Thesis assessment report by Ferruh Erdogdu, Ph.D.:

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Thesis title: Numerical analysis of conjugate heat and mass transfer phenomena in food freezing using hydrofluidisation impingement method

The overall objective of this study was to develop computational approach to perform a comprehensive analysis of hydrofluidisation impingement-based freezing for small food products.

For this purpose, the following studies were carried out:

- Development of an experimentally validated CFD model for this process and scale-up the process for full-size system with multiple orifices and jets
- Simulating the actual process to include the realistic movements of the individual sample through the impingement induced fluid flow and determine the particle interaction effects.
- To determine the mass absorption of the samples from the hydrufluidized liquid medium through a conjugate approach.

- With these objectives, the Ph.D. thesis consisted of 5 chapters:
  - Chapter 1: introduction
  - Chapter 2: simplified flow approach for numerical model development and experimental validation
  - Chapter 3: for a scale-up case based on the developed and experimentally validated model
  - Chapter 4: development of a CFD model for hydrofluidisation process using the macroscopic model approach to account the movement of the particles within the liquid medium
  - Chapter 5: accounting the simultaneous heat and mass transfer during the hydrofluidisation freezing process for mass absorption of the samples based on the porous media approach
- The objectives for different sections were explicitly stated with the procedures for the experimental work, and numerical and experimental validation studies were adequately described.

The Ph.D. thesis was examined for its effectiveness of the contribution and its originality. The results were presented in a clear way with the demonstrated tables and figures. Regarding issues in the various parts for the numerical solutions and experimental work were also discussed in an informatory and explanatory way. Therefore, it was evaluated to be a quality for the adequacy of the background provided.

In addition, the thesis demonstrates that:

- The candidate has an understanding of the relevant literature,
- The thesis provides a comprehensive background on its topic,
- The methods applied were properly applied, and publications in the peer-reviewed journals were presented, and
- The thesis makes an original contribution to the literature.

With respect to these comments, I am satisfied that the thesis meets the required standards for the award of the Doctoral degree.

The followings are the critiques observed during the evaluation:

Chapter – 2 / Paper 1:

As stated in the text, characteristic feature of the HF method is to enable a forced flow of the refrigerating liquid over the food products. This results in an increased velocity with increased convective heat transfer coefficient with enhanced freezing rate.

It is important to quantify the increase in the convective heat transfer coefficient compared to the conventional approach (where the product placed in the refrigerating liquid, and the heat transfer mechanism through the surface is with natural convection).

- Even though the 2-D axisymmetric approach holds for the orifice geometry, this will not be valid for the whole HF system. Therefore, using the 3-D domain is required. Based on this comment, I do not think that the 2-D axisymmetric is supposed to predict the same flow field (this comment should be based on the size of the domain). In addition, a symmetric approach was also possible to reduce the mesh size and computational time as applied in the next chapter (and paper 2).
- Turbulent flow conditions were assumed considering the nature of the HF process, but due to the higher viscosity values of the refrigerating liquids (specially at the

higher concentrations), a significant mass flow rate will be required to obtain the turbulent flow, and that will eventually lead to the requirement of a significant energy. It would have been valuable to consider having this discussion due to the industrial process nature of the HF process.

- It was indicated that 8M elements were used in the 3-D geometry (with the symmetry approach). It would have been interesting to report the applied time step and the required computational time (with the computer system used to run the simulations).

Chapter – 3 / Paper 2:

- Development of the numerical model for the HF freezing process was based on the previously developed (and experimentally validated) flow field model. The HF system was scaled – up to have 64 orifices for this purpose, and symmetrical approach was used to reduce the mesh size and the computational time, and various impingement parameters were considered in the sensitivity analysis.
- Considering that the freezing time of the samples depend upon the surface temperature, the flow rate should have a limit (maximum) for the optimum freezing time. For the given process conditions, convective heat transfer coefficient changed in the range of 3000 to 4000 W/m^2-°C with a minor effect on the freezing time of the 20 mm size samples. I was wondering how the HF affected the freezing time compared to the conventional approach (as also questioned above). I think an analysis on this issue is important to better characterize the system. Even a numerical calculation (where the samples are placed in the refrigerating liquid) would have given an idea on this improvement.
- Based on the given results for the given sample size, the increase in the convective heat transfer coefficient (at the given obtained range) was not effective to improve the freezing time since the process has become a surface temperature - controlled case. Therefore, knowing the mass flow rate limits of the HF system for an optimized freezing process might be valuable for the industrial applications. A previous study by Belis et al. (2015) reported the effect of the number of orifices and process variables on the heat and mass transfer in a HF system with static spheres. In this study, heat transfer coefficient was determined to change from ≈1000 to ≈6000

W/m^2-°C. From the same group, a sensitivity analysis for an HF process was also presented (Orona et al., 2018). The results of these studies might be discussed comparatively with the current study to comprehensively understand the effect of different HF systems on the convective heat transfer coefficient.

Chapter – 4 / Paper 3:

- Due to the effect of the gravitational and buoyancy forces with drag forces by the refrigerating liquid, the movement of the samples in the HF system were modeled using the macroscopic particle model (MPM) approach. The change in the convective heat transfer coefficient was from ≈800 to ≈4500 W/m^2-°C with respect to the mass flow rate of the refrigerating liquid while the effect of the liquid medium was not significant in this aspect.
- It would have been important to see the change in the freezing times, and comparison of this with respect to the static sample case might have been a significant input for the industrial applications.
- With respect to the significant inflow rate (and density and viscosity of the refrigerating fluid), the samples reach to the top (and pile up underneath the permeable net). This seems to take like 5 s, which is the very initial part of the process. Would this cause a negative effect on the freezing rate? If, for example, the samples are managed to float right over the inlet (out of the orifices), would there be a possibility to improve the process efficiency positively? This might have been adjusted with the flow rate (and/or concentrations of the refrigeration fluid), and it might have been a significant contribution!

  With respect to Figure 11, there is a significant non-uniformity observed for convective heat transfer coefficient distribution among the particles, and this becomes much more significant for the higher number of particles for the ones which are placed at the bottom of the pile. In addition, one of the conclusions (that the average convective heat transfer coefficient is not significantly affected by the load size) is contradicted with the results reported in Figure 11.

Chapter – 5 / Paper IV

- The possible side effect of the HF method, the solution uptake, was considered in this part of the thesis, and simultaneous heat and mass transfer for the HF process was numerically modeled with a conjugate approach where the mass transfer was assumed to be dependent upon the heat transfer and followed the Fick`s law of diffusion.

- The previous section where the sample movement was modeled and this section with the mass transfer effects are the significantly unique sections of this thesis. With this concept, the HF process was demonstrated to lead to a lower solution uptake compared to a similar conventional process.

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