INFLUENCE OF SELECTED EULERIAN MULTIPHASE MODEL PARAMETERS ON THE SIMULATION RESULTS FOR A SPOUTED BED GRAIN DRYER

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Abstract: The results of a numerical simulation of a spouted bed grain dryer based on the Eulerian Multiphase Model are presented. The influence of various model parameters on the height of the fountain forming in the drying chamber was analyzed. The following computer model parameters were considered: air inlet velocity, grain size and density, and the lowering of bed surface resulting from drying shrinkage and grain pack. An analysis of the approach of turbulence modeling of similar systems is included. The number of computation dimensions and numerical grids is discussed. The presented studies are based on earlier experiments conducted at a dedicated experimental station. Their main objective was to determine the basic principles of modeling fluidized beds found in grain dryers and the computer model's sensitivity to changes in its basic parameters.

Keywords: CFD, Eulerian Multiphase Model, spouted bed grain dryer

1. Introduction

Fountain grain dryers have been the subject of numerous analyses and scientific studies, including studies conducted by numerical methods. So far, the general mathematical model for this type of systems has been formulated and numerous detailed models (so-called "closures") adjusting the simulation model to specific actual systems. Models describing bed have been particularly numerous; studies in this area have covered the principles of momentum exchange between the environment phase (air) and the granular phase (grain), resistance of granulate particles, the influence of solid particles' shape on resistance generated by them, *etc.* There are also various options of mathematical description of the issues of heat and mass exchange (the grain drying process) found in the literature.

This paper presents the initial stage of a project the ultimate goal of which is to develop a spouted bed dryer simulation model maximally consistent with experiment at the qualitative and quantitative levels. This stage of the study is aimed at the development of design principles for the device's general simulation model, the establishment of experimental data sets and numerical parameters necessary for designing the computer model, the development of a set of "closures" offering the best quantitative matching, and determining the model's sensitivity to individual experimental data. The latter has been given particularly high importance. Determining the degree of the simulation model's reaction to change in the system's parameters shall facilitate planning further experiments. Conclusions concerning the level of quality and accuracy of individual experimental data should be particularly valuable. In that context of the studies, obtaining best quantitative match is not required, as that aspect will be the subject of the next stage of simulation studies based on another series of experiments to be planned with consideration for the conclusions drawn from this stage of numerical studies.

Some of the experimental studies from stage one have been presented in paper [1]. Certain concepts concerning adjusting the model to the results of numerical simulations have been presented in paper [2]. Paper [3] describes the method of quantitative comparison of selected parameters of fountain height obtained by numerical methods; it is an extension of this article.

2. Basic models of multiphase flows

Multiphase flows are very common in nature and technology and have been an area of interest for the classic (analytical and experimental) and numerical mechanics of fluids for many years. Unfortunately, despite numerous studies in this area, a universal mathematical model has yet to be developed for the multiphase medium. The following models are usually found in the literature in relation to multiphase systems:

- Discrete Phase Model (DPM), the model for description of a system consisting of the continuous phase in which spherical solid particles, bubbles or drops of another fluid are dispersed. The dispersed phase can exchange mass, momentum and energy with the continuous phase. The background phase is described according to the Eulerian approach, while the dispersed phase – according to Lagrange's approach.
- Eulerian Multiphase Model (EMM), intended for description of mixtures consisting of any number of phases: gases, liquids and particles of solids. A separate system of mass, momentum and energy equations is solved for each of the phases. Coupling of phases occurs through pressure and the so-called interphase mass, momentum and energy exchange coefficients. These coefficients are a characteristic feature of the model and play a key role therein. The description of interactions between individual phases depends mainly on whether liquid only or simultaneous liquid and solid phases (as in fluidized beds) are present in the flow. In this model, the Eulerian treatment is used for each phase. It is sometimes referred to in the literature as the Two-Fluid or Multi-Fluid Model.
- Mixture Model (MM), intended for description of homogenous mixtures of any number of phases: gases, liquids and solid particles. All phases are treated as a mixture and possess a single system of balance equations. The mixture

is described according to the Eulerian approach. The Mixture Model is also known as the Homogeneous Model.

- Volume of Fluid (VOF) Model, intended for description of flows with free surface or flows of non-mixing fluids. VOF belongs to the group of "single-fluid approach" models, where there is one system of equations within the entire computation area (according to the Eulerian approach) and a complementary equation describing the phases' separation surface. Other models, *e.g.* the Level Set Model or the Marker in Cell Model, are also applied to describe the phases' separation surface in addition to the VOF model.
- Porous Media Model (PMM), the simplest model of a multiphase medium. In this model, the medium's resistance – resulting from the presence of a solid fraction – is treated as an additional source in the momentum balance equation. These sources usually describe viscous resistances (Darcy's law) and resistances related to the flow dynamics (Forchheimer's law).

The EMM is applied in modeling spouted bed dryers. The model's individual balance equations are presented in Sections 3–5, followed by a discussion of the object of analysis (Section 6) and results of numerical simulations.

3. Mass balance equation

In EMM, the mass balance equation for phase q has the following form [4–6]:

$$\frac{\partial}{\partial t}(\varepsilon_q \rho_q) + \nabla \cdot (\varepsilon_q \rho_q \vec{v}_q) = \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp}) + S_{m,q}, \tag{1}$$

where ε_q is the volume fraction of component q [–], $\vec{v}_q$ – the velocity of phase q [m/s], ρ_q – its density [kg/m^3], $\dot{m}_{pq}$ – the mass transfer from phase p to phase q [kg/m^{3}s], $\dot{m}_{qp}$ – the mass transfer from phase q to phase p [kg/m^{3}s], and $S_{m,q}$ – an additional source of mass of phase q [kg/m^{3}s]. Mass exchange between flow components can result from *e.g.* chemical reactions or phase transformations.

4. Momentum balance equation

The Eulerian Multiphase Model can be used to describe and simulate phenomena occurring in systems of solid particles moving (suspended) in a moving liquid environment. In this case, the granular dynamics is described using analogies to the gaseous environment: forces, viscosity and pressure are dependent on the intensity of particles' velocity fluctuation. The notion of granular temperature is introduced in this description. A linear relation between the value of temperature and particle movement fluctuations is assumed.

The momentum balance equation for phase q is described in EMM with the following formula [4–7]:

$$\frac{\partial}{\partial t}(\varepsilon_q \rho_q \vec{v}_q) + \nabla \cdot (\varepsilon_q \rho_q \vec{v}_q \otimes \vec{v}_q) = \nabla \cdot \left(\vec{\vec{\tau}}_q - \varepsilon_q p \vec{\vec{I}} - p_s \vec{\vec{I}} \right) + \vec{R}_q + \vec{S}_{F,q}, \tag{2}$$

where $\vec{\vec{\tau}}_q$ is the total stress tensor of phase q [Pa], p – the mixture's static pressure [Pa], p_s – granular pressure [Pa], $\vec{\vec{I}}$ – a unit tensor [–], $\vec{R}_q$ – momentum exchanged between phases during movement [N/m^3], and $\vec{S}_{F,q}$ – additional source forces influencing phase q [N/m^3].

Granulate pressure, p_s, found in formula (2) depends on granulate temperature and other parameters, most often its solid phase density, the particles' collision restitution coefficient and the radial displacement function. Granulate temperature – proportional to the kinetic energy of particles' movement – is described by the separate transport equation.

The stress tensor in the momentum equation is defined as follows [4, 8]:

$$\vec{\vec{\tau}}_q = \varepsilon_q \mu_q \vec{\vec{D}}_q + \varepsilon_q \left(\lambda_q - \frac{2}{3}\mu_q\right) \nabla \cdot \vec{v}_q \vec{\vec{I}}, \tag{3}$$

where μ_q and λ_q are respectively the shear and bulk viscosity of phase q [kg/(m s)], and $\vec{\vec{D}}_q$ is the strain rate tensor [1/s].

Momentum exchange between flow components can be described with the following formula:

$$\vec{R}_q = \sum_{p=1}^{n} \left(\vec{R}_{pq} + \dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}\right), \tag{4}$$

where $\vec{R}_{pq}$ is the force of interaction between phases p and q [N/m^3] and $\vec{v}_{pq}$ – interphase velocity [m/s]. The value of interphase velocity depends on the direction of mass transfer:

$$\text{if } \dot{m}_{pq} > 0 \text{ then } \vec{v}_{pq} = \vec{v}_p,$$
$$\text{if } \dot{m}_{pq} < 0 \text{ then } \vec{v}_{pq} = \vec{v}_q.$$

The forces of interaction between phases are defined using the interphase momentum exchange coefficient, β_{pq} [kg/(m^{3}s)], as follows:

$$\sum_{p=1}^{n} \vec{R}_{pq} = \sum_{p=1}^{n} \beta_{pq} (\vec{v}_p - \vec{v}_q), \tag{5}$$

where additional dependences must be satisfied: $\beta_{pq} = \beta_{qp}$ and $\vec{R}_{qq} = 0$.

