MMVN05: Numerical Fluid Dynamics and Heat Transfer

Individual PhD Student Assignment

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1 Introduction

This work aims to discuss the application of CFD methods in modeling the drying of food stuffs. It begins with a short introduction to the systems being considered. The major dynamics in the physics of drying are then presented. This is then briefly put in the context of food stuffs. The final section describes a setup that could be used in a CFD based analysis.

The work is targeted largely at a future me: one that is going to need to write further about this topic and who will probably even do CFD modelling on a drying system of food stuffs. As such, the physics are not written in a technical manner, but more in the way I will talk about this with my colleagues (who similarly are not engineers). My apologies for it being longer than requested, but the topic is very relevant to my work, so I wanted to use this opportunity to go as deeply as the time permitted.

2 Two systems

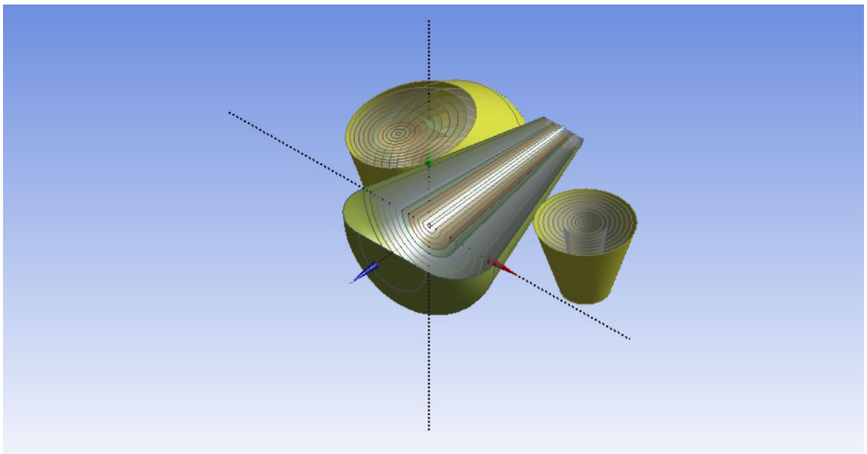
The intent of this work was to focus on two systems;

1. *The inner system* of a single solid (unprocessed, plant) food stuff, its surface, the surface air layer, and the air space beyond the surface layer; see Figure 2a.
2. *The outer system* of multiple solid (unprocessed, plant) food stuffs within a bulk storage unit, with bulk porosity, and a boundary of empty air; see Figure 2b. Please note that while the design of any storage and ventilation system is obvious very critical to drying, it will not be discussed in this work.

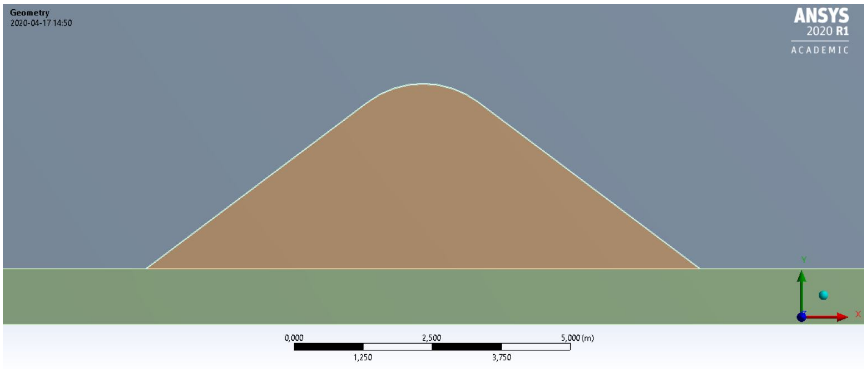
Please note: by the time I got to writing about the outer system, this work was already too long. To save the examiner more distress, I have refrained for completing the final section: CFD scheme for the outer system. Instead, you will be informed of another work I am currently completing thanks to the knowledge I have gained from this course.

