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Numerical Simulation of Drying Process within a Novel Rotary Drying Machine for Palm Oil Sludge

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ABSTRACT

This study investigated how to model a centre-offset annular rotary drum using OpenFOAM and the meshing software GMSH. The diameter of the outer cylinder D_o is 600 mm, diameter of the inner cylinder D_i 200 mm, the centre-offset $\alpha = 150$ mm, and rotation rate $n = 60$ rpm. When the centre-offset is zero, the quality of mesh is preserved as the drum rotates. Introduction of the offset causes the mesh to be deformed to the point of being unusable as the drum is rotated. The reason was found to be the fixed nodes adjacent to the walls of the outer and inner cylinder. These nodes only respect the motion of the wall they are adjacent to. To circumvent this, we separated the inner volume of the rotary drum to allow the implementation of an OpenFOAM dynamic mesh handling scheme called arbitrary mesh interface (AMI). Implementing AMI allows the quality of the mesh to be kept even when the inner cylinder is rotating under nonzero-offset conditions. This is because AMI permits the sliding of non-conforming meshes next to each other. This preserves the quality of the mesh and secures a reliable and reproducible dynamic mesh motion for the implementation of the drying process in the future.

1. Introduction

Palm oil has been one of the main drivers of the Malaysian economy, in addition to being one of its more effective instruments of expression in the geopolitical arena for over 50 years [1]. However, in recent years, environmental issues have been cited as grounds to impose restrictions on the nation's palm oil exports especially from the European Union and North America [2]. One of the main thrusts of the lobbying effort by the Malaysian government to ease the restrictions is by addressing the environmental concerns stemming from palm oil production. The treatment and repurposing of

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palm oil mill sludge can significantly cut down the amount of waste products released to the environment and harm the ecosystem, especially when it can be repurposed into fertiliser.

The sludge is most commonly dried through ponding - or lagooning - as part of the palm oil mill effluent (POME) treatment process. However, ponding is totally reliant on evaporative drying and is therefore time-consuming [3]. Furthermore, this method of treatment results in soil and water quality degradation, with immediate adverse effects to communities located within the vicinity of the palm oil industry [4].

The drying process that is key to the manufacturing of fertiliser is known to be energy intensive. Previous efforts to improve the efficiency of the process includes the introduction of rotation to wring the moisture away from the sludge through centrifugation [5]. This process is known as dewatering as the water content is mechanically removed from the moist substrate whilst in liquid form. Drying, on the other hand, involves removal of moisture whilst in the gas phase; its transport dictated by the relative humidity of air, speed of air flow, and the pressure and temperature of the surrounding air. Increasing the moisture removal rate and ensuring product consistency have been the issues overshadowing further improvement of the rotary dryer, requiring extensive trial-and-error to guide the development process. In this study, we propose that the dewatering a drying process take place simultaneously in an annular rotary drum. In addition, by placing the inner cylinder at an offset from the axis of the outer cylinder, we imposed a pseudo-pressing motion on the sludge to augment the removal of liquid water from centrifugation (Figure 1). The literature review in the next section gives an account of the previous works that inspired this idea.

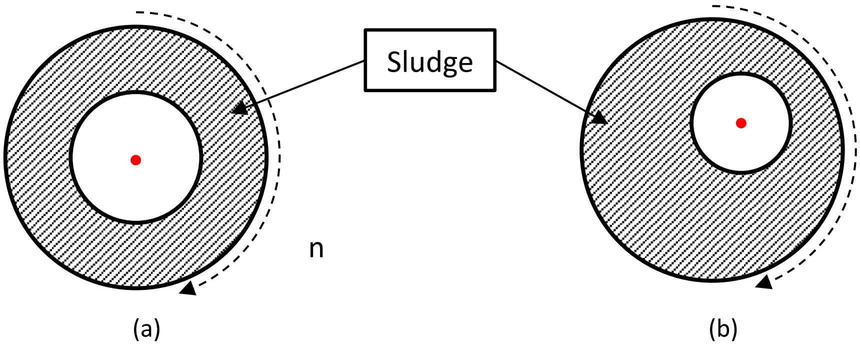

Fig. 1. The proposed annular rotary drum investigated in this study, (a) The coaxial annular rotary drum, (b) The offset annular rotary drum

