Computers and Chemical Engineering 106 (2017) 269–285

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Heat integration of multipurpose batch plants through multiple heat storage vessels

Nthabiseng Sebelebele, Thokozani Majozi*

School of Chemical and Metallurgical Engineering, University of Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, Johannesburg, 2001, South Africa

ARTICLE INFO

Article history:
Received 18 January 2017
Received in revised form 9 May 2017
Accepted 5 June 2017
Available online 7 June 2017

Keywords:
Batch plants
Heat integration
Energy
Minimisation
Heat storage
Optimisation

ABSTRACT

Energy minimisation in batch plants has garnered popularity over the past few decades, leading to direct and indirect heat integration techniques being formulated for multipurpose batch plants through the utilisation of mathematical formulations and insight-based methods Some mathematical formulations utilise predetermined scheduling frameworks which may result in suboptimal results, whilst other formulations only use one heat storage vessel which may cause limitations in the plant. The work presented in this manuscript is aimed at minimising energy consumption in multipurpose batch plants by exploring both direct and indirect heat integration through multiple heat storage vessels. It investigates the optimal number of heat storage vessels as well as design parameters, i.e. size and initial temperature of vessels. The cost of the heat storage vessels is considered within the model. The model is applied to two case studies resulting in significant increase in profits.

1. Introduction

The use of batch chemical processes has gained popularity globally, due to their use in the production of low volume and high value products in the pharmaceutical, food, explosives, and speciality chemical industries (Seid and Majozi, 2012). Due to the escalating growth in the utilisation of batch chemical processes, research and development within the field has been intensified in order to develop optimisation techniques that can be used to operate the processes at optimal conditions. In the past the focus has been on design methods that are aimed at minimising the capital investment based on the selection of capital equipment. The focus has since shifted to optimisation methods that lead to a reduction in operating costs, such as utility costs by reducing the energy requirement in the process (Bieler, 2004). Direct and indirect heat integration can be used to minimise energy in batch processes. Direct heat integration is applied when a hot stream and a cold stream exchange heat with one another and indirect heat integration refers to heat/energy savings via a dedicated heat storage facility for later use. There are two main ways in which energy minimisation in batch plants has been studied and conducted, namely; the graphical optimisation methods, where the schedule is predetermined, and mathematical modelling optimisation methods. Some heuristics methods, where the schedule is also predetermined, have also been developed in minimising energy.

1.1. Graphical techniques

Energy minimisation in batch plants was first conducted through the use of graphical techniques. There are two main methods which are used in the graphical techniques, which is the time average model as well as the time slice model. The time average model was first introduced by Clayton (1986) where the energy of each stream was averaged over the batch cycle time. The minimum external utility requirement is then determined by taking into account the heat exchanged internally between streams. This method does not consider the discontinuous existence of streams which results in an overestimation of energy exchanged between streams.

The second method is the time slice model. This method uses the schedule of the batch process and divides the starting and ending times of tasks into slices or intervals. Each interval is then observed as a continuous process. The pinch point of every interval is then obtained in a similar manner like that in continuous processes. This method was first introduced by Obeng and Ashton (1988). The vast majority of energy minimisation techniques in the last three decades constituted of mainly graphical techniques

---

* Corresponding author.
E-mail addresses: thokozani.majozi@wits.ac.za, thokomajozi@gmail.com (T. Majozi).

http://dx.doi.org/10.1016/j.compchemeng.2017.06.007
0098-1354/

Nomenclature

Sets

J	$\{j \mid j$ processing unit$\}$
J_c	$\{j_c \mid j_c$ cold processing unit$\}$
J_h	$\{j_h \mid j_h$ hot processing unit$\}$
P	$\{p \mid p$ time point$\}$
S_{jh}^{in}	$\{s_{jh}^{in} \mid s_{jh}^{in}$ task which needs cooling$\}$
S_{jc}^{in}	$\{s_{jc}^{in} \mid s_{jc}^{in}$ task which needs heating$\}$
S_{j}^{in}	$\{s_{j}^{in} \mid s_{j}^{in}$ any task$\}$
S_p	$\{s_p \mid s_p$ any product$\}$
V	$\{v \mid v$ is a heat storage vessel$\}$

