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ACOUSTIC ENHANCEMENT OF MALTODEXTRIN DROPLET DRYING: INSIGHTS FROM MODELLING AND EXPERIMENTAL OBSERVATIONS

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1. ABSTRACT

This study reveals that the drying of acoustic levitated maltodextrin droplets is enhanced compared to suspended droplets. Heat and mass transfer dynamics are investigated during the drying of levitated droplets by combining mathematical modelling and experiments. The mathematical model previously predicted experimental data for the suspended droplets to within 4%. Results demonstrate that the heat and mass transfer coefficients of the model must be increased by a factor of 1.625 to improve the alignment between the predicted and levitated experimental data for different maltodextrin concentrations and initial droplet sizes.

2. INTRODUCTION

The drying of sprayed liquid droplets is an integral phenomenon occurring in many industrial situations such as manufacturing of food products, pharmaceuticals and fertilisers, and in combustion operations. Understanding and optimising the heat and mass transfer dynamics during evaporation of liquid droplets and drying of resulting solid particles are essential for improving efficiency, product quality and overall process control.

Maltodextrin is a polysaccharide generated from starch. Maltodextrin in powder form is produced via spray drying. This study uses it as a model system to observe the drying behaviours due to its relevance in numerous industrial applications. Drying maltodextrin droplets involves complex physical and chemical transformations such as maillard reactions influenced by factors such as droplet size, initial concentration of the solution, temperature and humidity of the drying air.

This study focuses on the drying of droplets of maltodextrin solution through a synergistic combination of mathematical modelling and experimental observations of acoustic levitated droplets. The modelling provides valuable insights into the underlying heat and mass transfer phenomena occurring within and outside the droplet, and experimental observations enable the validation of the model's predictive capability.

3. METHODOLOGY

A diffusion based single droplet drying model in the solute-fixed coordinate system has been solved numerically using a fully implicit backward finite difference scheme to predict radial concentration distributions and the average temperatures of droplets of an aqueous maltodextrin solution during evaporation [1]. The model permits the prediction of the droplet shrinkage over time with a maximum deviation of approximately 4% of suspended maltodextrin droplets data reported in the open literature [2]. The only change to the drying model was the introduction of an enhancement factor $\boldsymbol{\varepsilon}$ in both the boundary conditions for the

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*Corresponding Author: p.j.heggs@leeds.ac.uk mass and heat transfer from the droplet surface, Equations (1) and (2). The mass transfer of a solute from the liquid phase to the surface of the droplet is represented by

$$-D_{ls}C_s^2 r_p^2 \frac{\partial u}{\partial z} = k_c \boldsymbol{\varepsilon}\left(a_w u C_s - C_{v,\infty}\right) = \frac{\partial m_p}{\partial t}/4\pi {r_p}^2 \qquad (1)$$

and the change in mean temperature of the droplet (T_p) as a function of time (t) as follows:

$$m_p c_{p,p} \frac{\mathrm{d}T_p}{\mathrm{d}t} = -4\pi r_p^2 \boldsymbol{\varepsilon} \alpha_p \left(T_p - T_g\right) - h_{fg}\left(\frac{\mathrm{d}m_p}{\mathrm{d}t}\right) \qquad (2)$$

The mass transfer k_c and the heat transfer α_p coefficients are obtained from Sh = 2 and Nu = 2 for a stationary sphere in stagnant air.

Figure 1 is a photograph of the single droplet acoustic levitator apparatus. The 40 kHz acoustic levitator consists of 72 acoustic transducers arranged in rings. Each array has a hole in the middle that is vertically aligned with the axis of levitation rather than a transducer [3]. [1]. Three maltodextrin solutions at concentrations of 10%, 30% and 50% (w/v) were prepared by dissolving maltodextrin DE 20 (Thermo Scientific Acros, UK) in distilled water and stored in the refrigerator at 4°C prior to use. Single droplets of initial size 2±0.05 µL volume (≈1.56 mm) were generated using a 5 µL micro syringe and placed in the middle of the acoustic levitator rig as shown in Figure 1. All were dried by air with a relative humidity (RH) of 40% at a room temperature of 24°C.

