

## A COMPARATIVE ANALYSIS OF THEORETICAL MODELS AND EXPERIMENTAL RESEARCH FOR SPRAY DRYING

### PRIMERJALNA ANALIZA TEORETIČNIH MODELOV IN EKSPERIMENTALNA RAZISKAVA RAZPRŠILNEGA SUŠENJA

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*Prejem rokopisa – received: 2010-09-14; sprejem za objavo – accepted for publication: 2011-02-24*

Spraying is very often applied in the chemical and food-processing industries. It includes the spraying of a suspension – spraying with a content of about 30 % to 65 % of a dry substance. The drying time is in most cases only several seconds. In this work the convective drying principle in warm air is presented.

A mathematical model of momentum, heat-and-mass transfer in the atomization-swirl zone was proposed. An uneven distribution of particles and entrainment effects were taken into account in the model. To verify the model an extensive experimental investigation was performed on water evaporation at different initial air temperatures, feed rates, flow rates of the drying agent for different parameters of the atomization and initial particle size distribution. Changes in the air temperature inside the stream of sprayed material, material temperature, evaporation rate, and changes in the Sauter diameter and the distribution of particle diameter vs. their distance from the atomizer were determined experimentally. Good agreement between the experimental results and the theoretical data was achieved.

In the paper an attempt was made to apply the model to the calculation of spray drying in a pilot-plant dryer. The air supplied to the dryer tangentially to the axis was characterized by a high swirl. In order to consider the swirl air flow pattern in the dryer, changes in heat-and-mass balance were made for the particle-drying agent system. The model was verified experimentally on the basis of results of investigations on the drying of a 55 % mass solution of starch and water.

It was found that our model described the process of drying in the analyzed system. An extensive literature survey on spray drying, including unsteady-state phenomena, is presented in the paper. The main sources of errors occurring in the modeling of the spray drying process were discussed. A critical estimation of the existing mathematical models of the process was made and some of them were described in detail.

**Key words:** spray dryer, model, evaporation, temperature distribution

Razprševanje je pogosto uporabljeno v prehrabni industriji in obsega razprševanje emulzije s 30–65 % suhe snovi. Čas sušenja je največkrat nekaj sekund. V tem delu obravnavamo princip konvektivnega sušenja v toplom zraku. Predlagamo model, ki obsega moment, transfer mase in toplote v coni atomizacije in vrtinčenja, neenakomerno porazdelitev delcev in efekte srkanja. Za verifikacijo modela je bila izvršena obsežna eksperimentalna raziskava izparevanja vode z zrakom z različnimi temperaturami zraka, hitrostjo napajanja, hitrostjo sušenja sušilnega sredstva, parametri atomizacije in z začetno porazdelitvijo delcev. Spremembe temperature zraka v toku razpršenega materiala, temperatura materiala, hitrost izparevanja, spremembe premera Sauter in porazdelitev premera delcev v odvisnosti od razdalje od atomizatorja so bile določene eksperimentalno. Doseženo je bilo dobro ujemanje eksperimentalnih in teoretičnih rezultatov. Obravnavan je bil tudi poskus uporabe modela za izračun razpršilnega sušenja v pilotnem sušilniku. Za zrak, ki je bil tangencialno vpihovan v sušilnik, je značilno močno vrtinčenje. Da bi se upošteval vpliv tega vrtinčenja, sta bili spremenjeni bilanci toplote in mase sistema delec – sušilno sredstvo. Model je bil eksperimentalno preverjen na podlagi rezultatov sušenja 55-odstotne vodne raztopine škroba. Ugotovljeno je, da model dobro opisuje proces sušenja v analiziranem sistemu. V članku je tudi pregled literature o razpršilnem sušenju in obravnavane so najvažnejše napake pri modeliranju. Kritično so ocenjeni dosedanja matematični modeli procesa. Nekateri pa so detaljno opisani.

**Ključne besede:** razpršilni sušilnik, model, izparevanje, porazdelitev temperature

## 1 INTRODUCTION

Different suspensions of certain products react with uneven drying, which depends on the properties of the material that is dried. It is very difficult to recommend a unique technique for spray driers. In comparison with other systems, spray drying requires a relatively small storage space. The service and maintenance are very simple and can be performed with little labor. These advantages and an economical heat transfer provide the optimal cost of the final dried product. The drying time is in most cases only a few seconds and sensitive products, such as vitamins, chemical and food products and others, who better submit to a high temperature in a

short period of time, but lower temperatures for a longer period of time could be dried.

