Stripping Medium Requirement in Continuous Countercurrent Deodorization

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ABSTRACT: A mathematical formula was derived that allows the stripping steam requirement of the countercurrent deodorization process to be calculated as a function of system pressure, vapor pressure of the pure volatile compound, initial and final volatiles contents, and the number of transfer units (an equipment parameter) of the countercurrent deodorizer. Just as in batch or cross-flow deodorization systems, the steam requirement in countercurrent systems is proportional to the system pressure and inversely proportional to the vapor pressure of the pure volatile compound. Increasing the number of transfer units (for instance, by increasing column height) to more than two makes the countercurrent system require less steam than cross-flow systems with a vaporization efficiency of 0.6. In addition, the short residence time in a countercurrent deodorization column minimizes side reactions and allows the deodorization temperature to be raised without generating unwanted by-products such as *trans*-isomers and/or oligomers of unsaturated fatty acids. The increased deodorization temperature increases the vapor pressure of the pure volatiles and leads to further savings in stripping medium and motive steam. Countercurrent deodorization systems therefore require less energy than cross-flow deodorization systems and/or produce oil with fewer unwanted by-products.

Paper no. J9074 in *JAOCS 76,* 989–993 (August 1999).

KEY WORDS: Countercurrent process, deodorization, energy savings, fatty acid oligomerization, *trans*-isomer formation, physical refining, stripping steam.

The observation that a countercurrent deodorizer requires far less stripping steam than currently used cross-flow, tray-type deodorizers (1) raises the question of whether this steam requirement can be expressed mathematically. This question has been asked before and various formulae have been proposed in the literature, the earliest in 1943 (2).

In countercurrent deodorization systems, the vapors leaving such systems have been in contact with oil entering the system. According to Raoult's law, which expresses the proportionality between the partial pressure of a volatile compound in the gas phase (stripping steam) and its mole fraction in solution (oil), the stripping medium that is in equilibrium with untreated oil has the highest volatiles concentration. Given the need to remove a set amount of volatiles, the highest volatiles concentration corresponds to the lowest stripping medium requirement.

In this respect, countercurrent deodorization has innate advantages over cross-flow deodorization systems. In these latter systems, the partial vapor pressure of the volatiles only attains this highest value at the very first stage of the process. For batch systems, this is at the beginning of the deodorization cycle and for tray-type deodorizers, this is in the top tray. As deodorization proceeds and the mole fraction of the volatiles fraction decreases, their partial pressures decrease and more stripping medium is needed to volatilize a set amount. This means that the stripping medium is used less efficiently than in countercurrent systems. However, calculating the difference in efficiency between the two systems requires a mathematical expression of the stripping medium requirements of both systems. For the cross-flow systems, the well-known Bailey equation (3) provides such an expression; the present paper derives such an equation for countercurrent systems.

DERIVATION OF THE STEAM REQUIREMENT FORMULA

A fundamental difficulty in deriving a mathematical expression for the stripping medium requirement in countercurrent deodorization systems was noted by Bloemen (4): Such systems exhibit a pressure drop over the deodorization column. Accordingly, the derivation will first negate the existence of this pressure drop and assume the system pressure to be invariant. Subsequently, the consequences of this assumption will be investigated.

Bloemen (4) also introduced the "transfer unit" concept. This concept will be used in the present derivation and thereby distinguishes this derivation from previous work (2). It is defined as the deodorization column segment that ensures that the oil leaving this segment at the bottom is in physical equilibrium with the stripping medium leaving the same segment at the top. Like the "theoretical plate" used in distillation studies, the transfer unit is a theoretical concept. Its actual height will depend upon the construction of the deodorization column, which governs the residence time of the oil, the way in which fresh oil surfaces are exposed to the stripping medium, and the extent to which the gas flow meets the exposed oil surface. Accordingly, the height of a transfer unit is very much an equipment design parameter. Several of these transfer units are represented schematically (Scheme 1), together with the compositions of the liquid and gas flows en-

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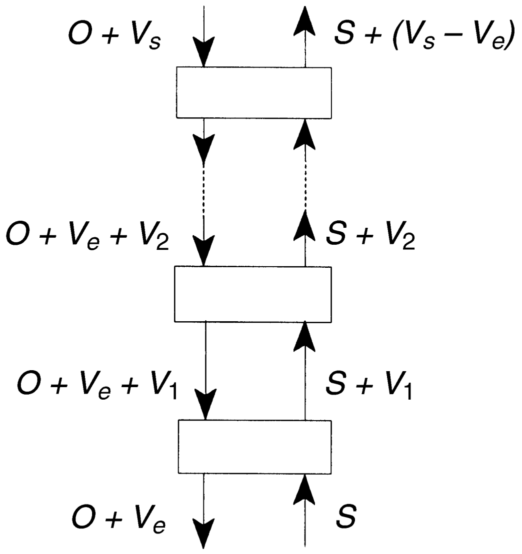

