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Analysis of vapor back flow in single-pass air-cooled condensers

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Abstract—In the present work a mathematical model of the vapor distribution in single-pass, multiple-row, cross-flow condensers is proposed. An analysis of the performances of such condensers is carried out by varying both the row number and the effectiveness of each row. Some convenient configurations, which reduce the pressure drop between inlet and outlet plena or avoid the accumulation of noncondensable gases, are finally distinguished. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

Tubular heat exchangers are applied in many engineering fields [1, 2]. The single-pass, multiple-row, cross-flow structure is most commonly used for air-cooled condensers. Nevertheless, in such application, if the inlet and outlet plena are common for all tube rows, problems with noncondensable contaminant accumulation and vapor back flow from one row to another often occur. Taking these problems into account complicates the tube condenser planning, mainly when the number of rows is high. For this reason, the planning is frequently carried out through simplifications of the problem on the basis of empirical experience. Therefore, many tube condensers used in practical applications are quite far from being the best solution with regard to the effectiveness and the costs for installation and working.

An accurate study of the vapor back flow and of noncondensable contaminant accumulation phenomena has been performed by Berg and Berg [3] for single-pass, cross-flow, air-cooled condensers with at most four tube rows. They investigated, at first, the case of a condenser composed of tube rows with identical effectiveness, supplied by vapor free from noncondensable contaminants, which was entirely condensed inside the apparatus. By varying the row effectiveness they determined for each row if the vapor coming from the inlet plenum was entirely condensed in the same row or was circulated back through the outlet plenum into other rows. For the rows in which the vapor entered from both ends, they distinguished the point where the flux of vapor became zero. Afterwards, taking the presence of noncondensable contaminants into account, they calculated the portion of each row in which these accumulated, for the limit case of row effectivenesses equal to 1.

The analysis of the noncondensable contaminant accumulation in the condenser tubes was extended by Breber *et al.* [4]. These authors determined the vapor distribution and the noncondensable contaminant accumulation by varying the row effectiveness (equal for all the rows) for condensers with at most four rows. Recently, Breber's analysis was extended [5] to the case of a condenser with up to 10 rows with different effectiveness.

The vapor back flow in condensers with more than four rows and with different row effectiveness was not studied so far. In this work, we therefore present a mathematical model of a single-pass, cross-flow, air-cooled condenser with different row effectiveness and friction factors and with as many rows as desired, supplied by vapor free from noncondensable contaminants. A calculation algorithm is presented, which allows a simple and fast solution of the model equations. With this model vapor back flow phenomena in condensers with up to 10 rows are studied (a higher number of rows is not of practical interest, as discussed in the next sections). The advantages coming from increasing the row number in correspondence with different values of the row effectiveness are evaluated. Moreover, some effectiveness value combinations for the different rows are analyzed, paying particular attention to the improvements which can be obtained with regard to the global effectiveness and with regard to the production and working costs of the condenser.

2. THE MATHEMATICAL MODEL

Let us consider a single-pass, cross-flow, air-cooled condenser, composed of N rows of horizontal tubes, with common inlet and outlet plena (Fig. 1). Let the pressure drops at both the tube ends be assumed neg-

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NOMENCLATURE

a_n	length of forward flow segment in the nth row (m)
λ	latent heat of vaporization (J kg^{-1})
c_p	specific heat of the air (J kg^{-1}°C^{-1})
E_g	global effectiveness of the condenser
E_n	effectiveness of the nth row
L	length of the tubes (m)
$\dot{M}$	mass flow rate of the air (kg s^{-1})
N	number of rows of the condenser
T_n	air temperature before crossing the nth row (°C)
T_s	vapor saturation temperature (°C)
U_n	vapor flow rate across the outlet end of the nth row (kg s^{-1})
w_n	vapor condensation rate per unit of tube length in the nth row (kg m^{-1} s^{-1})
w_0	reference vapor condensation rate per unit of tube length (kg m^{-1} s^{-1})
W_n	vapor flow rate in the nth row (kg s^{-1}).

Greek symbols

α_n	normalized length of the forward flow segment of the nth row
β_n	normalized vapor flow rate across the outlet end of the nth row
δ	normalized pressure drop between inlet and outlet end
δ^*	attempt value for the normalized pressure drop in the solution algorithm
δ_n	normalized pressure drop in the nth row
Δp_n	pressure drop in the nth row (Pa)
ζ_n	normalized vapor condensed in the nth row
ρ	density of the air (kg m^{-3}).

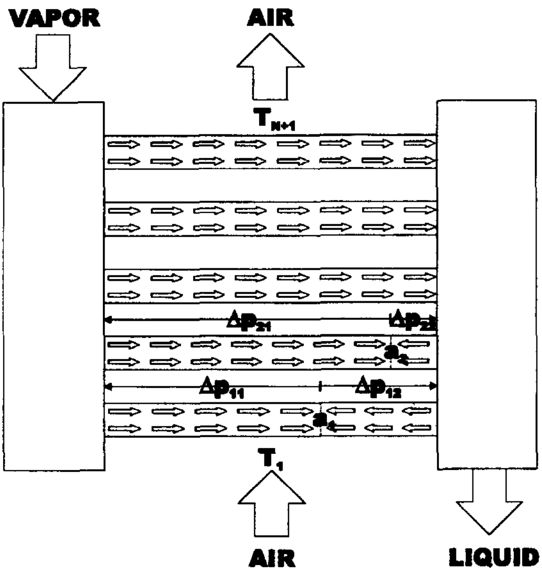

Fig. 1. Vapor back flow in a multiple-row, single-pass, cross-flow condenser.

ligible, as well as the pressure changes induced by deceleration. Moreover, let us suppose that all the vapor, which flows into the apparatus, condenses completely inside, without accumulation of non-condensable contaminants. Since the inlet and outlet plena are common, the vapor which enters in some rows and does not condense recirculates into the other rows, entering from the outlet end. The condensate flows out along the bottom of the tubes by gravity.

