

# Thermodynamics

The humid air  
(moist air)

Edited and written by dr. Zana János (2023)

η θερμοδυναμική (f) feminine  
ο αέρας (m) masculine gender  
το αἰρκοῦντισιον (n) neuter

[not to learn](#)

[http://efiz.alarmix.net/lecture\\_notes/](http://efiz.alarmix.net/lecture_notes/)  
[http://elfiz2.kee.hu/lecture\\_notes/](http://elfiz2.kee.hu/lecture_notes/)

- The psychrometric diagram
- Refrigerators
- Calculation for the refrigeration cycle

# Richard Mollier



2023. 04. 22.

# Richard Mollier

- 1863 november 30 \* Triest, Austria
- 1892 habilitation, Technische Hochschule München: Diagrams in thermodynamics
- 1896 Universität Göttingen: Professor für angewandte Physik und Maschinenlehre
- 1904 VDI-Zeitschrift: "*Neuen Diagrammen zur Technischen Wärmelehre*„ (Verein Deutscher Ingenieure)
- 1923 Los Angeles, Congress on Thermodynamics all diagrams used in thermodynamics, we call Mollier diagrams
- 1935 March 13, † Dresden

# Quantities

- Le kelvin, unité de température thermodynamique, est la fraction  $1/273,16$  de la température thermodynamique du point triple de l'eau. 13th CGPM (1967), Resolution 4.
- The kelvin, unit of thermodynamic temperature, is the fraction  $1/273.16$  of the thermodynamic temperature of the triple point of water.

(valid up to 20th May 2019)

# Quantities

- the kelvin will **continue** to be the unit of thermodynamic temperature,
- but its magnitude will be set by fixing the numerical value of the
- Boltzmann constant to be equal to **exactly**  $1.380\,648\,52 \times 10^{-23}$  when it is
- expressed in the SI unit  $\text{m}^2 \text{kg s}^{-2} \text{K}^{-1}$ , which is equal to  $\text{J K}^{-1}$

# Quantities

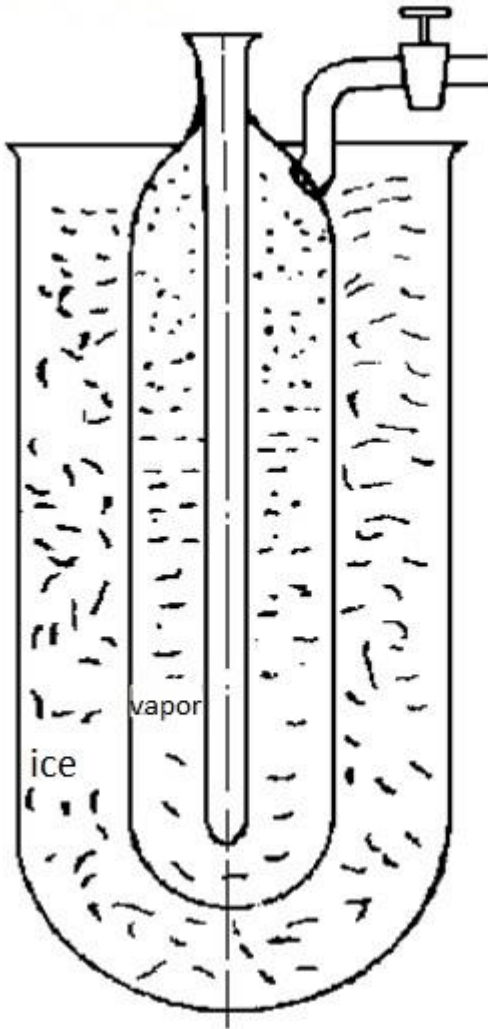
- The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant  $h$  to be  $6.626\,070\,15 \times 10^{-34}$  when expressed in the unit J s, which is equal to  $\text{kg m}^2 \text{s}^{-1}$ , where the metre and the second are defined in terms of  $c$  and  $\Delta\nu_{\text{Cs}}$ .

Greek nu is for frequency of Cesium atomic clock



thermometer

vacuum pump



Triple point cell

The tube inside contains low pressure 611,7 Pa.

It is well observable from outside that all the three phases coexist.

# Triple point cell



2023. 04. 22.

# Quantities

- La mole est la **quantité de matière** d'un système contenant autant d'entités élémentaires qu'il y a d'atomes dans 0,012 kilogramme de carbone 12.
- The mole is the **amount of substance** of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

(valid up to 20th May 2019)

# Quantities

- the mole will **continue** to be the unit of amount of substance of a
- specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles,
- but its magnitude will be set by **fixing** the numerical value of the Avogadro constant
- to be equal to exactly
- $6.022\,140\,857 \times 10^{23}$  when it is expressed in the SI unit  $\text{mol}^{-1}$ .

# Components of any mixture

- Mass, kg
- Volume, m<sup>3</sup>
- Amount of substance, mol
- Entity, 1

In SI system a number 1 is written expressing a unit. If the number of entities is known we write only the number alone

# Composition

- Relevant component: (used in chemistry as solute)
- Other component (in chemistry: solvent)

Physics: mixture (solid, fluid, or gaseous)

Numerical value of the composition: amount of relevant component **divided** by the other (or all other) components

# Composition

In the following examples:

O oxygen (relevant component)

N nitrogen (other component)

This composition is a useful model for the air when they both are almost perfect gases

# Composition

$$w = \frac{m_O}{m_O + m_N}, \quad 0 \leq w \leq 1 \frac{\text{kg}}{\text{kg}} \quad \text{mass fraction}$$

$$x = \frac{m_O}{m_N}, \quad 0 \leq x \leq \infty \frac{\text{kg}}{\text{kg}} \quad \begin{array}{l} \text{mass ratio} \\ \text{(signed as } x \text{)} \end{array}$$



# Composition

$$\phi = \frac{V_O}{V_O + V_N}, \quad 0 \leq \phi \leq 1 \frac{\text{m}^3}{\text{m}^3}$$

volume fraction

$$\Phi = \frac{V_O}{V_N}, \quad 0 \leq \Phi \leq \infty \frac{\text{m}^3}{\text{m}^3}$$

volume ratio

# Composition

$$y_m = \frac{n_O}{n_O + n_N} \quad 0 \leq y_m \leq 1 \frac{\text{mol}}{\text{mol}} \quad \text{amount of substance fraction}$$

$$Y_O = \frac{n_O}{n_N}, \quad 0 \leq Y \leq \infty \frac{\text{mol}}{\text{mol}} \quad \text{amount of substance ratio}$$

# Composition

$$\frac{z_O}{z_O + z_N}, \quad 0 \leq ? \leq 1 \frac{db}{db} \quad \text{number fraction}$$

$$\frac{z_O}{z_N}, \quad 0 \leq ? \leq \infty \frac{db}{db} \quad \text{number ratio}$$

**According the Avogadro law they are equal to the amount fraction, and the amount ratio**

# Composition

mass concentration

$$\rho_0 = \frac{m_0}{V_0 + V_N}, 0 \leq \rho_0 \leq 1,4 \frac{\text{kg}}{\text{m}^3}$$

end value is the density of the relevant component (oxygen)

$$\rho_0 = \frac{m_0}{V_0}, \frac{\text{kg}}{\text{m}^3}$$

mass density

---

amount of substance concentration

$$c_0 = \frac{n_0}{V_0 + V_N}, \quad 0 \leq c_0 \text{ or } \frac{1}{V_m}, \quad \frac{\text{mol}}{\text{m}^3} \text{ (end value is the reciprocal value of the molar volume)}$$

# Composition

| correct                         | incorrect |
|---------------------------------|-----------|
| kg/kg                           | m %       |
| g/kg                            | wt-%      |
| mg/kg                           | ppm       |
| m <sup>3</sup> /m <sup>3</sup>  | V %       |
| dm <sup>3</sup> /m <sup>3</sup> | V/V %     |
| mol/m <sup>3</sup>              |           |
| mol/dm <sup>3</sup>             | mol %     |

# Composition

## **NIST 7 Rules and Style Conventions for Expressing Values of Quantities**

Mass fraction, volume fraction, and amount-of-substance fraction of B may also be expressed as in the following examples:

$$w_B = 3 \text{ g/kg};$$

$$\varphi_B = 6.7 \text{ mL/L};$$

$$x_B = 185 \text{ }\mu\text{mol/mol}.$$

Such forms are highly recommended. (See also Sec. 7.10.3.)

# Composition

|                              |                       |             |        |           |
|------------------------------|-----------------------|-------------|--------|-----------|
| mass fraction                | fracción de masa      | $w_O$       | 0,2320 | kg/kg     |
| volume fraction              | fracción en volumen   | $\varphi_O$ | 0,2093 | $m^3/m^3$ |
| amount-of-substance fraction | fracción molar        | $x_m$       | 0,2117 | mol/mol   |
| mass concentration           | concentración en masa | $\rho_O$    | 0,30   | kg/mol    |
| amount-of-substance ratio    | proporción molar      | $r_O$       | 0,2178 | mol/mol   |

# Composition

- John *Dalton*  
(1766 IX 5 Eaglesfield-1844 VII 27 Manchester)
- $V_O = V_N = V_i$

$$p = \sum_{i=1}^n p_i$$



# Composition

- Émile Hilaire ***Amagat*** (1841-1915)
- Le statique des fluides la liquéfaction des gaz et l'industrie du froid
- $p_O = p_N = p_i$

$$V = \sum_{i=1}^n V_i$$

# Gas constant

- Henri-Victor **Regnault**  
(Aachen, Aix-la-Chapelle 1810 VII 21- Auteuil  
1878 I 19)

Relation des expériences entreprises pour  
déterminer les lois et les données physiques  
au calcul des machines à feu

$$R_m = \frac{pV}{nT}, \quad \frac{\text{J}}{\text{mol} \cdot \text{K}}$$

# Composition

- Perfect gas law

$$n_O = \frac{p_O V_O}{R_m T_O}$$

$$n_N = \frac{p_N V_N}{R_m T_N}$$

$$Y = \frac{n_O}{n_N} = \frac{\frac{p_O V_O}{R_m T_O}}{\frac{p_N V_N}{R_m T_N}}, \frac{\text{mol}}{\text{mol}}$$

# Composition

$$Y = \frac{n_O}{n_N} = \frac{\frac{p_O V_O}{R_m T_O}}{\frac{p_N V_N}{R_m T_N}}, \frac{\text{mol}}{\text{mol}}$$

$$Y = \frac{p_O V_O}{p_N V_N}, \frac{\text{mol}}{\text{mol}}$$

$$Y = \frac{p_O}{p_N} (V_O = V_N), \frac{\text{mol}}{\text{mol}}$$

$$Y = \frac{V_O}{V_N} (p_O = p_N), \frac{\text{mol}}{\text{mol}}$$

# Composition

Calculate the partial pressure of oxygen using the atmospheric pressure and the amount ratio:

$$p_o = \frac{Y_o}{Y_o + 1} p_t = \frac{0,271}{0,271 + 1} 101325 Pa = 21604 Pa$$

# Composition

First calculate the mass of oxygen using the gas law:

$$m_o = \frac{p_o V_o M_o}{R_m T_o}$$

# Composition

We calculate the *mass ratio* from the *amount ratio* using the quotient of the molar masses:

$$X = \frac{m_O}{m_N} = \frac{\frac{p_O V_O M_O}{R_m T_O}}{\frac{p_N V_N M_N}{R_m T_N}} = \frac{p_O V_O M_O}{p_N V_N M_N} = Y_O \frac{M_O}{M_N}$$

# Composition

Volume ratio of oxygen when the number of components more than two. We know the mass ratio and the volume for each components:

$$\phi_0 = \frac{w_0 V_0}{\sum_{i=1}^n w_i V_i} \cdot \frac{\text{m}^3}{\text{m}^3}$$



# Composition

When all  $\rho_i$  mass concentrations added we get the mixture density:

$$\rho_{\text{mixture}} = \sum_{i=1}^n \rho_i, \frac{\text{kg}}{\text{m}^3}$$

The numerical value of the mass concentration always less than the density of the mixture

# Composition

| compon<br>ent               | volume<br>fraction | mass<br>fraction | amount<br>fraction | mass<br>concentr<br>ation | partial<br>pressure |
|-----------------------------|--------------------|------------------|--------------------|---------------------------|---------------------|
| i                           | $\varphi$          | w                | $Y_m$              | $\rho$                    | p                   |
| N <sub>2</sub>              | 0,7809             | 0,755            | 0,7788             | 0,9758                    | 78915               |
| O <sub>2</sub>              | 0,2093             | 0,232            | 0,2117             | 0,3                       | 21450               |
| Ar                          | 0,0093             | 0,0128           | 0,0094             | 0,0166                    | 953                 |
| CO <sub>2</sub>             | 0,00003            | 0,00046          | 0,00003            | 0,00006                   | 3                   |
| $\Sigma$                    | 1                  | 1                | 1                  | 1,2925                    | 101325              |
| Four component model of air |                    |                  |                    | mixture<br>density        | total<br>pressure   |

# What we can state about the components of the air?

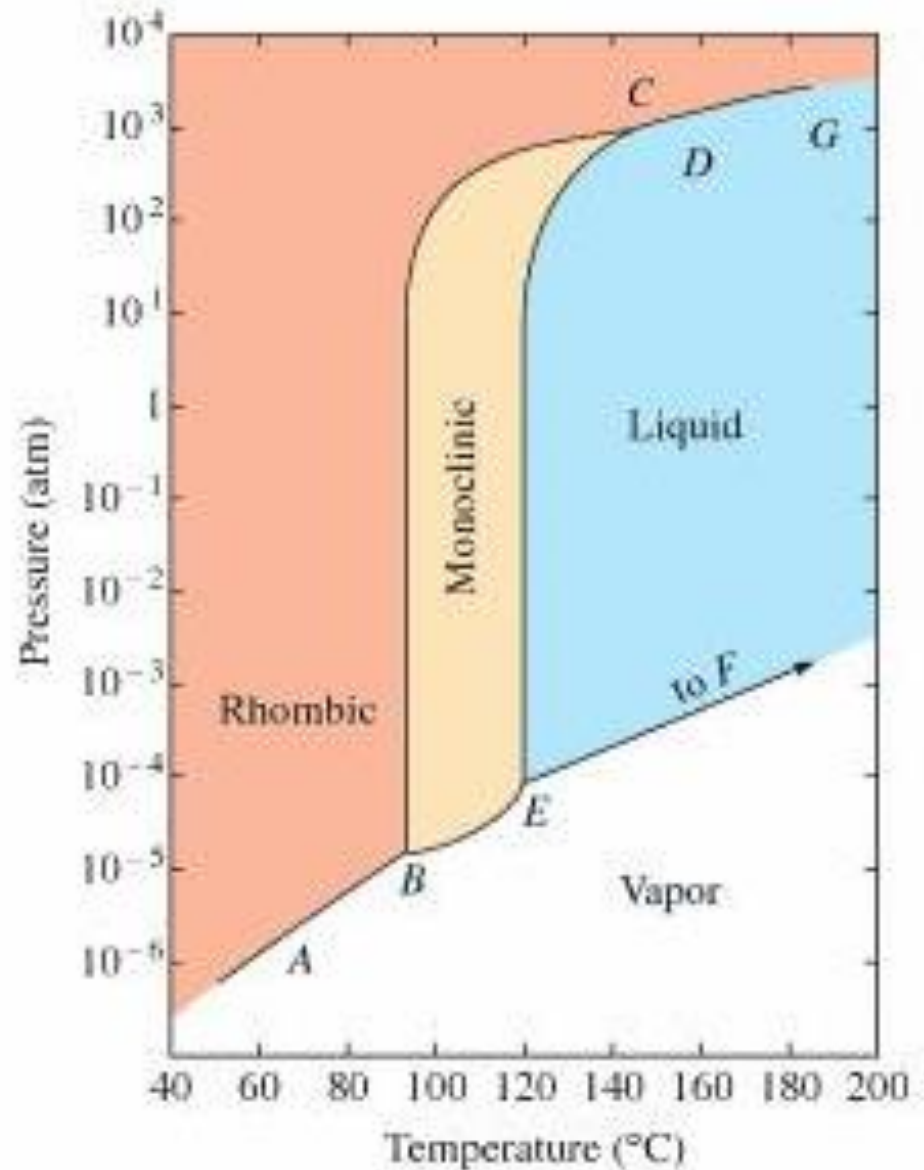
- Is there any component that can be separated from the air?
- Does the perfect gas law hold for all the components?
- What can we find in the thermodynamic tables?

# More components of air

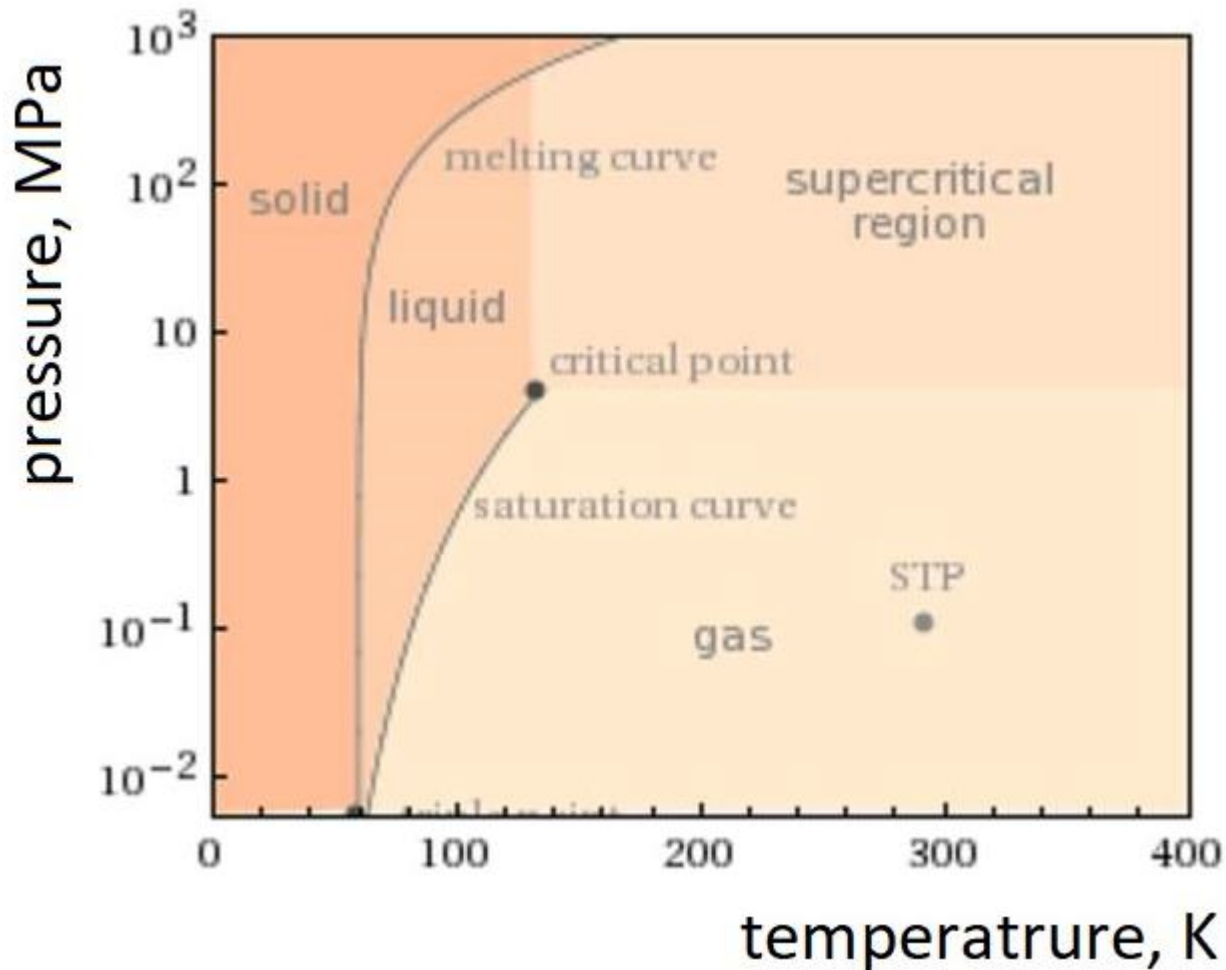
| compound        | critical point data (°C, bar, dm <sup>3</sup> /kg) |        |       |
|-----------------|--|--------|-------|
| N <sub>2</sub>  | -141,1   | 33,9   | 3,22  |
| O <sub>2</sub>  | -118,8   | 50,4   | 2,33  |
| Ar              | -122,4   | 48,64  | 1,92  |
| CO <sub>2</sub> | +31,0  | 73,9   | 2,17  |
| dry air         | -140,7   | 37,69  | 3,26  |
| water           | +374,2   | 221,23 | 3,067 |



Phase diagram,  
an example, the  
sulphur. This  
component has  
more triple  
points. We take  
in consideration  
the **E** (solid,  
liquid, gaseous)



