Mathematical modeling of a spray-dryer in Matlab and OpenFoam

Andrea Somma[1]

[1] *Chemical engineering student, Politecnico di Milano, Chemical plants and process operations management course, Github.*

Abstract

In this work a simplified modeling approach for a spray-dryer is presented, in particular a modified version of the Matlab script from SuPER, and a non-detailed CFD version made from scratch, from the 3D-design to the postprocessing.

Keywords: Spray-dryer, Matlab, OpenFoam.

1 1D-model, Matlab script

To describe what physically happens in a spray-dryer, some DE have to be defined, specifically:

$$\begin{cases} dz = v_p dt, & \boldsymbol{Coord-switch} \\ m_p \frac{dv_s}{dt} = (\rho_p - \rho_g)V_p g - 3 f_D \mu D_p v_s - v_s K_p S_p (P_w - P^0(T_p)), & \boldsymbol{MomB_p} \\ \frac{dm_p}{dt} = K_p S_p (P_w - P^0(T_g)), & \boldsymbol{MassB_p} \\ \frac{dG_i}{dt} = K_p S_p (P_w - P^0(T_g))\eta A v_p, & \boldsymbol{MassB_{gas}} \\ m_p C_{pL} \frac{dT_p}{dt} = h S_p (T_g - T_p) + K_p S_p (P_w - P^0(T_g))\Delta H_{ev}, & \boldsymbol{EneB_p} \\ G c_p \frac{dT_g}{dt} = h S_p (T_p - T_g)\eta A v_p, & \boldsymbol{EneB_{gas}} \end{cases} \tag{1}$$

Obtained results from the SuPER model Fig.1:

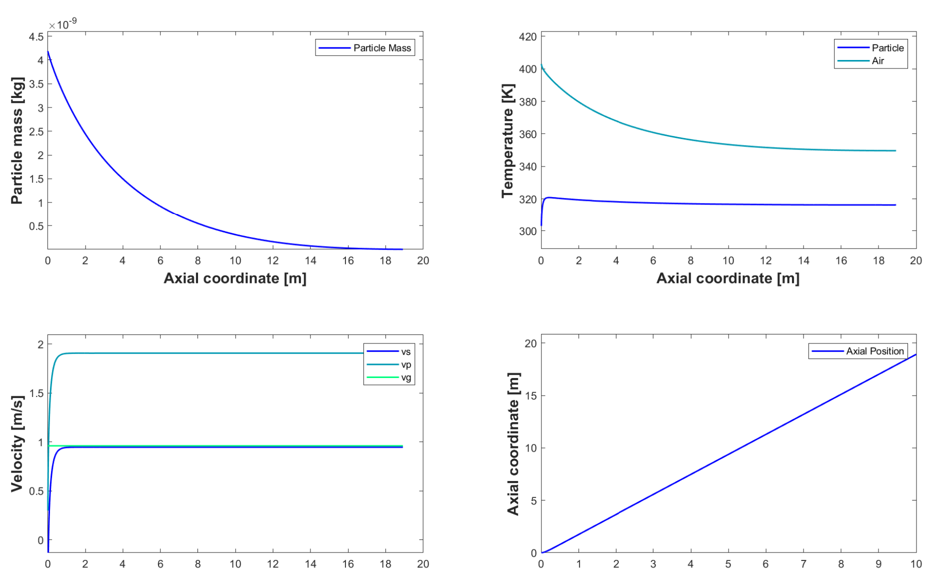


Figure 1. SuPER model, with starting data from spray-dryer slides presented in WeBeep.

