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Analysis of Heat and Momentum Transfer in Screw-Drive Heat Transfer Systems

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Screw drive systems might be used in various thermal food processing operations where the food product within the liquid (e.g. water) is moved with rotational effect of screw. The externally given inertial force creates a mixing within the system, and heat transfer rate increases. However, this mixing effect might lead to certain residence time problems for the processed particles. In the literature, there are studies focusing on determining heat and momentum transfer to optimize rotational systems like axial, end-over-end and reciprocal agitation retort systems, and they conclude a possible optimum condition based on a force analysis for gravitational, inertial, Coriolis and viscous forces. Therefore, the objective of this study was first to develop a numerical model for screw-drive system for a process including a processing liquid. For this purpose, a free-surface (liquid – air) fluid dynamics problem was considered. Two – phase volume of fluid (VOF) method was utilized to monitor headspace and solve fluid – thermal energy interactions. A compressive interface capturing scheme for arbitrary meshes was applied to track the interface adopting a moving mesh approach for hydrodynamic and shear forces with 3- rotational and translational degrees of freedom. This approach was used to determine how the rotation rate would affect the fluid movement inside the system. The results of this study are expected to be used for optimization in continuous systems to process the particulate food products in the hot liquid.

1. Introduction

Rotating screw systems generally consist of a central shaft mounted with a rotating screw inside a fitting cylinder. Even though they can be used for transport of liquid and granular products through the movement of the screw (Patel et al., 2012), their use in food thermal processing systems might also be possible. All mechanical screw where the pushing effect of the rotation is the main mechanism might be accepted to be the descendants of the Archimedes screw. In a general food processing use, the food products are placed in the liquid where the rotational effect of the screw enable their movement thorough the system while a direct heat transfer effect takes place. The use of hot or cold liquid as a heat transfer medium leads to the direct heat transfer (Patil et al., 2017), and fluid dynamics plays a significant role in the process with a possible effect of the liquid-gas interface. With this externally given inertial forces, the mixing effect leads to the increase of heat transfer due to the effective increase of heat transfer coefficient. However, with the increased mixing and turbulence inside the system, the products` movement forward might be prevented with the possible reverse currents formed between the pitches, and this results in certain residence time problems with under- or over-processed samples. Figure 1 shows a single blade with five pitches, using water as heat transfer liquid. The geometry of the screw drive systems is governed by external (outer radius and length of the system) and internal (inner radius of the screw, number of pitches and blade, distance between the pitches, etc.) parameters (Rorres, 2000). The inner parameters might be used to optimize the process performance. For the liquid to be trapped in the screw, the sinusoidal curve shown in Figure 1 must tilt downward as it crosses the screw axis (Rorres, 2000). Due to this requirement, the given tilt - inclination angle is an additional parameter to consider for optimal processing. The diameter of the casing must be arranged in a matter that it should prevent the escape of the processed solids through the gap between the blade and the casing.

