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THE EXPERIMENT OF DRYING PROCESS OF THE FIBROUS MATERIAL

EXPERIMENT PROCESU SUŠENÍ TKANINY

Abstract

The article describes the experiment of water evaporation from fibrous material (cotton). The material is placed in the tube and hot air flows through (process of drying). Temperature of air is measured by thermocouple. The textile represents porous medium with certain amount of water (wet textile). Porous layer makes pressure drop when airflow starts. Properties of air (temperature, relative humidity) change during evaporation process. Values of pressure drop, temperature and humidity measured during experiment are used for set up of boundary condition, porous layer and evaporation model in Ansys Fluent 13.

Abstrakt

Článek popisuje experiment odpařování vody, z bavlněné textilie, působením prouděním teplého vzduchu (proces sušení). Teplota vzduchu je měřena termočlánkem. Bavlněná tkanina vložená do potrubí představuje porézní vrstvu, která obsahuje dané množství vody. Při proudění vzduchu skrz tkaninu vzniká tlakový spád, který byl změřen. Vypařováním vody z textilie se mění vlastnosti vlhkého vzduchu (teplota, relativní vlhkost), které byly také měřeny. Cílem experimentu je získat podklady pro nastavení okrajových podmínek, porézní oblasti a model vypařování v programu Ansys Fluent 13.

Keywords

ANSYS Fluent, porous medium, water evaporation, Clausius − Claperyon equation, Evaporation model.

1. INTRODUCTION

Drying process is used in wide range of industrial application. Drying of textile is mainly used in commercial laundries, hotels etc. Textile is hydroscopic material which has the ability to attract water molecules. To remove water from linen is usually done by evaporation of water into hot air. Mass flow of hot air through textile can be interpreted as flow through porous zone. The experiment is based on this process and the main intent is obtaining the results for set up the constants of porous zone and evaporation in mathematical simulation.

2. POROUS MEDIUM CONDITION

Porous medium is modeled by the addition of an extra source in the momentum equation. The source term is composed of two parts. First is Darcy law expression, second is inertial loss term [2].

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The equation (1) is written for a homogeneous porous medium. Variables in equations means: $|v|$ - magnitude of velocity; μ – dynamic viscosity; α – permeability; C_2 – inertial resistance factor.

$$S_i = -(\frac{\mu}{\alpha}v_i + C_2 \cdot \frac{1}{2} \cdot \rho|v|v_i)$$ (1)

3. ANSYS FLUENT EVAPORATION MODEL

The Eulerian multiphase approach appropriately describes evaporation process in Ansys Fluent. Each phase (gas, liquid) is solved by separated equation in the Eulerian model. Momentum equation for evaporation model (2) [1] contents mass transfer expression from liquid state to gas state (evaporation). Mass transfer from gas to liquid state (condensation) is zero for our case. The symbols in equation (2) means: $\mathbf{v}$ – vapour index; $\mathbf{l}$ – liquid index; α – volume fraction of vapour; ρ_v – vapour density; $\vec{v}_v$ - velocity of gas state; $\dot{m}_{l \to v} - \dot{m}_{v \to l}$ - evaporation rate [kg/s/m^3].

$$\frac{\partial}{\partial t}(\alpha \cdot \rho_v) + \nabla \cdot (\alpha \cdot \rho_v \overrightarrow{V_v}) = \dot{m}_{l \to v} - \dot{m}_{v \to l}$$ (2)

Mass transfer for evaporation is started when saturation temperature T_{sat} (input for Fluent) is exceeded and is defined by equation (3) [1]:

$$T > T_{sat}; \; \dot{m}_{l \to v} = coeff \cdot \alpha_l \rho_l \frac{(T - T_{sat})}{T_{sat}}$$ (3)

coeff – coefficient which possible be tuned.