Variables

$Ec(s_{jc}^{in}, p)$	Duty of task which needs heating
$E_h(s_{jh}^{in}, p)$	Duty of task which needs cooling
$c_u(s_{jh}^{in}, p)$	Cooling water required by a hot task
$h_u(s_{jc}^{in}, p)$	Steam required by a cold task
$mu(s_{jc}^{in}, p)$	Amount of material processed by cold task
$mu(s_{jh}^{in}, p)$	Amount of material processed by hot task
$T^{i}(v, p)$	Initial temperature of a storage vessel
$T^{f}(v, p)$	Final temperature of a storage vessel
$T^{out}(s_{jc}^{in}, p)$	Outlet temperature of a cold task
$T^{out}(s_{jh}^{in}, p)$	Outlet temperature of a hot task
$T^{in}(s_{jc}^{in}, p)$	Inlet temperature of a cold task
$T^{in}(s_{jh}^{in}, p)$	Inlet temperature of a hot task
$t_u(s_{jc}^{in}, p)$	Time at which a cold task starts being active
$t_u(s_{jh}^{in}, p)$	Time at which a hot task starts being active
$t_p\left(s_{jc}^{in}, p\right)$	Time at which a cold task stops being active
$t_p\left(s_{jh}^{in}, p\right)$	Time at which a hot task stops being active
$t_o(s_{jc}^{in}, v, p)$	Time at which a heat storage starts being active when integrated with a cold task
$t_o(s_{jh}^{in}, v, p)$	Time at which a heat storage starts being active when integrated with a hot task
$t_f(s_{jc}^{in}, v, p)$	Time at which a heat storage stops being active when integrated with a cold task
$t_f(s_{jh}^{in}, v, p)$	Time at which a heat storage stops being active when integrated with a hot task
$qs(s_p, p)$	Amount of product at the end of the time horizon
$Qc(s_{jc}^{in}, v, p)$	Heat transferred from storage to cold task
$Q_h(s_{jh}^{in}, v, p)$	Heat transferred from hot task to storage
$Q_e(s_{jh}^{in}, s_{jc}^{in}, p)$	Amount of heat directly transferred between a hot and cold task
$W(v)$	Capacity of heat storage
$e_{sto}(v)$	Binary variable indicating the existence of a heat storage vessel
$x(s_{jc}^{in}, s_{jh}^{in}, p)$	Binary variable indicating direct integration between a hot and cold task
$y(s_{jc}^{in}, p)$	Binary variable indicating an active cold task
$y(s_{jh}^{in}, p)$	Binary variable indicating an active hot task
$z(s_{jc}^{in}, v, p))$	Binary variable indicating an active heat storage vessel integrated with a cold task
$z(s_{jh}^{in}, v, p))$	Binary variable indicating an active heat storage vessel integrated with a hot task

Parameters

α_{sto}	Fixed cost of heat storage vessel
β_{sto}	Variable cost of heat storage vessel
$\alpha(s_{j}^{in})$	Coefficient of constant term for processing time of a task
$\beta(s_{j}^{in})$	Coefficient of variable term for processing time of a task
A^F	Annualizing factor
a	Annual fractional interest rate
θ	Cost function exponent
$c_p(s_{jc}^{in})$	Specific heat capacity of a cold task
$c_p(s_{jh}^{in})$	Specific heat capacity of a hot task
C_p^w	Specific heat capacity of heat transfer medium
cu_c	Cost of cold utility
hu_c	Cost of hot utility
hr/yr	Amount of hours the plant operates per year
H	Time horizon of interest
M	Any large number
n	Lifespan of heat storage vessels in years
$SP(s_p)$	Selling price of products
$T^s(s_{jh}^{in})$	Inlet temperature of a hot task
$T^s(s_{jc}^{in})$	Inlet temperature of a cold task
$T^t(s_{jh}^{in})$	Outlet temperature of hot task
$T^t(s_{jc}^{in})$	Outlet temperature of a cold task
T^L	Lower bound for initial temperature of a heat storage vessel
T^U	Upper bound for initial temperature of a heat storage vessel
ΔT^L	Minimum allowable temperature difference
W^L	Lower bound for size of a heat storage vessel
W^U	Upper bound for size of a heat storage vessel
${Q_e}^L$	Lower bound for amount of heat transferred between two tasks
${Q_e}^U$	Upper bound for amount of heat transferred between two tasks

(Kemp and Macdonald, 1987; Kemp and Deakin, 1986; Wang and Smith, 1995) and were continuously explored in the 21th century (Fernandez, et al., 2012).

Recent work in energy minimisation through graphical techniques includes the work of Yang et al. (2014) and uses the Pseudo-T-H diagram (PTHDA) and the time slice model. The model applies both direct and indirect heat integration with the objective of minimising the total annual cost (TAC). Anastasovski (2014) presented work that aims to design a common heat exchanger network for batch operations with the use of the time slice model. Chaturvedi and Bandyopadhyay (2014) proposed a methodology aimed at overcoming the limitations that occur when using Time–Dependent Heat Cascade Analysis (TDHCA). The novelty of the methodology proposed by Chaturvedi et al. (2016) is the shifting or delaying of product streams, in order for the product streams to be integrated with available cold/hot stream later in the time horizon.

Although graphical techniques offer conceptual insight, the techniques have proved to be insufficient due to their use of time as a parameter, which implies that the start and ending times are specified a priori. In order to obtain a more realistic representation of batch processes, time should be allowed to vary, and this can be achieved through mathematical modelling techniques.

1.2. Mathematical modelling techniques

Time can be captured in its exact form through the use of mathematical modelling as demonstrated by Papageorgiou et al. (1994)