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Enhancing the productivity of batch deodorizers for edible oils

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A B S T R A C T

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 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.

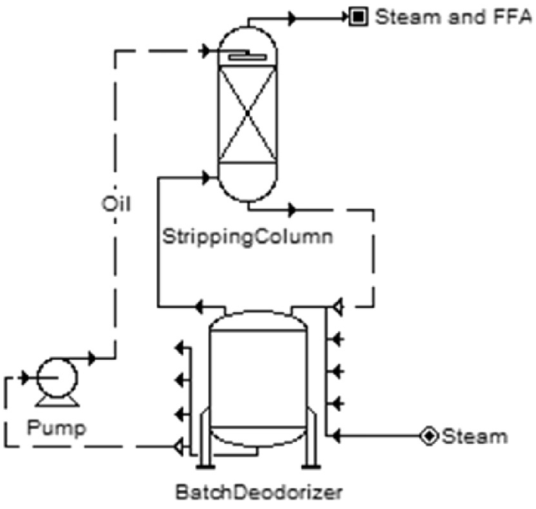

Fig. 1. Process flow diagram proposed: a batch deodorizer coupled to a continuous desorption column.

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:

$$(Y - m_p X)/(Y_{out} - m_p X) = \left(A^{N+1} - 1\right)\Big/(A - 1) \qquad (4)$$

where m_p is the same equilibrium constant as in Eq. (2), N is the number of separation stages and A is the absorption factor considered as $A = L/(m_p\, G)$.

The performance of the batch deodorizer working alone can be found by replacing Y taken from the vapor liquid distribution Eq. (2) into the mass balance Eq. (1) with L = 0.

$$dX/X = -\mu(Gm_p)/Bdt \qquad (5)$$

This simple differential equation can be analytically integrated from $X_{initial}$ to X_{final} to yield a prediction of the required processing time:

$$t = (B/Gm_p\ \mu)\ln\left(X_{initial}\Big/X_{final}\right) \qquad (6)$$

The batch deodorizer vessel was sized as a vertical cylinder with an oil level of 2.5 m and about the same amount of headspace (Gavin, 1981) with a diameter such that the vessel can contain the batch size B. The column diameter was sized in such a way that a steam velocity $v_G = 1.8/\sqrt{\rho}$ is obtained, where v_G has units [m/s] and ρ is the steam density in [kg/m^3]. The column height is computed as 0.5 m of regular packing per separation stage plus 1.5 m (Douglas, 1988). The pump was sized with Bernoulli with a mechanical efficiency of 0.6, a difference in height between the oil level in the vessel and the top of the column of 6 m, a pressure drop of 5×10^4 Pa (0.5 at.) in a control valve, and a velocity of 3 m/s in the pipe.

Investment costs of the column (Eq. (7)), the batch deodorizer (Eq. (8)) and the pump (Eq. (9)) were estimated using Douglas correlations, which are power laws of the diameter and height in the case of vessels (Luyben, 2014), and a function of the mechanical power in case of the pump. Stainless Steel 304 was considered for the material factors (Fc). Capital costs were updated through the Marshall and Swift index M&S published by Chemical Engineering and a capital charge factor of 0.325 was used to annualize capital investments (Douglas, 1988).

$$IC_{Column} = (M\&S/280)\left(101.9*(D*3.28)^{1.066}*(H*3.28)^{0.82}*Fc\right) \qquad (7)$$

$$IC_{Batch} = (M\&S/280)\left(101.9*(D*3.28)^{1.066}*(H*3.28)^{0.82}*Fc\right) \qquad (8)$$

$$IC_{Pump} = 10^{\left(3.3892+0.0536*\log_{10}(P_p)+0.1538*\left(\left(\log_{10}(P_p)\right)\right)^2\right)} \qquad (9)$$

The operative costs being considered were labor, stripping steam consumption, electric energy at the pump, and oil heating and cooling costs assuming that steam and cooling water are used as utilities. The economic performance index used was Profit (Douglas, 1988), which is defined in Eq. (10) (ignoring taxes), with all the terms in [$/yr].

$$\text{Profit} = \text{Revenues} - \text{Operating Costs} - \text{Annualized Capital Costs} \qquad (10)$$

