Mathematical Simulation of Drying Process of Fibrous Material

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Abstract. The article describes mathematical simulation of flowing air through porous zone and water vaporisation from mentioned porous area which actually represents dried fibrous material - cotton towel. Simulation is based on finite volume method. Wet towel is placed in pipe and hot air flow through the towel. Water from towel is evaporated. Simulation of airflow through porous element is described first. Eulerian multiphase model is then used for simulation of water vaporisation from porous medium. Results of simulation are compared with experiment. Ansys Fluent 13.0 was used for calculation.

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 mathematical modelling is a very good way how to simulate airflow through the porous medium. The porous area with defined parameters can be represented as linen - cotton towel. Porous parameters and next inputs for simulation are derived from the real experiment [2], [4]. The mathematical model of wet linen is achieved by patching liquid phase into porous zone. The simulation based on finite volume method can be complemented by evaporation model in Ansys Fluent so liquid phase is evaporated from porous zone and drying process is simulated.

The group of authors refers about simulation of drying process realized in industry. The example of simulation process of drying is the drying of soybean [5], spraying and evaporation of particles into hot airflow [6], vacuum drying of wood [7] or drying of the iron ore pellets [8]. Mathematical modelling of multiphase flow with phase change in energy facilities is refered [9].

2 Experiment Data - Base for Ansys Fluent Data

The drying process and a detailed description of the measurement procedure, measuring devices and measurement results have been described in [4]. The towel was placed in the long pipe (diameter of pipe is 200 mm) and fixed (length of the pipe with towel is 110 mm (Figure 2). The towel contained certain amount of water. The airflow through wet towel caused evaporation

of water. Temperature of air was regulated by thermostat. The drying rate was measured from wet towel with using the relative humidity sensor and temperature sensor placed behind towel. The pressure sensors were placed in the same sampling points. The schema of the test shows Figure 1. Hot air flows in arrows direction.
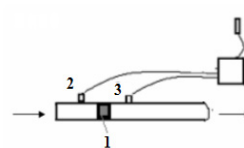
1 – wet towel
2 – temperature, flow rate and pressure sensors
3 – relative humidity, temperature and pressure sensors
4 – ambient humidity and temperature sensor

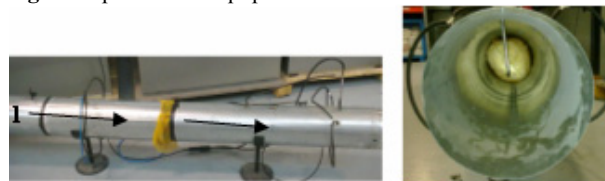**Fig. 1.** Experimental equipment.

Fig. 2. Experiment layout with fixed towel.

Diameter of the pipe was 0,2 m, distance between sampling points 2 and 3 was 2,14 m. The towel was placed between sampling points 2 and 3 and length of the pipe with towel was 0,11 m.

Water content before and after drying was defined as weight. Evaporation process removed 0,25 kg of water from towel (Table 1) and after the test the towel becomes totally dry. Weight of the dry towel was 0,2 kg. Measurement of evaporation taken 16 minutes.

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Table 1. Weight of towel and water.

Weight - wet towel	Weight after drying	Weight difference
0,45 kg	0,2 kg	0,25 kg.

3 Theory of Eulerian Model

The main purpose of using this type of simulation model is its ability to solve each phases by multiple separate way [1]. The phases of air, water-vapour and water - liquid are set in the model. To simulate drying of the wet fibrous material the phase water - liquid can be patched into porous zone and the velocity of water - liquid phase can be fixed to 0 m/s in this zone. Air phase (with included vapour phase to simulate ambient wet air) flows through porous zone. Eulerian model also allows use the vaporisation model and water-liquid is evaporated from the porous area.

3.1 Continuity equation

The continuity equation for phase q is described by equation (1), where $\vec{v}_q$ is velocity of phase q, γ is porosity of the porous area, ρ_q is density of the phase q, α_q is phase volume fraction, m_{pq} is mass transfer from phase p to phase q, S_q is source term considered to be zero in our case [1].3.1.

$$\frac{\partial(\gamma\alpha_q\rho_q)}{\partial t} + \nabla\cdot\left(\gamma\ \alpha_q\rho_q\vec{v}_q\right) = \gamma\sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + \gamma\ S_q \qquad (1)$$

