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Superheated steam dryer: simulations and experiments on product drying

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Abstract

This paper presents a CFD study as a way of conceiving and analyzing a new drying process: superheated steam spray dryer. A previous work has defined dryer design, on which CFD simulations have been validated in case of water drying. When drying a real product, which turns into dry powder, particle residence time distribution (RTD) seems to be strongly affected by fluid circulation and particle size distribution. Thus, time/temperature history, which rules final product quality, can be very different according to particle size and operating parameters. The CFD model is validated by comparing experimental and numerical RTD for two different operating conditions. Thus, we have a powerful tool for studying this dryer. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: CFD; Residence time distribution; Spray dryer

1. Introduction

Spray dryer design, especially scale-up, is based generally on empirical knowledge and relies heavily on designer experiences [1]. However, nowadays increase in computer speed and capacity and development of commercial computational fluid dynamics (CFD) softwares offer new possibilities [2]. They allow us to study new designs or consequences of modifications in operating conditions (flow rate, temperature). Moreover, particle characteristics can be obtained during drying according to temperature, diameter, and water content [3]. These data give the time/temperature/humidity history for each type of particles; with residence time, residence time distribution (RTD), this numerical approach provides valuable information for predicting the final product [4,5].

Still, CFD software uses laws which have to be fitted, as particle/wall interactions or models of turbulence, and approximations, especially in boundary conditions. Moreover, simulation requires knowledge of the process itself and of fluid dynamics to elaborate on the CFD model and analyze results in relation to approximations and numerical procedure [6]. Therefore, experiments are still necessary to determine unknown parameters of models, to verify hypotheses, and validate simulations.

Combining the numerical and experimental approaches has already been done in a previous work for designing of a new drying process: superheated steam spray drying. After feasibility tests, CFD models were used for studying different dryer designs and their associated operating conditions. Simulations have been validated by experiments, by comparing numerical and experimental temperature fields inside the drying room using pure water as the drying product [7].

This paper presents the continuation of the previous work and here CFD models are used for studying real product drying, and for predicting final product quality.

A new design is proposed. The first part of this work presents a study on water drying, which is compared with experimental results. Then, the model is modified and real product drying is presented. A special point is made on particle RTD in the dryer. The used method of particle RTD measurement is exposed. Experimental results are given and discussed in comparison with the model.

2. Simulation with water

2.1. Spray dryer

First, pilot was designed as a hot air spray dryer: it was 2 m in height and 0.5 m in diameter. Steam was superheated by sending it through a heating pipe, and spray was done with an pressure nozzle [8]. At the outlet, steam and dried particles were condensed with cold water, by using a shower; thus, no product generally be recovered.

To improve evaporating rate, a new steam inlet has been proposed (Fig. 1). It is a cone-shaped inlet, which entails a better steam/droplets mixing. Therefore, droplets are dried more rapidly, and the drying chamber can be smaller. Now the dryer is 1.4 m in height, with a 0.5 m diameter chamber vessel. The drying room is equipped with thermocouples.

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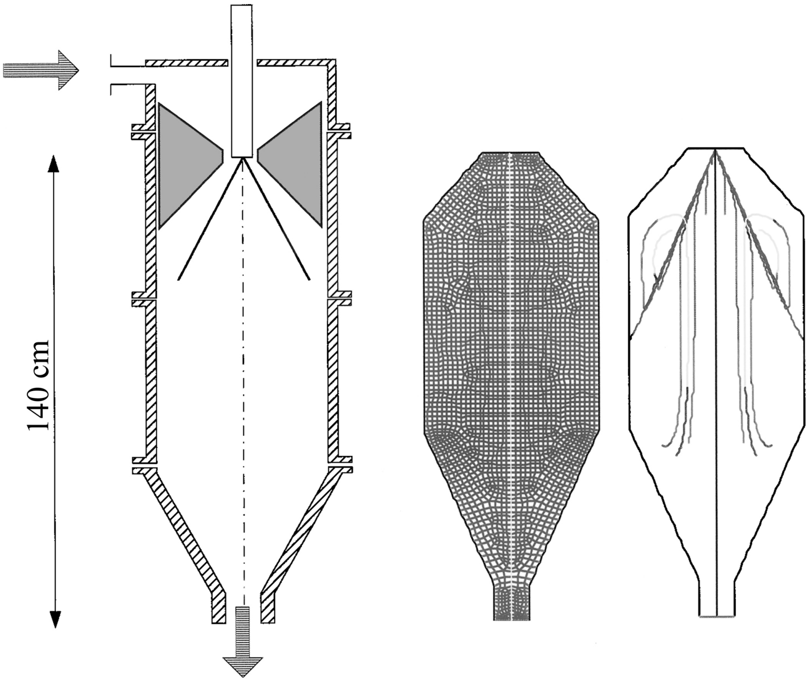

Fig. 1. Experimental pilot, CFD mesh and simulated water droplet trajectories.

