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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.

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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 CO₂ 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	CHE	combustor and heat exchanger
c_p	specific heat, $kJ/kg\ K$	eq	equilibrium
CV	calorific value, kJ/m^3	f	fryer
h_{Ca}	heat transfer coefficient of the ceasing of the combustor, $kW/m^2\ K$	fo	frying oil
h_{fa}	heat transfer coefficient of the ceasing of the fryer, $kW/m^2\ K$	fw	transmission through external wall of the fryer
h_{fg}	latent heat, kJ/kg	i	initial
H	oil level inside the fryer, m	in	inlet
J_1	constant, $1/K\ s$	o	oil
J_2	constant, $1/s$	out	outlet
k_m	rate of moisture loss, $1/s$	o,13	oil in fines removal
k_o	rate of oil uptake, $1/s$	o,14	oil in potato crisp
K_1	constant, $1/s$	ps	potato slice solid
K_2	constant, $1/K\ s$	pw	water in potato slices
$\dot{m}$	mass flow rate, kg/s	s	potato solid
Q	thermal energy, kW	s,10	potato solid in raw potato slices
Q_{Cw}	ambient loss through combustor wall, kW	s,14	potato solid in potato crisp
t	time, s	SC	surface of combustor
T	temperature, K	Sf	surface of fryer
V	volume, m^3	surf	surrounding wall surface
X	composition percentage, %	w	water
<i>Greek letters</i>		w,10	water in raw potato slices
ε_s	correction factor density,	w,14	water in potato crisp
η	efficiency, %	1	fuel
ρ	kg/m^3	2	combustion air
σ	Stefan–Boltzmann constant, $W/m^2\ K^{-4}$	3	foul gas
<i>Subscripts</i>		4	re-circulated exhaust gas
a	air	5	combustion products
amb	ambient	6	exhaust gas
c	combustion products	7	oil inlet
C	combustor	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

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