Proposed improvements for the SuPER model:

- calculation of non-dimensional numbers and closure coefficients inside the integration function;
- constrained evaluation of particle mass and diameter, since the particle mass can not be lower than the fully dried milk;
- weighted evaluation of particle volume based on the liquid fraction (eq 2), because powdered milk tend to form hollow spherical structures, so density can not be considered as the one of the liquid milk.

$$\rho_p = \rho_{water} x_{liq} + \rho_{powder} x_{dry} \tag{2}$$

Obtained results from the new model Fig.2:

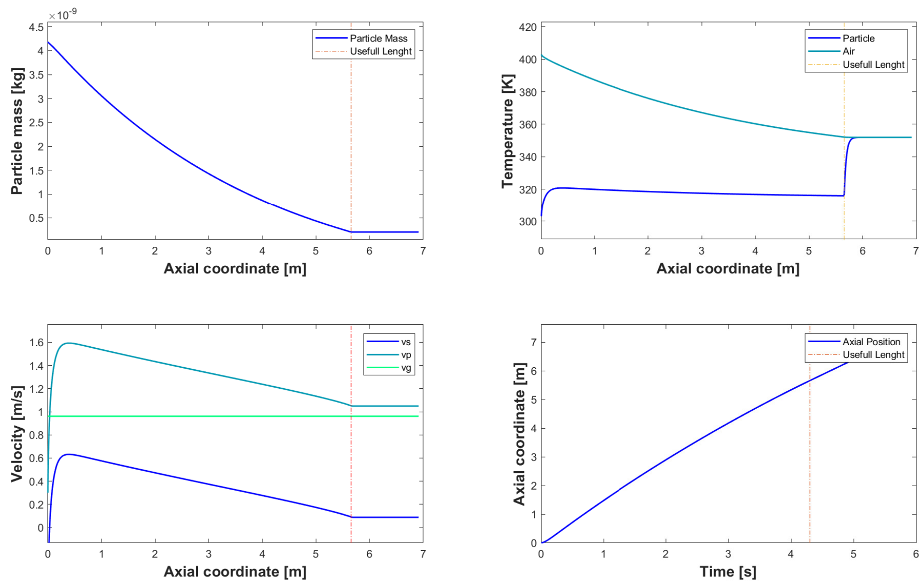


Figure 2. New model, with starting data from spray-dryer slides presented in WeBeep.

Captured phenomena from new model:

- particle mass reaches a non-zero minimum;
- gravity has a lower impact on v_p as time passes, due to the evaporation of the liquid fraction;
- T_p sharply increases when liquid fraction is null and quickly reaches air temperature.

2 3D-model, OpenFoam case

To ensure a better understanding of the **fluid-dynamic** of the process, a 3-dimensional model has been developed, with the following features:

- **solver**: denseParticleFoam and pimpleFoam;
- **solver-type**: Eulerian-lagrangian, no phase change, incompressible;
- **Forces**: ErgunWenYuDrag, gravity;
- **Mesh size**: 2M cells;
- **particle diameter and mass**: final value, from Matlab model;
- **boundary conditions**: slides data;
- **spray angle**: 45°;
- **geometry**: slide data, annulus jet radii: $R_{internal} = 0.56m$, $R_{external} = 1.5m$.

To obtain the following **results**, a steady state RAS has been solved on a coarse mesh, then a sample of 8000 particles has been added constantly trough $4s$ in a finer mesh on which PimpleFoam and DenseParticleFoam have been coupled, to account for the solution of both the continuous and dispersed phase. Anyways, as Fig 4 demonstrate, the RAS is not appropriate to account for air-velocity fluctuations, so the particle displacement (Fig 3) has to be considered as the most probable but **not** the only one possible.

