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Dimensionless Formulation of Convective Heat Transfer in Fry-Drying of Sewage Sludge

Fry-drying is an alternative for heat and mass transfer intensification. The process reuses waste oil as a heating medium for drying by contact with the wet sludge. At the end of the process, a stable derived fuel is obtained, a granular solid composed of the dried indigenous sewage solid and the impregnated oil. The fry-dried sludge is storable and transportable without any pathogen elements. Knowledge about heat and mass transfer rates during the frying process is essential in order to assess the quality of the final product such as calorific value, oil uptake, porosity changes, etc. The heat transfer properties including transfer by free convection between the solid and the frying oil are fundamental for the process design and manufacturing of the fry-dried product. The convective heat coefficient by temperature measurement and overall energy balance calculation is determined. The heat flux is calculated from the fry-drying kinetics including moisture loss and oil intake kinetics. Various hydrodynamic regimes for convective heat transfer during the frying process are discussed (non-boiling, boiling, and low-boiling regime). A dimensionless formulation for estimating the convective transfer is proposed.

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1 Introduction

The treatment of wet organic waste represents a major challenge for industries and communities. The main environmental, economical, and technological problems can heavily influence planning, design, construction, and operation of these waste management systems. As consequence of the increase of wastewater volumes, a total production of sewage sludge of 9786 million tons (dry solid) was recorded in 15 countries of the European Union in 2005 [1]. In order to reduce volume and weight of wet sludge and destroy toxics that may otherwise create adverse environmental impacts, current designs are based on drying with hot air. Despite the dewatering step that precedes thermal drying, evaporation of water from sludge requires considerable energy. Conventional drying with hot air necessitates high energy consumption. According to [2], the overall energy expenditure for evaporating 1 kg of moisture is 5000–7350 kJ kg⁻¹ water evaporated, which represents at least twice the latent heat of evaporation.

However, the typical energy consumption in boiling drying (e.g., fry-drying) is one times the latent heat of vaporization per kg of water evaporated (about 2450 kJ kg⁻¹ water evaporated). The fry-drying process is a new alternative to the heat-drying of sludge waste. It leads to major improvements over conventional processes commonly used: (i) production of a granular solid fuel with high heating value (15–25 MJ kg⁻¹), sterile, stored and transported safely [3,4]; (ii) distinct decrease in energy consumption by recovering heat contained in the steam (vapor compression and condensation); (iii) decrease in the dryer volume caused by heat and mass transfer intensification between wet solid and heated oil; (iv) lower environmental impacts compared to conventional heat-drying [5,6]. In this work, the heat and mass transfer during frying of sewage sludge with recycling cooking oil is evaluated.

The frying process involves drying by boiling, the dynamics of which is related to the nature of heat and mass transfer. The transfer mechanisms include diffusion of water toward the surface of the product, oil intake within the solid matrix, and heat input to the product. The thermal energy is transferred by convection and advection. Under this condition of drying, the oil provides energy to the product for the evaporation of water. Depending on the frying conditions, including mainly the surrounding pressure, the product immersed in the oil