2.2. *Statement of a case study problem*

By assuming that batches of B = 10,000 kg of oil are processed, the batch deodorizer vessel with an oil level of 2.5 m requires a diameter D = 2.5 m to hold this batch size. The oil was considered to be a binary mixture of triglycerides and FFA, the triglycerides with a Molecular Weight MW of 885 [g/mol] and the FFA having the properties of oleic acid with a MW of 282 [g/mol]. The oil was considered to initially contain 5% by weight of FFA and the final product specification was set to 0.05% (Mounts, 1981). For the batch deodorizer, the steaming rate recommended by Gavin (1981) is considered, which is 3 kg/h steam per 100 kg of oil being treated, whereby the steam flow rate will be G = 300 kg/h.

A processing temperature of 210 °C and an absolute pressure of 667 Pa (5 mmHg) were considered. For these operating conditions Ceriani and Meirelles (2005) report a distribution constant of 1.03 on a molar base, so that affected by the MW of the carriers oil 885 [g/mol] and water 18 [g/mol] yields $m_p = 50$. Also, by fixing the operating pressure and temperature, the diameter of the continuous desorption column is set: steam density is about $\rho = 3\times10^{-3}$ [kg/m^3], then $v_G = 1.8/\sqrt{\rho} = 33$ [m/s] and so D = 1 m.

Considering that Douglas (1988) recommends to take an absorption factor of 1.4 as a first approximation to the optimal L/G in continuous absorbers, in the present work an initial figure of A = 1/1.4 will be considered for desorption. Thus, applying the definition of A = L/(m G) leads to L/G = 35.75 and so L = 10,700 kg/h. As L is going to be an optimization variable this will be the initial base case value, and the optimization study will determine the optimal. For this oil flow rate, the power required by the pump is about 1 kW.

The performance of the batch deodorizer alone, described by Eq. (6) depends on its efficiency μ for which a value μ = 0.5 was adopted, which predicts a processing time t = 3 h for this base case problem. Both values (μ and t) fit conservatively (predict a relatively low time and large efficiency) inside the ranges reported by several authors (Gavin, 1981; O'Brien, 2009; Balchen et al., 1999). In accordance with the figures handled by Akterian (2009), an estimated 2.4 h time for charging, heating, cooling and discharging the vessel was added, which leads to a complete cycle time of 5.4 h. The annual production time was set in 7200 h/year, so that the batch deodorizer produces 1280 batches per year. To compute operating costs, a price of 0.019 $/kg was considered for steam, of 0.05 $/m^3 for cooling water, and of 0.1 $/kWh for electricity, according to Ulrich and Vasudevan (2006). After some calculations, the cost for heating each batch of 10,000 kg from 30 to 210 °C is 28.8 $/batch, and for cooling it back to 50 °C is 3.2 $/batch. The cost of stripping steam considers a flow rate of G = 300 kg/h during the 3 h deodorization time for each processed batch times the number of batches processed in one year, and labor cost was estimated assuming that the deodorizer requires half time of one operator.

The term Revenues in Eq. (10) is sales revenues (a product price times the annual production) minus raw material purchases. In the case presented in this work, the "product" is oil already deodorized but not yet packed, while the "raw material" is oil already pretreated but not yet deodorized. Here a "selling price" for the product is defined, by computing the value added by the original batch deodorizer (without the continuous desorption column). It is assumed that the pre-treated oil fed to the deodorization stage is obtained (bought) for free, and that a price is paid for the deodorized oil, which matches the sum of operating plus annualized capital costs. Thus, the Profit defined in Eq. (10) will be zero for the batch deodorizer alternative which is taken here as the base case, and a positive figure for the semi-batch process (if successful). The so calculated price was 0.0204 $/kg.