For substances and materials with over 30 % of moisture, spray drying is a good solution to the problem of drying.

Thanks to the principle of convective drying, the dried material and contact drying agent, the system receives intensive exchange of heat and mass and is very difficult to give an adequate mathematical model of the process, given the complex processes of heat-and-mass transfer involved.

There have been many attempts to formulate a mathematical description of spray drying since the

1950s. In spray drying there are many phenomena that are difficult to represent in the form of a mathematical model. For many years the polydispersity of spray, entrainment effects, or problems of internal heat-and-mass transfer in the disperse phase have been inadequately considered in models. In practise, models of the process that have been created since the beginning of the 1970s were concerned only with the flow of the drying agent.

A significant advancement was achieved in the 1970s, when the principles of momentum, heat-and-mass balances between the continuous and disperse phases <sup>1</sup> (for monodisperse spray and plug flow of the air), and especially when was presented a model in which the entrainment effects and non-uniformity of atomization were accountable were formulated <sup>2</sup>. The solution of the model of spray drying taking into account axial and tangential velocity distributions of air was presented, also. All the aforementioned relations (the entrainment rate and the hydrodynamics of the drying agent) were determined empirically. In further publications the researchers presented many successful applications of their model both in the modelling and the scaling-up of the process. The simple model was recognized by many researchers and studies based on this model have been published <sup>3</sup>.

However, the biggest change occurred when the so-called particle source in the cell (PSI-cell) model for gas-droplet flows was proposed <sup>4</sup>. A method for solving the Navier-Stokes equations and the continuity equation was developed where the droplets were treated as sources of mass, momentum and energy to the gaseous phase. In the model, the gas flow field and droplet trajectory are recalculated sequentially until the flow field fails to change with repeated interactions. In the model proposed originally <sup>1</sup> many simplified assumptions were made that referred mainly to the calculation of trajectories and the temperature of the particles. Further extensive studies resulted in developing more sophisticated versions of the PSI-cell model, also including commercial packages such as FLOW3D and PHOENIX.

The PSI-cell-type models were used successfully to predict such subtle phenomena as the analysis of low-frequency oscillations in the flow field inside the spray drying chamber <sup>5</sup>, a determination of the conditions in which recirculation zones appear in the chamber <sup>6</sup> or the effects of inlet air geometry and cone angle on the wall deposition rate <sup>7</sup>.

It should be stressed, however, that a practical application of the PSI-cell-type model requires profound knowledge of spray drying and some experience in the programming and calculation of systems with distributed parameters. One problem, which is still unsolved, is the choice of a turbulence model that should be applied in the calculations <sup>8</sup> in such a way that the theoretical results obtained are as near as possible to the experimental values.

Therefore, there is still a considerable demand for simple models that can be used to optimize the process, to minimize its costs, and to evaluate product quality <sup>9</sup>. However, there are many publications of a classical construction representing new concepts of mathematical models of spray drying and offering an extensive description of the whole process <sup>10</sup>.

The quality of a spray-drying simulation depends not only on the on the quality of the applied mathematical model but also, and sometimes mainly, on the accuracy of the determination of the initial parameters of the process, and, in particular, the parameters of atomization (mainly the initial particle size distribution and the spray cone angles). An error made in this stage is carried forward and may cause the results obtained to disqualify the modelling process fully, irrespective of the type of model applied.

In the literature, several interesting attempts have been undertaken to overcome this problem. It was proposed to determine experimentally the air temperature distributions in the dryer chamber and then to apply the results directly as the input in the integral equations for the simulation of heat-and-mass transfer of the process <sup>11</sup>. Unfortunately, the experimental determination of the temperature profiles in the dryer is as difficult as the determination of atomization parameters. It also proposed to perform calculations for a randomly generated initial particle size distribution. The model requires an assumption of the air temperature distributions in the dryer <sup>12,13</sup>. The authors state that the model can be developed in such a way that the temperature can be calculated iteratively. However, so far neither has its developed a version of the model been proposed nor has its experimental verification been given.