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bath begins to boil at the saturation temperature of the steam. The temperature difference between frying oil and saturation temperature is the motor for natural convection. This temperature difference can vary between 10 and 40 °C [3] and is related to the boiling point elevation (3–10 °C) due to the presence of soluble impurities in the sludge. The energy supply by advection takes place by imbibition of some amount of oil in the product. This oil which is initially at the temperature of the frying oil releases a quantity of its sensible heat. When the different phases are in thermal equilibrium, their temperatures are the same. Convection is the major mode of heat transfer compared to advection. An experimental study of heat flow indicates that the convective flow is about ten times higher than the advection [7, 8]. Several parameters, such as the hydrodynamic regime in the solid-oil interface, geometry of the product, and temperature difference between frying oil and product surface, control the convective transfer. One of the most important mechanisms combining the different heat and mass transfer in frying is the hydrodynamic regime due to the boiling [9]. This hydrodynamic regime is more or less intense according to the flow of water vapor released around the product. Three following periods can be defined: (i) The first period corresponds to the rise of the sludge temperature at the time of immersion in the frying oil. In [10], this phase was filmed. This step takes only a few seconds before boiling occurs. (ii) The second period corresponds to the onset of boiling. Turbulence is more important with the increase of bubble flow, which gives rise to an elevation of convective exchange between product surface and frying oil. In that case, the convective heat transfer coefficient reaches high values of about 500 [11], 2500 [10], and 3500 W m²K⁻¹ [12]. (iii) The third period corresponds to a decrease in the boiling heat flux. When all free water is vaporized on the surface, the solids content increases and a crust is formed with thermal insulation properties [13]. During this last step, convective exchange between frying oil and crust occurs with a low boiling regime or without boiling. The convective heat transfer coefficient reaches minimum values around 200 [11] and 300 W m²K⁻¹ [10].

The convective heat transfer coefficient also depends on the temperature of the surrounding oil [14, 15]. Budzaki and Seruga [14] determined the heat transfer coefficient based on the influence of the frying temperature. The coefficient is increased with the oil temperature: 643, 695, 696, and 774 W m²K⁻¹ at 160, 170, 180, and 190 °C, respectively. Vitrac et al. [15] found higher coefficient values: 1700, 2300, and 3500 W m²K⁻¹ at 120, 150, and 180 °C, respectively.

This work focuses on the determination of the overall convective heat transfer coefficient in frying, using temperature measurement and calculation of the overall energy balance. The energy balance includes the variation of internal energy in the sludge, boiling, oil intake, and the convective heat exchange between frying oil and surface of sludge. The balance calculation is based on the assumption of an isothermal product. The heat flows in/out are determined by calculating the kinetics of frying, including both drying kinetics and kinetics of oil intake. Finally, a discussion of the various regimes is provided that influence the hydrodynamic

convective heat exchange during the frying process, and a dimensionless formulation for estimating the convective transfer is presented.

2 Development of Frying Kinetics

2.1 Problem Description

The energy transfer rates between a porous solid phase (sewage sludge) and a liquid phase (recycled cooking oil) during fry-drying of an industrial sludge were estimated. Fig. 1 illustrates the transfer of energy to and from a cylindrical product immersed in a hot oil bath. During the process, heat is transferred into the solid by hot oil, providing sensible heat to heat solids and vaporize water. Water vapor leaves the product surface to the surrounding oil at the total pressure of the oil bath. The product is thus brought to a temperature such that its vapor pressure equals the total pressure in the oil bath. The flow of steam within the product may occasionally be followed by some rise in pressure significantly greater than the total external pressure and is accompanied with agitation of bubbles at an irregular frequency. The steam bubbles and the high agitation around the product are the principal factors for the development of microcracks in the product structure. Peregrina [10] presented a microphotography of the sewage sludge before and after fry-drying and provided a picture of the sludge particle microstructure. Consequently, the contact surface between the product and the frying oils increases significantly, which promotes oil intake into the empty pores left by vapor. The oil intake thus leads to heat transfer into the product by advection. Here, the thickness of sludge sample is thin, and the change in temperature according to the radial direction is considered negligible. Therefore, heat transfer by conduction is not considered.

2.2 Governing Equations

The fry-dried sludge is considered as a complex porous media including water, oil, and the solid matrix. Commonly, the mathematical description of heat and mass transfer in a porous media is formulated over a representative elementary volume (Fig. 1). In spite of heat and mass transfer between the

