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Optimising food dehydration processes: energy-efficient drum-dryer operation

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Abstract

Current environmental policies, which promote a more sustainable food sector, have boosted efforts to reduce energy demand during processing, and particularly during drying operations. One of the routes towards more sustainable and efficient drying processes is the design and implementation of optimal operational routines for the existing drying equipment. In the food industry, drum-dryers are typically employed for the production of food powders from viscous slurries (e.g. starchy slurries). Food powders are used in a wide range of applications in the food industry, from beverage powders (milk or cocoa), instant soups, spices or flours and flavours. In this framework, we propose a model-based optimisation routine for the operation of a double drum-dryer (product under atmospheric conditions) used in the manufacture of a breakfast cereal porridge. The problem defines optimal steam temperature and optimal rotation speed that minimises the energy demand of the dryer operation for a range of operating conditions that considered different: product formulation, final moisture contents, thickness and initial temperature of the wet slurry. Overall, this work demonstrates the potential of model-based approaches to the design and optimisation of more sustainable and efficient industrial drying technologies in the food sector, which can help in the achievement of short/medium-term energy reduction goals.

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Keywords: Drum-drying; modelling; optimisation;

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Nomenclature

A_h	heating area (m^2)
d_0	external diameter of the drum (m)
d_i	internal diameter of the drum (m)
f_{slurry}	slurry fouling factor ($W/m^2\,^oC$)
f_{steam}	steam fouling factor ($W/m^2\,^oC$)
g	gravitational acceleration (m/s^2)
h_{i0}	condensation film coefficient ($W/m^2\,^oC$)
k	thermal conductivity ($W/m\,^oC$)
L	further nomenclature continues down the page inside the text box
m	mass (kg)
$\dot{m}_w$	drying rate (kg/s)
$\dot{Q}$	overall heat transfer rate (kJ/s)
$\dot{Q}_h$	sensible heat rate (kJ/s)
r_{d0}	external fouling resistance ($m^2\,^oC$ /W)
r_{di}	internal fouling resistance ($m^2\,^oC$ /W)
t_{res}	residence time (seconds)
T	temperature (^oC)
U	overall heat transfer coefficient ($W/m^{2o}C$)
x	mass fraction (kg/kg)
$X_{scraper}$	scraper angle (rad)

Greek Symbols

ω	rotating velocity (r.p.m)
ΔH_{vap}	latent heat of vaporisation (kJ/kg)
ΔT_{lm}	logarithmic mean temperature difference (^oC)
ρ	density (kg/m^3)
μ	viscosity (Pa s)
Γ_h	condensate loading (kg/sm)
τ_{slurry}	slurry thickness (m)
κ	thermal conduction coefficient ($W/m^{2o}C$)

Subscripts

d-s	drum-slurry
fin	final
gel	gelatinisation
ini	initial
l	liquid
m	drum surface
v	vapour
w	water

1. Introduction

The Food Industry, the largest manufacture sector in the UK's [1], it is also the largest industrial consumer of energy, with approx. 12% of the total energy use according to the Department of Business and Industrial Strategy [2]. Over the last decade, the sector has undertaken important transformations to meet long-term reduction goals on energy demand: e.g. fuel switching, investment in new energy efficient equipment and low carbon technologies [1]. However, food manufacturers still use semi-empirical methods of process design and optimisation that have already exhausted their potential for energy demand reduction. In this context, additional efforts and different approaches to the design of food products and manufacturing processes are required to meet the 2030 sustainability goals (55% energy reduction from the 1990 baseline) [1,3]. One of the actions that could significantly contribute to reduce energy demand during food processing at short and medium term, and the scope of the present work, is the design and implementation of model-based optimal operational routines for existing food manufacturing equipment [4].

Recent studies on energy consumption during food manufacture showed that a small number of operations and products are responsible for large proportions of the energy demand and CO_2 emissions [4,5]. Drying/dehydration operations are commonly used to ensure safety and extend shelf life of foods and powders by processing dried products with moisture contents typically below 10% [6]. As the water content of foods typically ranges between 75%-90%, the removal of this water content by vaporisation demands a significant amount of energy (2.8 kJ/kg water removed on top of the energy required to change the temperature of the system). On the other hand, starch and starchy products are among the most energy intensive food products [5], as their manufacture involves different stages in which water is added and then removed using thermal processing [7].