In this paper, an attempt was made to formulate our own mathematical model for spray drying, which, based on the classical methods for balancing the transport processes between the continuous and disperse phases, would make it possible to analyze the phenomena on the level accessible only to PSI-cell-type models. The proposed model is a development of the concept presenting a theoretical method for the calculation of the entrainment rate <sup>14</sup>. One of the aims of the study was to apply the model and to verify it experimentally in two different drying systems (flat air velocity profile, pressure nozzle, evaporation of water and high swirl air-flow pattern in a chamber, two-fluid nozzle and drying of solution containing dissolved solids.).

## 2 MODEL OF THE PROCESS

The spray envelope was divided into two regions: the spray boundary region and the spray core region. The spray boundary region is determined by the location of the particles of the atomized material. A change in the location of the particles towards the radial direction also means an increase in the spray diameter and the amount

of air inside the spray which comes into contact with particles. The amount of air which controls the spray can be determined by defining the position of the particles as a function of the distance to the atomizer – swirler. The main assumption made when developing the model is the following: if spraying is monodisperse, or if only one fraction of particles is considered, then in the cross-section of the spray the temperature and air humidity are distributed evenly. The temperature and humidity gradients appear when the atomization is polydisperse. This distribution can be determined by solving the subsequent heat-and-mass transfer equations for particular fractions.

If the air velocity profile is flat, the total amount of air which should be taken into account in the heat-and-mass balance will be the sum of the air flowing through the main core of the spray and the air  $dw_g$  that entered the spray, determined by the change in the position of the particles (**Figure 1**).

The position of the particle as a function of the distance to the atomizer can be calculated from the generally known transfer equations that have the following form for three dimensions:

$$\frac{dU_{px}}{dh} = \left[ \left( 1 - \frac{\rho_g}{\rho_p} \right) g - \frac{3}{4} C_d \frac{U_p (U_{px} - U_{gx}) \rho g}{\rho_p d_p} \right] \frac{1}{U_{px}} \quad (1)$$

$$\frac{dU_{pr}}{dh} = \left[ \frac{U_{pt}^2}{r} - \frac{3}{4} C_D \frac{U_p (U_{pr} - U_{gr}) \rho g}{\rho_p d_p} \right] \frac{1}{U_{px}} \quad (2)$$

$$\frac{dU_{pt}}{dh} = \left[ -\frac{U_{pt}}{r} - \frac{3}{4} C_d \frac{3 U_p (U_{pt} - U_{gt}) \rho g}{\rho_p d_p} \right] \frac{1}{U_{px}} \quad (3)$$

where  $U_p$  is the relative particle velocity calculated from

$$U_p = [(U_{px} - U_{gx})^2 + (U_{pr} - U_{gr})^2 + (U_{pt} - U_{gt})^2]^{1/2} \quad (4)$$

In the case of flat velocity profiles in the systems, Eqs. (1)–(4) will be simplified, as  $U_{gr} = U_{gt} = 0$ . The tangential and radial locations of particules will be determined from

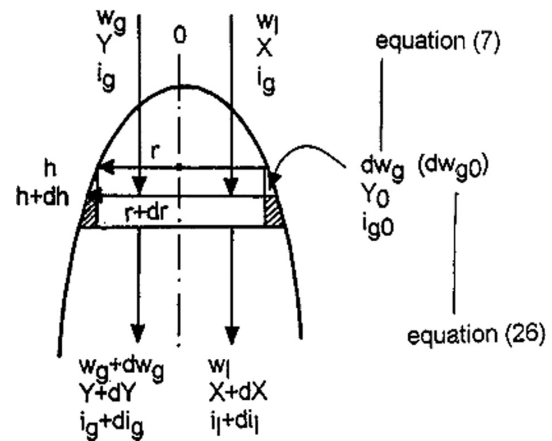
$$\frac{dr}{dh} = \frac{U_{pr}}{U_{px}} \quad (5)$$

$$\frac{dx_t}{dh} = \frac{U_{pt}}{U_{px}} \quad (6)$$

If at first the mass balances for a solid-gas system, assuming that atomization is monodisperse or that only one fraction of the dispersed material is to consider and assume that in the stream cross-section, there is neither a temperature nor an air humidity gradient and that continuous and dispersed phases are concurrent.