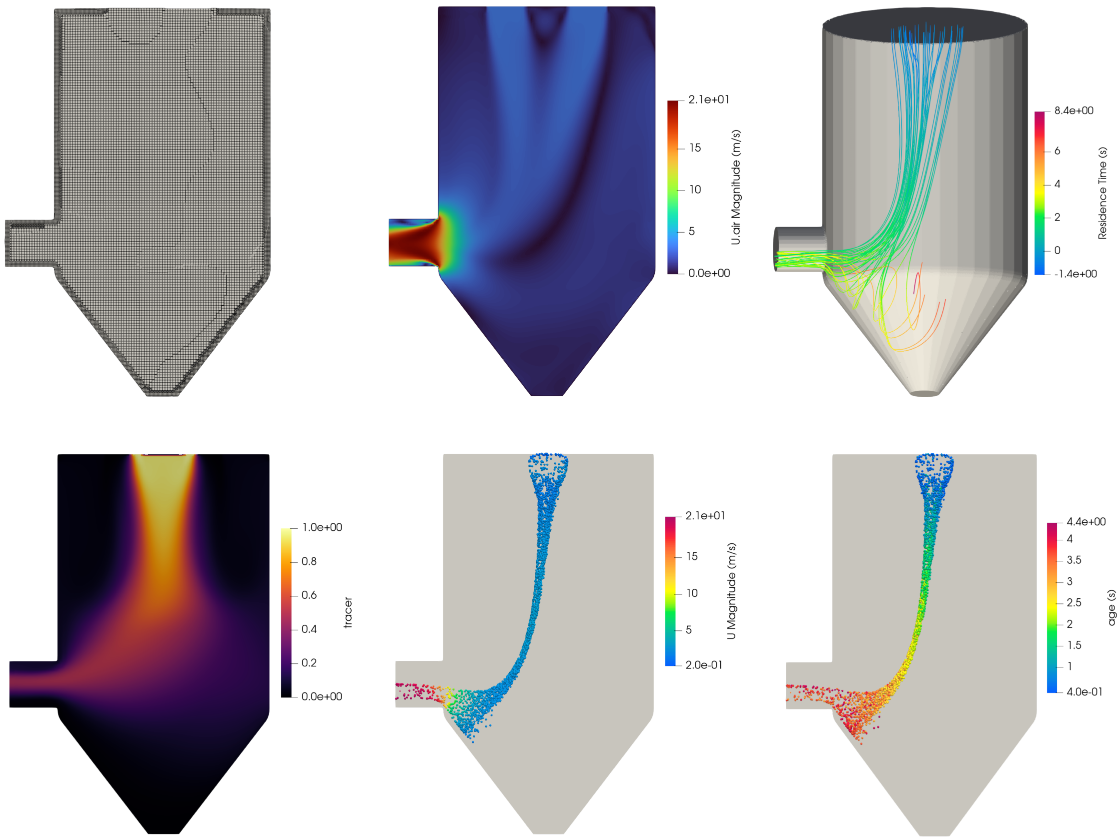


Figure 3. In order from left to right: fine mesh, velocity field with glyphs, streamlines colored with residence time, scalar transport of a tracer, particle velocity and particle residence time.

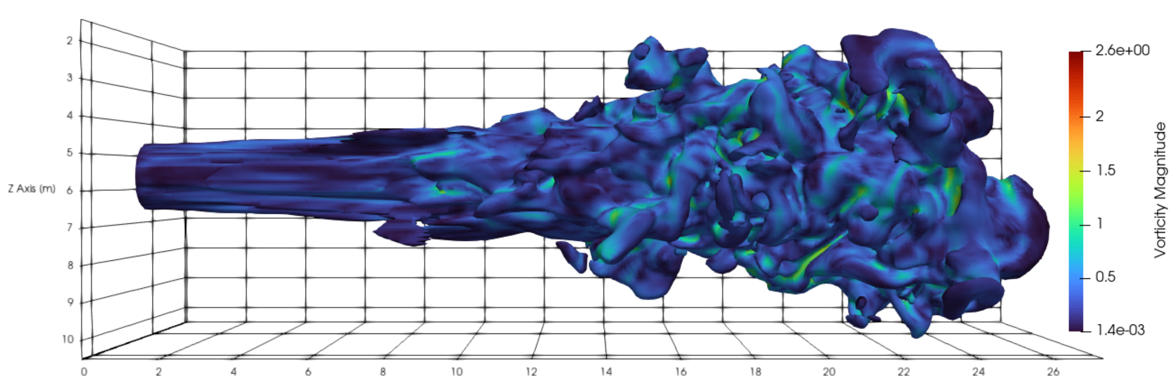


Figure 4. Velocity magnitude contour of a turbulent jet, with Lattice Boltzmann methods (OpenLB).

From this 3-dimensional model one can infer that:

- **Velocity field** is not well depicted in the 1D-model (Figs 3,5), since the spray dryer is not long enough to consider a fully developed stream.
- Tracer and particle-solver show that the totality of the dry milk is transported by the air stream, so a **cyclone** or a filtering system is mandatory.
- Due to the not developed velocity field, the **residence time** is much lower than expected from the 1D-model, this resulting in a not dried product (Fig 6a). In fact the 1D-matlab model exhibit, approximately, a residence time of $4.5s$, range bins from 3D-model, instead, between 3 and $4s$.