Computational fluid dynamics (CFD) can help expedite the trial-and-error loop and automate the testing of novel rotary drum designs and evaluate them against design targets. However, several challenges stand in the way of utilising CFD for numerical study of new rotary drum designs for sludge drying. For example, mathematical modelling of the sludge inside the rotary drum, implementation of the drying process, and imposing the rotation of the offset inner cylinder along a path parallel to the circumference of the outer cylinder. This work focuses on the latter, especially towards maintaining the quality of the mesh as the offset inner cylinder moves through the contents of the outer cylinder (rotary drum).

2. Literature Review

2.1 State-of-the-art of Drying Process

Drying, as opposed to dewatering, relies on the phase transition of water inside the moist substrate from liquid to gas. The change of phase from liquid to gas is mainly dependent on the saturation pressure and temperature of water under current atmospheric conditions. Other factors such as air movement, temperature and relative humidity also contributes to the rate of drying. In Kaveh *et al.,* [6], the temperature of air is manipulated through the use of infrared (IR) lights in their rotary drying chamber for green peas. They demonstrated how the drying rate which is regulated by the temperature elevation, IR intensity and drum rotation speed all enhanced the slope of the drying curve. Kalashnikov and Chernyaev [7] on the other hand, looked into the usage of a fluidised bed as the heat transfer agent to improve uniformity of heating - which - when combined with periodic mechanical stirring, decreased the drying time of livestock feed by a factor of 1.2 to 2.

As higher temperatures in the drying chamber have been shown to improve the drying process, some have investigated how to achieve higher temperatures from a combustive heat source. In Coradi *et al.,* [8], the source of heating comes from a gas burner. The combustion gases are then fanned over the moist substrate to accelerate the drying process. This study employed CFD as their methodology. Their results shown in Figure 2 highlighted the significance of convective heat transfer coefficient in determining the maximum temperature in the drying chamber.

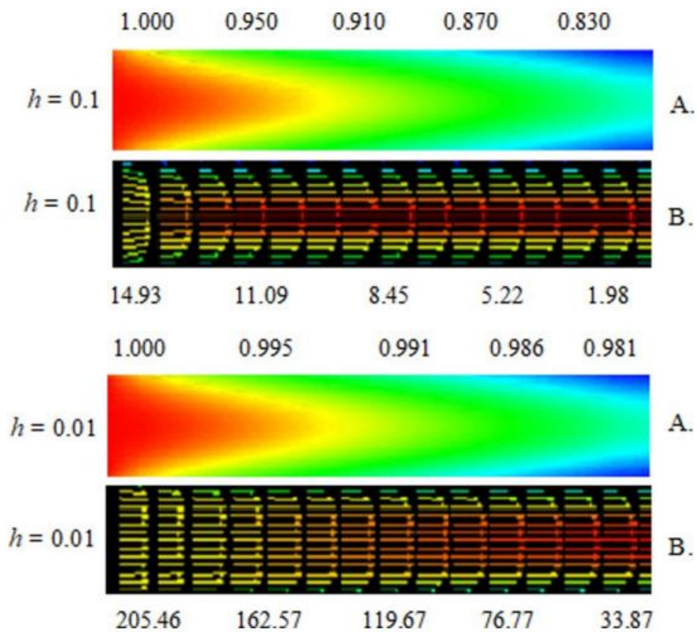

Fig. 2. The temperature map and velocity profiles inside the drying chamber for two different convective heat transfer coefficients h [8]

Inclusion of the drying process in numerical studies of requires using the appropriate mathematical model to simulate the process. To this end, Castro *et al.,* [9] reviewed mathematical models of fruit drying which includes semi-empirical and fully theoretical ones. Semi-empirical models are based on the idea of thin layers, while fully theoretical ones study the heat, mass and momentum transfer in two subdomains: the air domain and the fruit domain. This system of non-linear transport phenomena is made up of partial differential equations (PDEs). The PDEs are equations based on the general transport equation, which can be used to generate physical laws like Newton's law for momentum transfer, Fick's second law for mass transfer, and Fourier's law for heat transmission through conduction. The PDEs might be coupled in their boundary conditions or in the thermophysical characteristics of the air and fruit.