2.2. Numerical model

This dryer is modeled by CFD software. This code solves heat, mass and momentum balance equations by integrating them over finite volumes, to describe all the drying domain. Details of the model are fully given in Frydman's paper [9] and summarized here. Drying room is represented by a two-dimensional mesh (1550 cells), with axial symmetry. We impose boundary conditions, which are the mass flow rate and temperature for steam and water entering the

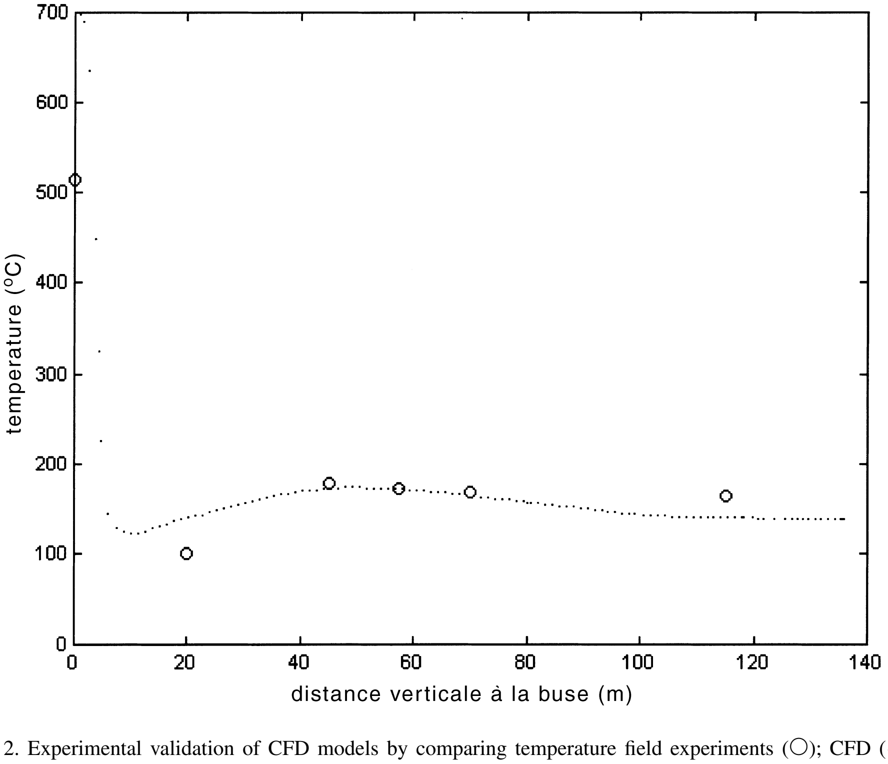

Fig. 2. Experimental validation of CFD models by comparing temperature field experiments (○); CFD (···).

chamber. We have chosen an Eulerian–Lagrangian approach in which steam represented the continuous phase, and particles the discrete phase. Code solved the heat and mass transfers between the continuous and the discrete phase.

The initial drop size distribution is represented by seven classes of droplet, determined from experimental size distribution of the nozzle (Table 1). Effects of turbulence are taken into account with a standard k–ε model.

Table 1
Particle size distribution

	Particle classes						
	1	2	3	4	5	6	7
Diameter (μm)	12	24	36	48	60	72	85
Mass fraction (%)	2	15	40	30	8	4.5	0.5

