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Heat and mass transfer model to predict the operational performance of a steam sterilisation autoclave including products

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ABSTRACT

Steam sterilisation using autoclaves or retorts is a widely used thermal process in the food processing and pharmaceutical industries. Unfortunately, sterilisation, using steam, consumes a significant amount of energy and is known to cause unwanted peak energy demand when a number of autoclaves operate in parallel. The objective of this paper is to extend the previously published numerical methodology developed to simulate in detail the thermal energy consumption of an industrial sized empty autoclave used for steam sterilisation, to include products, in this case, intravenous solution packed in plastic pouches and a steam flow controller. The external parameters supplied to the numerically modelled controller are the maximum steam flow rate and the autoclave temperature as a function of time which it needs to maintain. The numerical model is then used to predict the actual transient temperature and pressure profiles and the details of the mass transfers in the autoclave during a sterilisation cycle, the transient temperature distribution within the products as well as details of the transient thermal energy consumption. The results from numerical modelling were validated with measurements obtained under actual operating conditions. The simulated total steam consumption was within 3% of the measured data. A reduction of 8% in steam consumption was obtained due to insulation on the outer walls.

1. Introduction

While the globe has benefited from the industrialisation of nations through improved access to necessities such as medical supplies and food products, manufacturing has been identified as a major consumer of energy [1]. Researchers and companies around the world have delved into the field of energy and resource efficiency in striving for achieving cleaner and sustainable manufacturing practices in order to reduce operational cost and lower carbon emission [2]. One of the major hurdles faced by industry practitioners is that the majority of currently operational processes are located in brown-field facilities, where a significant amount of up front financial capital has been spent but the processes may have been designed and built at a time when energy efficiency may not have been the most important priority. This means that a solution towards achieving sustainability requires a two-pronged approach. Firstly, to address the inefficiencies that currently exist in brown-field manufacturing sites. The benefits of optimising existing processes and equipment have been documented in literature such as [3]. Secondly, there is a need to develop novel approaches in the design of green-field (new) processes that are more energy efficient without compromising quality. For example, in the pharmaceutical industry, product quality is of paramount concern and guidelines are strictly enforced. At the same time, companies recognise that critical processes such as steam sterilisation, is a major consumer of thermal energy [4].

An appropriate approach to the aforementioned challenges would require the development of a modular solution that could provide an insight into the thermal energy consumption in existing processes and at the same time, allowing for the ability of modifications to be made to process parameters and equipment design. This negates the option for a statistical top-down approach, which lacks the capability for alternations without an extensive data collection. Furthermore, apart from being a major consumer of energy, steam sterilisation is regarded as the cause of unnecessary peak boiler demand when operating in a batch configuration as similarly noted in the food processing industry. As such, any solution should provide not only total steam consumption for a sterilisation process, but also include insights to transient steam consumption so that future simulations would be able to provide thermal energy consumption for the purpose of optimising production schedule [5].

The rapid improvement in computer processing capabilities has allowed for numerical models of manufacturing processes to be

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Nomenclature

A	area, m^2
c	constant
C_p	constant pressure specific heat capacity, J kg^{-1} K^{-1}
D	diameter
F	factor
g	acceleration of gravity, m s^{-2}
Gr	Grashof number
h	heat transfer coefficient, W m^{-1} K^{-1}
h^*_{fg}	modified latent heat of vapourisation, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	length, m
M	molar mass of air, g kmol^{-1}
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
$\dot{Q}$	rate of heat transfer, W
Re	Reynolds number
R_u	universal gas constant, J kmol^{-1} K^{-1}
r	radius, m
T	temperature, °C
U	internal energy, J

Greek symbols

β	coefficient of thermal expansion, K^{-1}
γ	heat capacity ratio
μ	dynamic viscosity, g m^{-1} s^{-1}
v	kinematic viscosity, m^2 s^{-1}
φ	perimeter

Subscripts

a	air
amb	ambient
atm	atmosphere
au	autoclave
boiler	boiler
bw	bottom walls (in contact with water pool)
c	characteristic
cond	condensation
f	fluid
film	condensate liquid film surface
i	inner (radius/diameter/area)
in	into
ins	insulation
initial	initial simulation timestep ($t = 0$ s)
l	liquid (water)
lw	lower side walls
mix	mixture
o	outer (radius/diameter/area)
out	out of
ow	outer wall
p	pipe
pid	proportional integral derivative controller
prod	products
s	steam
sat	saturation
sensible	sensible (heat transfer)
surf	surface
trays	trays
w	wall
wp	water pool

built, based upon the physical phenomena occurring within the process. Numerical modelling is a common approach to analysing thermal processes, especially in the food industry whereby the physical principles of using steam for thermal processing in retorts and steam sterilisation in the pharmaceutical are not too dissimilar. The study of thermal processing of food has been well established and documented in the literature with earlier literature focusing on product quality [6]. Barrreiro et al. [7] developed a theoretical method for estimating the cumulative thermal energy consumption in a pea-puree steam sterilisation process. The results were used to validate the data from a theoretical model presented by Simpson et al. [8] for analysing the transient steam consumption of can pea puree sterilisation process. The methodology presented consists of steady-state equations which showed good agreement with results from Barrreiro et al. [7]. However, due to the obscure nature of published experimental data, the transient results presented were not validated with actual experimental measurements. Other researchers who have used theoretical modelling to better understand the energy consumption within a thermal process include Ploteau et al. [9] and Paton et al. [10] for a tunnelling oven used for baking bread, Wu et al. [11] for a continuous fryer used to cook potato chips.

When analysing transient energy consumption in the cooking of food within a pressure cooker, Poliméni et al. presented a methodology using a combination of theoretical and measured heat transfer coefficients [12]. The heat and mass transfer phenomena within the pressure cooker were accounted for to estimate the temperature and pressure performance. These results were validated with experimental measurements and showed good agreement. The model developed was capable of providing valuable insights to the breakdown of various thermal fluxes within the pressure cooker to identify design improvement opportunities. The authors demonstrated that the use of steady-state expressions is a promising way of predicting complex transient heat and mass transfer phenomena within an enclosure, albeit on a small scale home appliance.

At the same time, there is limited evidence in existing models that are capable of simulating both the transport processes within the vessel and the product temperature. Published methodologies often focused solely on either process or product conditions. For example, our earlier approach to model an empty autoclave for steam–air sterilisation demonstrated the capability of such an approach to predicting transient process conditions within an autoclave during a sterilisation cycle under two separate occasions [13]. However, the model presented was incomplete without the presence of products within the autoclave. The methodology presented utilised controlling parameters in conjunction with steady-state expressions whereby the controlling parameters were tuned using measured data. Similar modelling approach could be found in other engineering studies where constants were utilised with established expressions and validated using measured data [14]. Various methodologies have been developed and used in food processing industry to further understand the detail heat and mass transfer phenomena within a cooking process including the loads being heated up. Kannan et al. [14] presented a computational fluid dynamic (CFD) model for estimating the temperature of liquid within a can during a food retorting process. The model was for water, mainly describing the methodology for modelling of convective heat transfer within the can. The presented methodology assumed a constant can (boundary) temperature, hence focusing solely on the temperature modelling of a single can. Moreover, total simulation time required was 1.2 h for a single can. Similar