Report on the draft of the PhD dissertation of M.Sc. Michal Stebel
From Silesian University of Technology

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"Numerical analysis of conjugate Heat and mass transfer phenomena in food freezing using hydrofluidisation"

Mr. Michal Stebel, presents his PhD research work on the development of a strategy of "Numerical analysis of conjugate Heat and mass transfer phenomena in food freezing using hydrofluidisation".

The draft is presented in 5 chapters: 1 General Introduction, 2. Validated Model of Turbulent flow in hydrofluidisation system, Paper I. 3. Development of the food freezing numerical model. Paper II. 4. Modelling of hydrofluidisation hydrodynamics Paper III. 5 Numerical model of the conjugate heat and mass transfer during hydrofluidisation freezing-Paper IV. 6. Summary and conclusion.

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1 General Introduction. This chapter presents the state of the art on freezing using hydrofluidisation. Numerous methods were cited to increase freezing rate and to obtain high heat transfer coefficient (HTC) between the product and the cooling liquid. The literature review presents the principles of food freezing phenomena. Some inaccuracies might appears nevertheless. In page 2 to discuss about the initial freezing point that is lower than 0°C Mr. Stebel describes the effect of other components (carbohydrates, fats and proteins). According to Raoult's law the depression freezing point is strongly linked to the molecular weight of the molecules present in the solution. The smaller are the molecules (salts, sugars or acid) the higher is the effect on the freezing point depression. Large molecules such as Long carbohydrates (starch pectins etc) or proteins or fats have almost no effect on the freezing point depression. It is worth to mention or even compute the theoretical freezing depression point, based on the small molecules present in potatoes.

2 Validated Model of Turbulent flow in hydro fluidisation system. This chapter is based on the Paper number I "Numerical investigation of the fluid flow distribution for the hydrofluidisation food freezing method", published in the International Journal of Thermal Sciences. This paper investigate turbulent flow around a spherical object by using CFD ANSYS Fluent with highly turbulent refrigerating medium flow. The results were validated by an experimental device where jets were generated in an experimental tank in contact with a 20 mm copper sphere static placed at different fixed positions (20 mm to 80mm height) related to the orifices where the liquid jet is generated position in the tank. (orifices diameter 2mm and 5mm), Reynolds number ranged from 1700-93000 (0.00267 to 0.15kg/s). Two turbulence models (RSM and k-w SST) were compared to experimental results obtained by PIV measurements in particular the wake angle observed and simulated.

The results suggest that k-ω SST model performed better than RSM in the experimental validation conditions. Nevertheless the Case 9 both models failed to match experimental results obtained by PIV. The reader would like to know the reason because all condition were similar to Case 5 except the distance to the orifice

Is this related to the nature of the models? It is often presumed that RSM which solves Reynolds stresses using transport equations to predict anisotropy of Reynolds stresses is superior over two-equation models which use an isotropic eddy viscosity approach.

The turbulence generated by a wake shows anisotropy. How is the flow at different Reynolds numbers knowing that the wake angle depends on the Reynolds number?.

It would be interesting to discuss advantages and inconvenient of the two models selected and why they were selected?.

Another point that It would be interesting to know what is the intensity of turbulence of the fluid approaching the sphere. Indeed it is well known that the intensity of turbulence (IT) for the same velocity (IT: the fluctuation of the velocity) has a very strong impact of the heat transfer coefficient, in some cases the heat transfer coefficient, for the same velocity, turbulence intensity could increase up to 50% heat transfer coefficient.

Chapter 3. Development of the food freezing numerical model. Paper II " Numerical modelling of the food freezing process in a quasi-hydrofluidisation system ".This chapter shows and paper describes a CFD study Fluid flow and food freezing by hydrofluidisation of a group of spherical objects. He studied the effect of parameters such as distance from the jet generation hole (H), distance between two objects (S) and the diameter of the holes generating jets (d). The freezing model developed applies the enthalpic method where the apparent specific heat Cp is used to take into account the phase change. In addition, the change in effective conductivity that dramatically changes as expected during freezing.

Most of the presented freezing kinetics figures show very large temperature differences between the model and the experimental at the centre temperature experimentally obtained is much faster, this need to be discussed and explained on what are the reasons of that, the accuracy on the position of temperature sensors? The thermal properties evolution?., or cooled liquid went into the hole to insert the sensor? Parameters of the model need to be readjusted.