The additional source forces influencing the q component are the last segment of the momentum balance equation:

$$\vec{S}_{F,q} = \varepsilon_q \rho_q \vec{g} - \frac{1}{2}\varepsilon_p \rho_q (\vec{v}_q - \vec{v}_p) \times (\nabla \times \vec{v}_q) + \frac{1}{2}\varepsilon_p \rho_q \left(\frac{d_q \vec{v}_q}{dt} - \frac{d_p \vec{v}_p}{dt}\right), \tag{6}$$

the parts of Equation (6) being internal mass forces (originating *e.g.* from inertia), external mass forces (originating *e.g.* from gravity or electromagnetic influence) [N/m^3], forces originating from the surface tension [N/m^3] and those originating from the so-called "virtual mass" [N/m^3]. The effect of "virtual mass" is pronounced when the density of the dispersed phase is much lower than that of the medium (*e.g.* in a column of gas bubbles in a liquid). The d_q/dt derivatives appearing in Formula (6) are defined as follows:

$$\frac{d_q(\varphi)}{dt} = \frac{\partial(\varphi)}{\partial t} + (\vec{v}_q \cdot \nabla)\varphi. \tag{7}$$

In case of dense fluidized beds the Gidaspow drag model (1992) is applied to describe the coefficient of interphase momentum exchange. It relates the coefficient's value to the volume fraction of the phase forming the environment. For $\varepsilon_f > 0.8$, the coefficient of interphase momentum exchange is described by the following dependence [4, 9–11]:

$$\beta_{fs} = \frac{3}{4} C_D \frac{\varepsilon_s \varepsilon_f \rho_f}{d_s} |\vec{v}_s - \vec{v}_f| \varepsilon_f^{-2.65}, \tag{8}$$

where C_D is the environment's resistance [–] and d_s the diameter of granular particles [m]. In Gidaspow's model the environment's resistance depends on the local value of the Reynolds number [12–16]:

$$C_D = \begin{cases} \frac{24}{\mathrm{Re}_s}\left(1 + 0.15\mathrm{Re}_s^{0.687}\right), & \text{for } \mathrm{Re} \le 1000, \\ 0.44, & \text{for } \mathrm{Re} > 1000, \end{cases} \tag{9}$$

where [12, 13, 17–23]

$$\mathrm{Re}_s = \frac{\rho_f \varepsilon_f |\vec{v}_s - \vec{v}_f| d_s}{\mu_f}. \tag{10}$$

When $\varepsilon_f \le 0.8$, the coefficient of interphase momentum exchange is described by the following formula:

$$\beta_{fs} = 150 \frac{\varepsilon_s (1 - \varepsilon_f) \mu_f}{\varepsilon_f d_s^2} + 1.75 \frac{\rho_f \varepsilon_s}{d_s} |\vec{v}_s - \vec{v}_f|. \tag{11}$$

The s index in the above equations represents a *solid*, the f index – a *fluid* or another solid phase.

The Gidaspow drag model is actually a combination of the Ergun [4, 12, 14, 16, 24] and the Wen-Yu equation [4, 9, 10, 12, 14, 16, 24].

5. Energy balance equation

The energy balance equation for phase q is described in EMM with the following equation [4–6]:

$$\frac{\partial}{\partial t}(\varepsilon_q \rho_q h_q) + \nabla \cdot (\varepsilon_q \rho_q h_q \vec{v}_q) = \nabla \cdot \left(\overleftrightarrow{\tau}_q \vec{v}_q - \varepsilon_q p \vec{I} \right) + \nabla \cdot (\vec{q}_q) + Q + S_{h,q}, \tag{12}$$

where h_q is the enthalpy of phase q [J/kg], $\vec{q}_q$ – its total heat flux [J/(m^{2}s)], Q – energy exchanged between phases [J/(m^{3}s)], and $S_{h,q}$ – an additional heat source of phase q [J/(m^{3}s)].

Energy exchange between phases can be described by the following formula:

$$Q = \sum_{p=1}^{n} (Q_{pq} + \dot{m}_{pq} h_{pq} - \dot{m}_{qp} h_{qp}), \tag{13}$$

where Q_{pq} is the intensity of heat exchange between phases [J/(m^{3}s)] and h_{pq} – interphase enthalpy [J/kg]. Heat exchange between phases must be limited by additional conditions: $Q_{pq} = -Q_{qp}$ and $Q_{pp} = 0$.

6. Object of numerical analysis

Figure 1 presents the geometry of the spouted bed dryer used for a series of numerical simulations. The model system consisted of two basic parts: a charge cone and a cylindrical drying chamber. The air inlet was positioned symmetrically in the lower part of the charge cone; its diameter was smaller than that of the charge cone's lower surface. The air outlet matched the upper base of the drying chamber's cone.

The same height of the bed, equal to the height of the conical part of the chamber, was assumed in all simulations. An axially symmetrical geometry was assumed to develop the computer model. The effect of the model's dimensionality will be presented in greater detail below.

The height of the fountain forming during the device's operation was assumed to be the basic parameter determining the consistency of computer simulation results with those of empirical tests.

The point on the dryer's axis at which the volume of the granular phase was less than 0.00001 was used to determine the fountain's height. The height was computed automatically in all cases by means of the author's supplementary software processing result files obtained in the computer simulation process.

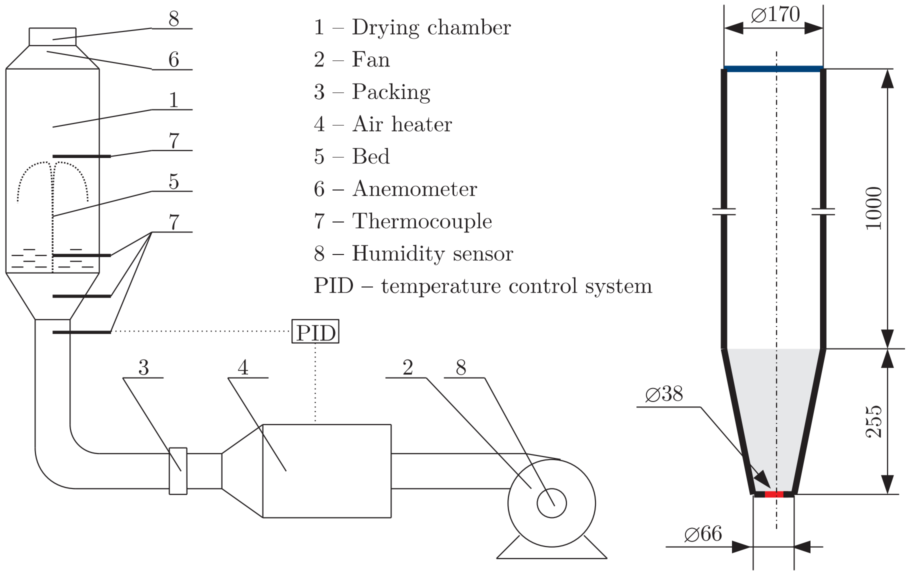


Figure 1. Dryer geometry

7. Effect of the model's dimensionality

Usually two-dimensional axially symmetrical geometry is used to simulate fluidized beds in spouted bed dryers [25, 10, 26, 27]. Although there are cases of assuming other computational domains, they usually apply to more complex systems where the drying chamber is only one of the modeled elements (*cf.* [28]).

The performed simulation studies have demonstrated that assuming computational domains other than axially symmetrical ones yields results that are absolutely inconsistent with reality, even at the qualitative level. A comparison of simulation results for a two-dimensional domain and a two-dimensional axially symmetrical domain is presented in Figures 2a and 2b. Despite assuming the remaining model parameters to be exactly the same, the expected fountain did not form in the absence of axial symmetry and the character of the flow was definitely incorrect. Similarly erroneous results were obtained from calculations in a three-dimensional domain (Figure 2c).

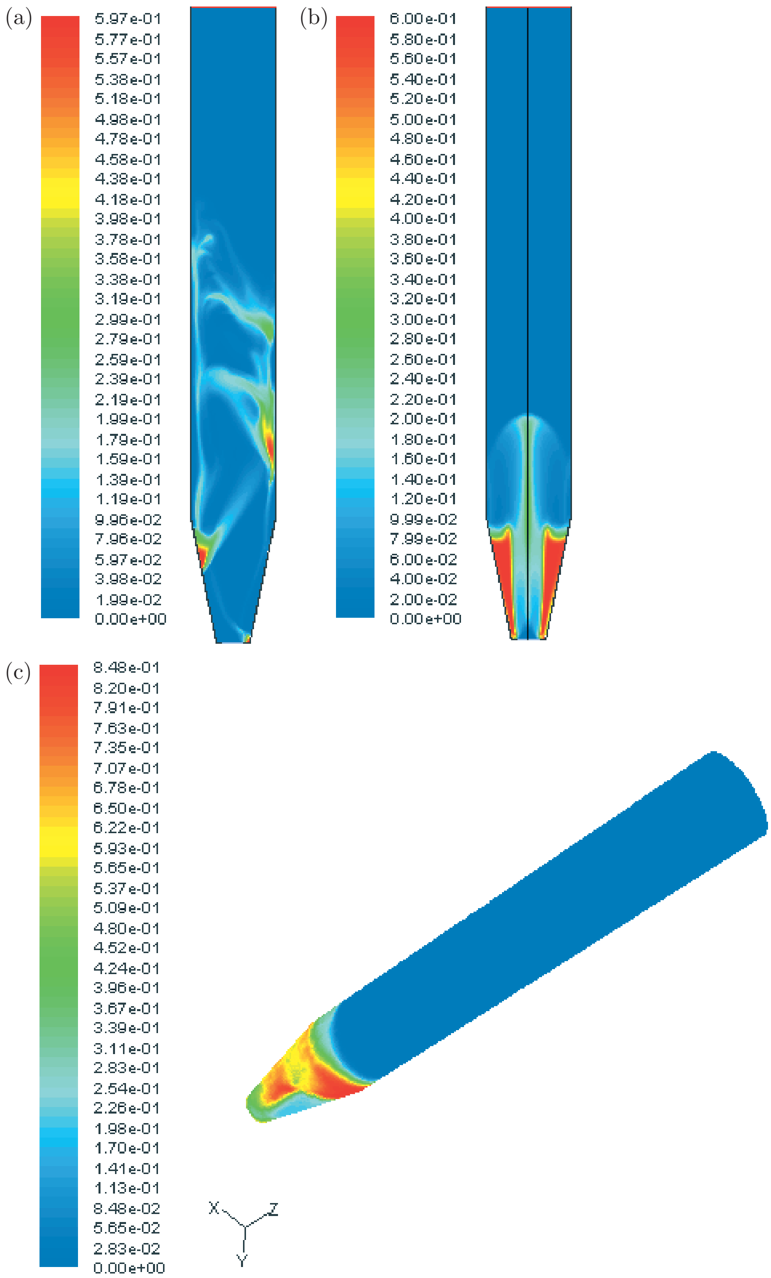


Figure 2. Examples of computations (contours of volume fraction – grain) in: (a) a 2D domain, (b) a 2D axially symmetrical domain, (c) a 3D domain

Studies of the bed's behavior assuming varying computation domains (and studies on the influence of the numerical grid) were the author's first studies in the area of fluidized beds. Although some parameters of that simulation stage were slightly different from those presented in Section 6, the general inconsistence of simulation results and observations from experiments remains for cases other than axially symmetrical.