Instead using heat generated from combustion and heating elements, Ploteau *et al.,* [10] took a different approach using heat pumps to dry sewage sludge. Since heat pumps transports heat from a low-temperature thermal reservoir to a higher one, they were able to use the air exiting the drying chamber as their low-temperature thermal reservoir. To provide the desired conditions at the dryer intake, a portion of the dehydrated air is then mixed with ambient air, depending on its characteristics, before entering the exchanger connected to the condenser. Thus, a small percentage of warm, wet air is released into the surrounding area. In the condenser of a heat pump, this air is heated. Then it interacts with the product at the cooled and humidified dryer stage while moving. Moreover, it is dehumidified fully or partially in the evaporator before being heated in the condenser.

From the literature reviewed thus far, heat is used to increase the kinetic energy of the molecules that make up the moist substrate and promote drying. However, heating often involves combustion and requires proper insulation to minimise unwanted heat loss that reduces the exergy that is otherwise available to accelerate the drying process. Mou and Chen [11] demonstrated a partial solution by blasting ultrasound to sewage sludge as a pre-treatment before the drying process takes place using hot air. They demonstrated the feasibility of this method resulting from reduced stratification of the sludge. This cuts down the drying time and results in more efficient fuel usage for heat supply.

2.2 State-of-the-art of the Dewatering Process

Dewatering involves removing the water content from the moist substrate while it is in the liquid phase. One of the methods used for dewatering is centrifugation. This means spinning the drum containing the moist substrate to force the moisture out by exploiting the centrifugal force. However, since the centrifugal force F_θ is given by

$$F_\theta = \omega r^2, \tag{1}$$

where ω (rad/s) and r (m) are the angular velocity of the object in curvilinear motion and the instantaneous radius of its path respectively, centrifugation is governed by these two parameters ω and r. Thus, to improve centrifugation, our choice is either to increasing ω, r, or both, depending on our dimensional constraints. Centrifugation should be exploited whenever feasible, but there exists another method that can be used for dewatering: mechanical pressing.

The mechanical press has been used to extract oil from seeds and the resulting oil has water as its constituent [12]. The press can either be of the hydraulic type, or the screw type (see Figure 3). If mechanical pressing such as these can be included as part of the overall moisture removal process, we can cut down on the energy expenditure for centrifugation, and for drying, since the moisture level has been reduced prior to the drying stage. Grosshagauer *et al.,* [13] have argued for the conditioning of the moist substrate before the mechanical pressing stage. This includes uniformising the substrate to reduce stratification and lowering its temperature. Mushtaq *et al.,* [14] also suggested that the mechanical pressing be done without heating. This is echoed in other works as well. For example, Satriana *et al.,* [15], Muangrat *et al.,* [16], Maestri *et al.,* [17], and Patel *et al.,* [18].