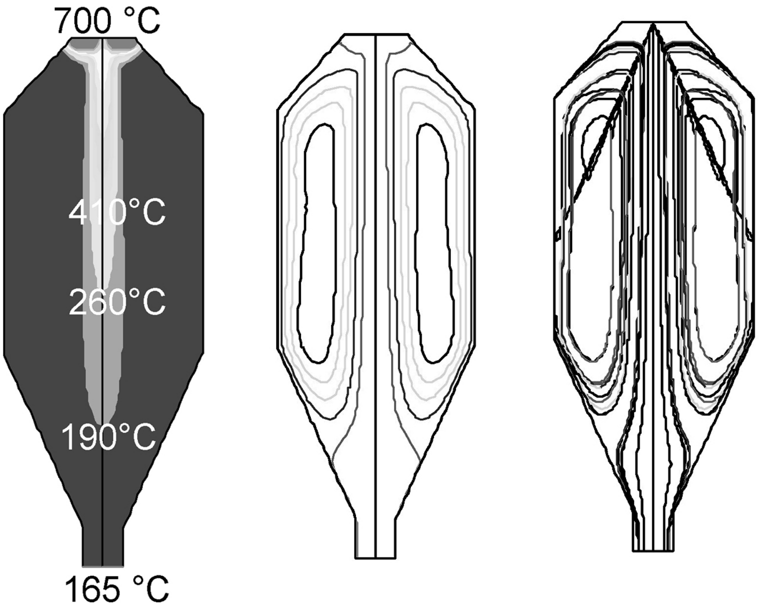

Fig. 3. CFD simulation: temperature field, stream lines, particle trajectories.

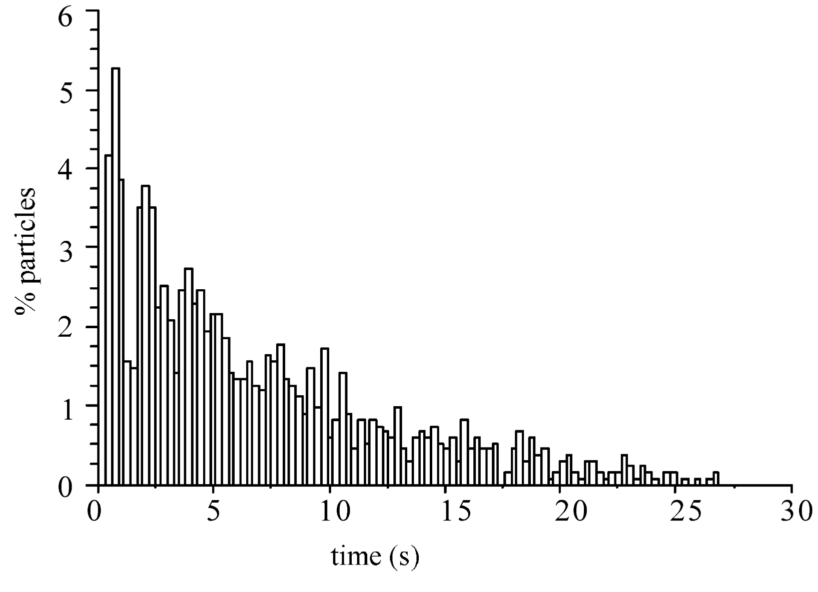

Fig. 4. Particle RTD of the dryer (simulation).

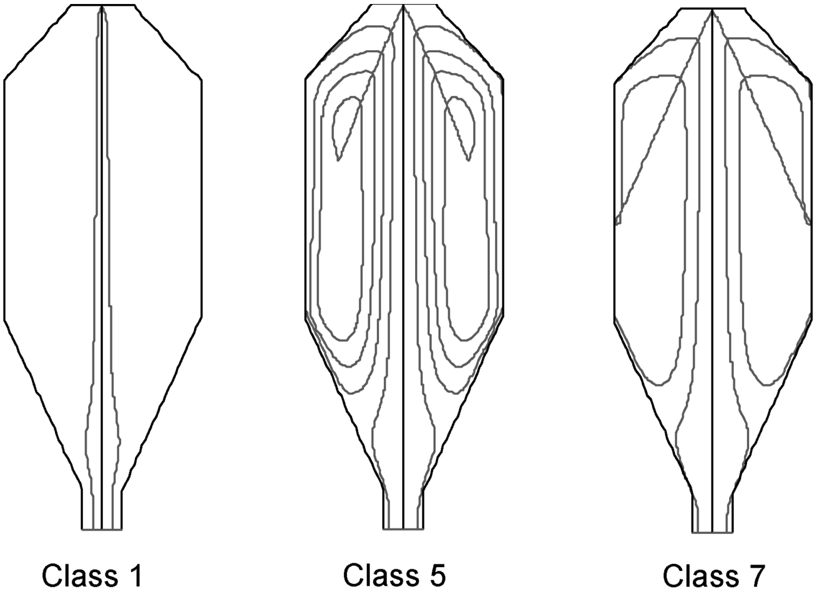

Fig. 5. CFD simulation: particle trajectories.