3. Results and discussions

Fig. 2 plots the evolution of instantaneous molar fraction of FFA in oil inside of the batch deodorizer, from the initial content of FFA

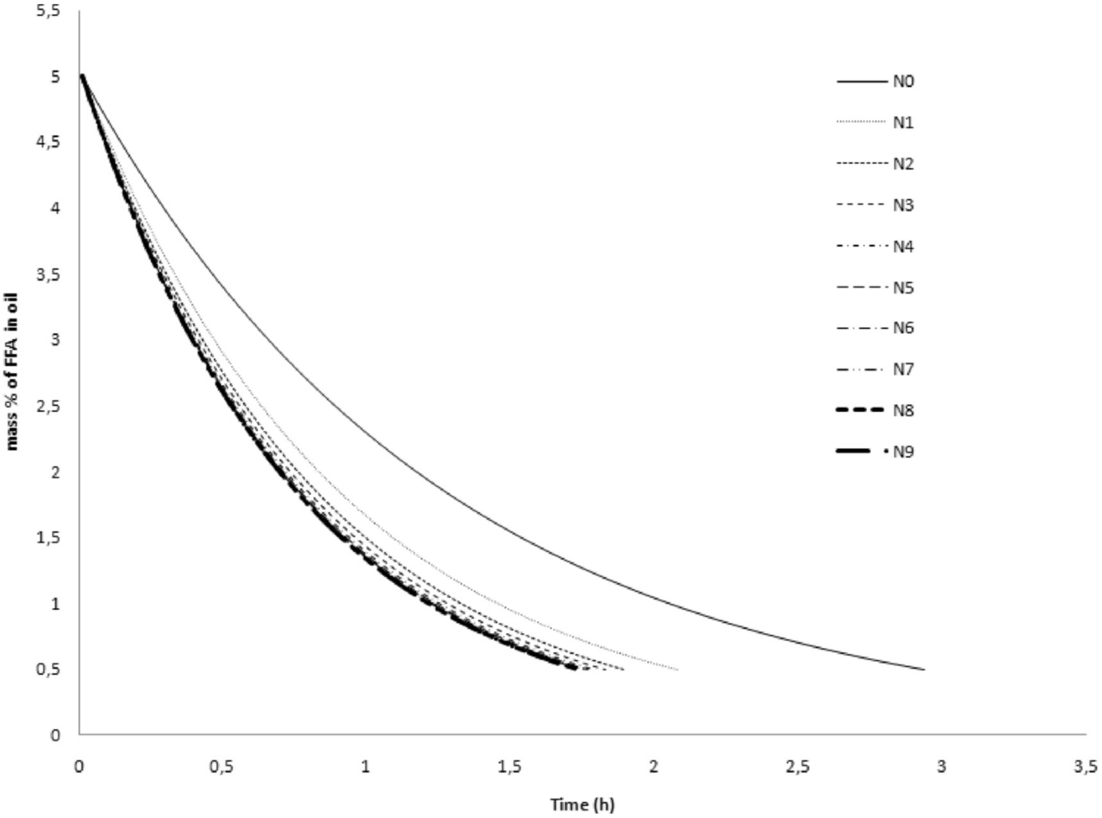

Fig. 2. FFA composition in the vessel vs. time. Parametric in number of stages N.

up to values smaller than the specified final concentration of the product 0.05% in weight. It is a function of processing time, parametric in the number of stages of the continuous desorption column, with L = 10,700 kg/h that corresponds to A = 1/1.4.

Increasing the number of stages reduces the time needed to achieve the target composition in the deodorizer. The line N = 0 corresponds to the batch deodorizer alone, without adding the continuous column. The first added continuous separation stages significantly reduce the processing times. However above 5 stages the effect is less pronounced, so the scanning was stopped there. The addition of a small 4 stages column strongly reduced the processing time from 3.0 h to 1.78 h. Thus, adding 2.4 h for charging, heating, cooling and discharging, leads to a cycle time of 4.2 h that corresponds to 1722 batches/yr against the 1285 of the batch deodorizer alone.

The capital investment costs for the two process alternatives being compared are presented in Table 1. The batch deodorizer vessel is the same in both cases, with a height H = 5 m and a diameter D = 2.5 m. For the continuous column a number of separation stages N = 4 was adopted which leads to a height H = 3.5 m and the diameter is D = 1 m, the pump size is 1 kW. The capital investment for the alternative here proposed is about 30% larger than that for the batch deodorizer alone, due to the addition of the continuous desorption column and the pump for recycling the oil.

The operating costs are displayed in Table 2 and are also larger for the new alternative, but in this case just about a 10% larger. The costs for heating and cooling the oil are proportional to the number of batches per year: 1280 in case of the batch deodorizer alone and 1720 for the new process alternative.