Let E_n be the nth row effectiveness. By definition it is:

$$E_n = \frac{T_{n+1} - T_n}{T_s - T_n} \tag{1}$$

T_n and T_{n+1} being the temperatures of the air before and after crossing the nth row, T_s the saturation temperature of vapor. If T_s does not change very much with the pressure inside the tubes, the condenser can be assumed isothermal and T_s constant for every row and along the row tubes.

If the amount of condensate which flows along the bottom of the tubes slightly affects the heat transfer, the vapor condensation rate per unit of tube length can be assumed constant along each tube. For the nth row it can be calculated as:

$$w_n = \frac{\dot{M}c_p}{L\lambda}(T_{n+1} - T_n) \tag{2}$$

$\dot{M}$ being the mass flow rate of the air which crosses the rows, L the length of the tubes, c_p the specific heat of the air and λ the latent heat of vaporization. It is possible to write:

$$w_n = \frac{\dot{M}c_p}{L\lambda}E_n(T_s - T_n). \tag{3}$$

Dividing w_n by w_{n-1}, it is possible to obtain:

$$w_n = \frac{E_n}{E_{n-1}}(1 - E_{n-1})w_{n-1} \quad \text{for } n > 1. \tag{4}$$

Let us now consider the rows of the condenser in which vapor enters from both the ends. The vapor flow in the nth row, as a function of the longitudinal coordinate x, can be written as:

$$W_n = w_n(a_n - x) \tag{5}$$

a_n being the length of the row segment in which vapor flows in the forward direction. The sign of W_n indicates the direction in which the vapor flows. The flow of vapor crossing the outlet end can be calculated as:

$$U_n = -w_n(L-a_n) \tag{6}$$

the negative sign indicate that the vapor crosses the outlet end in the backward direction.

Inside the tubes the pressure decreases for x varying from 0 to a_n and increases from a_n to L. Assuming the longitudinal pressure variation to be proportional to the square of the vapor flow [1], the pressure drop between 0 and a_n is:

$$\Delta p_{n1} = p_0 - p_{a_n} = -k_n \int_{a_n}^{0} W_n^2 \, dx = \frac{k_n w_u^2 a_n^3}{3} \tag{7}$$

k_n being a constant which can assume a different value for each row, on the basis of the kind of the tubes; for example: smooth, corrugated or finned [6, 7]. Moreover, the pressure drop between L and a_n is:

$$\Delta p_{n2} = p_L - p_{a_n} = k_n \int_{a_n}^{L} W_n^2 \, dx = \frac{k_n w_n^2 (L-a_n)^3}{3}. \tag{8}$$

The pressure drop between the inlet and the outlet end of the nth row is then:

$$\Delta p_n = p_0 - p_L = \Delta p_{n1} - \Delta p_{n2} = \frac{k_n w_n^2 [a_n^3 - (L-a_n)^3]}{3} = \frac{k_n w_n^2}{3}(2a_n^3 - 3La_n^2 + 3L^2 a_n - L^3). \tag{9}$$

From equation (6) Δp_n can be written as a function of U_n:

$$\Delta p_n = \frac{k_n w_n^2}{3}\left[2\left(\frac{U_n}{w_n}\right)^3 + 3L\left(\frac{U_n}{w_n}\right)^2 + 3L^2\frac{U_n}{w_n} + L^3\right]. \tag{10}$$

For the rows of the condenser in which no back flow occurs W_n can be written as:

$$W_n = w_n(L-x) + U_n. \tag{11}$$

U_n being the vapor flow which does not condense in the row and exits across the outlet end. The pressure drop between the inlet and the outlet end of the nth row can then be calculated as:

$$\Delta p_n = -k_n \int_{L}^{0} W_n^2 \, dx = \frac{k_n[(w_n L + U_n)^3 - U_n^3]}{3w_n} = \frac{k_n}{3}(3LU_n^2 + 3w_n L^2 U_n + w_n^2 L^3). \tag{12}$$

Both equations (10) and (12) are valid for the limit case in which U_n is zero. Moreover, they can be reduced to a dimensionless form by introducing the following dimensionless entities:

$$\beta_n = \frac{U_n}{w_0 L} \tag{13}$$

$$\gamma_n = \frac{k_n}{k_0} \tag{14}$$

$$\delta_n = \frac{3\Delta p_n}{k_0 w_0^2 L^3} \tag{15}$$

$$\zeta_n = \frac{w_n}{w_0} \tag{16}$$

k_0 being a reference value and:

$$w_0 = \frac{\dot{M}c_p}{L\lambda}(T_s - T_1). \tag{17}$$

It must be noticed that ζ_n depend only on the row effectiveness:

$$\zeta_n = \begin{cases} E_1 & \text{for } n = 1 \\ E_n \prod_{i=1}^{n-1}(1-E_i) & \text{for } n > 1 \end{cases}. \tag{18}$$

For the rows in which vapor enters from both the ends ($\beta_n < 0$) we can then write:

$$\delta_n = \frac{\gamma_n}{\zeta_n}(2\beta_n^3 + 3\zeta_n\beta_n^2 + 3\zeta_n^2\beta_n + \zeta^3). \tag{19}$$

For the other rows ($\beta_n \geqslant 0$):

$$\delta_n = \gamma_n(3\beta^2 + 3\zeta_n\beta + \zeta_n^2). \tag{20}$$

For any value of δ_n, equation (19) admits one and only one real value for β_n, while equation (20) admits one and only one positive value for β_n when $\delta_n \geqslant \gamma_n\zeta_n^2$.

