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Analysis and simulation of continuous food frying processes

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ABSTRACT

Frying is a very energy intensive process as it invariably involves the evaporation of significant quantities of water from the food product. The process is also complex to control due to the variability of raw materials, the large number of parameters involved and the interactions between these parameters. Good control of the process is, however, important as it determines not only the final product quality attributes but also has a significant influence on energy consumption. This paper presents a quasi steady state model for the simulation of a continuous frying system. The model which was implemented in the MATLAB/Simulink environment has been shown to reproduce data from an industrial crisp production line with a reasonable degree of accuracy. The model can be used to investigate the impact of different design and control strategies on energy consumption.

1. Introduction

With rapidly increasing energy prices and globalisation, food manufacturers seek opportunities to reduce production costs without adversely affecting output, profitability and the quality of their finished products. Investment in energy-efficient technologies can make a significant contribution towards reducing production costs. Energy-efficient technologies can also offer additional benefits, such as quality improvement, and improved environmental performance in terms of reductions in CO_2 emissions and other pollutants.

The food and drinks industry is a significant user of resources such as water, energy, and packaging materials and generates substantial quantities of waste and emissions. For these reasons it faces increased pressure from national governments and international organisations to improve resource use. The greenhouse gas footprint of the UK food chain is in the region of 160 MtCO2e and food manufacturing is responsible for around 13 MtCO2e and primary energy consumption of 42 TW h [1]. In food manufacturing approximately 68% of the energy is used by fuel fired boilers and direct heating systems for process and space heating. From the remainder, 16% is electrical energy used by electric motors, 8% is used by electric heating, 6% by refrigeration equipment and the remainder 2% by air compressors [2].

Frying is a common process in food manufacture and is also one of the oldest food preparation methods in existence. A wide range of fried food products have been developed over the years, which include convenience foods such as chicken and fish products, doughnuts, potato chips, and a rapidly expanding range of snack foods such as potato crisps and many other products based on corn, rice and wheat. Frying is a process in which food is cooked whilst floating or being immersed in hot oil. The latter is also known as deep fat frying and, in essence, is a fast dehydration process, in which water is removed from the food by rapid heating in oil. In addition to providing heat for cooking, the frying oil also becomes a component of the end product. The quantity of oil in the product can vary from as little as 10% by weight in breaded fish sticks to 40% in potato chips [3]. The quantity of oil absorbed by the food is a function of many factors which influence the heat and mass transfer between the oil and the food. These factors include the type of food, the characteristics of the oil and frying conditions.

Potato crisps are by far the largest single category of savoury snack food in the UK with annual sales in excess of £2.0 billion [4]. Crisps are normally produced commercially in a continuous frying process which is fed by a serial production line. In the line, described in more detail by Wu et al. [5], the raw potatoes are first washed, then peeled and sliced, with the slices washed again and dewatered before they are fed to the fryer. The continuous production requires tight control of throughput and high degree of reliability to avoid process disruptions and production losses. This is complicated by variability in the raw material properties, for example, size and water content of potatoes, and nonlinearities arising from the chemical reactions taking place during frying. In the production of potato crisps, the frying system consumes more than 80% of the total processing energy requirement so the greatest potential for energy savings is offered by design and control

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Nomenclature

A	surface area, m^2
c_p	specific heat, kJ/kg K
CV	calorific value, kJ/m^3
h_{Ca}	heat transfer coefficient of the ceasing of the combustor, kW/m^2 K
h_{fa}	heat transfer coefficient of the ceasing of the fryer, kW/m^2 K
h_{fg}	latent heat, kJ/kg
H	oil level inside the fryer, m
J_1	constant, 1/K s
J_2	constant, 1/s
k_m	rate of moisture loss, 1/s
k_o	rate of oil uptake, 1/s
K_1	constant, 1/s
K_2	constant, 1/K s
$\dot{m}$	mass flow rate, kg/s
Q	thermal energy, kW
Q_{Cw}	ambient loss through combustor wall, kW
t	time, s
T	temperature, K
V	volume, m^3
X	composition percentage, %

Greek letters

ε_s	correction factor density,
η	efficiency, %
ρ	kg/m^3
σ	Stefan–Boltzmann constant, W/m^2 K^{-4}

Subscripts

a	air
amb	ambient
c	combustion products
C	combustor
CHE	combustor and heat exchanger
eq	equilibrium
f	fryer
fo	frying oil
fw	transmission through external wall of the fryer
i	initial
in	inlet
o	oil
out	outlet
o,13	oil in fines removal
o,14	oil in potato crisp
ps	potato slice solid
pw	water in potato slices
s	potato solid
s,10	potato solid in raw potato slices
s,14	potato solid in potato crisp
SC	surface of combustor
Sf	surface of fryer
surf	surrounding wall surface
w	water
w,10	water in raw potato slices
w,14	water in potato crisp
1	fuel
2	combustion air
3	foul gas
4	re-circulated exhaust gas
5	combustion products
6	exhaust gas
7	oil inlet
8	oil outlet
9	air flow
10	raw potato slices
11	surface water of raw potato slices
12	oil return
13	fines removal
14	potato crisp

optimisation of the frying system to minimise the thermal energy input to the fryer and reduce losses [6].

