

I-x-w diagram of wet air and wheat grain

I. VITÁZEK, J. HAVELKA

Department of Transport and Handling, Faculty of Engineering, Slovak University of Agriculture in Nitra, Nitra, Slovak Republic

Abstract

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The authors have been working for 50 years in the research and development of drying in agriculture. In the way of drying applied, warmed air is used as the drying medium. The thermodynamics of wet air is used for the analysis of these processes of drying in the calculations and in graphic demonstrations applying an i-x diagram of wet air. This diagram does not include any information about the state of the dried material. The authors therefore enlarged this i-x diagram with the equilibrium moisture contents of the dried material. In their work, the authors present a method using this enlarged diagram and, as an example, the i-x-w diagram of wet air and equilibrium moisture of wheat grain.

Keywords: drying in agriculture; equilibrium moisture; thermodynamics; sorption isotherm

The majority of agricultural products are harvested with a high moisture content. Therefore, it is necessary to reduce the moisture content by drying to an optimal value for long-term storage, i.e. to the standard moisture content. Warmed atmospheric air is used as the drying medium for the energy input and moisture output.

The thermodynamics of wet air elaborated by CHYSKÝ (1977) is used for the process analysis of drying. The thermodynamics of drying has been presented in several basic publications (PABIS 1966, 1982; MALTRY, PÖTKE 1966; IMRE 1974). Equilibrium moisture contents in the form of sorption isotherms are presented in these publications and also in a detailed publication by NIKITINA (1963), and also in the recent publications by ŠTENCL (2000a, b).

A disadvantage of all methods published is that the process of drying consists of two parts:

- thermodynamics of wet air,
- thermodynamics of humid material.

In their research works from 1970 up to the present day, the authors therefore elaborated a new

complex diagram of wet air with inserted moisture information on the dried material (HAVELKA 1973; VITÁZEK 1996, 2011). The graphic description of the process of drying is significantly better.

In this paper, the authors present their most recent alternative of the method of importing the equilibrium moisture content into the i-x diagram of wet air.

Also in this paper, some specific parameters are used of wet air and humid material. Therefore, a brief description of them is introduced in the following section.

MATERIAL AND METHODS

Wet air. Wet air is used as a drying medium for delivering the necessary heat for humidity evaporation and taking away this evaporated humidity. Wet air is a mixture of several over-heated vapours. An exception is water vapour which condenses in the working temperatures area. Therefore, the thermodynamics of wet air was elaborated.

Relative humidity of wet air φ :

$$\varphi = p_p / p'' \quad (1)$$

where:

p_p – partial pressure of water vapour (Pa)

p'' – pressure of saturated water vapour at the temperature of the air concerned (Pa)

Specific humidity of wet air (x):

$$x = M_w / M_M \quad (\text{kg/kg}) \quad (2)$$

where:

M_w – mass of water vapour (kg)

M_M – whole mass of the wet air (kg)

The enthalpy of wet air is calculated with a specific mass unit $(1 + x)$ kg:

$$i_{(1+x)} = i_a + x \times i_p \quad (3)$$

where:

$i_{(1+x)}$ – enthalpy of wet air

i_a – enthalpy of dry air

i_p – enthalpy of water vapour

x – humidity ratio

The following numerical equation is used for wet air of temperature 0–100°C and pressure 100 kPa:

$$i_{(1+x)} = 1.02t + x(2,500 + 1.84t) \quad (\text{kJ}) \quad (4)$$

where:

t – temperature of wet air

Using these relations, Mollier constructed his i - x diagram of wet air. In the coordinates i , x , are demonstrated straight lines of $t = \text{const.}$, with curves $\varphi = \text{const.}$, and with the curve of saturated wet air $\varphi = 1$. These parameters are used in the modelling of the process of drying.

Humid material. The humidity of the material u can be described by means of two parameters STN 12 6000 (1996).

Moisture content dry basis u , which is predominantly used in the theory of drying:

$$u = M_w / M_{dM} \quad (\text{kg/kg}) \quad (5)$$

where:

M_w – mass of humidity (kg)

M_{dM} – mass of dry basis of the material (kg)

Moisture content wet basis w is used in the practice of drying:

$$w = (M_w / M_M) \times 100 \quad (\%) \quad (6)$$

where:

M_w – mass of humidity (kg)

M_M – whole mass of the material (kg)

Bilateral relations of this are as follows:

$$w = 100 \times u / (1 + u), \quad u = w(100 - w) \quad (7, 8)$$

Process of drying. The process of drying is divided into three sections. Schematic demonstration of these sections in graphic description in curve of drying is shown in Fig. 1. The three sections:

- (1) section of the growing rate of drying,
- (2) section of a permanent rate of drying, in which the evaporation of free moisture from the surface prevails, the decrease of moisture being directly proportional to time,
- (3) section of a falling rate of drying, in which the decrease of the bound moisture is not proportional to time. The evaporation from the inside of the material, the section ends with the equilibrium moisture content.