Drum-dryers are usually employed to manufacture food powders from highly viscous pastes, like different types of starchy food products [8,9] (e.g. potato flakes, cereal porridges) or fruit powders/flakes [10,11], applying high temperatures and short processing times [12,13]. A number of works are focused on the characterisation of drum-drying kinetics using thin-layer dehydration models [14,15] and the effect of process condition on the quality and attributes of the final products [8,10,11]. But only a few studies address transport phenomena in detail [16,17] or proposed formal control/optimisation strategies [18,19]. Thus, modelling and optimising the operation of a double drum-dryer still represents an opportunity for further energy reductions in food processing.

In this framework, we present a model-based approach to design energy-efficient protocols for the operation of a double drum-dryer used in the manufacture of a cereal porridge. The proposed routine assesses a range of operation conditions: (i) product formulation, (ii) final moisture content, (iii) thickness and (iv) initial temperature of the wet slurry to find optimal steam temperature and drum rotation speeds. The overall objective is to minimise the energy consumption of the drum-drying process while ensuring both safety and quality (understood as final moisture content) of the final product. The paper is organised as follows: the drum-drying process is described in Section 2, while the model formulation and the optimisation problem are presented in Section 3 and Section 4, respectively. Results are discussed in Section 5, and finally conclusions are outlined in Section 6.

2. Process description

In double drum-dryers, the product – typically a viscous slurry – is poured onto the external surface of the drums, i.e. metallic hollow cylinders that rotate together near each other in opposite directions and that are continuously filled with superheated steam, as schematically shown in Fig. 1. Inside the cylinders, the steam condensates, raises the temperature (common operating temperatures are above 100ºC) and heats up the slurry by conduction throughout the drum walls. After a given residence time, which depends on the drums rotating velocity of ω (r.p.m), a set of scrapers (placed at an angle $X_{scraper}$) will remove the dried product from the surface all along the width of each drum [10, 14].

3. Drum dryer model

The rate of heat transfer throughout the drums surface controls the drying process [12], so a simple model describing the overall heat transfer rate can be used to simulate the system [20]. Considering combined heat transfer modes (i.e. convection and conduction) as depicted in Fig 1., the overall heat transfer rate $\dot{Q}$ (kJ/s) can be calculated as follows [20,21]:

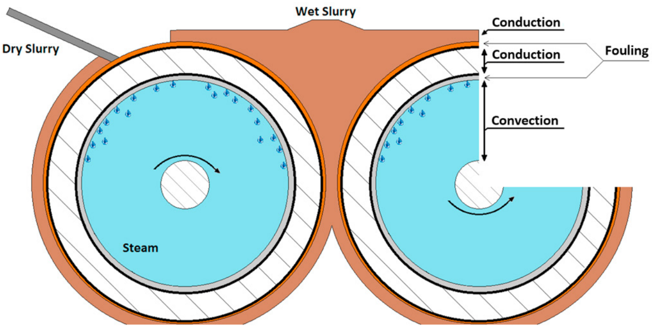


Fig. 1. Double drum-dryer schematics also showing the different heat transfer mechanisms included in the model: convection to define the heat transfer coefficient of the steam inside the drums, and conduction to describe heat transfer (i) through the drum walls and (ii) through the slurry layer. Fouling resistances have been also considered to account for condensed droplets on the inside surface of the drums and for residual slurry on the exterior surface.

$$\dot{Q} = U A_h \Delta T_{lm} \tag{1}$$

where A_h (m^2) is the heating surface of the drums, ΔT_{lm}(°C) is the logarithmic mean temperature difference between steam and slurry (considering different inlet and outlet slurry temperatures) and U (W/m^2°C) is the overall heat transfer coefficient, which has been calculated as a total thermal resistance [21] considering all layers and heat transfer mechanisms indicated in Fig. 1:

$$\frac{1}{U} = \frac{1}{h_{i0}} + \frac{1}{\kappa_{drum}} + \frac{1}{\kappa_{d-s}} + r_{di}\frac{d_0}{d_i} + r_{d0} \tag{2}$$

where, d_0(m) is the external diameter of the drum, d_i(m) is the internal diameter of the drum, r_{di}(m^2 °C /W) and r_{d0}(m^2 °C /W) are the resistance for the internal and external fouling, respectively [21]:

$$r_{di} = 1/f_{steam} = 1/3250 \;; r_{d0} = 1/f_{slurry} = 1/5000 \tag{3}$$

The condensation film coefficient for steam inside a horizontal tube h_{i_0} (W/m^2 °C) used in (2) is estimated as [21]:

$$h_{i0} = 0.76 k_l \left[\frac{\rho_l(\rho_l - \rho_V) g}{\mu_l \Gamma_h}\right]^{1/3} \tag{4}$$

where k_l(W/m°C), μ_l(Pa s) and ρ_l(kg/m^3) are the thermal conductivity, viscosity and density of the liquid state, ρ_V(kg/m^3) is the density of vapour, Γ_h(kg/ms) is the condensate loading and g(m/s^2) is the gravitational acceleration. The conduction coefficient for the dryer drum κ_{drum} (W/m°C) also used in (2) is calculated as follows [21]:

$$\kappa_{drum} = \frac{2 k_m}{d_0 \ln\left(d_0/d_i\right)} \tag{5}$$

where k_m(W/m°C) is the thermal conductivity of the drum surface (typically a metallic material). Finally, the conduction coefficient for the slurry κ_{d-s} (W/m °C) is defined as a function of the thermal conductivity k_{slurry}(W/m°C) and thickness τ_{slurry}(m) of the gelatinised slurry [21]:

$$\kappa_{d-s} = \frac{k_{slurry}}{\tau_{slurry}} \tag{6}$$

The rate of water evaporation (i.e. drying rate) $\dot{m}_w$ (kg/s) can be calculated from $\dot{Q}$ as follows:

$$\dot{m}_w = \left(\dot{Q} - \dot{Q}_h\right)/\Delta H_{vap} \tag{7}$$

where ΔH_{vap}(kJ/kg) is the vaporisation latent heat for water and $\dot{Q}_h$ is the sensible heat rate needed to heat up the slurry up to its vaporisation temperature. From the drying rate, the final water content in the dried product can be obtained through a simple mass balance:

$$x_w^{fin} = \left[\frac{m_{slurry}^{ini} x_w^{ini} - t_{res}\dot{m}_w}{\rho_{slurry}\, A_h\, \tau_{slurry} - t_{res}\dot{m}_w} \right] \quad (8)$$

where m_{slurry}^{ini} is the initial slurry mass, x_w^{ini} is the initial water content in the slurry (as mass fraction), ρ_{slurry} is the density of the slurry (kg/m^3) and $t_{res} = 60/\omega X_{scraper}$ is the residence time in seconds.

4. Energy-efficient operation conditions

A number of variables must be considered when designing an efficient operation for a double-drum dryer. First of all, the initial water content in the slurry; this, together with the target final water content x_w^{target}, defines the amount of water that needs to be removed. The thickness of the slurry sheet deposited on the drums also affects the rate of water removal (thicker sheets imply higher product throughputs) and can be varied by adjusting the gap (clearance) between drums. The overall heat transfer rate depends directly on the drums dimensions (length L and diameter d_0), and angle of the scrapers, as they defined the available heating surface. Finally, from an operational point of view, there are two main variables that can be manipulated [12] (and so controlled and/or optimised):

(i) the input steam temperature T_{steam} (ºC), which depends on the slurry formulation (e.g. water content, flour mixture) and it is chosen according to the desired characteristics of the final dried product [12].

(ii) the rotation speed of the drums ω (r.p.m), which is set to adjust the final moisture content of the product and defines the residence time of the operation.

According to this, different slurry formulations and thicknesses (i.e. product conditions) can be assessed to find those operational conditions - defined through ω *and* T_{steam} - that lead to reduced energy demand scenarios (Q_{red}). Formally, this can be done by minimising Q subject to the process dynamics defined by equations (1)-(8) and the following constraints:

$$x_w^{fin} = x_w^{target} \quad (9)$$

$$\dot{m}_w = \dot{m}_w^{target} \quad (10)$$

$$\dot{Q} = \dot{Q}_{target} \quad (11)$$

$$100 \le T_{steam}\left(℃\right) \le 300 \quad (12)$$

$$1.5 \le \omega\left(\text{r.p.m.}\right) \le 15 \quad (13)$$

where equation (9) is an end point constraint related to the target final moisture content and equations (10) and (11) are related to the fulfilment of mass and energy balances. The upper and lower bounds for the manipulated variables are defined by (12) and (13) according to equipment technical specifications.

5. Results and Discussion.

To solve the optimisation problem proposed in Section 4, the dimensions of the drums have been set to L = 2 m and d_0 = 1 m, with $X_{scraper}$ = 5/6, which leads to a heating surface for each drum of $A_h = 5\pi L d_0/3$. It has been also considered that the slurry is cooked in a previous step, and the corresponding gelatinisation temperature of the mixture is used as the slurry temperature T_{slurry} (ºC) when is poured onto the drums. Results show wo different slurry compositions obtained using (i) only oat flour and (ii) a mixture of rice, maize and oat flours at varying mass fractions, with a constant throughput in both cases of $\dot{m}_{slurry}$= 250 kg/h. The effect of different initial and final moisture contents, as well as the effect of the slurry thickness have been evaluated.

5.1. Oat slurry

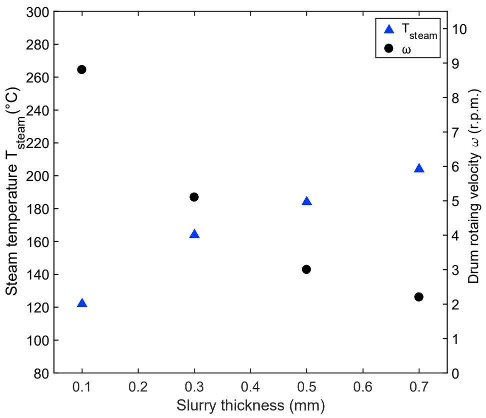
The effect of the final moisture content in the dried product has been evaluated for a (gelatinised) slurry with an initial water content of $x_w^{ini} = 0.8$ (kg water/kg slurry). The cereal used in this case was oat flour ($x_{oat}^{ini} = 0.2$). Thermal properties for oat flour – also for rice and maize flours – have been taken from [22]. Table 1 presents optimal steam temperatures T_{steam} and drum velocities ω, alongside energy consumption values for the double-drum dryer $\dot{Q}$(kJ/s). These results show that the energy consumption of the double-drum dryer increases (with linear dependence) when the final moisture content decreases, reaching its maximum (652 kJ/s) for the lowest moisture target (4%) assessed. The increase on the energy demand is also linked to higher steam temperatures and shorter residence times (i.e. faster rotation of the drums).

Table 1. Optimal values for the manipulated variables together with corresponding energy consumption values calculated considering an oat slurry (80% water, 20% oat flour) and a range of final moisture contents.

Target final moisture content (%)	T_{steam} (ºC)	ω (rpm)	$\dot{Q}_{red}$(kJ/s)
4%	169	5.3	652
6%	167	5.2	635
8%	164	5.1	618
10%	162	5.0	601
12%	159	4.8	584

The variation of the manipulated variables for different thicknesses of the oat slurry is shown in Figure 2(a). Results suggest that thinner slurries can be dried in shorter times (i.e. faster ω) and at lower steam temperatures. As the slurry thickness increases, a larger amount of water must be evaporated. This results in a gradual rise of the steam temperature (i.e. faster heat transfer rates) coupled with a (steeper) reduction of the residence times (i.e. faster ω), which allows more time to reach the final target moisture content – fixed at 8% for this particular case.

Figure 2(b) presents T_{steam} and ω values corresponding to varying initial moisture contents of the oat slurry. In this case both manipulated variables show similar trends, with values rising as the initial water content of the slurry increases from 60% to 90%, and residence times decrease for higher T_{steam}, similarly to data presented in Table 1.



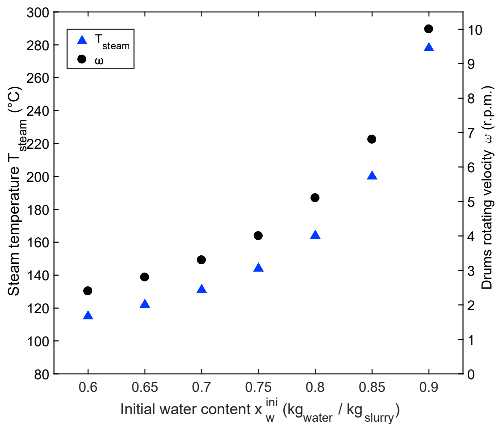
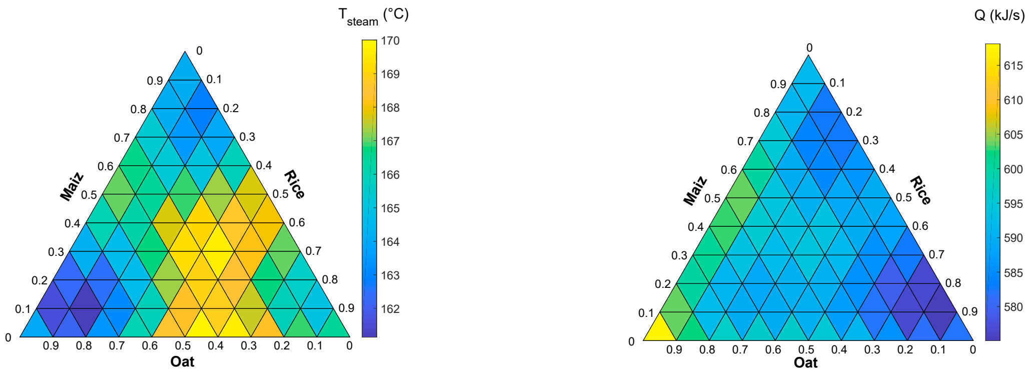