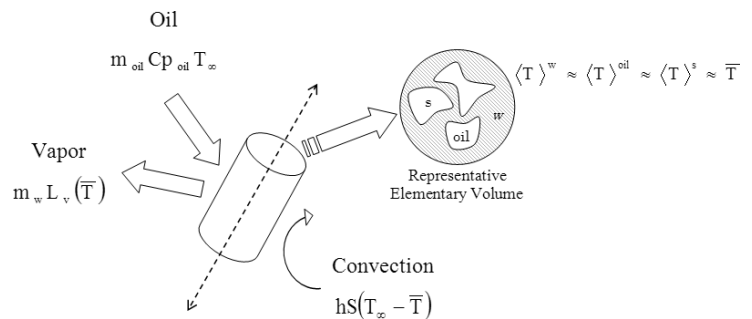


Figure 1. Schematic description of the heat transfer mechanisms in fry-drying of a cylindrical sludge particle immersed in the hot oil bath.

different phases, all components are assumed to be in local thermodynamic equilibrium and in particular are considered at the same temperature [13, 16]:

$$\langle T \rangle^w \approx \langle T \rangle^{\text{oil}} \approx \langle T \rangle^s \approx T \quad (1)$$

where T is the average equilibrium temperature between the phases. The energy balance equation in the sludge body may be written as follows:

$$\sum_{a \text{ w,oil,s}} \langle m_a \rangle C_{p_a} \frac{dT}{dt} = hS(T_\infty - T) - \dot{m}_a H_w + \dot{m}_{\text{oil}} H_{\text{oil}} \quad (2)$$

The left-hand side of Eq.(2) represents the time rate of change of internal energy of the sludge body. The first term on the right-hand side denotes the heat flux transmitted by thermal convection to the sludge, the second term stands for the rate at which energy is released by water vapor, and the last term denotes the transport of heat by thermal advection due to diffusion of frying oil within the porous matrix product.

The oil enthalpy at the surrounding oil temperature is given by:

$$H_{\text{oil}} = C_{p_{\text{oil}}} T_\infty \quad (3)$$

Fick's law of diffusion is used to calculate the water transfer rate in the product. The basic one-dimensional mass diffusion equation is:

$$\frac{\partial m_w}{\partial t} = \frac{\partial}{\partial r} \left(D_w \frac{\partial m_w}{\partial r} \right) \quad (4)$$

where m_w (% kg water by kg fried product) is the local moisture content.

The water transfer is described as a diffusion mechanism. This is a global quantitative interpretation which gives no detailed description of the actual mechanisms involved in frying. By using this approach, a local concentration profile can be determined.

The mass transfer boundary condition for moisture at the center of the cylinder is [13, 17]:

$$\left. \frac{\partial m_w}{\partial r} \right|_{r=0} = 0 \quad (5)$$

At the surface of the product, moisture is in instantaneous equilibrium with oil [18]. The boundary condition takes the form:

$$m_w(R, t) = \langle m_w \rangle_{\text{eq}} \quad (6)$$

$\langle m_w \rangle_{\text{eq}}$ is the equilibrium moisture content determined from long-term experiments and calculation. Moreover, during calculation, this parameter is still not known until the end of the frying process. Therefore, a very low value (4% w.b.) is attributed to the moisture content at the surface of the product as boundary condition.

The initial condition is the following:

$$m_w(r, 0) = \langle m_{w,0} \rangle \quad (7)$$

A physical model is used to describe oil imbibition. Oil uptake is assured to fill the space left by water during boiling. The expression was given by Romdhana et al. and experimentally validated [3, 19]:

$$\langle m_{\text{oil}} \rangle = \frac{\rho_{\text{oil}}}{\rho_w} (\langle m_{w,0} \rangle - \langle m_w \rangle) \quad (8)$$

The average moisture content $\langle m_w \rangle$ is calculated by numerical integration of the local concentration at each time step.

$$\langle m_w \rangle = \frac{1}{V} \int_V m_w dV \quad (9)$$

Finally, the two mass flows are calculated from the average water $\langle m_w \rangle$ and oil $\langle m_{\text{oil}} \rangle$ contents in the fried product.

$$\dot{m}_a = \frac{d \langle m_a \rangle}{dt} \quad a = \text{w, oil} \quad (10)$$

3 Modeling of Thermal Convection

The convective exchange coefficient can be estimated from correlations between similarity invariants. Convection is related to three hydrodynamic regimes (non-boiling, low-boiling, and boiling regime) of oil around the product during the frying process.