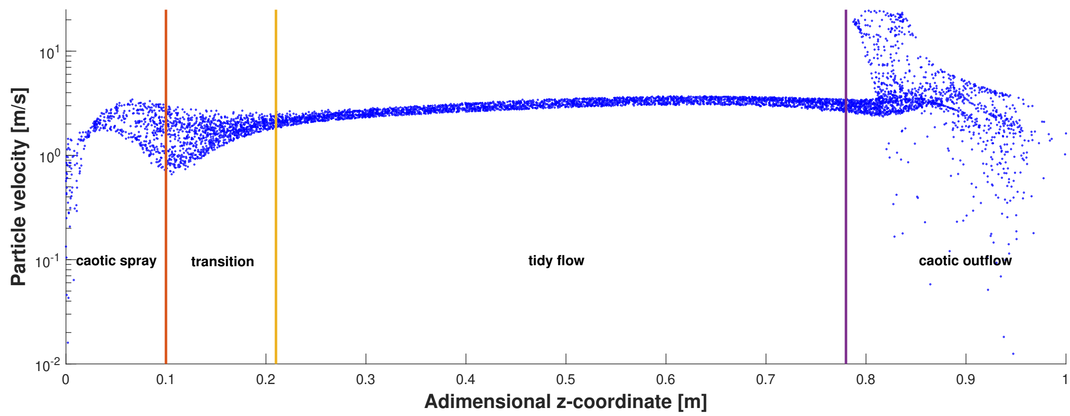
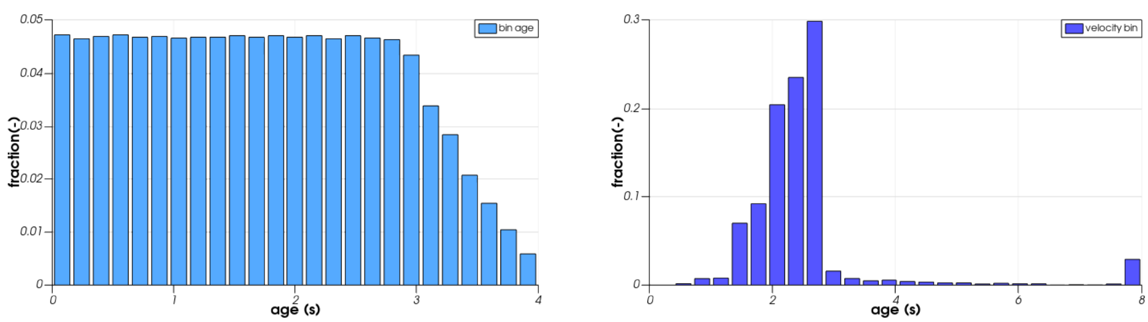


Figure 5. Particle velocity scatter plot varying in z-coordinate after 4s of spraying.



(a) Particles age bins, after 4s of spraying.

(b) Particle velocity bins (m/s), after 4s of spraying.

Figure 6. (Last bin ranges collect particles fraction up to an hypothetical infinite age and velocity value.)