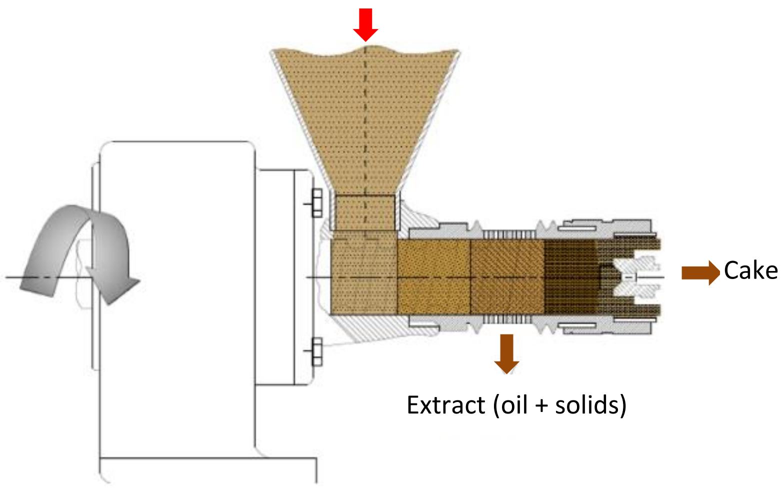

Fig. 3. A typical schematic of a screw press [17]

It should be noted, nevertheless, that the literature cited above that argues for mechanical pressing at low temperatures are working towards extracting oil from seeds - not water. Therefore, they paid great attention to the purity and quality of the oil. Higher temperatures during the mechanical pressing leads to a drop in oil quality for the consumer because less desired chemicals are extracted through the process. This, however, can be a desirable result in dewatering palm oil mill sludge as we only want the water to be removed from the sludge, while other chemical components remain with the sludge to make a high-quality fertilizer.

On the subject of hydraulic pressing, Ivanov *et al.,* [19] experimented with hydraulic pressing of moist peat soil in a bucket. They pointed to the importance of understanding the characteristics of pressure transfer in thin layers in selecting the hydraulic pressure to be applied. They also brought attention to the total perforated area on the bucket surface as a parameter that increases the efficiency of the drying. Mechanical drying has also been shown to cut down drying time for coffee beans [20].

Overall, the literature seems to suggest that there is still no precedent to the moisture removal process that includes centrifugation, mechanical pressing, and convective drying in one package. Therefore, this study seeks to address this gap by focusing our attention to the study of an annular rotary drum as sketched in Figure 1.

3. Methodology

3.1 Problem Geometry

The annular rotary drum is modelled as two cylinders of different diameters, with the smaller one placed inside the larger, shown in Figure 4. The diameter of the inner cylinder is denoted as D_i, diameter of the outer cylinder D_o, centre-offset between the axis of the inner to the outer cylinder α, and the rotation rate, n. In this investigation, $D_o = 600$ mm, $D_i = 200$ mm, $\alpha = 150$ mm and $n =$ 15 rpm. These parameters are selected to allow simple testing of the ability to keep a good quality mesh while the rotary drum is spinning. To simplify the problem, the sludge is taken as possessing the properties of a Newtonian fluid.

(a) (b)

Fig. 4. The geometry of the annular rotary drum, where D_i, D_o, α, and n are the diameters of the inner and outer cylinders, offset between the axes of the inner to the outer cylinder, and the rotation rate of the drum, respectively

To impose the mechanical pressing to the contents of the annulus, only the outer cylinder is rotated at n (rpm), while the inner cylinder has its position fixed during the tumbling cycle. Following momentum transport, the fluid inside the drum will start to spin in the same direction as the outer cylinder. While in rotation, the flux will pass through the narrow area when the inner and outer cylinder shells are at their closest. This repetitive pass-through creates a squeezing motion that creates the mechanical pressing for this setup.

3.2 Meshing and Dynamic Mesh Handling Procedures

Meshing is done using GMSH, a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. As shown in Figure 5, in GMSH, the annular cylinder is defined as two cylinders with diameters D_o and D_i - where $D_o > D_i$ - and the cylinder with diameter D_i placed inside the cylinder with diameter D_o. In the concentric annular drum, the inner and outer cylinders share the same axis. The internal region of the annulus is then divided into four equal areas, each with four sides. This allows us to implement quadrilateral cells inside the annulus (Figure 5(a)).