Since the inlet and the outlet plena are common, the pressure drop between one end and the other one in each row must be the same (δ). By solving equations (19) and (20) it is then possible to write β_n as a function of δ:

$$\beta_n(\delta) = \begin{cases} \zeta_n\left[\frac{1}{\sqrt[3]{4}}\left(\sqrt[3]{\sqrt{\frac{\delta^2}{\gamma_n^2\zeta_n^4} + \frac{1}{4}} + \frac{\delta}{\gamma_n\zeta_n^2}} - \sqrt[3]{\sqrt{\frac{\delta^2}{\gamma_n^2\zeta_n^4} + \frac{1}{4}} - \frac{\delta}{\gamma_n\zeta_n^2}}\right) - \frac{1}{2}\right] & \text{for } \delta < \gamma_n\zeta_n^2 \\ \sqrt{\frac{\delta}{3\gamma_n} - \frac{\zeta_n^2}{12}} - \frac{\zeta_n}{2} & \text{for } \delta \geqslant \gamma_n\zeta_n^2 \end{cases}. \tag{21}$$

Moreover, since the vapor which exits from the rows without back flow is equal to that flowing back into the other ones, it must be:

$$\phi(\delta) = \sum_{n=1}^{N} \beta_n(\delta) = 0. \tag{22}$$

By differentiating equations (19) and (20) or equation (21) it is possible to observe that for any row β_n is an increasing function of δ. That means that also ϕ is an increasing function of δ and only one value of the normalized pressure drop satisfies equation (22). Therefore, only one vapor distribution is consistent with the parameters of equation (21), which are determined only by k_n and E_n.

Equation (22) can easily be solved with an iterative algorithm, such as the following, which is derivative based:

$$\delta = \delta^* - \frac{\phi(\delta^*)}{\left(\frac{\mathrm{d}\phi}{\mathrm{d}\delta}\right)_{\delta^*}} \tag{23}$$

δ^* being the attempt value for δ at each iteration. At the first iteration δ^* can be assumed to be zero. Less than eight iterations are needed to reduce changes in δ to a negligible value. In order to make the algorithm faster it is convenient to calculate:

$$\left(\frac{\mathrm{d}\phi}{\mathrm{d}\delta}\right)_{\delta^*} = \sum_{n=1}^{N} \frac{1}{\left(\frac{\mathrm{d}\delta_n}{\mathrm{d}\beta_n}\right)_{\beta_n(\delta^*)}}. \tag{24}$$

In the following sections we will utilize this solution algorithm to determine the vapor distribution in single-pass, air-cooled condensers with up to 10 rows, in correspondence with different values of the row effectiveness. Particular attention will be paid to the configurations which allow to increase the global effectiveness of the condensers or to reduce the pressure drop between inlet and outlet plena and the production and working costs.

3. RESULTS

3.1. *Condensers with rows of the same effectiveness*

Assigning the same values k_0 and E_0 to k_n and E_n for any row, the solution algorithm proposed can be utilized to extend Berg and Berg's analysis to the case of a condenser with as high a number of rows as desired. In Fig. 2 the normalized forward flow lengths $\alpha_n = a_n/L$ are shown vs E_0 varying between 0 and 1, for condensers with a number of rows from three to 10. In the first case ($N = 3$) back flow occurs only in the first row and tends to reduce when the row effectiveness E_0 decreases. In the second case in correspondence with low values of E_0 back flow occurs also in the second row, whose normalized forward flow segment reaches a minimum value when E_0 is equal to 0.31. In general, back flow appears in an additional row for every two rows added to the condenser, in correspondence with ever lower values of E_0. In every row higher than the first the forward flow segment, as a function of the common row effectiveness, presents a minimum value.

In Fig. 3 the normalized vapor flow at the outlet end of each row vs E_0 is illustrated for condensers with three, four, five and 10 rows. When the common row effectiveness tends to 1 the flows in the rows other than the first converge at the same positive value, equal to $-1/(N-1)$ times the flow at the outlet end of the first row. In the limit case of E_0 equal to 1 in fact, the rows from the second to the last are identical because no condensation occurs in them. The vapor only flows through them and condenses in the first row entering from the outlet end.

The normalized pressure drop between the inlet and outlet plena vs E_0 are shown in Fig. 4(a) for condensers with two to 10 rows. The higher values are obviously reached by the pressure drop of the condenser with the lowest number of rows. By adding some more rows, the resistance to the vapor flow is, in fact, reduced. But the higher the number of rows is, the less the pressure drop decreases by adding one more row. Moreover, in condensers with more than four rows the normalized pressure drop presents a maximum value in correspondence with a value of E_0, which becomes ever lower when N increases.

In order to investigate the convenience of increasing the number or the effectiveness of the rows of single-pass, air-cooled condensers in presence of back flow phenomena, it is also important to analyze the global effectiveness, defined as:

$$E_g = \frac{T_{N+1} - T_1}{T_s - T_1} \tag{25}$$

T_1 and T_{N+1} being identical to the input and output temperature of the air. The difference between this temperatures can be written as a function of the row effectivenesses:

$$T_{n+1} - T_n = E_n \prod_{i=1}^{n-1} (1 - E_i)(T_s - T_1) \tag{26}$$

$$T_{N+1} - T_1 = \sum_{n=1}^{N} E_n \prod_{i=1}^{n-1} (1 - E_i)(T_s - T_1). \tag{27}$$

We then obtain:

$$E_g = \sum_{n=1}^{N} E_n \prod_{i=1}^{n-1} (1 - E_i). \tag{28}$$

The global effectiveness E_g vs the common row effectiveness E_0 for different numbers of rows is shown in Fig. 4(b). We can observe that in a condenser with at least three rows, for E_0 greater than 0.7 E_g hardly grows, while it presents an evident increase when E_0 is low. Therefore, it is not useful to bring the row effectiveness beyond the quoted value, if this setting causes a noticeable increase of the costs relative to the production, the installation and the maintenance of the tubes. Moreover, an evident improvement in the global effectiveness is not always obtainable by