The stripping steam consumption is lower for the new alternative: as the stripping time is shorter but the time for charging, heating, cooling and discharging remains 2.4 h, the number of stripping hours per year is lower. The cost of electric energy is also related to the stripping time: 1722 batches/yr 1.7 h/batch 1 kW = 4370 kWh/yr and is small compared with the other cost components. The labor cost was assumed not to change.

The complete preliminary cost assessment comparing both alternatives is presented in Table 3. The Profit as computed from Eq. (10) is zero for the batch deodorizer alone, because a “selling price” was adopted such to cover just the added value in this alternative. With this same product price the batch deodorizer coupled to a continuous desorption column yields a Profit of about 62,000 $/yr that would permit a return of investment in the extra equipment 67,700 $ in about 1.1 years.

Table 1
Total Capital Investment TCI for both alternatives [$].

Equipment	Batch process	Semi-batch process
Deodorizer	306,190	306,190
Column	–	57,661
Pump	–	10,036
TCI	**306,190**	**373,887**

Table 2
Operating costs for both alternatives [$/year].

Cost component	Batch process	Semi-batch process
Stripping steam	29,087	24,317
Electric energy	–	387
Heating steam	47,814	66,890
Cooling water	2684	3755
Labor	72,000	72,000
Total operating costs	**151,580**	**167,350**

Table 3
Preliminary cost assessment of both alternatives.

Cost component	Batch process	Semi-batch process
Sales revenues [$/yr]	251,090	350,830
Operating costs [$/yr]	151,580	167,350
Annualized capital cost [$/yr]	99,510	121,510
Profit [$/yr]	–	**61,970**

3.1. Optimization of the semi-batch process

Fig. 3 plots the effect of changing N holding L constant, on the economic performance of the new process. The tradeoff is: increasing N increases the cost of the column, but reduces the stripping time required to achieve the target product specification, which increases production capacity. The graph indicates an optimal solution at N between 4 and 5. This corresponds to the finding in Fig. 2: the first added stages significantly reduce the processing times, but above 5 stages the effect is less pronounced, while the cost increases almost linearly with N.

Fig. 4 plots the effect of changing L holding N constant at N = 4 on the economic performance of the new process. The tradeoff is: increasing L increases the size of the pump needed to recycle the oil and its electricity consumption, but increases the efficiency of the new process by increasing the content of FFA in the steam that leaves the column, with the same beneficial consequences as increasing N.

The graph indicates that increasing L monotonically increases the economic performance of the process, without showing a maximum in the range of L explored. Increasing L linearly increases both the size and the energy consumption of the pump, but as shown in Tables 1 and 2 the costs associated to these items are significantly smaller than any other cost component: the effect of increased efficiency exceeds them along the entire interval plotted in the figure.

The increment of L in Fig. 4 was stopped before arriving to A = L/(m G) = 1 for other reasons. On one hand because increasing A beyond 1 (an operating line with a slope larger than the equilibrium line) in desorption, would generate a pinch in the high concentrations end of the column (in the top), with wastage of separation stages there. But before this, the liquid load is constrained to not approach flooding of the column. Even if this effect is less pronounced for structured packings, Zakeri et al. (2012) present experimental evidence that some of them show a sharp increase in pressure drop at a liquid load of 25 m^3/m^2h. Conclusion: the optimal L should be as large as possible, while safely short of the flooding liquid load.

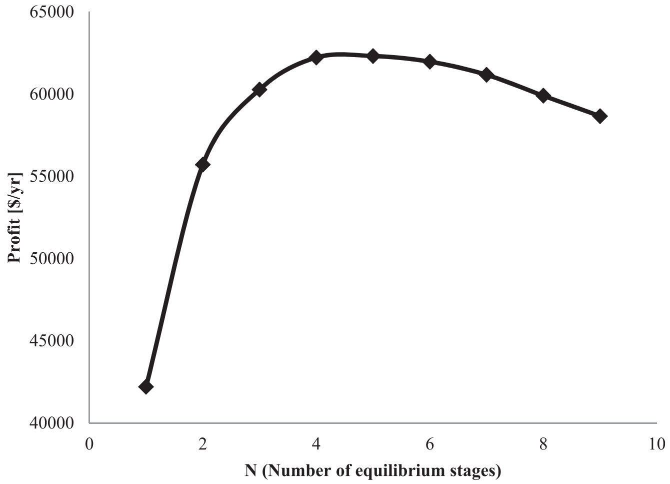

Fig. 3. Profit [$/yr] vs. number of stages [N], holding L = 10,500 kg/h constant.