3 The important physics

The process of drying, in the realm of physics, is centered on a process of mass transfer; that of water out of a solid body and into the surrounding air. Momentum and energy dynamics are also at play. There is no mass transfer without momentum, and the transfer of heat into the drying solid body is expected with evaporation. Evaporation at the surface of the solid body is central to both these processes. On either side of this central dynamic, there



(a) The inner system: Central shape. ca. 15cm wide



(b) The outer system: Brown area. ca. 8m wide at the base

Figure 2: Example geometry of the systems for sugar beets

is also the mass transfer of the liquid water within the solid body, and the mass transport of the evaporated fluid away from the surface and across the system boundaries.

Through the solid The movement of a liquid within the solid body suggests that it might not be appropriate to consider this object as a solid body at all, but rather a porous one in which there is free space for a fluid to move and exit. With this view, transport is through a porous media across a pressure gradient. This transport process can be viewed in an analogous way; that of diffusion within a solid body over a concentration gradient. This view of a solid body, diffusion and a concentration gradient, is the more traditional approach when dealing with food stuffs as the drying solid. At the outer layer of the solid, a relatively low concentration of fluid develops as moisture evaporates from the surface. This then causes the fluid from the inside to move outwards as it looks to balance the concentration.

In the diffusion interpretation of the physics, it is only necessary to model the surface. The application of the porous media interpretation is still under development in conjunction with CFD methods, but has to date proved successful and given insights beyond the diffusion models [4].

Across the surface Liquid evaporates from the surface of a solid object when it is free (not caught within the structure of the solid) and when it is energised beyond the point of that holding it to the bulk of the liquid. This suggests that the surface must be porous for moisture and heat to cross it. This evaporation process is not one of diffusion. The net evaporation rate, however, is dependent on diffusion, with liquid moving from the high concentration at the surface of the solid object to the lower concentration in the air at, and at a distance from, the surface. As a process dependent on diffusion in the net, evaporation is accelerated when the concentration gradient in the air out from the surface is greater. It is also a necessary condition that the free liquid particles can be received by the air. As such, the psychrometrics become critical. Air humidity, velocity, and temperature at both the surface and in the rest of the system must be considered.

Heat transfer across the surface is through diffusion and thus driven by the temperature gradient. Even if the temperature of the solid object and the ambient air are in equilibrium, a temperature gradient can be maintained by evaporative cooling. Evaporative cooling occurs as the evaporated fluid takes thermal energy with it, reducing the average thermal energy of the fluid component of the solid and thus its temperature.

Relative humidity In terms of relative humidity, the more saturated the air, the lower its ability is to receive and hold moisture from the solid object. The extreme of this is 100% humidity, in which the air is unable to absorb any more moisture. If such a high value is maintained across the entire air domain, from the surface out, then drying from evaporation stops. Alternatively, if there is also a concentration gradient in the air, decreasing from the surface out, then diffusion can proceed. Convection processes can also be non-zero. So non-zero, in fact, that convection processes come to dominate the entire process.

Velocity Air velocity is the dominating force maintaining a low surface air humidity, and thus the ability for the air in this space to receive, hold, and then carry away moisture. At any relative humidity below 100%, it is reasonable to expect that the air humidity at the surface of the solid object is greater than the ambient air owing to the above discussed evaporation over a concentration gradient. Convection forces cause the replacement of this higher humidity surface air with the lower humidity distance air, and thus the transport of mass away from the surface and the rate of diffusion across the gradient at the surface layer will only increase.

Velocity also drives a pressure differential in the system. The convective mass transfer coefficient is defined as:

$$CMTC = \frac{g_{c,w}}{p_{v,w} - p_{v,ref}}$$

where;

$g_{c,w}$ is the convective mass flux normal to the wall
c is convection
p is pressure
v is vapour
w is the wall
ref is somewhere in the air away from the wall

This shows that the rate of mass transfer from the wall is dependent on a pressure gradient, and thus air velocity.

Absolute humidity In terms of absolute humidity, it is not simply again a case of more is less; that the more the total moisture held by the air, the lower its ability to receive and hold moisture. The interaction with temperature must be considered.