2.3. Numerical results and experimental validation

The new design provides effectively better volumic evaporating rate, and removes dead zones on top of the room. With this new design, chosen operating conditions are as follows:.

- Steam: mass flow rate, 22 kg h^{-1}; temperature, 700 °C.
- Water: mass flow rate, 9 kg h^{-1}; temperature, 27 °C.

Evaporating rate of this SHS spray dryer is 9 kg h^{-1}, and its specific evaporating rate is very high and reaches 50 kg h^{-1} m^{-3}.

As for the previous design, simulations are validated by comparing numerical and experimental steam temperature (Fig. 2) and fit quit well without any adjustment.

3. Product drying simulation

3.1. New hypotheses

Now, water is replaced by a product, with 10% of dried matter. To keep same evaporating rate as previous, 9 kg h^{-1}, mass flow rate is then 9.9 kg h^{-1}. We suppose the initial particle size distribution is quite the same as that presented in Table 1.

To simplify model, the product is supposed to have the same characteristics as pure water, with density, heat capacity, thermal conductivity, latent heat and thermal conductivity all remaining constant during drying. Boiling point temperature remains constant and equal to 100 °C. But, some particle properties change during drying: diameter and mass diminish as if particles were pure water droplets, until there is no water left in the particles. Then, particle is supposed to be completely dried. So, unlike in water, the case of particles do not disappear but finally leave after a residence time in the chamber.

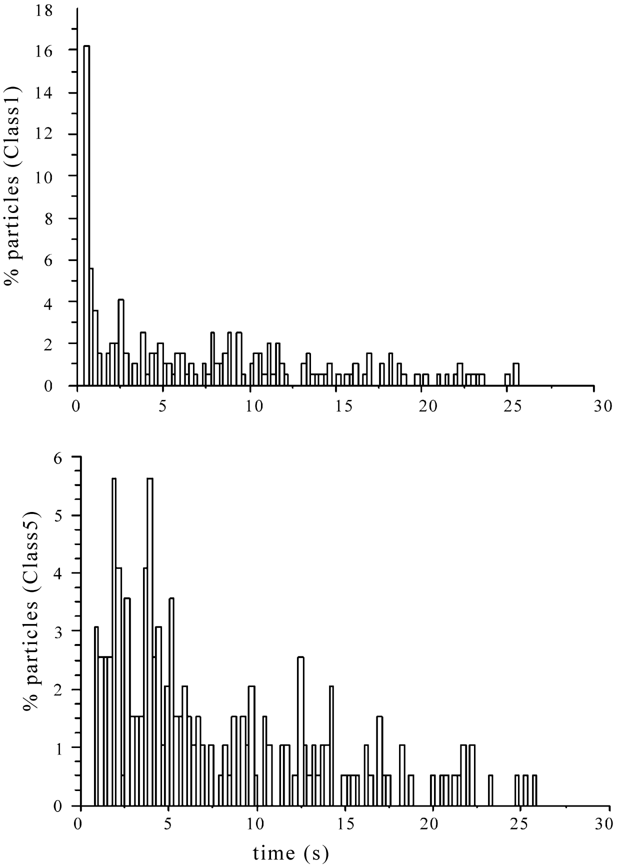

Fig. 6. Particle RTD (classes 1 and 5).

Wall law is as follow: when a particle reaches a wall, it rebounds.

3.2. Results

In Fig. 3, temperature field, stream lines and particle trajectories, which are different for all the seven size classes, are reported. We see how recirculation flow drags some particles, which turn several times inside the chamber before leaving. Particle average residence time is 5 s, but particle RTD shows that some particles could stay in the drying room more than 25 s (Fig. 4). The average residence time of steam, calculated from dryer volume and steam flow and taking into account the changes in steam density