Phase diagram for sulfur

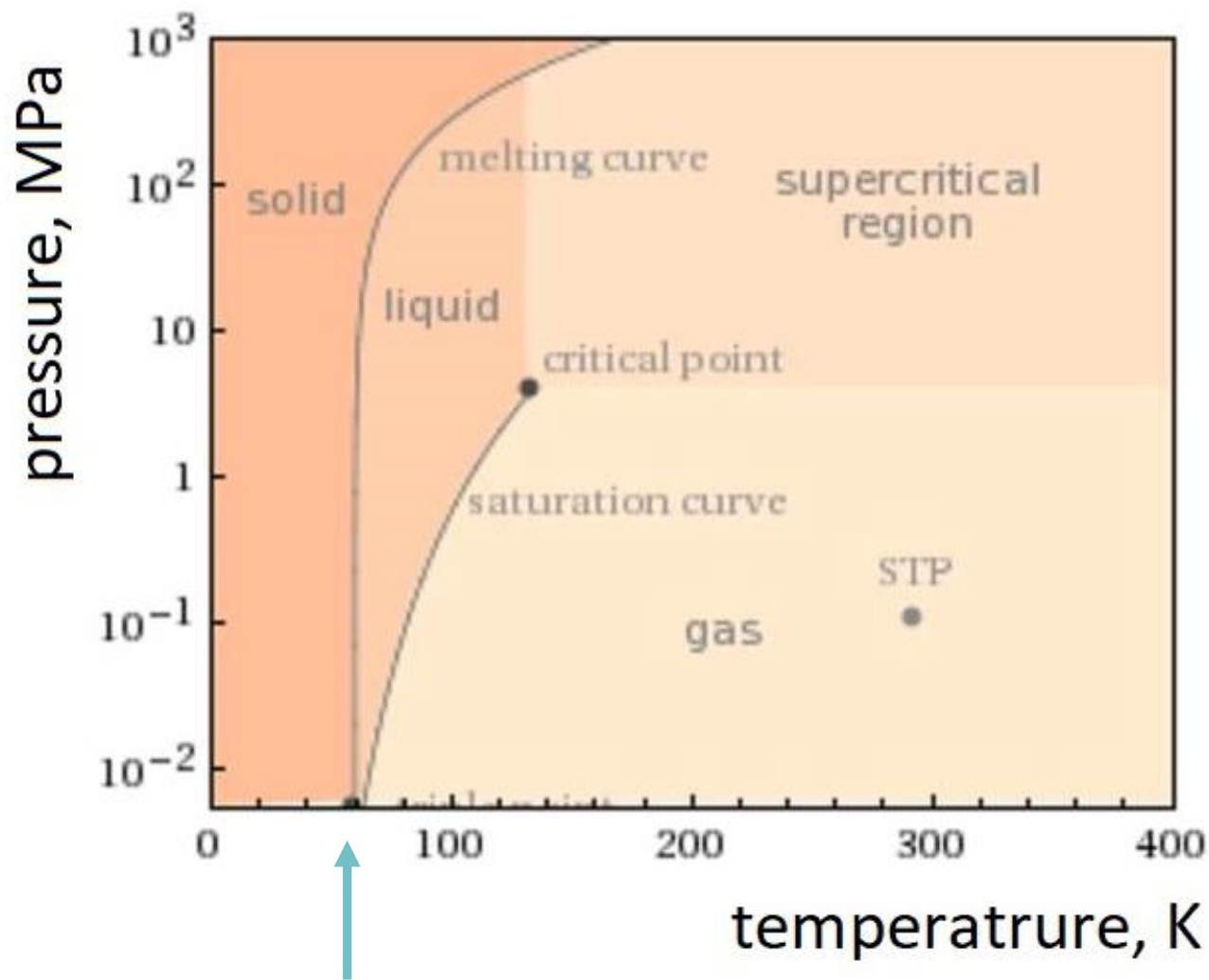


## Phase diagram of air

STP= standard temperature and pressure

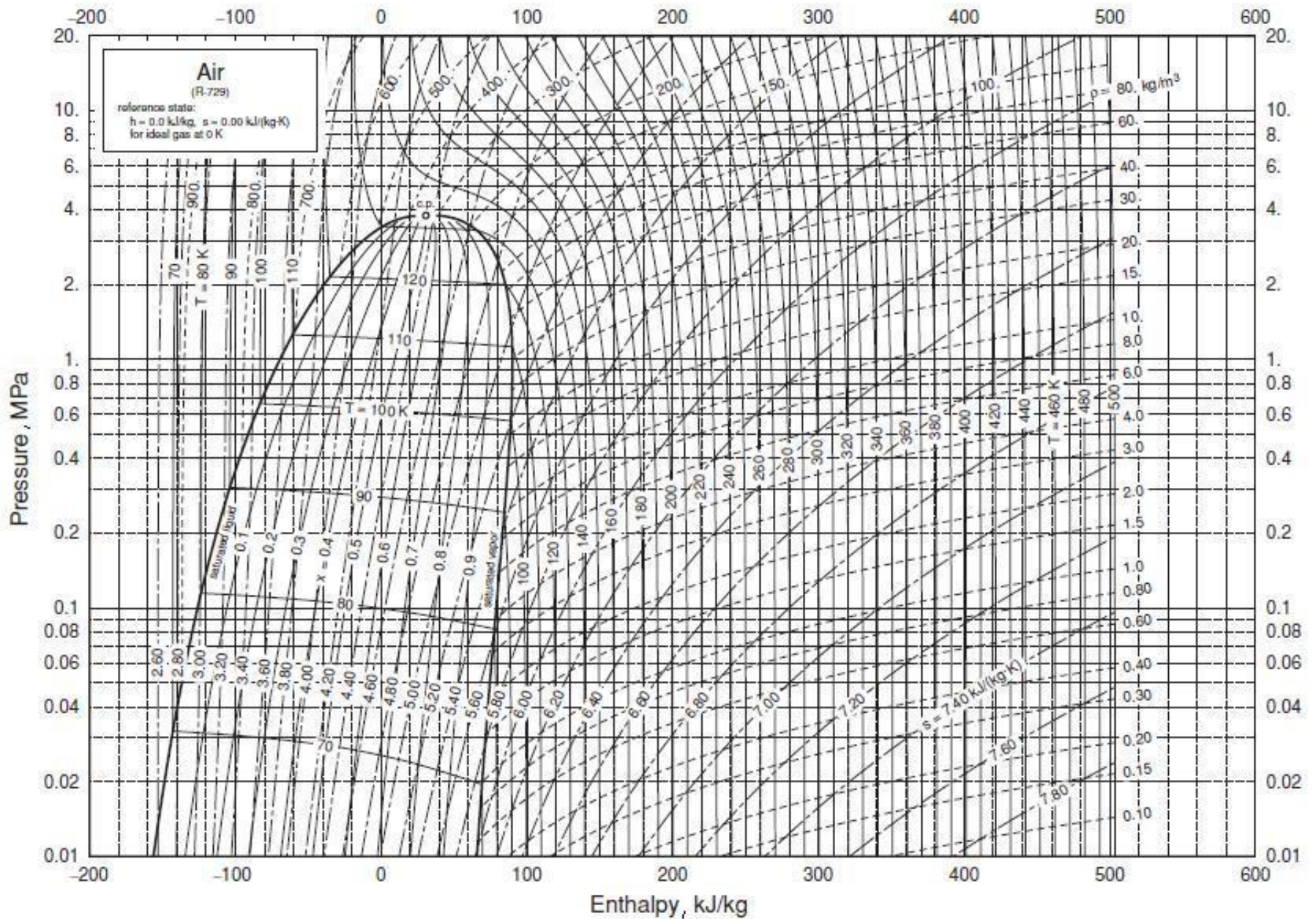
triple point  
59 K  
(O<sub>2</sub>, N<sub>2</sub>, Ar)

oxygen 54 K  
nitrogen 63 K  
argon 83 K



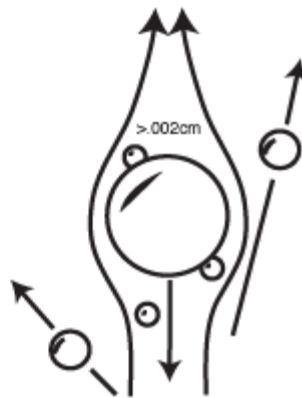
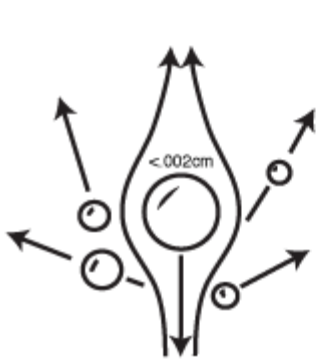
The freezing point lower than the components'  
(freezing-point depression)





# Size of particles, saturation

|                   |    |        |        |        |      |       |       |
|-------------------|----|--------|--------|--------|------|-------|-------|
| radius            | μm | 10     | 1      | 0,1    | 0,02 | 0,01  | 0,001 |
| Relative humidity | %  | 100,01 | 100,11 | 101,15 | 105  | 112,1 | 314   |



coagulation and dispersion of droplets

Equilibrium of forces:

- gravity ↓
- buoyancy ↑
- friction loss ↑
- surface tension ↑

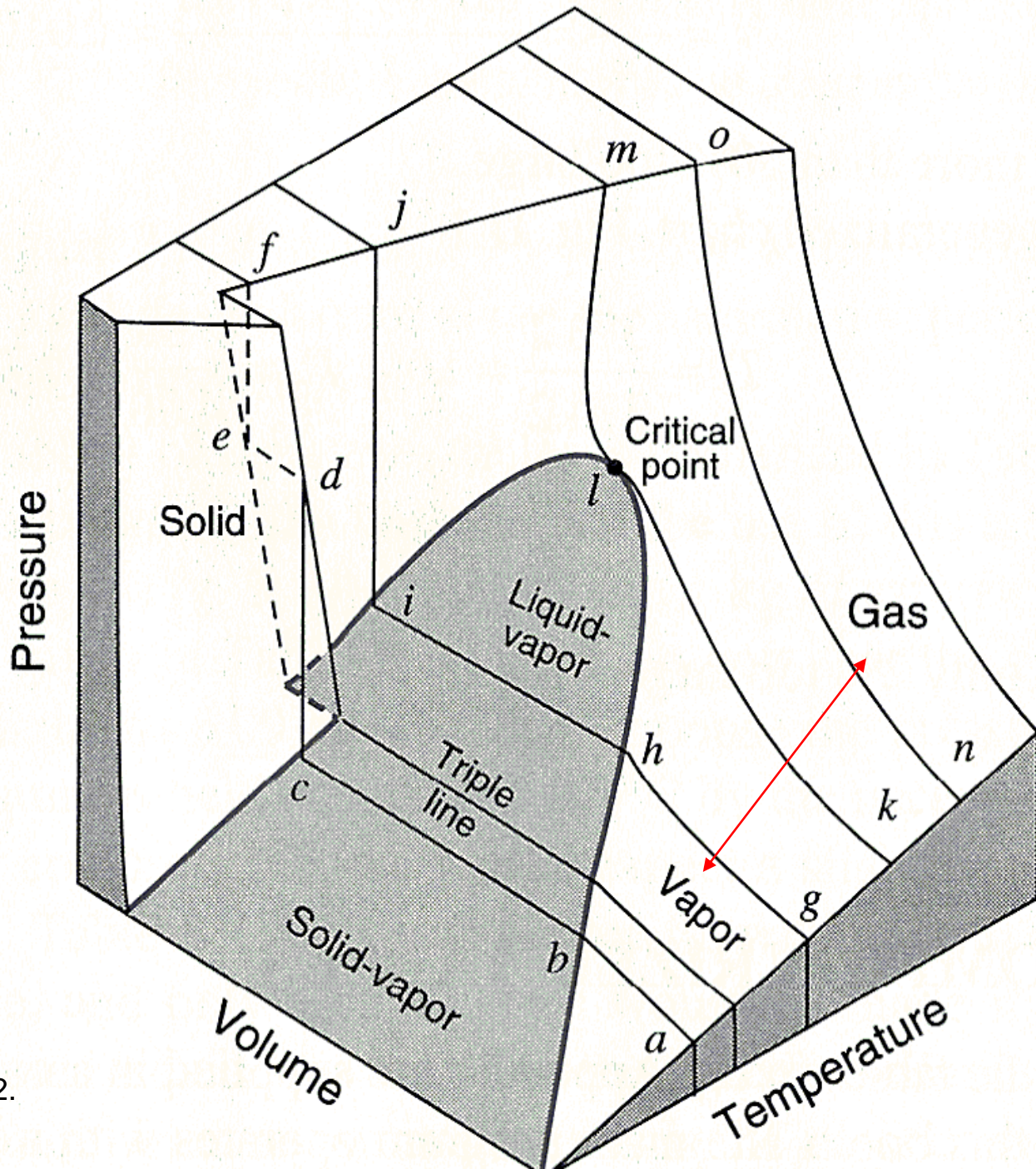
# Particle size and velocity of sedimentation

| p=900 hPa,<br>t=5°C | radius,<br>μm | velocity,<br>m/s | path length to<br>evaporation,<br>m |
|---------------------|---------------|------------------|-------------------------------------|
| cloud               | 1-100         | 0,00003-0,27     | 1                                   |
| drizzle             | 200-500       | 0,72-2,06        | 150                                 |
| raindrops           | -5000         | 9                | 4200                                |

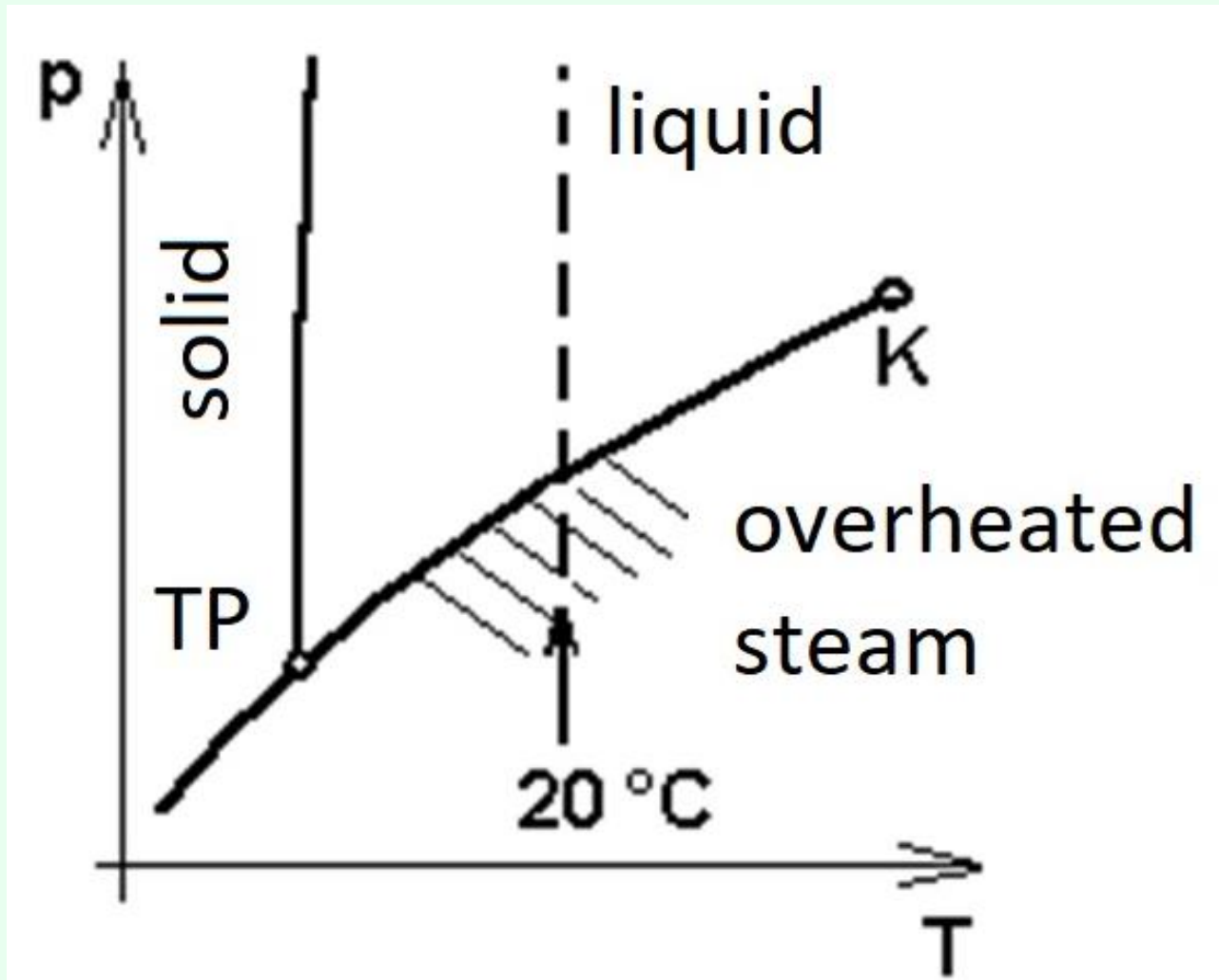
# State of components

The water can be:

1. superheated steam
2. saturated steam
3. saturated above water (vapor and liquid coexistent)
4. saturated above ice (vapor and solid)
  - 3.** fog, haze, cloud
  - 4.** frosty fog



# State of components



# Enthalpy of air

- $H=U+pV$  (full, extensive)
- $h=u+pv$  (specific, intensive)

$$dh = du + pdv + vdp$$

About isobaric circumstances  $dp=0$ , so:

$$dh = du + pdv = dq$$

# Enthalpy of air

1. Heat to warming the dry air only
2. Heat to warming the vapor
3. Heat to vaporising the water

Added all heat components each after the other



# Enthalpy of air

$$1. Q_a = c_a m_a \Delta T$$

$c$  isobaric heat capacity (air „a” or water vapor „w”)

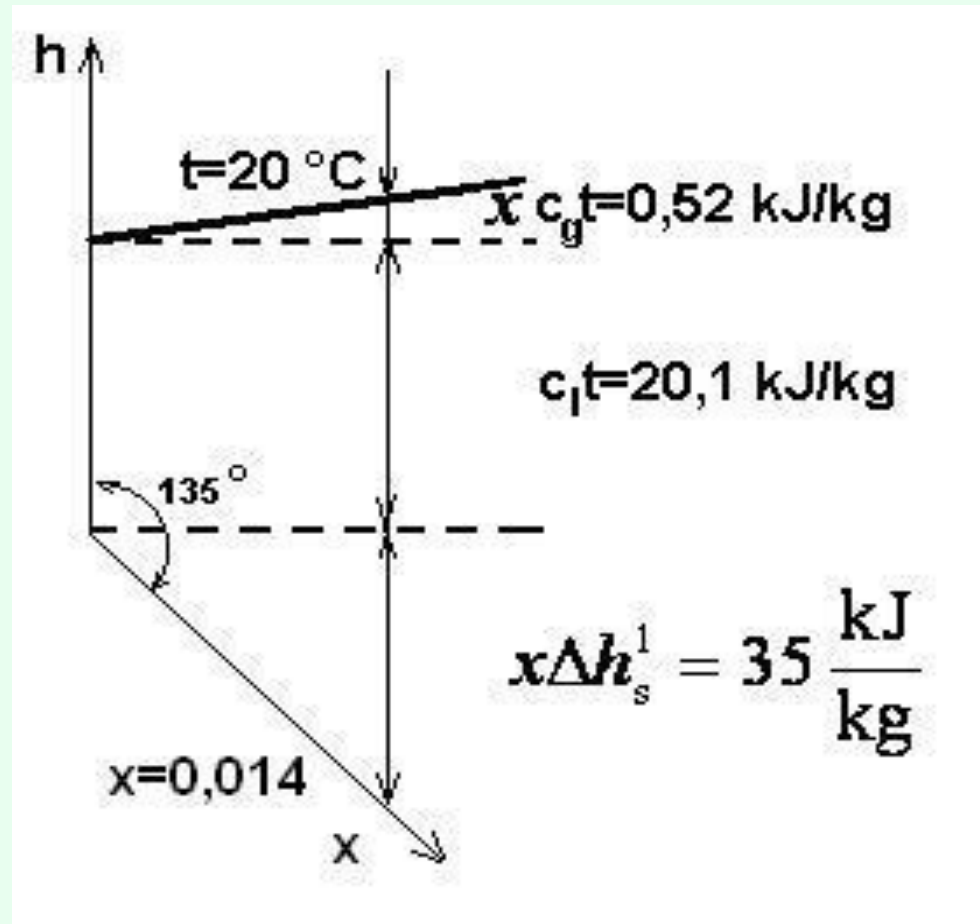
$$2. Q_w = c_w m_w \Delta T$$

$\Delta_{\text{vap}} H$  the heat of evaporation

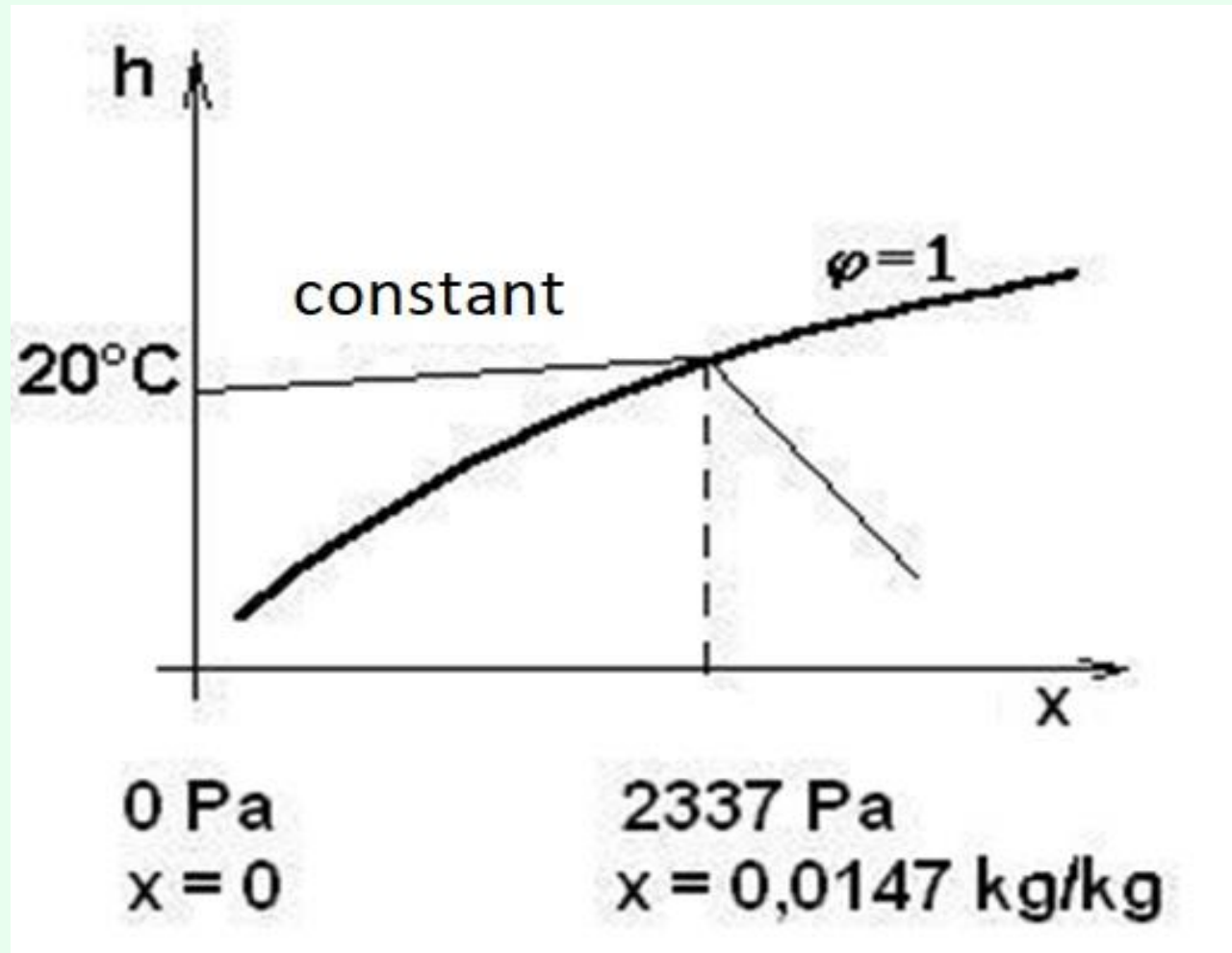
$$3. Q_{\text{vap}} = m_g \cdot \Delta_{\text{vap}} H$$

# Enthalpy of air

- Example: air at room temperature
- *Sensible enthalpy*: proportional to temperature



# Structure of Mollier's diagram



# Structure of diagram

The angle between axes is 135 grad. We don't use that part of the chart exists under a horizontal line

The direction of the zero centigrade is horizontal above the saturation limit, 135 grad in the fog

The saturation line is curved. The water above is oversaturated, below is fog or dew.

The name of mass ratio called absolute humidity (mixing ratio). Its unit is kg/kg; namely  $\text{kg}/\text{m}^3$

Read more about [the psychrometric diagram](#)

# Structure of diagram

$$1. Q_a = c_a m_a \Delta T$$

$$2. Q_w = c_w m_w \Delta T$$

---

$$1. Q_a = c_a m_a t_a$$

$$2. Q_w = c_w m_w t_w$$

We can simplify the equations selecting the unit of temperature to centigrade. The start point of diagram fits to the zero centigrade

*The temperature of components in mixture are equal*

# Structure of diagram

$$3. Q_{\text{vap}} = m_w \Delta H$$

$\Delta_{\text{vap}} H$  heat of vaporisation

$\Delta_{\text{fus}} H$  heat of fusion

$\Delta_{\text{vap}} H + \Delta_{\text{fus}} H = \Delta_{\text{sub}} H$   
heat of sublimation

$$\Delta_{\text{vap}} H = 2500,38 \text{ kJ/kg}$$

$\Delta H_{\text{lg}}$  g=gas

$$\Delta_{\text{fus}} H = 333,15 \text{ kJ/kg}$$

$\Delta H_{\text{sl}}$  l=liquid

$$\Delta_{\text{vap}} H + \Delta_{\text{fus}} H = 2833 \text{ kJ/kg}$$

$\Delta H_{\text{sg}}$  s=solid

# Structure of diagram

$$3. Q_{\text{vap}} = m_w \Delta_{\text{vap}} H$$

Initial state: liquid. This is why the equation contains the heat of vaporisation (enthalpy of vaporisation)

- The enthalpy **decreases** when the water is solid because of heat of fusion.
- The enthalpy **increases** when the water is gaseous because of heat of vaporisation.