8. Mesh sensitivity study

All computer simulations presented in this paper were performed by applying a structural grid with the total number of cells equal to 26 961 (its fragment is shown in Figure 3). An additional simulation based on a non-structural grid was carried out at the initial stage of the study in order to test the applied computational grid's influence on the results. In this case, the number of grid cells was 58 626. The tests proved that grid type did influence the obtained results, the differences being noticeable throughout the bed volume (see Figure 4).

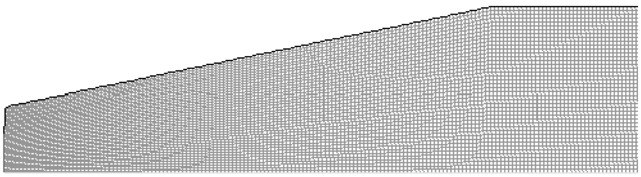


Figure 3. Fragment of the computation grid used in computer simulations

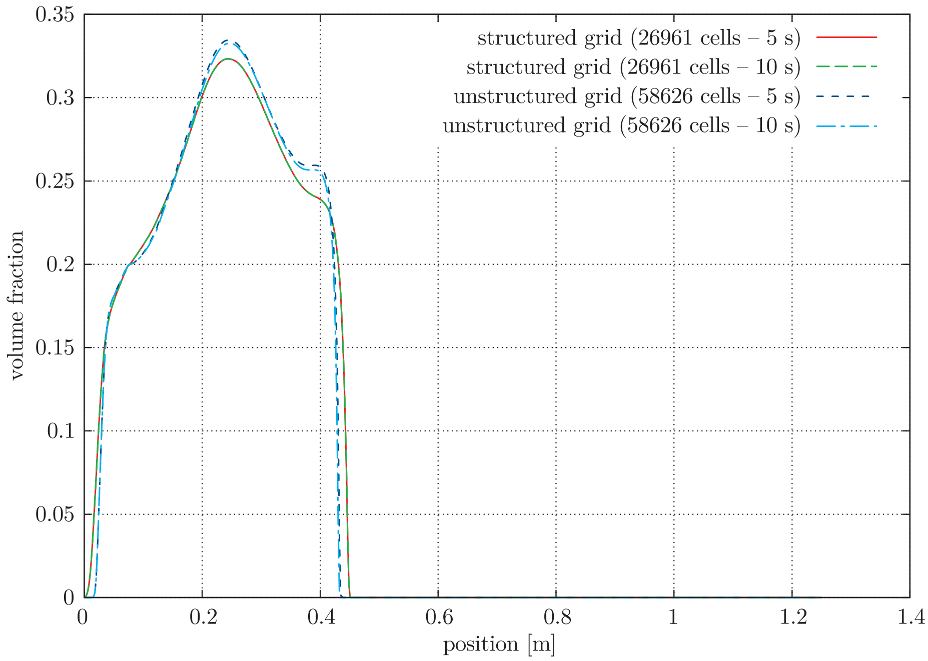


Figure 4. Comparison of the grain volume fraction's distribution on the dryer's axis for two selected numerical grids (inlet velocity 30 m/s)

The generated non-structural grid possessed more than twice the number of cells of the structural grid, which resulted in roughly twice longer computation time. In the discussed case, difficulties were encountered while generating a non-structural grid with the number of cells similar to that of the structural grid. Because of the computational time involved, the similarity of results and for the impossibility of direct experimental verification of the obtained differences, it was finally decided to apply the structural grid in the simulations.

Table 1. Sample literature data on numerical grid sizes and types

Author	Size of numerical grid	Numerical grid type
Boyalakuntla *et al.* [29]	2240, 7040, 8772	structural
Duarte *et al.* [10]	6862	structural (cylindrical dryer part) and non-structural (conical dryer part)
Duarte *et al.* [25]	8400	structural (cylindrical dryer part) and non-structural (conical dryer part)
Křišťál *et al.* [28]	2000	non-structural
Křišťál *et al.* [28]	3000	structural
Szafran [27]	3985, 8823, 12575	non-structural, hybrid
Faulkner [26]	–	non-structural

Generally speaking, simulations of fluidized beds found in the literature are based on structural and/or non-structural grids (Table 1).

9. Model parameters

The parameters used in the computer model are specified in Table 2. In a number of items the base model value is indicated with bold font, the other values used to determine the computer model's sensitivity. All computations were performed using the Fluent 6.2 package.

10. Simulation results

Computations carried out considering the basic parameters given in Table 2 produced qualitative matching of results encompassing the following:

- an initial, rapid throw of the granular phase (grains) to the height equal to around a half of the drying chamber's height. After that, the fountain dropped, stabilized and maintained a constant height (in simulations) or heights oscillating around an average value (in the experiment). The time for fountain formation was around 3 seconds both in the experiments and in the simulations;
- the fountain's shape and its clear division into zones (see Figure 5): a feeding zone, a float zone, a fountain zone, a zone of particles falling and an annular zone [10, 27, 30]. The grains are caught in the feeding zone by the stream of air and lifted, forming a fountain shape. In that area, the grains also move towards the dryer's walls. Then, the particles fall and settle on the bed surface. The bed surface is unstable and subject to continuous changes during the dryer's operation. Having fallen on the bed surface, the particles sink into the so-called annular zone and move downwards towards the feeding zone. The cycle is repeated many times causing the bed's circulation.

As the numerical simulations were unsuccessful in achieving satisfactory quantitative matching of fountain height (see Figure 6), further studies were initiated aimed at determining the influence of individual model parameters on the results. The studies were aimed at finding a method to improve the quantitative match. Some of their results have been presented in paper [1]; here, the presentation is limited to studies on the sensitivity of the Eulerian Multiphase Model to changes in its basic model parameters.

Table 2. Specification of computer model parameters

Parameter	Value or description
Solver type	pressure based/segregated, non-stationary
Computational domain type	axially symmetrical
Multiphase flow model	Eulerian
Number of phases in the flow	2 (air, grain)
Air density [kg/m^3]	1.225
Air viscosity [kg/ms]	$1.7894 \cdot 10^{-5}$
Grain density [kg/m^3]	1200, **1300**, 1400
Grain diameter [mm]	3.4, 3.6, **3.8**, 4.0, 4.2
Type of interaction between phases	Gidaspow's model
Bed height at rest [m]	0.245, 0.2475, **0.25**
Initial packing coefficient	0.38, **0.42**, 0.46
Maximum packing coefficient (pack limit)	0.57, **0.6**, 0.63
Energy equation	switched off
Turbulence model	– κ-ε Standard, Standard Wall Function (SWF), Mixture – κ-ε Standard, Standard Wall Function (SWF), Per Phase – κ-ε Standard, Standard Wall Function (SWF), Dispersed – **κ-ε Standard, Enhanced Wall Treatment (EWT), Dispersed** – κ-ε RNG, Standard Wall Function (SWF), Dispersed – κ-ε RNG, Enhanced Wall Treatment (EWT), Dispersed – κ-ε realizable, Standard Wall Function (SWF), Dispersed – κ-ε realizable, Enhanced Wall Treatment (EWT), Dispersed – Reynolds Stress Model, Dispersed – laminar model
Operational pressure [Pa]	101325
Acceleration of gravity [m/s^2]	9.81
Inlet type	velocity inlet
Inlet air velocity [m/s]	15, 20, 25, **30**, 35, 40, 45, 50, 55
Outlet type	pressure outlet
Outlet air pressure [Pa]	0 (relative to operational pressure)
Volume fraction of air in inlet and outlet streams	1
Volume fraction of grain in inlet and outlet streams	0
Turbulent kinetic energy (inlet and outlet)	10
Turbulent dissipation rate (inlet and outlet)	10

11. The influence of air velocity

The dryer's inlet air velocity is the model's most natural physical parameter influencing the simulation process and results. Consequently, the initial phase of computer simulations included determination of the dependence between that velocity and the volume distribution of grain in the dryer; the results are presented in Figure 7.