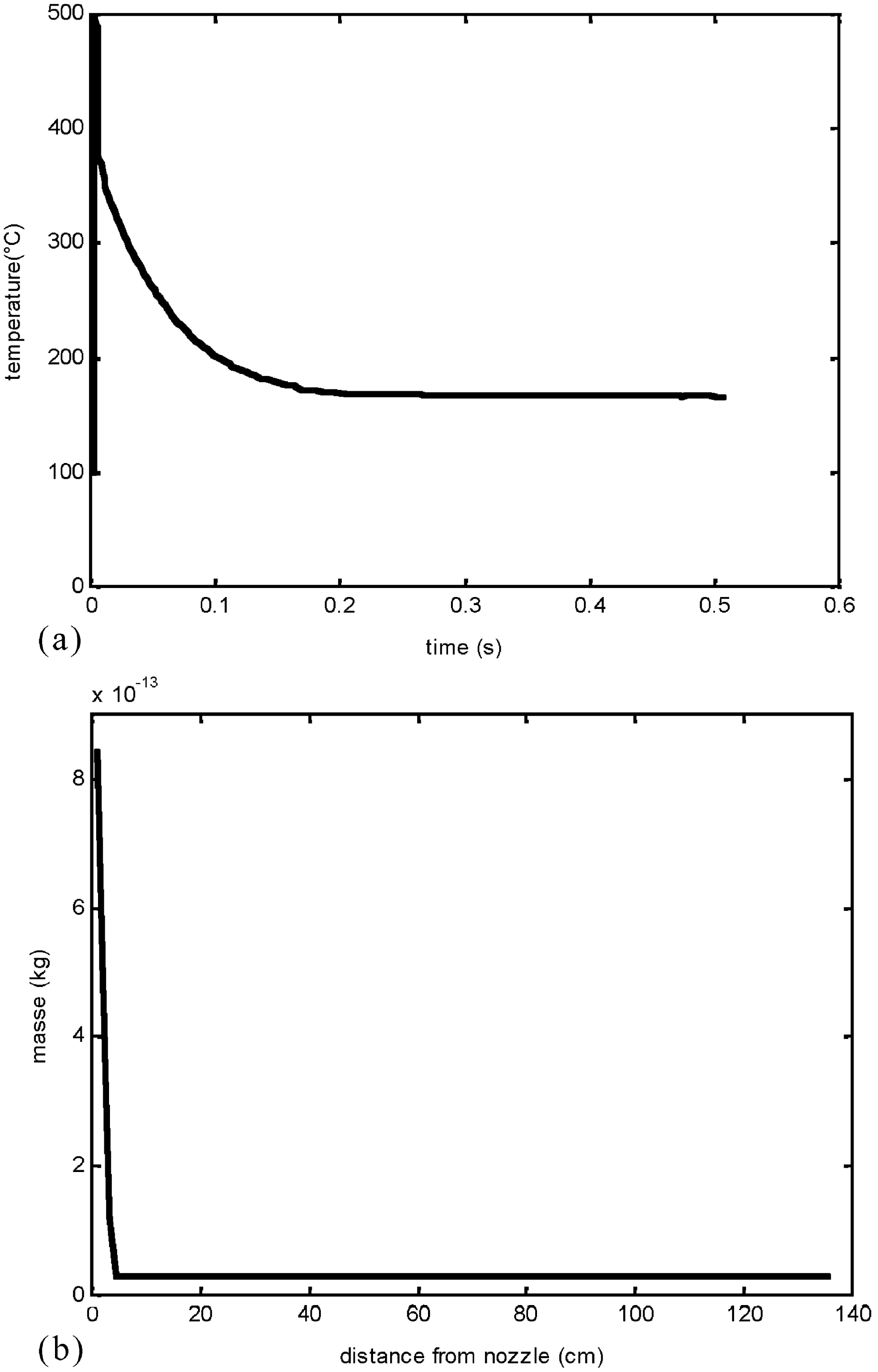

Fig. 7. Drying particle history: (a) temperature of class 1 particle; (b) mass of class 1 particle; (c) temperature of class 5 particle; (d) mass of class 5 particle.