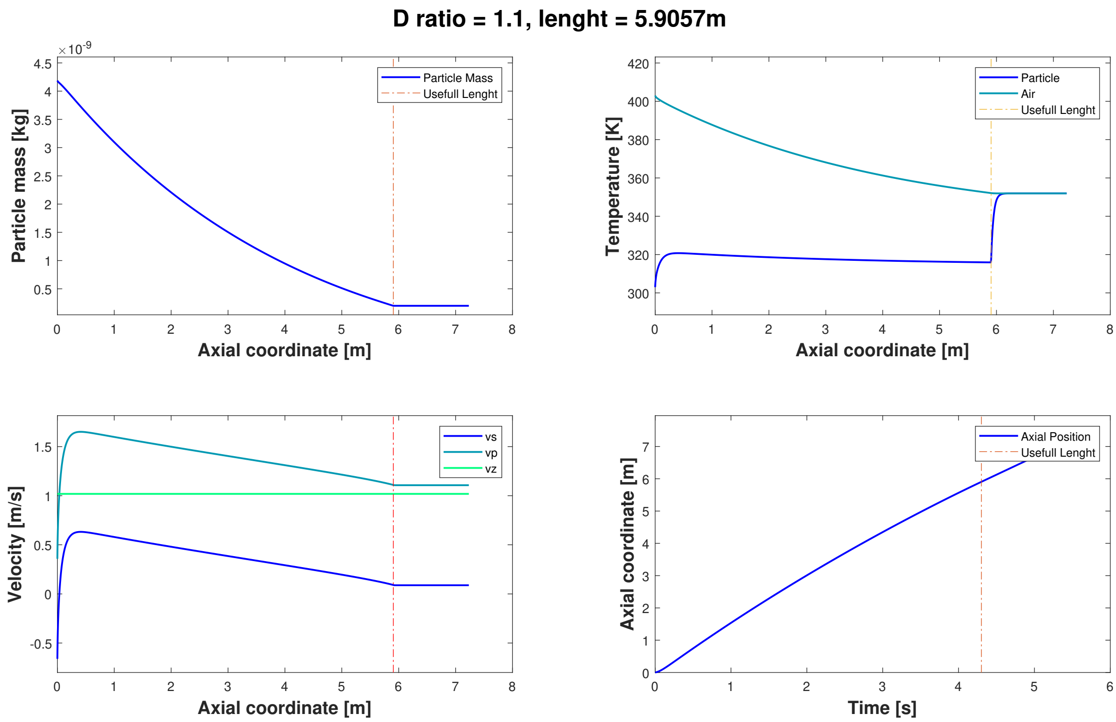
3 1D-model-corrected

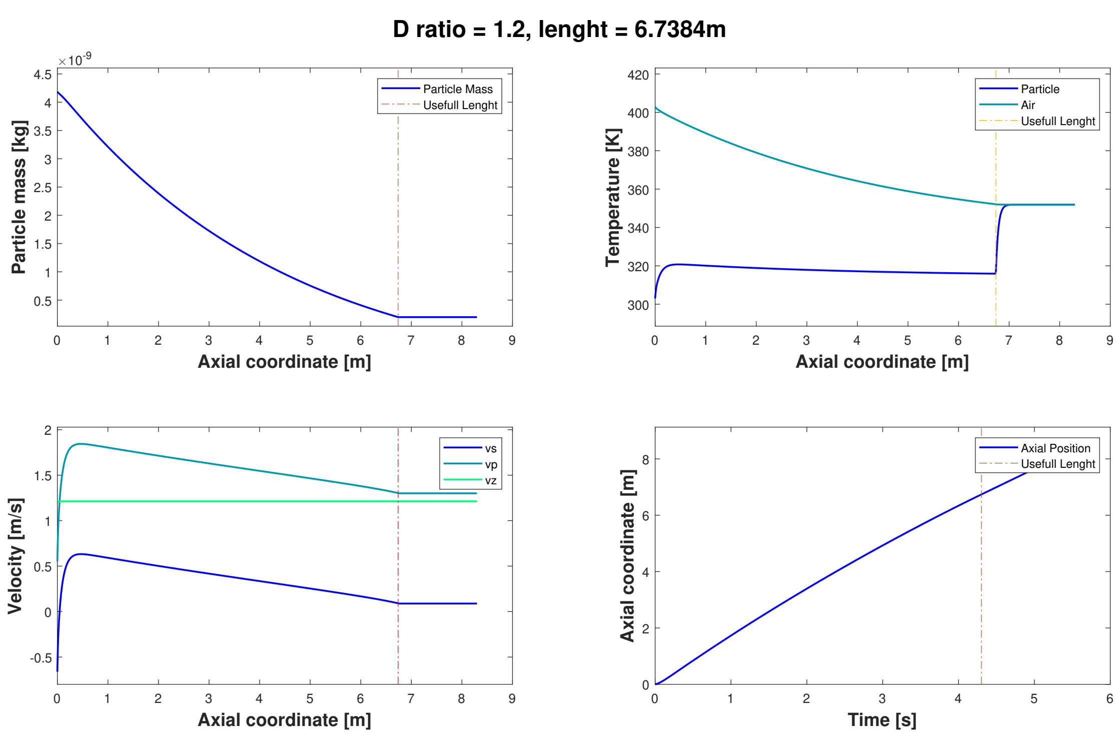
To better predict the particle displacement a modified turbulent jet axial velocity correlation (Riyaz and Ahmad 2014) can be introduced:

$$v_z = \begin{cases} U_{exit}, & \boldsymbol{if}\ 0 \leq z \leq x \\ 6.11 D_{outlet} U_{exit} \frac{1}{z}, & \boldsymbol{if}\,(\ z > x\ \&\ v_z > v_{dev}) \\ v_{dev}, & \boldsymbol{otherwise} \end{cases} \tag{3}$$

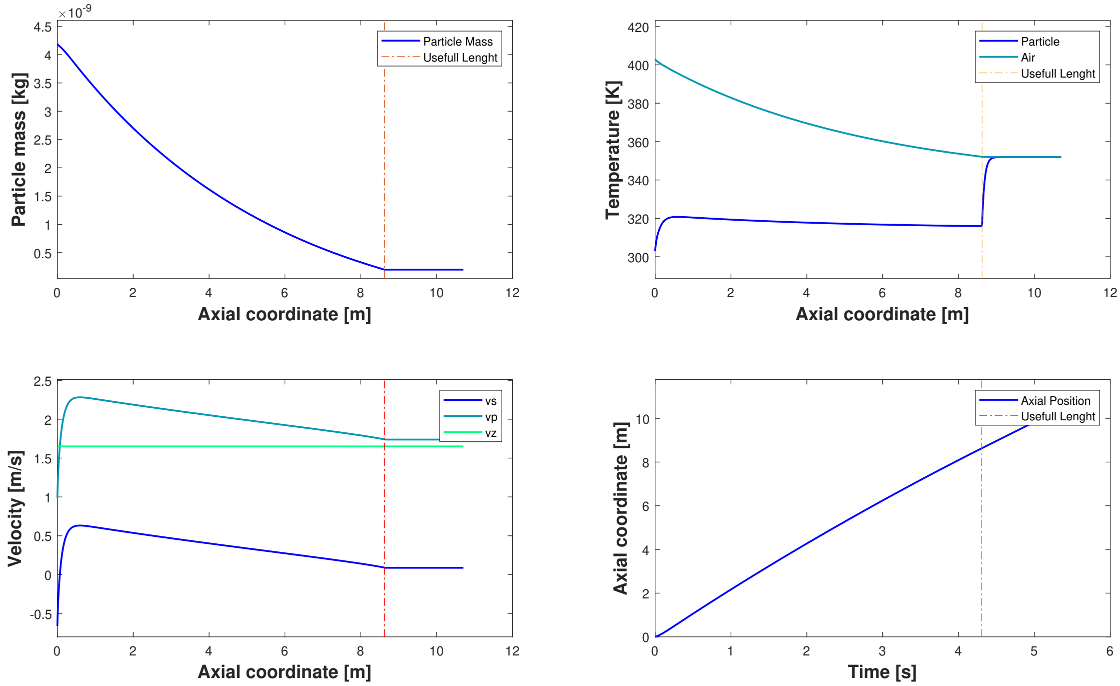
where v_z is the axial velocity, U_{exit} is the jet outlet velocity, D_{outlet} the jet diameter, v_{dev} the fully developed velocity, and $x = 6.11 D_{outlet}$ (this last parameter is also recognizable in Fig 4). Gas velocity is now substituted by this new $\mathbf{v_z}$ for every inter-phase computation.