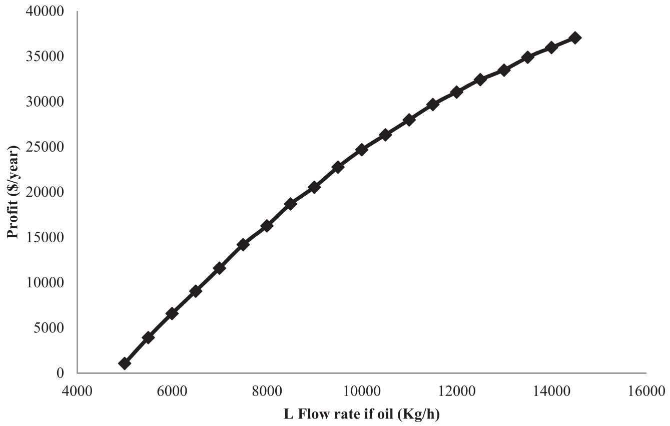

Fig. 4. Profit [$/year] vs. the oil recycle flow rate L [kg/h] for N = 4.

The numerical optimization finds the optimal point at N = 6 and constraint L = 14,500. In Table 4 cost assessment is redone, by comparing the batch and semi-batch alternatives with the last alternative computed at the optimal L and N.

Comparing Tables 3 and 4 one finds that the net profit of the semi-batch alternative increased about a 6 percent. The annualized capital cost increased due to the larger sizes of the column and the pump, and the operating cost increased too due to larger energy consumptions: electricity, and heating - cooling a larger number of batches. These cost increments are outweighed by the sales revenues due to the increase in separation efficiency, which leads to a reduction of stripping time per cycle from 4.18 to 3.9 h with an increase of the number of batches processed per year from 1720 to 1845.

3.2. Analysis of other process design scenarios

In the above sections, the reduction in operating time was used to increase annual production (without an upper bound on this annual production), but this would only match the scenario of an independent oil deodorization company that e.g. buys unfinished oil from suppliers and sells the deodorized oil. Next, two more realistic scenarios will be considered: a process modification project for an existing oil refinery, and a grass roots design project.

In the case of a process modification project for an existing whole refinery plant, the production rate cannot be changed because the feed oil comes from upstream stages, but the reduction of cycle times could be exploited to reduce operating time and hence, cost components related to it: stripping steam and labor (heating steam and cooling water consumption will remain the same for an unchanged annual production rate). From Table 2 it can be seen that labor cost is the most significant operating cost. The modified process would require a smaller number of shifts: in a 2/3 ratio (e.g. reducing from 3 to 2 the number of shifts per day), and thus reducing annual labor cost from 72,000 to 48,000. Table 5 displays cost assessment by comparing the conventional batch and the semi -batch alternatives for the process modification

Table 4
Cost assessment of both alternatives at L and N optimal.

Cost component	Batch process	Semi-batch process
Sales revenues [$/yr]	251,090	370,990
Operating costs [$/yr]	151,580	170,570
Annual capital cost [$/yr]	99,510	124,470
Profit [$/yr]	–	**75,950**

Table 5
Cost assessment in a process modification project scenario.

Cost component	Batch process	Semi-batch process
Sales revenues [$/yr]	251,090	251,090
Operating costs [$/yr]	151,580	115,250
Annual capital cost [$/yr]	99,510	124,470
Profit [$/yr]	–	**11,370**

project scenario.

As can be seen, the economic impact of reducing operating time is much less pronounced than increasing production rate. In this case the return of investment in the extra equipment 67,700 $ is about 6 years. In case that the process modification project was motivated because deodorization is the bottlenecking stage, the benefits will be larger because the production rate could be raised up to the next bottleneck figure. And beyond economic considerations, lowering the time that the oil is exposed to high temperatures also protects its quality.