In Figure 5(b) the meshing for the off-centre annular drum is shown, and it also follows a similar scheme. The difference between Figure 5(a) and Figure 5(b) lies in the area of each of the four regions the internal of the annulus is divided into - they are not of equal area. This cannot be overcome due to the offsetting of the internal cylinder. To ensure the use of quadrilateral cells inside the annulus, the region still needs to be divided into four enclosures, each with exactly four sides. As the inner cylinder is now closer to one side of the outer cylinder compared to the other, the mesh density in enclosure 1 is less than in enclosure 2 because both have the same number of cells, but the area of enclosure 2 is larger than enclosure 1.

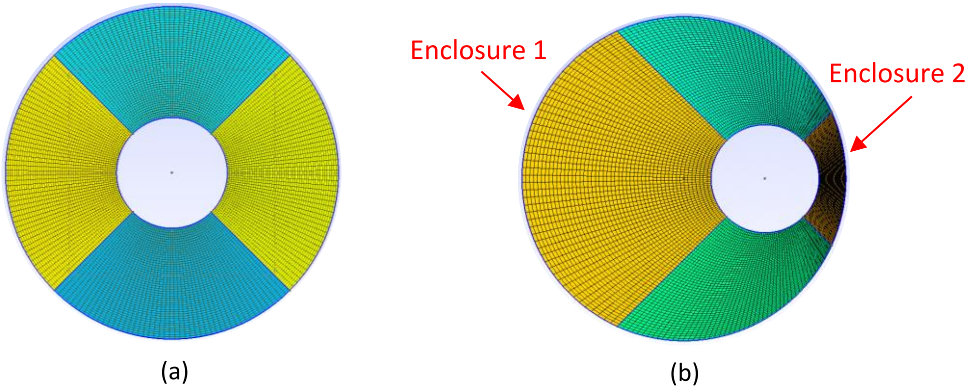

Fig. 5. Visualisation of the meshing scheme used for the annular cylinder. (a) shows the meshing for the concentric annular drum, while (b) shows the off-centre annular drum

OpenFOAM is a free and open-source C++ libraries developed to handle field operations and manipulations. It runs natively on Linux-based operating systems and can also be made to run on Windows and Mac operating systems with a few additional steps. As OpenFOAM runs natively on Linux, its interface is mainly textual, with the end used setting up case files and dictionaries that specify the simulation's initial and boundary conditions, fluid parameters and solver settings. The directory structure of a typical OpenFOAM case is shown in Figure 6, where the "0" (zero) directory lists the initial and boundary conditions, the "const" directory lists the fluid, thermal, and other parameters, while the "system" directory lists the solver control for the simulation.

The textual interface allows the OpenFOAM user to tap into the power of extensible text editors such as VIM or Emacs, and it also allows the user to quickly check their case files into a source control workflow, e.g., using Git. In OpenFOAM, several libraries exist natively to the platform for handling moving meshes. To access this capability, the user must define a dictionary, i.e., a text file, specifying how the motion of the mesh is defined - if predetermined - and handled - if resulting from the solution of the governing equations.

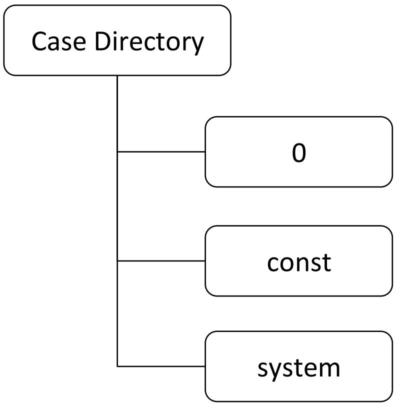

Fig. 6. A typical directory structure for an OpenFOAM case

In prescribing the motion of the annulus, which in this case is rotational motion, a dictionary that describes the dynamic motion of the mesh - the "dynamicMeshDict" - is defined. For our case, a prescribed rigid body motion is chosen, as we are just looking to emulate the tumbling motion of the rotary drum. Therefore, the dynamicMeshDict is defined as the following code block in Figure 7. The code block specifies that the cell zone named "outerCylinder" is to be prescribed a rotational rigid-body motion that centers at coordinates $(x, y, z) = (0,0,0)$, and the angular velocity of the outerCylinder is kept constant at $15\ \text{rpm} = 90°/\text{s}$. OpenFOAM specifies the angular velocity of cell zones in degrees per second (°/s).

```
cellZone outerCylinder;
       solidBodyMotionFunction axisRotationMotion;
       axisRotationMotionCoeffs
       {
           origin         ( 0 0 0 );
           radialVelocity ( 0 0 90);
       }
```