Corrected-model Results:

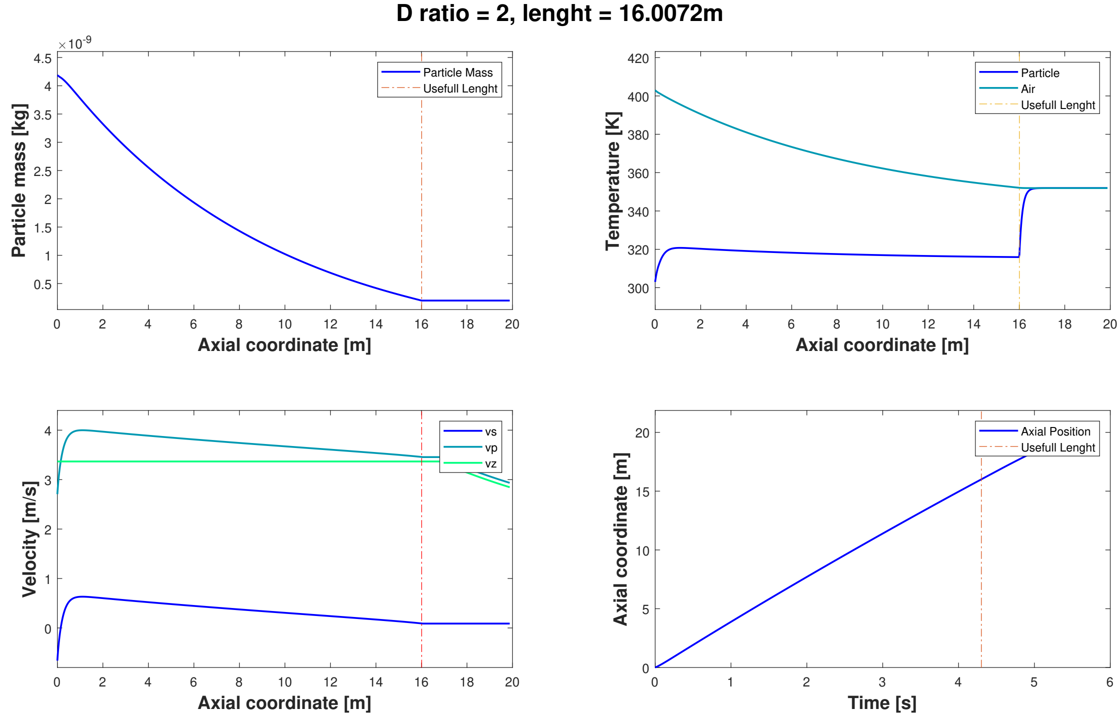




D ratio = 1.4, lenght = 8.6211m



D ratio = 2, lenght = 16.0072m



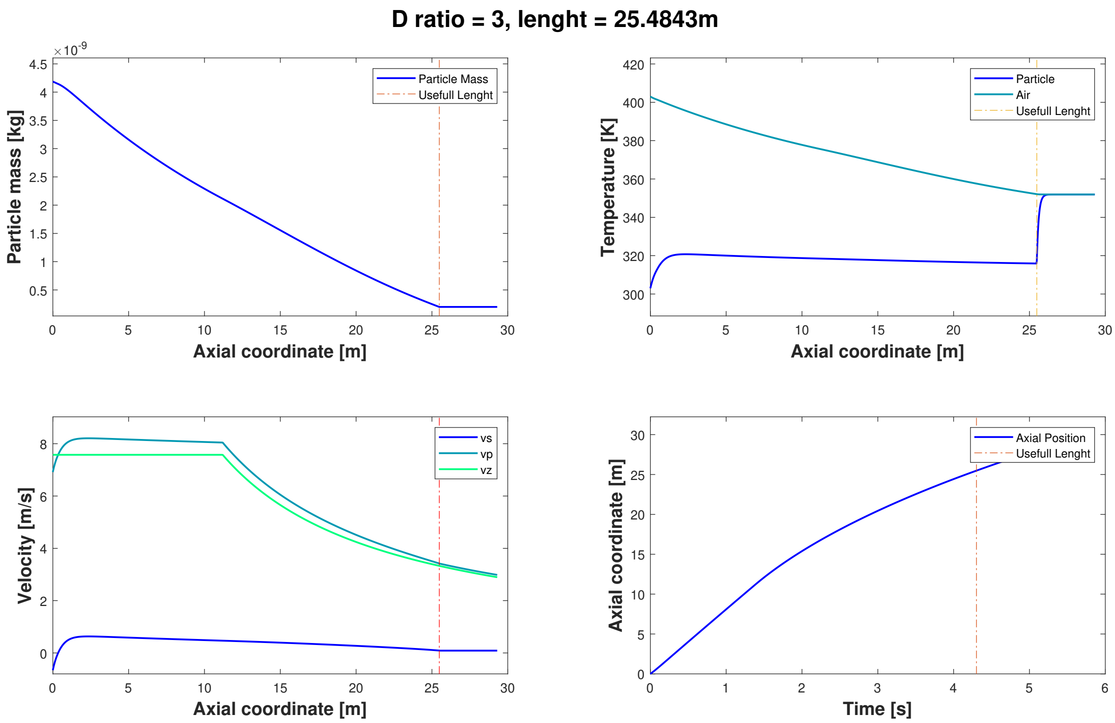


Figure 7. Corrected model, with starting data from spray-dryer slides presented in WeBeep and varying air-jet/spray-dryer diameter ratio.

New captured phenomenon from corrected model:

- Particle is now subject to the axial velocity of a jet, which is more consistent than considering a fully developed flow inside the spray dryer.

The corrected model is now able to predict the particle residence time in a more accurate way, taking in consideration also the velocity gradient development, furthermore this is managed adding only datum, that accounts for the spray dryer geometry (D_{ratio}), without complicating too much the user experience.

Data Availability Statement. Obtained data and code can be found in https://github.com/sommaa/spray_dryer, OpenFoam and OpenLB data can be obtained under request, due to size issues.

References