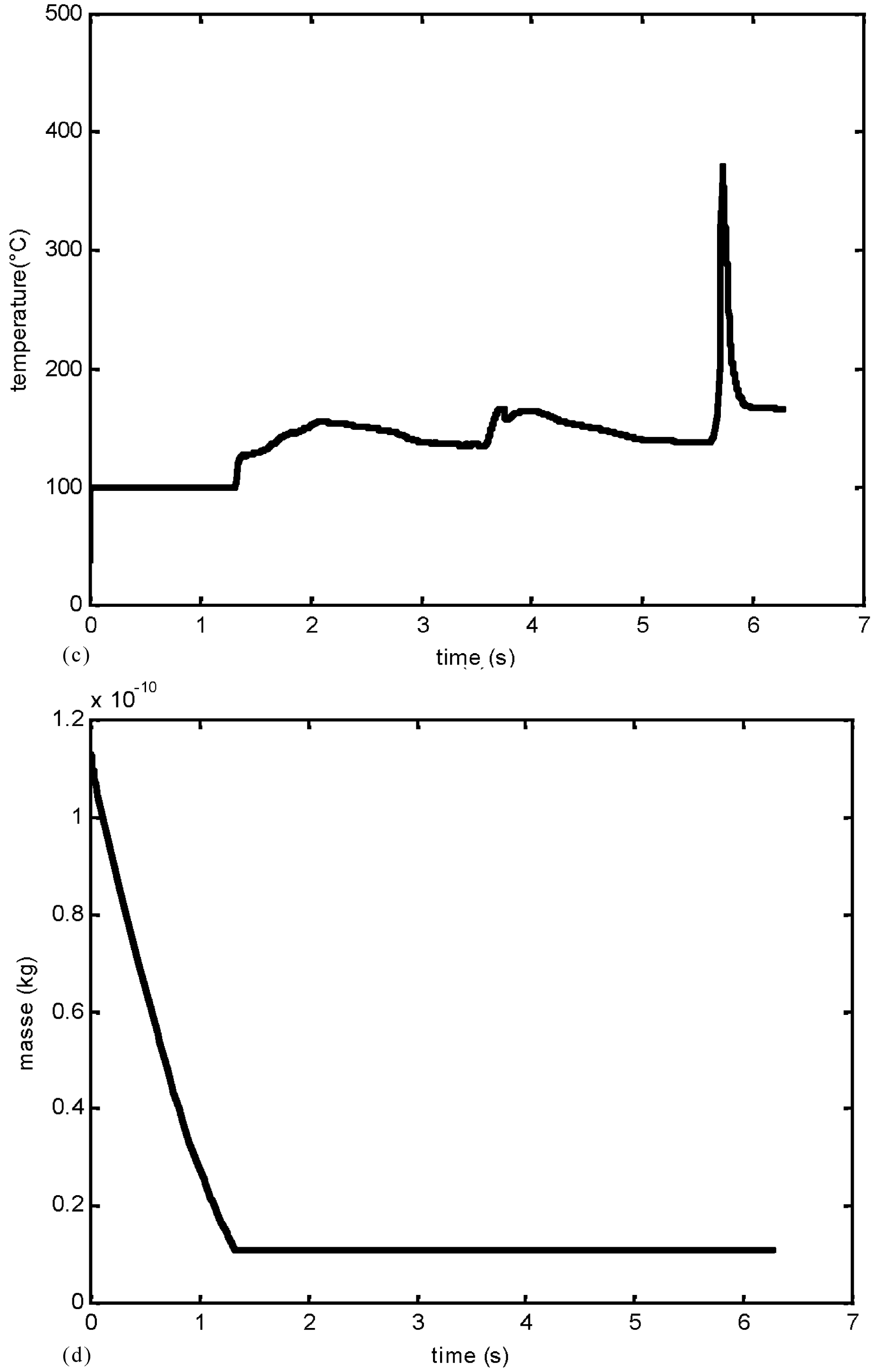

Fig. 7. (*Continued*).

when cooling and steam generated by the drying, is about 17 s.

We can see different cases: small particles, class 1, are dried very quickly, and are dragged by steam directly out of the dryer; bigger particles recirculate inside the drying room before quitting (Fig. 5). Because they are dried just in the middle of recirculation zone, average particles, class 5, have the longest residence time (Table 2).

These results could be observed on RTD curves in Fig. 6. Most of the small particles (16%) leave during the first second. Big particles stay in the chamber during 2–4 s. Consequently, these different behaviors give different

Table 2
Particle average residence time

	Particle classes						
	1	2	3	4	5	6	7
Residence time (s)	0.5	0.8	2.8	4.9	6.3	3.9	4.2

time/temperature histories. If we look at mass particles vs. times, we see that particles are dried very quickly. Therefore, they stay no longer at 100 °C but, in the model, reach steam temperature, and particle temperatures change along their recirculations (Fig. 7a–d). So, Figs. 3–7 show that time/temperature history depends on particle diameter and on steam stream lines in the drying room, in other words, on characteristics of final product and function of steam and product flows, particle size distribution, nozzle type, and of general dryer design.