The equilibrium moisture is the moisture relevant to the state of thermodynamic equilibrium of the material parameters and ambient atmosphere.

Sorption. Sorption isotherm is the graphic demonstration of the equilibrium moisture of the material u_r , in relation to the relative humidity w_r of ambient air at the given temperature and pressure.

The literature contains tables of u_r for various φ_r (relative humidity of wet air) at a constant temperature, which were investigated with the use of laboratory experiments.

A great number of authors have presented also analytic relations $\varphi_r = f(u_r, t)$ in various forms.

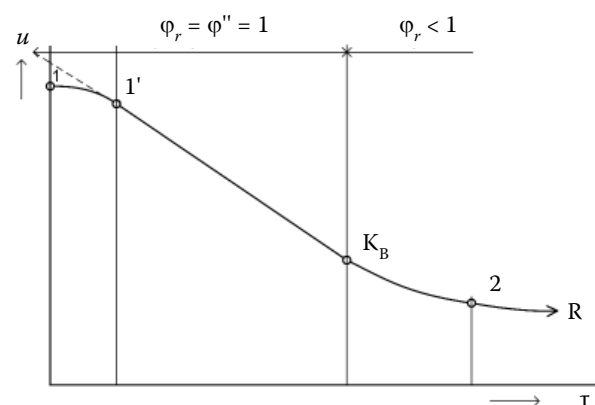


Fig. 1. Drying curve

1 – start of drying; 2 – end of drying; K_B – critical point; R – point of equilibrium humidity, in the theory in infinity; 1–1' – section of increasing rate of drying; 1'– K_B – section of permanent rate of drying; K_B –R – section of falling rate of drying; u – moisture content dry basis; τ – time

The best form for agricultural materials is the relation from HENDERSON (1952), which was brought into Europe by PABIS (1982):

$$1 - \varphi_r = \exp(-a \times T \times u_r^n) \quad (9)$$

where:

φ_r – equilibrium relative humidity of wet air

u_r – equilibrium moisture content dry basis

T – absolute temperature (K)

a, n – coefficients, individual for every material

Regression. The authors adapted Eq. (9) for regression to obtain coefficients a, n with regression values.

The authors took from the literature the tabulated values of the isotherm of the given material and, using regression, they calculated the coefficients of Henderson's relation.

By adaptation, Eq. (9) is transformed to logarithm and multiplied with -1 :

$$-\ln(1 - \varphi_r) = a \times T \times u_r^n \quad (10)$$

and the logarithm of this Eq. (10) is:

$$\ln(-\ln(1 - \varphi_r)) = \ln a + \ln T + n \times \ln u_r \quad (11)$$

This equation is transformed to the linear form and used for linear regression of the tabulated values of the given material. The linear form of Eq. (11) is:

$$Y = A + B \times X \quad (12)$$

where:

$$Y = \ln(-\ln(1 - \varphi_r)) \quad (13)$$

$$A = \ln a + \ln T \quad (14)$$

$$X = \ln u_r = \ln(w_r / (100 - w_r)) \quad (15)$$

where:

Y, A, X – coefficients of linear equation

By means of the linear regression of the tabulated values of the given material, we obtain the values of A and B , from which we deduce:

$$N = B \quad (16)$$

$$A = \exp(A - \ln T) \quad (17)$$

These new coefficients a, n are used in a modified equation of Henderson:

$$\varphi_r = 1 - \exp(a \times T \times u_r^n) \quad (18)$$

where:

n – coefficient of Henderson's modified equation

T – thermodynamic temperature of given material

RESULTS AND DISCUSSION

Wheat

From the tables specified by PABIS (1982), the authors took the values of the isotherm for wheat, i.e. equilibrium moisture contents w_r at the temperature of 20°C and pressure of 101.325 kPa (Table 1).

This isotherm is presented in a graphic form in Fig. 2 in the coordinates w_r, φ_r .

Using the regression of these values, we obtained the constants for Henderson's analytical relation for this wheat:

$$\varphi = 1 - \exp(-0.2053 \times T \times u^{2.2376}) \quad r = 0.994 \quad (19)$$

where:

φ – relative humidity of wet air

T – thermodynamic temperature of given material

u – moisture content dry basis

r – correlation coefficient

With this Eq. (19) the authors calculated the equilibrium moisture contents (w.b.) $w_r = 8, 10, 12, 14, 16, 18, 20, 24\%$ course for temperatures of 10 to 50°C and drew these curves $w_r = \text{const.}$ into the i - x diagram of wet air using lines $t = \text{const.}$ and curves $\varphi = \text{const.}$ as new coordinates.

The authors propose this new form of diagram to be designated as i - x - w diagram of wet air and humid wheat grain.