Temperature Warmer air has a higher moisture holding capacity than colder air. That is, the saturation point of air (dew point) is at a greater concentration for warm air than it is for cold air. For example, air at 5°C and 100% relative humidity has an absolute moisture content of 5.40g water/kg air, while at 20°C and 100% relative humidity, the moisture content is 14.68g water/ kg air. This suggests that warmer air has the ability to maintain a higher drying rate by being able to accept a greater mass of water. Counter to this, the higher moisture concentration at a given relative humidity for warmer air means a lower ability to maintain a high concentration gradient at the surface. However, and while the difference between 5.40 and 14.68 is nearly three fold, both these values are low when compared to the moisture content of a solid object like a sugar beet, which is around 700g water/ kg sugar beet. The other factor with temperature is that a higher thermal energy of water at the surface of the solid object means an increased ability for molecules at the surface to escape the bulk and evaporate. In general, higher temperatures lead to higher rates of drying.

The temperature differential between the solid and the fluid in the system is also a key driver of heat transfer. The convective heat transfer coefficient is defined as:

$$CHTC = \frac{q_{c,w}}{T_w - T_{ref}}$$

where;

$q_{c,w}$ is the convective heat flux normal to the wall
T is temperature
c is convection
w is the wall
ref is somewhere in the air away from the wall.

4 The solid as a food stuff

When the solid body that is drying is a food stuff, there are some unique considerations.

Re-hydration It is possible that the drying process is reversed, with moisture entering (or re-entering) the solid. This is often relatively minor in relation to the rate of drying, does not prevent the ultimate targets of drying from being met, and is often driven by osmosis rather than a pressure gradient, but it can have important consequences for the total drying time [1]. This is especially so in natural, solar driven drying systems.

Both systems With regards both systems:

- The shape of the solid bodies has important implications.

  The total surface area of the food stuff is a function of the shape and texture, with a greater surface area to volume ratio meaning greater drying potential.

  The flow of air around the objects can result in variations in the velocity around the food stuff and thus variations in the drying rates [1].

- Foods stuffs of plant materials are living, and produce heat.

The inner system With regards the inner system:

- It is possible that the movement of the fluid through the food stuff is driven by other processes than just a concentration gradient of water, such as osmosis.

- The surface of the solid food stuff is a critical feature in the inner system. The permeability of this surface will strongly regulate the rate of evaporation.

- It has been shown that the cellular structure of food stuffs results in changes to the pathways through which the fluid passes as it dries [1].

The outer system With regards the outer system:

- The shape of the solid bodies themselves tends to change due to the loss of the fluid mass fraction [1]. This can have impacts on the bulk porosity and thus air flow.

5 Theory to CFD Practice

Here is how I would tackle the problem with CFD. As my first attempt and an attempt not supported by application, I expect there to be some debatable suggestions, for as Ramachandra *et al* note, "Modelling of drying is a complex process that touches on multidisciplinary areas with a fusion of transport phenomena, material science, and fluid and solid properties." [4, p272]. The review by Ramachandra *et al*, and the study by Defraeye *et al* [2] are two sources I draw on heavily for this work.

I note also that it is clear from reviewing a limited amount of literature that experimental determined input parameters are critical to this process.

5.1 The Inner System

Starting with the inner system and taking the example of a sugar beet, it is pertinent to ask what the purpose of a model of this system is. Primarily it is to provide a platform to discuss the physics of the system. As such, the model must be based on convective heat and mass transfer with a focus on the exchange at the surface of the solid. The emphasis of this work will be on the air-side transfer. That is, dealing with the change in shape mentioned previously will be saved for a later date.

Geometry Taking the shape at the centre of Figure 2a as a reference, with air flow moving opposite to the blue arrow. A combination of simple geometric shapes rotated into three dimension will suffice for the geometry of the solid in this case. For example, a half circle sitting on an isosceles triangle gives something akin to a sugar beet (and an ice cream cone). The two ends of the combined shape can be removed in order to model the harvested sugar beet, which often has these parts removed. Given the use of simple geometric shapes, there is infinite symmetry around the shape's central axis. Following [2], it would be possible to include two symmetry planes through this central axis of the solid - one on both the XZ and YZ axis of Figure 2a (which only has a XZ symmetry shown). This would reduce the computational model by a factor of four.