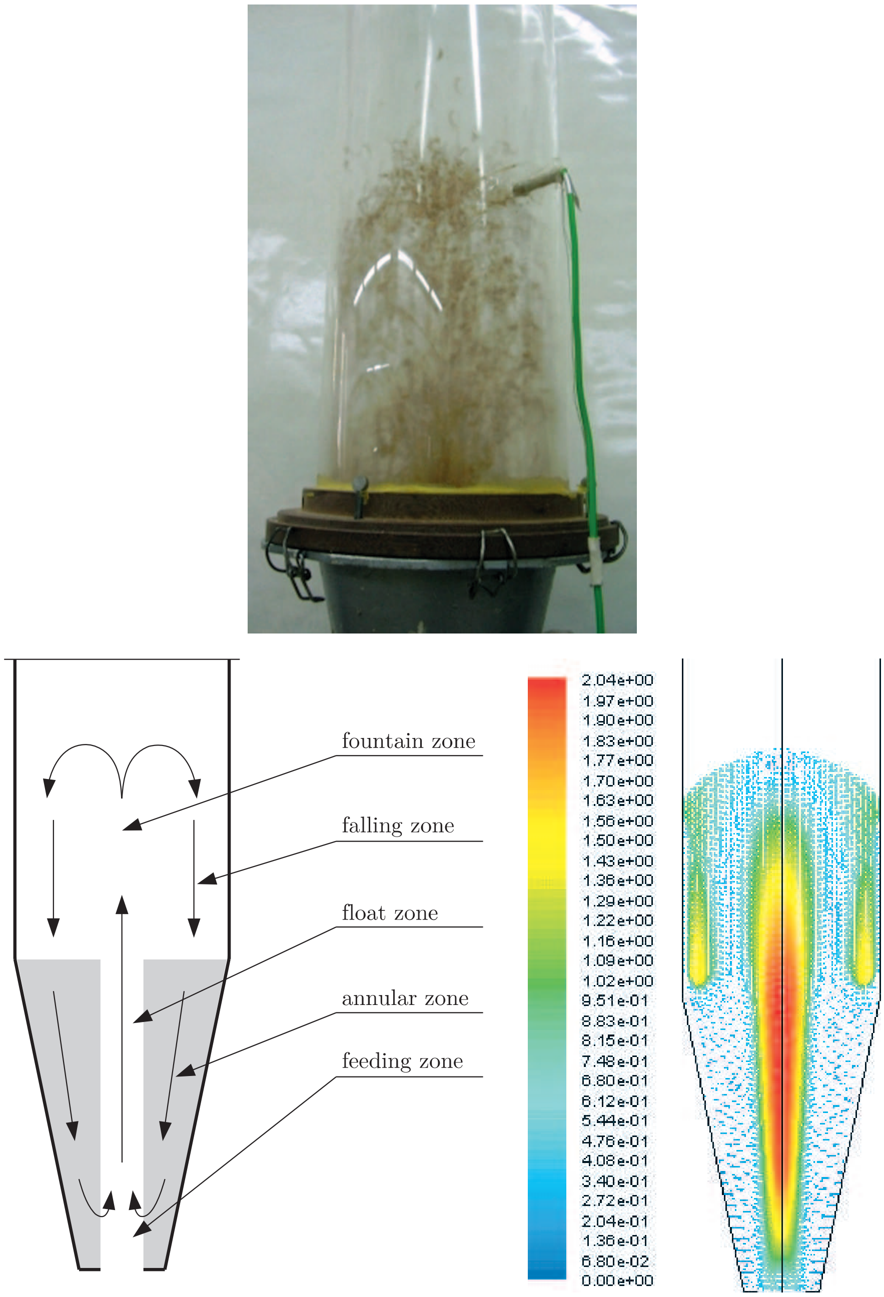


Figure 5. Qualitative comparison of experimental and simulation results

The performed computations enabled determination of the fountain's height (see Figure 8) and the grain's volume distribution in the dryer axis (see Figure 9) for each case. In this series of computations, all parameters other than the dryer's inlet air velocity had constant values.

In line with expectations, the mass intensity of the flow was directly proportional to the given inlet velocity (see Figure 10).

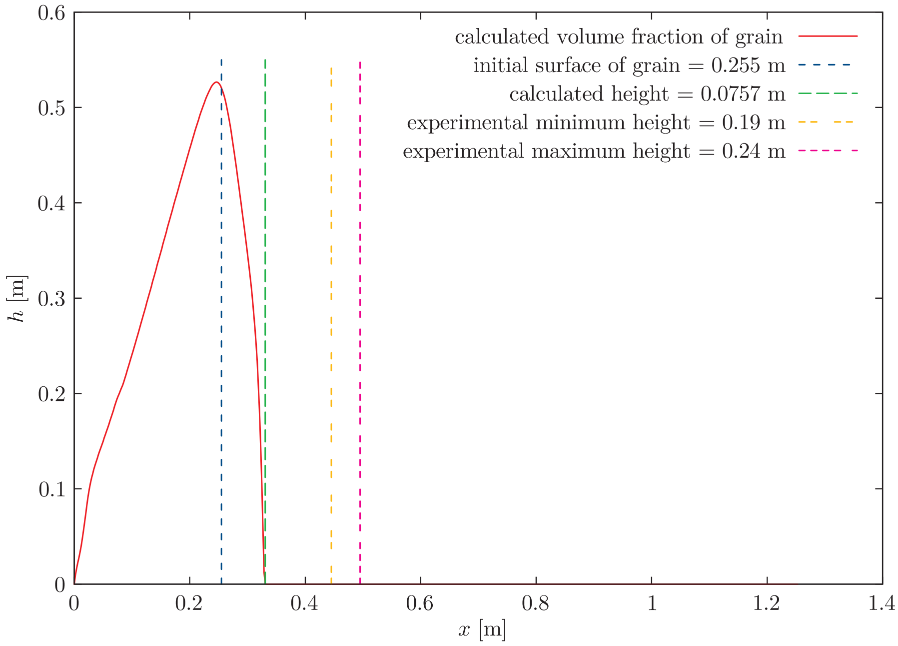


Figure 6. Quantitative comparison of experimental and simulation results (height of fountain)

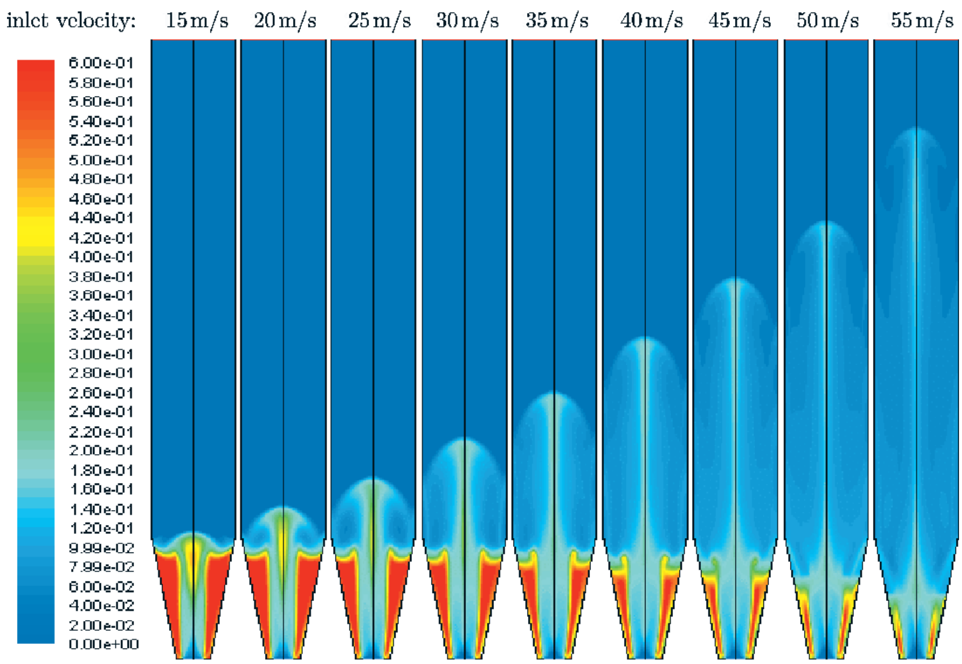


Figure 7. Volume fraction distribution of grain for various inlet air velocities

12. The influence of equivalent grain diameter

The Eulerian Model is effective for spherical granules, but barley grains differ significantly from this shape; it was therefore necessary to apply the so-called

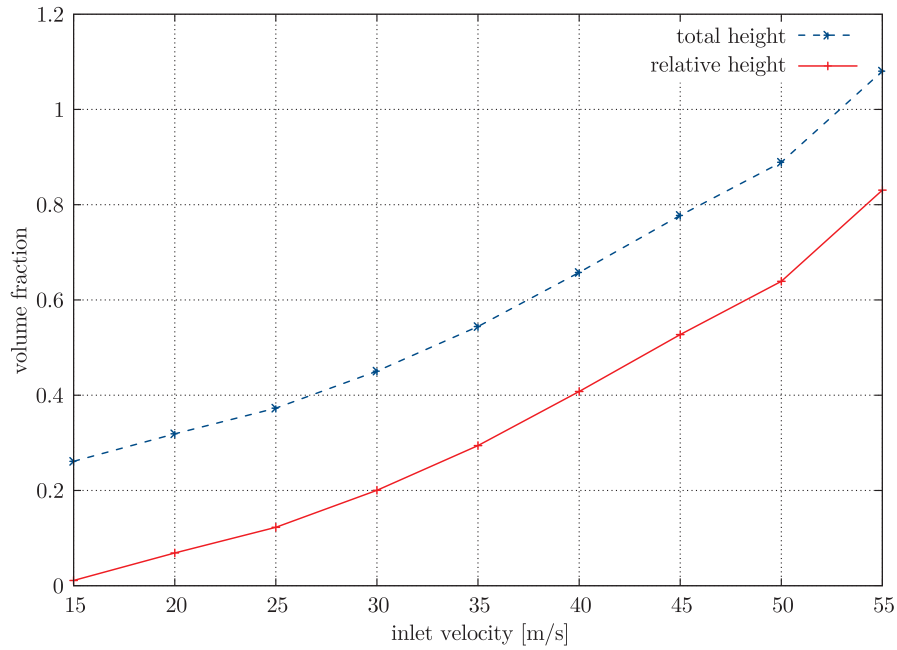


Figure 8. Dependence between the dryer's inlet air velocity and the fountain height

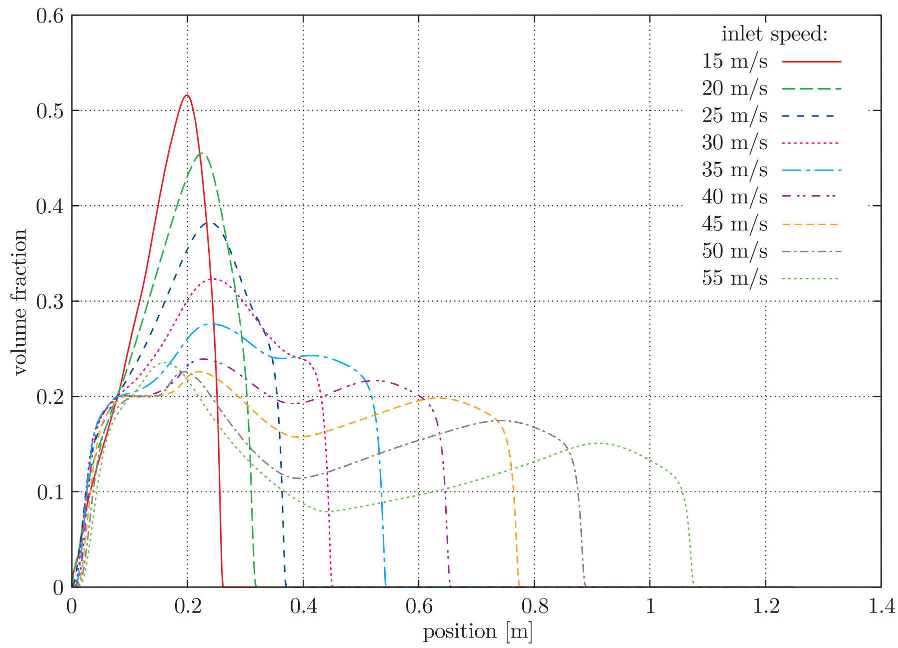


Figure 9. Volume fraction distribution of grain in the dryer's axis

equivalent grain diameter or the diameter of a sphere of volume equal to the volume of a typical barley grain. Additional experimental measurements and statistical processing were necessary to determine this parameter.