- (i) Non-boiling regime: this step shows the periods of frying without boiling and in particular the beginning of the process for which the product temperature rises.
- (ii) Low-boiling regime: this regime means the period during which boiling is very low and energy intake is converted into sensible heat. The correlations in free convection can satisfy these two regimes (non-boiling, low-boiling). Therefore, average Nusselt ($\text{Nu} = \frac{2hR}{\lambda}$) numbers are expressed as functions of the descriptive geometrical and thermal parameters covering the Grashof and Prandtl numbers:

$$\text{Nu} = f(\text{Gr}, \text{Pr}) \quad (11)$$

In this particular case, the convective heat transfer coefficient can be estimated directly from correlations obtained for natural convection and developed for a horizontal cylinder in a cross flow:

$$\text{Nu} = a(\text{Ra})^b \quad (12)$$

where a and b are 0.52 and 0.25, respectively, given by Whitaker [16], Ra being the Rayleigh number expressed as:

$$\text{Ra} = \frac{g\beta(T_\infty - T_{\text{sur}})}{\nu a} \quad (13)$$

- (iii) Boiling regime: the phase change occurring on the surface of the product leads to a high boiling rate. The increased bubble flow unleashes an intense agitation and turbulence. For this purpose (i.e., boiling regime), the convective heat transfer coefficient depends on the evaporation flux. Costa [9] proposed a linear correlation between the coefficient of convection and steam flow:

$$h = h_{\min} + C^{\text{st}} \dot{m}_w \quad (14)$$

In order to rewrite this expression in dimensionless form and especially the relation to the physical and thermal frying oil, it is found that the expression of the convection coefficient may be written as:

$$h = C_1^{\text{st}} + C_2^{\text{st}} \xi \quad (15)$$

where ξ is the normalized evaporation rate:

$$\xi = \frac{\dot{m}_w}{\dot{m}_w^{\max}} \quad (16)$$

During the first phase of drying, the product temperature is initially lower than the saturated vapor and the evaporation rate is substantially low or even zero (i.e., $\xi \ll 1$). Under these conditions, the heat transfer is minimal since frying oil motion is restricted. Then, the first constant in Eq. (15) can be expressed as:

$$C_1^{\text{st}} = h_{\min} \quad (17)$$

where h_{\min} is the heat transfer coefficient during the non-boiling/low-boiling regime, estimated from Eq. (12).

During the second drying period, the evaporation rate depends essentially on the heat transferred by convection. Therefore, the evaporation rate is maximum (i.e., $\xi = 1$) when the heat transfer is the highest. Then, the second constant in Eq. (15) can be expressed as:

$$C_2^{\text{st}} = h_{\max} - h_{\min} \quad (18)$$

where h_{\max} is the convection heat transfer coefficient which is maximum at the beginning of frying and depends on the temperature difference between frying oil and water boiling temperature. Finally, we can express Eq. (15) as a function of dimensionless quantities:

$$\text{Nu} = \xi \text{Nu}_{\max} + a(1 - \xi)(\text{GrPr})^b \quad (19)$$

4 Thermal and Physical Properties

The mathematical model requires physical and thermal property data of the sludge to be fried and the process conditions used. The moisture diffusion coefficient is calculated from the following correlation in which the surrounding oil temperature is expressed in °C [3, 19]:

$$D_w = 1288 \cdot 10^{-8} \exp\left(\frac{518.4}{\theta}\right) \theta \frac{T_{\infty} + T_0}{2} \quad (20)$$

The specific heat of the solid phase is experimentally determined using a calorimetric thermobalance (TG-DSC 111). The following correlation is valid:

$$C_{p_s} = (83T - 0.97T^2 - 44) \times 10^3 \quad (21)$$

The following linear correlations are used to describe the density and specific heat of recycled cooking oil [10]:

$$C_{p_{\text{oil}}} = 2009.84 + 2.92T \quad (22)$$

$$\rho_{\text{oil}} = 934.43 - 0.6379T \quad (23)$$

The thermodynamic properties of water are calculated from the formulation suggested by the International Association for the Properties of Water and Steam (IAPWS-95) [20].