In the case of a grass roots plant project, the design would be done to meet a target annual production e.g. 8,500,000 in a specified horizon time, e.g. 7200 h, i.e. both alternatives should be designed to meet the same production rate. As in the semi-batch case the number of batches is increased from 1280 to 1,720, the batch size can be reduced by the same ratio and thus the deodorizer size would be smaller than in the batch alone alternative. The batch size is then 7000 kg oil, and the deodorizer diameter and height are 1.6 m and 4 m respectively. The continuous desorption column has $N = 6$ as in the other scenarios, but the diameter is smaller because the stripping steam flow rate is smaller (respecting the steaming rate 3 kg/h steam per 100 kg oil treated). Then the column diameter and height are 0.9 m and 4.5 m respectively. And the pump is smaller too because the oil recycle stream is smaller 10,150 kg/h for the same L/G ratio. Table 6 shows that the capital investment cost of the semi-batch alternative is now significantly lower than that for the conventional batch deodorizer.

With respect to the operating costs: labor cost is the same (same horizon time), heating and cooling costs are the same (same amount of oil to be heated and cooled), stripping steam is smaller (as in the other semi-batch designs) and electricity cost is smaller than in the other semi-batch designs (smaller recycle oil flow rate) while it is zero for the batch alone alternative. Table 7 displays the cost assessment comparing the alternatives for the grass roots plant design scenario.

3.3. *Comparison with a continuous process*

This section does, for the sake of completeness, a comparison of the batch and semi-batch processes with a continuous column design. Even if the main goal of this work was to improve the performance of the conventional batch deodorizer, this comparison is illustrative of the tradeoff batch vs. continuous, and highlights how the semi-batch process performs.

Table 6
Total Capital Investment [$] in a grass roots plant project scenario.

Equipment	Batch process	Semi-batch process
Deodorizer	306,190	158,460
Column	–	57,680
Pump	–	8940
TCI [$]	**306,190**	**215,080**

Table 7
Cost assessment in a grass roots plant project scenario.

Cost component	Batch process	Semi-batch process
Sales revenues [$/yr]	251,090	251,090
Operating costs [$/yr]	151,580	147,080
Annual capital cost [$/yr]	99,510	69,900
Profit [$/yr]	**-**	**34,110**

The continuous column is sized for the same production rate as for the optimal semi-batch process which is 18,450 tons oil per year. The sizing was done with the same Kremser model used previously, with an absorption factor that takes a L/G ratio of 1.3% as in Yerien et al. (2010) for a similar case. This ratio is also in the range 0.5–2% recommended for continuous deodorization by O'Brien (2009). The continuous design needs a column with $N = 3$ separation stages that lead to an investment cost of $ 40,000. The cost performance comparison among alternatives is presented in Table 8.

The annualized investment cost is the key for the disproportionate economic success of the continuous process. Although it should be said that in practice, the continuous design needs to provide some extra residence time to allow the hydrolysis reaction of components, because the residence time of oil in the column is very small. If this residence time is provided by a holding vessel, the cost of the whole process would be closer to that of the semi-batch. With respect to the operating costs, they are larger for the continuous process mainly due to labor cost. While the semi-batch process works with two shifts per day, the continuous process needs three. The stripping steam consumption is pretty smaller for the continuous process. Nevertheless, as it stands, the net profit of the continuous process is more than twice the one of the semi-batch.

In addition, a very simple sensitivity analysis to changes in the feed composition or specification of the product was done, because it is also useful to compare the alternatives, and in this respect it can be expected that batch processes be superior. Variation in the feed composition was chosen because the specification of 0.5% FFA in the product is kind of tight: more FFA increases proneness to turn rancid, but less to hydrolyze much oil.

It was assumed that the feed composition changed from 5% in the base case, to 10% weight percent of FFA in oil for this analysis. For this figure, the stripping time required to achieve product specification climbed, for the batch process from 2.9 h to 3.8 h and for the semi-batch process from 1.5 h to 2.05 h. After addition of the 2.4 h of idle time to get the cycle time, the reduction of the number of batches produced in one year can be computed. In the batch process the reduction is from 1285 to 1110 batches of 10 tons oil and in the semi-batch process from 1845 to 1620 batches. For the continuous process, Kremser equation was used to find out the value of L that would permit a column of $N = 3$ equilibrium stages, get an exiting oil with the product specification of 0.5% if fed with oil of 10% L has to be reduced from 2565 kg/h to 300 kg/h. Table 9 summarizes the reduced annual production of the different processes.