The conducted Eulerian Model tests have demonstrated that, apart from the inlet air velocity, the equivalent grain diameter is a major parameter influencing the

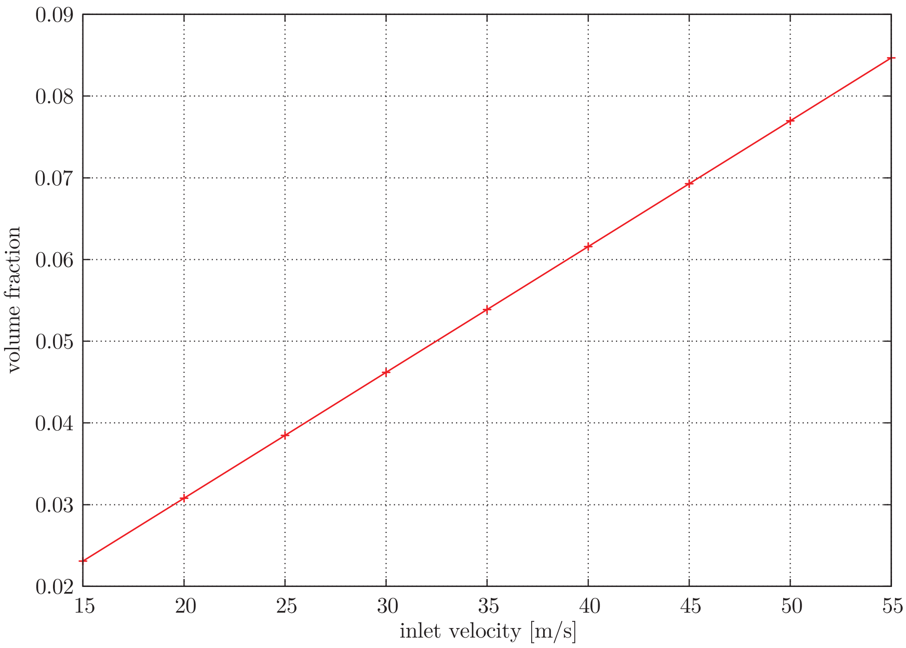


Figure 10. Mass flow rate of air at various inlet air velocities

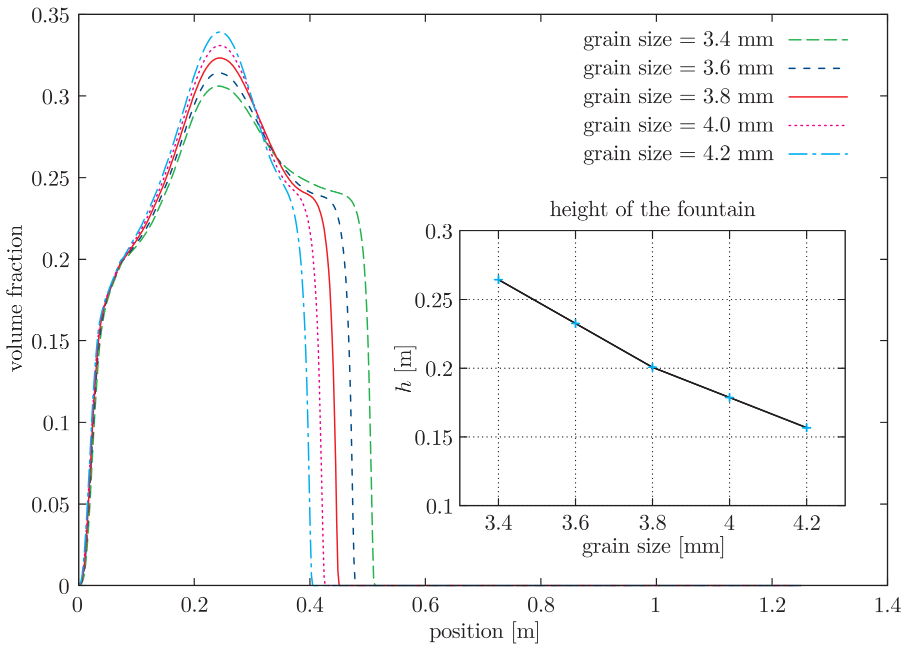


Figure 11. The influence of grain diameter on distribution and fountain height (inlet velocity 30 m/s)

fountain's height. A modification of this value by mere 0.2 mm resulted in a significant and clearly noticeable change in the fountain's height (see Figure 11). This leads to an important conclusion that particular care and accuracy of measurements should be maintained during determination of the equivalent grain diameter. Due to the lack

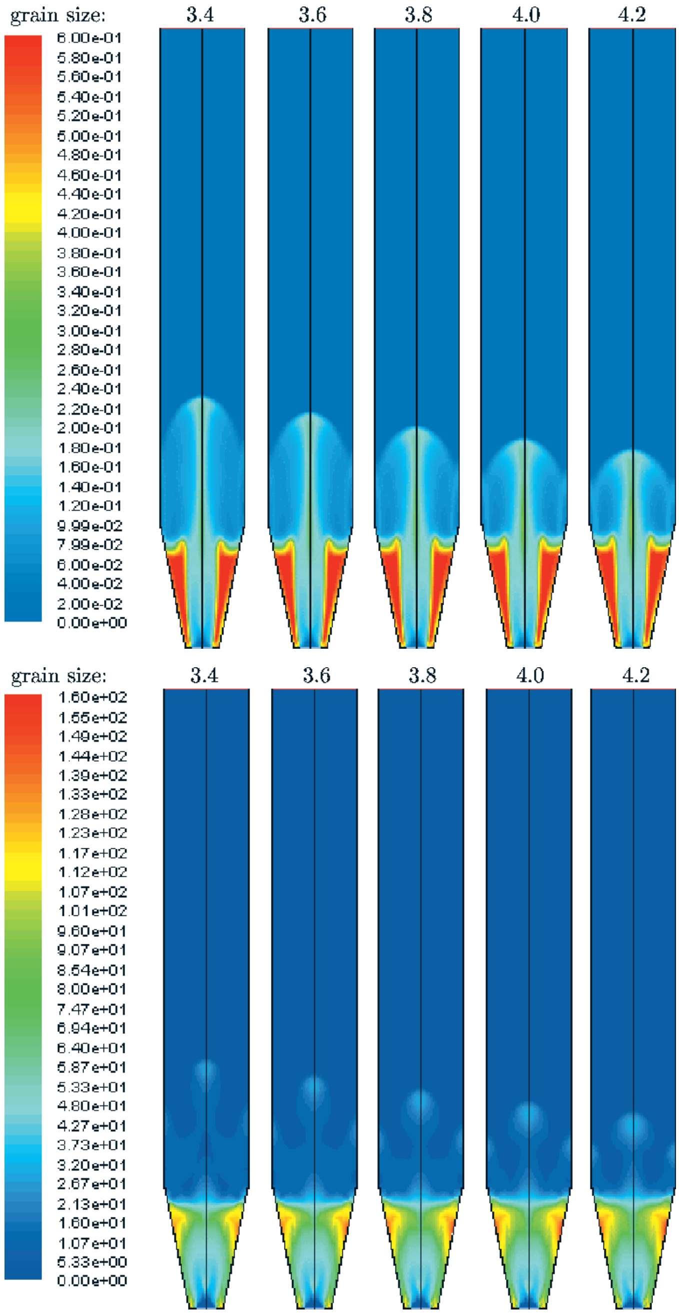


Figure 12. Grain diameter's influence on distribution and fountain height: volume fraction (top) and granular pressure distributions (bottom)

of homogeneity of materials such as grain, literature data should not be relied on in this respect.

Further analysis of this aspect is required to adjust the Gidaspow model to granules of non-spherical shapes. Such studies have already been initiated and will be discussed elsewhere.

Important information on the model bed's behavior is also provided by granular pressure distribution. Increased pressure in the top part of the fountain is a characteristic feature of this parameter (see Figure 12).

13. The influence of grain density

Grain density was another factor with significant influence on grain distribution and fountain height (see Figure 13). Increased density reduced the total fountain height and altered the proportions of the air-grain mixture in various flow zones. The simulations used three grain density values: 1200, 1300 (basic) and 1400 kg/m^3.

Fountain height increasing with decreasing grain density results from reduced source forces of gravitational origin.

14. The influence of grain volume change

The influence of the total grain volume in the dryer on fountain height was also investigated during test simulations. Changes in volume occur in real systems as a consequence of humidity discharge from air and grain interior coupled with the simultaneous shrinkage of organic material. The effect is the most pronounced during the first minutes of drying.

Numerical computations have shown minor influence of changes in the total grain volume (simulated by gradual decreasing of the surface of grains in the charger cone) on the fountain height (see Figure 14). The fountain's height was calculated relative to the actually given bed surface height.