The following conditions were set for this case study, i.e., horizontal cylinders, $R = 2$ mm having an initial temperature of $T_0 = 20$ °C and immersed in oil at $T_{\infty} = 160$ °C with the following properties: kinematic viscosity, $\nu = 3.6 \cdot 10^{-6}$ m²s⁻¹; thermal diffusivity, $\alpha = 1.3 \cdot 10^{-7}$ m²s⁻¹; thermal volumetric expansion coefficient, $\beta = 7.7 \cdot 10^{-5}$ K⁻¹, and thermal conductivity, $\lambda = 263 \cdot 10^{-3}$ Wm⁻¹K⁻¹.

5 Materials and Methods

The sewage sludge used in the experiments was produced by TEMBEC SA Co. (Saint-Gaudens, France), manufacturer of pulp paper. The frying oil was provided by the Sud Recuperation Co. (France). It is primarily used oil collected from restaurants and food industry.

The experiments were carried out in an electric-powered fryer with a capacity of 5 L of oil and an electrical resistance of 2 kW submerged at the bottom of the tank. The oil temperature was kept at the required temperature by a PID controller. One impeller driven by an adjustable speed motor was added to the device. A light-speed stirrer was adjusted to homogenize the oil temperature through the tank.

Frying is very turbulent so that the product may move around randomly in the oil. Therefore, in order to measure its temperature, the sludge is extruded into a metallic grid cylinder with a mesh of 1 mm (Fig. 2). Sample diameter and length are 8 mm and 32 mm, respectively. The initial moisture content of sewage sludge is quantified between 1.47 and 1.53 (dry basis). A sludge sample is immersed in oil with three thin thermocouples (K-type microthermocouple, 2/10 mm wire diameter and 5/10 mm welding thickness).

Temperature history is monitored at three locations in the sample, at the center ($r = 0$ mm), the intermediate ($r = 2$ mm), and the surface ($r = 4$ mm). The frying oil temperature is set for these experiments at 110, 120, 130, and 140 °C. A data logger is used to acquire real-time sample and frying oil temperature.

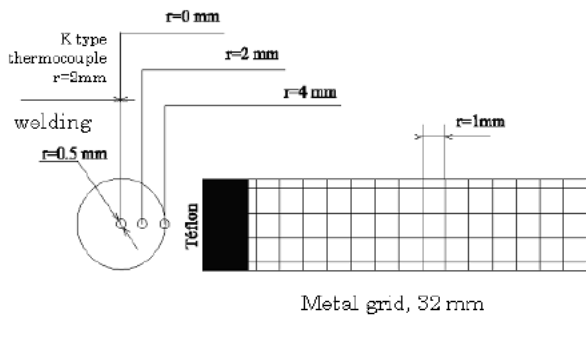


Figure 2. Detail of the sample container and microthermocouples.

6 Results and Discussion

Analysis of heat and mass transfers during fry-drying of sewage sludge is based on the drying kinetics, oil intake, and bulk temperature curve. The partial differential equation (PDE, Eq. (4)) is solved in MATLAB using the solver *pdepe* which solves initial-boundary value problems for parabolic-elliptic PDEs. Then, the result of local moisture content is integrated (using the *quad* function in MATLAB) in order to predict overall moisture content and oil intake (Eq. (8)) at each time step. The temperature required to calculate the heat energy balance is estimated from the average local temperature. The bulk temperature during frying time and the calculation of mass flux (water loss and oil intake) are used to predict the energy spent on water evaporation and the energy added through oil uptake.