4. Experimental RTD validation

4.1. Method

When drying pure water, validation was made by comparing experimental and calculated temperature fields. But, when drying real product, temperature measurement is no more possible because of thermocouple encrusting [10]. Therefore, the method chosen is to compare numerical and experimental particle RTD.

This RTD characterization is based on conductivity-based measurement, using a KCl solution. A special injection system has been developed to introduce this solution just before the nozzle, consisting of a set of valves. At the dryer outlet, vapor is condensed with a "shower" and an in-line conductivity measurement is achieved (Fig. 8). Obtained signal corresponds to experimental particle RTD of the complete system nozzle + drying room + condenser.

For the moment, CFD models give only RTD in the drying chamber. In order to compare numerical and experimental results, experimental RTD signals of the injection nozzle alone and condenser alone are convoluted to simulate the entire dryer signal. This is achieved by numerical convolution of the third data files.

4.2. Tests

To compare simulation and experiment, two different cases with two different operating conditions were selected:.

- Case 1: Steam mass flow rate, 12 kg h^{-1}; product mass flow rate, 5 kg of water per hour.
- Case 2: Steam mass flow rate, 40 kg h^{-1}; product mass flow rate, 13 kg of water per hour.

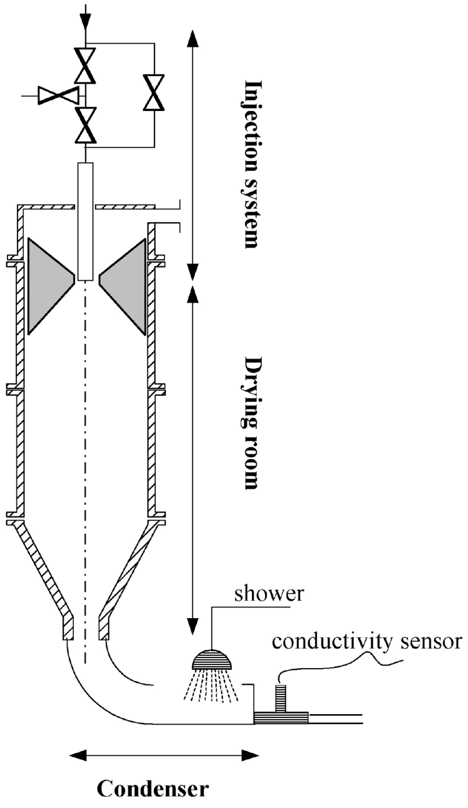

Fig. 8. Particle RTD measurement system.

For each case, experimental particle RTD were measured for injection alone, condenser alone and system nozzle + dryer + condenser. The two simulations give two dryer RTD signals, and then convolutions are carried on RTD signals of nozzle (experimental signal) + dryer (numerical signal) + condenser (experimental signal).

4.3. Results

All signals are reported in Fig. 9. Each experiment has been repeated three or five times to ensure reproducibility of the results. We can see that simulation predicts quite different RTD for the two cases studied. Because of very different product flow rates, RTD of injection system and nozzle are different too. We did not notice big changes in condenser signals between the two cases.

The final curves compare convoluted and experimental signals.

Comparing the two cases, we see that:.

- experimental curves are different from each other;.
- convoluted curves report these differences;.
- mainly, for the two cases, convoluted curves are in good accordance with experiments.

Therefore, CFD simulations are experimentally validated in case of product drying.