SCHEME 1

tering and leaving these units. The deodorized oil leaves the deodorizer at the bottom at a rate of O moles of oil and V_e moles of residual volatiles per unit of time. At the same plane, stripping medium enters the system at the rate of S moles per unit of time. At the top, the deodorization column is fed with O moles of oil and V_s moles of volatiles per unit of time, so that the stripping medium leaves the column at the top with $(V_s - V_e)$ mole of volatiles per unit of time.

In a plane somewhere above the bottom of the deodorizer and denoted with the subscript "1," the vapor pressure of the volatiles is assumed to be in equilibrium with the oil leaving the system; this means that the distance between this plane and the bottom of the column corresponds to one transfer unit. This assumption allows the partial vapor pressure (p_v) of the volatiles in this plane to be related to the volatile content (V_e) of the oil stream leaving the system according to:

$$p_v = P_v \frac{V_e}{O + V_e} = P \frac{V_1}{S + V_1} \qquad [1]$$

where p_v = partial vapor pressure of volatile compound (pressure units); P_v = vapor pressure of pure volatile compound (same pressure units); P = system pressure (same pressure units); O = rate of oil flow (moles per unit of time); S = rate of stripping gas flow (moles per unit of time); V_e = rate of volatile flow leaving bottom of column (moles per unit of time); and V_1 = rate of volatile flow leaving lowest transfer unit (moles per unit of time). In Equation 1, the left-hand equality follows from Raoult's law that relates the partial vapor pressure (p_v) of the volatiles to the composition of the liquid and the pressure of the pure volatile compound. The right-hand side of Equation 1 expresses this p_v according to Dalton's law as a function of the vapor composition and the total pressure in the system.

Equation 1 can be rewritten to express V_1 as:

$$V_1 = \frac{P_v S V_e}{PO - (P_v - P)V_e} \qquad [2]$$

For the next transfer unit, the vapor leaving this unit at the top can again be assumed to be in equilibrium with the oil leaving this unit at the bottom at a rate of O moles of oil and $(V_e + V_1)$ moles of volatiles per unit of time. The vapor leaves this unit at the top at the rate of S moles of steam and V_2 moles of volatiles per unit of time. The actual value of V_2 can be arrived at by substituting V_1 by V_2 and V_e by $(V_e + V_1)$, respectively, in Equation 2. This substitution leads to an expression for V_2 as a function of V_1, but this latter variable can be eliminated by using Equation 2. The expression for V_2 that results this way is far from elegant, so the possibility of an acceptable form of simplification was investigated by assuming the following realistic deodorization conditions: P = system pressure (4 mbar); O = rate of oil flow (1 mole per unit of time); P_v = vapor pressure of pure volatile compound (44 mbar); and V_e = residual volatile content (0.001 mole per unit of time). Expressed as the weight percentage oleic acid of the deodorized oil, this residual volatile (fatty acid) content corresponds to about 0.03 wt%, which is not unrealistic. With the foregoing assumptions, both terms in the denominator of Equation 2 can now be quantified. The first term (PO) equals 4 mbar/mol/time whereas the second term equals only 0.04 mbar/mol/time which means that the second term can be omitted without introducing unacceptable errors. This means that Equation 2 can be simplified to

$$V_1 = \frac{P_v S V_e}{PO} \qquad [3]$$

so that V_2 can now be expressed as

$$V_2 = P_v S V_e \frac{PO + P_v S}{(PO)^2} \qquad [4]$$

By assuming the countercurrent deodorization column has n transfer units, the vapor leaves the nth unit (at the top of the column) at the rate of S moles of stripping medium, and $V_n = V_s - V_e$ moles of volatiles per unit of time according to

$$V_n = V_s - V_e = P_v S V_e \frac{(PO)^{n-1} + (PO)^{n-2} P_v S + \cdots + (P_v S)^{n-1}}{(PO)^n} \qquad [5]$$

Equation 5 can be written somewhat differently to highlight the contribution of each transfer unit according to

$$V_n = V_e \left[\frac{P_v S (PO)^{n-1}}{(PO)^n} + \frac{P_v S^2 (PO)^{n-2}}{(PO)^n} + \cdots + \frac{(P_v S)^n}{(PO)^n} \right] = V_e \sum_{i=1}^{n} \left(\frac{P_v S}{P_i O} \right)^i \qquad [6]$$

In addition, because the system pressure *(P)* occurs in each term of Equation 6, this equation may well be used to take a pressure drop over the deodorization column into account by introducing values of P_i pertaining to transfer unit i, as indicated by the denominator after the summation.

