Study of the Drying Behavior of High Load Multiphase Droplets in an Acoustic Levitator at High Temperature Conditions

Rosa Mondragón, Leonor Hernández , J. Enrique Juliá* and Sergio Chiva
Departamento de Ingeniería Mecánica y Construcción
Universitat Jaume I
Campus de Riu Sec. 12071-Castellon de la Plana. Spain

Juan Carlos Jarque and Vicent Cantavella
Instituto de Tecnología Cerámica, Asociación de Investigación de las Industrias Cerámicas
Universitat Jaume I
Campus de Riu Sec. 12071-Castellon de la Plana. Spain

Abstract

Experimental data on the drying behavior of suspension droplets is limited, although its importance in industrial applications for the material processing, chemical or food industry involving sprays dryers. This fact is particularly significant for high load and temperature conditions close to those found in the mentioned industrial applications. In this work, the drying behavior of acoustically levitated multiphase droplets has been experimentally investigated. The experiments have been performed using water-glass particles suspensions. The glass particles have a mean particle size and relative density of 13 μm and 2.5 respectively. The acoustic tube levitator has been modified in order to allow experiments at high temperature conditions. The flow rate, temperature and relative humidity of this air stream can be controlled by an air conditioning system. A CCD camera and a back-light illumination system are used to measure the droplet cross-sectional area and vertical position of the droplet during the drying process. The effect of the initial droplet volume (0.05 μl < V_0 < 0.7 μl), initial solid mass load (0.01 < Y_S < 0.5), ambient air relative humidity (0.05 < HR < 0.45) and ambient air temperature (60ºC < T < 120ºC) on the mean porosity of the grain and first drying period duration has been studied. An experimental correlation that predicts the final porosity of the dried grain has been obtained. The most important parameters to be considered for the porosity are the initial solid mass load and the initial droplet volume. The relative humidity of the air presents a moderate influence on the drying behavior of the droplet and the temperature is the parameter that presents a lower impact on the mean porosity. In addition, particular attention should be given to the drying behavior of small droplets that present a very low mean porosity values for high solid mass loads.

Introduction

Drying behavior of droplets of liquid-solid suspensions in a gas is of significant importance for many applications in the chemical, food and material processing industries [1]. In these industrial applications powder products are produced by spray dryings of liquid-solid suspensions. The spray drying is a complex industrial process that includes physical processes such as spray atomization, heat and mass transport from the droplets to the surrounding gas, drop-wall interactions, etc. There is a great interest in modeling the complete spray drying process, where submodels are used to describe the individual processes mentioned before. In particular, droplet drying models can be used to relate the final powder properties (such as the grain diameter distribution, mean porosity, morphology, etc) with the spray dryer design and process parameters. The drying process of a liquid-solid suspension droplet is characterized by two drying periods. In the first period, the evaporation is produced in the droplet surface and the droplet diameter, d, decreases following the d^2 law. In the second drying period a crust is formed in the droplet surface and the evaporation is produced through the pores of the crust. In this stage the droplet (or grain) diameter is constant and a droplet collapse, hollow or explosion can occur, modifying the final grain morphology.

It is not possible to obtain detailed information about the droplet drying process in industrial or laboratory-scaled dryers. For the study of the drying behavior of the suspension droplets single droplets experiments are needed. In this regard levitator tubes (ultrasonic, optical, electrodynamic and aerodynamic types) present some ad-

*Corresponding author

vantages with respect to conventional methods since there is no contact between the droplet and the solid. However, the influence of the levitation method on the drying droplet should be considered in order to interpret the experimental results. In the case of the ultrasonic levitator tubes, the acoustic streaming in the gas provides a convective mechanism much stronger than the Stefan flow or natural convection and dominates the evaporation process [2].