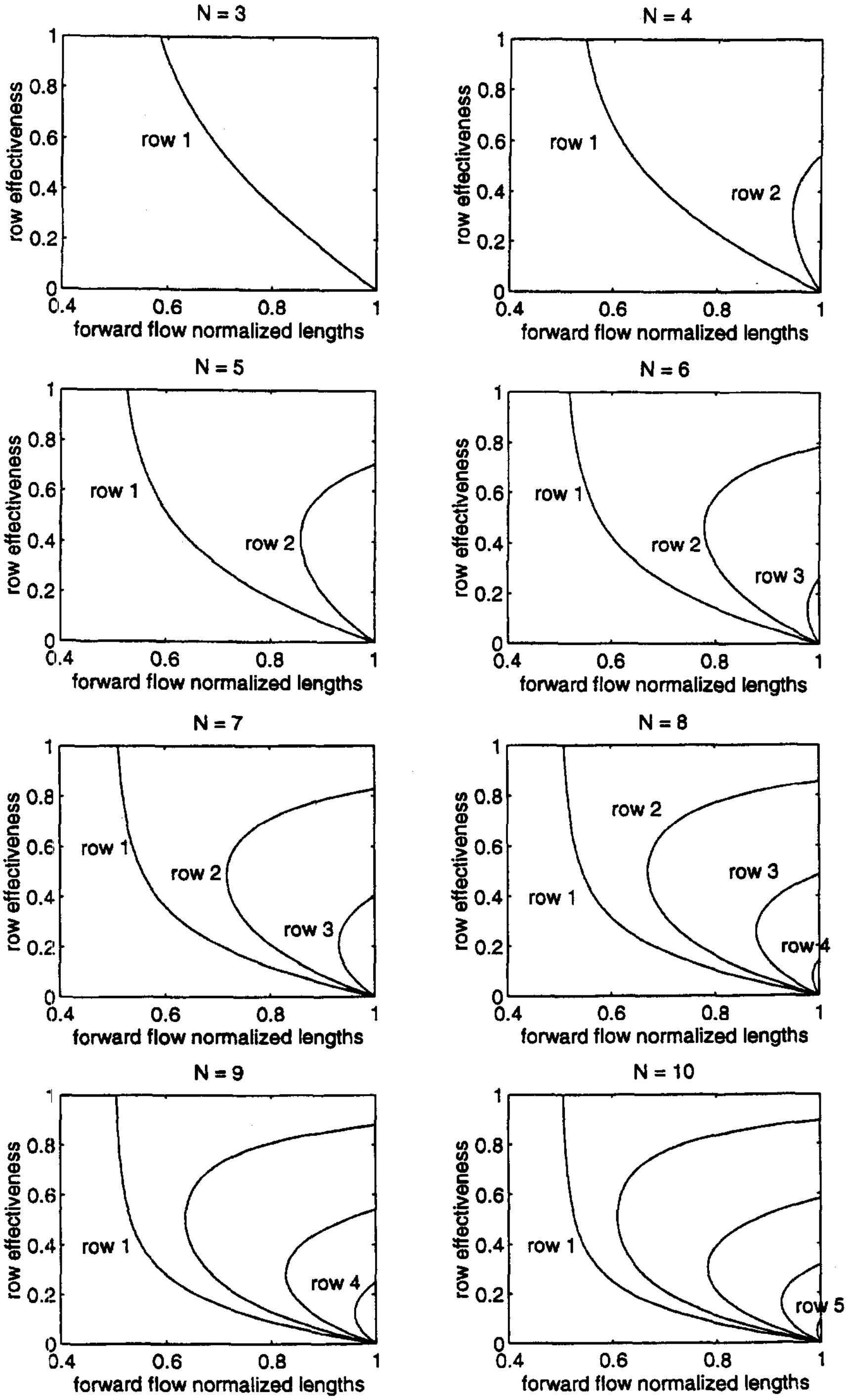

Fig. 2. Normalized lengths of vapor forward flow vs row effectiveness in condensers with three to 10 rows, which have the same effectiveness.

increasing the number of the rows when the row effectiveness is high.

In Fig. 5 the percentage changes in the pressure drop obtainable by increasing the number of the rows are compared with those in the global effectiveness. It is evident that the biggest changes in the global effectiveness occur in correspondence with the lowest values of E_0, while the biggest reductions of the pressure drop are obtainable when E_0 is high.

3.2. *Condensers with rows of different effectiveness*

When high values for the row effectiveness cause excessive costs for the installation and the functioning of the condenser, it can be convenient to reduce the

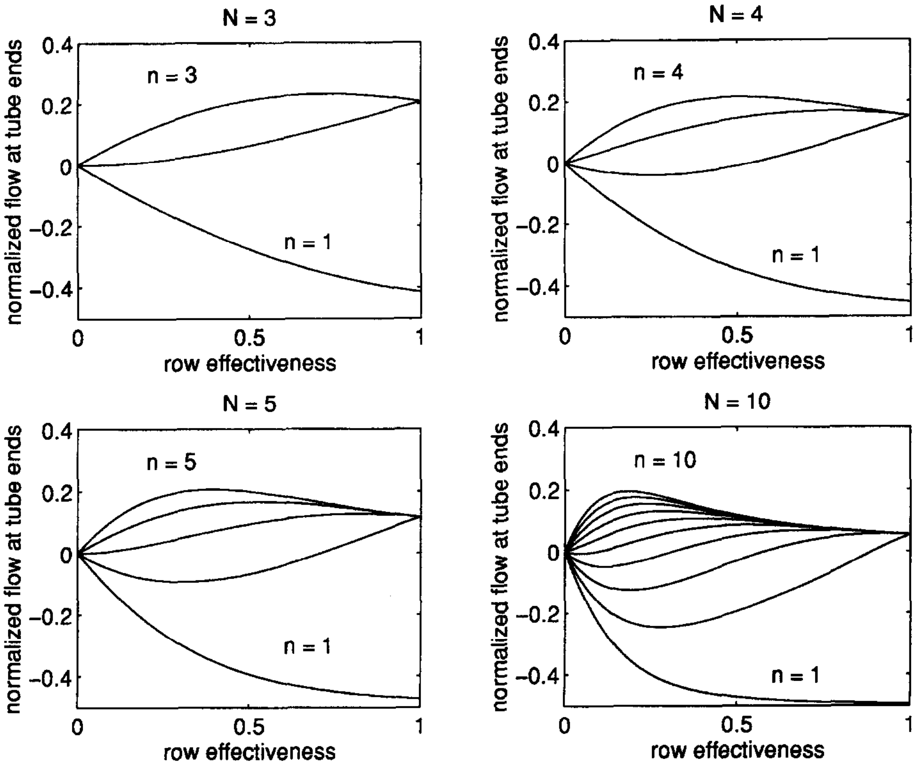

Fig. 3. Normalized vapor flows at the outlet end vs row effectiveness in condensers with N rows, which have the same effectiveness.