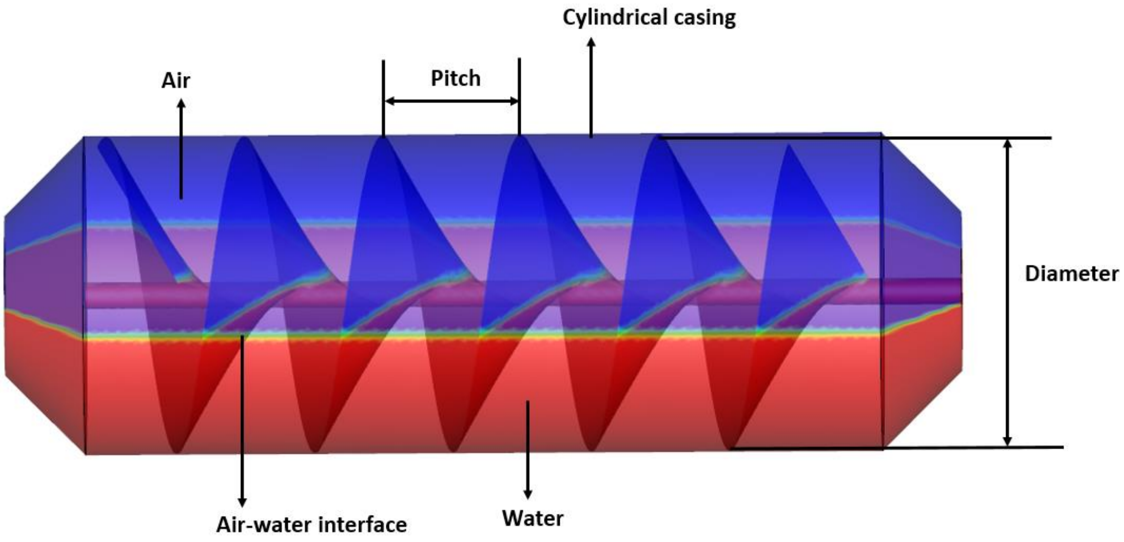


Figure 1. A view of one-blade screw system

In the literature, the use of these systems for transport purposes are mostly studied while the heat and momentum transfer occurring in these systems for thermal food processing are not observed in detail. Owen and Cleary (2009) carried out a computational study for operational performance of a screw conveyor where the effects of flow characteristics, inclination angle and rotation rate. Nachenius et al. (2015) reports a detailed study for the residence distribution in a screw conveyor for coarse biomass particles. The chaotic effects on heat transfer and impeller mixing are other related subjects studied in the literature (Metcalfe and Lester, 2009; Ameur, 2016). The studies focusing on determining heat and momentum transfer to optimize rotational thermal processing systems like axial (Tutar and Erdogdu, 2012), end-over-end (Sarghini and Erdogdu, 2016) and reciprocal agitation (Erdogdu et al., 2016) retort systems generally conclude optimum processing conditions. Due to the main rotational effect for the screw drive systems, a similar case study might be simulated to determine the momentum transfer effects as a function of rotation rate. Therefore, the objective of this study was to develop a numerical model for screw-drive system to observe the effect of rotation on the liquid movement.

2. Method

2.1 Numerical method

Simulations were performed by using the Volume of Fluid (VOF) (Rider et al., 1998) approach relying on the fact that two or more fluids are not interpenetrating. The volume of fluid (VOF) method is an Eulerian free-surface modelling technique for tracking and locating the free surface or a fluid-fluid interface. As such, VOF is an advection scheme allowing to track the shape and position of the interface, but it is not a standalone flow solving algorithm, and this is why the Navier–Stokes equations describing the motion of the flow have to be solved separately.

Introducing the volume fraction α_q for the q-th phase, tracking of the interface between the different phases is carried out by the solution of a continuity equation for the volume fraction of one of the two phases while the internal energy and temperature are treated as mass-averaged variables. In each control volume, the volume fractions of all phases sum to unity. The fields for all variables and properties are shared by the phases and represent volume-averaged values, as long as the volume fraction of each of the phases is known at each location. This means that the variables and properties in any given cell are either purely representative of one of the phases ($\alpha_\iota = 1$ or $\alpha_\iota = 0$), or representative of a mixture of the phases ($0 < \alpha_\iota < 1$), depending upon the volume fraction values.

The tracking of the interface between the two phases is obtained by solving a continuity equation for the volume fraction of one of the phases, according to the following equation:

$$\frac{1}{\rho_r}\left[\frac{\partial}{\partial t}\left(\alpha_r \rho_r\right)+\nabla \bullet \left(\alpha_r \rho_r\right)\vec{v}_r\right]=S_{\alpha r}+\sum_{s=1}^{n}(\dot{m}_{rs}-\dot{m}_{sr}) \tag{1}$$

where $\dot{m}_{rs}$ is the mass transfer from phase r to phase s and $\dot{m}_{sr}$ is the mass transfer from phase s to phase r a and $S_{\alpha r}$ is a possible source term which is set to 0 in the current study. A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases; the equation (2) depends on the volume fractions of all phases through the density and viscosity of the phases according to the following equations.

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \bullet (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \bullet \left[\mu\left(\nabla\vec{v} + \nabla\vec{v}^{T}\right)\right] + \rho\vec{g} + \vec{F} \tag{2}$$

$$\rho = \alpha_r \rho_r + (1-\alpha_r)\rho_s \tag{3}$$

$$\mu = \alpha_r \mu_r + (1-\alpha_r)\mu_s \tag{4}$$

The density ρ and the effective thermal conductivity k_{eff} are shared among the phases, and the energy equation as well:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \bullet (\vec{v}(\rho E + p)) = \nabla \bullet \left[k_{eff}(\nabla T)\right] + S_h \qquad \backslash \tag{5}$$

where E and T are mass averaged variables.