15. The influence of the packing coefficient

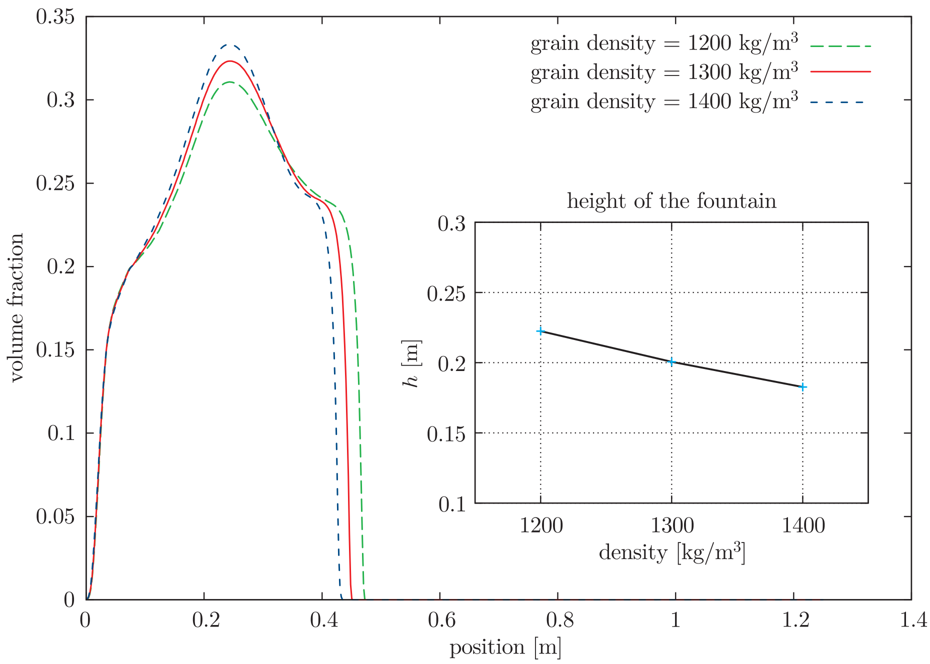
In the Eulerian Multiphase Model, a value referred to as the packing coefficient is included defining the relation between the volume of component q particles and the total bed volume. The packing coefficient's distribution for component q is also one of the most important results of numerical computations.

When designing the computer model, its initial density (the so-called *initialize path*) and maximum density that cannot be exceeded during computations (the so-called *limit pack*) should be specified in addition to the initial bed position in the device. In this paper, these parameters will be treated separately.

The level of packing of particles of the solid phase is very important for the Eulerian Model. It has also been found that a change in the initial packing value does not influence fountain height but does influence the distribution of grain in the bed (see Figure 15): with tighter packing, more grain mass was positioned in the fountain zone above the rest surface. This means that "denser" beds have greater resistance causing stronger influences between the two phases (see Figure 16). Notably, practically no changes in grain fraction distribution are observed in the lower part of the bed (up to ca 80% of rest height).

The situation is slightly different in the case of limit pack changes, as allowing tighter packing of particles results in increased fountain height and simultaneous "dilution" of the part of the bed above the rest surface (see Figure 17).

Generally speaking, the solid phase particles' pack value depends on the type of material, the relative granular size and area filled [31]. Generally, in the literature



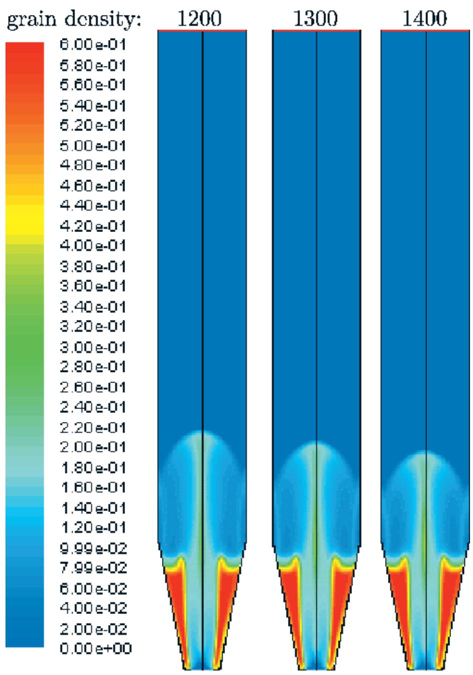


Figure 13. Grain density's influence on distribution and fountain height (inlet velocity 30 m/s)

concerning fluidized beds consisting of spherical particles, the packing coefficient values range from 0.26 to 0.55 [9, 10, 32, 33]. Particles of other shapes are considered by assuming their equivalent grain diameter. In this study, the values were assumed according to [4, 34] (Table 2).

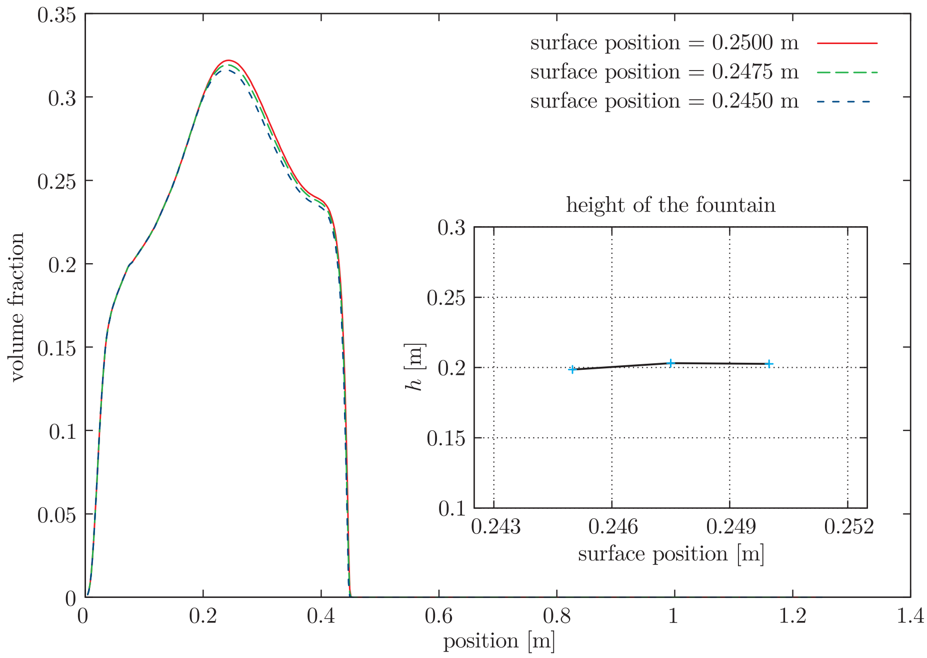


Figure 14. Total grain volume change influencing distribution and fountain height (inlet velocity 30 m/s)

16. The influence of the turbulence model

Another series of simulations was related to the issue of turbulence. The following turbulence models were available:

- In the κ–ε model approach:
  - mixture turbulence model,
  - dispersed turbulence model and
  - turbulence model for each phase (per phase).
- In the Reynolds-Stress model approach:
  - mixture turbulence model and
  - dispersed turbulence model.

The standard κ–ε "dispersed" model [4] or standard κ–ε "per phase" model [27] are most often used for modeling fluidized beds. The κ–ε models are also recommended by authors of other studies, *e.g.* [13, 19, 28].

A comparison of results obtained for different versions of the standard κ–ε model is shown in Figure 18. As should be expected, a change of the turbulence model had a significant influence on fountain height and flow characteristic resulting in different grain distributions, practically in the entire bed (including its lower parts).

In the „mixture" and „dispersed" models, the volume fraction of the granular phase decreased very rapidly in the end part of the fountain, which facilitated determination of the fountain's height according to the assumptions described earlier. In the „per-phase" model, the granular phase's fading was not so rapid: the mass fraction of grain decreased less consistently, oscillating several times around the

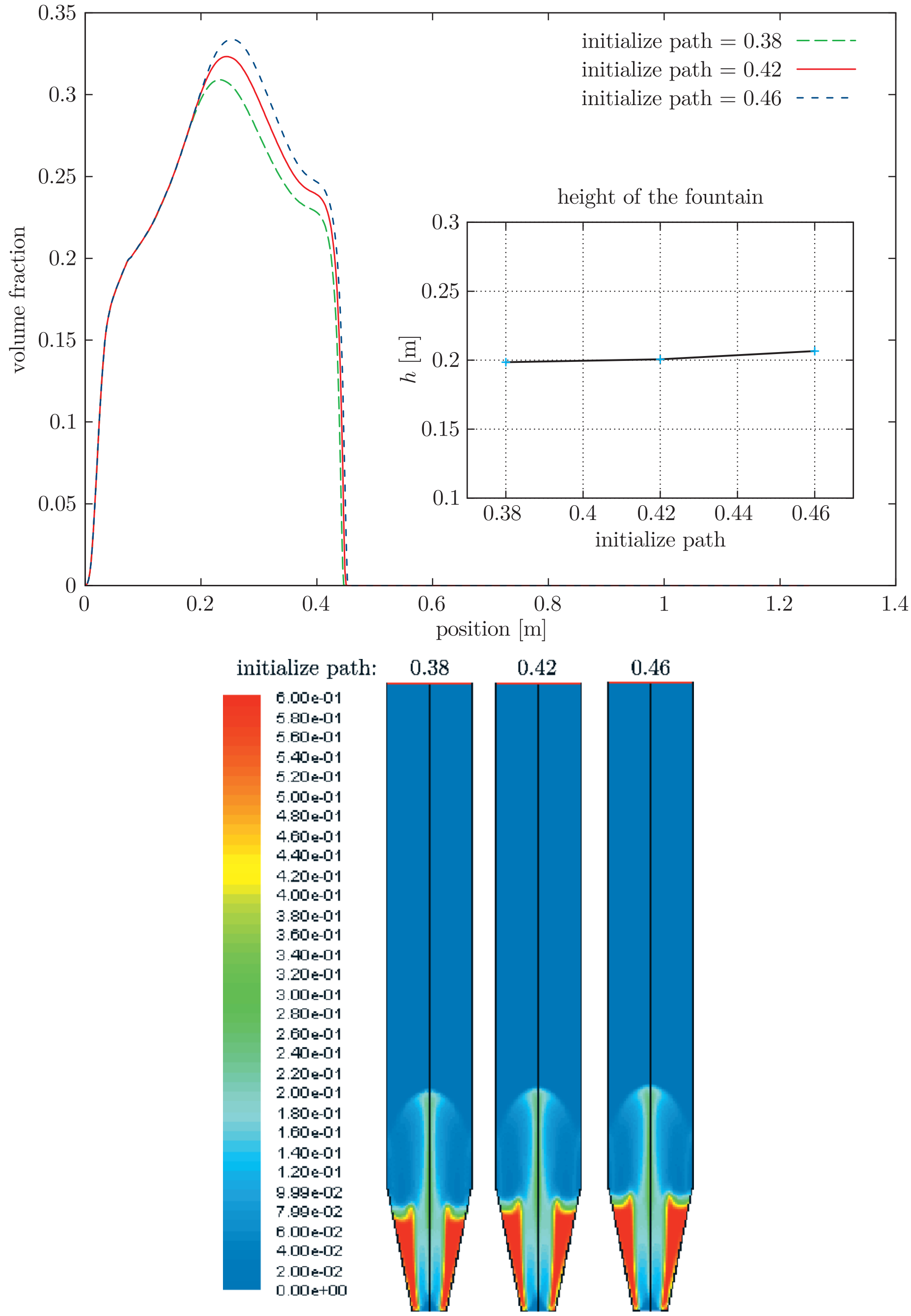


Figure 15. The influence of the initial value of the packing coefficient on distribution and fountain height (inlet velocity 30 m/s)

limit value of 0.00001 (exceeding it only slightly). Therefore, minor concentrations of grain above the fountain's upper surface were omitted in determining its height. The difference between the height computed automatically (by the above-mentioned author's software) and the adjusted height is inset in Figure 18.