Most of the published work on the optimisation of frying systems has concentrated on the investigation and modelling of the heat and mass transfer processes in the potato slices during frying. Many of these have considered and combined heat and mass transfer principles to describe the temperature and moisture content profiles of the product [7,8] whilst others have concentrated on empirical [9,10] and semi-empirical [11] relationships for heat and mass transfer. The vast majority of this work was carried out in the laboratory using batch frying systems. Only limited work has been reported on continuous frying systems and their control [12–14]. Rywotycki [12] presented an analytical model of heat energy consumption during the process of food frying. It was concluded that the analysis of energy balances in the process of food frying makes possible formulating detailed mathematical models allowing calculation of power requirements for actual conditions. Brescia and Moreira [13], analysed the dynamics of a continuous frying process using X (exogenous input), ARX (autoregressive with exogenous input), and ARMAX (autoregressive moving averaging with exogenous input) models. They concluded that both ARX and ARMAX models could simulate the process adequately and final colour and oil content could be used as the control parameters for the process. Rywotycki [14] explored the application of fuzzy logic control to a continuous frying system developed in the laboratory. It was identified that it would be feasible to use automatic control of frying parameters, based on fuzzy logic, to match individual consumer preferences for the characteristics of the final fried product.

In large industrial continuous frying systems, the operation of the fryer is directly linked to the operation of the oil heating system. Effective control to maintain product throughput and quality and at the same time reduce energy consumption requires understanding of the behaviour and interactions between the two systems. The limited work published in the open literature so far, concentrated only on the fryer. The authors, in a previous publication [1], presented a steady state analysis of the energy flows in the frying system that includes the fryer, the combustor and the heat exchanger. The work was aimed at quantifying the energy flow streams and identifying opportunities for energy conservation.

This paper presents a quasi steady-state simulation of the whole frying system. The model was developed in the MATLAB/Simulink environment because of its built-in algorithm control design, optimisation toolbox and simulation capabilities. The model was validated using data from an industrial crisp production line that employs a continuous frying system. Even though steady state simulation is popular for its computational efficiency, dynamic simulation can provide a greater insight into the behaviour of the system as the operating states change, particularly when the response of the system to this changes is very fast. In the present analysis, a quasi steady state modelling approach has been employed to consider its applicability to the simulation of the complete frying system as a first step in the identification of the most suitable approach for integrated frying system simulation and control.

2. Description of the frying system and governing equations

The frying system, shown schematically in Fig. 1, consists of three major components: the combustor, the oil heat exchanger and the fryer. In the combustor, a gas burner burns natural gas with fresh air and foul gas (vapours from the fryer) to produce combustion gases that flow through a heat exchanger to heat up the frying oil that is re-circulated through the fryer. In many cases exhaust gas recirculation is used to increase turbulence, provide combustor surface cooling and reduce emissions. To reduce emissions and smells, vapours generated from the frying process are directed from the fryer to the combustor where they are incinerated.

2.1. Combustor

In this study, combustion of methane (CH_4) is modelled by a one-step global reaction mechanism, assuming complete conversion of the fuel to CO_2 and H_2O. The stoichiometric combustion equation is given as:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

For complete combustion the theoretical air to fuel ratio is 17.1 by mass. In practical applications excess air is used to ensure that sufficient air for complete combustion is always available. For the case of this study an excess air quantity of 20% was assumed, which gives an air to fuel ratio of 20.5. Referring to Fig. 2, the mass and energy balance equations for the combustor can be written as follows:

Applying the conservation of mass equation,

$$\frac{d(\rho_c \cdot V_C)}{dt} = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 - \dot{m}_5 \quad (1)$$

where ρ_c is the density of combustion products ($\rho_c = \rho_5$ in Fig. 2), V_C is the control volume of the combustor and t is the time. The total

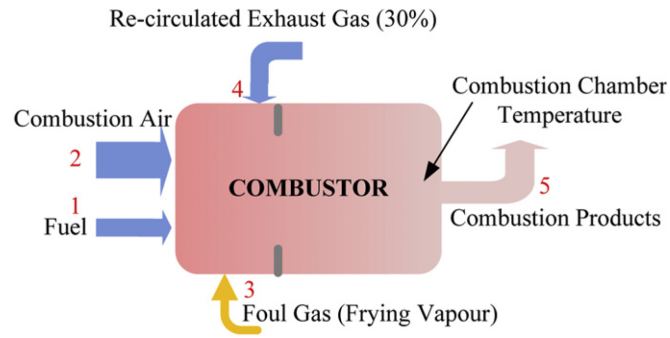

Fig. 2. Schematic diagram of flows through the combustor.

mass flow rate of combustion products ($\dot{m}_5$) is equal to the sum of the input rates for fuel ($\dot{m}_1$), combustion air ($\dot{m}_2$), foul gas ($\dot{m}_3$) and re-circulated exhaust gas ($\dot{m}_4$).

The change of temperature in the combustor can be determined by the difference in heat input and output at a given time interval,

$$\frac{d(\rho_c \cdot V_C \cdot c_{pc} \cdot T_c)}{dt} = Q_1 + Q_2 + Q_3 + Q_4 - Q_5 - Q_{Cw} \quad (2)$$

where c_{pc} is the specific heat of the combustion products ($c_{pc} = c_{p5}$ in Fig. 2), T_c is the temperature of the combustion products ($T_c = T_5$).