In the last decades acoustic levitator tubes have been extensively used to study the drying behavior of pure liquid, multi-component liquid and liquid-solid suspension droplets. In this regard, Yarin et al. [3] predicted the droplet shape and evaporation rate of acoustic levitated liquid droplets. Kastner et al. [4] developed the experimental procedure to measure evaporation rates in both drying periods. Yarin et al. [5] modeled the drying behavior, obtaining the duration of the first drying period, t_I, and an experimental correlation for the final grain porosity (ε). Finally, Brenn [6] modeled the solid concentration fields inside the droplet; predicting the appearance of hollow grains. All this correlations and models needs of experimental data in order to support its initial hypothesis as well as for validating its final results. Most of the available data on the drying behavior of suspension droplets in acoustic levitators were obtained for moderate temperatures (T<80ºC), initial droplet volumes (V_0) higher than 0.25 µl, solid mass loads (Y_S) lower than 0.3 and low relative humidity conditions (HR<4%) [8-9]. However, higher temperature, solid mass load and relative humidity conditions can be found in important industrial applications such as ceramic tile, detergents, electro-porcelain, milky products, abrasives, fertilizers production [1].

In this work we present experimental data on the drying behavior of liquid-solid suspension droplets in an acoustic levitator with experimental conditions closer to those found in industrial applications (Y_S, T and HR maximum values of 0.5, 120ºC and 0.45, respectively and minimum V_0 value of 0.05 µl). In order to meet this requirement a standard levitator tube has been modified in order to work at high temperature conditions. The influence of the temperature, initial droplet volume, mass fraction, and relative humidity on the final characteristics of the dried grain (mean porosity and diameter) and the duration of the process (first drying stage) have been studied. In addition, an experimental correlation that predicts the final porosity of the dried grain has been obtained in a wider range of experimental conditions.

Experimental Setup and Measurement Techniques

The experimental setup is composed of 4 systems (see Fig. 1 a): (1) an acoustic levitator consisting of an ultrasonic 58 kHz horn and a concave reflector, (2) an optical system consisting of a white light source with a diffuser and a CMOS camera with a macro lens, (3) a gas conditioning system (not shown in the Figure) controlling the temperature, flow rate and relative humidity of the air inside the levitator tube.

The levitator tube (tec5 AG Sensorik und Systemtechnik) produces a standing wave and pressure nodes and the droplet goes there. In addition, the levitator tube has been modified in order to allow experiments at high temperature conditions (see Fig. 1b). In this way, two separated metallic chambers can be found in the levitator tube. The identified as "cold chamber" contains the ultrasonic transducer of the levitator. The temperature of this chamber can not be higher than 60ºC in order to prevent damages in the piezoelectric transducer and it is controlled by forced convection using cold air. The identified as "hot chamber" contains the levitator reflector and the multiphase droplet. The temperature of this chamber is controlled by an electric heater at the wall and an air stream that enters to the levitator tube through an array of holes located in the reflector. The flow rate of the air stream is set to 0.5 l/min and it is used to ensure constant drying conditions around the droplet and deplete the acoustic vortex system around the droplet from liquid vapor [4]. The droplet is inserted into the acoustic field with a syringe. The needle of the syringe can be introduced into the acoustic field using a hole centred in the horn. Using this levitator tube configuration it is possible to work with temperatures up to 150ºC. However, the droplet insertion method limits the maximum temperature working condition to 120ºC (for higher temperatures the droplet is dried before it is expelled from the syringe tip).

The air conditioning system (CEM System W-202A, Bronkhorst High-Tech B.V) is composed of an air-drying cartridge, a 2 mass flow controllers and a mixer/evaporation unit. This system allows temperatures up to 200ºC and a humidity up to a dew point of T=80ºC. In order to prevent the air stream cooling from the conditioning system to the levitator tube the tube that connect both devices as well as the reflector need to be heated using electric heaters.

A CCD camera (UI-1220M, IDS-Imaging Development Systems GMBH) (752x480 pixels, 87 frames per second) and a back-light illumination system are used to measure the droplet cross-sectional area and vertical position of the droplet during the drying process. The spatial resolution of the images can be varied with the macro lens. A resolution range between 250 and 500 pixels/mm has been used in the experiments depending on the initial droplet volume value. The image processing of the images has been implemented in Matlab. With this information is possible to obtain the duration of the two drying stages as well as the mass transfer rate and the mean porosity of the droplet [4]. The mean porosity can be obtained using the following equation:

$$\varepsilon = 1 - \frac{V_S}{V_G} \qquad (1)$$

where V_S and V_G are the volumes occupied by the solid phase and the dried grain, respectively and,

$$V_S = V_0 Y_S \frac{\rho_D}{\rho_S} \qquad (2)$$

where ρ_D and ρ_S are the densities of the liquid-solid suspension and solid phase respectively.