# Enthalpy of air

Let's calculate the enthalpy

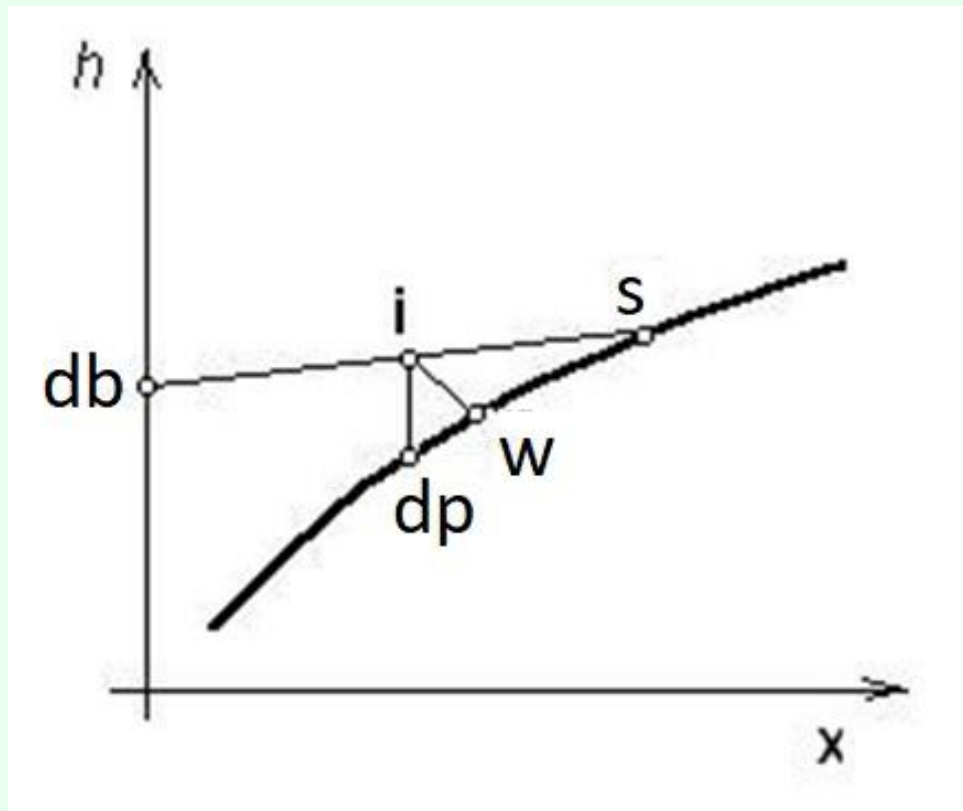
$$\Delta H = c_a m_a t + c_w m_w t + m_w \Delta_{\text{vap}} h$$

$$\Delta h = \frac{c_a m_a t}{m_a} + \frac{c_w m_w t}{m_a} + \frac{m_w \Delta_{\text{vap}} h}{m_a}$$

$$\Delta h = c_a t + x c_w t + x \Delta_{\text{vap}} h = c_a t + x (c_w t + \Delta_{\text{vap}} h)$$



# Relative humidity



db=dry bulb

s=saturated

i=actual state

between them

laying on the

same

isotherm

# Relative humidity

$$\varphi = \frac{p_i}{p_s} = \frac{Y_i}{Y_s}$$

The relative humidity is the ratio of the actual and the saturated partial pressure

We can not define it in case of the fog; the air consists vapor and liquid water (below zero centigrade ice, too)

# Equations

Antoine state equation (water)

[NIST chemistry webbook](#)

$$\log_{10} p_{bar} = 5,40221 - \frac{1838,675}{T_K - 31,737}$$

$$\ln p = A + \frac{B}{T + C} + DT + ET^2 + F \ln T$$

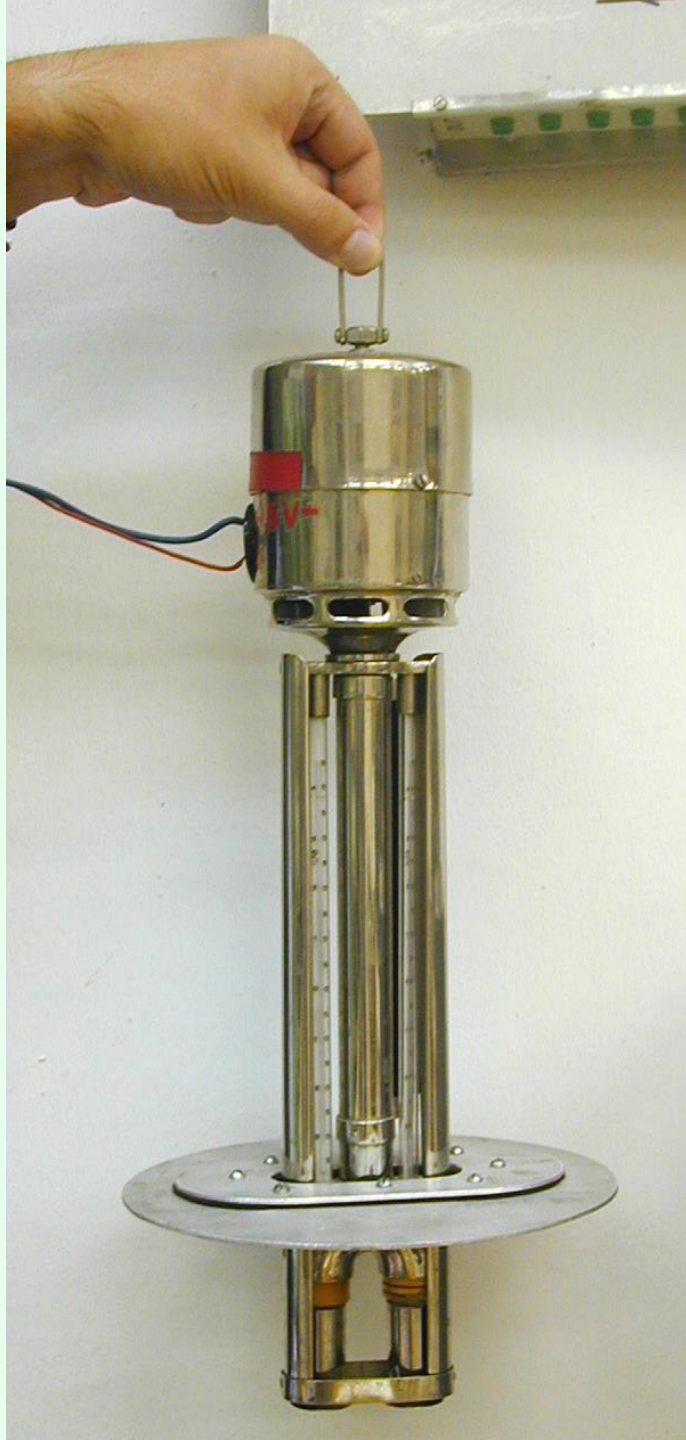
(B is negative for water)

Clausius–Clapeyron-equation:

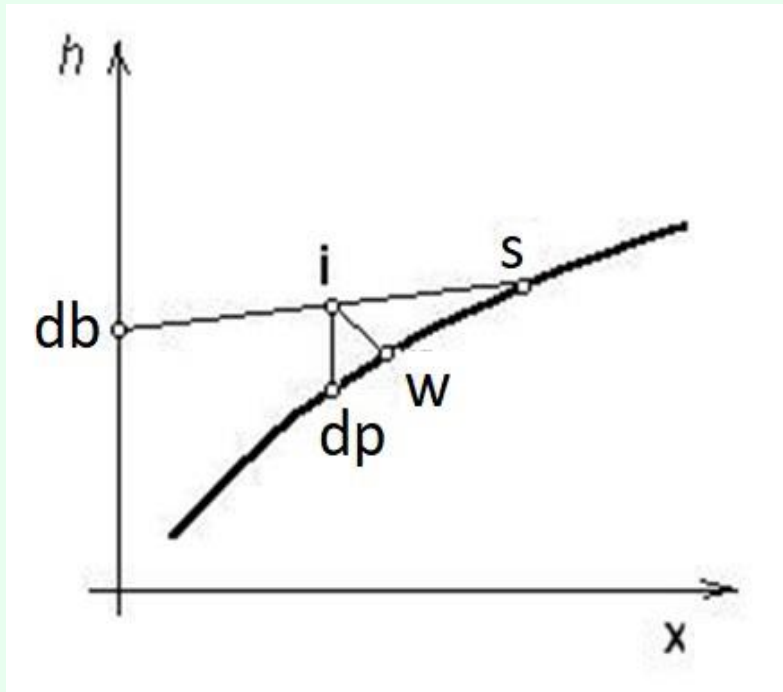
$$\log_{10} p_{Pa} = -\frac{2311,711}{T_K} + 11,255$$

# Assman aspiration- psychrometer wet-and-dry bulb thermometer

2023. 04. 22.



# Psychrometer



- dry bulb thermometer **db...s** isotherm line
- Wet bulb thermometer the **w** saturated state
- The **i..w** line fits on an isenthalpic line (called adiabatic line)

db = dry bulb, dp = dew point

# Psychrometer

$$dh = du + pdv + vdp$$

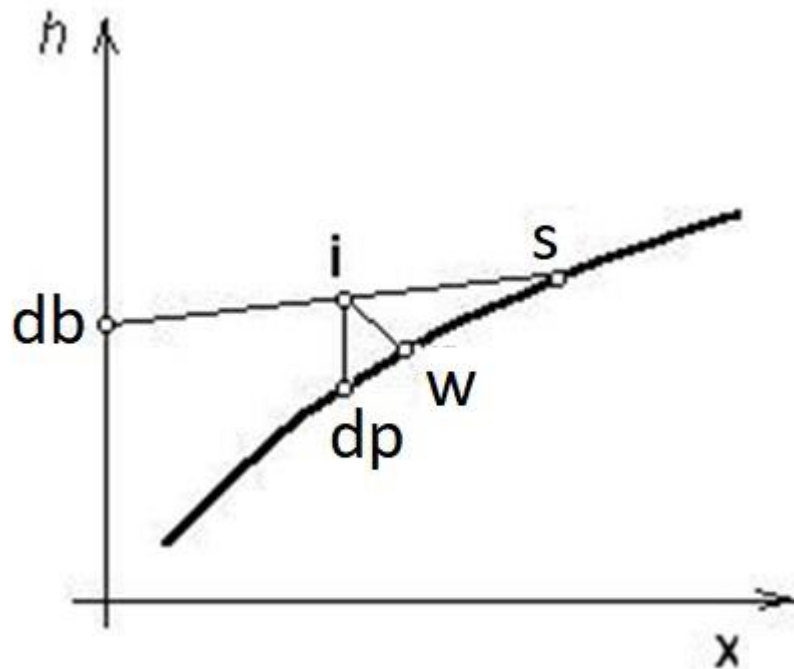
$$dh_{\text{isobar}} = du + pdv = dq$$

Between **isobaric** circumstances the third member is zero, so the heat and the change of enthalpy are equal. Hence the adiabatic and the isenthalpic change of state are identical

# Psychrometer

- At industrial measuring we don't follow the direction of the isenthalpic lines but the elongation of the **fog isotherms**

# Dew point



Starting from the **i** real state of air we draw a vertical line down to the saturation point **dp**

$db$  = dry bulb,  
 $s$  = saturated vapor



# The fog

## Separated phase

1. The fog contains separated droplets, with own boundary surface. Inside the droplets only water exists
2. In extreme circumstances the water get separated, and is deposited on the surrounding equipment's (puddle, splash, rain)

# The fog

| component    | mass fraction       | mass concentration      | volume fraction                    |
|--------------|---------------------|-------------------------|------------------------------------|
| i            | $w_i, \text{kg/kg}$ | $\rho_i, \text{kg/m}^3$ | $\varphi_i, \text{m}^3/\text{m}^3$ |
| vapor        | 0,0089              | 0,01098                 | 0,001434                           |
| liquid water | 0,0019              | 0,0024                  | 0,0000024                          |
| dry air      | 0,9891              | 1,2182                  | 0,98565                            |
| Sum of all   | 1                   | 1,2316                  | 1                                  |

# Thermodynamic process

The special thermodynamic process cannot be interpreted because

- They are valid only one-component thermodynamic systems
- Following the line any of thermodynamic process we would force the mixture to change of its composition
- The special thermodynamic process can be drawn only in the 3D-space

# Thermodynamic process

## Isotherm process

When the water content is increasing, they are almost horizontal lines up to the saturation point, and bend at 135 grad (if the temperature greater than zero)

# Thermodynamic process

## Isochoric process

When the water content is increasing they are bending upward. We don't speak about isochoric processes in case of fog. The volume of liquid water almost ten thousandth of steam

# Thermodynamic process

## Isobaric process

All part of diagram related to standard air pressure. So any straight or curved line is isobaric. More of this diagrams calculated for 100000 Pa.

The standard atmosphere in U.S. is 101325 Pa (NIST)

The standard atmosphere is 100000 Pa (International Standards Organization)

# Thermodynamic process

## Adiabatic process

The adiabatic process parallel to the isenthalpic process.

The diagram calculated from the composition so their lines pitch is 135 grad

This is why the isentropic lines are missing.  
They would be an other group of parallel lines.

# Thermodynamic process

An example: the specific entropy can be calculated (first member is analogous the internal energy, the second is analogous the work)

$$\Delta s = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$



# Thermodynamic process

Composition of the mixture

This is called to absolute humidity.

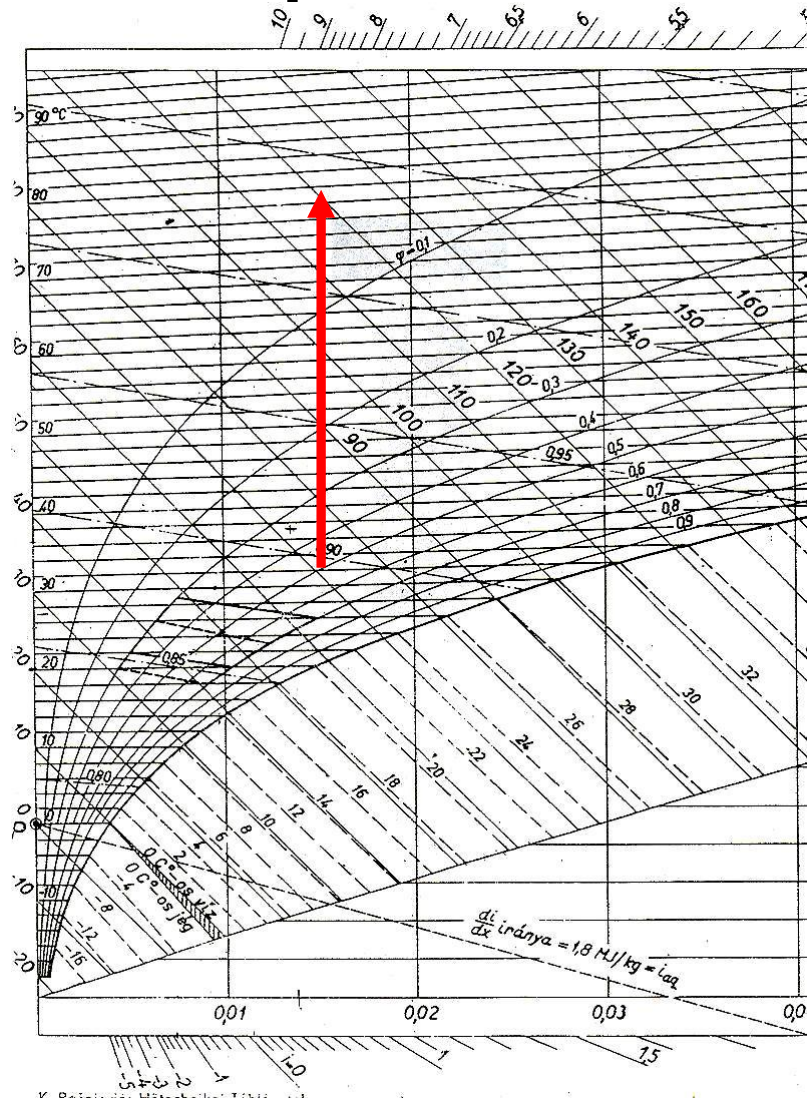
The lines are straight vertical lines.

Their values were calculated from the partial pressure of water.

Consequently the lines of the partial pressure also straight vertical lines.

# Thermodynamic process

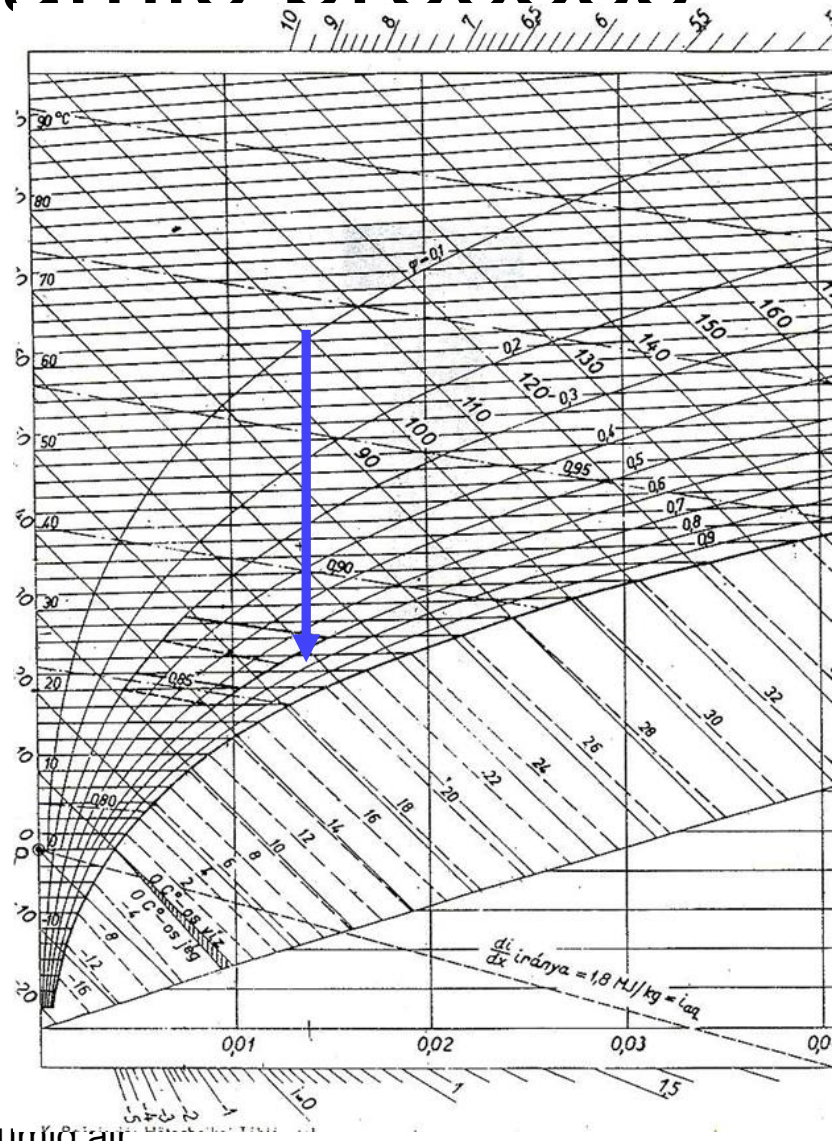
**Heating** on plate  
heat exchanger:  
Vertical straight lines.  
They are directed to  
the increasing  
enthalpy values



# Thermodynamic process

**Cooling** on plate heat exchanger:

Vertical straight lines. They are directed to the decreasing enthalpy values



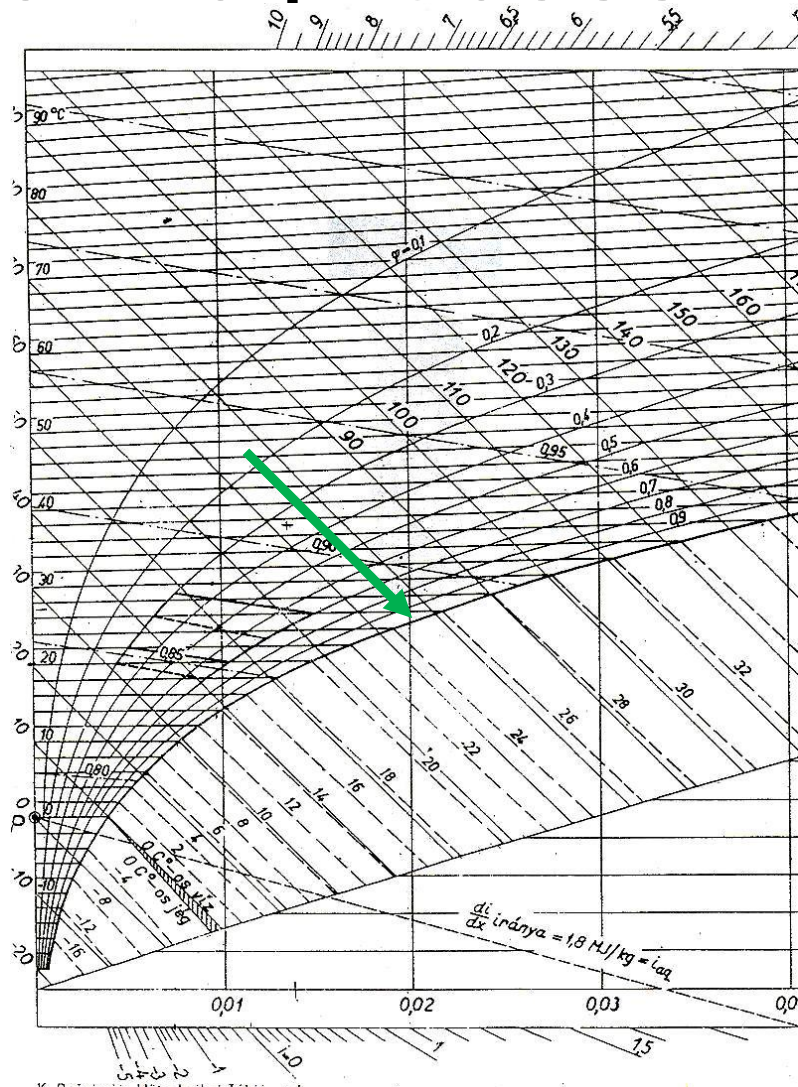
# Thermodynamic process

## Adiabatic wetting

Evaporation of water.

These lines are parallel to the enthalpy lines so that the composition of mixture is growing.

Applications: air condition unit, drying in food technology



# Thermodynamic process

Evaporation of water at constant temperature:

Application: air conditioning unit from water pipeline. The line of change of state follows the direction of fog isotherms

# Thermodynamic process

Mixing different air quanta

The enthalpy and the composition can be calculated according the method of weighted mean

# Mixing

## Temperature

Good approximation can be calculated if we don't cross the borderline of the fog region.

The inaccuracy comes from the dependency of the specific heat capacity of the temperature

# Mixing

Temperature

Crossing the border line of the fog region we have to calculate the heat of vaporisation



# Mixing

Volume, specific volume

Good approximation can be calculated if we don't cross the borderline of the fog region

The specific volume depends on the temperature

In case of condensation the volume of water ten thousandth of the vapor so we can't obtain this data in the fog region

# Mixing

## Partial pressure

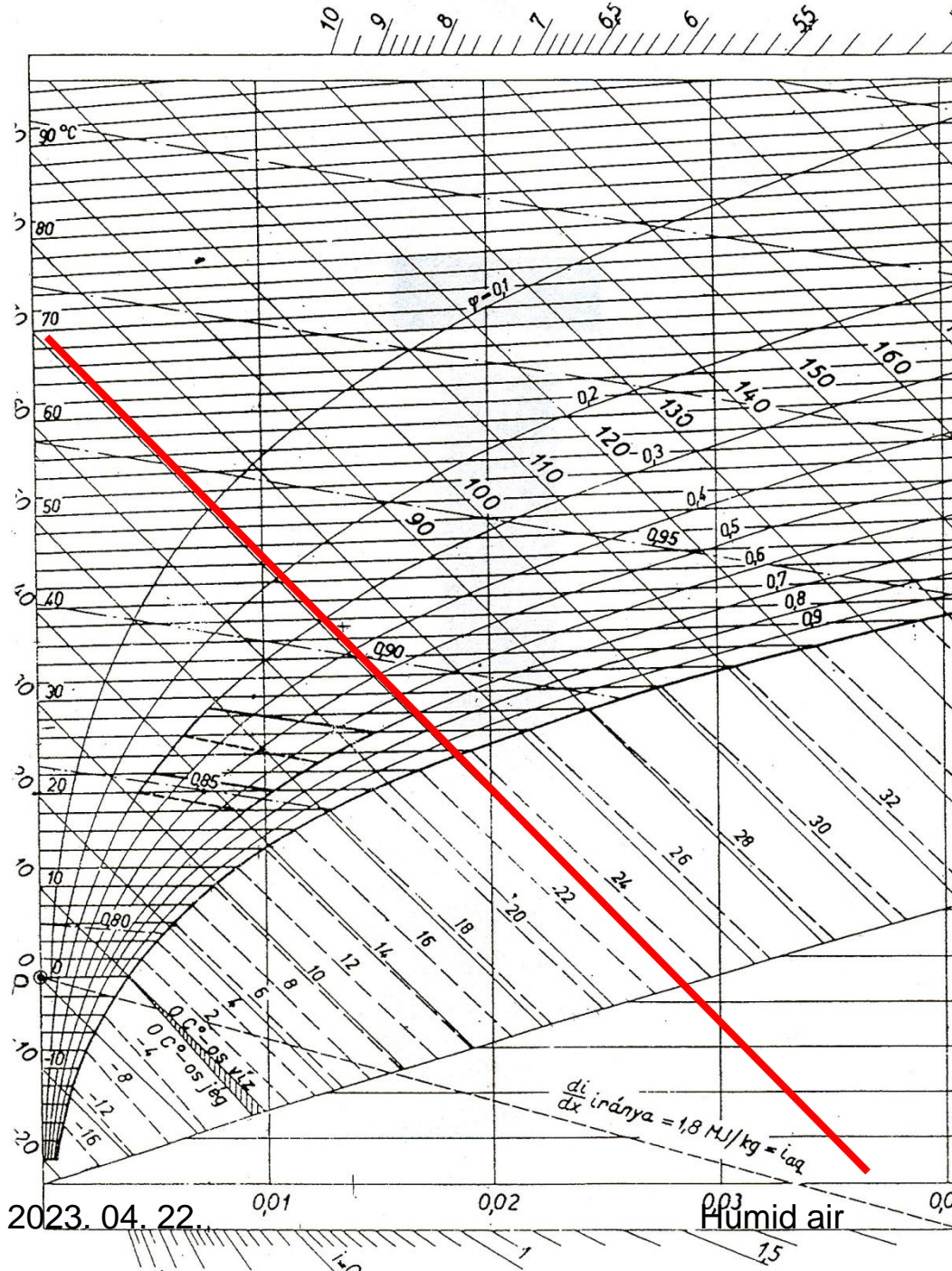
The partial pressure analogous the mixing ratio (absolute humidity) drawn on the horizontal axis. So it is correctly calculated at mixing.