4. EXPERIMENT

Drying process is done as simplified experiment of drying to get results of evaporation of water content from cotton linen (towel). The towel is placed in the pipe (diameter 200 mm) and fixed. The towel contains certain amount of water which is measured as weight. First part of the experiment is measure of pressure drop in the pipe. The structure of the pressure drop test shows Figure 1. Pressure of air in the first part of the pipe is higher and dependences on character of the porous medium.
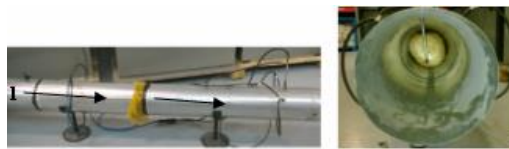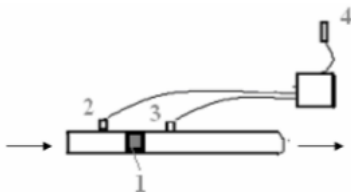

Figure 1 **Measure track**

The second part of experiment - drying rate is measured from wet towel with using relative humidity sensor and temperature senor. The schema of the test shows Figure 2. Hot air flows in arrows direction. Sensors of temperature and relative humidity are connected with data logger and data records during the test.

1 – wet towel

2 – temperature sensors

3 – relative humidity and temperature sensor

4 – ambient humidity and temperature sensor

Figure 2 **Experiment layout**

Flow of hot air acts the wet towel and water evaporates into hot air. Water content before and after drying is defined as weight. Evaporation process removed 0,3 kg of water from towel (Figure 3) during the test. Measurement of evaporation takes 16 minutes.

Weight - wet towel	Weight after drying	Weight difference
0,45 kg	0,15 kg	0,3 kg

Figure 3 **Weight of towel and water**

4.1. Flow measurement

Flow measurement is performed by the Pitot tube. As a device is used Testo 521 provides the calculation of velocity and flow rate. The scheme of measurement and device shows Figure 4 [7]. Measurement range is $0 – 2,5$ hPa. Accuracy $+/-0,5$ Pa.
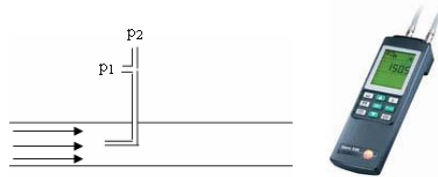

Figure 4 **Device for flow measurement**

4.2. Pressure measurement

Principal of pressure measurement is based on deformation of piezoresistive tensiometer. Device SBS 3000 (Figure 5) is equipped by semiconductor sensor (silicon sensor). The logger can operate in range $\pm$ 2 kPa and accuracy 0,1 %.

Figure 5 **Device SBS 3000**

4.3. Temperature and humidity measurement

Temperature and humidity monitoring is done by thermocouples and capacitive humidity sensor. Both connected to data logger Squirrel 2020 (accuracy 0,05 %). The thermocouple is K – type with measurement range -270 – 1372 ˚C and accuracy $+/-0,018$ %. The capacitive humidity sensor can be used in range $0 – 100\%$ relative humidity with temperature -20 – 80 ˚C and accuracy $<\pm2\%$ RH (10–90% RH). Sensors and data logger shows Figure 6.
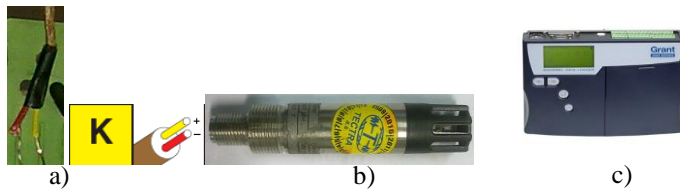

Figure 6 **a) Thermocouple, b) Humidity sensor c) Data logger**

5. RESULTS OF MEASUREMENT

5.1. Permeability and inertial resistance factor based on measured pressure drop and velocity

For set up of the porous layer in Ansys Fluent is necessary to find coefficients C_2 and $1/\alpha$. Ansys Fluent manual [2] describes a technic which helps to find porous coefficients from pressure drop measurement in the manner described below [2]. Measured experimental data of pressure loss and velocity across the towel are used for creating trend line (Figure 7).