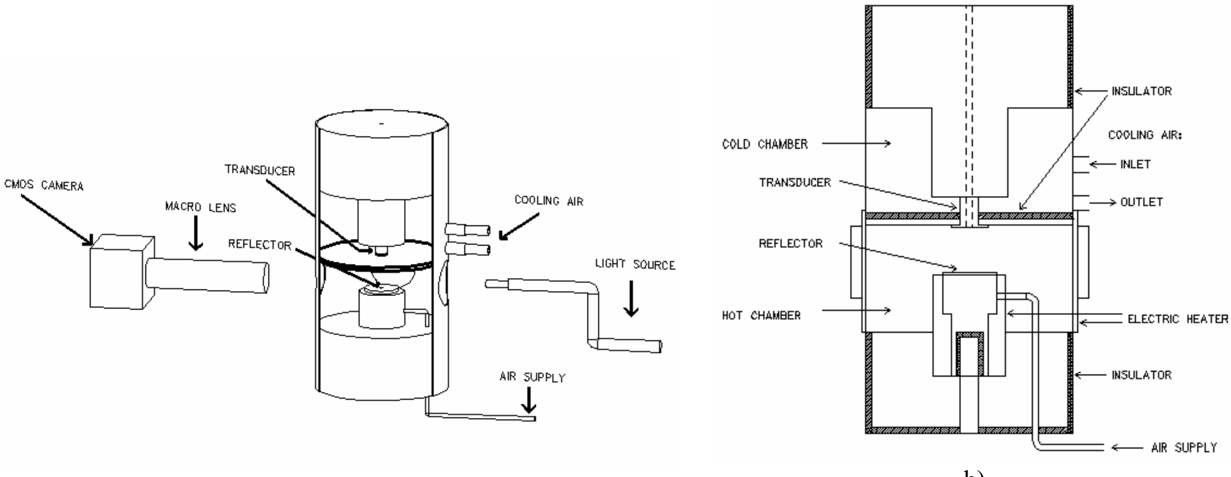


Figure 1. a) General sketch of the experimental set-up, b) acoustic levitator tube.

Results and Discussion

The effect of the initial droplet volume (0.05 µl < V_0 < 0.7 µl), initial solid mass load (0.01 < Y_S < 0.5), ambient air relative humidity (0.05 < *HR* < 0.045) and ambient air temperature (60ºC < *T* < 120ºC) on the drying behavior of the droplet has been studied. All the experiments were carried out with suspension droplets containing water and solid glass particles (particle mean diameter, d_p, 13µm and ρ_S=2500 kg/m^3). The effect of the studied parameters on the porosity of the dried grain and duration of the first drying period are presented in the next Figures.

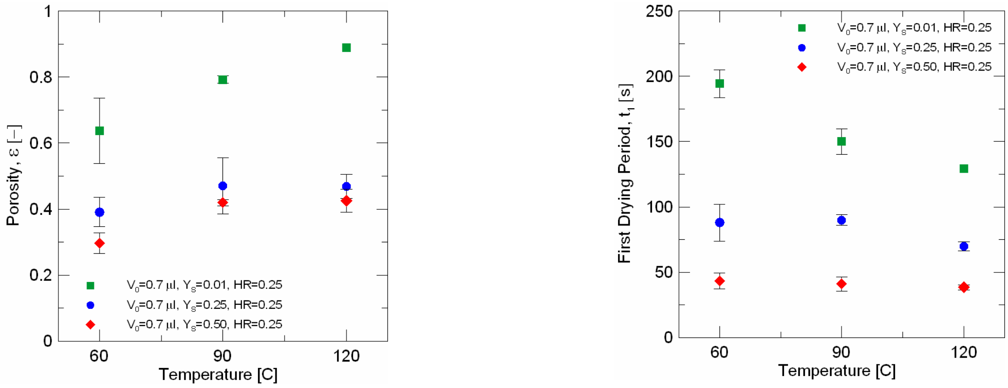


Figure 2. a) The mean porosity of the dried and, b) the first drying period duration as a function of the air temperature.