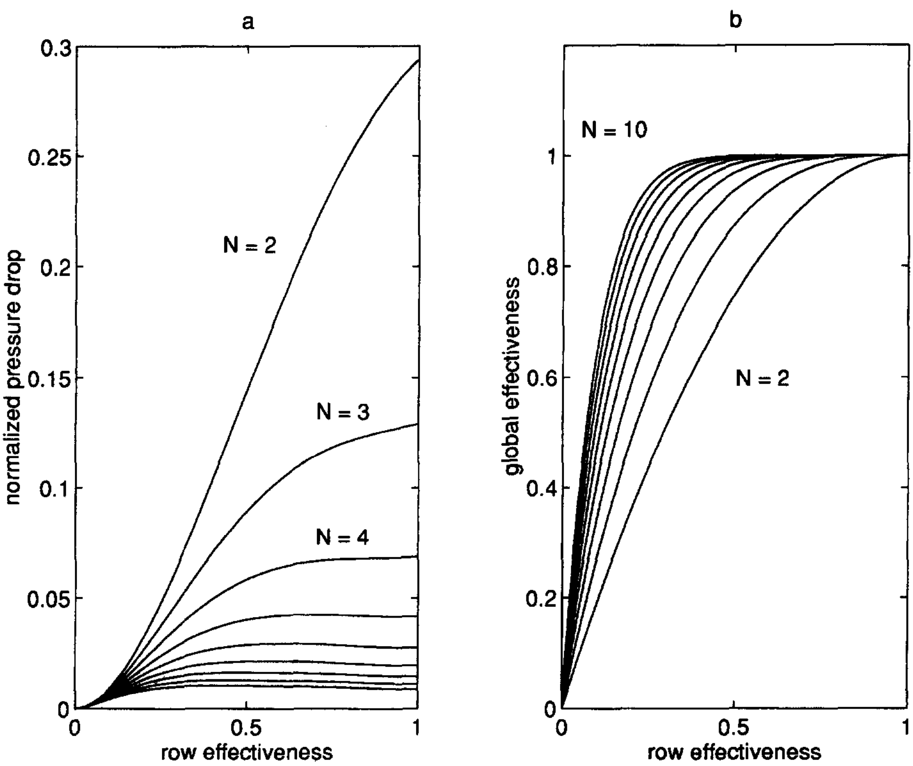

Fig. 4. Normalized pressure drops between inlet and outlet plena (a) and global effectiveness (b) vs row effectiveness in condensers with two to 10 rows, which have the same effectiveness.

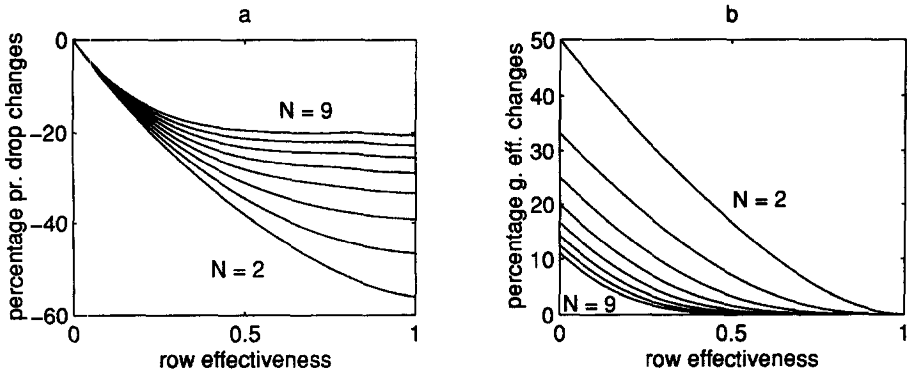

Fig. 5. Percentage changes in pressure drops between inlet and outlet plena (a) and in global effectiveness (b) vs row effectiveness, which are obtainable by adding a row to the condensers with two to nine rows, which have the same effectiveness.

effectiveness of some of the rows, aiming to not noticeably damage the global effectiveness. Therefore, it is interesting to take a condenser composed of rows with the same effectiveness as a reference and to evaluate how the global effectiveness changes as a result of the variation of the different row effectiveness.

Let us vary the effectiveness of only one row at a time. It must be observed that the changes in the global effectiveness are independent from the row in which the effectiveness is varied. For condensers with two to 10 rows the percentage changes in the global effectiveness induced by the variation of the effectiveness of one row at a time, are shown in Fig. 6. In the previous section it has been noticed that for a condenser with rows of the same effectiveness E_0 the global effectiveness is more sensitive to change in the row number and in E_0 when this last is low than when it is high. As references two different cases have therefore been chosen. In the first case [Fig. 6(a)] the effectiveness of all the rows is equal to 0.4 (low), and in the second case [Fig. 6(b)] it is equal to 0.7 (high). It is evident in the figures that the global effectiveness changes induced by the variation of the effectiveness of one row are still more noticeable when the row effectivenesses, which do not vary, are equal to 0.4 than when they are equal to 0.7. In both cases the biggest changes in E_g are obtainable in the condensers with the lowest number of rows.

It must be noticed that by reducing the effectiveness of one row and keeping that of the other ones at an higher value, a lower global effectiveness is obtained. If the only constraint in setting the row effectiveness is the technology, in order to optimize the global effectiveness there is no use in assigning a row an effectiveness lower than the maximum available. In such a situation, the optimum global effectiveness is obtained when all the rows have an effectiveness equal to the maximum made available by the technology. But if the planning of the condenser is constrained by the production and maintenance costs, as in most practical applications, by reducing the effectiveness of a row to the value obtainable with less expensive or more resistant materials it becomes possible to utilize more sophisticated technologies to increase the effectiveness of the other rows.

