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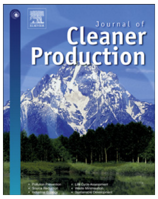

Maximising heat recovery in batch processes via product streams storage and shifting

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ABSTRACT

In a batch process, either direct or indirect heat integration may be employed. The former involves direct heat transfer from hot to cold process streams. In the latter, heat from a hot process stream is first transferred to an intermediate fluid where the heat is stored until it is finally transferred to a cold stream. Storage of product streams allows direct heat integration to be delayed, thereby providing an opportunity for energy conservation while avoiding the use of an intermediate fluid. This paper presents a new methodology for batch heat integration that involves the direct storage of product streams within the procedure to set the minimum utility targets. Application of the proposed methodology on illustrative examples demonstrates that significant energy reduction can be achieved by shifting product streams on the time scale. Potential reductions of 33.2% cold utility and 45.1% hot utility were estimated for the first example when the product stream was stored. Similarly, reductions of 3.5% cold utility and 6.5% hot utility were observed for a two-product batch plant when the cooling requirement for one of the products was shifted on time scale.

1. Introduction

Batch processes offer the flexibility and adaptability that are vital for a manufacturing plant to produce varieties of products. Procedure for the design and synthesis of a batch process is more complex than that of a continuous process due to the need to consider time as a variable in a batch process. Over the years, increasing batch process efficiency, minimizing make-span and maximizing productivity have been the subjects of extensive research.

Various works related to minimizing make-span and maximizing production have been reported in the literature. Burkard and Hatzl (2005) reviewed and investigated various formulations for batch processes scheduling developed for minimizing make-span. Arbiza et al. (2008) presented a mathematical framework for scheduling batch processes aimed at improving the environmental, make-span and/or financial performances.

Minimizing freshwater and wastewater flow-rates for batch processes has also been the subject of extensive studies. Foo et al. (2005) developed a method for cyclic batch process to minimize fresh water consumption. Majozi (2005) proposed a mathematical formulation to reduce freshwater requirement and wastewater generation in batch processes. Oliver et al. (2008) proposed a method combining pinch analysis with mathematical programming to synthesize an optimal water network for batch processes. Tokos and Pintarič (2009) proposed mathematical models for fixed schedule batch processes to minimize waste-water contaminant load and thereby fresh water. Cheng and Chang (2007) presented a mixed-integer nonlinear programming (MINLP) model for synthesizing batch water allocation networks (WAN) which simultaneously considers scheduling, water-reuse subsystems, and wastewater treatment subsystems. Chaturvedi and Bandyopadhyay

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(2014a) proposed a mathematical formulation to simultaneously maximize productivity and minimize water requirement for a batch process. Lee et al. (2014) presented a water minimisation method for batch water allocation network (WAN) to optimize the wastewater and fresh water flow rates, storage capacity and interconnections simultaneously. Tokos et al. (2013) presented a bi-objective optimization method for investigating the environmental and economic impacts of batch WAN retrofit.

Several works related to waste reduction for batch processes have also been developed. Zhao-Ling and Xi-Gang (2000) proposed a multi-objective formulation for the optimal design of a minimum-waste batch process. Grundemann et al. (2012) presented a procedure to minimize the cleaning waste for a batch process. Yi and Reklaitis (2006) presented a methodology to determine the optimal size of batch processes with storage units when the processes are exposed to random failures (operating time and material spoilage). Shrouf et al. (2014) recently proposed a mathematical model for production scheduling on a single machine aimed at minimizing the energy requirement.