2.2 Computational model

The overall length of the screw-cooker, demonstrated in Figure 1, was set to 1.8m, while the drum diameter was equal to 0.6 m. The rotation rate values for the screw were 10, 20 and 40 rpm, and a mass flow rate of 0.16667 kg/s of water at T=300 °K was set for inflow boundary condition from a circular hole, while a rectangular slot was used as outflow (Figure 2). These inflow and outflow geometries were preferred to demonstrate the inlet of a processing fluid into the system while the outlet is used to the processed product out. No-slip condition was applied over all the solid boundaries. The outer boundary of the system was assumed to be insulated. The initial temperature of the fluid inside the system was set to 363.15 K. The following studies will consider to have particulates in the inlet stream to supply a certain heat treatment to the particles while the rotating screw will carry the particles to the outlet.

To include the possible natural convection effects in the process especially at lower rotation rates, Boussinesq approximation was applied for both water - air phases. Their themophysical properties were function of temperature. For the numerical solution procedure, a finite volume method (FVM) based solver (Ansys Fluent V17.2, Ansys, Inc., Canonsburg, PA, USA) was used to solve the preceding partial differential governing equations of the given two-phase flow problem with a moving geometry by using the following numerical schemes:

- A multiphase model for VOF approach with two Eulerian phases,
- The pressure-velocity coupling was carried out with SIMPLE scheme with skewness-neighbour coupling,
- transient formulation was first order implicit, and
- Spatial discretization for gradient was Green-Gauss node based; for pressure PRESTO; for momentum QUICK; for volume fraction modified HRIC; and for energy QUICK schemes were used.

For the numerical solution, the computational geometry consisted of 1.25E6 control volumes. A compressive interface capturing scheme for arbitrary meshes was applied to track the interface adopting a moving mesh approach for hydrodynamic and shear forces with 3- rotational and translational degrees of freedom. The surface tension value along the interface of air and water was assigned to be 0.72 N/m, and the time step size used in all simulations was 1E-4 s., and the resulting computational time was ≈24 hrs to complete 0.25 s of the process in a 3.7 GHz – 4 processor – 48 GByte system.

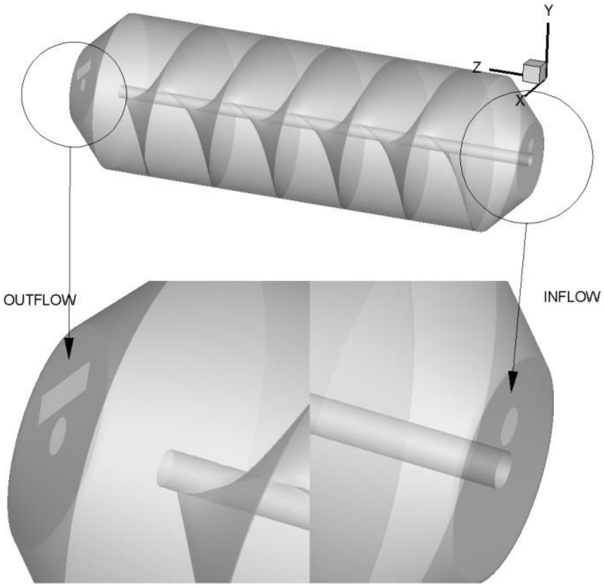
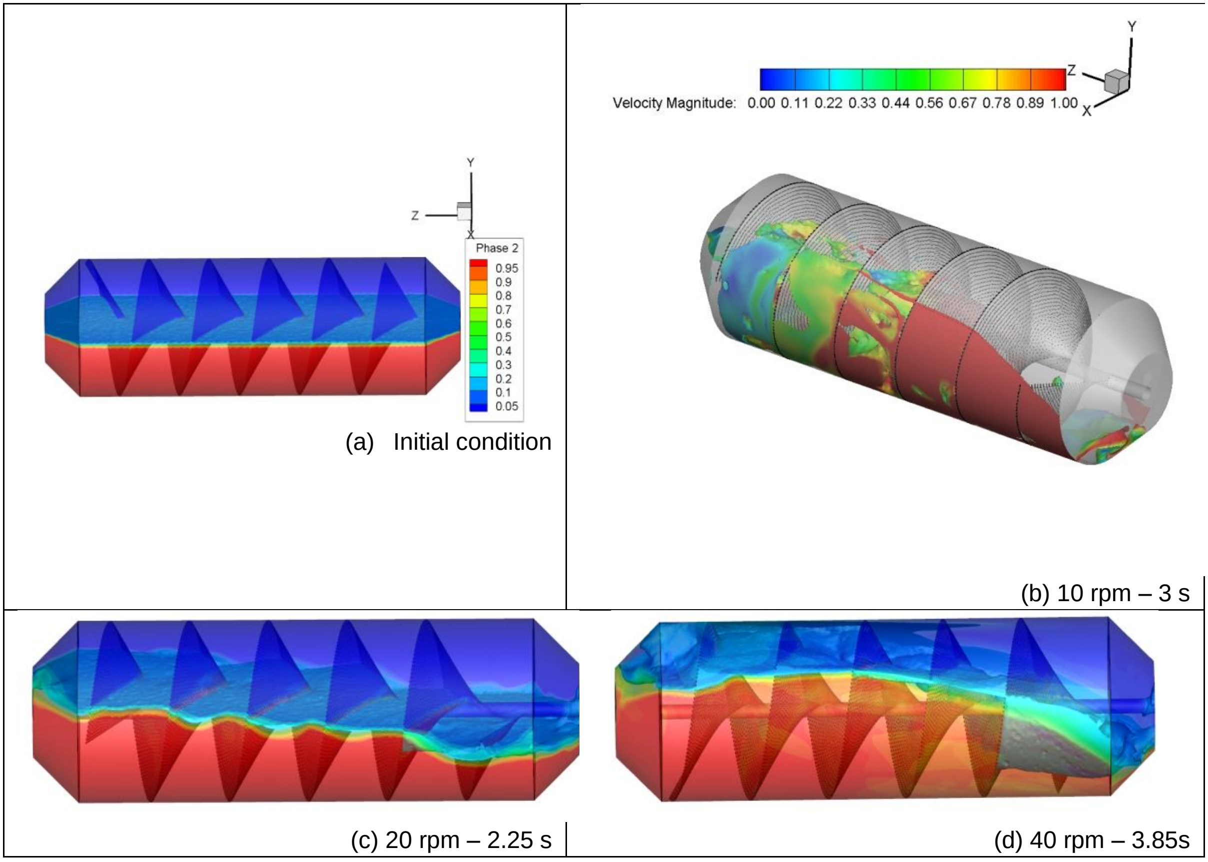