Fig. 3 displays the product temperature profile monitored at different depths in the sample, namely at the surface (i.e., $r \approx 4$ mm), at the geometrical center (i.e., $r \approx 0$ mm), and in the middle of those points (i.e., $r \approx 2$ mm). The three periods are well observed. Initially, the product temperature increases to the boiling point of water. This period follows the immersion

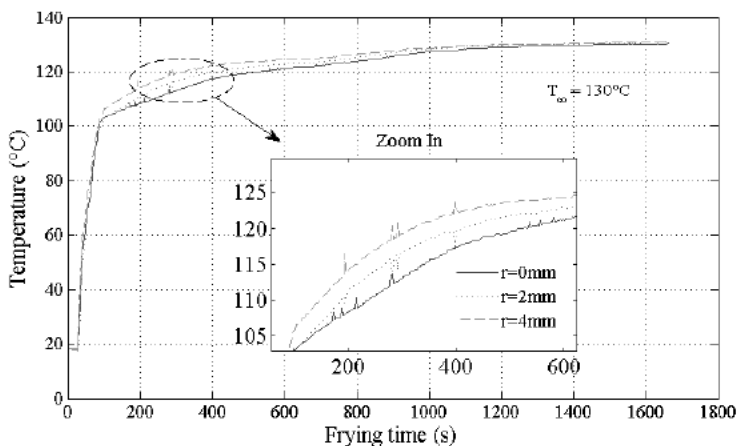


Figure 3. Sludge temperature profile during fry-drying at 130 °C, using a sample diameter of 8 mm.

of the sample and takes several tens of seconds. The second period corresponds to the boiling step, in which case the temperature profile is not exactly homogeneous [21, 22]. The product temperature continues to rise but more gently than in the first period. Although the product contains free-water surface, the temperature is well above the saturated steam temperature. This indicates that the internal heat transfer is also controlled by the oil intake. The end of drying (last period) is initiated by the critical water content below which the drying rate decreases. During this period, the drying rate is governed by a combination of three phenomena: (i) the rise of the product temperature and thus the decrease of the temperature difference ($T_\infty - T$) for external heat transfer and, therefore, of the heat transfer by convection, (ii) the flow of vapor to the surface of the product increases locally the temperature and reduces local heat input, (iii) the water mobility is very low and the attractive forces between the product components are very high, then the energy required to extract the remaining water becomes higher.

The average heat transfer coefficient h is determined during the frying time and is defined as the rate of heat convected at the sludge surface if a unit temperature gradient exists between product surface and surrounding oil. The heat transfer coefficient rises quickly at the beginning of frying and peaks at about 48–168 s of frying depending on the supplied frying temperature ($T_\infty = 110 \rightarrow 140^\circ\text{C}$). The achieved maximum is higher for higher oil temperatures. The maximum values are estimated as 900, 1100, 1400, and 1700, respectively, for the temperatures 110, 120, 130, and 140 °C. After reaching the maximum, h decreases during frying and stabilizes between 200 and 100 $\text{W m}^{-2}\text{K}^{-1}$. These values agree with those reported by Peregrina [10] and Hubbard and Farkas [12].

Fig. 4 presents the heat transfer coefficient calculated from the dimensionless Eq. (19). The coefficient values are aligned with those determined from the energy balance. The different regimes are clearly defined (non-boiling, low-boiling, and boiling regime). When the product temperature reaches the boiling point, the water pressure on the product surface is in equilibrium with that of the saturated steam. Under these conditions, the boiling begins. At this time, the evaporation rate is very important because most of the vaporized water is free water (and/or free-water surface). Then, the kinetics decreases because the water activity decreases in the product. Most of the evaporation rate is produced from the internal water diffusion and thus requires more energy. At the end of the process, the kinetics is very slow because the temperature difference decreases.