Various insight-based and mathematical optimisation techniques for minimizing the energy requirement in a batch process have been reported in the literature (Fernández et al., 2012). In one of the earlier works, Vaselenak et al. (1986) proposed mixed integer linear programming formulation and heuristic rules for heat integration in a batch process for a given schedule. The possibility of rescheduling was also investigated in their later work (Vaselenak et al., 1987). Ivanov et al. (1993a, 1993b, 1993c) presented in three parts, the mathematical model to analyze heat integration in a system of two batch reactors operating at different time intervals, utilising heat storage tanks. The first part presents a model with two storage tanks (Ivanov et al., 1993a). The second model consists of one common heat storage (Ivanov et al., 1993b), whereas the third involves the design and synthesis of systems with a series of heat storage tanks (Ivanov et al., 1993c). Papageorgiou et al. (1994) presented a mathematical model to calculate the trade-offs between scheduling and heat integration constraints. Corominas et al. (1994) proposed a methodology for heat integration in batch process involving multi-products. Lee and Reklaitis (1995) developed a mathematical formulation for the optimizing schedule to explore possibilities of heat recovery for cyclic and single-product batch process. Zhao et al. (1998) developed a mathematical model for batch process scheduling that includes heat integration without intermediate storage. Adonyi et al. (2003) developed a procedure that considers heat integration and process scheduling simultaneously. Chen and Ciou (2008) proposed an MINLP model for a batch process which includes indirect heat recovery. Later, Chen and Ciou (2009) extended their work in order to incorporate the variable temperature storage associated in a batch process and developed a method to design indirect heat recovery system. Majozi (2006) presented a mathematical formulation for the synthesis of a batch process that includes direct heat integration only. The formulation was later extended to incorporate heat storage and indirect heat integration (Stamp and Majozi, 2011). Chen and Chang (2009) developed a mathematical model to combine heat integration and task scheduling in a single formulation for a batch process. Halim and Srinivasan (2009) formulated heat integration along with task scheduling in a sequential way, and later extended their work (Halim and Srinivasan, 2011) to include water minimization. Chaturvedi (2014) proposed water and energy targeting methodologies for batch processes with fixed and with variable schedules.

Apart from the mathematical programming techniques, various methodologies to minimize the energy requirement of a batch process based on pinch analysis have also been reported. Initially, Clayton (1986) proposed a time average model (TAM) to calculate cold and hot utility targets in batch processes by stretching heat flows uniformly over the horizon of batch process. The targets, calculated using TAM method were under-estimated as this method bypasses the exact time constraints. Linnhoff et al. (1988) proposed the time slice model (TSM) to overcome this limitation by dividing the time horizon of the batch process into different time intervals. The utility targets for each interval were calculated using the Problem Table Algorithm (PTA) (Linnhoff and Flower, 1978). This method did not include the heat integration between the time intervals and hence, over-estimated the utility targets. Kemp and Deakin (1989) proposed the Time-Dependent Heat Cascade Analysis (TDHCA) to calculate the minimum cold and hot utility requirements for a batch process algebraically. TDHCA calculates utility targets by determining the overall infeasibility while heat is cascaded on both the temperature and time scales. Pourali et al. (2006) presented a method, that decomposed the time horizon of a batch process into time intervals, and then identified the time–interval combination that yielded the minimum cost. The computational complexity of this method increases with number of time intervals. Chaturvedi and Bandyopadhyay (2014b) developed an algebraic methodology to determine the utility targets for a batch process that included indirect heat integration across different time intervals.

Besides utility targeting, several other issues associated to batch HEN synthesis were addressed. Stoltze et al. (1995) utilised TAM to determine heat recovery potential and proposed a methodology incorporating heat storage to attain the energy targets. Sadr-Kazemi and Polley (1996) investigated heat storage design and indirect heat recovery for batch processes and reported that heat storage might offer a more flexible option in comparison to direct integration. Krummenacher and Favrat (2000) presented a method based on TAM to determine the minimum number of heat storage units. Foo et al. (2008) proposed a targeting technique using TDHCA to minimize the number of units in batch HEN. Anastasovski (2014) developed a methodology to design a heat exchanger network for a batch process using the TSM model. Seid and Majozi (2014) proposed a continuous time mathematical model considering direct and indirect heat integration along-with scheduling framework simultaneously for designing batch HEN.

The flexibility of batch operations may be capitalised to reduce the energy demand. A process typically includes the feed, intermediate and product streams. While the heating or cooling requirement of the feed and intermediate streams may not be delayed or shifted, the heating or cooling demands of product streams can be delayed or shifted. For example, if a product stream needs to be dried, it may be possible to delay the drying process in order to utilize process heat that is available at a later time. Similarly, the cooling of a product stream may be delayed until a cold stream is available at a later time. Contrary to the case of product streams, storing or delaying the operations of the intermediate and feed streams for heat recovery will result in significant loss of opportunity to manufacture products, and ultimately, loss of productivity. The flexibility of utilising product streams at different time intervals via direct storage offers the opportunity for energy conservation as the use of intermediate fluids can be avoided.

This paper presents a methodology to set the minimum utility targets for a batch process that involves the direct storage of

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