometers: RÜEGER

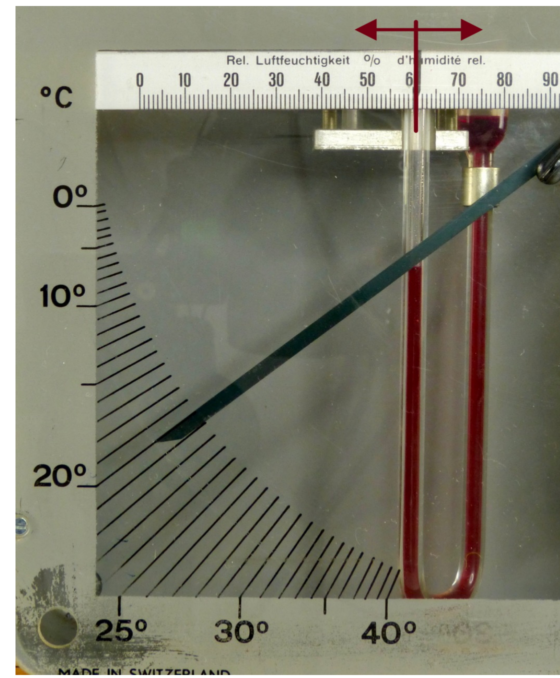
Why were they not made by Haenni at Jegenstorf, near Bern, important and well established maker of thermometers, hygrometers, etc. ?

RÜEGER (now Rüeger SA) was founded in 1942 at Lausanne by Ernst A. Rüeger, to make bimetallic thermometers



1953:
1st model of Diffusion Hygrometer "Hygro-Therm"

H = 21.5 cm



1954: 2nd model of the "Hygro-Therm"
Direct readout of *RH* !
Sold at least until 1958

IV.2. Commercial Diffusion Hygrometers: TESA

TESA (founded in 1941 at Renens near Lausanne as “TE”léphonie“SA”): specialized in precision length measurement instruments for mechanical workshops, first micrometers, then other ones such as vernier calipers, etc. Still in activity !

Direct RH readout! Rotating calibrated drum, driven by a bimetal spiral

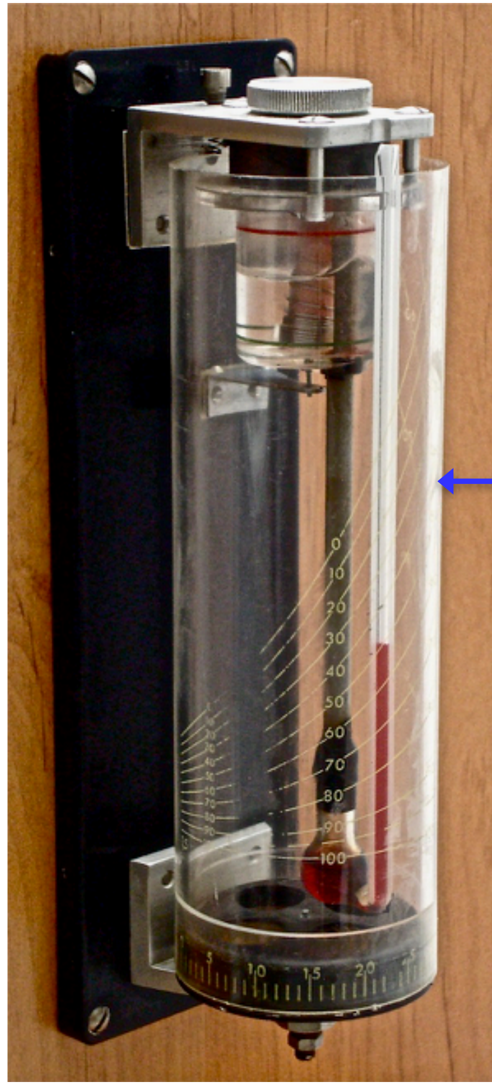
H = 19 cm

To be screwed vertically on a wall !

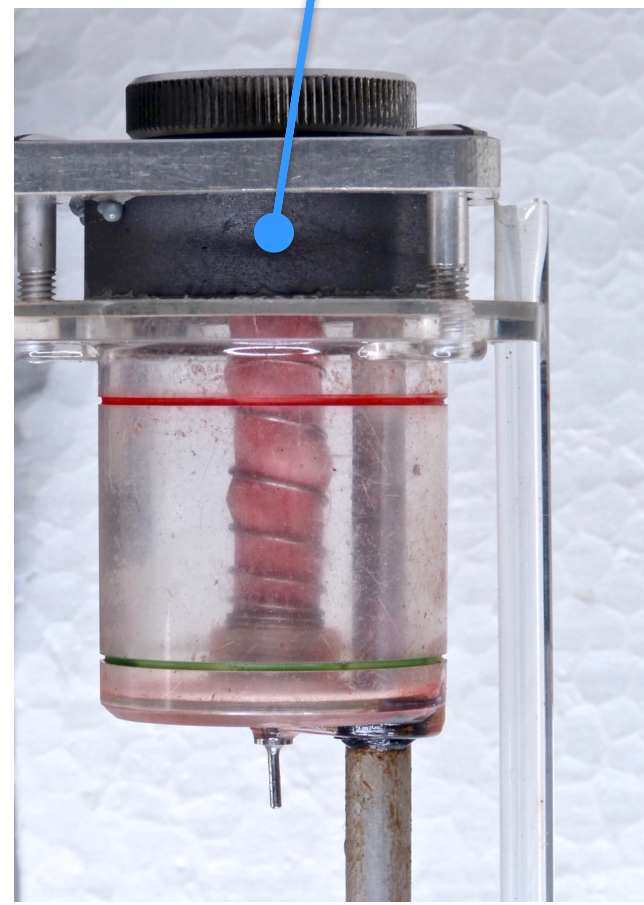
Water refill
(every 2 to 3 months)

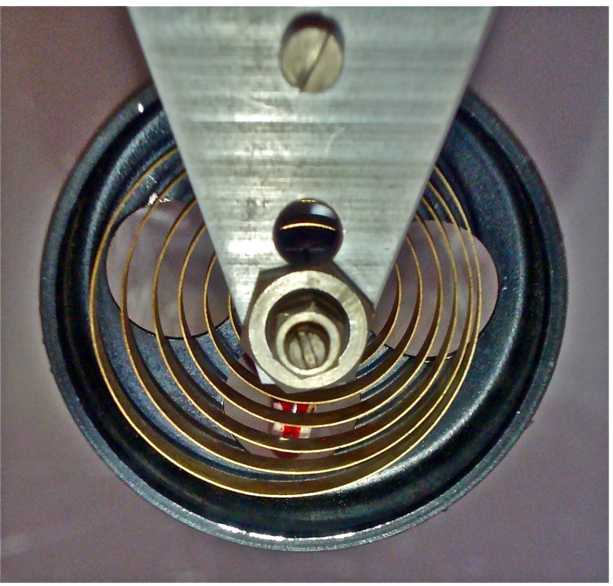
TESA Diffusion Hygrometer. In UK, also available from Rototherm

Rotating drum



Porous ring (carbon)





Bottom view
(bimetal thermometer)

RÜEGER and TESA: better porous plates ($K = 0.25 \pm 0.01$)

IV. 3. Diffusion Hygrometers: reception

- Experimental results with Diffusion Hygrometers used by Spencer-Gregory and Rourke (1947, 1957) for a comparison of diffusion theories (Knudsen Law and alternative ones)
- TESA/Rototherm model seriously mentioned for possible use in Museums (1960)
- Commercial flop…
- Otherwise, a few short mentions of diffusion hygrometers, more as a curiosity, in books about hygrometry, with the last known one in 1978
- After about 1965, progress in electronics made possible *novel types of hygrometers* (for example with capacitive or resistive sensors), more accurate and/or more convenient to use, affordable – or the *modernisation of ancient types* (automatic, high-accuracy dew-point hygrometers)

CONCLUSIONS

Was, as advertised by Greinacher, the Diffusion Hygrometer actually better than the then available hygrometers ?