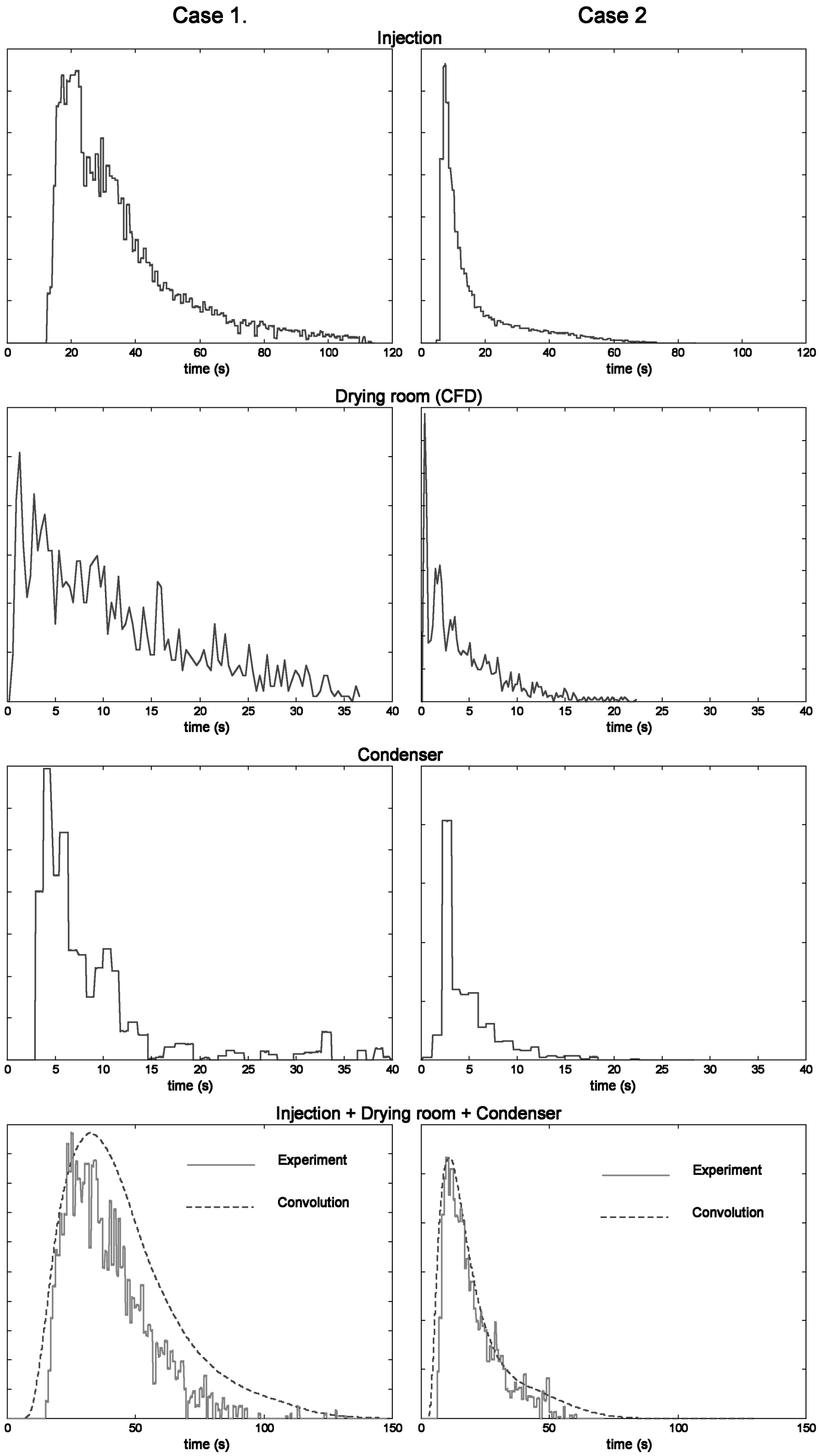

Fig. 9. Particle RTD of system nozzle + drying room + condenser. Comparison with experimental and convoluted signals.

5. Conclusion

A CFD approach has been used for studying a new type of spray dryer: the SHS spray dryer. A new design has been defined and operating conditions have been determined. This study has led to a very high specific evaporating rate: $50\,\mathrm{kg\,h^{-1}\,m^{-3}}$, showing that superheated steam allows a smaller chamber. Therefore, building cost is lower and price is reduced. SHS spray dry with $50\,\mathrm{kg\,h^{-1}}$ evaporating rate will soon be marketed by the manufacturer TECHNI PROCESS, partner in the project.

Experimental RTD study has allowed us to validate CFD simulations. Now, we have a very interesting tool for understanding and studying particle size distribution effects and flow rates. This analysis could be carried on by studying adjustable parameters, operating parameter influence and product characteristics. Then, pilot could be optimized following final product characteristics. These depend on the wished product, and should be defined. However, they are clearly linked to RTD and time/temperature/humidity history of particles.

To improve models, simulation should take into account product characteristic evolution laws during drying. Two points seem to be particularly important:.

- boiling point elevation, to represent real water content;.
- density and diameter, to simulate porosity, puffing or collapse.

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