According to the reverted series,

$$a^n + a^{n-1}b + a^{n-2}b^2 + \cdots + b^n = \frac{a^{n+1} - b^{n+1}}{a-b} \qquad [7]$$

Equation 5 can be rewritten as

$$V_n = V_s - V_e = P_v S V_e \frac{(P_v S)^n - (PO)^n}{(PO)^n (P_v S - PO)} \qquad [8]$$

Equation 8 is linear in V_e. Consequently, this variable, the rate at which residual volatiles leave the bottom of the column per unit of time, can be expressed as

$$V_e = V_s \frac{(PO)^n (P_v S - PO)}{(P_v S)^{n+1} - (PO)^{n+1}} \qquad [9]$$

Accordingly, a mathematical expression is provided by Equation 9 that implicitly expresses the stripping medium requirement *(S)* to lower the volatile content of an oil stream *(O)* from V_s to V_e given the system pressure *(P)* and the pressure of the pure volatiles *(P_v)*. These variables are the same variables as contained in the Bailey equation for batch and cross-flow deodorization systems; but, in addition, Equation 9 contains the variable n, the number of transfer units of the countercurrent deodorization column. This additional parameter is an illustration of the fact that the countercurrent deodorization system has an additional degree of freedom over the cross-flow systems.

RESULTS AND DISCUSSION

In order to facilitate comparing stripping steam requirements of the batch or cross-flow deodorization system (Bailey equation) and the countercurrent system, the full Bailey equation (5) is given:

$$S = \frac{PO}{EP_v} \ln \frac{V_s}{V_e} + \frac{P}{EP_v}(V_s - V_e) - (V_s - V_e) \qquad [10]$$

In Equation 10, the same notation has been used as for the derivation of Equation 9 but the Bailey equation contains a further parameter, E, the vaporization efficiency. This is an equipment parameter indicative of the extent to which stripping gas leaving the oil is in equilibrium with the oil. On a laboratory scale, the maximal value of unity has been observed for this evaporation efficiency (6); but, in industrial practice, this efficiency is lower, and values below 0.6 have been reported (7).

The right-hand side of Equation 10 has three terms. The left term suffices for deodorization processes but the middle and right-hand terms must be included when calculating the stripping medium requirement during physical refining (5), otherwise this requirement would be overestimated. In comparing the countercurrent deodorization system (Eq. 9) and the cross-flow system (Eq. 10), only the left-hand term will be taken into account. This comparison shows the following four similarities between stripping medium requirements in the cross-flow and the countercurrent deodorization systems:

(i) *Stripping medium usage* (S) *is proportional to the system pressure* (P). This proportionality is not immediately clear from Equation 9 since this does not explicitly express this usage. However, dividing both the numerator and the denominator of the right-hand side of Equation 9 by $P^{(n+1)}$ causes V_e to be expressed as a function of the new variable *(S/P)* without either P or S becoming separate variables. Accordingly, an increase in system pressure *(P)* can be fully compensated by a proportional increase in steam usage *(S)* without affecting the other variables.

(ii) *Stripping medium usage* (S) *is inversely proportional to the vapor pressure of the pure volatile compound* (P_v).

For the simplified Bailey equation, this inverse proportionality is clear when both sides are multiplied by P_v as a result of which the product $P_v S$ becomes invariant. In Equation 9, this product is already the only term in which P_v and S occur, which demonstrates their inverse proportionality.

(iii) *Only the ratio* (V_s / V_e) *of the initial* (V_s) *and the final* (V_e) *mole fractions of the volatiles is determined by the other variables.* In the simplified Bailey equation, this follows from their presence as a ratio; in Equation 9, their inverse ratio can be arrived at by dividing both sides by V_s. In both cases, the variables V_s and V_e do not occur outside these ratios.

(iv) *Stripping medium requirement is proportional to the amount of oil being deodorized.* This similarity holds for both the simplified and the full Bailey Equation 10 since the amount of volatile is proportional to the amount of oil. Its validity for the steam requirement in the countercurrent deodorization system (Eq. 9) becomes evident by dividing both the numerator and the denominator of the right hand side by O^{n+1}, which leads to the new variable *S/O* without either S or O occurring outside this new variable.