The mass balance has the form in **Figure 1** and it is given by equation 7.

$$w_g Y + w_1 X + dw_g Y_o = (W_g + dw_g) (Y + dY) + w_1 (X + dx) \quad (7)$$



**Figure 1:** Heat-and-mass transfer balances for spray-air system  
**Slika 1:** Bilance prenosa toplote in mase za sistem razprševanje – zrak

With the transformation we obtain where  $Y_0$  is the bulk humidity (outside the stream).

$$\frac{dY}{dh} = \frac{dw_g}{dh} \frac{Y_0 - Y}{W_g} - \frac{w_2}{w_g} \frac{dX}{dh} \quad (8)$$

Similarly, a heat balance for both phases can be derived (**Figure 1**):

$$w_g i_g + w_1 i_1 + dw_g i_{g0} = (w_g + dw_g)(i_g + di_g) + w_1 (i_1 + di_1) \quad (9)$$

After the transformation we obtain:

$$dw_g i_{g0} = w_g di_g + dw_g i_g + w_1 di_1 \quad (10)$$

Humid air and material enthalpies are described by the equations

$$i_g = c_{gs} T_g + (cvTg + \Delta H)Y \quad (11)$$

and

$$i_1 = (Xc_w + c_s)T_1 \quad (12)$$

through the calculation of the derivatives of air and material enthalpies from

$$di_g = c_H dT_g + (cvTg + \Delta H)dY \quad (13)$$

and

$$di_1 = (Xc_w + c_s) dT_1 + c_w T_1 dX \quad (14)$$

and subsequent substitution into Eq. (10), we obtain the equation that can be used to determine the gas temperature in the stream cross-section taking into account entrainment effects

$$\frac{dT_g}{dh} = \frac{1}{w_g C_h} \left[ (i_{g0} - i_g) \frac{dw_g}{dh} - w_g (c_v t_g + \Delta H) \frac{dY}{dh} - w_1 (Xc_w + c_s) \frac{dT_1}{dh} - w_1 c_w T_1 \frac{dX}{dh} \right] \quad (15)$$

The entrainment rate  $dw_g/dh$  can be determined on the basis of the increment of the stream cross-section (**Figure 1**):

$$dw_g = \frac{U_{gx} \rho_g}{1+Y} [\pi(r+dr)^2 - \pi r^2] \quad (16)$$

therefore, the entrainment rate can be determined from

$$\frac{dw_g}{dh} = 2\pi \frac{U_{pr} \rho_g}{1+Y} \frac{dr}{dg} \quad (17)$$

Where the increment of the stream diameter  $dr/dh$  is calculated from Eq. (5).

A complete description of the process requires a determination of the humidity and material temperature in the process.

To evaporate water from a solution containing solid material of moisture  $X$ , the mass balance has the form

$$\frac{dx}{dh} = \frac{W_D(1+x)}{\rho_g V_p} \frac{1}{U_{px}} \quad (18)$$

where  $w_D$  is the evaporation rate given by

$$W_D = f N k_s r_g (Y^* - Y) \quad (19)$$

and  $f$  is the relative drying rate defined by

$$\int \frac{x-x_0}{x_{cr}-X_e} \quad (20)$$

where the subscript  $e$  refers to the equilibrium between the gas and the solids and the subscript to the critical point, above which drying is unhindered and the drying rate depends solely on the rate of heat transfer to the material.

In the case of drying of a solution containing solid material, the drying is unhindered until a crust forms on the droplets. The moisture content during crust formation is the critical moisture content. For a moisture content higher than the critical content or to evaporate the solution that does not contain solid material, the value of  $f$  should be substituted as unity.

The heat balance for a particle material enables a determination of the particle temperature as a function of the distance to the atomizer. The heat delivered to the particle will be used to evaporate the particle:

$$d(m_p c_p T_p) = [k_h S_p (T_g - T_p) - W_D / N (\Delta H + c_v T_g)] dt \quad (21)$$

Assuming that changes in the drying process concern mainly the moisture content and temperature, the left-hand side of Eq. (21) can be transformed to:

$$d(m_p c_p T_p) = d[r_p v_p (c_s + c_w X) T_p] = r_p v_p [(C_s + C_w X) dT_p + c_w T_p dx] \quad (22)$$

Substituting the right-hand side of Eq. (22) into (21), we obtain after rearrangements

$$\frac{dT_p}{dh} = \frac{6a(T_g - T_p) - [W_D N (\Delta H + C_v T_g)] s_p}{d_p \rho_p (c_s + c_w X)} + \frac{U_{px} c_w T_p}{C_s + c_{wX}} \frac{1}{U_{px}} \quad (23)$$

In this process, a continual change in the particle diameters takes place, which has a significant effect on

heat-and-mass transfer coefficients and on the drag coefficient. The actual particle diameter can be determined from <sup>1</sup>:

$$d = d_{p0} \left( \frac{P_{sw0} - P_w}{P_{sw} - P_w} \right) \quad (24)$$

For a moisture content lower than the critical.