Figure 2 shows the effect produced by the variation of the air temperature that surrounds the droplet on the mean porosity of the dried grain and the duration of the first drying period. As a general rule, it is possible to observe that the increment in the air temperature produces an increment in the grain porosity (Fig. 2a). However, the influence is stronger for low solid load values (45 % increment in ε for air temperatures from 60 ºC to 120 ºC for Y_S=0.01) than for high solid load values (25 % averaged increment in ε for the same range of air temperature and Y_S values of 0.25 and 0.5). In addition, the increment in the porosity is not proportional with the air temperature. In particular, for high solid load values the mean porosity value can be considered almost constant for air temperatures higher than 90ºC. The increment of the air temperature causes a decrement in the first drying period duration (Fig. 2 b) and, consequently, the higher liquid evaporation rate increments the mean porosity of the dried grain. If the maximum porosity value for compact grains given by the percolation theory is accepted [8, 9], ε_{max}=0.8, almost all the drying conditions showed in Fig. 2 result in compact grains.

The effect of the initial droplet volume value on the mean porosity of the dried grain and the duration of the first drying period is presented in Fig. 3. It is possible to observe that the dependency showed by the mean porosity with V_0 is highly dependant on the solid mass load (Fig. 3 a). For low solid mass load values the porosity can be considered as constant with respect to V_0. However, for Y_S values higher than 0.25 the mean porosity drops to values lower than 0.1 for small droplets (V_0 values of 0.05 µl). In these conditions the first drying period duration is not dependant on the Y_S value. Additional experimental data with V_0 values between 0.05 µl and 0.4 µl is needed in order to study this dependency in detail. The available experimental data [8] shows that this porosity drop is produced for V_0 values lower than 0.25 µl. All the drying conditions showed in Fig. 3 result in compact grains.

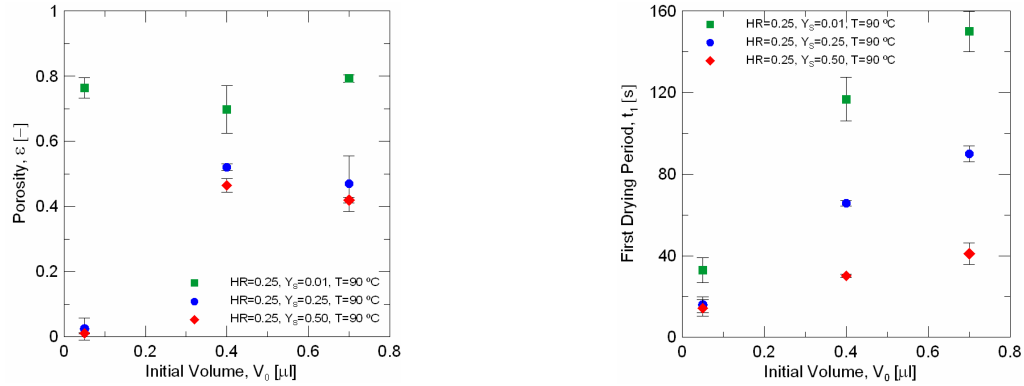


Figure 3. a) The mean porosity of the grain and, b) the first drying period duration as a function of the initial volume of the droplet.

Figure 4 shows the effect produced by the variation of the initial solid mass fraction on the mean porosity of the dried grain and the duration of the first drying period. As a general rule, it is possible to observe that the increment in the solid mass load produces a decrement in the grain porosity (Fig. 4a).The influence is especially important for low V_0 values. In addition, the decrement of the porosity and the first drying period duration (Fig. 4 b) is not linear with the solid mass load, being more important for the low Y_S range. All the drying conditions showed in Fig. 4 result in compact grains.