The inclusion of the internal structures seen in Figure 2a is of less importance. These represent the cambium structure of a sugar beet. As such, they may also be useful in modeling the internal flow of a fluid, and are likely critical to a model that will capture how the beet shrinks as it dries. However, it seems unlikely that the thermo-physical properties will be different across these layers. More critically, it is the air-side transfer I wish to model here: I will, however, not consider these internal structures further.

The inclusion of the other shapes seen in Figure 2a is also worth considering. Rates of drying at the points of contact of these shapes will certainly be different to the parts of the surface that are in the open air, and thus modeling this will give a more complete picture of the true system. I will not consider these further in this initial work.

The extent of the air domain around the solid shape is conservatively defined (i.e. probably bigger than it needs to be). The air flow of this system will be quite low - a maximum of 5m/s - so even if this will likely result in large Reynolds numbers (e.g. a value of 32 500 was computed in a similar system to that developed here, at 6.325m/s [2]), the size of domain to counter system effects does not need to be grand. Further, the extent will not represent any boundary of the physical system, so will be modeled as such. All considered, a simple rectangular cuboid of ten times the radius in-front, above, and to the side of the solid is suitable [2]. The trailing edge should be closer to 40 times the radius, from the cut-off triangle end of the solid shape (in the opposite direction of the blue arrow in Figure 2a). The inlet faces the larger end of the solid (in the direction of the blue arrow in Figure 2a), which should result in a blockage ratio of 0.65% - well below the 3% best practice rule of thumb defined in Franke *et al* (2009) [cited in 2]. The symmetry plane of the solid would sit against the edge of this domain.

In total, the following surfaces would be defined for the geometry such that they are also incorporated into the downstream work flow:

- velocity-inlet on the near side of the rectangular cuboid,
- pressure-outlet on the fair side of the rectangular cuboid,
- the wall of the solid can be named given its importance to the analysis,
- the cut-off ends of the solid can be named separate to the main wall given these will have different properties to the rest of the surface.
- symmetry on the two walls of the fluid space that the solid shape is in contact with.

The domain walls that are not a symmetry plane will automatically be defined as walls (in ANSYS).

Meshing The emphasis will be on the boundary at the face of the solid and the region near this boundary. A hybrid, unstructured grid of hexahedral, tetrahedral and prismatic cells can be applied. The refinement at the surface of the solid in [2] meant this area accounted for 2% of the total cells. Given the dimensions of the solid in this example, this percentage could be expected to double. Following [2], Low Reynolds number modelling (LRNM) will be employed: this requires high mesh resolution at surfaces. Thus, the domain around the solid surface will similarly account for a disproportional large number of the total cells, with an internal rectangular cuboid volume being subject to refinement. This area is approximately two times the radius of the solid, from the solid; so, h = 3 x radius, w = 3 x radius, l = 4 x radius + length of the solid object. Beyond this highly refined area, further refinements in the immediate trailing edge are likely desirable. All this is subject to a mesh independence study.

Materials The fluid zone is defined as air. The solid is not part of the domain. It may be necessary to define a solid of water (see "Models").

Boundary conditions Again following [2], with no reason known to change the majority of values used;

- Inlet

  Velocity: uniform. Maximum of 5ms^{-1}

  Turbulence intensity: 0.1%

  Specific dissipation rate: $\omega = k^{1/2}/0.07C_u^{1/4}L$ where $C_u = 0.09$, and $L = 2\text{r}/10[\text{m}]$. (NB: this feels more like a model parameter than a boundary condition?).

  Temperature: 5°C.

- Outlet

  Gauge pressure: 0 Pa

- Symmetry planes

  Slip

- Solid object walls

  No slip

  Zero roughness (condition of LRNM)

  Temperature: 8°C.