At the beginning of frying, the convective heat transfer is very high, thus providing an important amount of oil in the product. Therefore, the product is considered a good fuel with high net calorific value (Fig. 5). For low convective heat transfer coefficients, frying is becoming increasingly difficult and energy consumption increases. Therefore, it is useless to continue the process until the last period of frying.

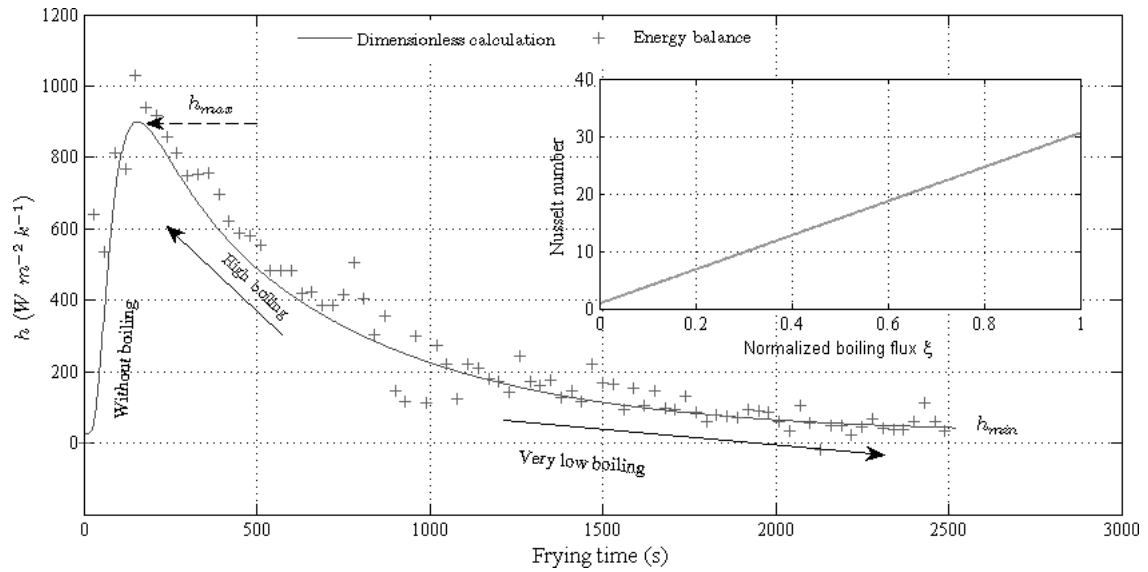


Figure 4. Evaluation of convective heat exchange coefficient according to the hydrodynamic regime of frying oils.

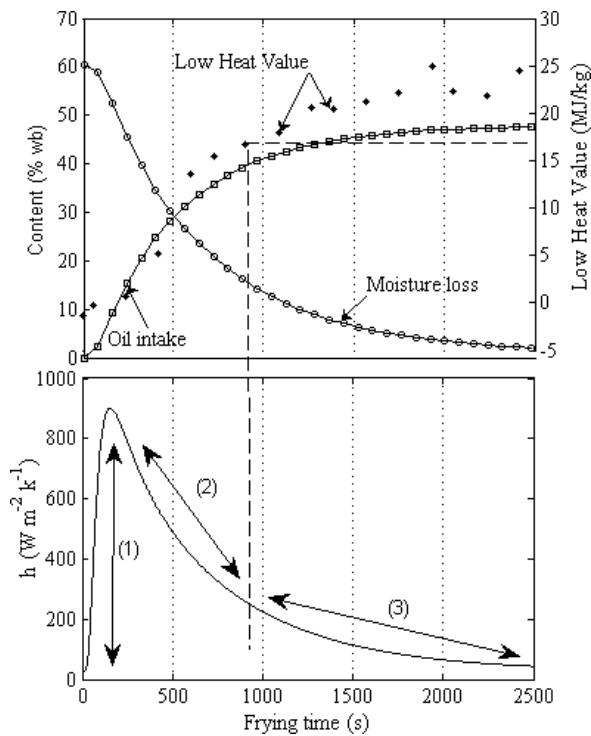


Figure 5. Lower heating value of fried sludge during the process time, according to [3].