3.2 Momentum equation

Momentum balance for the phase q shows (2), where $\vec{R}_{pq}$ is interaction force between phases, $\vec{F}_q$ is external body force, $\vec{F}_{lift,q}$ is lift force, $\vec{F}_{vm,q}$ is virtual mass force, $\vec{v}_{pq}$ is interphase velocity, τ is stress tensor [1].The continuity equation for phase is

$$\frac{\partial(\gamma\alpha_q\rho_q\vec{v}_q)}{\partial t} + \nabla\cdot\left(\gamma\ \alpha_q\rho_q\vec{v}_q\vec{v}_q\right) = -\gamma\alpha_q\nabla p + \nabla\cdot\left(\gamma\ \tau_q\right) + \gamma\alpha_q\rho_q\vec{g} +$$
$$+\gamma\sum_{p=1}^{n}\left(\vec{R}_{pq} + \dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}\right) + \gamma\left(\vec{F}_q + \vec{F}_{liftq} + \vec{F}_{vmq}\right) + \alpha_q\left(\frac{\mu}{K} + \frac{C_2\rho}{2}\left|\vec{v}_q\right|\right)\vec{v}_q \qquad (2)$$

Coefficients C2 and 1/α for porous area were determined by manner described in reference [2].

3.3 Energy equation

Energy equation for multiphase Eulerian model has form (3), where h_q is enthalpy of phase q, is heat flux, Q_{pq} is intensity of heat exchange between phases p and q [1].

$$\frac{\partial(\gamma\alpha_q\rho_q h_q)}{\partial t} + \nabla\cdot\left(\gamma\ \alpha_q\rho_q\vec{v}_q h_q\right) = -\gamma\alpha_q\frac{\partial(p_q)}{\partial t} + \gamma\tau_q:\nabla\vec{v}_q - \nabla\left(\gamma\ \vec{q}_q\right) + \gamma S_q + \qquad (3)$$
$$+\gamma\sum_{p=1}^{n}\left(Q_{pq} + \dot{m}_{pq}h_{pq} - \dot{m}_{qp}h_{qp}\right)$$

Ranz - Marshall correlation (5) [1] was used for solving the heat transfer coefficient h_{pq} (4) between phases air and water. Here κ_q is thermal conductivity, Nu is Nusselt number, d_p is particle diameter, Re is Reynolds number, Pr is Prandtl number.

$$h_{pq} = \frac{6\kappa_q\alpha_p\alpha_q Nu_p}{d_p^2} \qquad (4)$$

$$N_u = 2.0 + 0.6R_e^{1/2}\ \mathrm{Pr}^{1/3} \qquad (5)$$

3.4 Ansys Fluent Evaporation model

Momentum equation for evaporation model (6) [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 (6) means: v is vapour index; l is liquid index; α is volume fraction of vapour; ρ_v is vapour density; $\vec{V}_v$ is velocity of gas state; $\dot{m}_{l\rightarrow v} - \dot{m}_{v\rightarrow l}$ is evaporation rate [kg/(s·m^3)].

$$\frac{\partial}{\partial t}(\alpha\cdot\rho_v) + \nabla\cdot(\alpha\cdot\rho_v\overrightarrow{V_v}) = \dot{m}_{l\rightarrow v} - \dot{m}_{v\rightarrow l} \qquad (6)$$

Mass transfer for evaporation is started when saturation temperature T_{sat} (input for Fluent) is exceeded by ambient temperature in certain part of domain. Mass transfer is defined by equation [1]:

$$\dot{m}_{l\rightarrow v} = coeff\cdot\alpha_l\rho_l\frac{(T - T_{sat})}{T_{sat}} \qquad (7)$$

4 Simulation in Ansys Fluent 13

Mathematical model consists from pipe zone and from porous zone. Model is simplified and defined as 2D axisymmetric case, see Figure 4. Diameter of the pipe is 0,2 m and length of the porous zone is 0,11 m.
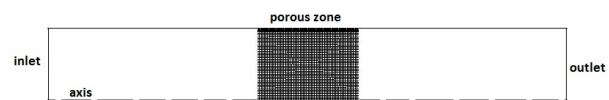

Fig. 4. Mathematical model

4.1 Boundary conditions

4.1.1 Inlet of airflow and its humidity

At the inlet the mass flow of hot wet air (0,084 kg/s) containing the water vapour (mass fraction 0,0087) is defined. Ambient air temperature is 26 ˚C and relative humidity 35%. Specific humidity is then 0,0075 kg/kg. Basically specie defined in the calculation as mass fraction 0,0087 represents humidity available in the air.