The particle diameter no longer decreases and thus Eq. (24) ceases to be valid.

In all calculations, heat-transfer coefficients were determined from the Ranz-Marshall equation and mass-transfer coefficients from the Chilton-Colburn analogy, where the psychrometric coefficient and humidity potential coefficient were taken as unity.

The model described above can be solved in the following way:

1. For monodisperse atomization, the solution of Eqs. (1)–(24) is used to calculate all the process parameters taking into account the entrainment effects.
2. For polydisperse atomization assuming constant air temperatures and humidities in the cross-section of the spray, the evaporation rate (Eq. (19)) should be calculated as a sum of the evaporations from particular fractions i:

$$W_d = \sum_{i=1}^n -1 \int N_i k_i S_{pi} \rho_g (Y^* - Y) \quad (25)$$

For the entire stream of atomized material, the entrainment rate (Eq. (17)) can be calculated on the basis of the motion of the largest diameter particles. Heat-and-mass balance equations for particles solved separately for particular fractions are used to calculate temperatures, moisture contents and the position of the particular fraction in the dryer.

For polydisperse atomization when the air humidity and temperature distributions in the spray cross-section, the system of model equations should be solved

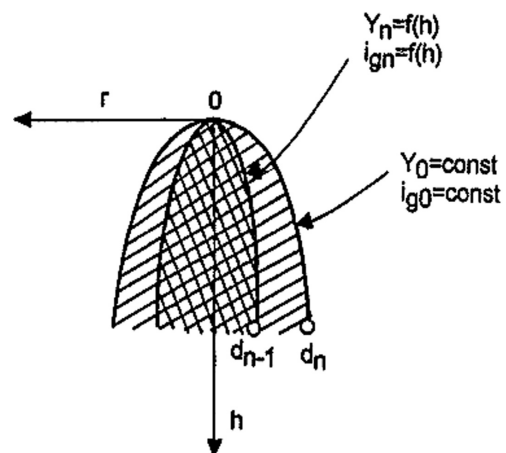


Figure 2: Calculating of humidity and temperature distribution in spray

Slika 2: Izračun porazdelitve vlage in temperature v curku

individually for each fraction starting with the particles of the largest diameter  $d_{pn}$ . A uniform temperature and air humidity field  $T_{gr}$  and  $Y_{ng}$  will be obtained in the stream cross-section. The files should be stored in the computer's memory because the motion of the next fraction of particles of diameter  $d_{pn-1}$  will take place in the field of gas humidity  $Y_n$  and temperature  $T_{gn}$  determined by the fraction of diameter  $d_{pn}$  (Figure 2).

Proceeding in this way, we will obtain the temperature and air humidity distributions in the stream cross-sections: the more fractions that are considered the more accurate is the final calculated result.

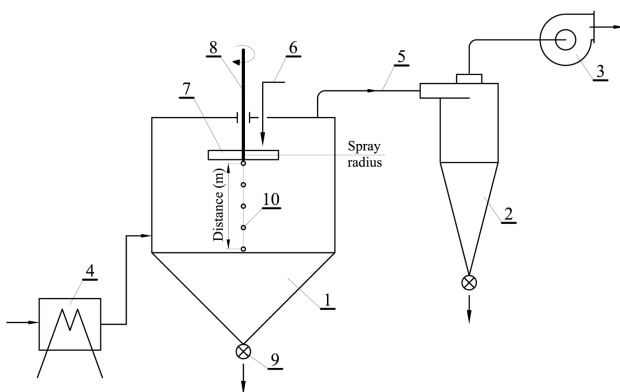
### 3 EXPERIMENTAL DETAILS

To test the proposed mathematical model, experimental investigations were carried out in a dry 55 % solution of starch and water in spray drying. Figure 3 shows a schematic of the experimental equipment of the spray dryer in which the experiments took place. In Table 1 are given the basic characteristics of the spray dryer.