The end of freezing is almost well predicted except in certain cases, this is not surprising as heat transfer coefficient is high and after all water is frozen thermal conductivity is almost 4 times higher than at the beginning.

It would be preferable to give the % experience-model rather than difference.

The effect on supercooling in cases 10,21,27 is impossible to predict, because nucleation is a random phenomena.

The cases where Separation distance between spheres was 8mm and the distance from the outlet of the jet was smaller, we can observe a very large difference in the heat transfer coefficient, compared with the other cases, this should be discussed, in terms flow around the objects. The wake behaviour formed between two objects depends very strongly of this separation distance. It would be interesting to have the velocity profiles and turbulence profiles.

Chapter 4 Paper III deals with a numerical study of HF with movement of of macroparticles (food products) by using the MPM model to simulate for 0,02 m diameter food products immersed in different liquids: ethanol (30%) and glycerol (40%) and ethanol and glucose (15% and 25%). Fluid velocity field was simulated by CFD simulation combined with MPM model for the particle flow, which affects the liquid phase velocity field. Experiments with high-speed camera recordings allowed to validate the numerical model for a range of HTC very wide from 1 000 W·m·K to 4 500 W·m·K which were reached, depending on the fluid mass flow rate. Mr. Stebel affirms that the liquid type had a minor effect on the heat transfer coefficient (HTC) but affected the behaviour of food samples. This is probably related to the difference of viscosity of the liquids.

It would be interesting to have some information about the minimum fluidisation velocity for each liquid. This could be performed by making a force balance across the fluidized bed.

For the food particles the factors that play a role are namely the density of the particle (which changes during freezing) ρs, the minimum porosity €mf (this posority changes as the particles move)and Φs and the factor related to the shape of the food, diameter of the food particles

The effect of the food product suspension within the HF tank was noticed only for the ethanol solution with a moderate mass flow rate.

Chapter 5 Paper IV deals with conjugated heat and mass transfer associated to hydrofluidisation freezing. In this part of work Mr. Stebel investigate freezing process conjugated with mass transfer during hydrofluidisation of spherical products in binary ethanol (30%) and glycerol (40%) solutions and ternary solutions containing ethanol and glycerol. The thermal model was completed by a mass diffusion Model, that allows computing the solution uptake by the products.

As expected the uptake solution was influenced by the size of the sample and by the process parameters the range being between 8,9 and 35 g/kg of product.

The mass absorption of different solutes is function of the temperature of the liquid, the lower the temperature, the lower the mass intake; this is also expected as the effective mass diffusion coefficient depends on the temperature. Mass diffusion also depends on the mass transfer coefficient, as the analogies on heat and mass transfer were considered, the higher is the HTC the higher is the mass transfer coefficient MTC. Also if the temperature drops very rapidly at the surface (High HTC) lower diffusion is to be expected.

Solute concentration in the food is also decreasing with the size of the product, (for the same reasons of fast freezing).

In previous studies of RFPI (Refrigeration and freezing by immersion in solutions such as salt and sugar was evidenced by many authors (ex.Lucas etal 1998 https://doi.org/10.1016/S0140-7007(98)00014-0) . They showed that it is also important to take into account is the fact that the solute concentration at the surface of the product could be more concentrated that in the rest of the solution, modifying the liquidus thermos dynamical equilibrium, which creating a possibility of thawing the product at the surface. The second drawback of Immersion freezing is the degradation of the solution over time, dealing with potential microbiological contamination (spores) or the degradation of the molecules in the food (ex proteins , or other macromolecules). This can be generated by the modification of the physicochemical equilibrium inside the food. The third drawback is the need of a permanent control of the solution and its treatment to keep it clean at safe and at the same concentration. The solute uptake is unavoidable unless we have packed products.

Those are probably the more problematic situations of this kind of technology

In conclusion, in spite of some comments presented above I think that the work performed by Mr. Michal Stebel is considerable, as well experimental than numerical. He works with a very complex problem with a system composed of models (fluid dynamics, freezing and MPM combined with Mass transfer) which have strong interactions between them. His work allows a very original strategy of modelling and simulating hydrofluidisation-freezing systems. The structure of the manuscript allows an easy reading each chapter has an introduction, and a paper associated that gives more details on the work performed, and the summary and conclusions

For all these reason, I think that Mr. Michal Stebel work's deserves without any doubt a distinction honours degree and the acceptability to prepare his public defence to obtain the PhD degree of the Silesian University of Technology, Poland.

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