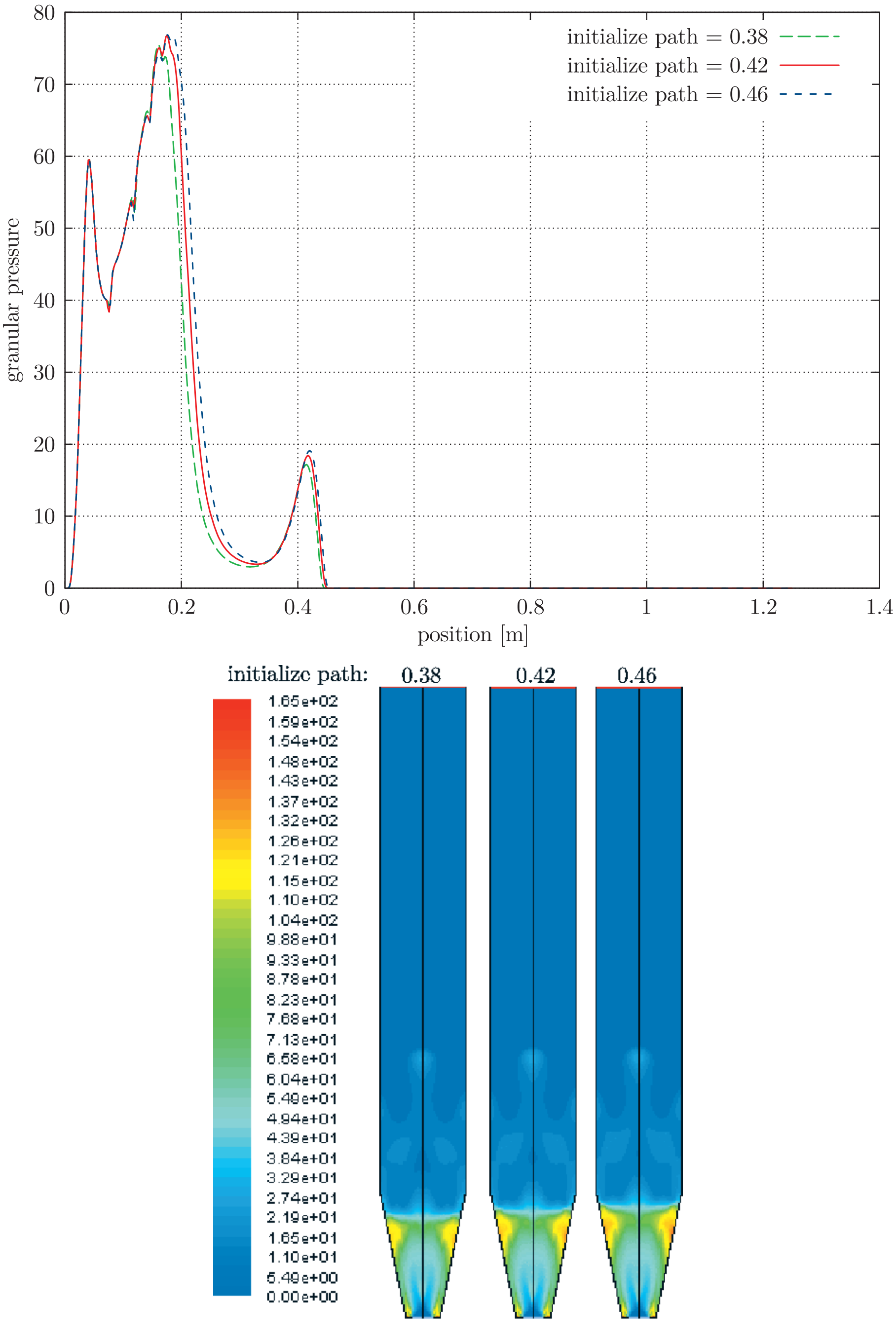


Figure 16. Initialize path influencing distribution of granular pressure (inlet velocity 30 m/s)

The influence of other models and parameters available in the Fluent software was also tested during simulation studies, particularly the influence to wall layer modeling. The results are presented in Figures 19 and 20.

The part of the study concerning modeling turbulences in the spouted bed dryer's fluidized bed was mainly based on information available from literature, due

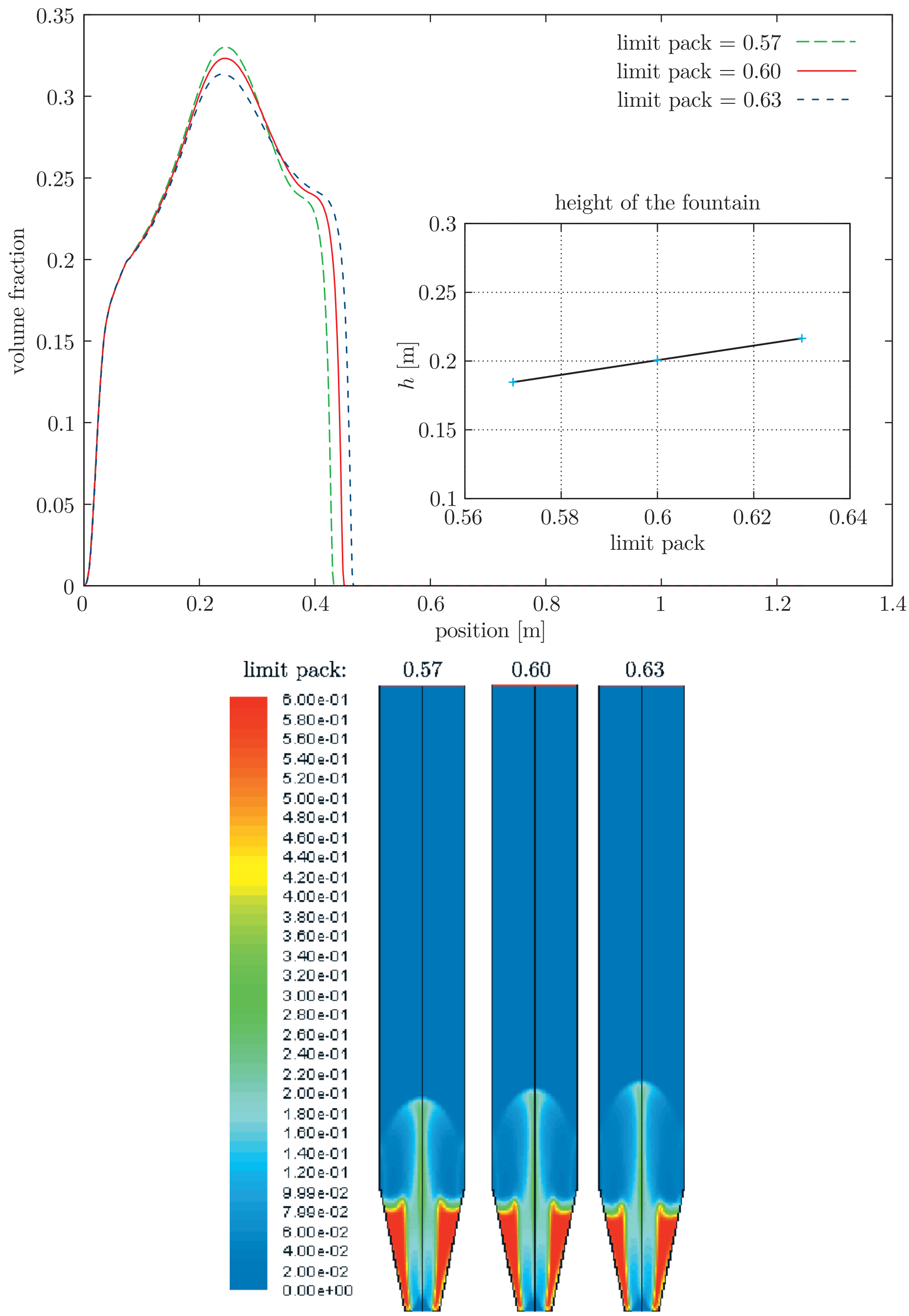


Figure 17. Limit pack coefficient influencing distribution and fountain height (inlet velocity 30 m/s)

to the lack of experimentally determined volume or mass distributions of grain in the considered bed. Such data would have enabled much more precise verification of individual versions of turbulence models and selecting the one offering the closest results. Applying fountain height only is insufficient in this case.