# Mixing

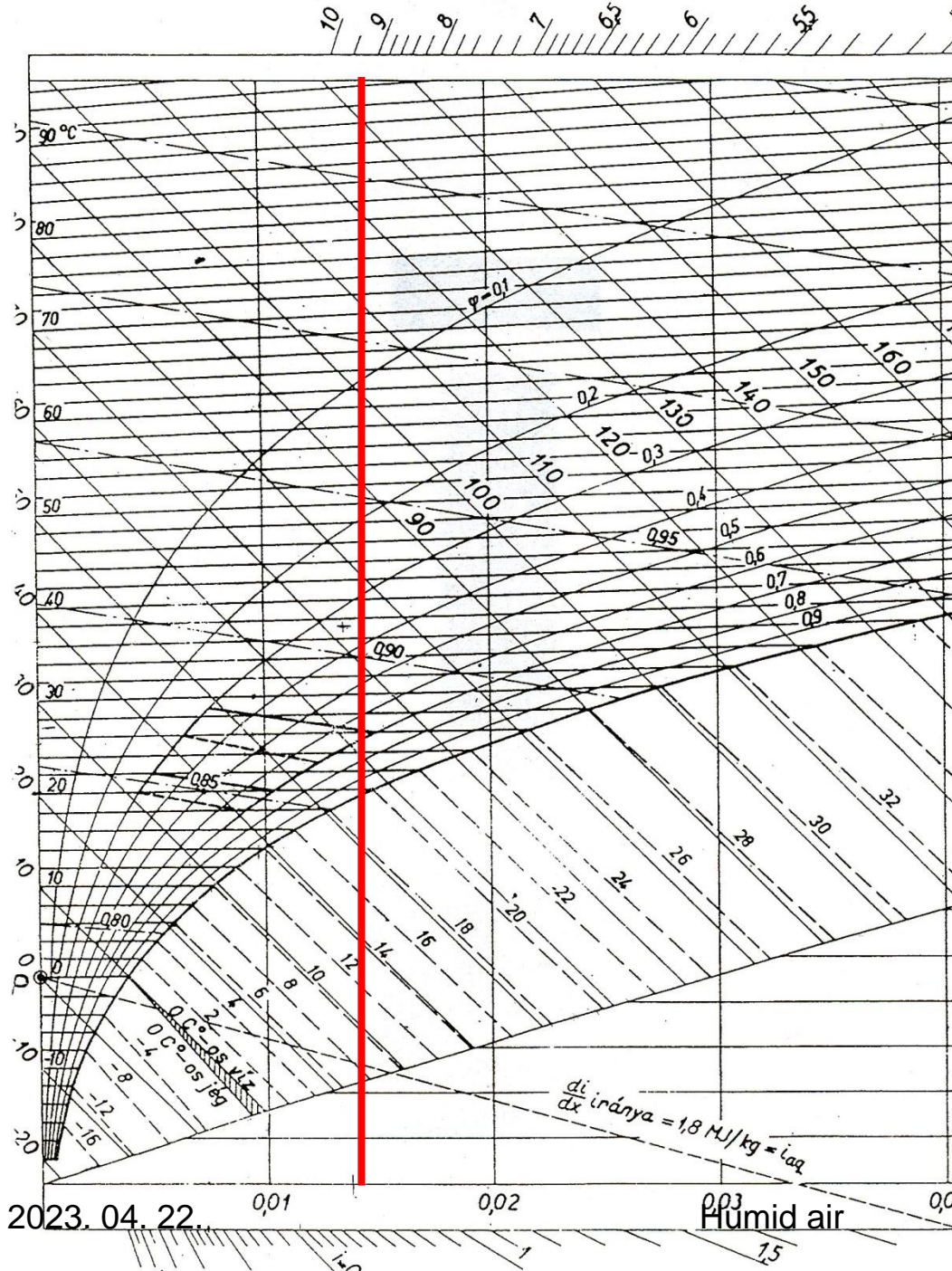
Relative humidity

The relative humidity cannot be calculated using the weighted mean method.

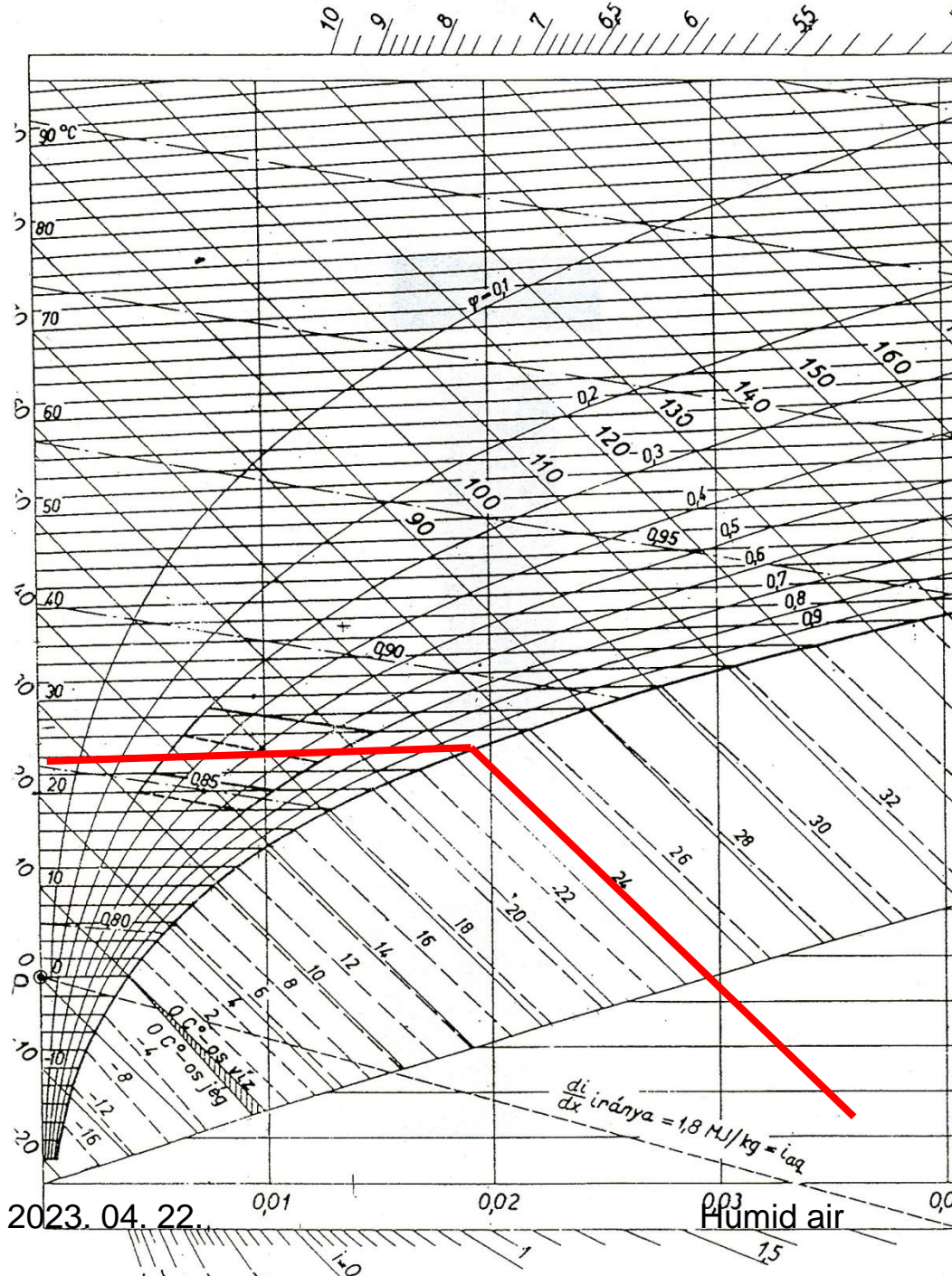
Mainly the result is greater than any of the mixed air amounts



Constant specific enthalpy line (example: 70 kJ/kg)

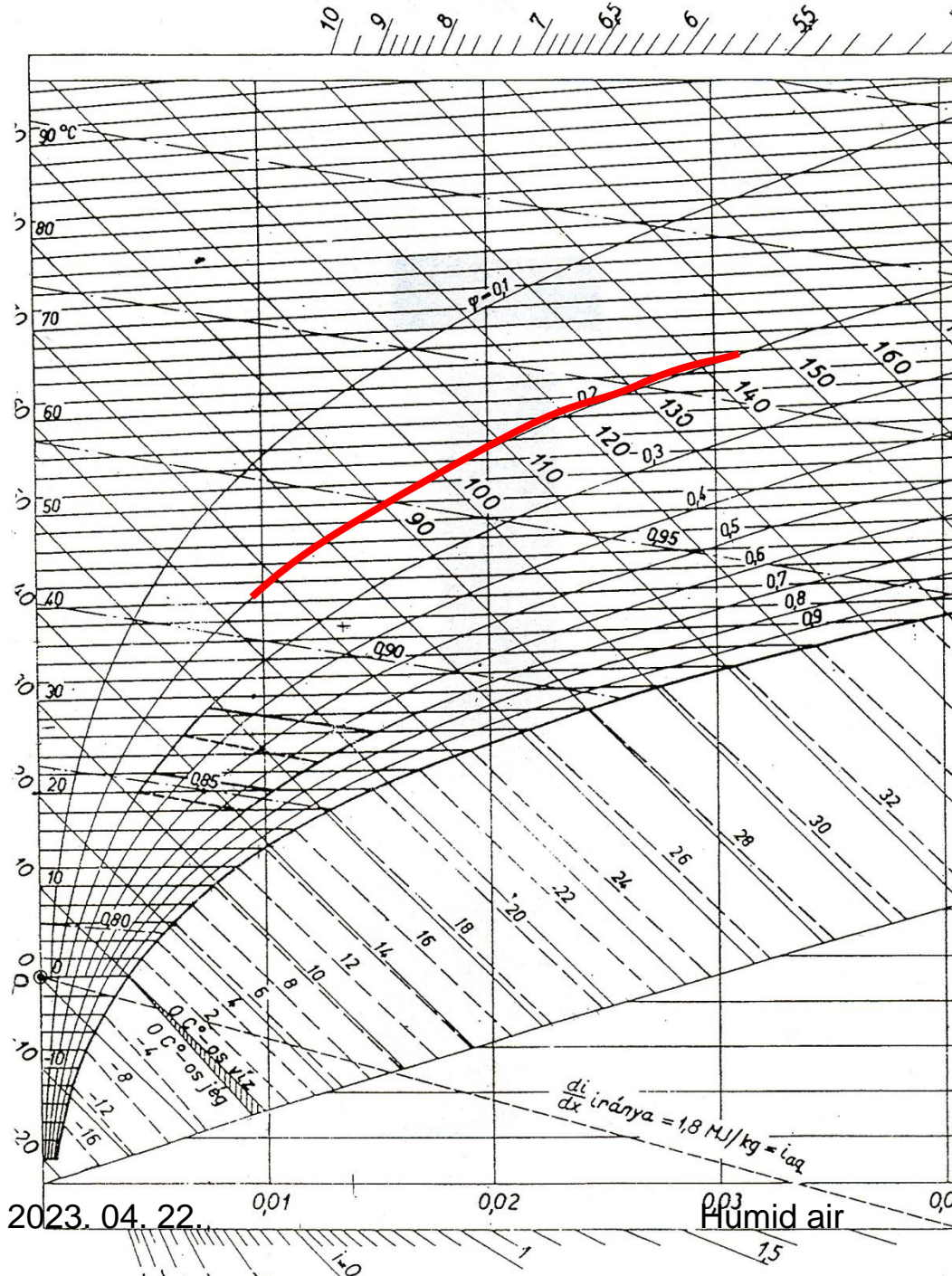


Constant absolute humidity (mixing ratio, or mass ratio) (example: 0,014 kg/kg)



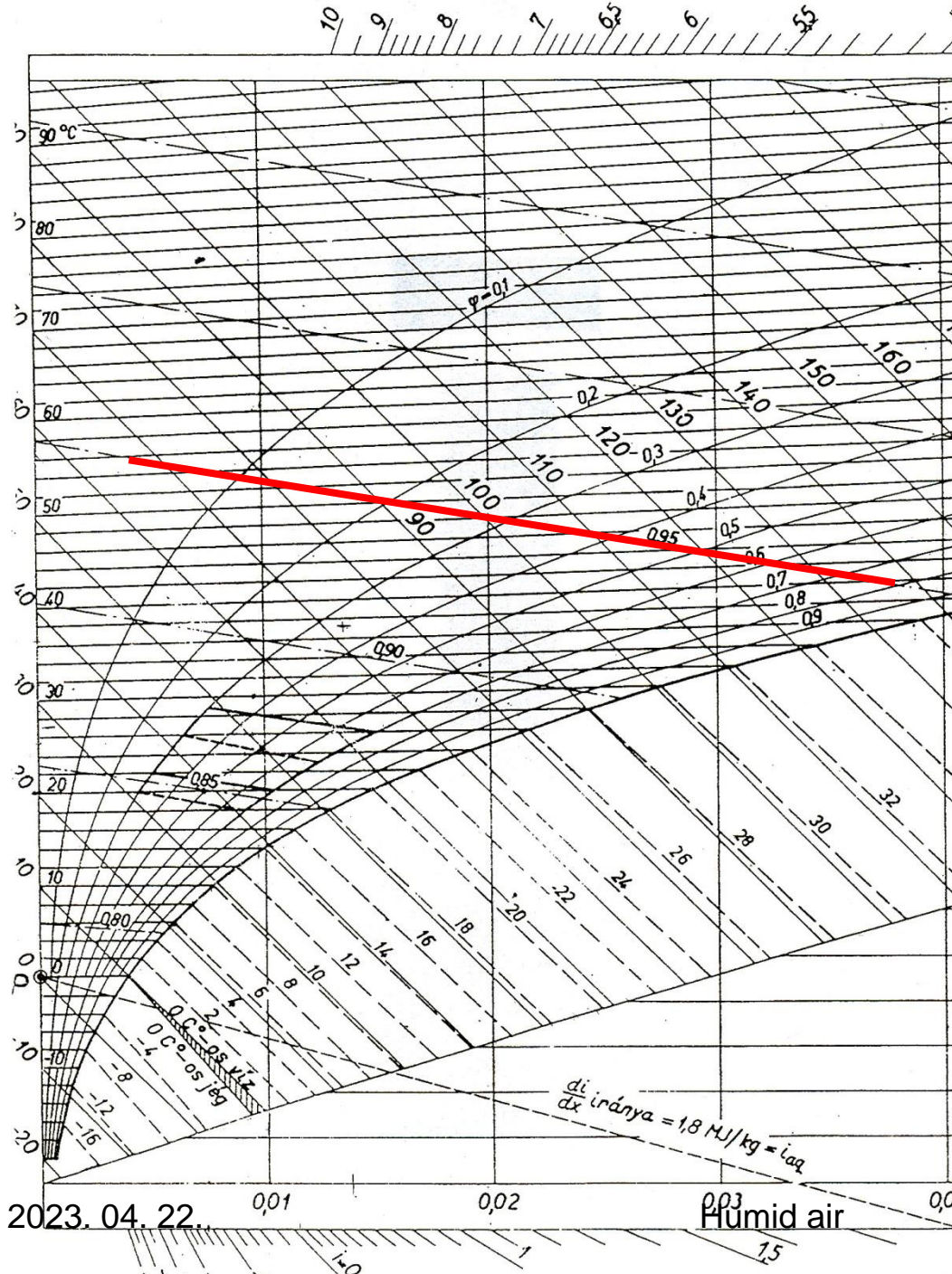
Constant temperature (example: 24 °C)

Namely is missing below the line needed to calculate the partial pressure



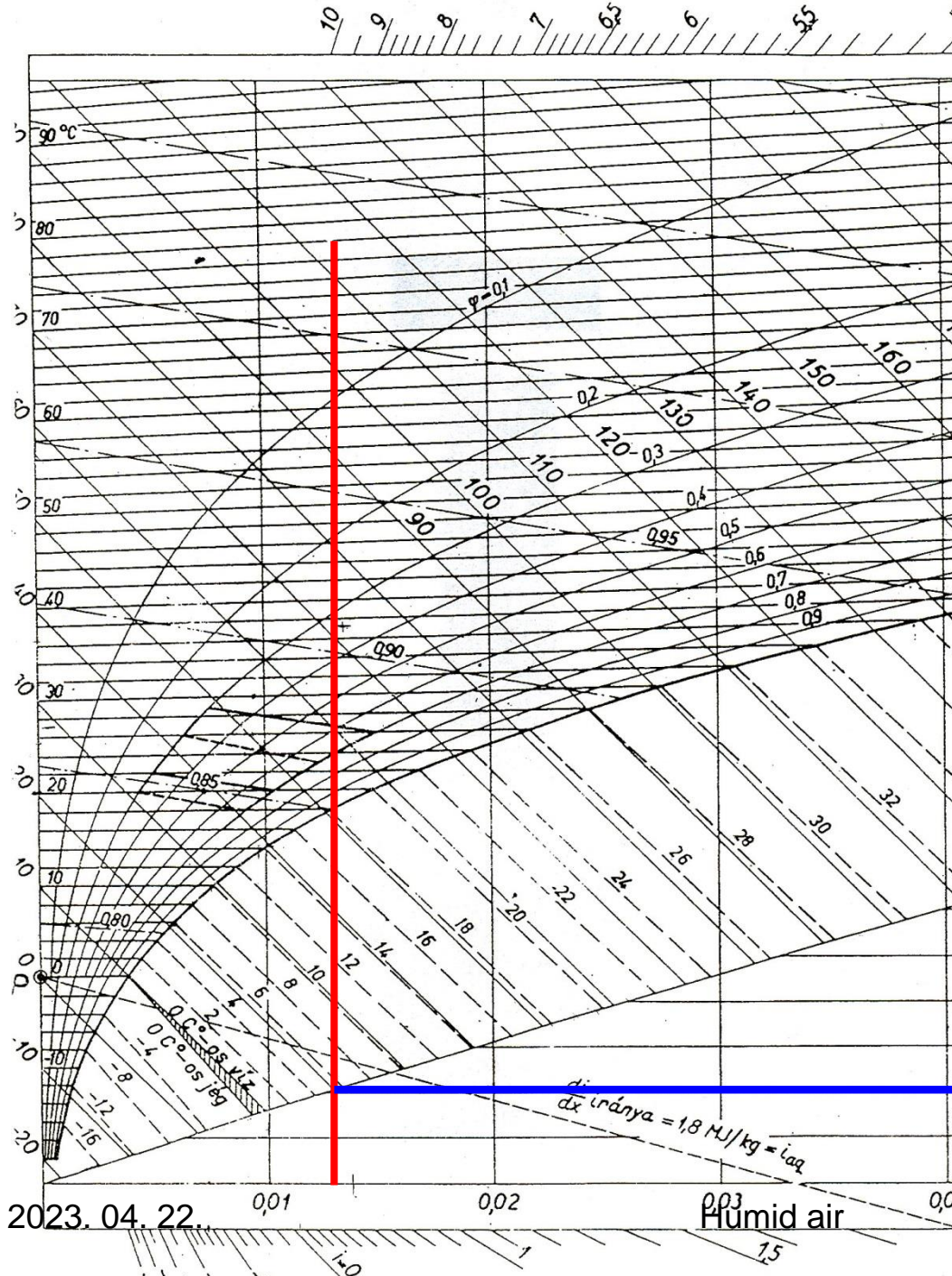
Constant relative humidity  
(example: 0,2)

Namely expressed as percentage



Constant specific volume (example:  $0,95 \text{ m}^3/\text{kg}$ )

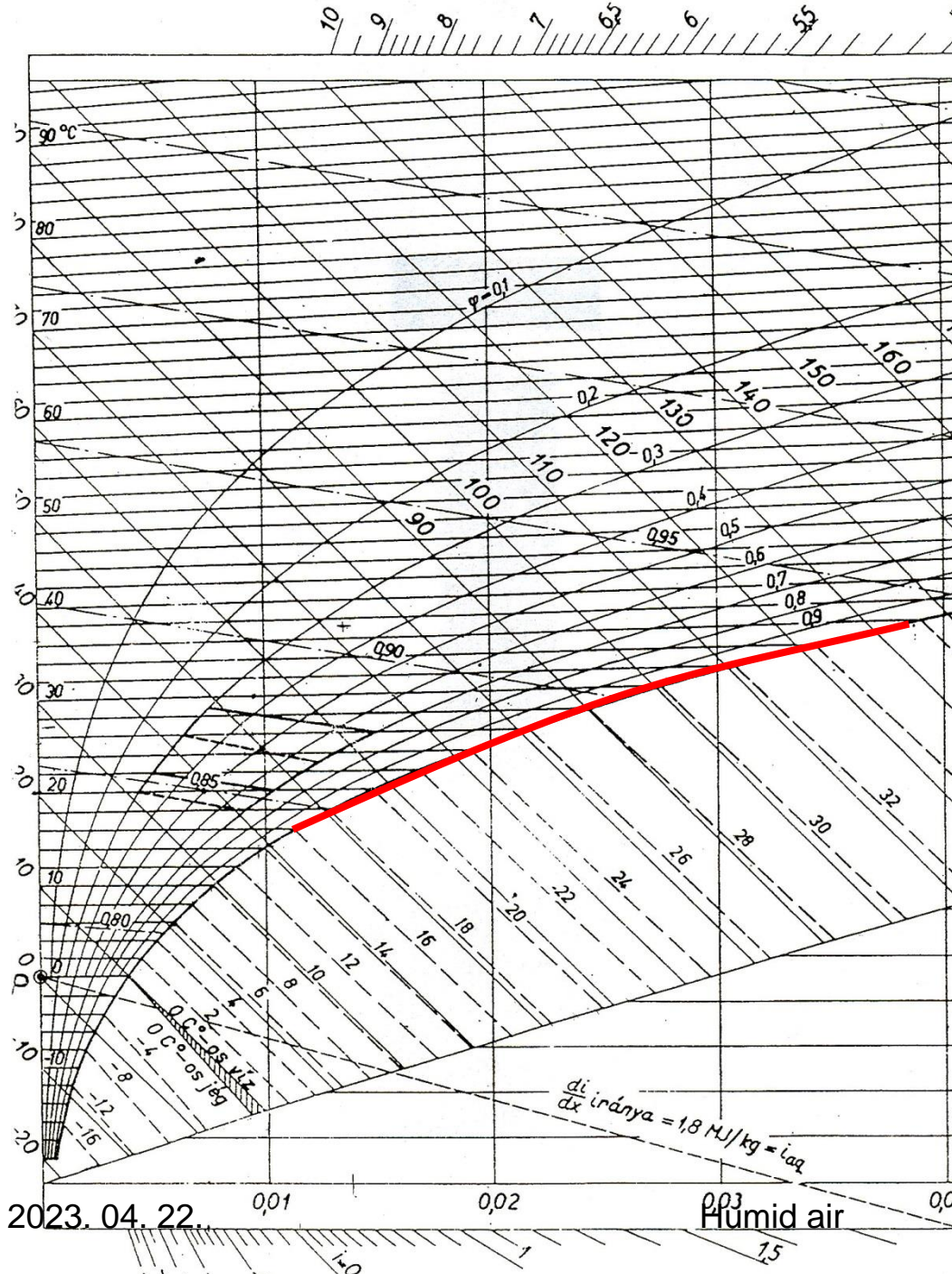




**Red line:** constant specific pressure (example: 20 hPa, which is equal to 2000 Pa)

Using the straight-edge (isopleth) line we read its value at another axis (**blue arrow**)