There are also fundamental differences between the cross-flow and the countercurrent-flow deodorization systems in that the stripping medium requirement of the former incorporates the vaporization efficiency *(E)* whereas for the countercurrent system this requirement depends upon the number of transfer units *(n)*. Therefore, the questions to be discussed now are: How many transfer units does a countercurrent deodorization system need to be competitive with industrial cross-flow systems? And, how much energy (stripping and motive steam) can be saved by increasing the number of transfer units?

Whereas the Bailey equation (Eq. 10) provides the stripping medium requirement explicitly, Equation 9 cannot be

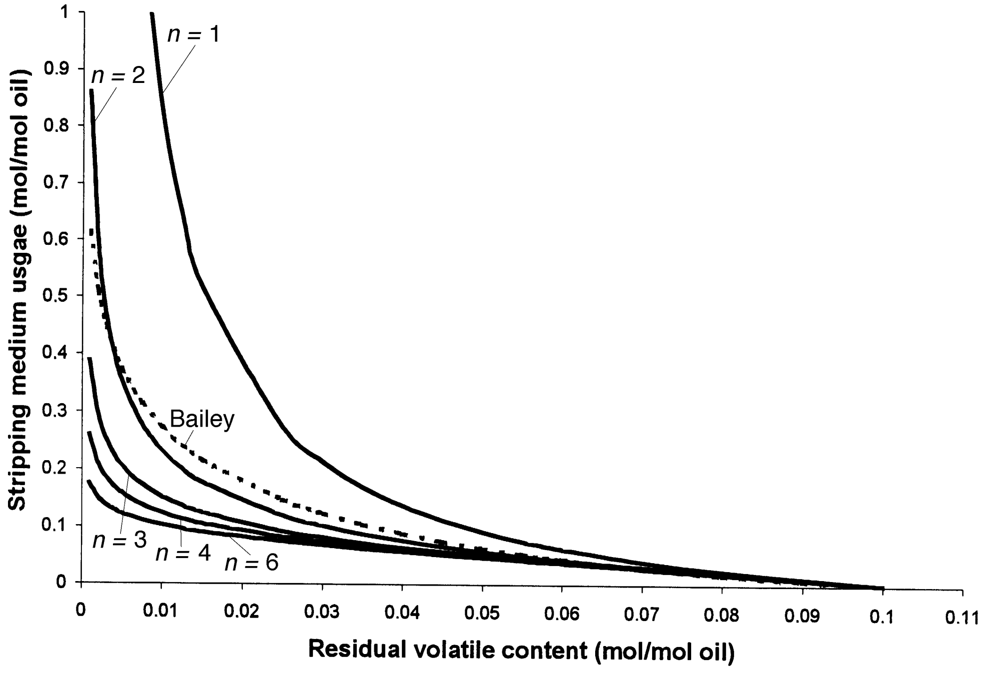

FIG. 1. Calculated stripping medium requirements for cross-flow (Bailey, Equation 10) and countercurrent-flow systems with increasing number of transfer units (Eq. 9, see Ref. 8).

solved analytically to provide this requirement explicitly. Accordingly, the "Goal Seek" iteration subroutine of Excel®97 (8) has been used to calculate the stripping medium requirements for the countercurrent deodorization process for values of $n = 1, 2, 3, 4$ and 6. The same process conditions ($P = 4$ mbar; $P_v = 44$ mbar) have been assumed as when investigating the possibility of simplifying Equation 2. Under these conditions, the partial pressure (p_v) equals the system pressure (P) when the mole fraction of the volatiles equals 0.100; this value has been assumed for the initial volatile concentration (V_s). Consequently, the calculated stripping medium requirements (Fig. 1) pertain to physical refining. The stripping medium requirements for a column with a single transfer unit ($n = 1$) have been represented by the uppermost curve. These are far higher than those of the cross-flow physical refining systems (Bailey) as represented by the dotted line. For physical refining, the stripping medium requirement of cross-flow systems corresponds to the requirement of a countercurrent system with two transfer units. Increasing the number of transfer units to three or four leads to a two- to threefold savings in stripping steam, but further increases in the number of transfer units lead to smaller savings. Accordingly, the design of a countercurrent column can be optimized by taking operating costs (energy requirement) and fixed costs (height of column) into account.

Stripping medium requirements during deodorization are listed in Table 1. These requirements have been calculated by using the same values for the system pressure ($P = 4$ mbar) and the vapor pressure of the volatiles ($P_v = 44$ mbar) for various deodorization efficiencies (V_s/V_e). The co-current system ($n = 1$) requires by far the most stripping medium (Table 1) but a comparison between the cross-flow and the countercurrent systems shows that two transfer units already require less stripping medium than do the cross-flow systems; this advantage of the countercurrent system is especially pronounced at low deodorization efficiencies. As expected, increasing the number of transfer units diminishes the stripping medium requirement, but the effect is more pronounced at high deodorization efficiencies. Again, this permits the design of countercurrent deodorization columns to be optimized.