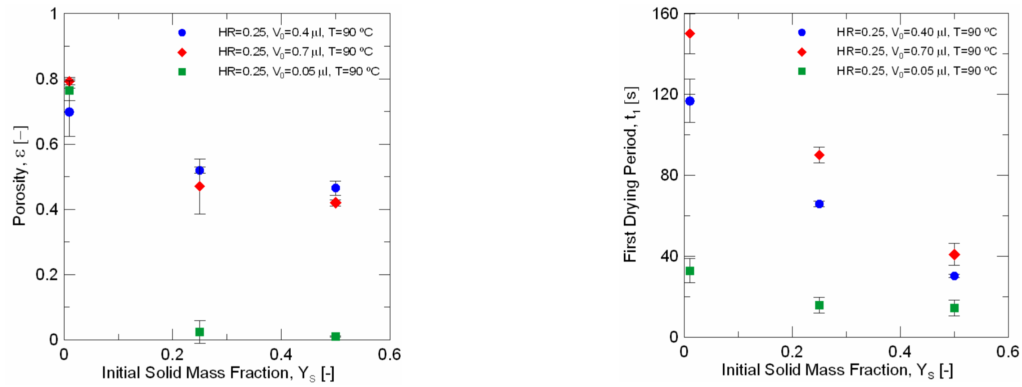
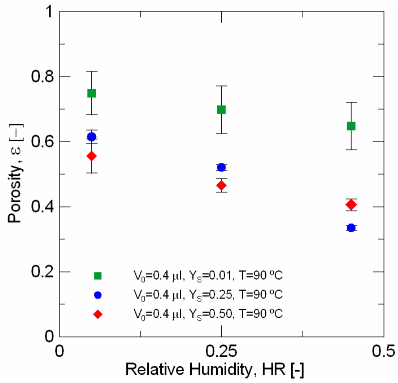


Figure 4. a) The mean porosity of the grain and, b) the first drying period duration as a function of the initial solid mass load.

The effect of relative humidity of the air that surrounds the on the mean porosity of the dried grain and the duration of the first drying period is presented in Fig. 5. As a general rule, it is possible to observe that the increment in the air humidity produces a decrement in the grain porosity (Fig. 5a). The influence is stronger for low high solid mass load values (34 % averaged decrement in ε for *HR* values between 0.05 and 0.45 and Y_S values of 0.25 and 0.5) than for low solid mass load values (13 % decrement in ε for the same range of relative humidity and for Y_S=0.01). The decrement in the porosity is almost proportional to the HR value. However, the increment in the first drying period duration is more important for *HR* values higher than 0.25. All the drying conditions showed in Fig. 5 result in compact grains



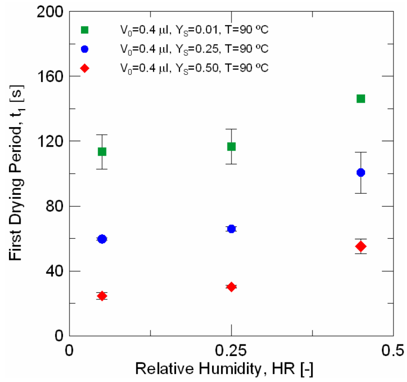


Figure 5. a) The mean porosity of the grain and, b) the first drying period duration as a function of the relative humidity of the air.

An experimental correlation for the mean porosity of the dried grain has been obtained in order to quantify the dependence of the different parameters analyzed in the previous paragraphs. Genetic algorithms (GA) have been used as the optimization technique to fit the coefficient and the exponents of the correlation. In these algorithms, the search for a global minimum is performed through the application of reproduction operators and "survival of the fittest" strategies. Moreover, the mutation operator introduces the possibility of exploring the whole search space, an interesting ability that reduces the risk of finding a local minimum [10, 11]. The main target of the optimization process was to minimise the predicting error of the correlation. The GA was implemented in Matlab, using a population size of 1000 individuals and stopping conditions of 100 generations, confirming that any improvement in the results was observed during the last generations. Input and output data were preprocessed so that their range of variation lies within zero and one. This fact allows an easier fitting of the parameters in the adjusted equation and an easier interpretation of the results. The obtained correlation is given by equation (3) and Fig. 6 shows the prediction results given by the correlation,

$$\varepsilon = 0.37\ V_0^{0.293} T^{-0.0182} Y_S^{-0.339} HR^{0.061} \qquad (3)$$

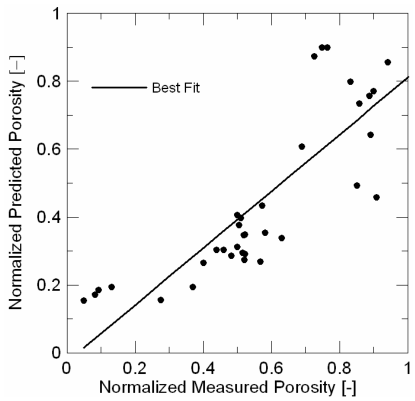


Figure 6. Prediction results given by equation (3)..