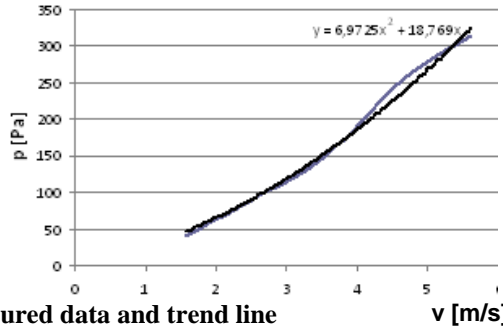| v [m/s]	p [Pa]
1,57	40
2,37	83
3,55	150
4,64	255
5,61	315

Figure 7 **Measured data and trend line**

Trend line equation can be written as function of pressure and velocity as variable:

$$p = 6,9725v^2 + 18,769v \tag{4}$$

Coefficients from equation (4) are used as inputs for derivative the pressure drop coefficients:

$$6,972 = C_2 \frac{1}{2} \rho \cdot t$$

$$18,769 = \frac{\mu}{\alpha} \cdot t$$

where:
μ – kinematic viscosity of air [$m^2 \cdot s^{-1}$]
ρ – air density [$kg \cdot m^{-3}$]
t – thickness of porous component [m]

The results for coefficients C_2 and $1/\alpha$ used in Ansys Fluent for porous zone are C2 = 76 m^{-1}; $1/\alpha$ = 6990000 m^{-2}.

5.2. Mass flow, inlet and outlet temperature

The pipe is connected to the device which provide flow rate of hot air 249 m^3/h with velocity 2,2 m/s. The inlet temperature is regulated by the thermostat and indicated by a thermocouple. Outlet temperature is as well measured (Figure 8). Ambient temperature during the test is 26 ˚C.
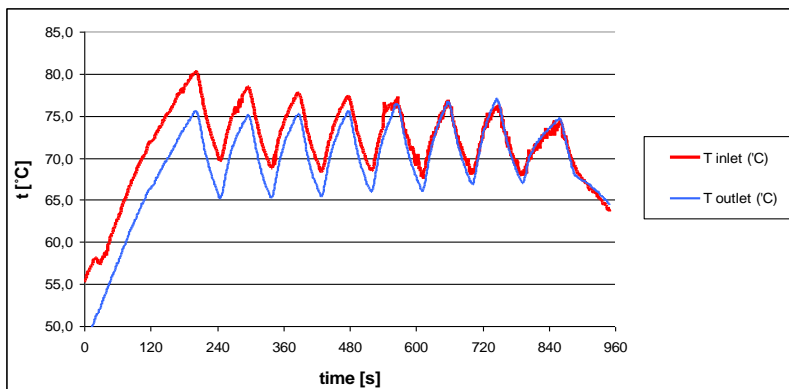

Figure 8 **Inlet and outlet temperature**

The monitor point for outlet temperature is situated behind towel (point 3, Figure 2) and at the same position is installed the relative humidity sensor.

5.3. Relative humidity

Measured progress of relative humidity during water evaporation shows Figure 9. As it is visible from the graph the humidity sensor indicates almost constant value of relative humidity (circa 8%) after some time. Ambient relative humidity is 35 %.
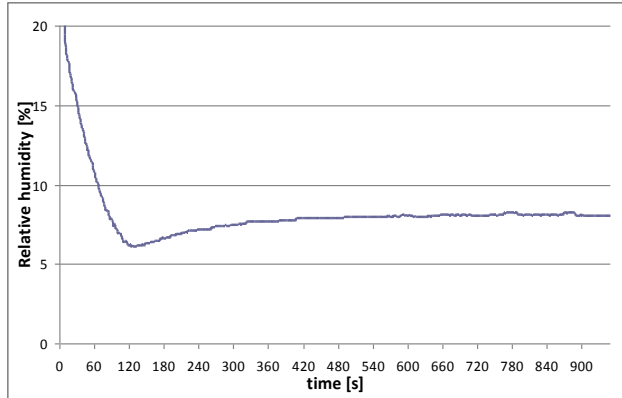

