CHEMICAL ENGINEERING TRANSACTIONS, Volume 12, 2007
Edited by Jiri Klemeš
ISBN 88-901915-4-6

Towards the Design of a Zero Effluent Facility in the Pharmaceutical Industry

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One of the main goals of any production facility is to have the least negative effect on the surrounding environment, while still producing the required output. The perfect scenario would be a production facility that produces zero effluents.

The pharmaceutical production industry has some unique characteristics that make it possible to reach the goal of zero effluent. In such industries wastewater is generally produced from washing out of mixing vessels. The wastewater thus contains valuable product residue. It is possible, under the correct conditions, to reuse the wastewater as part of the formulation of a subsequent batch of a compatible product, thereby producing zero effluent from the operation. From this the question arises on the design of the production facility as to maximise the opportunity to reuse the wastewater, thus producing zero effluent, and keeping the capital costs of such a plant to a minimum.

The derived methodology addresses the design aspect of a zero effluent pharmaceutical facility. The methodology takes storage and scheduling of the pharmaceutical operation into consideration.

Keywords: *zero effluent, batch processing, design*

1. Introduction

Effective usage of water in batch processes is becoming ever more important as environmental pressure mounts on process industries to produce less effluent. In certain industries, such as the pharmaceutical industry, the effluent generated from the facility may contain valuable product. This product is lost, which amounts to significant financial losses.

Wastewater minimisation methodologies in batch processes have in the past been focussed on maximising the reuse of water between units, while still obeying concentration constraints that apply to each unit (Wang & Smith, 1995; Almató *et al.*, 1997; Majozi, 2005). The methodologies do not take into consideration the possibility of operations where there are no concentration limitations or where water can be reused as part of product constituents. In certain operations in the pharmaceutical industry the main source of wastewater is from washing operations. This water often contains valuable product residue and thus the opportunity exists to reuse this water as part of the formulation for the same product. Reusing water as part of product formulation means that there is no effluent produced, and hence the operation tends to operate in zero effluent mode.

Natural progression would then be to design processing plants for the pharmaceutical industry based on this type of operation. The design of batch processes was first addressed by Sparrow *et al.* (1975). This formulation took scheduling of the operations into consideration during the design. Subsequent formulations (Ravemark & Rippin: 1998, Lin & Floudas: 2001) were derived for the design of batch processes while taking the scheduling aspect of the operation into consideration.

The methodology derived determines the number of vessels, and capacity and number of water storage vessels needed to fulfil the required production.

2. Problem Statement

The problem statement can be stated as follows:

Given:

i.) the product recipe and raw material requirements,
ii.) the duration of washouts and production times,
iii.) the time horizon of interest,
iv.) the required production in the time horizon of interest,
v.) the amount of water used for washouts and
vi.) the maximum allowable storage time of the wastewater,

determine the number of processing vessels as well as the number and size of wastewater storage vessels, resulting in minimum capital cost and minimum amount of effluent.

3. Mathematical Formulation

The following sets, variables and parameters were used in the derivation of the model.

Sets

$P \quad = \{p \mid p = \text{time point}\}$
$J \quad = \{j \mid j = \text{unit}\}$
$U \quad = \{u \mid u = \text{storage vessel}\}$
$S_{in} = \{s_{in} \mid s_{in} = \text{input state into a unit}\}$

Variables

$e_{unit}(j)$	Binary variable showing existence of an unit *j*
$e_{storage}(u)$	Binary variable showing existence of a storage vessel *u*
$y(s_{in},j,p)$	Binary variable showing the usage of unit *j* at time point *p*
$ys_{in}(s_{in},j,p)$	Binary variable showing water going to storage vessel *u* from unit *j* at time point *p*
$ys_{out}(s_{in},j,p)$	Binary variable showing water going from storage vessel *u* to unit *j* at time point *p*
$v_{storage}(u)$	Size of storage vessel *u*
$fe(s_{in},j,p)$	Effluent water from unit *j* at time point *p*

Parameters

V^{min}	Minimum capacity of a storage vessel
V^{max}	Maximum capacity of a storage vessel
C_U	Cost per unit of a processing vessel
C_S	Cost per unit of a storage vessel
C_{eff}	Cost of the effluent water treatment
C_V	Cost factor of storage vessel due to size variations

3.1. Design constraints

Existence variables are defined to show whether a vessel exists or not. This is used to determine the number of processing units needed and the number of storage vessels. If a state is processes then a processing unit must exist. This is given in constraint (1). A similar constraint is defined for the storage vessel. Constraint (2) states that if water is sent to a storage vessel, then the storage vessel must exist .

$$e_{unit}(j) \geq y(s_{in}, j, p), \forall\ s_{in} \in S_{in}, j \in J, p \in P \tag{1}$$

$$e_{storage}(u) \geq ys_{in}(s_{in}, j, p), \forall\ s_{in} \in S_{in}, j \in J, p \in P \tag{2}$$

The capacity of a storage vessel is also a design consideration. The capacity of a storage vessel is restricted to a maximum and a minimum. This is given in constraint (3)

$$V^{\min} e_{storage}(u) \leq v_{storage}(u) \leq V^{\max} e_{storage}(u), \forall\ u \in U \tag{3}$$

3.2. Mass balance constraints

The mass balance constraints include mass balances over the processing units and storage vessels.

In the zero effluent type of operation the contaminant mass added from the wastewater can either be considerable or not. In the case, where there is a considerable contaminant mass in the wastewater, the mass of raw materials, other than water, that is used is the sum of the contaminant mass from the reused water, either directly or indirectly, and the mass from bulk storage. In the case where there is no considerable mass of contaminants in the wastewater the amount of raw material used from bulk storage is a fixed amount.