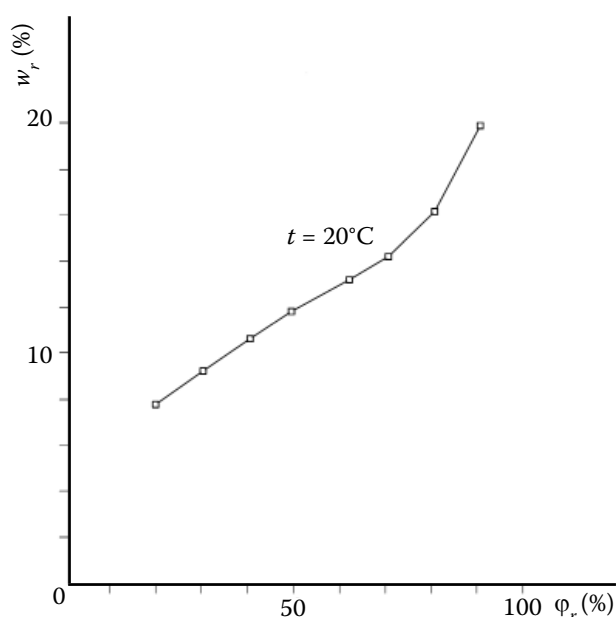


Fig. 2. Sorption isotherm of wheat grain

w_r – equilibrium moisture content wet basis; φ_r – equilibrium relative humidity of wet air

Table 1. Wheat equilibrium moisture content wet basis for temperature 20°C

ϕ (%)	20	30	40	50	60	70	80	90
w_r (%)	7.80	9.24	10.68	11.84	13.10	14.30	16.02	19.95

ϕ – relative humidity of wet air; w_r – equilibrium moisture content wet basis

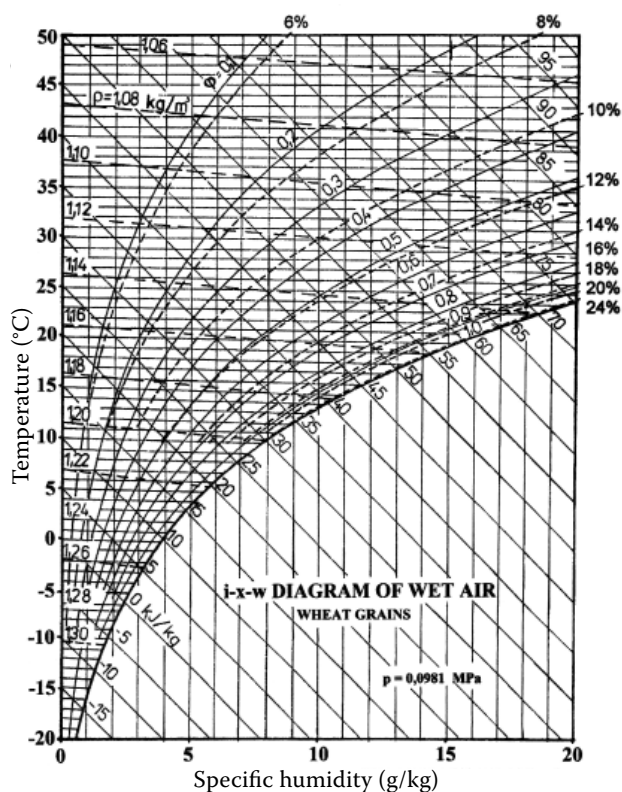


Fig. 3. I-x-w diagram of wet air and equilibrium moisture of wheat grain

p – atmospheric pressure

The application of wet air thermodynamics is a significant method for the analysis of the drying processes in agriculture. Since 1970, the authors have developed the thermodynamics of drying in agriculture. In this work, they refer to their improvement on this thermodynamics with a combination of i-x diagram of wet air and with the equilibrium moisture values of the given material, which were confirmed with laboratory experiments.

In Fig. 2 is presented the sorption isotherm of wheat grains at 20°C. Information in this diagram is short for its utilisation in the thermodynamics of drying.

The i-x diagram of wet air is used advantageously for the graphic demonstration of the state changes of the drying medium in the drying process, without any information on the state changes of the dried material.

In Fig. 3 is shown a new i-x-w diagram of wet air and equilibrium moisture of wheat grains. This new diagram is able to demonstrate, in graphic form, parallel state changes of the drying medium and of the dried material. This diagram enables therefore an improved thermodynamic analysis of the drying process.

CONCLUSION

The i-x-w diagram of wet air and equilibrium moisture of a given material is a new type of diagram, which is unknown in the specialised literature. This diagram enables the most suitable analysis of the drying process.

The authors used this diagram in their works with a great success. They will continue in the development of the thermodynamic analysis of drying processes through modelling the process in research, and in the evaluation of drying processes in practice.

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Corresponding author:

doc. Ing. IVAN VITÁZEK, CSc., Slovak University of Agriculture in Nitra, Faculty of Engineering,
Department of Transport and Handling, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic
phone: + 421 376 414 756, e-mail: ivan.vitazek@uniag.sk