Table 8
Comparison of the economic performance of process alternatives.

Cost component	Continuous process	Semi-batch process	Batch process
Sales revenues [$/yr]	370,990	370,990	251,090
Operating costs [$/yr]	188,793	170,570	151,580
Annual capital Cost [$/yr]	12,802	124,470	99,510
Profit [$/yr]	**169,404**	**75,950**	**-**

Table 9
Comparison of the flexibility performance of process alternatives.

	Continuous process	Semi-batch process	Batch process
Annual production [ton/yr]	2160	16,200	11,100

As expected, batch processing is far superior than continuous in respect to flexibility. Also, the semi-batch process improved the batch process performance.

4. Conclusions

The economic impact of improving the efficiency of batch deodorizers by coupling them to a continuous desorption column was studied. The working hypothesis was confirmed by results: the reduction in processing time from 3 h to 1.78 h causes an increase in production capacity from 1285 batches/yr to 1722 batches/yr that increase profits above the cost of implementing the alternative: a positive profit of 61,970 $/year. Beyond economic considerations, lowering the time that the oil is exposed to high temperatures also protects its quality.

The optimization study showed a sharp optimal solution for N the number of stages in the column, beyond which the effect of reducing processing time is less pronounced. The optimal number of stages in the column was between 4 and 5. Otherwise, the increase in the flow rate of the oil recycle L monotonically increases the economic performance of the process. Thus, the optimal operation of the column should be close to the physical limit when the liquid flow rate starts flooding the column.

The economic impact of the here proposed alternative was analyzed in different process design scenarios. The impact is very strong if the smaller stripping times required by this alternative could be exploited to increase production rate, as analyzed in the first considered scenario. In case of a process improvement project for an existing oil refinery, if the deodorization is not the bottlenecking stage, one can exploit the smaller processing times to reduce the number of shifts and thus labor cost, but the net profit is much smaller in this case. If the process modification project was motivated because deodorization is the bottlenecking stage, the benefits will be larger because of the production rate increase. Also the grass roots plant design scenario was analyzed, where the impact again increases, mainly because the semi-batch alternative requires a smaller deodorizer.

To the best of our knowledge, this hybrid process has not been explored before now in the open literature. Actually, the process is kind of counter-intuitive, because of feeding the oil at the top of a column and afterwards remixing it with the poorer quality oil in the vessel. However, the batch deodorizer alone has such a poor efficiency, that improving it pays off.

Overall, the comparison of the performance of the here proposed semi-batch with the conventional batch and continuous designs is as follows. The economic performance of continuous is superior to both batch modes, semi-batch being superior to conventional batch. And flexibility of the semi-batch alternative is better than batch alone, while both batch modes are far better than continuous.

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Nomenclature

A	Absorption factor
B [kg]	Batch size
D [m]	Diameter
FFA	Free fatty acids
Fc	Material factors in investment cost of equipment
G [kg/h]	Flow rate of steam
H [m]	Height
IC [$]	Investment costs of equipment
L [kg/h]	Flow rate of oil recycled through the column
m_p	Equilibrium constant
M&S	Marshall and Swift index
MW [g/mol]	Molecular Weight
N	Number equilibrium stages in the column
P_p [KW]	Power of pump
Profit [$/yr]	Net revenues
t[h]	Processing time
TCI [$]	Total Capital Investment
X	Instantaneous mass fraction of FFA in oil in batch vessel
X_{final}	Mass fraction of FFA in finished oil (Product)
$X_{initial}$	Mass fraction of FFA in initial oil
X_{out}	Instantaneous mass fraction of FFA in the oil that exits the column
Y	Mass fraction of FFA in G
Y_{out}	Mass fraction of FFA in G that exits the column
μ	Efficiency factor of batch process
ρ [kg/m^3]	Steam density
v_G [m/s]	Steam velocity

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