4.1.2 Inlet of air temperature

Temperature values at inlet were measured and regulated by the thermostat, see Figure 5. Boundary condition of air temperature is driven by values from file.
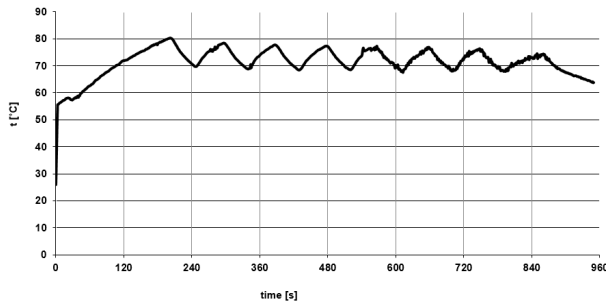

Fig. 5. Inlet temperature

4.2 Initial conditions

4.2.1 Pressure and content of moisture in porous zone

Pressure initialization is specified by value 101300 Pa. Other important initial value is volume fraction of water in the porous zone. Practically it means moisture content in fibrous material (cotton towel). Defined volume fraction 0,058 of phase water reflects 0,25 kg of water in the porous area. Water droplet diameter is set to value 0,0025 mm. It reflects good results of vaporisation process in simulation process in Fluent.

Porosity of the porous area is set to 0,95. This value is determined on basis of experimental and numerical testing. Water phase has fixed value of velocity in porous zone (0 m/s) so it does not move in the zone.

4.3 Saturation temperature and pressure

The evaporation model described in chapter 3.4 needs to define saturation temperature in terms of pressure. For saturation temperature the value of dew point is used. It corresponds to relative humidity 8% (mainly measured value in experiment) and operating temperature [4]. Table 2 shows set of values.

Table 2. Saturation temperature and pressure

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

5 Results of Calculation and Comparison with Experiment

The results of the calculation are compared with data measured during experiment [4]. It is mainly pressure drop across the pipe, temperature, specific humidity, relative humidity.

5.1 Pressure drop in the pipe

Result of pressure drop from experiment [4] is 83 Pa at airflow velocity 2,37 m/s and corresponds with result from simulation. For calculated velocity of airflow 2,66 m/s (right part of Figure 6) the simulation shows the pressure drop 86 Pa (left part of Figure 6). Velocity through porous zone is modelled as a model of physical velocity [2] it leads to higher values of velocity in porous area (Figure 6).
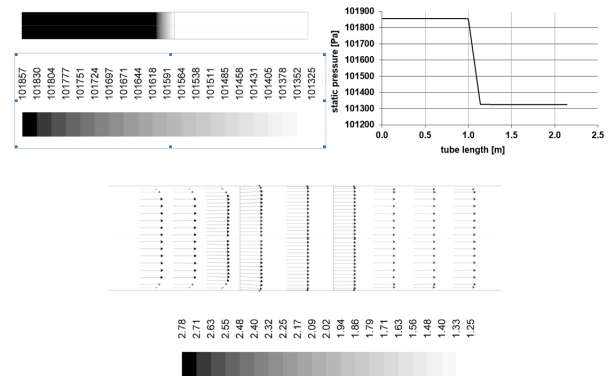

Fig. 6. Static pressure and velocity profile in porous zone

5.2 Relative humidity

Relative humidity indicated at the outlet varies and dependents on temperature and intensity of water evaporation. Ambient relative humidity is 35,5% at the temperature 26 ˚C. Calculated relative humidity at outlet - Fluent shows higher values till flow time 360 s then it continues with values placed under measured data (Figure 7). Relative error of simulation results for certain time is shown in Table 3.
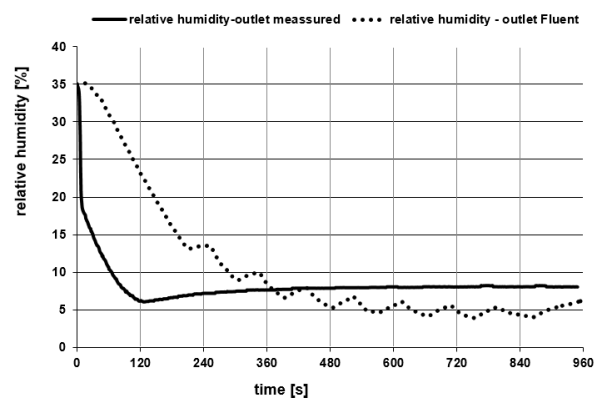