The total mass of raw materials used for a product is the sum of the fresh water, the reused water and the total raw materials, other than water. In this formulation it is assumed that there is a fixed ratio between the amount of water in a product and the amount of other raw materials in the product. To ensure product integrity the water that is reused can only contain the same product as that which is being mixed.

Mass balances for the storage vessel have to be included. Here the mass balances have to ensure that the correct wastewater goes to the correct storage vessel, in the case of multiple storage vessels. If there is only one storage vessel, however, one has to ensure that only wastewater with a particular contaminant is stored at any given point in time. This implies that water with different contaminants cannot be stored in one vessel at the same time.

3.3. Scheduling constraints

The time aspect of batch processes has to be taken into consideration. The timing constraints used are similar to those developed by Majozi (2005). The constraints considered ensure that the direct and indirect reuse of wastewater takes place at the correct time and that the starting and ending times of each operation are correct. Finally the scheduling constraints ensure that the amount of time the wastewater is stored is less than the maximum allowable to prevent microbial growth.

3.4. Objective function

The objective function is the minimisation of capital cost and cost of effluent water. The objective function is given in equation (4). The first term represents the cost due to the number of mixers (processing units), the second and third terms represent the cost of the storage vessels. The last term represents the cost associated with the effluent.

$$\min \sum_{j} eunit(j) C_U + \sum_{u} \left(estorage(u) C_S + v_{storage} C_V \right) + \sum_{s_{in}, j, p} fe(s_{in}, j, p) C_{eff} \qquad (4)$$

$$\forall\ s_{in} \in S_{in}, j \in J, u \in U, p \in P$$

4. Illustrative Example

The illustrative example involves the design of a small pharmaceutical mixing operation. In this operation three products are produced. On average two batches of the first product and three batches of products two and three respectively need to be produced in 24 hours. The product composition is given in Table 1. Each product requires different processing times which are dependent on the type of product.

Table 1: Product composition

Product	Amount of fresh water (kg)	Amount of other raw material (kg)	Processing time (hr)
Product 1	1600	400	8
Product 2	1650	350	5
Product 3	1800	200	7

In the example there is an option of only one storage vessel that has a maximum capacity of 2000kg and a minimum of 100kg. The maximum number of potential mixing vessels is 4. The cost of each mixing (processing) vessel is fixed at 12 737 c.u.. The value of C_s is 5617 c.u. and C_v is 0.25 c.u. per ton . Treatment costs of the wastewater was 7 c.u. per kg of water. In this example it is assumed that the mass load in the wastewater does not add to the raw material mass.

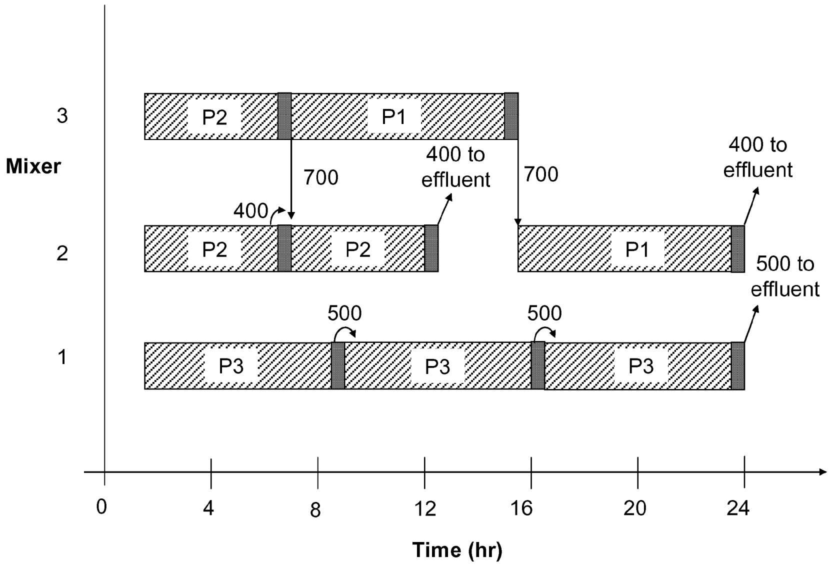

Figure 1. Schedule for the designed plant

The example was solved using GAMS/CPLEX solver. The processor used was a Pentium 4 3.2GHz. The solution time was 97.5 CPU seconds and the optimal number of time points was 8. The resulting formulation had 421 binary variables. The resulting design had three mixing vessels and no storage vessel. The operation only produced 1300kg of wastewater, which relates to a 68% savings in wastewater when compared to the operation without reuse. The resulting value of the objective function was 48 152 c.u.. The optimal schedule is shown in Figure 1. In the figure the black striped boxes represent mixing and the grey box represent washing out of a mixing vessel. The values given in the figure represent the amount of water that is reused. The product produced by each mixer is represented by the letter "P" and the corresponding product number within the black striped box.

5. Conclusions

The method derived determines the optimal design together with the corresponding schedule of a plant that is able to run in a near zero effluent mode. The methodology determines the number of operating units needed as well as the number and size of storage vessels that are used for wastewater storage. The methodology ensures that a maximum storage time of the wastewater in the storage vessel is obeyed.

In the example the resulting design also had three mixing vessels with no storage for the wastewater. This result is expected as direct reuse of water is assumed to feasible in the example.

6. References

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