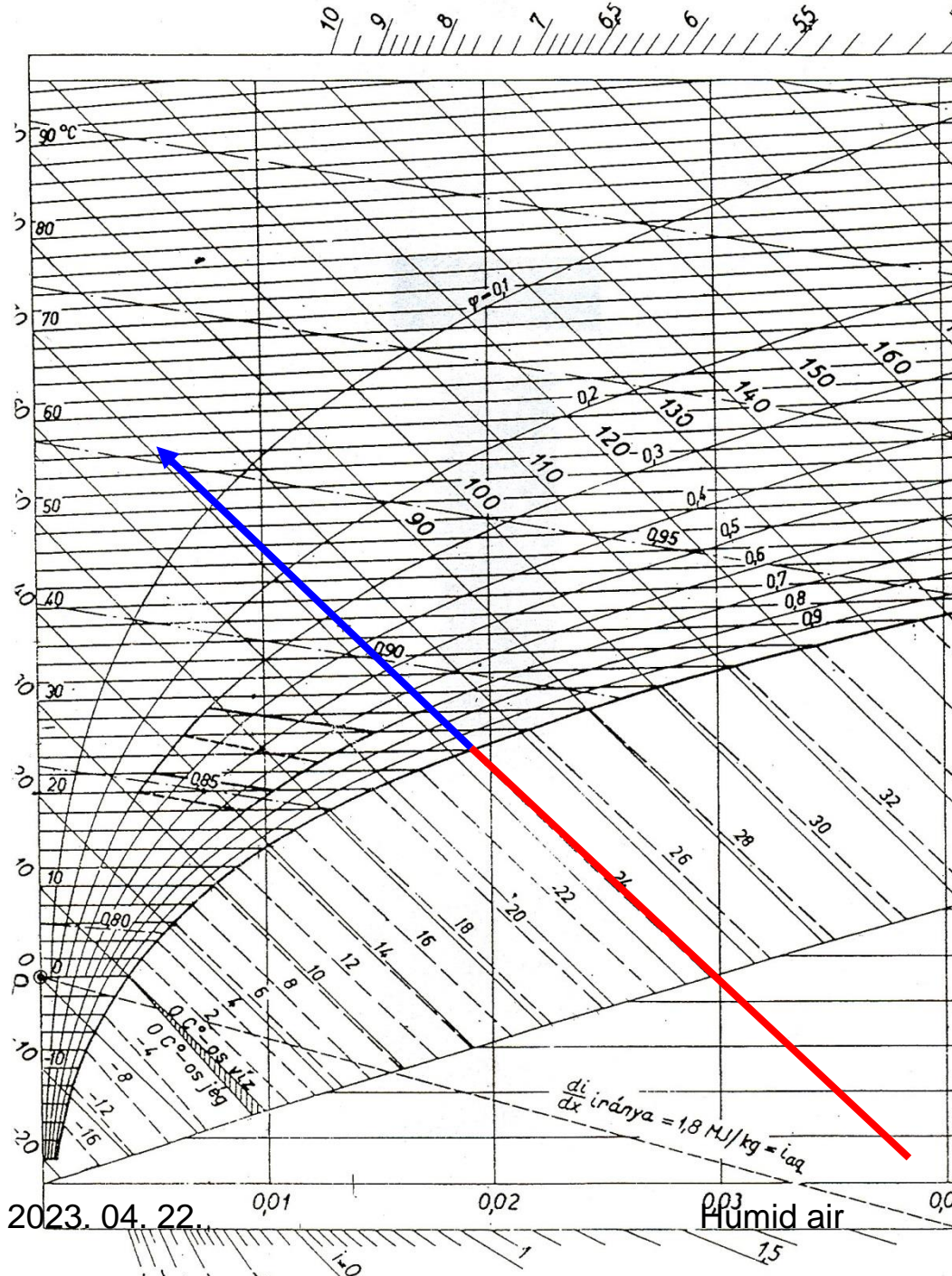
Namely the old unit mbar is drawn  
 20  
 1 mbar = 1 hPa



Border line of saturation

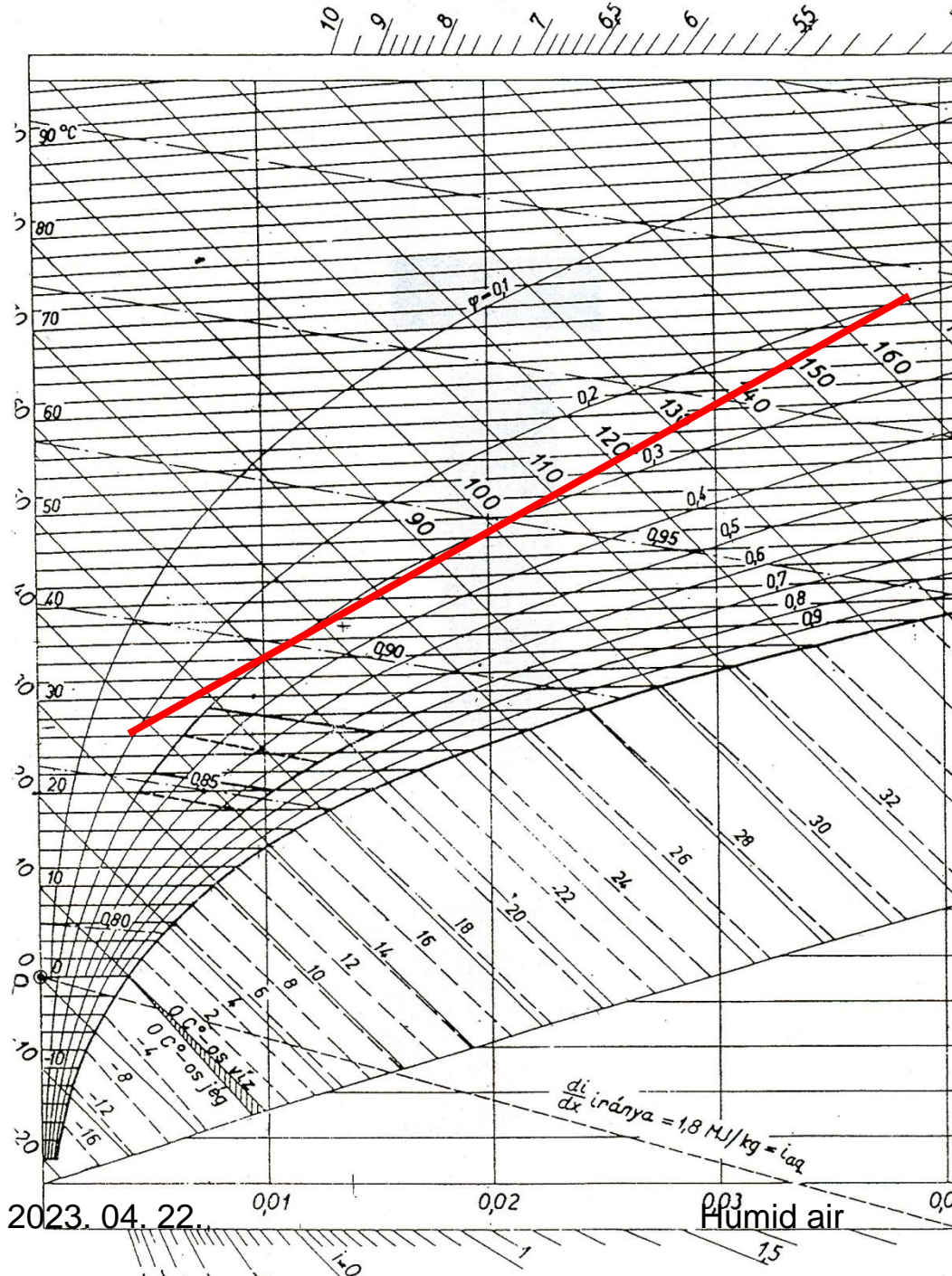
Above: the water is gaseous (steam, vapor)

Below: fog region



## Elongation of fog isotherms

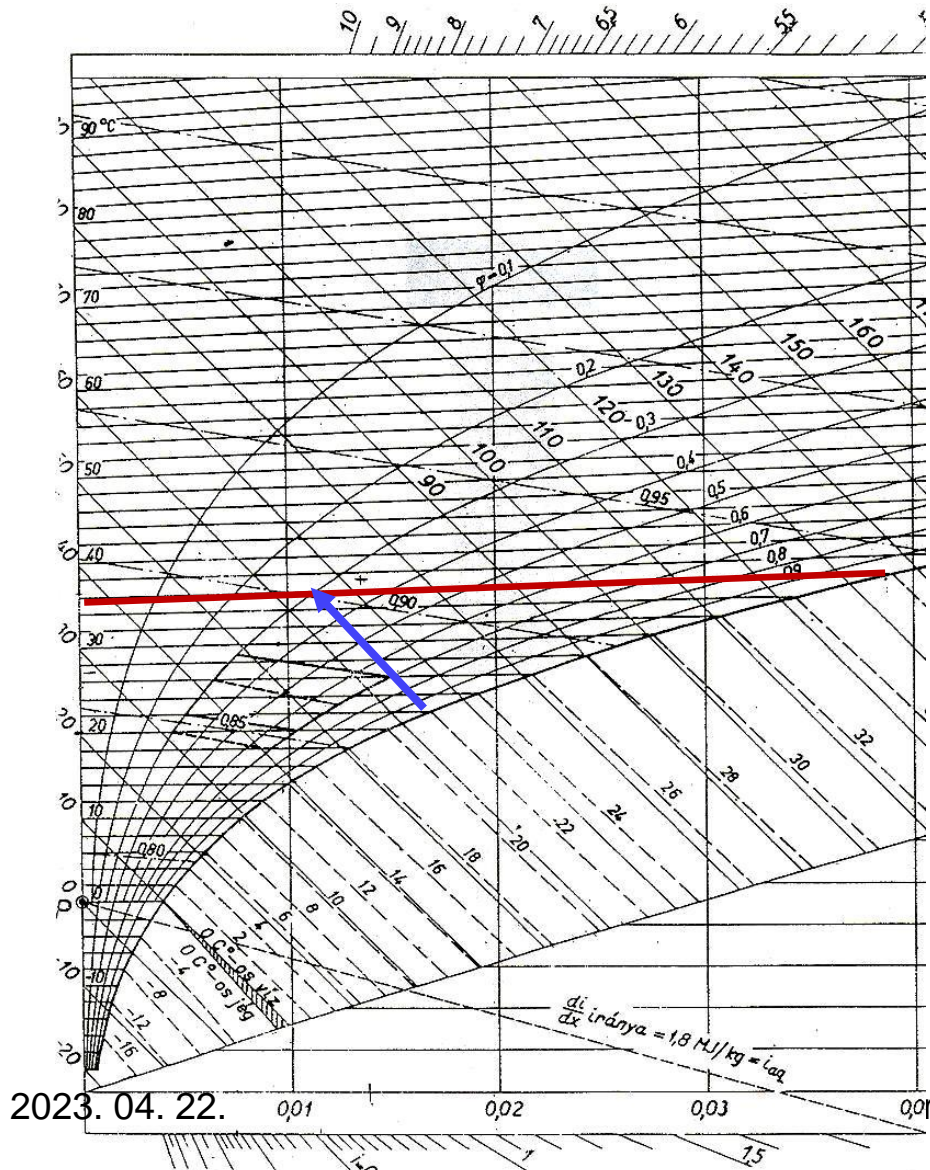
Fog isotherm line (example: 24 °C)



Mixing cold and warm air quanta

(example: 26 °C 19%, *left*, mixed 69 °C temperature and 20% partial humidity; *right above*)

# Reading of the psychrometer



**Dry bulb temperature: 36 °C**

**Wet bulb temperature: 22 °C**

Real state of air: crossing point of red and blue lines

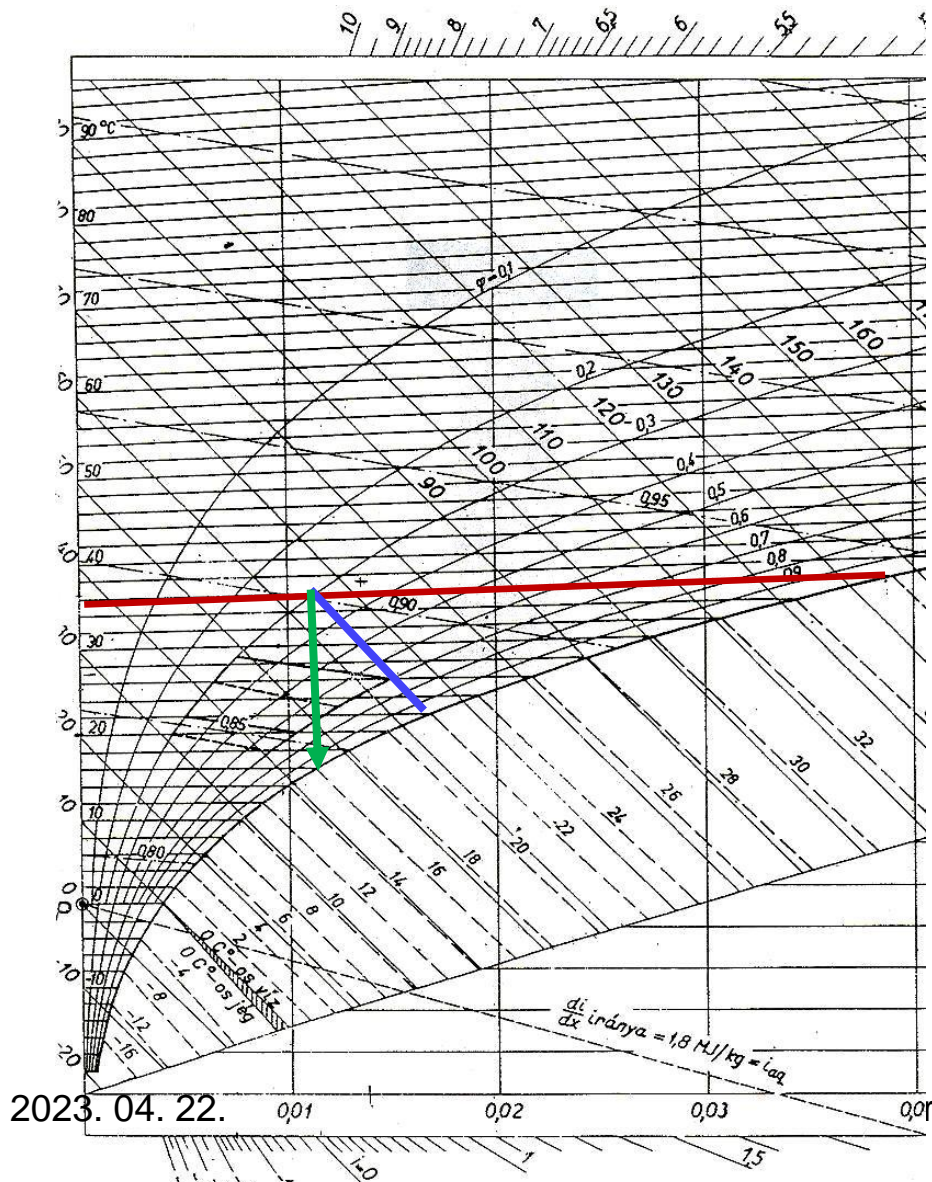
$x=0,012$  kg/kg

$h=66$  kJ/kg

$v=0,9$  m<sup>3</sup>/kg

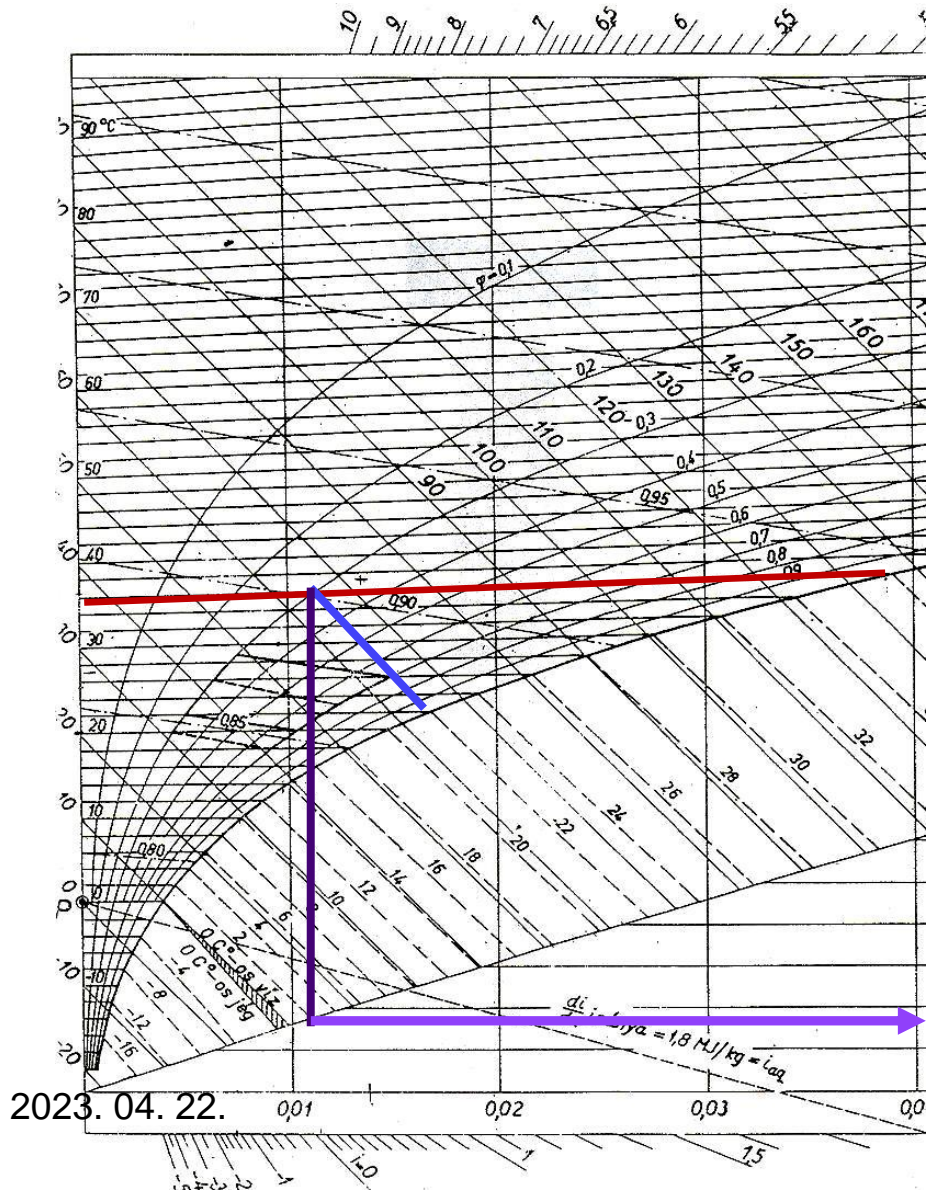
$\varphi=0,3$ ; or 30 %

# Reading of the psychrometer



Dry bulb temperature: 36 °C  
Wet bulb temperature: 22 °C  
Real state of air at the crossing point  
Dew point: 16 °C  
(vertically down to the saturation line)

# Reading of the psychrometer



Dry bulb thermometer: 36 °C

Wet bulb thermometer: 22 °C

Real state of air: crossing of red and blue lines.

Dew point: 16 °C

Partial pressure:

We draw a vertical line down to the nomogram isopleth line, following it a horizontal line to the secondary axis

The whole chart consists of the pressure numbers. The horizontal lines belong to the 0, 10, 20, 30... hPa values (scaled with 10 hPa each other). The violet line can be found between the 10 and the 20. So **p = 18 hPa = 1800 Pa**