Q_1 is energy input by the combustion of fuel.

$$Q_1 = \dot{m}_1 \cdot CV_1/\rho_1 \quad (3)$$

CV_1 and ρ_1 are the lower calorific value and density of fuel, respectively.

Q_2, Q_3 and Q_4 are the energy inputs to the combustor by the combustion air, the foul gases and re-circulated exhaust gases respectively. Q_5 is the energy in the products of combustion before entry to the heat exchanger. These quantities can be determined by multiplying the respective mass flow rates with the respective specific heats and temperatures of each flow stream. Q_{Cw} is the heat loss to the ambient through the combustor wall given by:

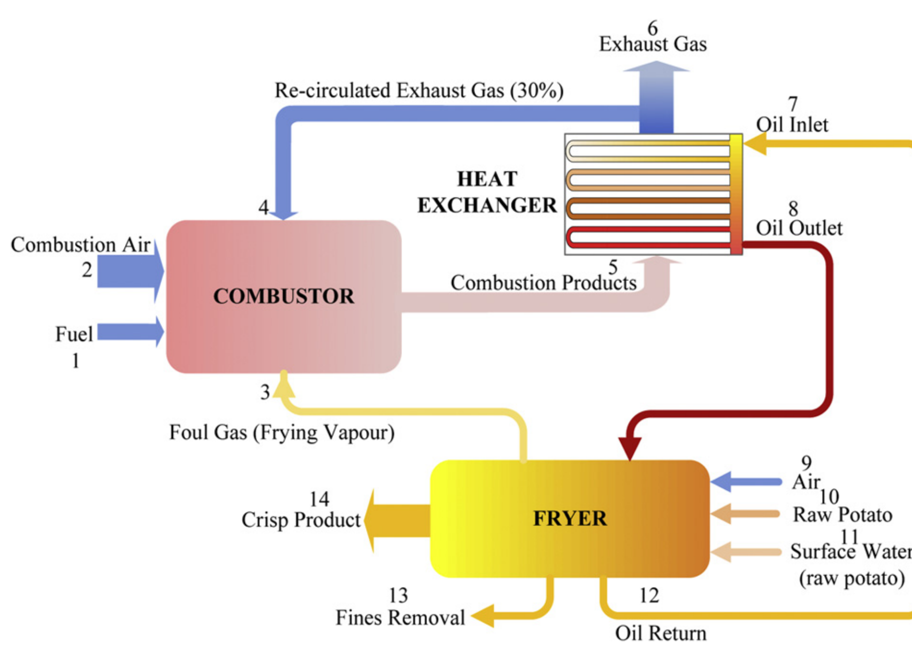

Fig. 1. Schematic diagram of frying system.

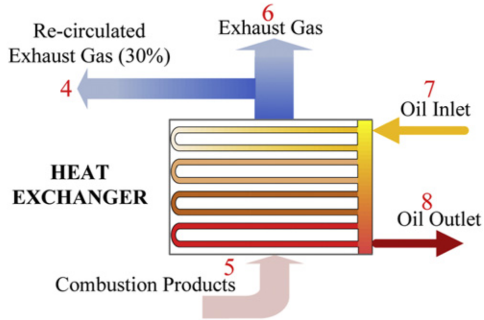

Fig. 3. Schematic diagram of flow streams through the heat exchanger.

$$Q_{CW} = h_{Ca} \cdot A_{SC} \cdot (T_C - T_{amb}) + \varepsilon_{SC} \cdot A_{SC} \cdot \sigma \cdot \left(T_C^4 - T_{surf}^4\right) \quad (4)$$

where h_{Ca} is the convective heat transfer coefficient of the casing of the combustor, A_{SC} is surface area of the combustor, T_C is the temperature of the external combustor wall, ε_{SC} is the emissivity (dimensionless) of the combustor and σ is the Stefan–Boltzmann constant (5.669×10^{-8} W/m^2 K^4). T_{amb} is the average ambient temperature for the location at which the system under consideration operates and T_{surf} is the temperature of the surrounding wall surfaces. In this analysis T_{amb} and T_{surf} were assumed to be 25 °C and 15 °C respectively.

Substituting Eqs. (3) and (4), into Eq. (2) gives:

$$\begin{aligned}\rho_5 \cdot V_C \cdot c_{p5} \frac{dT_5}{dt} &= \dot{m}_1 \cdot CV_1/\rho_1 + \dot{m}_2 \cdot c_{p2} \cdot T_2 + \dot{m}_3 \cdot c_{p3} \cdot T_3 \\ &+ \dot{m}_4 \cdot c_{p4} \cdot T_4 - \dot{m}_5 \cdot c_{p5} \cdot T_5 \\ &- \Big[h_{C\to a} \cdot A_{SC} \cdot (T_C - T_{amb}) \\ &+ \varepsilon_{SC} \cdot A_{SC} \cdot \sigma \cdot \left(T_C^4 - T_{surf}^4\right)\Big] \quad (5)\end{aligned}$$

2.2. Heat exchanger

Large industrial frying systems normally employ an indirect oil heating system where the oil is heated in a heat exchanger by the exhaust gases from the combustor. These heat exchangers are normally of the cross-counter flow type and are designed to maximise the heat transfer area whilst reducing the volume of oil contained in the tubes and the temperature difference between the exhaust gases and the oil. The fluid flow streams in the heat exchanger are illustrated in Fig. 3.