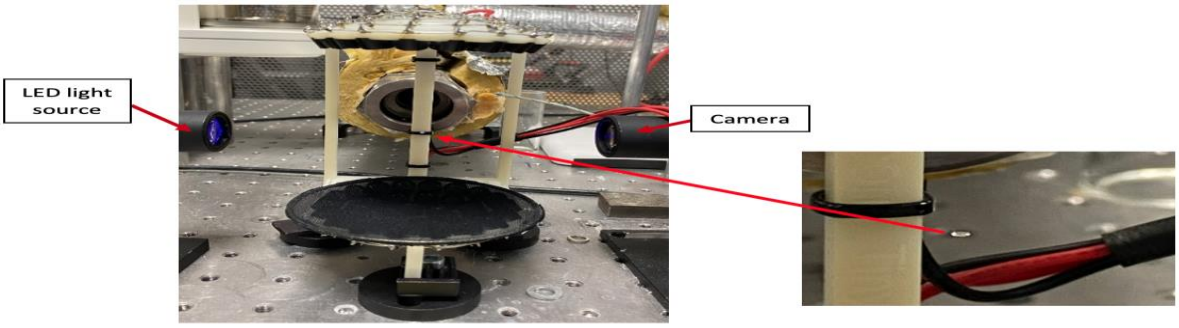

Fig. 1 Single droplet acoustic levitator apparatus and position of a droplet

4. RESULTS

During drying, a droplet undergoes morphological changes related to the instantaneous solid concentration at the droplet surface. Initially, the droplet experiences uniform volume shrinkage, as can be seen from the first two pictures of droplet shape evolution demonstrated in Figure 2. Then, the top of the droplet starts to flatten as the droplet surface cannot hold a uniform spherical shape.

Fig. 2 Morphology changes of 30 % Maltodextrin during drying on the levitator rig

Figure 3(a) is a plot of the experimental droplet diameter over time of the experiment during the drying for 30 % maltodextrin solution in air at 24°C and 40% relative humidity. The software catches the two-dimensional shape and determines the equivalent circle. The model prediction of the droplet shrinkage with an enhancement factor of unity $\boldsymbol{\varepsilon = 1}$ is considerably slower than the observations. A binary search of values of the enhancement factor revealed that with $\boldsymbol{\varepsilon = 1.625}$ **,** the model prediction is very good, see Figure 3(a). The temperature increases very rapidly due to the relatively low temperature of the droplet in comparison to that of the surrounding air. It then plateaus at around 15°C until about 20 mins have lapsed. After this the there is a steady increase up the air temperature. Figure 3(b) are plots of predictions of thermal and mass fluxes variations from the surface of the droplet with $\boldsymbol{\varepsilon = 1.625}$ corresponding to the results in Figure 3(a). The mass flux change variation is identical to the predicted diameter changes and the approximate temperature plateau is caused by the balancing of the positive convective and negative latent heat fluxes during the first twenty minutes of drying. The sigmoidal shaped temperature profile after 20 minutes reflects the final stages of drying and the increase in temperature of the droplet to the air value. The sum in the plot represents the total energy flux involved in the drying process. Very similar results were observed for the droplets of 10% and 50% maltodextrin solutions and excellent predictions of the reductions in droplet diameter were also obtained with $\boldsymbol{\varepsilon = 1.625}$. These observed dynamics in convective heat transfer, latent heat energy absorption and droplet diameter behaviour are consistent and robust, regardless of the maltodextrin concentration.

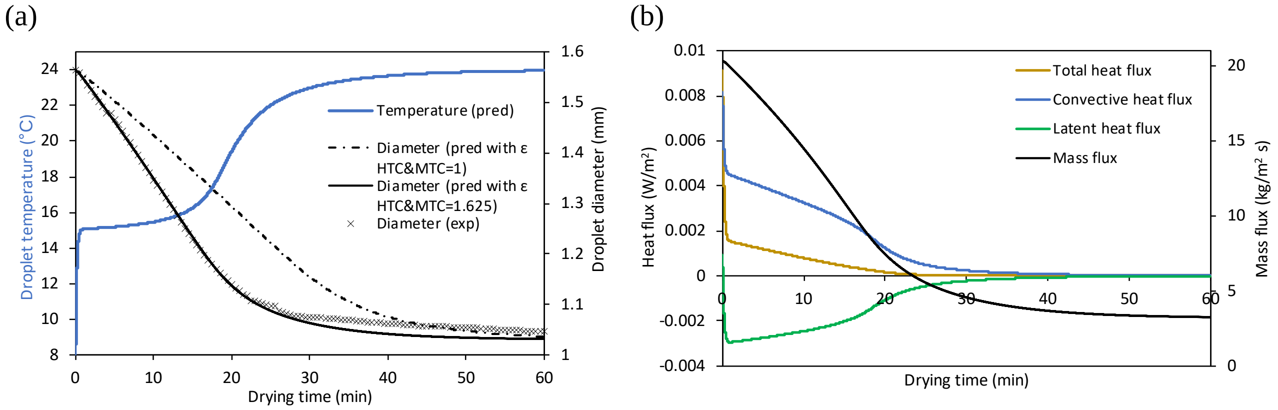

Fig. 3 (a) Predicted droplet temperature, measured and model predicted diameter changes with $\varepsilon = 1.0$ *and* 1.625 and (b) Heat and mass fluxes during the drying of a 30% maltodextrin droplet in air at 24°C and 40% RH.

5. CONCLUSIONS

The study reveals key insights into drying processes for a single droplet of maltodextrin solution using an acoustic levitator rig. The adjustment of the heat and mass transfer coefficients by 1.625 in the model revealed the enhancement of the drying of levitated droplets compared to suspended droplets. These findings stress the importance of considering heat and mass transfer dynamics in predictive modelling of experiments.

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