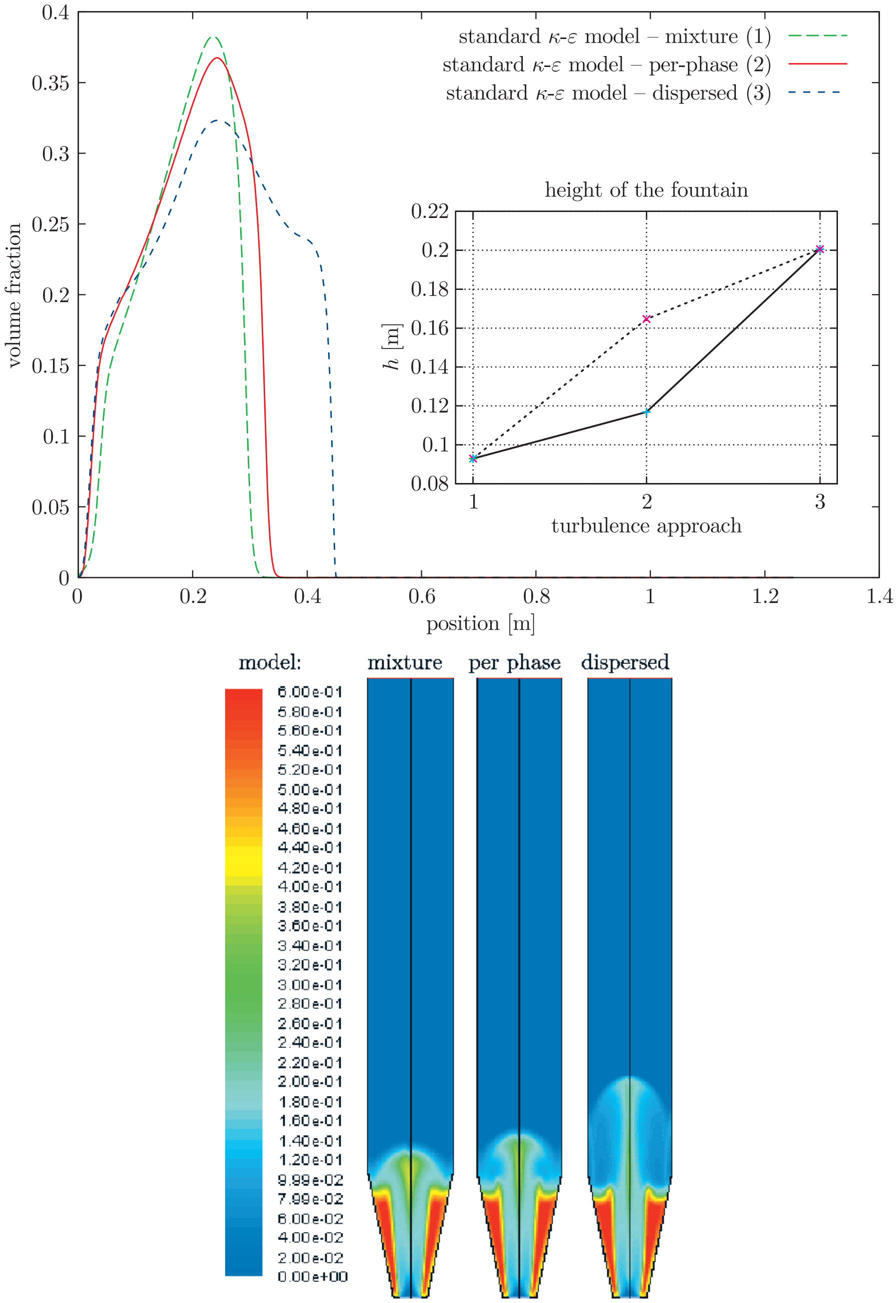


Figure 18. Comparison of turbulence equations for the standard κ-ε model (inlet velocity 30 m/s)

The lack of appropriate experimental data is a consequence of difficulties in obtaining it. Data of appropriate quality could probably be obtained by applying a fast camera and an image analysis method (a technique applied by the authors of paper [9] and others). It appears that the distribution of the volume fraction could also be obtained by other techniques.

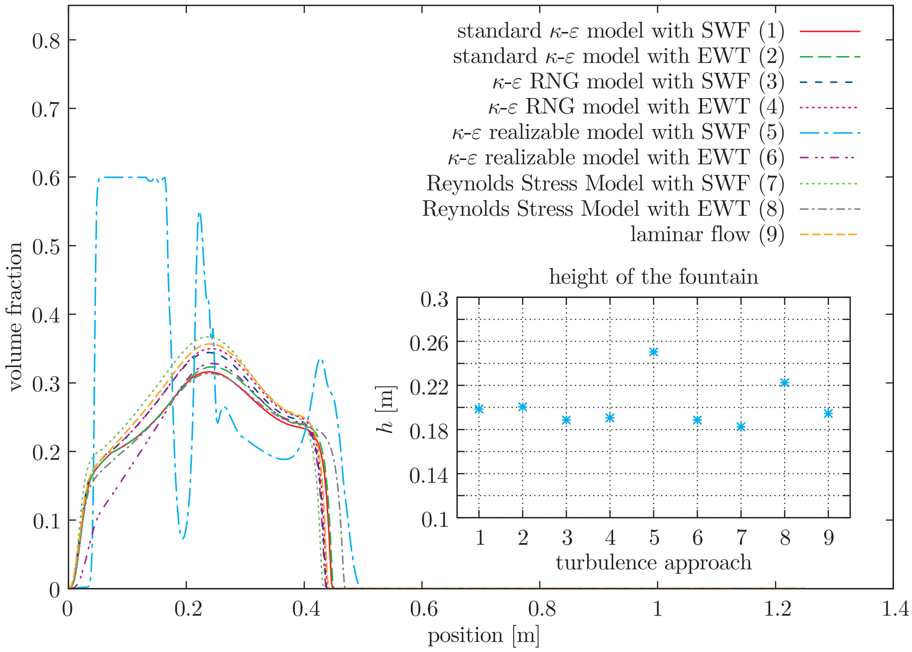


Figure 19. Turbulence model's influence on distribution and fountain height (inlet velocity 30 m/s)

The strongly non-stationary character of phenomena occurring in the fluidized bed and preparing that would represent the fountain's typical dynamics during operation also remain open issues.

17. Conclusion

The studies carried out have lead to the following conclusions:

- The Multiphase Eulerian Model is applicable in simulation studies on spouted beds present in spouted bed grain dryers.
- Computer simulation results are qualitatively and quantitatively consistent with results of laboratory experiments (with satisfactory accuracy).
- Agreement of results is obtained for a certain time-averaged bed condition.
- The Multiphase Eulerian Model yields correct results in two-dimensional axially symmetrical computation domain only.
- Numerical simulation results are fully repeatable.
- The influence of changes in individual data and parameters on the computation results is neither uniform nor symmetrical: an increase or decrease of a parameter by the same value does not result in the same change in fountain height.
- Eulerian Model sensitivity tests enable identification of key parameters requiring special care in determination.
- Knowledge of a computer model's behavior due to changes in its conditions significantly facilitates increasing the consistency of results.
- The studies carried out (and a review of professional literature) have revealed the need for more detailed description of the numerical modeling aspects.

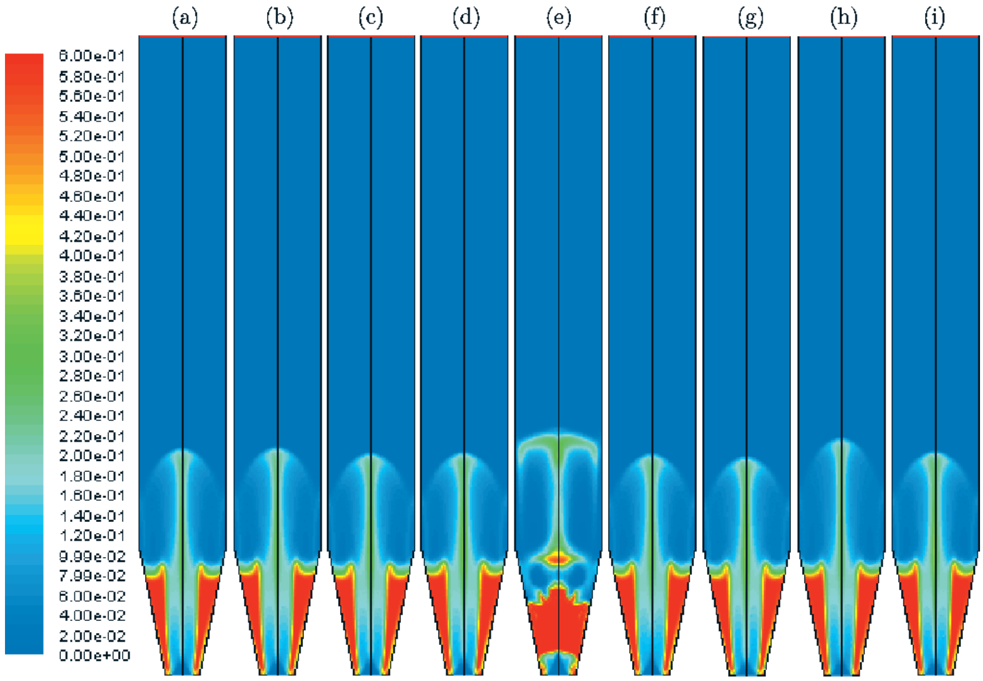


Figure 20. Distribution of the volume fraction for different turbulence models (inlet velocity 30 m/s): (a) standard κ-ε model with SWF (dispersed), (b) standard κ-ε model with EWT (dispersed), (c) κ-ε RNG model with SWF (dispersed), (d) κ-ε RNG model with EWT (dispersed), (e) κ-ε realizable model with SWF (dispersed), (f) κ-ε realizable model with EWT (dispersed), (g) Reynolds Stress Model with SWF (dispersed), (h) Reynolds Stress Model with EWT (dispersed), (i) laminar flow

Collecting experimental data of the highest possible quality is one of the most important issues concerning fluidized bed modeling in spouted bed dryers. Even slight carelessness in obtaining such data can contribute to numerical simulation results' deviating significantly from the results of laboratory experiments.

The importance of this stage of studies cannot e overestimated; the conducted tests of Eulerian Model sensitivity proved highly useful in developing a numerical model of the given spouted bed dryer. When the bed's behavior under given conditions is know, all parameters can be easily matched in a way providing simulation results maximally consistent with observations made at the actual testing station. The issue has not been presented in the present paper in full detail, as it is the subject of another paper.

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