**Table 1:** The basic characteristics of the spray-drying chambers

Name	Units	Dimensions
Diameter chamber spray dryer	(mm)	5000
Elevation spray drying chamber	(mm)	5500
Cyclone diameter	(mm)	1400
Power fan	(kW)	18.5
Air flow	(m <sup>3</sup> /h)	9750–14400
Atomizer (swirler)	(kW)	0.75
Electric motor $r/min$	(min <sup>-1</sup> )	3800

Inlet air drying is done by fans (3). Air over the absorptive heater (4), with the help of fans (3). Thermal power heater (4), can be regulated in the range 40–65 kW. The material is drying leads through the entrance



**Figure 3:** Schematic of the experimental plant spray dryer: 1 – chamber spray dryer, 2 – cyclone, 3 – fan, 4 – heater, 5 – air outlet, 6 – supply of material, 7 – swirler (atomizer), 8 – drive axle, 9 – rotary feeder, 10 – measuring points

**Slika 3:** Shema eksperimentalnega sušilnika: 1 – komora sušilnika, 2 – ciklon, 3 – vetrilo, 4 – grelnik, 5 – dovod zraka, 6 – dovod materiala, 7 – razprševalnik (atomizer), 8 – gonilna os, 9 – vrteči se napajalnik, 10 – merilne točke

(6). Material for drying (55 % mass solution of starch and water), empties into the atomizer (7) with the axle (8) using electric propulsion. Spray nozzle rotates with an rpm of  $n = 3800 \text{ min}^{-1}$  and disperses the liquid solution in small droplets. Aerosols are derived in the form of a rotational disc with the diameter of 320 mm and with a paddle. The extensive spray speed is  $63.5 \text{ ms}^{-1}$ .

In contact with hot gas – air drying dispersed droplets one obtains and the intensive exchange of heat and mass is achieved. Air flow to the fan (3), can be regulated, and the drying air velocity  $V = (0.17 \text{ to } 0.24) \text{ ms}^{-1}$  can be obtained.

The dried material using the rotary feeder is transported as a finished product (9). Air with dust particles are drains with the piping (5) in the cyclone (2) and the completion separation is achieved and discharged in the atmosphere using fans (3).

### 4 MEASURING METHODS

The main part of the paper is concerned with the measurement of the air and material temperature in the spray, the evaporation intensity, and the particle size distribution for various air-flow velocities, feed rates, inlet air temperatures and spray cone angles. The temperature profiles of the air and atomized material as a function of the distance to the nozzle were determined by means of type T thermocouples and an EMT-02 temperature meter. To determine the temperature of the gas flowing inside the spray, the thermocouples were placed in special Teflon casings with an 18 mm external diameter. The Teflon casing diameter was selected on the basis of numerous tests as it achieved a stable temperature read-out. A similar measuring technique was used by <sup>17</sup>. To measure the evaporation intensity, a specially designed measuring plate was used. This plate was inserted into the funnel through the hatches in the measuring section where atomized material was collected on the whole cross-sectional area of the tunnel, which made it possible to calculate the evaporation intensity.

The change in the particle size distribution of the atomized material as a function of the distance to the spray nozzle was determined using the method of image analysis. A sample of atomized material was placed in a Petri dish where the surface was covered with a layer of non-volatile silicone oil. The image obtained from a microscope and camera was recorded on a video cassette, and then processed by a microcomputer image analyzer (IMAL 2561128). To minimize the statistical error for every analyzed sample, 600 particle size distributions of the atomized material were calculated <sup>15,16</sup>. The ambient air temperature and humidity were also measured with a THERM 2285-2 meter produced by Alhborn with the probe FH 9626 -11.