The temperature values are the only values not as per [2]. They used 10°C and 20°C for the inlet and solid walls respectively. The values given here are more in keeping with those of sugar beet storage. The use of a uniform temperature on the solid wall is noted as somewhat counter intuitive in comparison to the flux described to be occurring across this surface. It is rationalised in [2] as being more appropriate as it allows for correlations of convective transfer coefficients with air speed, and comparisons with other literature.

To model the ends of the sugar beet that are removed during harvest, it is possible to modify the temperature of these and the rest of the walls of the solid. To model the effect of discrete heat flux locations at the surface of their solid (eg pore openings or cuts), [2] set the constant temperature condition only on these areas while setting a no-flux condition over the rest (and majority) of the surface.

Models Turbulence modelling really is an interesting topic. And a critical choice. To (mis-)quote Prof. Christer Fureby: "The SST k-ω model is usually better than k-ϵ". Experience from the course and reading some literature suggest that the k-ϵ RANS model with enhanced wall treatment should produce accurate results, but Fureby is supported in the argumentation of [2]. They note that other literature has shown this is a sufficient model (when supported with a fine grid at walls). They also test the model against numerous parameters, showing it is stable. They further note that the SST k-ω model is a Low Reynolds number model.

The energy model is activated. I had thought that the Species (or Multiphase) model might need to be activated in order to model the role of humidity, but there is no mention of it in [2]. This may be because the modelling is focused on the heat transfer, with moisture transport derived from these results.

Spatial discretization Finite volume seems to be the only way forward, especially if using ANSYS FLUENT. I have not noted this previously, but I intend to attempt this model with openFOAM. Prof. Christer Fureby has been contacted regarding the applicability of openFOAM.

[2] state that they use second order discretization throughout. I am sure that this warms the heart of Lea, who loves a higher order numerical method. Second order gives the possibility of introducing overshoot/ wiggles.

Pressure–Velocity Coupling To again (mis-)quote Christer Fureby: "always use the Coupled solver". But to draw from my group assignment, given the emphasis on the surface, SIMPLE might be better. The choice of SIMPLE is also supported by the literature [2], and will undoubtedly increase computational speed.

Solution technique Given the need for a stable solution, it will be necessary to forget about a maximum number of iterations and focus instead on the residuals and some parameters in some of the key zones of interest. [2] took convergence as having stable temperature, velocity, and k in recirculation zones (owing to the presence of large gradients in these regions), and the drag and heat fluxes at the surface of the solid.

Post–processing Heat transport is studied directly, with mass derived under assumption. Some data is currently being obtained for the drying of sugar beets. This will be used to model drying rates (MR), but I am honestly not sure they will be able to use for comparisons to the model at this level, or if I can only end up with an empirical model of a bulk system.

5.2 The Outer System

Starting again at the end; the purpose of a model of the outer system as described here is to predict drying in a sugar beet clamp that is subject to the uncontrolled 'natural' environment in which it stands. As such, the model will be based on a porous media theory with non-equilibrium approach.

Given the length of this work already, instead of developing this system, I would like to note that I am currently writing an extended version of this section that includes three arrangements of this system: a 2D, a 3D with an infinite z-axis, and a 3D version of an entire sugar beet clamp. Should the examiner wish to see this work, they only need to ask.

I thank you.

References

[1] T. Defraeye. Using multiscale modeling to analyze the drying of cellular foods. 2018.

[2] T. Defraeye, E. Herremans, P. Verboven, J. Carmeliet, and B. Nicolai. Convective heat and mass exchange at surfaces of horticultural products:a microscale cfd modelling approach. *Agricultural and Forest Meteorology*, 2012:71–84, 2012.

[3] T. Inazu, K.-i. Iwasaki, and T. Furuta. Effect of temperature and relative humidity on drying kinetics of fresh japanese noodle (udon). *LWT - Food Science and Technology*, 35(8):649–655, 2002.

[4] R. P. Ramachandran, M. Akbarzadeh, J. Paliwal, and S. Cenkowski. Computational fluid dynamics in drying process modelling—a technical review. *Food and Bioprocess Technology*, 11:271–292, 2018.