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Enhancing the productivity of batch deodorizers for edible oils

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ABSTRACT

This paper addresses the potential of a process alternative aimed at improving the efficiency of batch deodorizers, coupling them to a small continuous desorption packed column: the steam exiting the batch deodorizer is fed to the bottom of the column, while the oil contained in the batch vessel is recycled through the top of the column and then returned to the vessel. This strongly increases the efficiency of separation, reducing stripping steam consumption by 16.5% and processing time by almost a half, from 3.0 h to 1.8 h. The required additional equipment consists of a small column section and a pump, that increase the cost of investment by 22% compared to conventional batch. Thus, the alternative here proposed achieved a pretty good preliminary economic assessment with a positive profit of 61,970 ($/year) above the conventional batch process. Overall, the semi-batch design proved to have a better performance than the batch mode in both economic and flexibility terms, while continuous is far better in economics but far worse in flexibility than both batch designs.

1. Introduction

Deodorization is the last stage of oil refining, by which odorant compounds are removed and the content of free fatty acids FFA minimized by means of a high-temperature and high-vacuum steam-desorption process.

Deodorization is usually performed either in continuous, semi-continuous or batch mode, depending on several factors. Batch technology is used for small production capacities e.g. 50–100 ton/day (Carlson, 1996), or in plants where the type of oil to be processed is frequently changed (a multiproduct processing plant, e.g. soybean, sunflower, etc). Batch deodorization consists in treating the oil in a closed container with direct steam injection through a distributor, to strip the undesirable components. This is attractive in several respects: it is easy to design and to operate, has a low investment cost and is very flexible for product changeovers. However it also has disadvantages: it does not allow efficient heat recovery which leads to a high consumption of heating and cooling utilities (Gavin, 1981), and the times required to process a batch are quite long due to poor vapor-liquid contacting efficiency e.g. 8–12 h, which implies a high stripping steam consumption per ton of treated oil (Gavin, 1981; O'Brien, 2009). At industrial scale, the stripping steam requirement for batch deodorizers is 2–4% of the oil to be treated, while continuous and semi-continuous deodorizers need 0.75–1.5% and continuous thin-film systems can operate with as low as 0.3–0.6% steam (Carlson, 1996). This paper addresses the potential of a process alternative aimed at improving the efficiency of the batch deodorizer, thus reducing one of its main disadvantages.

While for distillation many configurations have been explored: the batch - one stage (the simple batch still), continuous - one stage (the flash), continuous - multistage (the traditional continuous distillation column), and batch - multistage operated in several alternative forms: as a rectifier, as a stripper, or fed from a middle vessel (Sørensen and Low, 2005; Barolo et al., 1996). Furthermore, also the use of continuous distillation columns to perform batch separations has been studied (Mujtaba, 1997).

Otherwise, for absorption (desorption in this case) the configurations studied are fewer: the continuous - multistage (cross-flow and counter-current), semi-continuous also multistage, and batch - one stage (Gavin, 1981; Ceriani and Meirelles, 2004). To the best of our knowledge, the batch-multistage alternative has not been proposed nor assessed before in the open literature.

The goal of present study is to enhance the deodorization of edible oils by implementing a semi-batch process. The following tasks were solved so that the advantages of this new process design be revealed and evidenced: (2) introducing the new process design; (2.1) process modeling; (2.2) stating a case study problem; (3.1) techno-economical optimizing the semi-batch deodorization process proposed; (3.2) analyzing other process optimization

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scenarios; and (3.3) comparing the semi-batch process proposed here with batch and continuous processes.

2. Introducing semi-batch deodorization process

The process alternative proposed in this paper is the incorporation of a continuous desorption column section coupled to the batch deodorizer: while the steam exiting the batch deodorizer is fed to the bottom of the column, the oil contained in the batch vessel is recycled through the top of the column and then returned to the vessel. This increases the efficiency of the separation, i.e. the steam leaving the column will have a larger concentration of undesirable compounds than the steam leaving the batch deodorizer, thus reducing stripping steam consumption and the cycle time of the batch facility.

Fig. 1 presents the process flow diagram to be studied here. The fresh stripping steam enters the system through the steam distributor of the batch deodorizer, exits the vessel from the top with the concentration of volatile components that it would have if only this unit were in operation, enters the continuous desorption column section through the bottom, exits the column from the top enriched in these components at a concentration close to equilibrium with the incoming oil, and exits the system. The oil in the batch vessel is pumped to the top of the column, where it makes contact with the up-rising steam while flowing down by gravity as a thin film through a structured packing and then returns to the vessel from the bottom of the column. In Fig. 1 the path taken by the steam was drawn as a solid line while the path taken by the recycled oil was drawn as a dashed line.