As expected, the more important parameters to be considered for the porosity are the initial solid mass load, Y_S, and the initial droplet volume, V_0. The relative humidity of the air, *HR*, presents a moderate influence on the drying behavior of the droplet and the temperature is the parameter that presents a lower impact on the mean porosity. The predicting error of equation (3) is quite high. However this fact can be explained by the simple functional form chosen for the correlation and the wide experimental range used in the experiments.

Conclusions

The drying behavior of liquid-solid suspension droplets has been investigated in an experimental condition range closer to those found in important industrial applications. In this way, a standard acoustic levitator tube has been modified in order to work up to 120 ºC. The effect of the air temperature, initial volume of the droplet, initial solid mass load and relative humidity of the air on the mean porosity of the grain and first drying period duration has been analyzed:

- The air temperature presents a low effect on the mean porosity, with an increment of ε with respect to T. The porosity can be considered almost constant for $T \geq 90$ºC and $Y_S \geq 0.25$.
- The initial droplet volume has a major impact on the mean porosity, but only for high solid mass loads ($Y_S \geq 0.25$) and small droplet volumes ($V_0 \approx 0.05$µl). The dependence of the mean porosity with the initial droplet volume in the range of 0.2 µl ≥ $V_0 \geq$ 0.05 µl and high solid mass loads needs to be analyzed with additional experimental data.
- The initial solid mass load has a major impact on the mean porosity, with a decrement of ε with respect to Y_S.
- The air relative humidity presents a moderate effect on the mean porosity, with a decrement of ε with respect to HR.

Nomenclature

d	diameter
HR	air relative humidity
T	air temperature
V	volume
Y	mass fraction
ε	mean porosity
ρ	density

Subscripts

D	droplet
G	grain
max	maximum
p	particle
S	solid
0	initial

Acknowledgments

The authors gratefully acknowledge the financial support from Fundació Caixa Castelló-Bancaixa (project: P11B2006-37).

References

1. Masters, K., *Spray Drying Handbook*, Longman Scientific and Technical, 1991.
2. Kawahara, N., Yarin, A.L., Brenn, G., Kastner, O. and Durst, F., *Phys. Fluids* 12:912-923 (2000).
3. Yarin, A. L., Brenn, G., Kastner, O., Rensink, D. and Tropea, C., *J. Fluid Mech.* 399: 151-204 (1999).
4. Kastner, O., Brenn, G., Rensink, D., and Tropea, C., *Chem. Eng. Technol.* 24: 335-339 (2001).
5. Yarin, A. L., Brenn, G., Kastner, O., and Tropea, C., *Phys. Fluids* 14:2289-2298 (2002).
6. Brenn, G., *Int. J. Heat Mass Transf.* 48: 395-402 (2005).
7. Kastner, O. Brenn, G., Rensink, D., and Tropea, C., Mass Transfer from Multiphase Droplets during Drying in a Tube Levitator, *Eight International Conference on Liquid Atomization and Spray Systems*, Pasadena, USA, July 2000.
8. Kastner, O. Brenn, G., Rensink, D., Tropea, C., and Yarin, A. L., Investigation of the Drying Behavior of Suspension Droplets in an Acoustic Tube Levitator, *16th Annual Conference on Liquid Atomization and Spray Systems*, Darmstadt, Germany, September 2000.
9. Satuffer, D., and Amnon, A., *Introduction to Percolation Theory*, Taylor and Francis, 1992.
10. Wright, A. H., Genetic algorithms for real parameter optimization, in *Foundations of Genetic Algorithms*. San Mateo, CA:, pp. 205–218, 1991.
11. Davis, L., *The Handbook of Genetic Algorithms*, Van Nostrand, Reingold, 1992.