Riyaz, F., and Z. Ahmad. 2014. "Hydraulic characteristics of turbulent circular jets under surface confinement." *ISH Journal of Hydraulic Engineering* 20 (September). https://doi.org/10.1080/09715010.2013.876725.

Appendix

Closure models:

$$\begin{cases} Nu = 2 + 0.4Re^{0.5}Pr^{0.33} \\ Sh = 2 + 0.4Re^{0.5}Sc^{0.33} \\ fd = 1 + 0.14Re^{0.7} \end{cases} \tag{4}$$

where Nu,Sh and fd are respectively Nusselt and Sherwood numbers and drag factor ($fd = Cd/\frac{24}{Re}$), they represent the non-dimensional interaction between the dispersed phase and the continuous one. The first two non-dimensional numbers can be further manipulated to get the heat transfer coefficient and the mass transfer one, in order to practically exploit them in Eq 1.

$$\begin{cases} h = \frac{kNu}{L} \\ k = \frac{DSh}{L} \end{cases} \tag{5}$$

where k is the thermal conductivity, L the characteristic length and D the diffusivity.

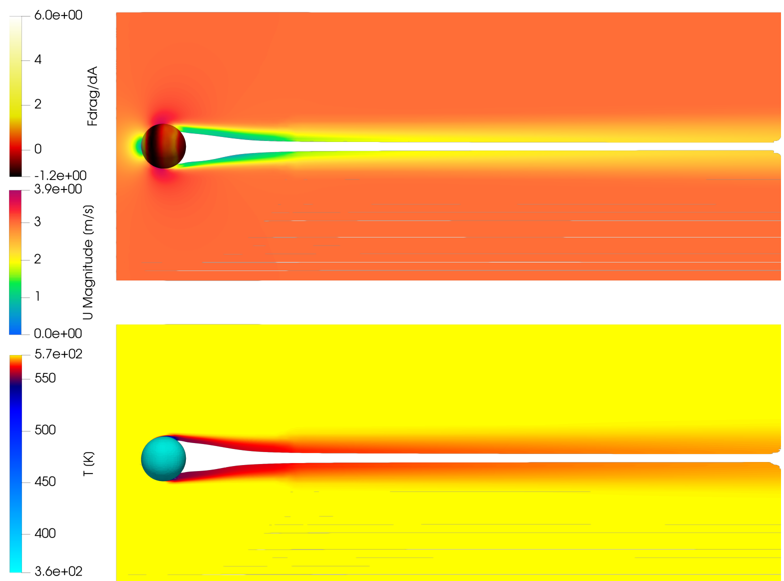


Figure 8. Representation of the drag force acting on a spherical cold particle and the velocity boundary layer in the upper image, and temperature boundary layer in the lower one.