Fig. 2: Evolution of the manipulated variables T_{steam} (ºC) and ω (r.p.m) for an oat slurry with: (a) 80% initial water content and increasing thickness; (b) constant thickness and initial water content ranging from 60% to 80%.

5.2. Cereal mix slurry

The effect of different product formulation on the energy consumption of the double-drum dryer has been investigated using a varying mixture of oat, rice and maize flour that represents 20% of the slurry initial mass. The thickness of the sheet has been kept constant, as well as the initial water content (set up to 80%), which caused no variations on the drying rates, i.e. residence times and drums rotating velocities. Therefore, results for the steam temperature T_{steam} and the overall energy consumption of the double-drum $\dot{Q}$ are shown in Figure 3(a) and 3(b), respectively, using ternary graphs to represent all the possible flour combinations - each component (oat, rice or maize) varying from 0% to 100%.

Slightly higher steam temperatures (around 168ºC-170ºC) are required to dry mixtures of rice and oat flours (target final moisture set up to 8%), while mixtures with higher contents of maize flour could be processed at temperatures around 163ºC. However, this trend does not translate in terms of energy consumption: mixtures of rice and oat flours resulted in lower $\dot{Q}$ values (580 kJ/s – 590 kJ/s), intermediate energy values (~600 kJ/s) corresponded to maize and oat mixtures, while flour with oats as single components led to the highest energy consumption in the system (~615 kJ/s). This is a consequence of the different gelatinisation temperatures of the slurries. As $T_{gel}^{oat} < T_{gel}^{maiz} < T_{gel}^{rice}$, ΔT_{lm} (i.e. the difference between T_{slurry} and T_{steam}) is smaller for rice than for oats, which according to equation (1) must lead to also smaller values of $\dot{Q}$ for rice than for oats, as suggested by results presented in Figure 3(b).



(a) (b)

Fig. 3: (a) Steam temperatures and (b) energy consumption values obtained for slurries with a ternary composition of flours (rice, oat and maize). The initial water content is 80%, with a constant slurry thickness of 0.3 mm and a target final moisture content of 8%.

6. Conclusions

A model-based approach to the design of energy-efficient drying processes - one of the most energy intensive operations used in food manufacture - has been presented. Focusing on the manufacture of a cereal porridge, optimal steam temperatures and drum rotating velocities have been obtained for a double-drum dryer that minimise the overall energy required to dry the slurry. Different process variables, such as product formulation (e.g. flour composition, initial and final water content) or slurry throughputs (i.e. sheet thicknesses) have been assessed. Results reveal that there is potential for energy demand reduction by adjusting the water content (both initial and final) in the product formulation including the slurry throughput (i.e. slurry thickness) as variable to be optimised: thicker slurries require drying processes defined by higher steam temperatures and longer residence times, while medium/low temperatures and shorter residence times will be preferable for thinner sheets – a trade-off could be found through multiobjective optimisation (minimise energy, maximise drying rate).

This work demonstrates that further energy reductions can be achieved at short and medium term by using model-based approaches to the design and optimisation of current processing technologies. In addition, by setting the basis for more sustainable processing of food powders – products that are easy to use, pack, distribute and handle – this works also contributes to the development of an alternative supply scenario for dried products based on distributive manufacturing principles, where powders and dried components could be shipped (at lower costs), and rehydrated and/or used for other manufacture processes in points located closer to the consumer.

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