Figure 2. Inflow and outflow boundaries of the screw drive system.

3. Results and Discussion

Figure 3 shows the variation in the air-water interface as a function of rotation rate of screw after different times of the process upon the initialization. As observed, at the highest rotation rate the liquid is forced to the outlet while a gentle rotation gave the moving effect at the lower rotation rates.



(a) Initial condition

(b) 10 rpm – 3 s

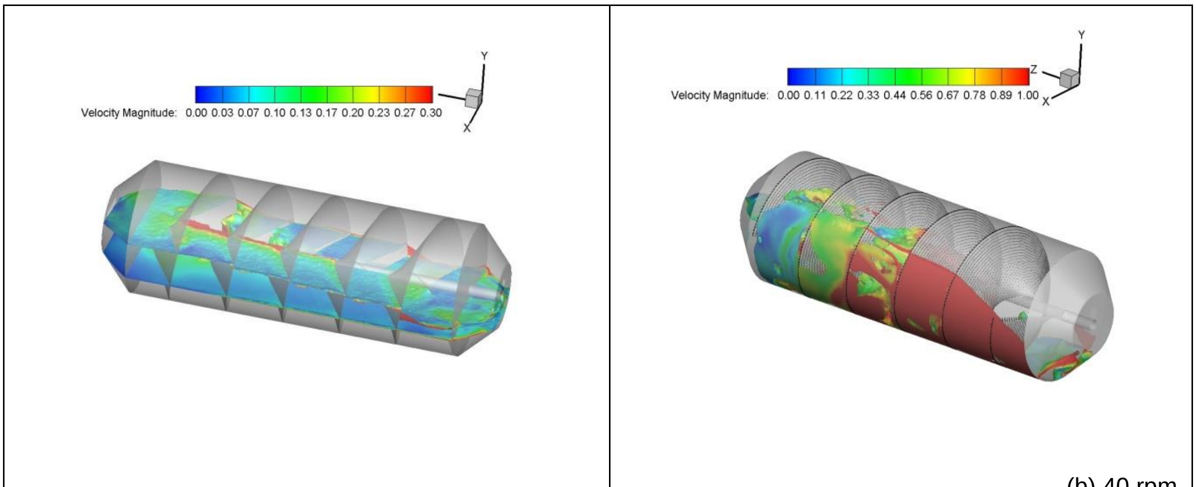
(c) 20 rpm – 2.25 s

(d) 40 rpm – 3.85s

Figure 3. Variation in the air-water interface as a function of rotation rate (a) initial condition – stationary case; (b) 10 rpm – 3 s; (c) 20 rpm – 2.25 s; (d) 40 rpm – 3.85 s.