### 5 EXPERIMENTAL RESULTS AND DISCUSSION

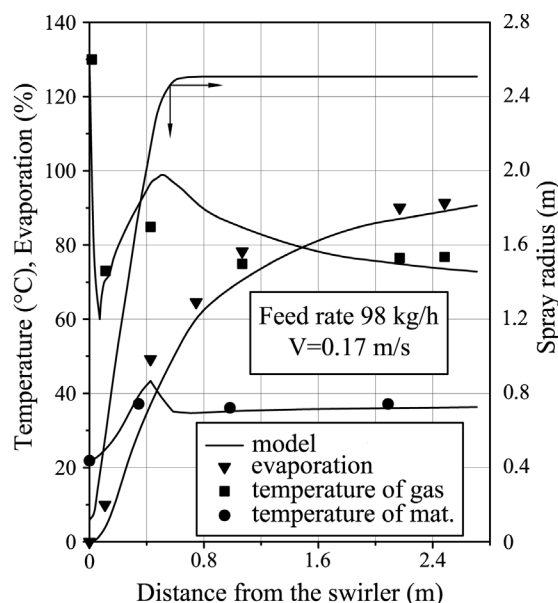
One of the main sources of error in the spray drying simulation is an imprecise specification of the initial process parameters, for example, the spray cone angle and particle size distribution. The parameters were carefully determined for each swirl insert and for each feed rate. Experimental investigations of the water evaporation were carried out for three feed rates (98, 135, 157) kg h<sup>-1</sup>, and three values of air temperature (80, 100, 130) °C. An example of the initial particle size distribution obtained at feed rate of 98 kg h<sup>-1</sup> is shown in **Figure 4**.

Both in this case and for other values of the initial atomization parameters a characteristic log-normal particle size distribution was obtained. The experimental investigations show that the character of the distribution does not change as a function of the distance to the atomizer-swirler in all experimental runs.

All theoretical calculations were made with the assumption that the sign of negligible changes in the air and material temperature in the cross-section of atomized material spray which was confirmed experimentally.

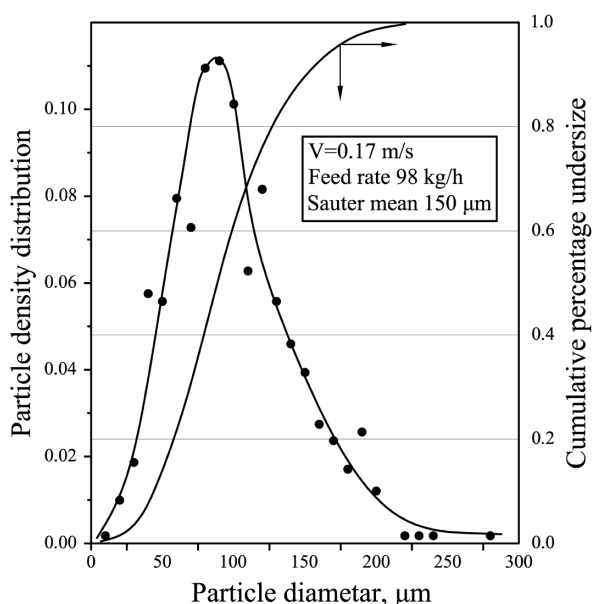
The increase of the temperatures in the cross-section spray dryer is only slight, **Figure 5**. The absence of an air temperature gradient in the spray cross-section can be explained with the design of the experimental set-up and by process parameters. The air-velocity profile in the tunnel of the dryer is flat and the turbulence is low. In the study is up<sup>18</sup> a temperature distribution along the spray dryer radius was observed and similar results were obtained.

As simulation calculations show that in agreement with experimental observations (in all experimental trials

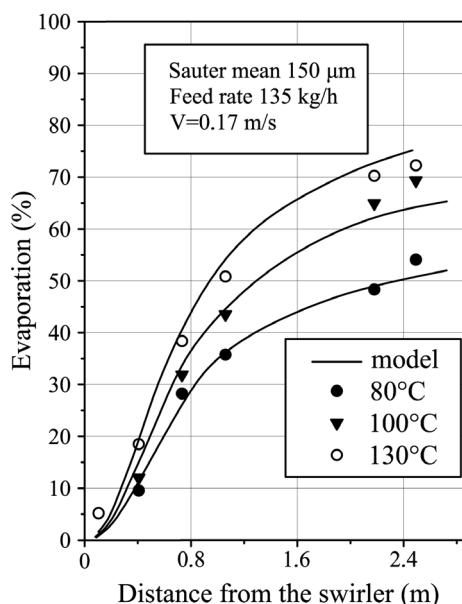


**Figure 5:** Comparison of theoretical and experimental results  
**Slika 5:** Primerjava teoretičnih in eksperimentalnih rezultatov