Since the oil outlet temperature of the heat exchanger plays a key role on the determination of the heat supply to the fryer, it is important to predict this temperature with respect to the fuel flow rate and re-circulated exhaust gas.

Assuming a constant oil mass flow rate and specific heat, no heat losses to the surroundings and applying the energy balance equation to the heat exchanger gives:

$$Q = \dot{m}_5 \cdot c_{p5} \cdot (T_5 - T_6) = \dot{m}_7 \cdot c_{po} \cdot (T_8 - T_7) \quad (6)$$

where Q is the thermal duty of the heat exchanger and c_{po} is the specific heat of oil.

According to Eq. (6), the oil outlet temperature at 8 can be determined from:

$$T_8 = \frac{\dot{m}_5 \cdot c_{p5} \cdot (T_5 - T_6)}{\dot{m}_7 \cdot c_{p7}} + T_7 \quad (7)$$

The efficiency of the oil heating system (combined combustor and heat exchanger) can be calculated from:

$$\eta_{CHE} = \frac{\dot{m}_7 \cdot c_{po} \cdot (T_8 - T_7)}{\frac{\dot{m}_1 \cdot CV_1}{\rho_1}} \quad (8)$$

2.3. Fryer

Fig. 4 shows a schematic diagram of the fryer and the mass flows in and out of the system. Potato slices are fed into the fryer by a conveyor from the dewatering system which is designed to remove surface water from the slices, after the hot wash, before frying [1]. The potato slices are kept submerged in oil by paddles, which also control the flow of the slices through the fryer along the same direction as the oil flow. The rotational speed of the paddles can be changed to adjust the residence time of the slices in the fryer which, alongside other parameters, determines the final properties of the potato crisps exiting the fryer. The moisture content of the crisps, measured on a wet basis is a control parameter that determines the residence time in the fryer.

2.3.1. Energy conservation for oil

Applying the energy balance equation to the oil in the fryer gives:

$$\rho_o \cdot V_{fo} \cdot c_{po} \frac{dT_{fo}}{dt} = Q_8 + Q_9 - Q_{12} - Q_{13} - Q_{ps} + Q_{pw} - Q_{o,14} - Q_{fw} \quad (9)$$

where T_{fo} is the average oil temperature in the fryer, Q_8 is the total energy input to the fryer by the frying oil, Q_9 is the energy removed by the air entering the fryer and withdrawn with the foul gases, Q_{12} is the energy lost through fines removal from the fryer, Q_{13} is the energy carried away by the oil return to the heat exchanger, Q_{ps} is the energy needed for heating the raw potato slice during frying, Q_{pw} is the energy needed for heating and evaporation of the water

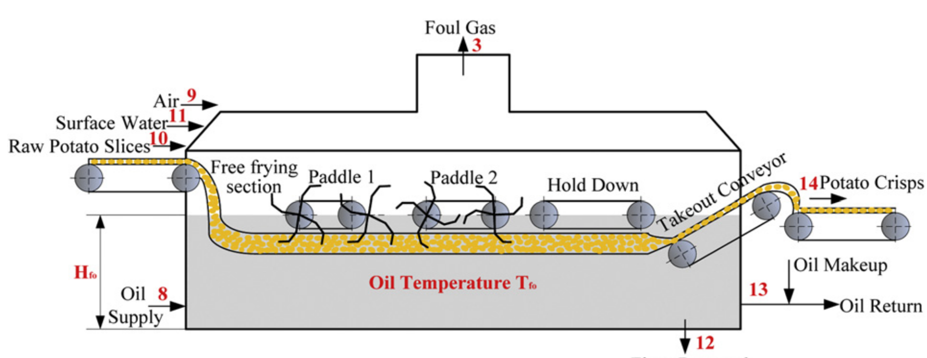

Fig. 4. Schematic flow diagram of an industrial continuous fryer.

associated with the raw potato, including water in the potato as well as surface water on the potato slices, $Q_{o,14}$ is the energy associated with the oil in the final crisp product, and Q_{fw} is the thermal energy lost through the external wall of the fryer to the environment:

$$Q_{fw} = h_{fa} \cdot A_{Sf} \cdot \left(T_f - T_{amb}\right) + \varepsilon_{sf} \cdot A_{Sf} \cdot \sigma \cdot \left(T_f^4 - T_{surf}^4\right) \quad (10)$$

where h_{fa} is the convective heat transfer coefficient of the casing of the fryer, A_{Sf} is the surface area of the casing of the fryer, T_f is the temperature of the fryer external wall, and ε_{sf} is the emissivity.