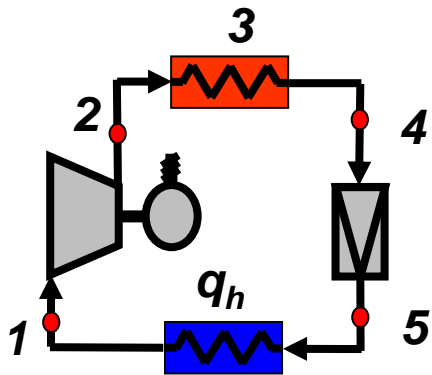




# Refrigeration cycle

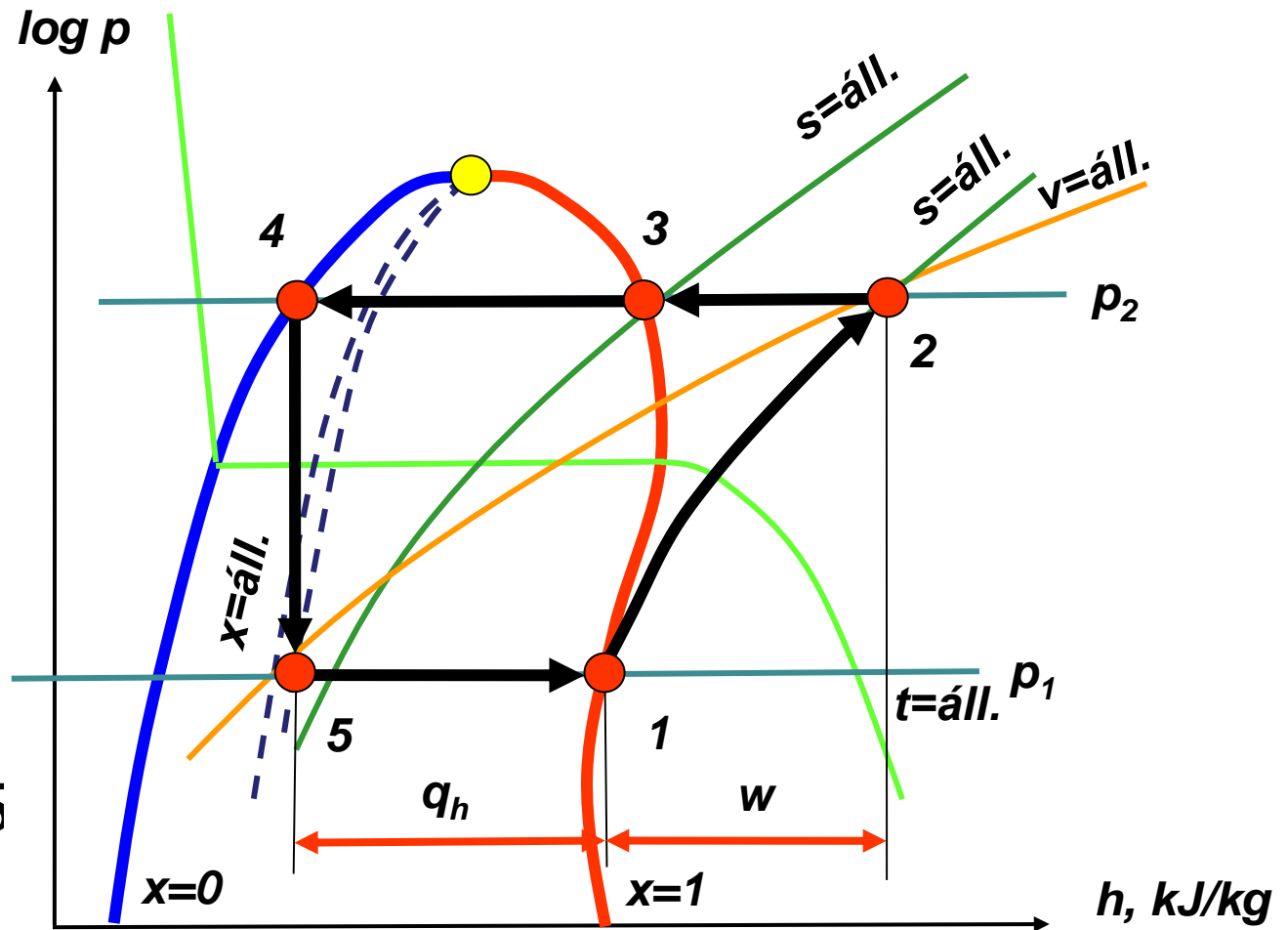
## Calculation

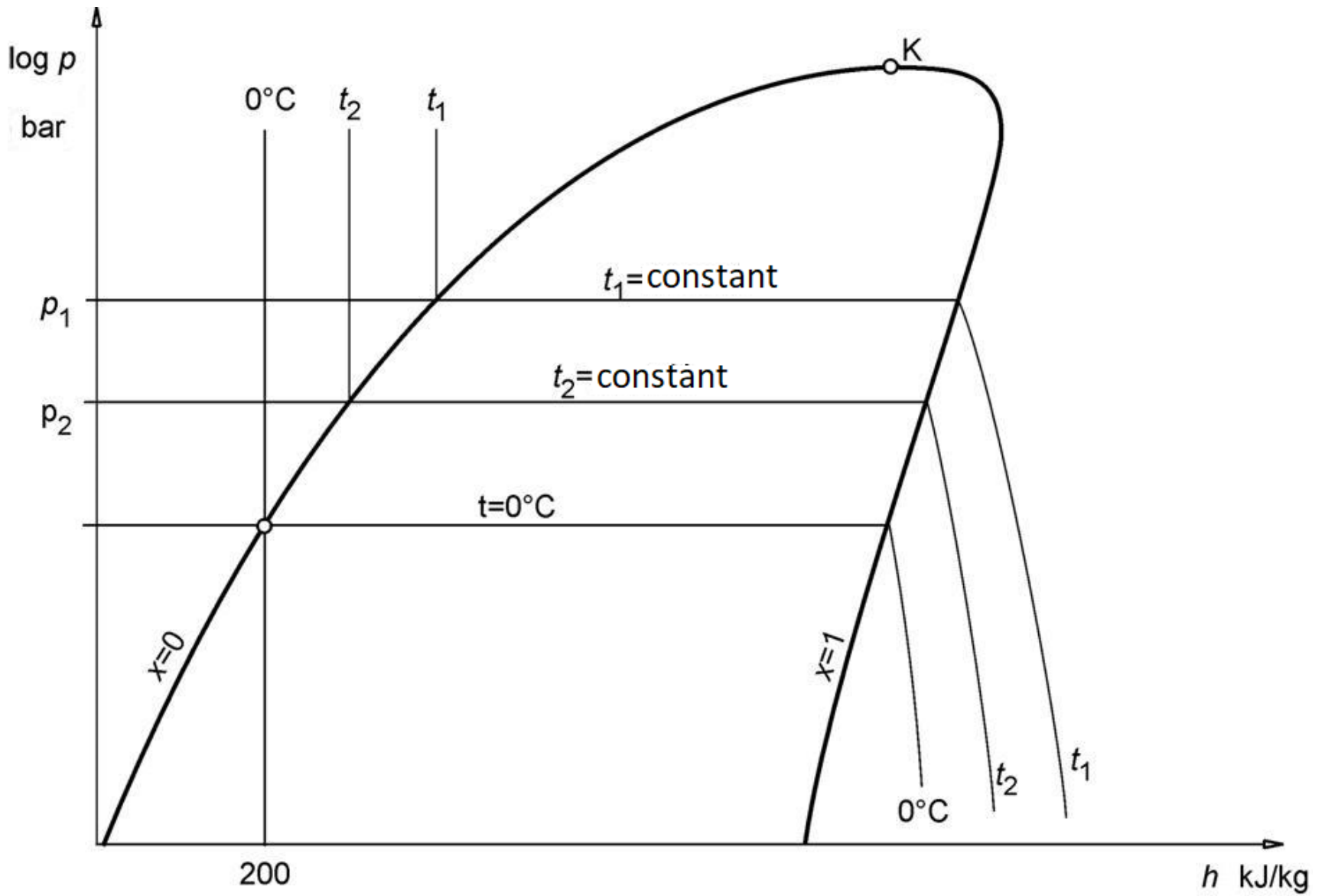
# Vapor compression refrigeration process

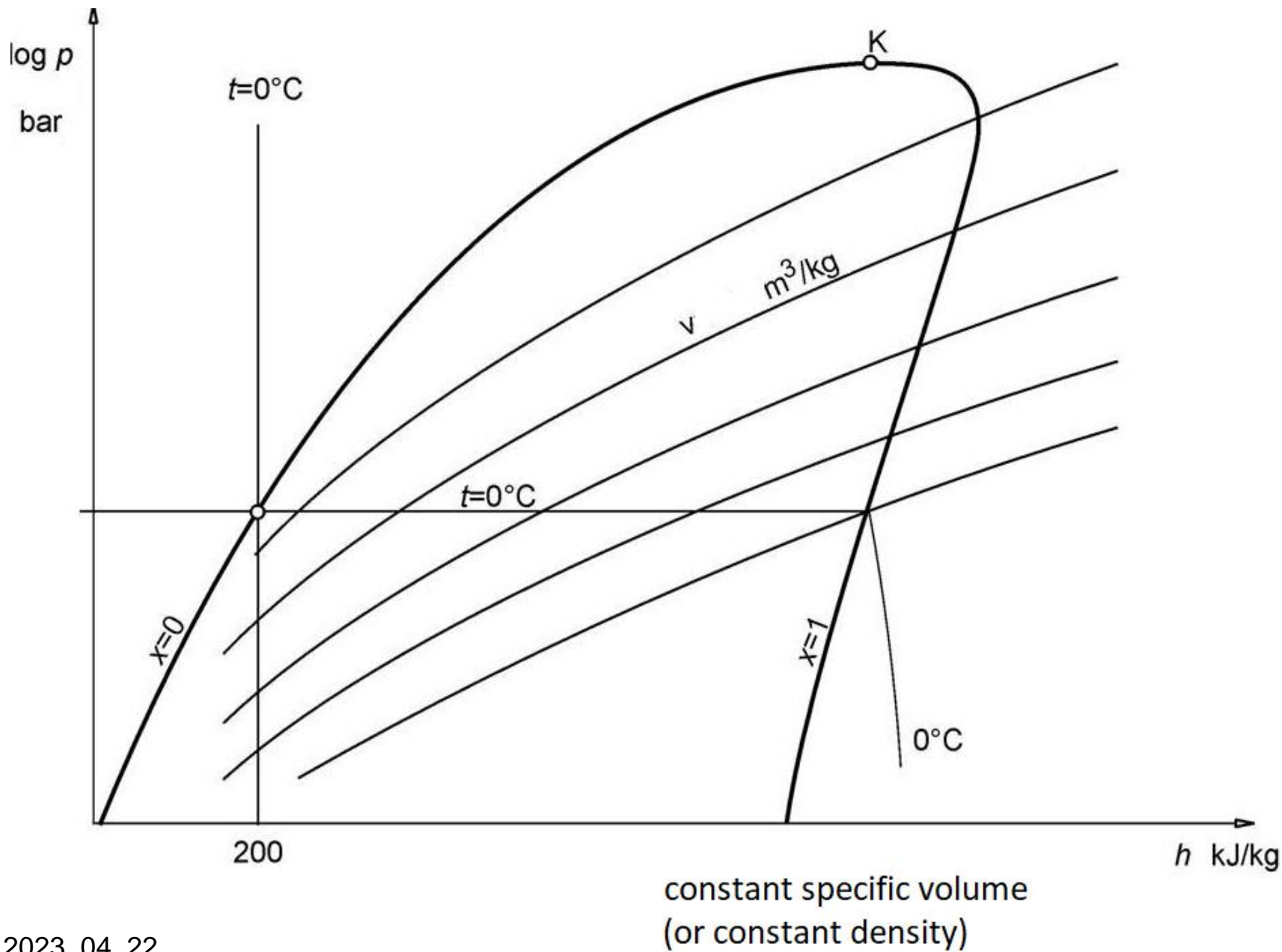


$$\varepsilon = \frac{q_h}{w}$$

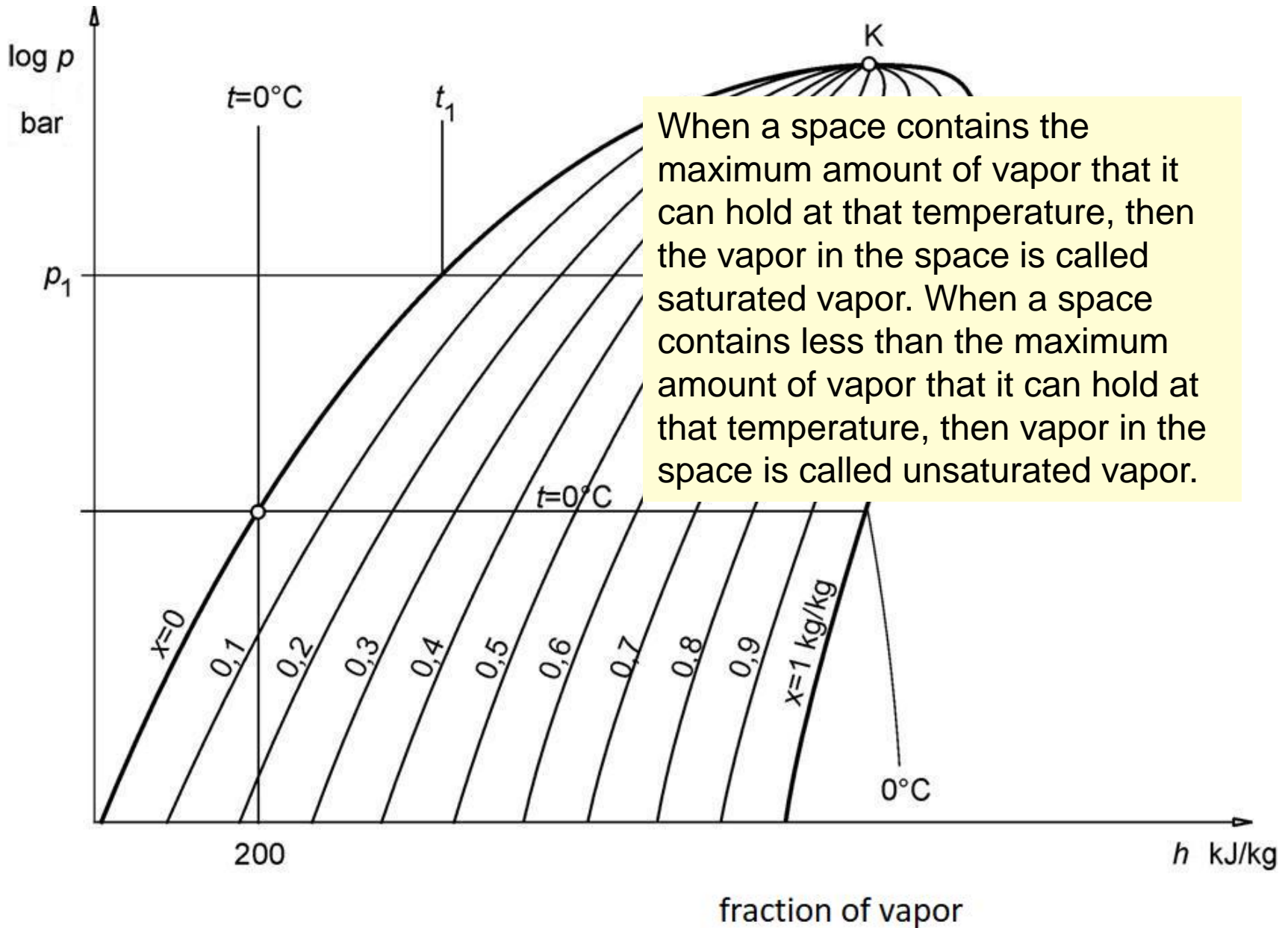
$$\varepsilon = 15 \dots 35$$

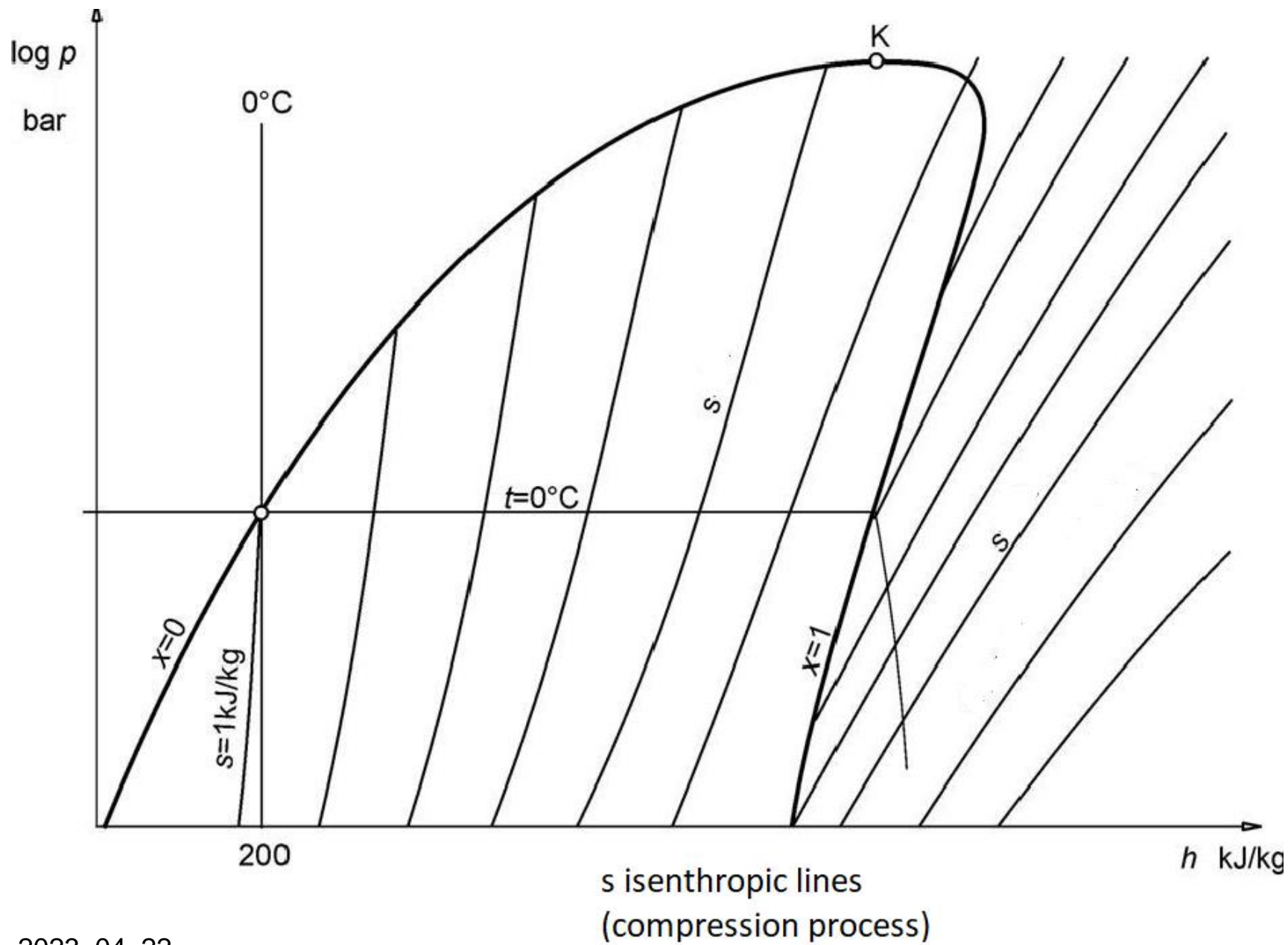






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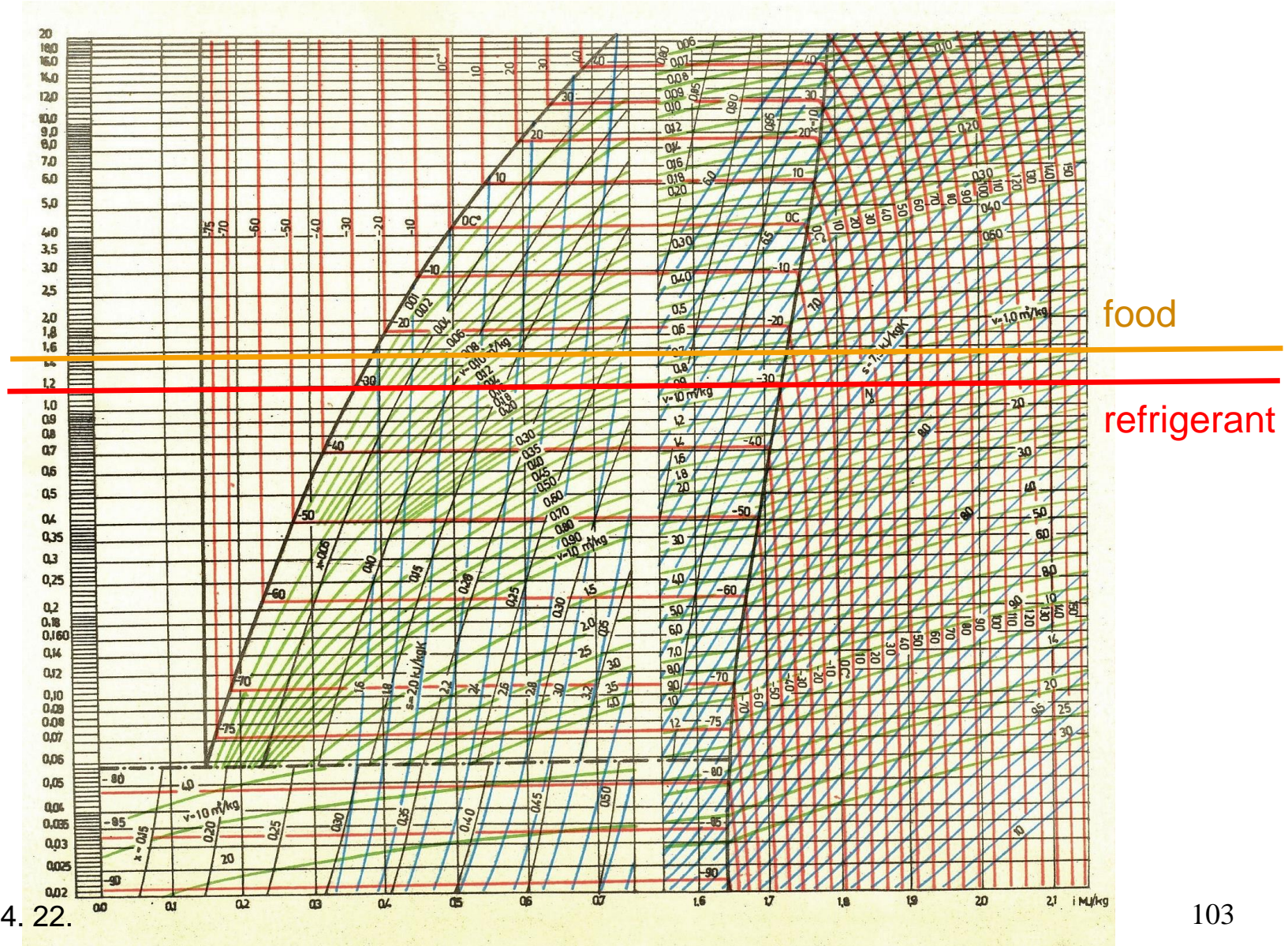




2023. 04. 22.

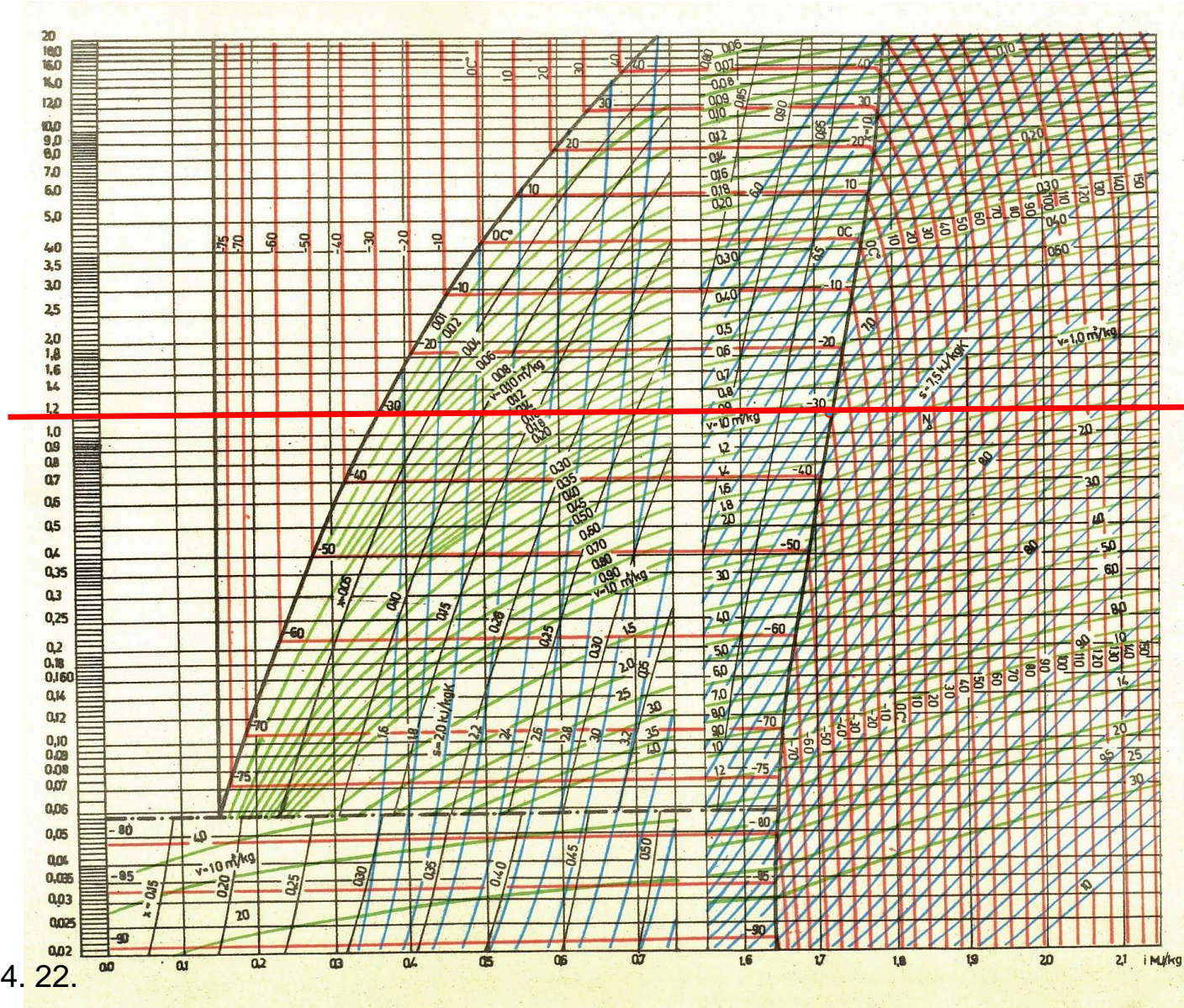
First step: calculating the pressure in the evaporator  
The refrigerant must be cooler than the food  
Example:  $-25^{\circ}\text{C}$  food,  $-30^{\circ}\text{C}$  refrigerant

Ammonia (R717)