It is therefore interesting to compare the global effectiveness obtained by varying the effectiveness of one row and keeping that of the other ones at the reference values quoted above, with that of a condenser of the same production or maintenance costs. If we assume that the cost of a row is ideally proportional to its effectiveness we can compare the global effectiveness obtained with that of a condenser with the same average row effectiveness and with equal rows. In Fig. 6(c) the percentage changes between the global effectiveness obtainable in a condenser by varying the effectiveness of one row and keeping that of the other one equal to 0.4, and the global effectiveness of another condenser with the same number of rows and with the same effectiveness value for each rows equal to the average of the row effectiveness of the first condenser are reported for different values of N. Similar percentage changes relative to a reference common row effectiveness equal to 0.7 are shown in Fig. 6(d). From this point of view we can observe that the configuration in which all the rows have the same effectiveness is the least convenient. In any case the more the effectiveness of one row is different from the common value of the other ones the bigger the percentage changes in the global effectiveness are. Moreover, the greatest percentage variations are obtained in condensers with the lowest number of rows.

By utilizing the proposed mathematical model we can now observe how the pressure drop between the inlet and the outlet plena varies in the same situations analysed above. It must be noticed that on the contrary of the global effectiveness the pressure drop changes depend on the row in which the effectiveness is changed. In Fig. 7 the percentage variations between the pressure drop obtainable in a condenser by varying the effectiveness of one row and keeping that of the other ones equal to 0.4, and the pressure drop in another condenser with the same average row effectiveness but equal rows are reported for different values of N. Similar patterns, relative to a reference

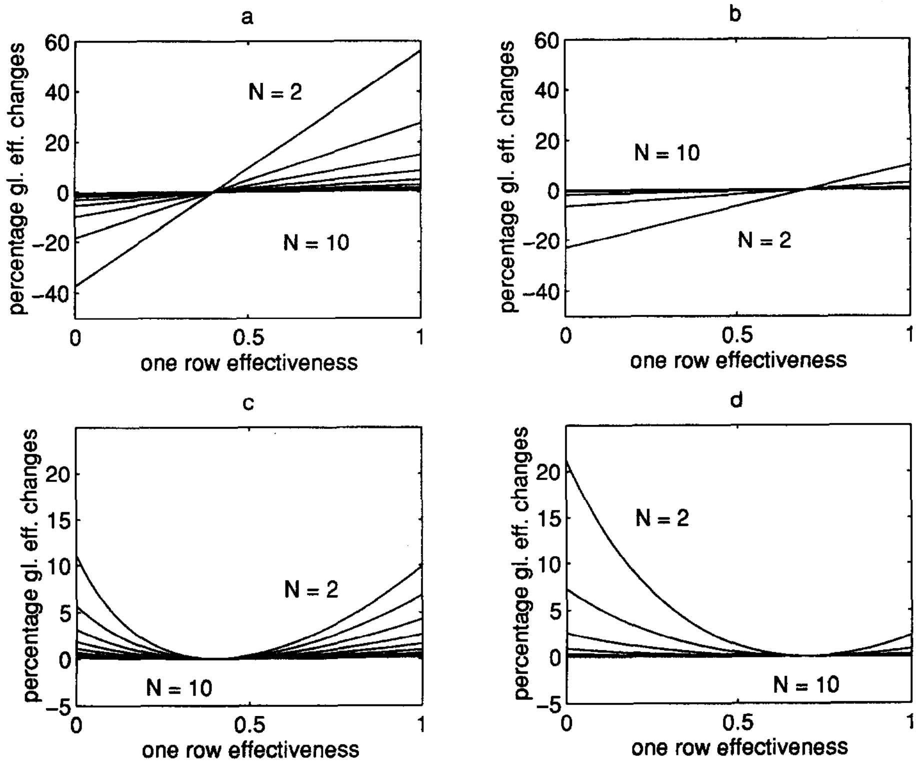

Fig. 6. Percentage changes between the global effectiveness of a condenser in which the effectiveness of one row is varied while that of the other ones is kept at the same value [0.4 in (a) and in (c), 0.7 in (b) and (d)], and the global effectiveness of a condensers with rows of the same effectiveness, which is equal to the maximal [(a) and (b)] or to the average row effectiveness of the first condenser.

common row effectiveness value equal to 0.7, are shown in Fig. 8. In both the figures the pattern relative to the variations in the effectiveness of the first row noticeably changes shape by increasing N. This is more evident in Fig. 8. Similar changes also appear for the variations of the effectiveness of the second row for high values of N in Fig. 7. We can observe that, by reducing the effectiveness of the first rows, it is also possible to reduce the pressure drop between inlet and outlet plena without altering the costs of the condenser. When the reference effectiveness is equal to 0.7 and N is high (greater than 5), this is possible by reducing the effectiveness of all the rows with exception of the first.

We must notice that in the practice reductions in the pressure drop between inlet and outlet plena greater than those shown in Figs. 7 and 8 can be obtained by reducing the effectiveness of one row. In order to increase the row effectiveness, in condensers corrugated or finned tubes are often used [8–12]. These tubes oppose a higher resistance to the vapor flow. By avoiding such expedients for one row, the global resistance of the condenser to the vapor flow can be reduced.

3.3. *Designs which avoid back flow*

At the beginning of the condenser functioning, as a consequence of back flow, if the vapor is not completely free from noncondensable contaminants, these accumulate in the rows at those points where the pressure is lower. The accumulation of noncondensable contaminants noticeably reduces the global effectiveness of the condensers.

With the same approach as in Section 2, by letting the row effectiveness be zero in the segment in which contaminants accumulate, it is possible to determine the vapor flow patterns and the global effectiveness for a multiple-row, single-pass, cross-flow, air-cooled condenser supplied by vapor containing noncondensable contaminants [4, 5]. In Fig. 9 the global effectiveness of such a condenser with rows of the same effectiveness is reported and compared with that of a condenser supplied by vapor free from contaminants. It is possible to observe that the accumulation of contaminants causes reduction in the global effectiveness which are greater when the number of rows is high and the row effectiveness is low.

To prevent noncondensable gas accumulation some condenser designs have been studied [3]. One of them consists in avoiding back flow by reducing the effectiveness of the first rows. This solution causes an unavoidable decrease of the global effectiveness regarding that of a condenser with all the rows of the highest effectiveness, but can be very convenient, as discussed above, when the costs are constrained.