Substituting Eq. (10) into Eq. (9), gives the variation of the average fryer oil temperature with time.

$$\rho_o \cdot c_{po} \cdot A_f \cdot H_{fo} \cdot \frac{dT_{fo}}{dt} = \dot{m}_8 \cdot c_{po} \cdot T_8 - \dot{m}_9 \cdot c_{pa} \cdot (T_3 - T_9) - \dot{m}_{12} \cdot c_{po} \cdot T_{12} - \dot{m}_{o,13} \cdot c_{po} \cdot T_{13} - \dot{m}_{s,10} \cdot c_{ps} \cdot (T_{14} - T_{10}) - \dot{m}_{o,14} \cdot c_{po} \cdot T_{14} - (\dot{m}_{w,10} + \dot{m}_{w,11} - \dot{m}_{w,14}) \cdot \left[c_{pw} \cdot (T_3 - T_{10}) + h_{fg_w}\right] - \left[h_{f \to a} \cdot A_{Sf} \cdot \left(T_f - T_{amb}\right) + \varepsilon_{sf} \cdot A_{Sf} \cdot \sigma \cdot \left(T_f^4 - T_{surf}^4\right)\right] \quad (11)$$

The final moisture and oil content of the crisps can be determined either from detailed transient modelling of the heat and mass transfer processes during frying [15,16], or from empirical relationships established from experimental investigations [17,18]. The latter approach has been employed in this paper. The general form of the relationships proposed by Krokida et al. [18] and given in Eqs. (12) and (14) has been used but with the indices adjusted to fit data from the frying plant considered in this investigation.

The moisture content of the crisp for a frying time, t, can be determined as a function of the initial moisture content of the potato, the equilibrium moisture content at an 'infinite' frying time, $X_{w,eq}$, and the rate of moisture loss during the process, k_m, which can be expressed as a function of average frying temperature [18].

$$X_{w,14} = X_{w,eq} + (X_{w,i} - X_{w,eq}) \cdot e^{-k_m \cdot t} \quad (12)$$

where,

$$k_m = J_1 \cdot T_{fo} - J_2 \quad (13)$$

The oil content of the crisp for a frying time, t, can be determined as a function of the equilibrium oil content at an 'infinite' frying time, $X_{o,eq}$, and the rate of oil uptake, k_o, which can also be expressed as a function of frying temperature [18].

$$X_{o,13} = X_{o,eq} \times \left(1.0 - e^{-k_o \cdot t}\right) \quad (14)$$

where,

$$k_o = K_1 + K_2 \cdot T_{fo} \quad (15)$$

The constants J_1, J_2 and K_1, K_2 obtained from the test data and are given in Table 1.

Table 1
Parameters used to fit the moisture content and oil content in Eqs. (13) and (15).

Symbol	Value	Symbol	Value
J_1	0.001	K_1	−0.14
J_2	−0.136	K_2	9.8×10^{-4}

To generalise the modelling approach the authors are now in the process of developing a 2-Dimensional model of the frying system that should lead to more accurate representation of the process and relationships between the variables.

3. Data from a frying system

The data used in this study were obtained from a real continuous frying system. The average throughput from the fryer was approximately 0.28 kg/s of crisps for an input of 1.1 kg/s of raw potatoes and average gas energy input to the combustor of around 2600 kW. The key control parameters in a continuous crisp fryer are the final moisture content of the crisps which is desired to be in the range between 1% and 2% by mass on a wet basis, the temperature of the frying oil and the resulting oil content by mass, in the range 30%–40% on a wet basis.

Steady state parameters for the fryer and the variation of these parameters during a 45 min period during which the flow of potato slices to the fryer is switched off are shown in Figs. 5 and 6. Fig. 5 shows the variation of combustion and heat exchanger parameters. It can be seen that during steady state operation the fuel flow rate is around 280 m^3/h, and the temperature of the combustor before the heat exchanger is 510 °C. The heat exchanger inlet temperature is 155 °C the outlet temperature 174 °C and the stack temperature 168 °C. The foul gas temperature is around 107 °C. On stoppage of the flow of potato slices to the fryer, the combustor burner is switched to 20% fuel flow rate (80% turndown) and this reduces the combustor temperature to around 200 °C. The oil flow to the fryer is maintained constant and the absence of load on the fryer equalizes the oil temperature in the system to around 168 °C. This temperature remains fairly constant during the nonfrying period which indicates that the energy input to the system during this period is approximately equal to the losses from the system.

On restart of the frying process, the fuel flow initially increases from 20% to 50% which causes the combustor temperature and the

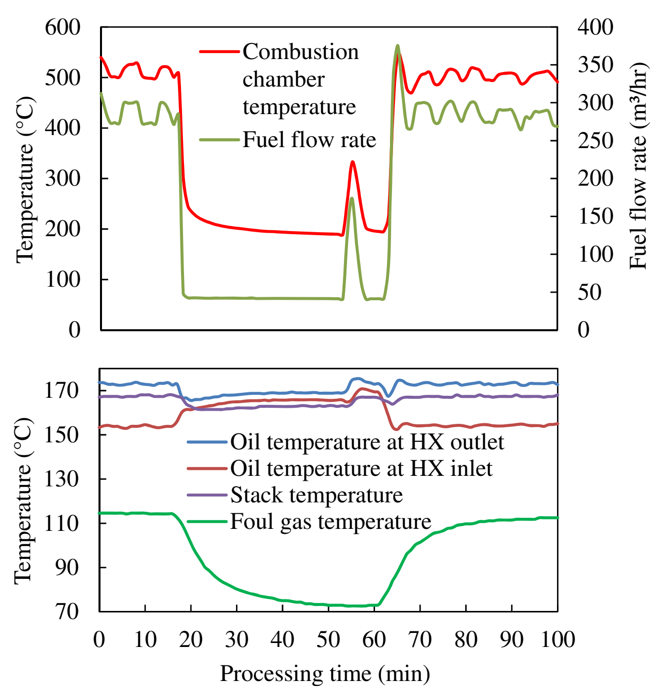

Fig. 5. Variation of combustion and heat exchanger parameters from a real continuous frying system.