Figure 9 **Relative humidity**

5.4. Absolute humidity

For the better result representation the measurement of relative humidity is used as input for calculated absolute humidity (Figure 10). From the equation of state $p_p.V = m_p.r_p.T$ [4] vapour density can be expressed as $\rho_p = \dfrac{p_p}{r_p.T}$ [4] which is actually absolute humidity [kg/m^3]. The partial pressure of vapour $p_p = \varphi.p_p^{"}$ [3] is derived from relative humidity φ and from saturated vapour pressure $p_p^{"} = \exp\left(23,58 - \dfrac{4044,6}{235,628 + t}\right)$ [Pa] [3] at the given temperature t [$°C$]. Figure 10 shows ambient (inlet) absolute humidity which is constant and intensity of evaporation it means absolute humidity behind towel. Evaporation intensity reacts to the temperature (chapter 5.2)
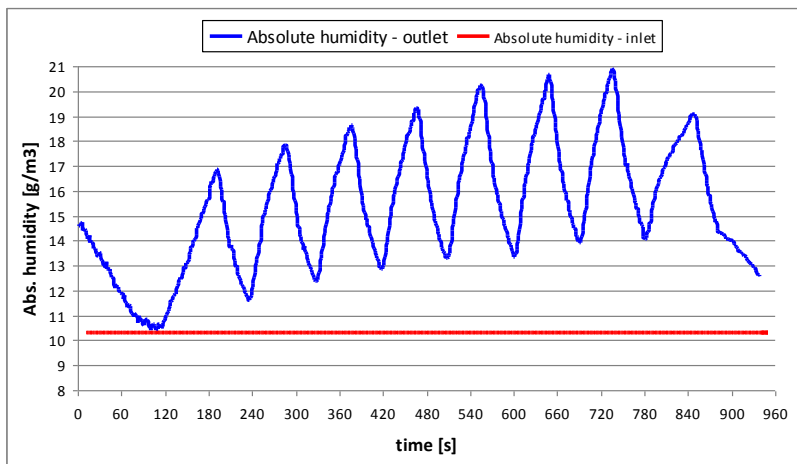

Figure 10 **Absolute humidity**

5.5. Evaporated mass

Values of absolute humidity and airflow can be use for evaluation of evaporated mass from towel. Figure 11 describes weight of vapour behind wet towel. The curve of total mass vapour is calculated with ambient absolute humidity. The second curve represents just amount of vapour evaporated from towel and it is difference between total mass of vapour and mass of vapour in ambient air which is used for drying. Amount of water evaporated from towel is a sum of values (lower curve) across time and it is 0,3 kg. This result is comparable with Figure 3 at chapter 4.
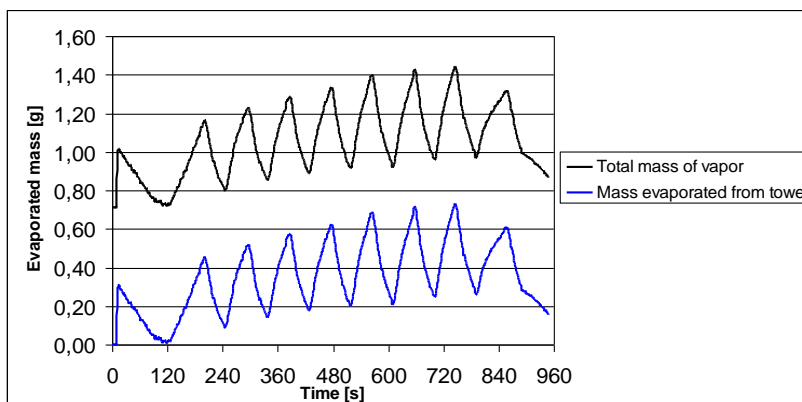