By using the proposed mathematical model we can now evaluate the convenience of a condenser in which vapor flows only in the forward direction in com-

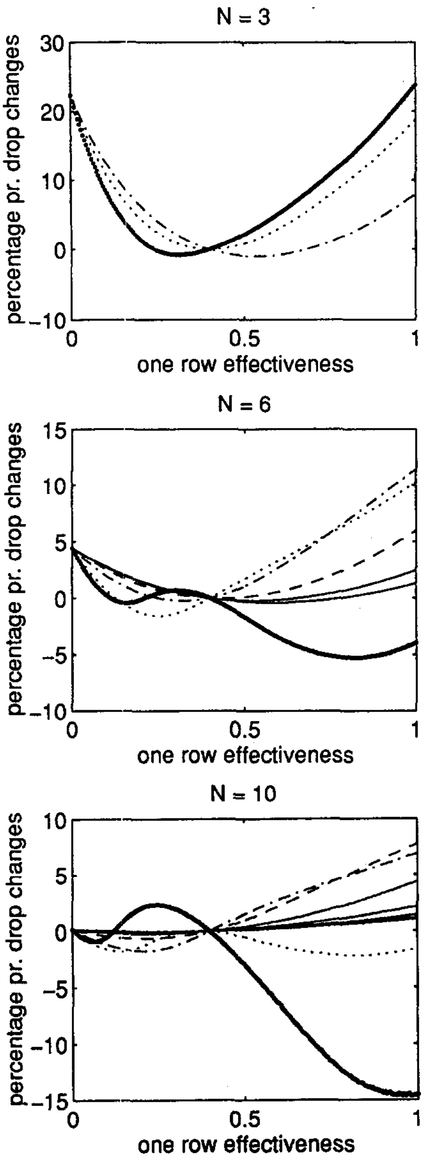

Fig. 7. Percentage changes between the pressure drop in a condenser, in which the effectiveness of one row is varied while that of the other ones is kept at the same value (0.4), and the pressure drop of a condenser with rows of the same effectiveness, which is equal to the average row effectiveness of the first condenser. Changes induced by the variation of the effectiveness of the first (thick dots), the second (thin dots), the third (dashes and dots), the fourth (dashes) row and of each of the others (solid).

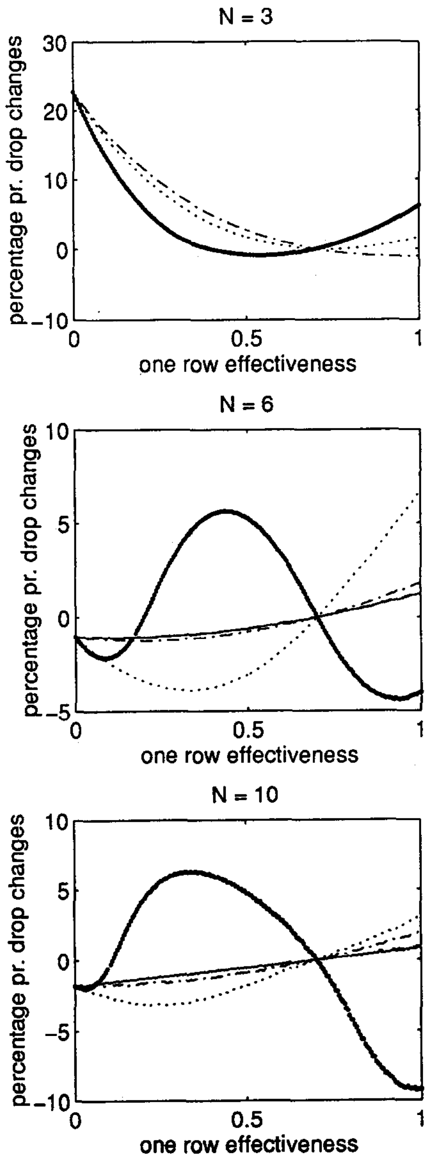

Fig. 8. Percentage changes in the pressure drop as in Fig. 8, but with a common row effectiveness reference value equal to 0.7.

parison with another with the same average row effectiveness of the first one but with all rows having the same effectiveness. In absence of back flow, in the first condenser β_n must be zero and the product $\gamma_n \zeta_n^2$ must be the same in every row. If the friction factor is the same in every row, the vapor flow must also be the same. From equation (4) it then follows:

$$E_n = \frac{E_{n+1}}{1+E_{n+1}}. \qquad (29)$$

By assigning an arbitrary value to the effectiveness of the last row we iteratively obtain the effectiveness of the other rows for the first condenser. It must be noticed that only the effectiveness of the last row in such a configuration can assume an arbitrary value between 0 and 1, while the maximum values of the effectiveness of the other rows are constrained, depending on the order. Therefore, the following analysis is carried out by referring to E_N.

In Fig. 10 the percentage changes between the global effectiveness (a) or the pressure drop (b) of the first condenser and those of the second one are reported for E_N varying between 0 and 1 and N between 3 and 10. We can observe that the percentage changes in the global effectiveness are always positive, while those in the pressure drop are always negative when N is high. The first condenser performs therefore better from the