# Ammonia (R 717)

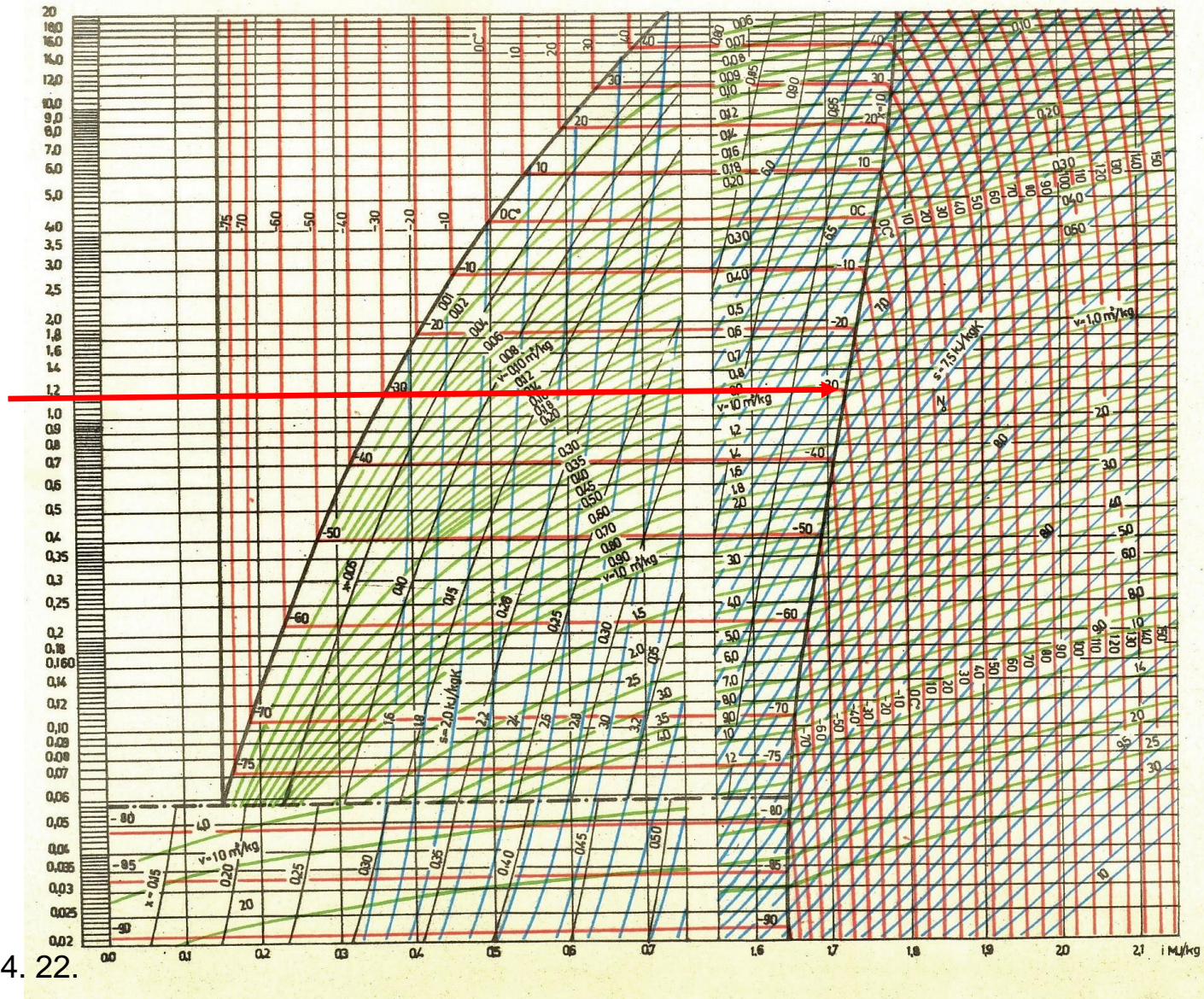
First step: calculating the pressure in the evaporator  
looking up the pressure fitting to the temperature  
Example: saturated vapor pressure 1.2 bar for -30°C refrigerant





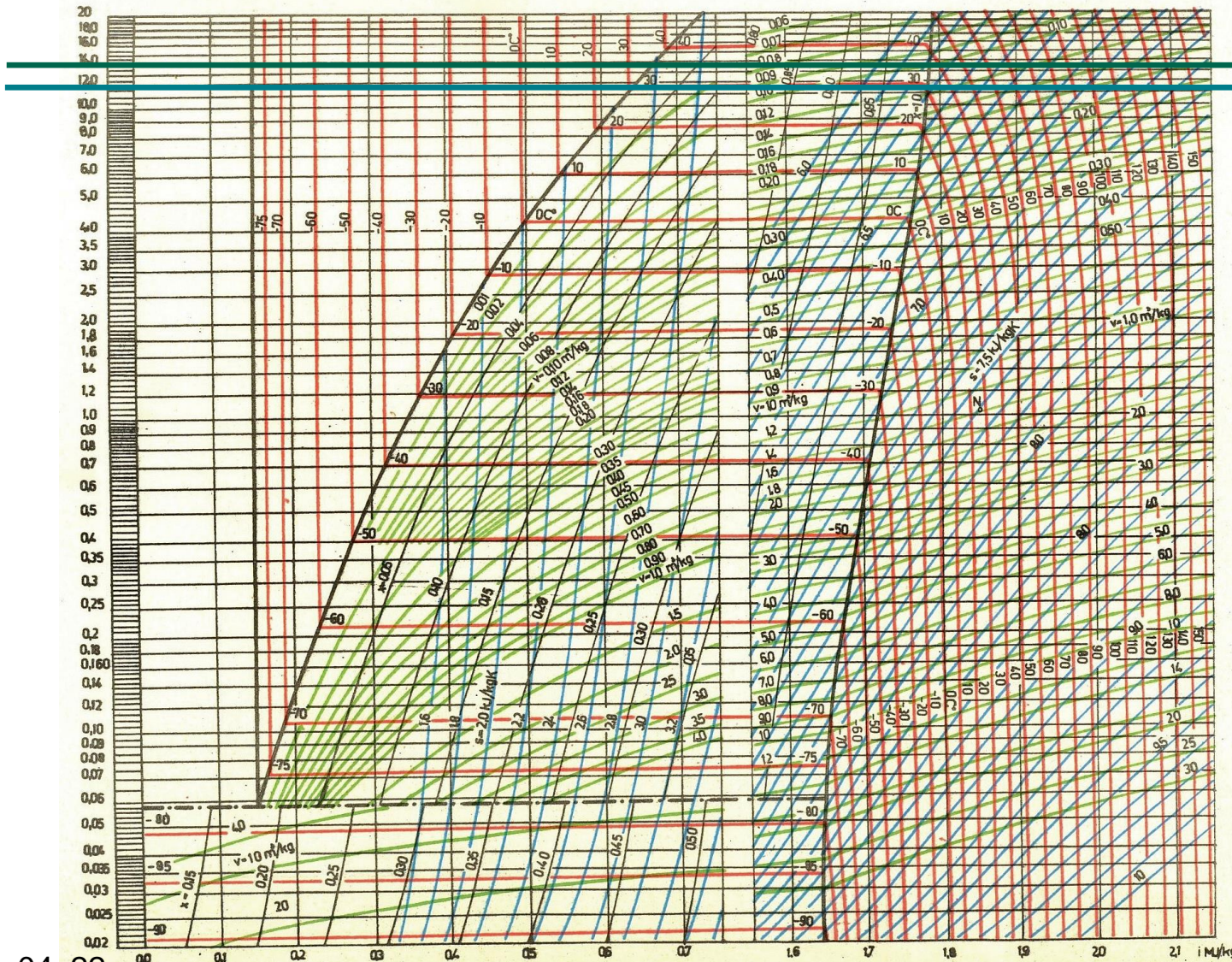
# Ammonia (R717)

First step: calculating the pressure in the evaporator  
Looking up the endpoint of the evaporation  
Example: saturated vapor pressure 1.2 bar for -30C° refrigerant



# Ammonia (R717)

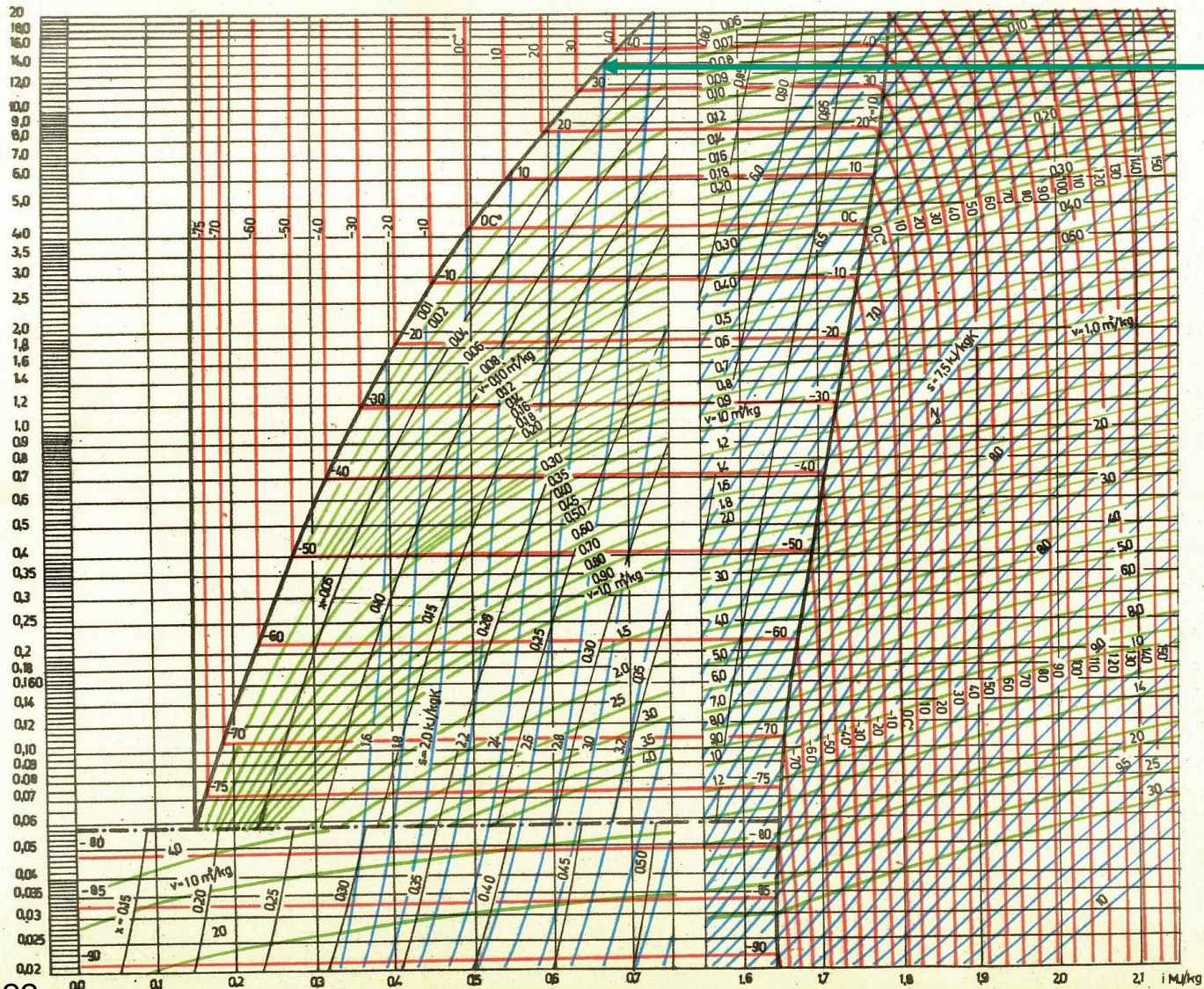
Second step: looking up the pressure of the condenser  
The temperature of surroundings must be warmer than the refrigerant  
Example: heat transport from +35 refrigerant to +30 surroundings



refrigerant  
surroundings

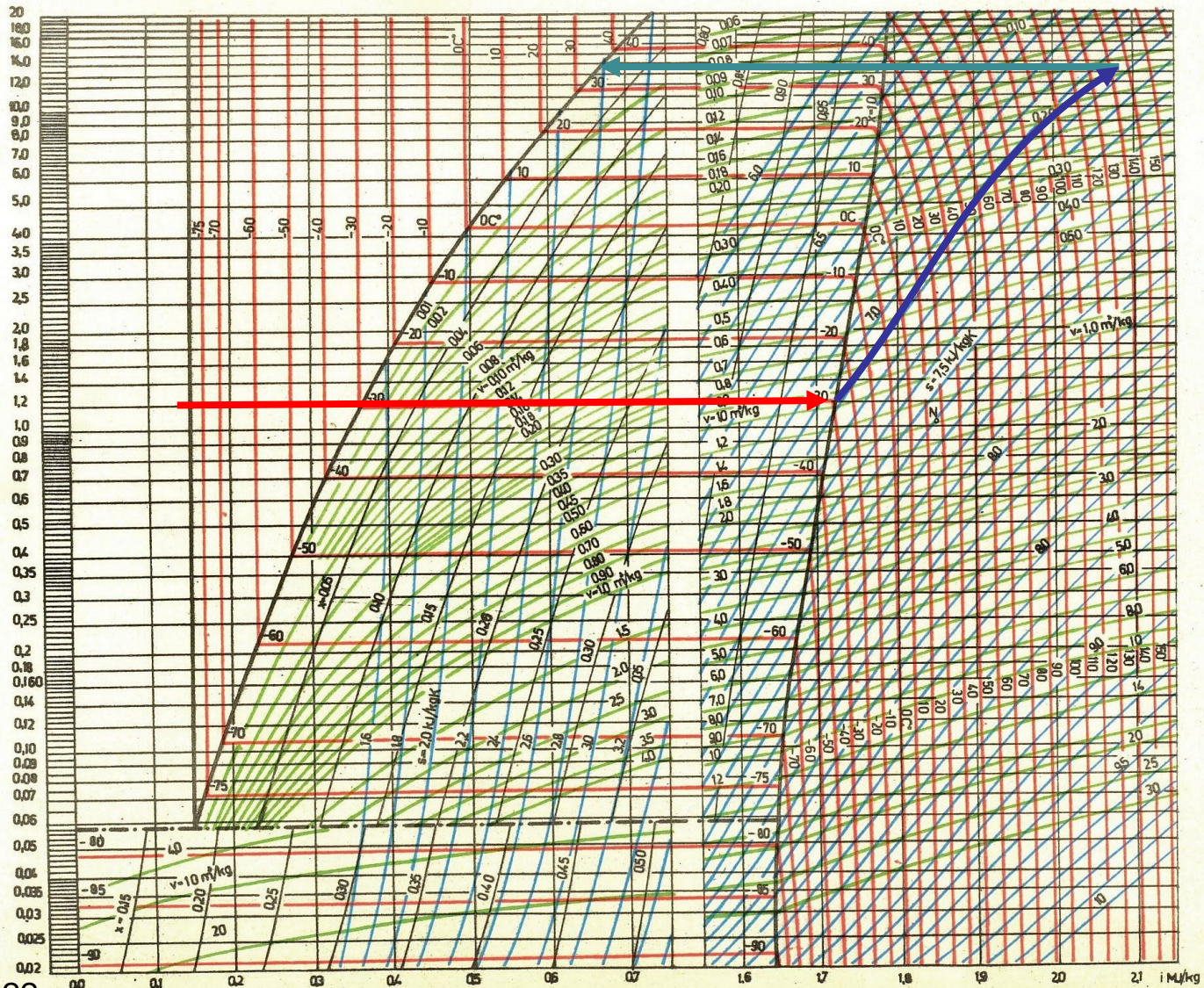
Second step: looking up the pressure of the condenser  
At the end of condensation, the refrigerant is liquid  
Example: endpoint for liquid at 13,5 bar pressure

# Ammonia (R717)



Third step: the compression process  
Adiabatic compression from 1,2 bar to 13,5 bar  
Example: the specific entropy is 7.05 kJ/(kg K) at 1,2 bar pressure

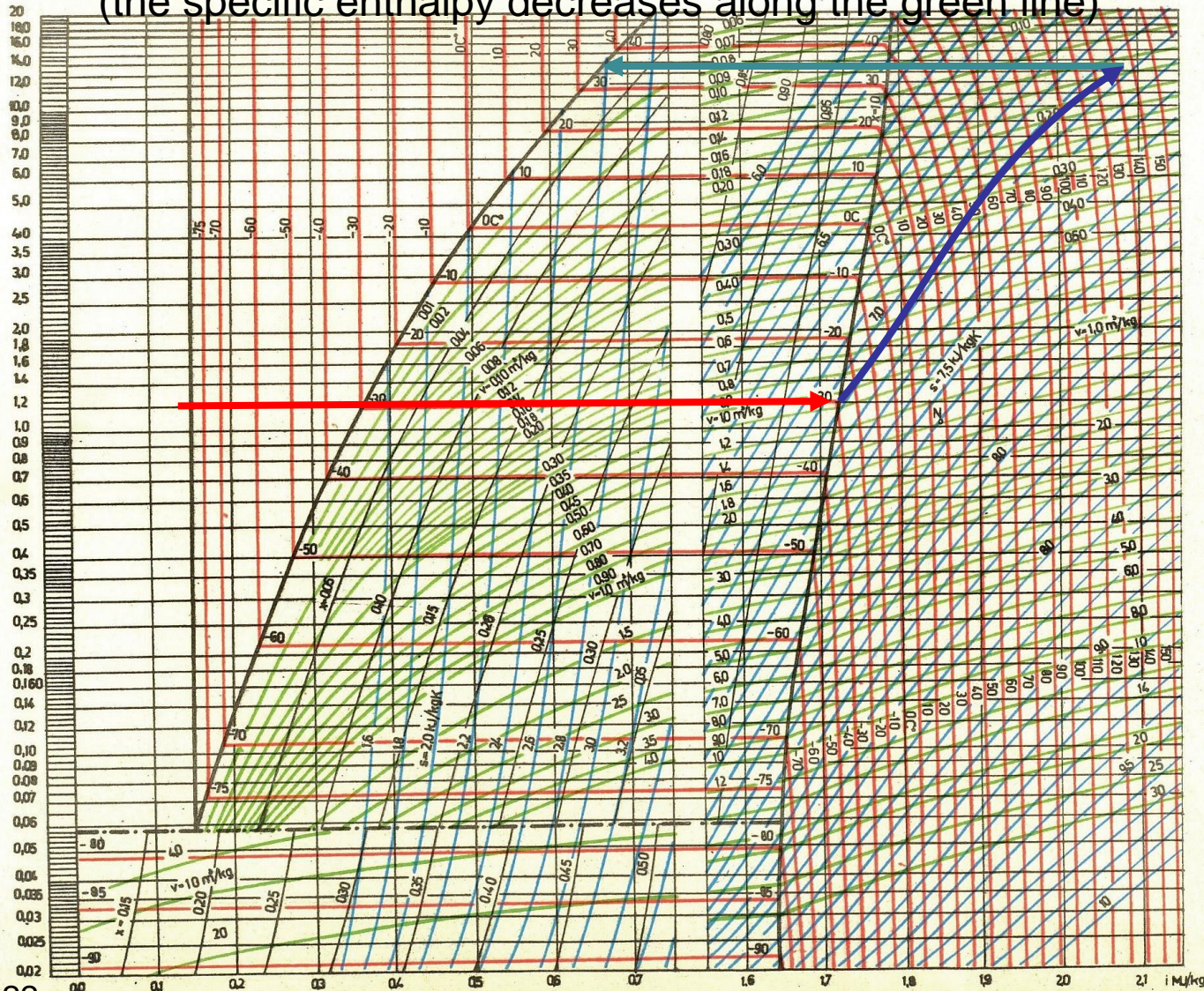
Ammonia (R717)





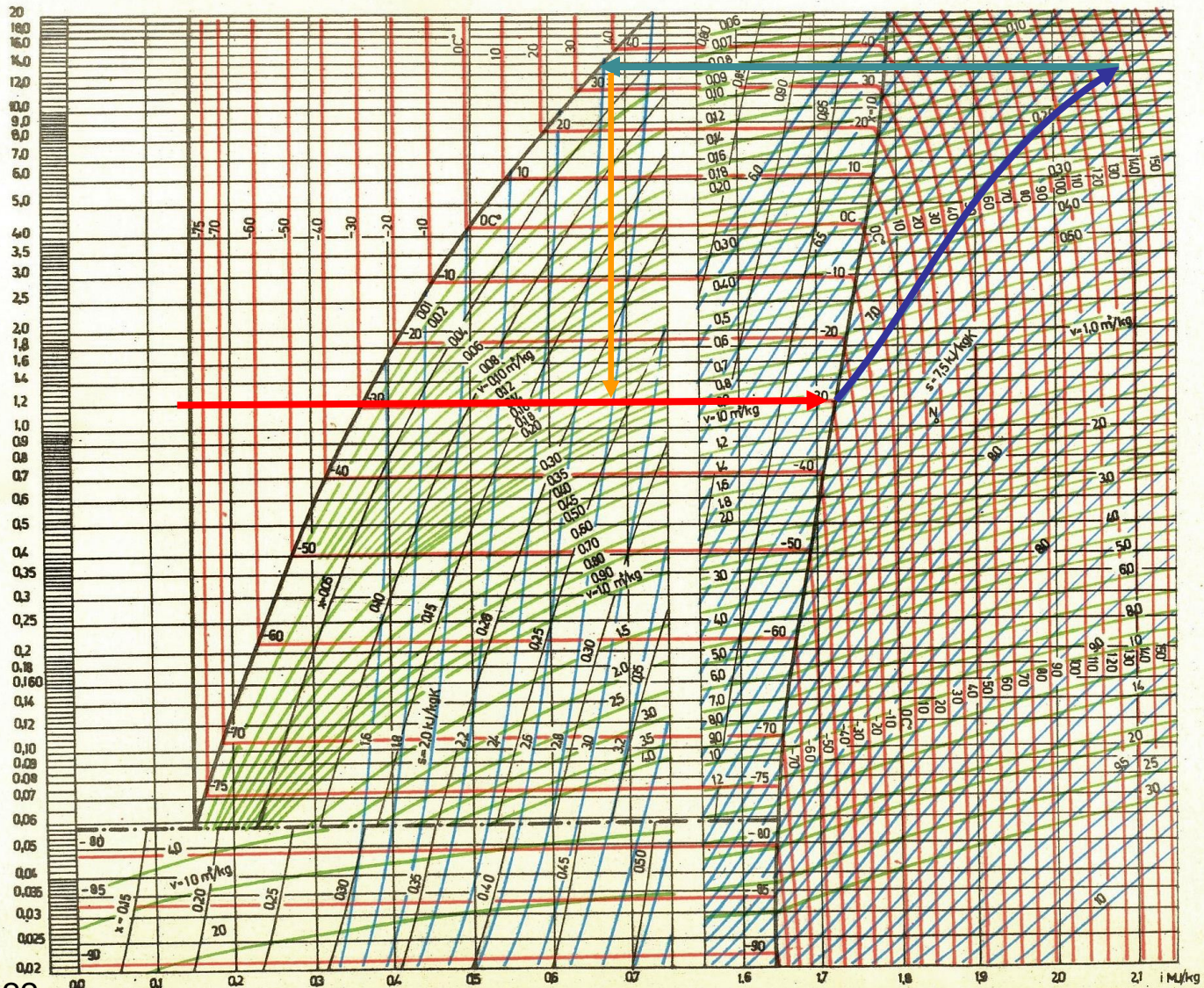
# Ammonia (R717)

Fourth step: calculating the process of condensation  
Isobaric condensation at 13.5 bar pressure to reach the liquid state  
Example: 13,5 bar isobaric heat transfer: both overheating and condensation heat  
(the specific enthalpy decreases along the green line)



# Ammonia (R717)

Fifth step: isenthalpic expansion by expansion valve  
The isenthalpic process is vertical line here (orange)  
Example: 0.68 MJ/kg