Fig. 7. Defining the dynamicMeshDict for this mesh setup. The radial velocity is specified is units of degree per second (°/s)

4. Discussions

A simple implementation of the rigid-body motion described in Figure 7 on the mesh depicted in Figure 5(b) results in a severe deformation of the mesh inside the annulus. In OpenFOAM, it is possible to test the dynamic mesh motion without starting the solver. This is done by running the moveDynamicMesh utility on the case directory. This allows us to test the prescribed motion and study whether our setup of the mesh movement in sufficiently robust for the actual simulation.

As showcased in Figure 8, when the gap between the offset inner cylinder and the outer cylinder is further divided into separate regions, it is possible to implement the arbitrary mesh interface protocol to the mesh motion, while keeping a good quality mesh. This is because the mesh sliding can take place at the interface of the separation. As such, the problem of severe deformation of the mesh is circumvented, the mesh is now fit for use in further simulations.

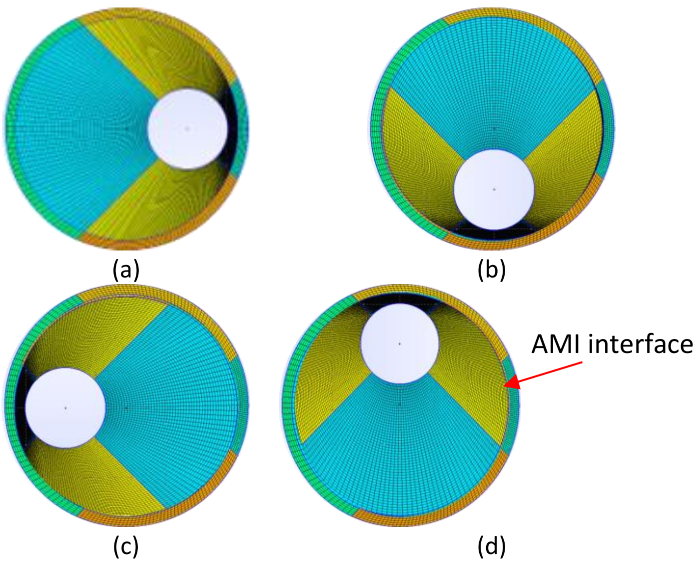

Fig. 8. The mesh motion of the offset-centre rotary drum at quarter cycle timings. Here, T is the period of the rotation; (a) $t = 0$, (b) $t = \frac{1}{4}T$, (c) $t = \frac{2}{4}T$, (d) $t = \frac{3}{4}T$

5. Conclusions

This study investigated how to model a centre-offset annular rotary drum using OpenFOAM and the meshing software GMSH. The diameter of the outer cylinder D_o is 600 mm, diameter of the inner cylinder D_i 200 mm, the centre-offset $\alpha = 150$ mm, and rotation rate $n = 60$ rpm. When the centre-offset is zero, the quality of mesh is preserved as the drum rotates. Introduction of the offset causes the mesh to be deformed to the point of being unusable as the drum is rotated. Separating the inner volume of the rotary drum allows the implementation of an OpenFOAM dynamic mesh handling scheme called arbitrary mesh interface (AMI). Implementing AMI allows the quality of the mesh to be kept even when the inner cylinder is rotating under nonzero-offset conditions. This secures a reliable and reproducible dynamic mesh motion for the implementation of the drying process in the future.

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