- Claims of high accuracy not backed up by serious calibration data
- Drawbacks: periodic water refill; calibration based on the *a priori* unknown properties of a porous plate; not portable (contact of oil with the porous plate to be avoided at all costs); no recording
- Effects of changing p_{atm} ? Long term stability ?
- Doubtful availability of porous plates with reproducible properties

¡ Not better than a good Hair Hygrometer !

Why did Greinacher put so much energy promoting his device ?

Acknowledgements

I am very thankful to *Mr. H.-J. Bühlmann* for returning both hygrometers to working condition, testing them and making photographs.

Surprisingly, the firm RÜEGER was able to find the missing “Mode d’emploi” of their Hygro-Therm of 1958. Many thanks !

Last but not least, I am grateful to the *EPFL*, through my laboratory, the *LPHE*, for its continued support.

¡ THANK YOU FOR YOUR ATTENTION !

Notes

1. Physics Museum Inventory UNIL Inv. 603.027
2. Physics Museum Inventory UNIL Inv. 603.510
3. Hygrometry: air moisture content measurement is fundamental for meteorology, very important for human comfort, and for the preservation of materials in museums, libraries, film archives, and in many industrial domains. In 1945, there were no solid-state electronics (only power-hungry vacuum tubes), no microcontrollers, no optoelectronics, no LCD displays, no pocket calculators, no Peltier elements...
4. Geneva is the city where the first practical hygrometer, the Hair Hygrometer, was perfected by H.-B. de Saussure, and built by the mecanician Paul. Very successful, still in use!
5. Physics Museum Inventory UNIL Inv. 603.328
6. Physics Museum Inventory UNIL Inv. 603.977
7. The main use of psychrometers was in meteorology. The static August psychrometer is too imprecise. To give correct results, the speed of air around the wet bulb has to be high enough (v_{air} between 2 and 4 m/s). Thus Sling psychrometers were designed (to be used mainly onboard ships, being rotated by hand). Later, Assmann Aspiration psychrometers, with a mechanical fan, became standard instruments.
8. Here are shown 3 examples of aids to calculate *RH* from a psychrometer data: numeric table, circular rule, chart (Mollier diagram). The operator needs probably at least 10 minutes for a single, complete measurement!
9. Water vapor is far from being a perfect gas! Its pressure depends only on the temperature. The experimental data can be approximated by several formulas, among them the Tetens one.
10. The Mirror Condensation (Dew Point) hygrometer has for a long time been the most accurate one in common use, mainly for calibration of other devices. Remote viewing was necessary to avoid the disturbing influence of body temperature and moist operator's breath. Nowadays, it has been transformed in an electronic recording instrument, allowing quasi-continuous, remote and very precise ($< 0.1\%$ *RH*) measurements.
11. The "Foehn" is a dry, warm, down-slope wind that occurs in the lee (downwind side) of a mountain range, here in Switzerland with moist winds off the Mediterranean Sea blowing over the Alps, often tempestuously.

Selected bibliography (in chronological order)

Biographies:

— Henri Dufour : Louis DUFOUR (1832–1892) – Notice biographique
Bull. Soc. Vaud. Sc. Nat. XXIX/112 (1893) 211–228
— H. Balmer: Heinrich GREINACHER (1880–1974) – Obituary
Verhandlungen der Schweizerischen Naturforschenden Gesellschaft 154 (1974) 239–251

Diffusion Hygrometers:

— L. Dufour : Recherches sur la diffusion entre l'air sec et l'air humide à travers une cloison de terre poreuse
Bull. Soc. Vaud. Sc. Nat. XIII/72 (1874–1875) 165–217
— L. Dufour : Sur la diffusion hygrométrique
Bull. Soc. Vaud. Sc. Nat. XIII/74 (1874–1875) 608–64
— A. Kundt: Zur Erklärung der Versuche Dufour's und Merget's über die Diffusion der Dämpfe
Annalen der Physik (T238=SER3, T2), 1877, 17–24
— F. Schidlowsky: Versuch einer Anwendung der Diffusion der Gase und Dämpfe durch poröse Körper zur Bestimmung der Feuchtigkeits- und Kohlensäuregehaltes im umgebenden Medium
Full paper in Russian: Journal der russischen physikalisch-chemischen Gesellschaft 18/6 (1886) 182–204
German summary in Beiblätter zu den Annalen der Physik und Chemie, Bd. 11 (1887) p. 618–620
— F. Schidlowsky: Attempt to apply the diffusion of gases and vapours through porous bodies to determining the amount of moisture and carbonic acid in the surrounding air
English summary in Phil. Mag. Series 5, Vol. 25, Iss. 152 (1888) 77–78
— A. Jouveneau : Nouvel hygromètre à diffusion
Bull. de la Société Belge d'Astronomie 1ère année (1895–1896) 27–28
— H. Greinacher: Ein neuer Feuchtigkeitsmesser: das Diffusionshygrometer
Helv. Phys. Acta 17 (1944) 437–454
— Schweizer Patent Nr. 252382 (21.10.1944) and U.K. Patent No. 612716 (21.10.1944):
H. Greinacher, Apparat zur Messung der Feuchtigkeit von Gasen
— H. Greinacher: Das Diffusionshygrometer
Schweizerische Bauzeitung 127/5 (1946) 52–53
— H. Greinacher: Ein neuer Feuchtigkeitsmesser: das Diffusionshygrometer
Schweizerische Technische Zeitschrift 13 (1947) 189–192
— H. Spencer-Gregory and E. Rourke: A Theoretical Basis for the Diffusion Hygrometer
Phil. Mag. 38 (1947) 573–580
— H. Greinacher: Das Diffusionshygrometer
Schweizer Archiv für angewandte Wissenschaft und Technik 15 (1949) 353–355
— H. Greinacher: Das Diffusionshygrometer. ein neuer Feuchtigkeitsmesser
Chimia 7 (Januar 1953) 11–16. [*Shows a first model by Rüeger*]
— H. Greinacher: Die Diffusion der Gase und ihre Anwendung
Technische Rundschau 45. Jahrgang (5. Juni 1953) 1–2
— H. Greinacher: Diffusionshygrometer mit direkter Ablesung
Schweizer Archiv für angewandte Wissenschaft und Technik (Juni 1954) 198–200. [*Shows the second model by Rüeger*]

Directions for use:

— TESA : Mode d’emploi du constructeur (s.d.)
— Rüeger, Lausanne : Gebrauchsanweisung / Mode d’emploi pour l’hygromètre à diffusion “Hygro-Therm”, type HR (2 p., 1958)

Books and other documents about hygrometry:

— Arnold Wexler and W. G. Brombacher (eds.): Methods of Measuring Humidity and Testing
(National Bureau of Standards Circular 512, September 28, 1951) .
[*Short mention of the Diffusion Hygrometer, p. 11*]
— Arnold Wexler and William A. Wildhack: Fundamental and standards (1965)
— H. Spencer-Gregory and E. Rourke: Hygrometry (London, Crosby Lockwood & Son, Ltd., 1957)
[*Diffusion Hygrometer: p. 35-40 and Chapter VIII, p. 201-214*]
— Climatology and conservation in museums (Raymonde Frin, ed.)
Museum, vol. XIII/No. 4 (1960).
[*Diffusion hygrometer (TESA) p. 221-222, 254, 260]*
— J. Hengstenberg, B. Sturm, O. Winkler: Messen und Regeln in der chemischen Technik (Springer, 2. Auflage, 1964)
[*Diffusionshygrometer (TESA und Rüeger) S. 659-661*]
— W. Lück: Feuchtigkeit (München-Wien, R. Oldenbourg, 1964)
[*Diffusionshygrometer S. 147-148*]
— W. E. Knowles Middleton: Invention of the Meteorological Instruments (The John Hopkins Press, 1969)
— Dale L. Johnson: Instruments for measuring the amount of moisture in air
(NASA TM-78190, August 1978).
[*Short and last known mention of the Diffusion Hygrometer, p. 21*]
— M. Archinard : L’apport genevois à l’hygrométrie (Musée d’histoire des sciences de Genève, 1980)
— R. Wernecke und J. Wernecke: Industrial Moisture and Humidity Measurement - A Practical Guide (Wiley-VCH, 2014)