The hypothesis formulated in this work is: the coupling of a continuous desorption column to the batch deodorizer produces a reduction of processing time by increasing the efficiency of the separation, and this will positively affect the economic performance of the batch deodorizer. Satisfaction of this hypothesis depends on how large is the increment of the efficiency, and how expensive the capital and operating costs added by the new equipment (the column and the pump).

The oil contained in the batch deodorizer is well mixed due to the bubbling steam, so that the composition of the oil entering the column will be the same as that of the oil that is instantaneously held in the vessel. Thus, the maximum attainable efficiency of the whole process would be the one corresponding to an ideal batch

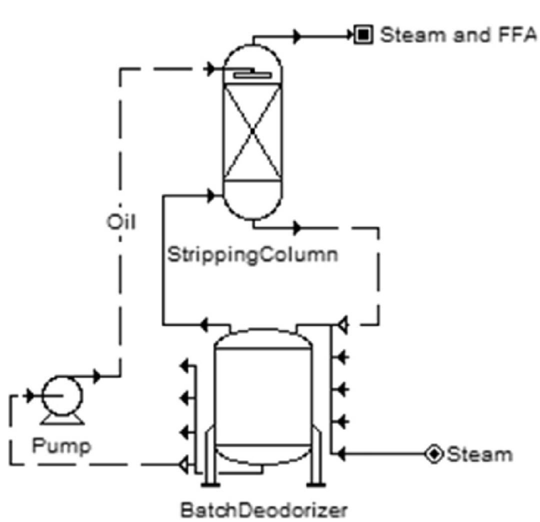

Fig. 1. Process flow diagram proposed: a batch deodorizer coupled to a continuous desorption column.

stripper alone, if the composition of the steam leaving the column were in equilibrium with the oil entering the column. Its closeness to equilibrium depends on the number of stages of the column and on the slope of the operating line.

The flow rate of steam entering the column is the same as the flow entering the batch deodorizer and must fulfill a certain relationship to the amount of oil present in the batch vessel (a steaming rate) to provide appropriate steam-oil contact, and mixing (Gavin, 1981). So, for a batch deodorizer with a given "base case" holding capacity, the flow rate of stripping steam will be fixed. This flow determines the cross sectional area of the column and, therefore, its diameter is also fixed. Otherwise, the number of stages remains as an optimization variable, the tradeoff being: an increase in the number of stages N means a larger cost of the column but a better efficiency of the process.

With the flow rate of steam fixed the only remaining degree of freedom is the flow rate of recycled oil L [kg/h], and so this is the second optimization variable. If the operating conditions in the column section were to be chosen to increase the solute concentration in the outlet steam, this is done by increasing L but requiring an increased pump size (a larger mechanical power) and electric energy consumption.

This optimization problem will be addressed following the same methodology as that used by Luyben (2014) to solve the trade-off between product recovery and costs (both investment and operating costs) in distillation separations. This author applies Douglas's (1988) approach using simple calculations (e.g. Fenske-Underwood-Gilliland plus heat and mass balances) to scan the economic impact of process decision variables, which highlights the problem at hand better than the single optimal point found by numerical optimization.

2.1. Process modeling

Next, the process mathematical model implemented in MATLAB is outlined to perform the mass and energy balances, equipment sizing, costs estimation and process optimization, which uses first level of detail models following Douglas's Conceptual Process Design Procedure (1988). The system was simplified by assuming it is binary (just oil and FFA), i.e. the model does not consider the hydrolysis reaction of components as in the model by Cerpa et al. (2009). The differential equation that represents the mass balance in the batch vessel is:

$$B(dX/dt) = -GY - L(X - X_{out}) \tag{1}$$

where B [kg] is the batch size of oil to be treated, X is the instantaneous mass fraction of FFA in B, G [kg/h] is the flow rate of steam leaving the vessel, Y is the mass fraction of FFA in G, L [kg/h] is the flow rate of oil recycled through the column and X_{out} is the instantaneous mass fraction of FFA in the oil that exits the column returning to the vessel.

Y and X were assumed to be linearly related through an efficiency factor μ with $0 < \mu < 1$ times the equilibrium partition constant m_p:

$$Y = \mu m_p X \tag{2}$$

The mass balance of FFA in the column is given by:

$$LX + GY = LX_{out} + GY_{out} \tag{3}$$

And the separation achieved in the column is described by Kremser equation: