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Heat integration of intermittently available continuous streams in multipurpose batch plants

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ABSTRACT

Presented in this paper is a mathematical technique for simultaneous heat integration and process scheduling in multipurpose batch plants. Taking advantage of the intermittent continuous behavior of process streams during transfer from one processing unit to another, as determined by the recipe, the presented formulation aims to maximize the coincidence of availability of hot and cold stream pairs with feasible temperature driving forces, while taking into consideration process scheduling constraints. Contrary to similar contributions in published literature, time is treated as one of the key optimization variables instead of a parameter fixed a priori. Heat integration during stream transfer has the added benefit of shortened processing time, which invariably improves throughput, as more batches are likely to be processed within a given time horizon, compared to conventional heating and cooling in situ. Application of the proposed model to a case study shows improvements of more than 30% in energy savings and up to 15% in product output.

1. Introduction

Batch processing has gained considerable industrial and academic interest because of its flexibility and adaptability to produce different products using the same facility. Such processes are perfectly suited to the production of low volume, high value-added products, which are commonly found in industries such as agrochemicals, pharmaceuticals, polymers, foodstuffs and fine/specialty chemicals. A common feature of the various batch processes, like any types of manufacturing, is the use of fossil fuels as the main energy source. The dependence on fossil energy in turn causes serious problems to the environment. With increased public awareness toward and the need for sustainable development, stricter environmental regulations have urged the process industries to seek alternative energy sources and efficient use of energy. In addition to enhancements in plant machinery, improved energy efficiency can be achieved through *process integration*. While there has been significant progress in the development and application of process integration techniques for energy conservation in continuous processes, different and more sophisticated methodologies are required for batch processes, where time is also an important constraint apart from temperature. The complexity of the design and operation of batch plants makes it challenging to develop effective techniques for energy optimization. A review of significant works published in the past decades is presented in the following subsections.

1.1. Methodologies for batch heat integration

Heat integration in batch processes can be carried out directly or indirectly. Direct heat integration requires the hot and cold tasks to coincide in order for process–process heat exchange to take place. On the other hand, indirect heat integration uses thermal storage allowing heat exchange between hot and cold tasks performed in different time intervals, thereby providing more flexible and further heat recovery. The methods developed for batch heat integration may be broadly divided into pinch-based and mathematical techniques, as discussed below separately.

1.1.1. Pinch-based techniques

Early studies aiming to minimize energy consumption in batch plants were mostly based on pinch analysis and carried out by extending methods originally developed for continuous processing plants. Clayton (1988) determined the energy reduction potential using the *time average model* (TAM), assuming that the hot and cold streams exist simultaneously as in continuous processes. Stolze et al. (1995) addressed this unrealistic assumption by incorporating

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Nomenclature

Indices and sets

$j \in J$	processing units
$j \in J_{\mathrm{in}}^{\mathrm{c}}$	processing units to have cooling for input material
$j \in J_{\mathrm{out}}^{\mathrm{c}}$	processing units to have cooling for output material
$j \in J_s^{\mathrm{c}}$	processing units consuming state s
$j \in J_{\mathrm{in}}^{\mathrm{h}}$	processing units to have heating for input material
$j \in J_{\mathrm{out}}^{\mathrm{h}}$	processing units to have heating for output material
$j \in J_s^{\mathrm{p}}$	processing units producing state s
$j \in J_{\mathrm{in}}^{*}$	processing units to have heating or cooling for input material
$j \in J_{\mathrm{out}}^{*}$	processing units to have heating or cooling for output material
$p \in P$	time points
$s \in S$	states
$s \in S_j^{\mathrm{c}}$	states consumed in unit j
$s \in S^{\mathrm{i}}$	intermediate states
$s \in S^{\mathrm{p}}$	product states
$s \in S^{\mathrm{r}}$	raw material states
$s_{\mathrm{in},j} \in S_{\mathrm{in},j}$	input streams
$s_{\mathrm{in},j} \in S_{\mathrm{in},j}^{\mathrm{eff}}$	effective states representing tasks
$s_{\mathrm{out},j} \in S_{\mathrm{out},j}$	output streams
$s_{\mathrm{in},j}^{\mathrm{r}} \in S_{\mathrm{in},j}^{\mathrm{r}}$	raw material streams
$s_*^{\mathrm{c}} \in S_*^{\mathrm{c}} \subset S_{\mathrm{out},j} \cup S_{\mathrm{in},j}^{\mathrm{r}}$	cold streams
$s_*^{\mathrm{h}} \in S_*^{\mathrm{h}} \subset S_{\mathrm{out},j}$	hot streams

Parameters

CCW	cooling water cost
$Cp(s)$	specific heat capacity of state s
$Cp_{\mathrm{in}}(s_{\mathrm{in},j})$	specific heat capacity of the input material to the task
$Cp_{\mathrm{out}}(s_{\mathrm{in},j})$	specific heat capacity of the output material from the task
Cp^{cw}	specific heat capacity of cooling water
CST	steam cost
H	time horizon of interest
$\dot{M}^{\mathrm{cw}}$	constant cooling water flow rate through the jacket
$\dot{M}^{\mathrm{st}}$	constant steam flow rate through the jacket
$Q_0(s)$	initial amount of state s in the storage
Q_s^{max}	maximum storage capacity for state s
Q^{U}	upper bound for heat loads
$T_{\mathrm{op}}(s_{\mathrm{in},j})$	operating temperature for the task
$T_{\mathrm{stor}}(s)$	storage temperature of product state s
$T_{\mathrm{in}}^{\mathrm{cw}}$	inlet temperature of cooling water
$T_{\mathrm{out}}^{\mathrm{cw}}$	outlet temperature of cooling water
$T_{\mathrm{sat}}^{\mathrm{st}}$	saturated steam temperature
$Ts_0(s)$	initial temperature of state s in the storage
tt	material transfer time
V_j^{max}	maximum capacity of unit j
V_j^{min}	minimum capacity of unit j
ΔT_{min}	minimum temperature difference
$\mathit{\Gamma}$	a large enough positive value
λ^{st}	steam latent heat
$\rho_s^{\mathrm{c}}(s_{\mathrm{in},j})$	fraction of state s in the input consumed by the task
$\rho_s^{\mathrm{p}}(s_{\mathrm{in},j})$	fraction of state s in the output produced by the task
$\tau(s_{\mathrm{in},j})$	constant duration of the task

Variables

$ms_{\mathrm{in}}(s, j, p)$	amount of state s sent to storage from unit j at time point p
$ms_{\mathrm{out}}(s, j, p)$	amount of state s sent from storage to unit j at time point p
$mt(s, j, j', p)$	amount of state s sent from unit j to unit j' at time point p
$m_{\mathrm{u}}(s_{\mathrm{in},j}, p)$	amount of material used for the task at time point p
$q_{\mathrm{ex}}(s_*^{\mathrm{h}}, s_*^{\mathrm{c}}, p)$	heat exchanged between the hot and cold streams at time point p
$q_{\mathrm{in}}^{\mathrm{c}}(s_{\mathrm{in},j}, p)$	amount of cooling for the input material at time point p
$q_{\mathrm{out}}^{\mathrm{c}}(s_{\mathrm{in},j}, p)$	amount of cooling for the output material at time point p
$q_{\mathrm{in}}^{\mathrm{h}}(s_{\mathrm{in},j}, p)$	amount of heating for the input material at time point p
$q_{\mathrm{out}}^{\mathrm{h}}(s_{\mathrm{in},j}, p)$	amount of heating for the output material at time point p
$qs(s, p)$	amount of state s stored at time point p
$T_{\mathrm{f}}(s_{\mathrm{out},j}, p)$	final temperature of the output stream at time point p
$T_{\mathrm{f}}(s_{\mathrm{in},j}^{\mathrm{r}}, p)$	final temperature of the raw material stream at time point p
$T_{\mathrm{i}}(s_{\mathrm{out},j}, p)$	initial temperature of the output stream at time point p
$T_{\mathrm{in}}(s_{\mathrm{in},j}, p)$	temperature of the input material at time point p
$T_{\mathrm{out}}(s_{\mathrm{in},j}, p)$	temperature of the output material at time point p
$t_{\mathrm{p}}(s_{\mathrm{in},j}, p)$	end time of the task at time point p
$t_{\mathrm{u}}(s_{\mathrm{in},j}, p)$	start time of the task at time point p
$t_{\mathrm{in}}^{\mathrm{r}}(s_{\mathrm{in},j}, p)$	time required for heating or cooling for the input material at time point p
$t_{\mathrm{out}}^{\mathrm{r}}(s_{\mathrm{in},j}, p)$	time required for heating or cooling for the output material at time point p
$tm_{\mathrm{in}}(s, p)$	time at which state s is sent to storage at time point p
$tm_{\mathrm{out}}(s, p)$	time at which state s is sent from storage at time point p
$Ts_{\mathrm{out}}(s, p)$	outlet temperature of state s from storage at time point p
$w_{\mathrm{in}}(s, j, p)$	binary variable indicating if state s is sent to storage from unit j at time point p
$w_{\mathrm{out}}(s, j, p)$	binary variable indicating if state s is sent from storage to unit j at time point p
$x(s_*^{\mathrm{h}}, s_*^{\mathrm{c}}, p)$	binary variable indicating if there is heat exchange between the hot and cold streams at time point p
$y(s_{\mathrm{in},j}, p)$	binary variable indicating if the task is active at time point p
$y_{\mathrm{in}}^{\mathrm{c}}(s_{\mathrm{in},j}, p)$	binary variable indicating if there is cooling for the input material at time point p
$y_{\mathrm{out}}^{\mathrm{c}}(s_{\mathrm{in},j}, p)$	binary variable indicating if there is cooling for the output material at time point p
$y_{\mathrm{in}}^{\mathrm{c}}(s_{\mathrm{in},j}, p)$	binary variable indicating if there is heating for the input material at time point p
$y_{\mathrm{out}}^{\mathrm{h}}(s_{\mathrm{in},j}, p)$	binary variable indicating if there is heating for the output material at time point p
$z(j, j', p)$	binary variable indicating if there is material sent from unit j to unit j' at time point p

heat storage to achieve the maximum energy saving targets identified by the TAM. Another drawback of these previous studies is that the time schedule is not considered. In order to address the time dimension, the *time slice model* (TSM) was used for heat integration analysis (Corominas et al., 1993; Ivanov and Vaklieva-Bancheva, 1994; Kemp and Macdonald, 1987; Obeng and Ashton, 1988). This method divides the time horizon into a number of time