Fig. 7. Relative humidity outlet Fluent

Table 3. Relative error

Flow time [s]	Relative error [%]
205	49,2
520	17,4
920	30

5.3 Temperature

Inlet temperature reported by Ansys Fluent consists from same values which was measured Figure 5. Temperature t - outlet is gained from experiment and is lower than at the inlet due to water evaporation. Temperature t - outlet Fluent is calculated from simulation. It is lower at the beginning and with flow time rises to measured values at the outlet. This behaviour is logical and reflects results from chapter 5.1. Dew point temperature in front and behind of the towel is lower than temperature t - inlet and t - outlet (Figure 8). It means air is not saturated and no condensation occurs, just evaporation. Relative error of calculated temperature t - outlet Fluent in comparison with measured temperature at the outlet for selected time is shown in Table 4.
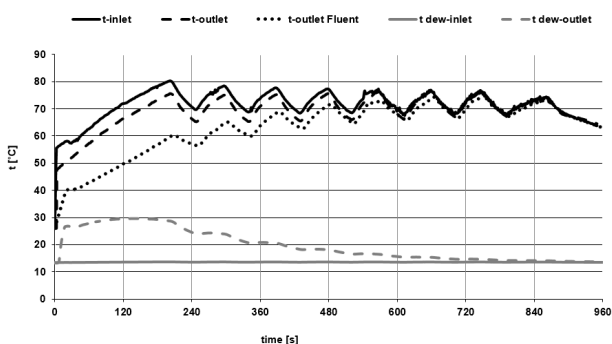

Fig. 7. Measured and calculated temperature

Table 4. Relative error

Flow time [s]	Relative error [%]
205	20,2
520	1,2
920	0,8

5.4 Specific humidity

Specific humidity is derived from measured values of temperature and relative humidity at the outlet. Graph (Figure 8) show ambient specific humidity which is constant (0,0075 kg/kg of dry air) because amount of moisture does not change. The same situation will be at the inlet where just temperature varies but humidity does not. More interesting is state behind porous zone and at the outlet. Water is evaporated from porous zone. Measured specific humidity at the outlet is higher than calculated from time 250 s. Results from simulation shows more intensive evaporation at the beginning and then decreasing trend. Relative error of calculated specific humidity - outlet Fluent related to measured specific humidity for selected time is shown Table 5.
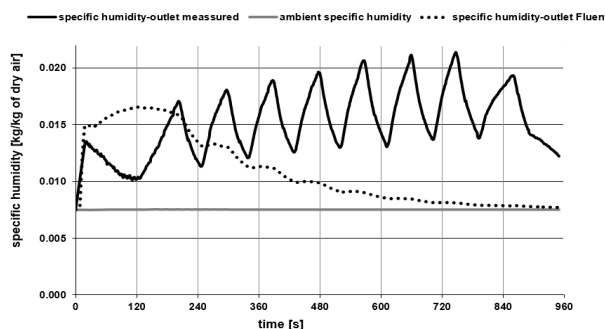

Fig. 8. Calculated and measured specific humidity

Table 5. Relative error

Flow time [s]	Relative error [%]
205	1,8
520	23
920	34

5.5 Volume fraction of water in porous zone

Calculated evaporation process removes volume fraction of water from porous zone. Volume fraction patched into porous zone is set to 0,058 and it is derived from water weight in the towel (0,25 kg) at the beginning of experiment. At the end of calculation volume fraction is 0,0007 and it corresponds to 0,003 kg of water. Almost all the water is evaporated to vapour during calculation and the flow time of vaporisation is specified. The results correspond with Table 1.
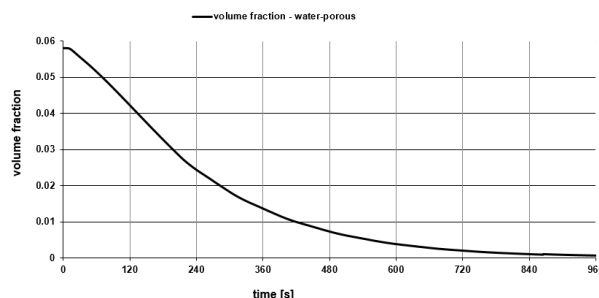

Fig. 9. Water volume fraction in porous zone vs time

5.4.1 Contours of evaporation

Example of evaporation (Figure 10) gives an idea how the simulation principle of drying works and that water liquid is transferred to water vapour state.
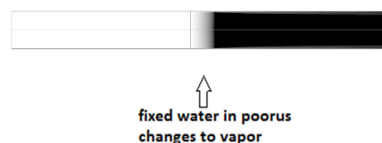

fixed water in poorus changes to vapor

Fig. 10. Evaporation from the porous zone

6. Conclusions

Mathematical simulation of drying process is continuation of the physical experiment of drying [4]. Computational case can be set in Ansys Fluent 13 by a very meaningful way. Due to ability to fix the phase velocity (water-liquid) to zero in the porous zone then the wet fibrous material can be simulated in the mathematical model. The multiphase Eulerian model, thanks of its complexity, is more than suitable for this kind of settings. Final results of the temperature and relative humidity at the outlet are close to measured values. The specific humidity which is calculated [3] has higher relative error in comparison with mathematical simulation. The simulated and measured drying process removes almost all water from linen (porous area).

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