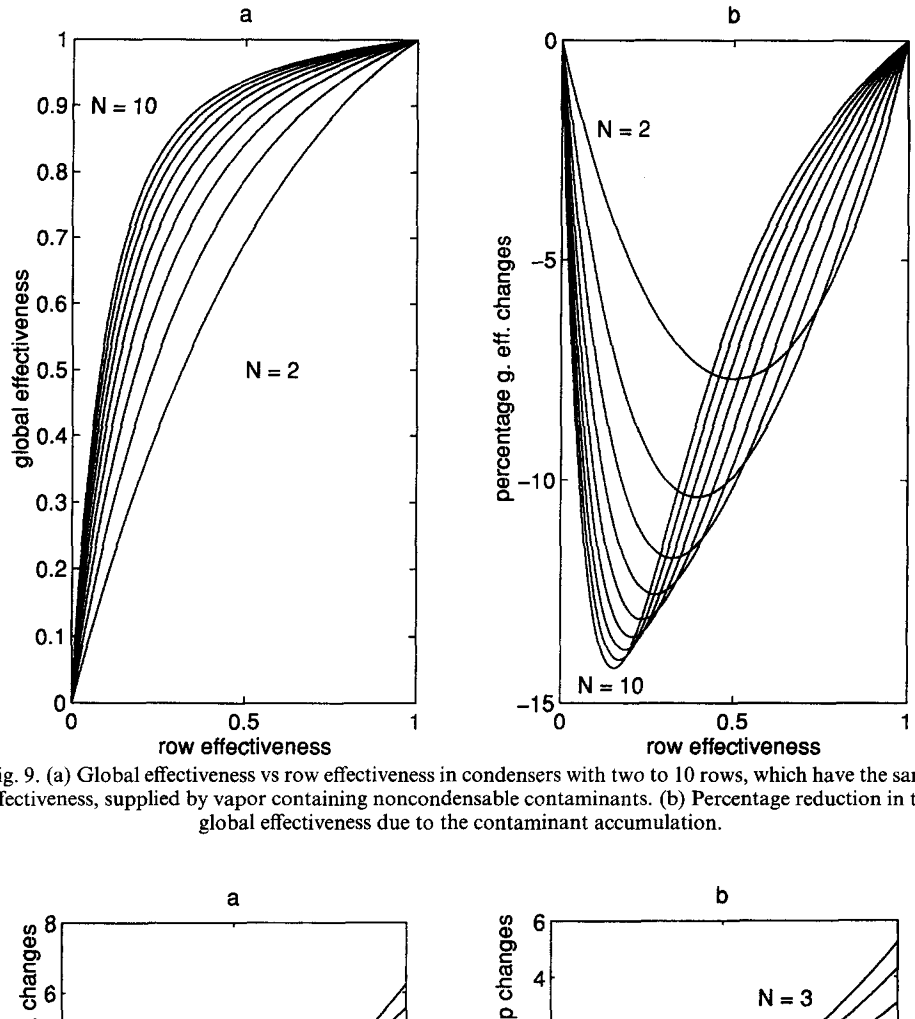

Fig. 9. (a) Global effectiveness vs row effectiveness in condensers with two to 10 rows, which have the same effectiveness, supplied by vapor containing noncondensable contaminants. (b) Percentage reduction in the global effectiveness due to the contaminant accumulation.

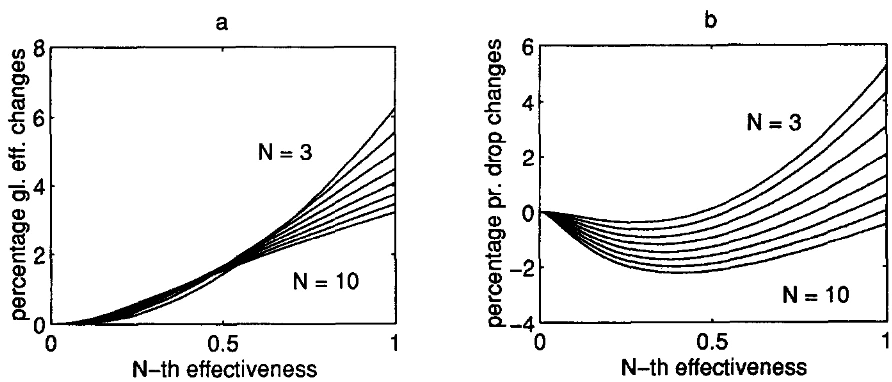

Fig. 10. Percentage changes in (a) the global effectiveness; or (b) in the pressure drop of a condenser, in which no back flow occurs, referring to a condenser with rows of the same effectiveness, which is equal to the average row effectiveness of the first condenser.

point of view of the global effectiveness and, for a large range of E_N, which increases with the row number, it is also expedient from the point of view of the pressure drop between the inlet and outlet plena.

The behavior of the changes in the pressure drop depend on the following reason. For a given w_n the pressure drop in the row is lower when back flow occurs. Moreover, the pressure drop is proportional to the square of w_n, which grows proportionally to the row effectiveness. As seen in Section 3, in condensers with many rows with the same effectiveness, back flow does not occur in most of the rows, and in some others appears just for a short length. The advantages of the reduction in the pressure drop due to the back flow are therefore smaller when the condenser has many rows, and do not overcome the disadvantages connected with the higher effectiveness of the first rows.

4. CONCLUSIONS

The proposed mathematical model is useful to determine the vapor distribution in single-pass, multiple-row, cross-flow, air-cooled condensers, supplied by vapor free from noncondensable contaminants. The solution of the model equations requires very short computing times (a few tenths of second on computer PC 486 DX 100), for great numbers of rows as well. The results provided by the model are interesting also for the planning of those condensers which operate in presence of noncondensable contaminants, as in many cases of common practice. At the beginning of the functioning the contaminants accumulate, in fact, inside the rows as a consequence of the back flow. The knowledge of the vapor flow patterns during this initial phase could be useful in order to develop and opportunely locate separator systems which avoid the subsequent accumulation of the contaminants.

The analysis performed demonstrates that, in condensers with rows of the same effectiveness, back flow appears in one more row for every two added to the device. Moreover, it is not always possible to noticeably improve the global effectiveness of the condenser by increasing the number or the effectiveness of the rows.

The design in which all the rows have the same effectiveness is convenient when the only constraint in the condenser planning is the available technology, but does not represent the best solution if the constraint are the costs connected with the production and the maintenance of the device, as in most practical applications. In the last case, in fact, by reducing the effectiveness of a row to the value obtainable with less expensive or stronger materials, it becomes possible to utilize more sophisticated technologies to increment the effectiveness of the other rows and, as shown in the previous section, the global effectiveness of the condenser.

By assigning different effectiveness to the rows of the condensers it is also possible to reduce the pressure drop between the inlet and the outlet plena.

Finally, it must be remembered that the global effectiveness of condensers in which all the rows have the same effectiveness can decrease noticeably if the vapor which supplies the device is not completely free from noncondensable contaminants. In order to avoid the accumulation of the contaminants, if the friction factor is the same in every row, it is then expedient to progressively reduce the effectiveness of the rows from the penultimate to the first. In such a manner it is in fact, possible to let vapor flow only in the forward direction. Also if no contaminant is present a higher global effectiveness and a lower pressure drop are obtainable with this design at the same costs.

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