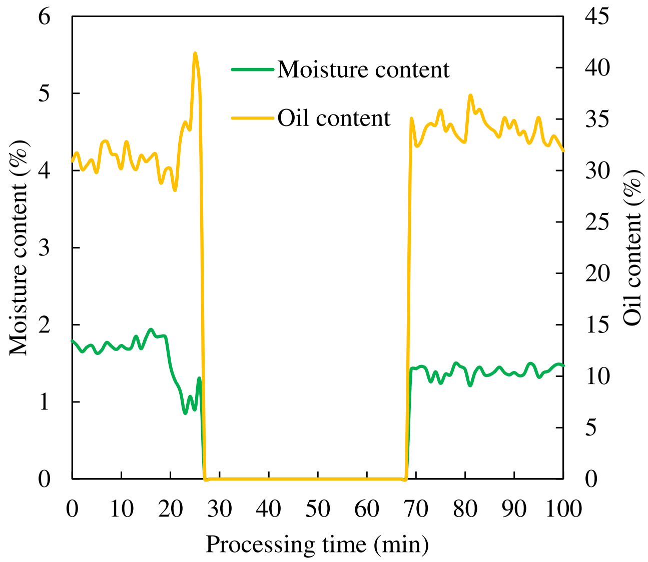

Fig. 6. Variation of moisture content and oil content of potato crisps in a real continuous frying system.

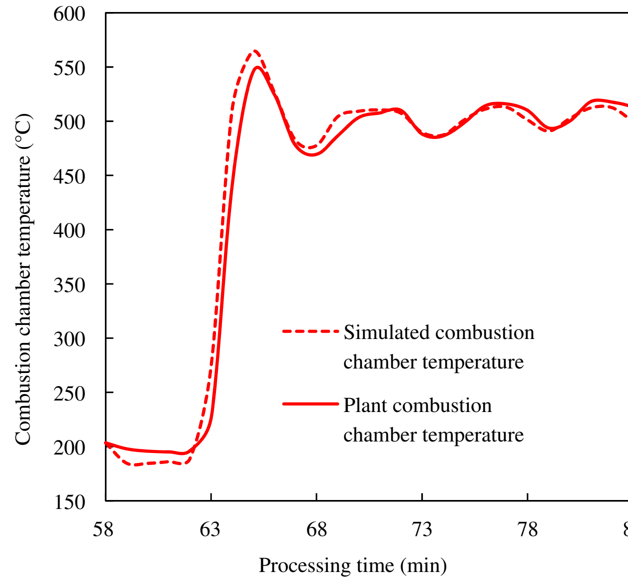

Fig. 8. Comparison of actual and predicted combustor temperature.

oil temperatures in the system to increase, reaching the oil flow set-point of 174 °C very quickly. This causes a reduction in the fuel flow rate back down to 20% before the potato slices begin to flow into the fryer again. This causes the oil temperature to drop initially and then rises again as the fuel flow rate increases to maximum and the system reaches steady state.

Fig. 6 shows the resulting variation of the moisture content and oil content of the potato crisps during the same time period. The moisture and oil content were measured with a NIR (Near Infrared Reflection) gauge which is a well-established method of on-line measurement for monitoring and control in the snacks industry. A PID control system uses these values to control the flow of potato slices through the fryer (the paddle, hold down and take out speeds), to maintain the final moisture content of the crisps at around 1.5% and oil content at around 35%. Before frying stopped, the moisture content of the potato crisps was 1.7% and the oil content 32%. The potato slices stopped flowing to the fryer at around minute 20 in the cycle at which time the moisture content of the crisps began to fall and the oil content rise. At minute 27 all crisps exited the fryer with both the moisture and oil content reading zero. The restart of frying sees both the moisture and oil content rise to their steady state values within a couple of minutes.

4. Model implementation and discussion

The model of the frying system was implemented in the MATLAB/Simulink environment, version R2009a. MATLAB/Simulink was selected because of its general-purpose nature and its extensive use by the thermal modelling and control community [19,20]. Fig. 7 shows a representation of the inputs and outputs from the model. The inputs to the open loop-model, apart from the geometric and thermo-physical characteristics of the frying system, as well as other design and operating parameters such as oil flow rate, are the raw potato mass flow to the fryer and the fuel flow rate to the combustor. Main model outputs are the moisture and oil content of the crisps on a wet basis as well as operating parameters at different points in the system.