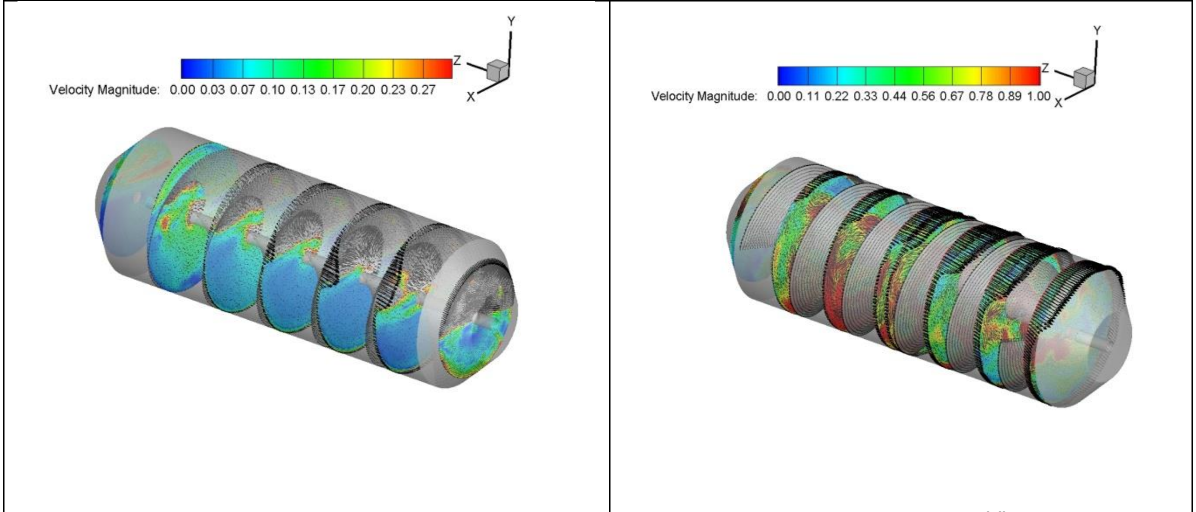
This intense mixing also indicates a possible higher heat transfer rates that might be obtained in processing the particulate foods through the system.

In Figure 4, details of iso-surfaces ($\phi_{water} = 0.99$) at 10 rpm and 40 rpm are presented. The change in the water iso-surface indicated that that a trade-off between mixing and residence time is required.



(a) 10 rpm

(b) 40 rpm



(c) 10 rpm –3.25 s

(d) 40 rpm – 3.85s

Figure 4. Variation in the air-water interface and velocity flow field .in water for different rpm (a,c for 10 rpm, b d for 40 rpm).

The evolution of flow field during rotation involves the interactions between inertial forces, due to the rotational effects, gravitational forces and viscosity. Therefore, a force analysis by introducing Froude (Fr) and Taylor (Ta) numbers was performed to compare the effect of rotation on flow field evolution. The Fr and Ta numbers are defined to be the ratio of rotational – inertial forces to gravitational and viscous forces, respectively. Based on this concept, these two dimensionless numbers might be defined:

$$\mathrm{Fr}= \frac{f_{rf}}{f_{gf}} = \frac{\omega^2 R}{g} \tag{6}$$

$$\mathrm{Ta}= \frac{f_{rotational-inertial}}{f_{viscous}} = \frac{\omega^2 R^4}{\nu^2} \tag{7}$$

where f_{rf} is the rotational, f_{gf} is the gravitational, $f_{rotational\text{-}inertial}$ is the rotational - inertial and $f_{viscous}$ is the viscous forces, $\left(\omega = \frac{2\pi f}{60}\right)$ with f is the rotation rate (rpm), and R was the radius of the blades. Based on this, Fr and Ta numbers increased 16 times from 10 to 40 rpm (Fr_{10}= 0,0335358627,Ta_{10}=12,6) considering the negligible changes in the viscosity for the given process conditions and simulation times due to the higher computational cost demonstrating the higher effect of rotational – inertial forces over gravitational and viscous forces at the higher rotation rates.

4. Conclusions

Screw cookers represent a promising technology for in-line continuous sterilization of particulate products, allowing at the same time an increased thermal mixing and simple operative procedures. Further details are required to understand buoyancy effects vs inertial effect on particulate to provide data for an optimal design of the screw cooking system.

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