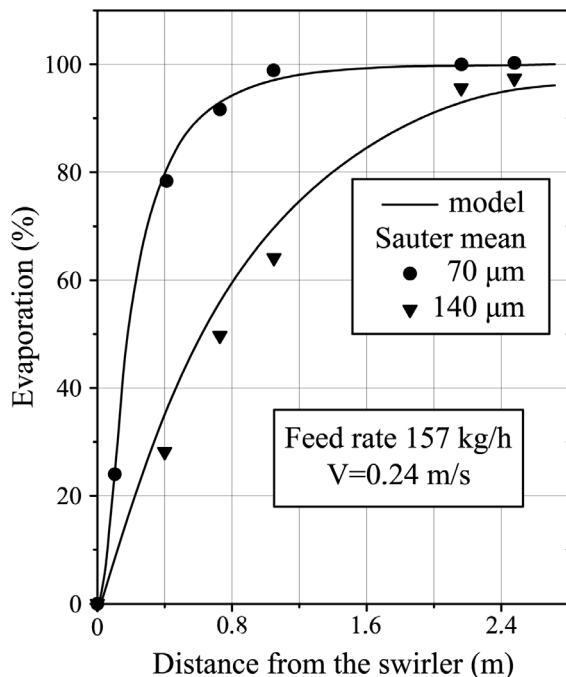
no wetting of the tunnel wall was reported) the particle of diameter corresponding to a 95 % cumulative percentage undersize did not contact the walls of the tunnel dryer, **Figure 5** shows a comparison between the theoretical and experimentally calculated changes in the air temperature, material and evaporation rate as a function of the distance from the atomizer for the same feed rate and air-flow velocity. A theoretically calculated spray radius is also plotted on the same graph. A rapid drop in the air temperature and then its characteristic rise are related to entrainment effects. An increase in the amount of air in the spray due to its expansion causes the



**Figure 4:** Initial particle size distribution  
**Slika 4:** Začetna porazdelitev velikosti delcev



**Figure 6:** Evaporation at different air temperatures  
**Slika 6:** Izhlapevanje pri različnih temperaturah zraka



**Figure 7:** Effect of sauter mean on evaporation rate  
**Slika 7:** Vpliv povprečja Sauter na hitrost izhlapevanja

temperature to rise despite intensive evaporation, until the moment when the balance occurs between the heat used for evaporation and the heat supplied into the spray by the entraining air is achieved. After this time a drop in the air temperature as a function of the distance to the atomizer is observed. Similar profiles of particular functions were obtained in many studies<sup>17</sup>.

The experimental results shown in **Figure 6** illustrate the changes in the evaporation rate along the tunnel of the dryer for different temperatures of the drying agent. Air temperature has a decisive effect on the evaporation rate. No significant influence of the drying agent velocity on the shape of the curves discussed was observed. Particles achieve a zero relative velocity after a short period of time, which limits the convective heat transfer between the continuous and disperse phases.

Lack of air circulation zones in the tunnel causes the spray to compact and move parallel to the tunnel of the dryer walls. The very good agreement between the theoretical and experimental results is worthy of note.

The final figure discussed (**Figure 7**) shows the effect of the initial particle size distribution on the evaporation rate at the same air temperature and feed rates. The analyses of the results show that the character of the initial particle size distribution has a remarkable influence on the whole evaporation process. Particles with a smaller Sauter mean diameter are evaporated much faster than particles having larger mean diameters. In the case when the initial particle size distributions are similar, the feed rate is the parameter that determines the evaporation rate. Good agreement between theoretical and experimental results was also obtained in this case.

## 6 CONCLUSIONS

A mathematical model of momentum, heat-and-mass transfer during spray drying was proposed and verified. The model of a classical construction reflects the majority of phenomena occurring between the conclusions and dispersed phases during atomization. The main difference between the proposed model and the models described in the literature is the balancing of the transport processes between the continuous and disperse phases. It is possible to describe the trajectories of the particle fractions and take into account the entrainment effects. The model was verified both for the system of simple as well as complex drying agents and for the solution containing solid particles. The model presented in this paper can be used to predict many subtle phenomena that occur during spray drying, in particular during complex air flow. In all theoretical simulations of the drying process of evaporation, reasonable agreement with the experimental data was achieved.

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