Fig. 8 shows a comparison between the simulated and actual temperature of the combustor at the restart of the frying process, minute 63 in Fig. 5. It can be seen that the model predicts the actual combustor temperature before the oil heat exchanger quite well. Small differences can be due to a number of factors, including the assumption of constant potato slice flow rate and moisture and surface water content at the start of frying. In reality there will be some variation in these parameters which will have some influence in both the quantity of foul gas which is an input to the combustor

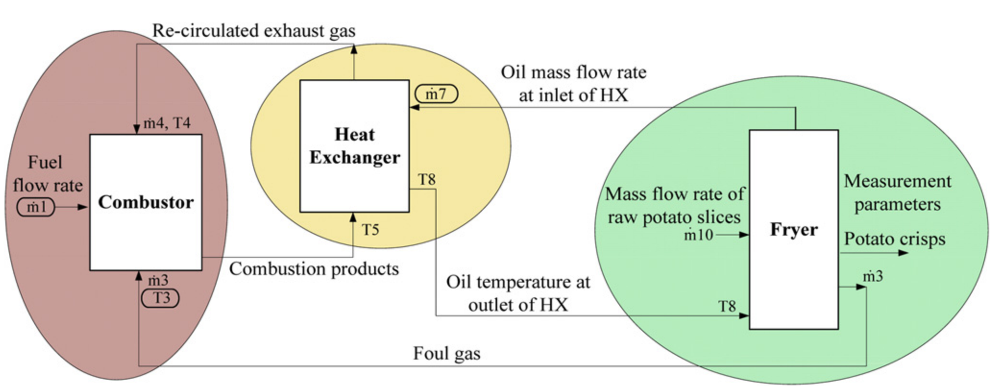

Fig. 7. Schematic block diagram of frying system model in Simulink.

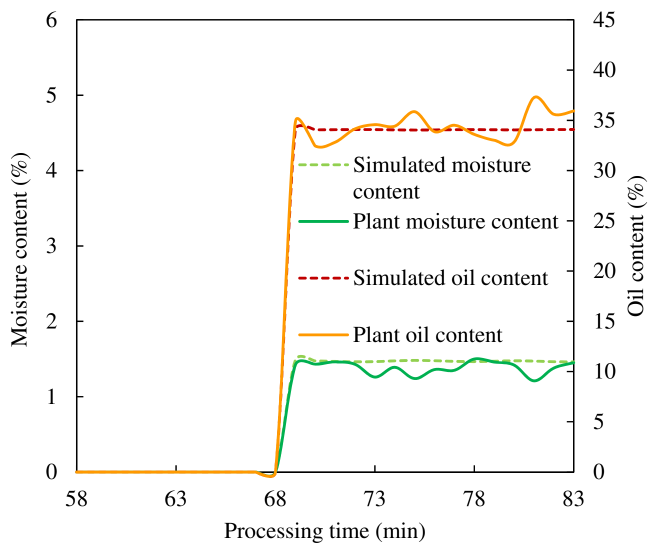

Fig. 9. Comparison of actual and predicted crisps moisture and oil content.

model as well as the properties of the final product. In this simulation the actual fuel flow rate is an input to the model and hence the fluctuations in the combustor temperature mirror the fluctuations in the fuel flow rate.

Fig. 9 shows a comparison between the simulated and actual moisture and oil content during the restart of frying. It can be seen that again the model predicts the average moisture and oil content of the crisps quite well. The simulation results do not show fluctuations in the two crisp properties because the model, at this stage, does not incorporate the PID control used in the real system.

The variation of the fuel flow rate and the resulting oil and moisture content of the crisps during a 3 h period of continuous operation of the fryer is shown in Fig. 10. It can be seen that at steady state conditions, the fuel flow rate fluctuates in the range between 240 m^3/h and 310 m^3/h, the moisture content between 1.2% and 2.2% by mass on a wet basis, and the oil content between 31% and 37% by mass. The variation in the fuel flow rate is a result of the control of the oil temperature entering the fryer to maintain the moisture and oil content of the crisps within desirable limits. These limits, also shown in Fig. 10, are between 1.2% and 2.2% by mass on