Equation 9 pertaining to the countercurrent deodorization system has been derived while assuming the system pressure to be invariant. During operation, there will be a pressure drop over the deodorization column, otherwise there would not be any gas flow. This pressure drop has two consequences: (i) it causes the stripping medium to expand when

TABLE 1
Stripping Medium Requirements (mol/mol oil) During Deodorization[a]

		Number of transfer units				
V_s/V_e	Bailey	$n = 1$	$n = 2$	n = 3	n = 4	n = 6
5	0.244	0.455	0.142	0.105	0.091	0.080
	(0.499)	(0.931)	(0.313)	(0.215)	(0.186)	(0.164)
10	0.349	0.909	0.231	0.151	0.123	0.102
	(0.714)	(1.859)	(0.472)	(0.309)	(0.252)	(0.209)
25	0.488	2.273	0.402	0.226	0.170	0.129
	(0.998)	(4.648)	(0.822)	(0.462)	(0.348)	(0.264)

[a] Figures in parentheses refer to steam consumption, expressed as wt%, when deodorizing an oil with a molecular weight of 880. V_s, rate of volatiles flow into the top of the deodorization column (moles per unit time); V_e, rate of volatile flow leaving bottom of column (moles per unit time).

rising to the top of the column and thus become more effective as a stripping agent. On the other hand, (ii) the stripping medium at the bottom of the column rises less rapidly and this may increase the rate of volatile take-up and thus decrease the height of a transfer unit. The two consequences have opposite effects. The net effect cannot be predicted. However, in absolute terms it will be quite small since proper design has caused this pressure drop to be quite small (9). Moreover, the use of Equation 6 and measurement of the pressure drop can provide further insight in column performance.

Another simplification introduced during the derivation of Equation 9 concerns the omission of the term $(P_v - P)V_e$ from Equation 2 to arrive at Equation 3. Under normal deodorization conditions, this omission was found to be fully justified. However, if the vapor pressure (P_v) of the pure volatiles were to increase as a consequence of raising the temperature and especially if the final volatile content (V_e) were to be raised, this term might become significant in comparison with the first one (PO) so that its omission would have a significant effect.

However, the value of 44 mbar assumed for P_v corresponds to a temperature in excess of 240°C, so that a substantial increase in P_v is unrealistic for acceptable final oil quality. Similarly, a free fatty acid (FFA) content of fully deodorized oil above 0.03 wt% is not realistic either. Accordingly, the simplification will only affect the validity of Equation 9 when hardly any fatty acids are removed from a high FFA oil at very high temperature. Since this removal does not require any stripping medium anyway, the limitation of the validity of Equation 9 by introducing the simplification is immaterial.

Stripping medium usage is not the only criterion by which to judge a deodorizer or physical refining system but it is an important criterion because of the multiplier effect. Less stripping steam also means lower motive steam usage in the vacuum ejector system. Another criterion is final oil quality. In this respect, the continuous countercurrent deodorization system offers advantages in that the oil residence time can be kept quite short. Since the extent of side reactions is proportional to the time that the oil is exposed to high temperatures, the continuous countercurrent deodorizer suppresses the formation of unwanted by-products (*trans*-isomers and oligomers of unsaturated fatty acids).

Moreover, suppression of the formation of these undesirable by-products may well permit the use of a higher oil temperature in countercurrent deodorization than in the cross-flow systems. This higher temperature causes the volatiles to have a higher vapor pressure and thus leads to further energy savings (stripping medium and motive steam).

On the other hand, the wish to retain tocopherols may necessitate the use of reduced deodorization temperature. This of course increases the stripping medium requirement; but, since this increase is proportional for the cross-flow and the countercurrent deodorization systems, the increase in absolute terms is smallest for the system exhibiting the lowest requirements to start with. This again highlights the advantages of the countercurrent system.

These advantages of the countercurrent deodorization system over currently used cross-flow deodorization systems stem from its additional degree of freedom (number of transfer units) and from its short oil residence time. They allow for a flexibility in equipment design that can focus on energy saving, avoidance of the formation of undesirable by-products and tocopherol retention.

ACKNOWLEDGMENT

The author hereby acknowledges the suggestion made by S. Balchen, Technical University of Denmark, to rewrite his Equation 5 as Equation 6.

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[Received November 4, 1998; accepted April 6, 1999]