Figure 11 **Mass of water vapour**

5.6. Saturation temperature and pressure

Results from experiment of evaporation will help to find the values for saturation temperature and vapour pressure being set to Evaporating model in Ansys Fluent. Ansys Fluent application needs to define saturation temperature in terms of pressure for run the evaporation process. For saturation temperature is used value of dew point which corresponds to relative humidity 8% (mainly measured value in our experiment) and operating temperature. For example for relative humidity 8% and temperature 60°C is dew point 13,9°C and partial vapour pressure 1592 Pa. By this way are got next values of saturation temperature and pressure (Figure 12) for our operating temperature 50-80°C. These values will be set to evaporation model as saturation temperature and vapour pressure for evaporation process. Atmospheric pressure is 101,6 kPa.

t [°C]	t_{dew} [°C]	pp [Pa]
50	6,7	986
60	13,9	1592
70	21	2491
80	28	3789

Figure 12 **Partial pressure vs. dew points**

The phase change equation is used for verification that described approach is correct. Phase change from liquid to vapour expresses the Clausius – Claperyon equation. The Clausius-Clapeyron equation (5) relates the latent heat of evaporation to the rate of change of vapour pressure with temperature [3], [6].

$$\ln \frac{p_2}{p_1} = -\frac{l_v}{r_p} \cdot \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \tag{5}$$

In the equation (5), l_v means latent heat of vaporisation for water [J/kg], p – pressure [Pa], T - temperature [K]. The graphic interpretation of equation shows Figure 13. The curve means interface between liquid state and gas state.
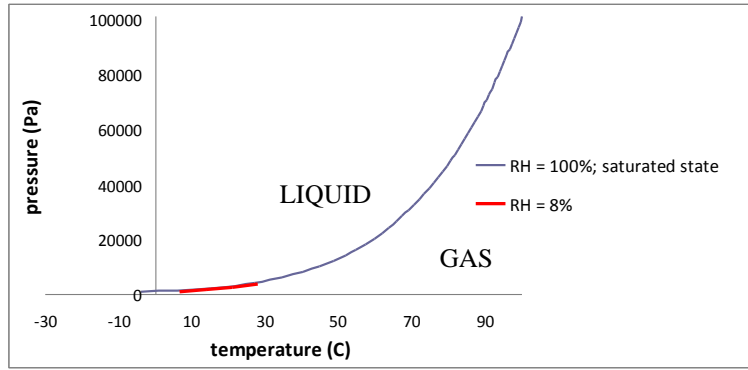
Figure 13 **Phase state interface**

The curve for saturation conditions (relative humidity 100%) defines interface (temperature – pressure) with wide range of temperature values. The dew point corresponds with value of temperature. It means i.e. at 100 ˚C and at saturation condition (RH = 100%) is temperature of dew point T_{dew} = 100 ˚C, for 80 ˚C and RH = 100% is T_{dew} = 80 ˚C.

Temperature in our case varies and maximum is till 80˚C. However relative humidity during evaporation is not in saturation level (100%) but measured mainly at 8%. Dew point temperature for this state can be calculated according to the equation (6) [5].

$$T_{dew} = \frac{243,5 \ln\left(\frac{RH}{100} \cdot e^{\frac{17,67 \cdot t}{243,5+t}}\right)}{17,67 - \ln\left(\frac{RH}{100} \cdot e^{\frac{17,67 \cdot t}{243,5+t}}\right)} \tag{6}$$

The values of dew point and vapour partial pressure for relative humidity 8% and operating temperature 50-80˚C represents the red curve in Figure 13. Vapour partial pressure at given temperature is calculated from known relative humidity φ = 8 % and vapour pressure at saturation condition $p_p^{''}$ (7) [3].

$$p_p = \varphi . p_p^{''} \tag{7}$$

6. CONCLUSIONS

The physical experiment of drying helps to find values for saturation temperature and partial vapour pressure (Figure 12) which are set in Ansys Fluent for evaporation model. Evaporation of water from the cotton towel is measured by relative humidity sensor. Values of temperature and relative humidity are used for finding values of absolute humidity which gives an idea of drying intensity.

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