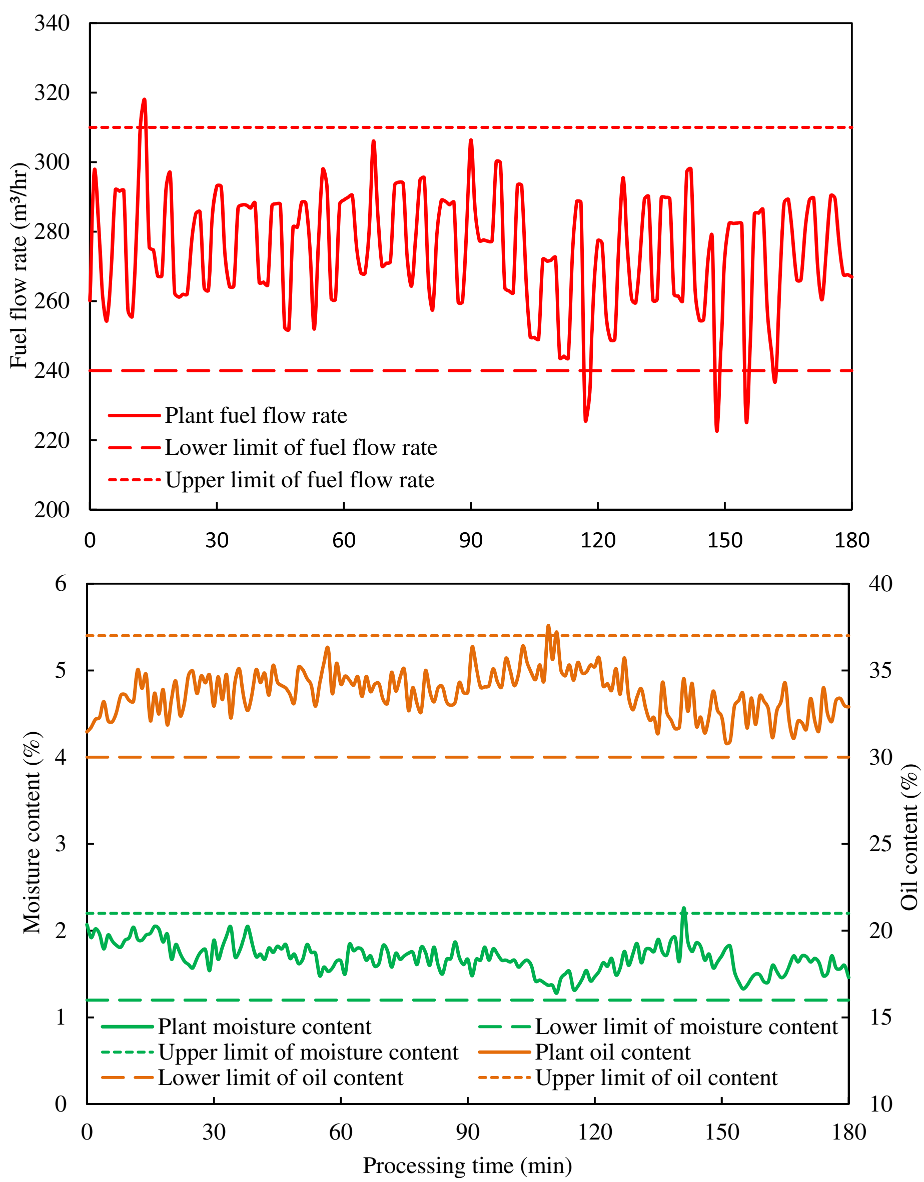

Fig. 10. Variation of combustor fuel flow rate and moisture and oil content at steady state conditions.

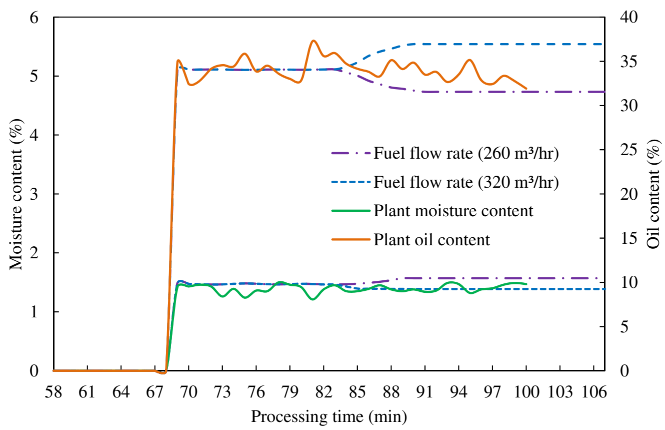

Fig. 11. Variation of moisture and oil content with time and impact of step changes to combustor fuel flow rate.

a wet basis for the moisture content and between 30% and 37% by mass for oil content.

Fig. 11 shows the changes in the moisture and oil content resulting from a step increase in the fuel flow rate from 290 m^3/h to 320 m^3/h and a step decrease from 290 m^3/h to 260 m^3/h respectively, predicted by the model. It can be seen that operation within the range of fuel flow rate of $\pm$30 m^3/h results in moisture and oil content within the acceptable range for the process achieved by the plant as shown in Fig. 10. The predictions do not show any fluctuations because the impact of controls has not been included in the simulation at this stage. Never the less, they demonstrate that a more stable control system operating with a much narrower dead-band, will be able to achieve energy savings whilst maintaining the properties of the final product within the desired limits. In the case of this example, a 30 m^3/h reduction in the fuel flow rate from 290 m^3/h to 260 m^3/h will produce a 10% reduction in energy consumption, whilst maintaining the crisp oil content at 36% and the moisture content at 1.6%. Of course, with any control system, however sophisticated, some perturbations will be introduced, but even with these it is reasonable to assume that at least 5% energy savings will be possible. Future work will focus on the development and testing of more advanced control techniques and demonstrate their potential to achieve better product consistency a well as energy savings.

5. Conclusions

A quasi steady state model has been developed for the simulation of the behaviour of a continuous frying system. The model which includes sub-models of the 3 major components, the combustor, heat exchanger and fryer was developed in the MATLAB/Simulink environment to facilitate investigation of the impact of design and control parameters on the energy consumption of the system.

For simplicity, and as a first approximation, a number of assumptions were made such as to ignore the thermal mass of the walls of the combustor, the fryer and the heat exchanger. This was justified from the very fast response of the actual system to changes in operating conditions.

The results show that the model can accurately represent the overall behaviour of an industrial frying system and the processes occurring in the major components of the system. The dynamic simulation provides insights into the sensitivity of the response of the main variables of the process to perturbations in the system which occur frequently in commercial frying lines. It is also shown that better control of the combustion fuel flow rate in response to final product parameters such as moisture content and oil content can produce energy savings of the order of between 5% and 10%. This information will be useful in the investigation of controls that can reduce control perturbations and energy consumption.

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