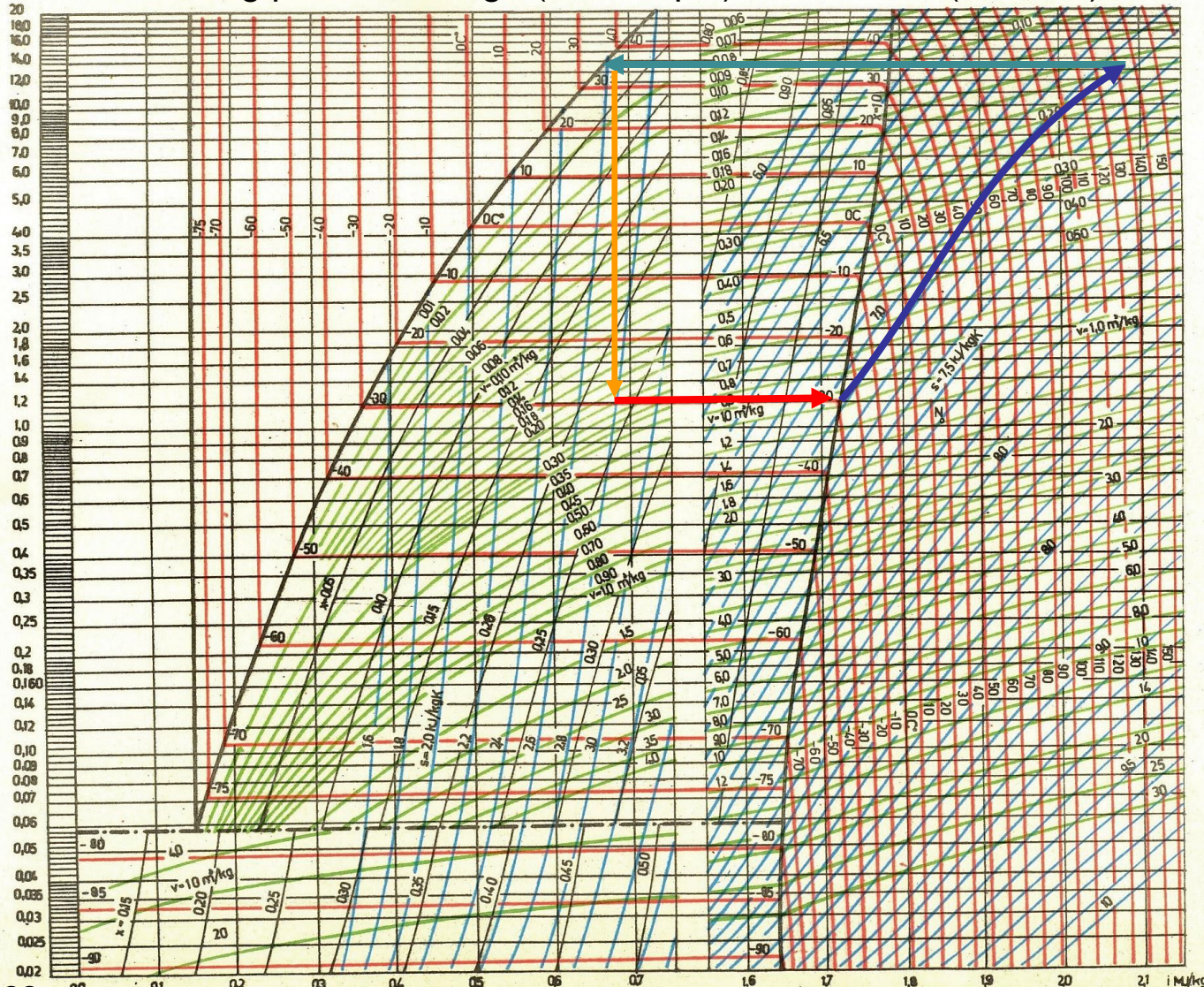


# Ammonia (R717)

Fifth step: isenthalpic expansion by expansion valve

The isenthalpic expansion (orange) determines the start point of the evaporation

Example: the vapor fraction is 0.23 kg/kg (a part of liquid evaporated)  
see the crossing point of orange (isenthalpic) and the red (isobaric) lines



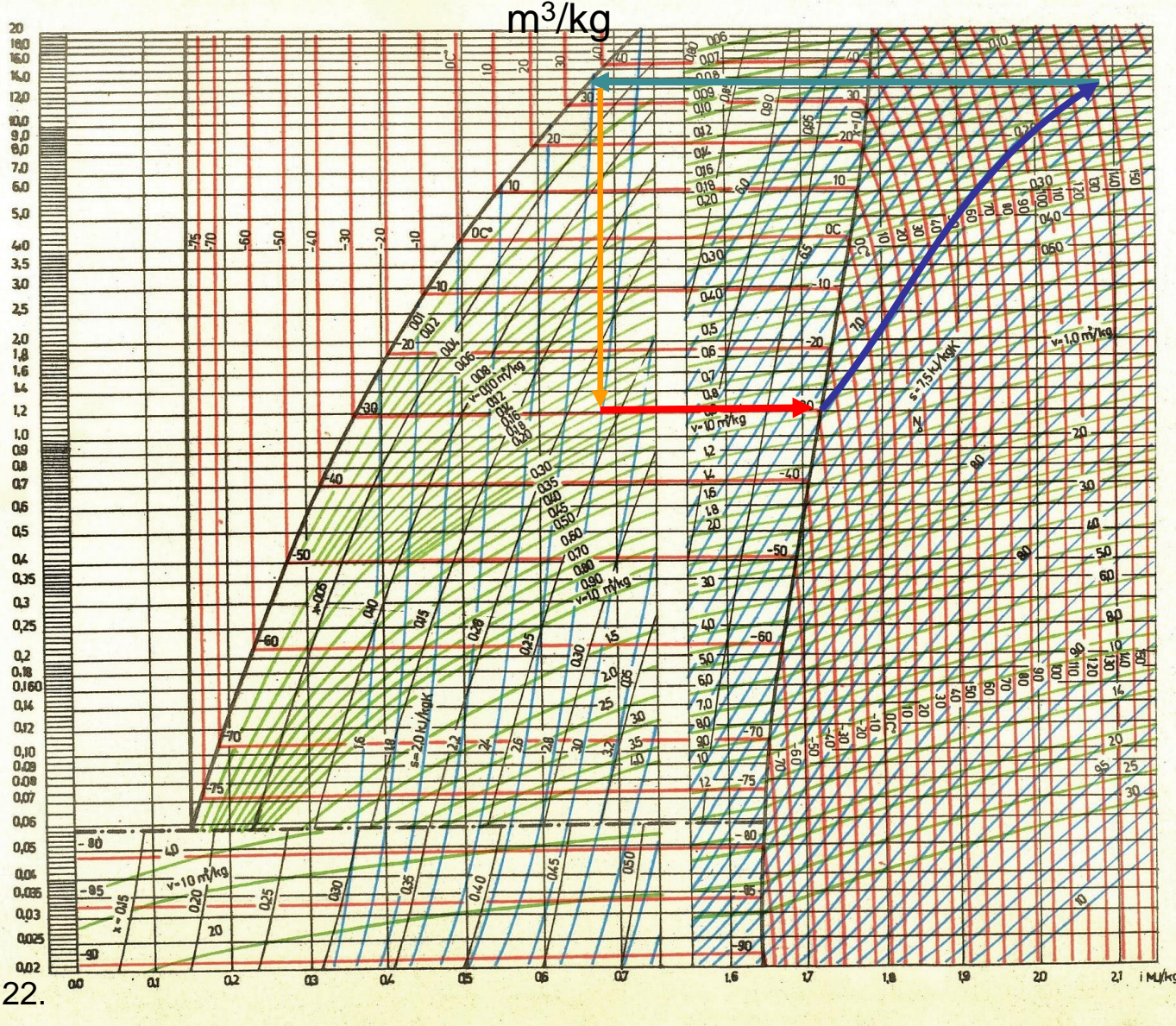


# Fifth step: isenthalpic expansion by expansion valve

The isenthalpic expansion (orange) determines the start point of the evaporation

Example: as a result of evaporation the specific volume increases from 0.001 to 0.280

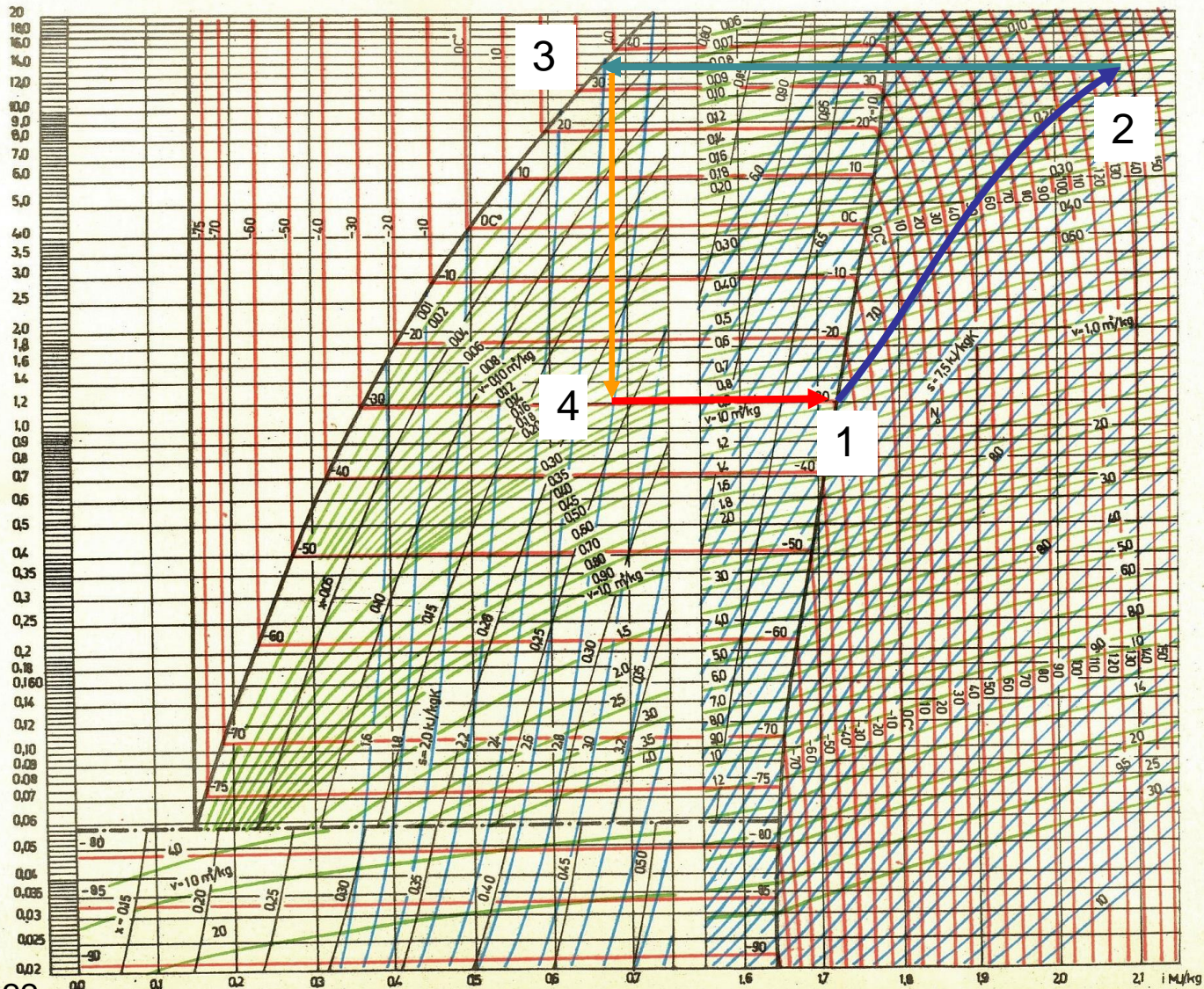
Ammonia (R717)



Sixth step: reading the results

1 h = 1.72 MJ/kg, 2: h = 2.1 MJ/kg, both 3 and 4: h = 0.67 MJ/kg

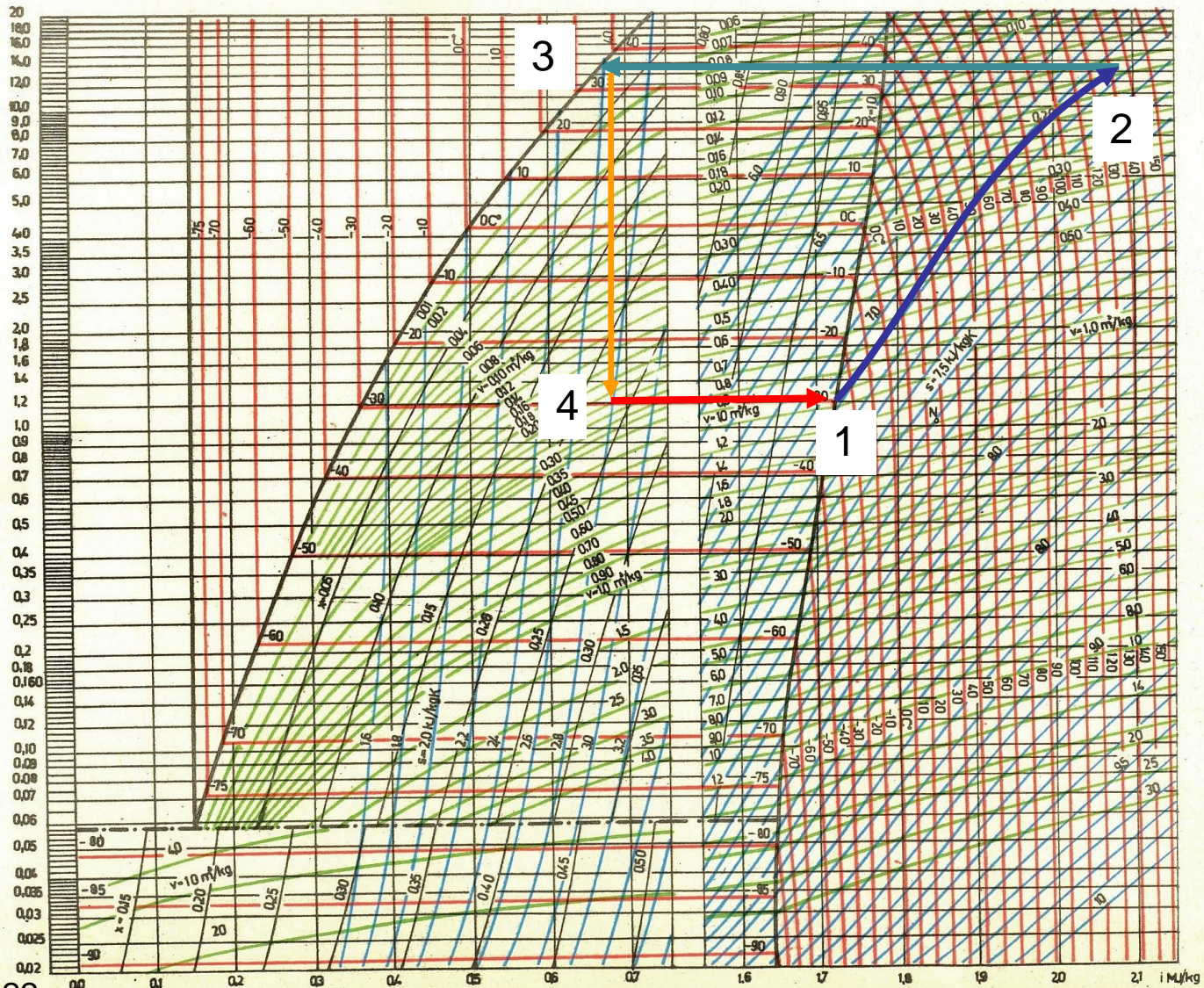
Heat entered in the evaporator:  $h_1 - h_4 = (1.72 - 0.67) \text{ MJ/kg} = 1.05 \text{ MJ/kg}$



## Sixth step: reading the results

1 h = 1.72 MJ/kg, 2: h = 2.1 MJ/kg, both 3 and 4: h = 0.67 MJ/kg

The work needed by the compressor:  $h_2 - h_1 = (2.1 - 1.72) \text{ MJ/kg} = 0.38 \text{ MJ/kg}$

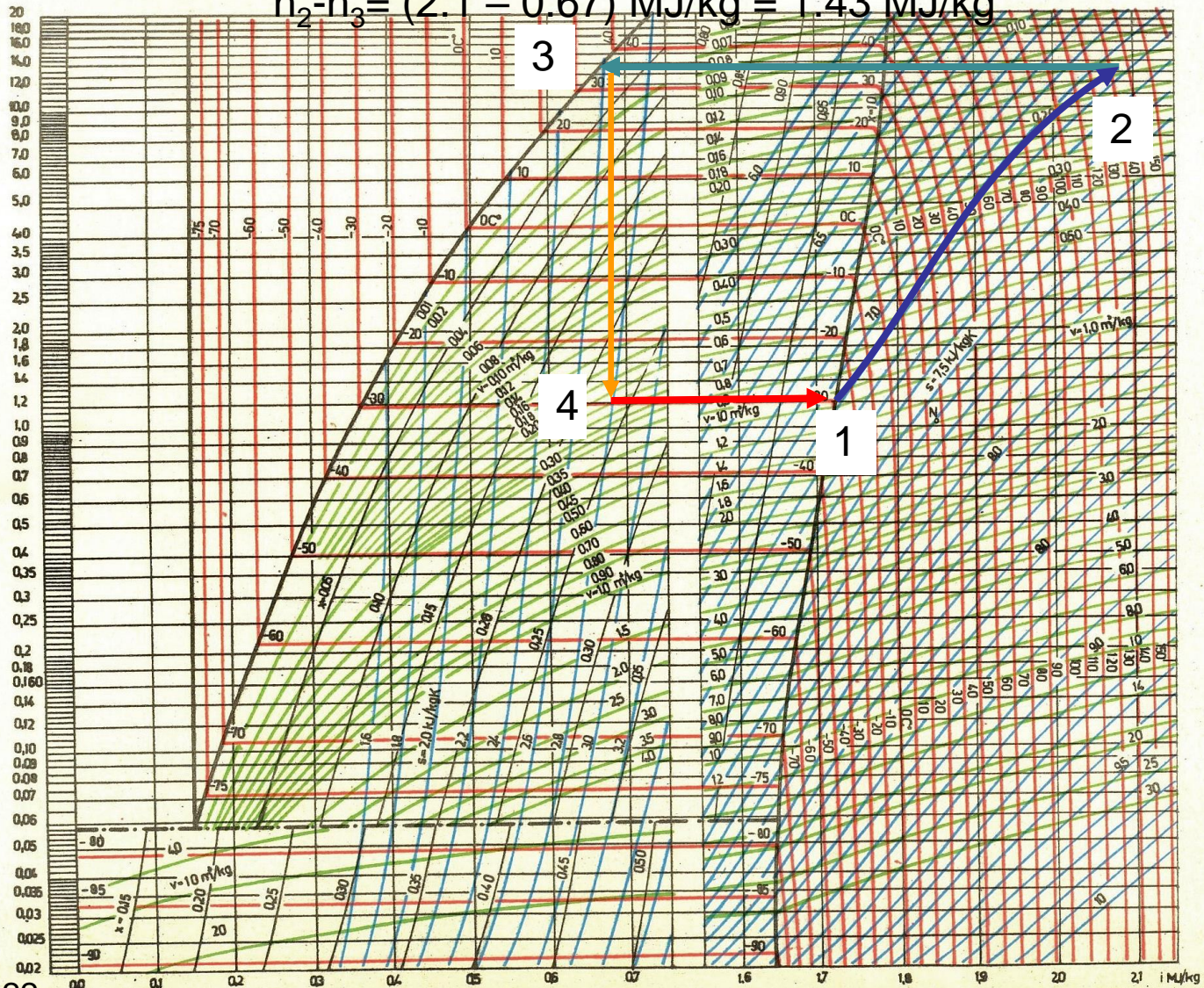


Sixth step: reading the results

1  $h = 1.72 \text{ MJ/kg}$ , 2:  $h = 2.1 \text{ MJ/kg}$ , both 3 and 4:  $h = 0.67 \text{ MJ/kg}$

Heat transfer sent to the surroundings:

$$h_2 - h_3 = (2.1 - 0.67) \text{ MJ/kg} = 1.43 \text{ MJ/kg}$$



# Calculations

Coefficient of performance: quotient of the heat transfer in the evaporator and the work of compression

$$\varepsilon = \frac{1.05\text{MJ/kg}}{0.38\text{MJ/kg}} = 2.76$$

The real cycle calculated including wastage. Example: friction loss of mechanics, flow friction loss (liquid and vapor), the power consumption of lubricant pump, etc.

Try to calculate it on the theoretical base!

$$\varepsilon = \frac{T_0}{T - T_0} = \frac{(273.15 - 30)\text{K}}{(273.15 + 35)\text{K} - (273.15 - 30)\text{K}} = \frac{243.15}{65} = 3.74$$

Huge difference. The equation below related to proper gases, while the equation above related to the real material, values originated from the chart of real refrigerant

## calculations

Let's calculate a refrigerator with  $J_m=0.1$  kg/s flow rate of the refrigerant!

The work needed by the compressor

$$P = w_k J_m = 380 \text{kJ/kg} \cdot 0.1 \text{kg/s} = 38 \text{kJ/s} = 38 \text{kW}$$

Heat flow in the evaporator

$$\Phi = q_0 J_m = 1050 \text{kJ/kg} \cdot 0.1 \text{kg/s} = 105 \text{kJ/s} = 105 \text{kW}$$

Usually the heat flow calculated a more practical unit:

$$\Phi = 105 \text{kW} = 105 \frac{\text{kJ}}{\text{s}} \cdot 3600 \frac{\text{s}}{\text{h}} = 378000 \frac{\text{kJ}}{\text{h}} = 378 \frac{\text{MJ}}{\text{h}}$$

## Calculations

To gain the size of the refrigerator we need to know the flow ratio!

Specific volume of the vapor at temperature  $-30^{\circ}\text{C}$

$$v_g = 0,963 \text{ m}^3/\text{kg},$$

and the liquid at  $+35^{\circ}\text{C}$   $v_l = 0,0017 \text{ m}^3/\text{kg}$

Vapor flow rate at the inlet of the compressor:

$$J_{Vg} = J_m \cdot v_g = 0,1 \frac{\text{kg}}{\text{s}} \cdot 0,963 \frac{\text{m}^3}{\text{kg}} = 0,0963 \frac{\text{m}^3}{\text{s}} = 96,3 \frac{\text{l}}{\text{s}}$$

Liquid flow rate at the outlet of the condenser:

$$J_{Vl} = J_m v_l = 0,1 \frac{\text{kg}}{\text{s}} \cdot 0,0017 \frac{\text{m}^3}{\text{kg}} = 0,00017 \frac{\text{m}^3}{\text{s}} = 0,17 \frac{\text{l}}{\text{s}}$$

# Saturated Ammonia --Temperature Table

<http://energy>

<http://www.>

| deg-C<br>temperatur | kPa<br>saturated | Spec, Volume<br>m <sup>3</sup> /kg |                          | Enthalpy<br>kJ/kg         |                          |
|---------------------|------------------|------------------------------------|--------------------------|---------------------------|--------------------------|
|                     |                  | saturated<br>liquid<br>vf          | saturated<br>vapor<br>vg | saturated<br>liquid<br>hf | saturated<br>vapor<br>hg |
| T °C                | p_sat@T          |                                    |                          |                           |                          |
| -40                 | 71,7             | 0,00145                            | 1,55256                  | 0                         | 1388,8                   |
| -35                 | 93,2             | 0,001463                           | 1,21613                  | 22,06                     | 1396,5                   |
| -30                 | 119,5            | 0,001476                           | 0,96339                  | 44,26                     | 1404                     |
| -25                 | 151,6            | 0,00149                            | 0,77119                  | 66,58                     | 1411,2                   |
| -20                 | 190,2            | 0,001504                           | 0,62334                  | 89,05                     | 1418                     |
| -15                 | 236,3            | 0,001519                           | 0,50838                  | 111,66                    | 1424,6                   |
| -10                 | 290,9            | 0,001534                           | 0,41808                  | 134,41                    | 1430,8                   |
| -5                  | 354,9            | 0,00155                            | 0,34648                  | 157,31                    | 1436,7                   |
| 0                   | 429,6            | 0,001566                           | 0,2892                   | 180,36                    | 1442,2                   |
| 5                   | 515,9            | 0,001583                           | 0,24299                  | 203,58                    | 1447,3                   |
| 10                  | 615,2            | 0,0016                             | 0,20541                  | 226,97                    | 1452                     |
| 15                  | 728,6            | 0,001619                           | 0,17462                  | 250,54                    | 1456,3                   |
| 20                  | 857,5            | 0,001638                           | 0,14922                  | 274,3                     | 1460,2                   |
| 25                  | 1003,2           | 0,001658                           | 0,12813                  | 298,25                    | 1463,5                   |
| 30                  | 1167             | 0,00168                            | 0,11049                  | 322,42                    | 1466,3                   |
| 35                  | 1350,4           | 0,001702                           | 0,09567                  | 346,8                     | 1468,6                   |
| 40                  | 1554,9           | 0,001725                           | 0,08313                  | 371,43                    | 1470,2                   |

Start point of this table: of the liquid at -40 °C temperature: h=0 kJ/kg

This is why the enthalpy difference between the liquid and vapor is -40 °C: 1388,8

kJ/kg  
2029. 04. 22.



Our servers' name  
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efiz.alarmix.net (spare server)

e-mail [zana.janos@uni-mate.hu](mailto:zana.janos@uni-mate.hu)  
Write me and put a question if you need

The end