7 Conclusions

During the frying process, the heat and mass transfer is particularly complex with the presence of several phases (solids, liq-

uid water bound/free, steam, immiscible phases). A complete description of transfers requires a characterization of transport phenomena in porous media, thermal interactions between phases, and different phenomena that can interact passively as the condensation. Despite the complexity of the topic, this study has been conducted by considering some simplifying assumptions: (i) the material has a uniform temperature; (ii) local equilibrium temperature is assumed between the different phases. This allowed establishing an overall balance for an isothermal product.

The heat transfer coefficient by convection is determined from experiments performed on a cylindrical sample of sewage sludge by temperature measurement and calculation of frying kinetics. The value of the critical convection coefficient (h_{max}) is more important if the product is fried at high temperatures. At the end of drying, the heat transfer coefficient is stabilizing around a low value (h_{min}) that corresponds to natural convection calculations.

A preliminary assessment of the exchange coefficient demonstrates that it depends on the hydrodynamic oil around the product. Three regimes can be considered, namely, non-boiling, low-boiling, and boiling regime. The validation of the proposed correlation remains to be demonstrated with a larger number of experiments.

Based on this work and experimental data, a pilot apparatus has been sized with a treatment capacity of about 40–100 kg h⁻¹ of wet sludge. The process relates to the manufacturing apparatus and manufacturing method of solid fuel from organic sludge and organic waste, in which various organic sludges and organic wastes of a desired type with a moisture content of 40–90% are put into oil for the fry-drying technology, which is fried for 5–25 min, so that the moisture in the sludge is rapidly vaporized and thus the moisture content is lowered to 1–20 wt-%; thus, a calorific value of the sludge is increased to 15–20 MJ kg⁻¹.

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Symbols used

| | | |
|-----------------|-----------------------------------|--------------------------------------|
| C_p | $[\text{J kg}^{-1}\text{K}^{-1}]$ | specific heat |
| C^{st} | $[-]$ | constant |
| D | $[\text{m}^2\text{s}^{-1}]$ | diffusion coefficient |
| h | $[\text{W m}^{-2}\text{K}^{-1}]$ | convection heat transfer coefficient |
| H | $[\text{J kg}^{-1}]$ | enthalpy |
| g | $[\text{m s}^{-2}]$ | acceleration due to gravity |
| m | $[\text{kg kg}^{-1}]$ | mass fraction |
| \dot{m} | $[\text{kg s}^{-1}]$ | mass flow |
| r | $[\text{m}]$ | radius of cylindrical particle |
| R | $[\text{m}]$ | characteristic radius |
| S | $[\text{m}^2]$ | product surface |
| t | $[\text{s}]$ | frying time |
| T | $[\text{°C}]$ | temperature |

Greek letters

| | | |
|-----------|----------------------------------|-------------------------------|
| α | $[\text{m}^2\text{s}^{-1}]$ | thermal diffusion coefficient |
| β | $[\text{K}^{-1}]$ | thermal expansion coefficient |
| λ | $[\text{W m}^{-1}\text{K}^{-1}]$ | thermal conductivity |
| ν | $[\text{m}^2\text{s}^{-1}]$ | kinematic viscosity |
| ρ | $[\text{kg m}^{-3}]$ | density |
| ξ | $[-]$ | normalized evaporation |

Subscripts

| | |
|----------|--|
| 0 | initial value |
| min | minimum |
| oil | denotes quantities associated with oil |
| s | solid phase |
| sur | surface product |
| w | water phase |
| ∞ | surrounding oil |

Dimensionless numbers

| | |
|----|----------|
| Gr | Grashof |
| Nu | Nusselt |
| Pr | Prandtl |
| Ra | Rayleigh |

Operator

$\langle \dots \rangle$ volume average of the associated quantities in the considered phase

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