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Research paper

Energy thermal management in commercial bread-baking using a multi-objective optimisation framework

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HIGHLIGHTS

- A multi-objective optimisation framework to design commercial ovens is presented.
- High fidelity CFD embeds experimentally calibrated heat transfer inputs.
- The optimum oven design minimises specific energy and bake time.
- The Pareto front outlining the surrogate-assisted optimisation framework is built.
- Optimisation of industrial bread-baking ovens reveals an energy saving of 637.6 GWh.

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ABSTRACT

In response to increasing energy costs and legislative requirements energy efficient high-speed air impingement jet baking systems are now being developed. In this paper, a multi-objective optimisation framework for oven designs is presented which uses experimentally verified heat transfer correlations and high fidelity Computational Fluid Dynamics (CFD) analyses to identify optimal combinations of design features which maximise desirable characteristics such as temperature uniformity in the oven and overall energy efficiency of baking. A surrogate-assisted multi-objective optimisation framework is proposed and used to explore a range of practical oven designs, providing information on overall temperature uniformity within the oven together with ensuing energy usage and potential savings.

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1. Introduction

The worldwide commercial bread baking sector is a hugely significant manufacturing industry, with over 94 million tonnes of bread consumed each year [1]. The baking process is of major environmental importance as it is the most energy intensive process in the bread manufacturing cycle, consuming an estimated 804 kJ per kg of bread [2], and ultimately determines many of the final physical properties of bread, such as crust colour, crumb texture and taste [3].

Traditionally, energy efficiency has not been the main goal in oven design with other features such as ease and reliability of operation, access for cleaning, costs of maintenance, consistency of production and ability to cope with high production rates being of greater importance. This has resulted in typical commercial bread ovens having efficiencies of less than 50% [2,4]. Higher energy prices and the increasing importance of environmental sustainability and corporate responsibility have led to much greater incentives to reduce energy consumption within industrial ovens [5] as required by the European Energy Efficiency Directive [6]. This Directive, which entered into force on 4 December 2012, establishes a common framework of measures for the promotion of energy efficiency within the European Union (EU) in order to ensure the achievement of the EU's 2020 20% target on energy efficiency. Recent research has identified significant opportunities for energy savings and the need to develop procedures for thermal optimisation within manufacturing processes as discussed in Ref. [7]. A systematic approach has been constructed embedding key process variables to engineer optimized industrial ovens [7,8].

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Nomenclature

Abbreviation

CFD	Computational fluid dynamics
DOE	Design of experiments
BC	Boundary condition

Symbols

c_p	specific heat capacity [J/(kg K)]
d	nozzle jet diameter [m]
f	relative orifice area
H	nozzle-to-surface distance [m]
H/d	dimensionless nozzle-to-surface distance
h_c	heat transfer coefficient [W/(m^{2}K)]
I	turbulence intensity
L	characteristic length [m]
k	thermal conductivity [W/(mK)]
Nu	Nusselt number [$Nu = h_c d/k$]
P	power [kW]
p	pressure [Pa]
Q	volumetric flow rate [m^3/s]
Pr	Prandtl number [$Pr = \nu/\tau$]
q	heat flux [W/m^2]
Re	Reynolds number [$Re = u_{noz}d/\nu$]
s	nozzle-to-nozzle spacing [m]
t	time [s]
T	temperature [K]
u_{noz}	nozzle velocity [m/s]
V_{in}	velocity inlet condition [m/s]
w	nozzle to nozzle width spacing [m]
x	distance from centre of nozzle [m]
$x_{1,2,3}$	design variables 1, 2 and 3
α	degree of gelatinisation
ε	emissivity
ρ	density [kg/m^3]
ν	kinematic viscosity [m^2/s]
σ	Stefan–Boltzmann constant [$\sigma = 5.67 \times 10^{-8}$ Wm^{-2}K^{-4}]
σ_T	temperature functional for minimization [K]
$\sigma_{cooking}$	cooking time functional for minimization [min]
σ_i	standard deviation of minimum distance of DOE$_i$
θ	closeness-of-fit parameter
τ	thermal diffusivity [m^2/s] [$\tau = k/(\rho c_p)$]

Subscript

b	model building DOE
i	index i
j	index j
m	combined model DOE
v	model validation DOE

Accordingly the present paper proposes a scientifically-rigorous methodology for optimising the energy consumption within commercial baking ovens.

Baking ovens can be classified broadly according to the heating method used: either direct-fired or indirect-fired ovens. In the direct-fired approach the combustion products come into contact with the bread, whilst the latter use heat exchangers to separate the products of combustion from the baked product. Commercial bread ovens can typically be in the region of 30–40 m long, baking up to 10 tonnes of bread per hour on a continuous basis. The focus of the present study is on forced convection ovens, which transfer heat to the surface of the dough from hot air issuing out of jet impingement nozzles, drying and setting the bread crumb structure, see Fig. 1. The rate of convective heat transfer to the surface of the bread, which is often specified in terms of a convective heat transfer coefficient, is a function of the air jet velocity and temperature, and important geometric variables –specifically those associated with the nozzles orifices: the nozzle-to-surface distance, hole diameter and spacing.

Several experimental studies on jet impingement heat transfer have appeared in the literature, prominent among these being the work of Martin [9], who published heat transfer correlations for a number of different types of nozzles and arrays of nozzles. These have, however, focussed on lower impingement velocity cases than is relevant for many modern baking ovens. The present study uses experimental heat transfer coefficient correlations taken for the specific oven operating conditions of interest here.

Computational Fluid Dynamics (CFD) is now used widely to predict airflows in the food industry [10] and is increasingly being used an alternative to experimental design of baking ovens. Previous relevant CFD studies of bread ovens have predicted air flow and temperature distribution within baking ovens [11] and to optimise temperature uniformity at the bread surface for a baking regime in order to improve energy efficiency [12]. CFD has also been used to reduce moisture loss [13,14] by altering the temperature profile along the length of the oven; to optimise temperature, heat transfer coefficient and bread radius (i.e. dough shape) to improve product quality [15]; and to

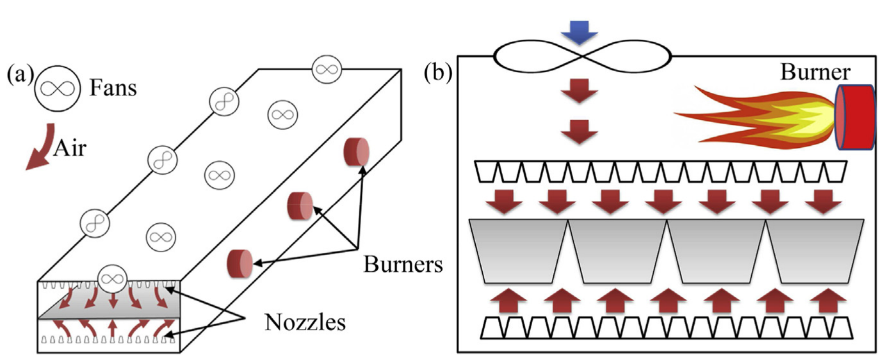

Fig. 1. Schematic diagram of a forced convection commercial bread oven: (a) overall view and (b) cross section view.

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