

# USE AND ABUSE OF EFFICIENCIES IN SEPARATION PROCESSES

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In two phase separation processes often confusion arises about the meaning and definition of stage-contact-efficiencies. The efficiency, sometimes erratically, is considered to be a measure of the purification obtained in the process under study or in part of it. Moreover, there are many ways to define an efficiency e.g. the Murphree plate efficiency based on the vapor feed or on the liquid feed, a Hausen efficiency and a point efficiency. In this paper we will look shortly into the difference between degree of purification and efficiency and elaborate somewhat further upon the physical meaning of the efficiencies, as normally used in literature.

Most separation processes can be shown to be built-up from units in which two flows make physical contact and thereby exchange part of their components, or heat. For simplicity's sake let us first suppose that one feed,  $F$ , is introduced and that two flows,  $L$  and  $V$ , leave the unit. A component, called  $A$ , has to be separated in purified form. All other components are taken together, as  $B$ . The composition of the flows is then  $x_A$  resp.  $x_B$ .  $x_A$ ,  $x_B$  and  $F$ ,  $V$  and  $L$  must be taken in consistent units, e.g. concentrations in mole fractions and flows in mol/s. Or flows in kg/s and concentrations in weight fractions.

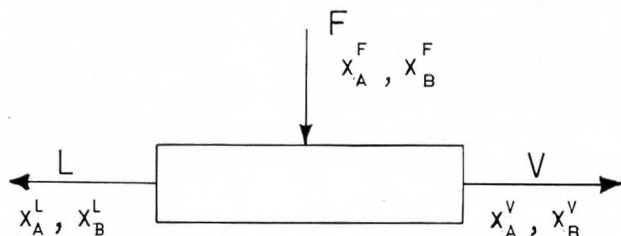


FIGURE 1. Process with one inlet and two outlets.

Now the degree of purification can be defined as

$$P = \left| \frac{L \ x \ \frac{L}{A}}{F \ x \ \frac{F}{A}} - \frac{L \ x \ \frac{L}{B}}{F \ x \ \frac{F}{B}} \right| = \left| \frac{V \ x \ \frac{V}{A}}{F \ x \ \frac{F}{A}} - \frac{V \ x \ \frac{V}{B}}{F \ x \ \frac{F}{B}} \right| \quad (1)$$

Note that this expression has the advantage that the degree of purification remains the same, irrespective 1) which outlet stream ( $L$  or  $V$ ) is taken into consideration and 2) whether com-

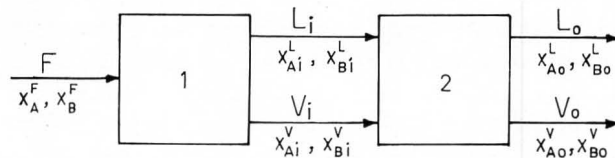
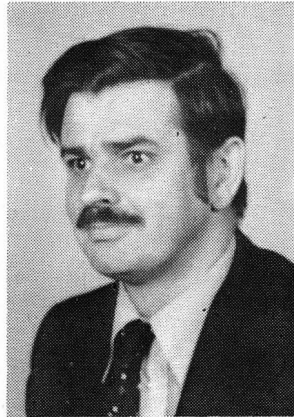


FIGURE 2. Two phase separation process.

ponent  $A$  or the sum of all other components,  $B$ , is considered.

Also important is that  $P$  will always have a value between 0 and 1, zero if the flows  $L$  and  $V$  have the same composition as flow  $F$ , thus when no separation has actually taken place and one if the two components  $A$  and  $B$  are completely separated.

The expression for  $P$  was originally introduced for cyclones [1]. In many cases the feed entering the separation unit is in itself split up into two flows, for example when a stage of a counter-current separation process is considered. Now the incoming flows may be taken as those leaving an imaginary process (drawn on the left in figure 2, marked with the number 1), which is fed by  $F$ . This means that the incoming flows in the actual



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piece of equipment on the right 2, already have a degree of purification:

$$P_{in} = \left| \frac{V_i x_{Ai}}{F x_A} - \frac{V_i x_{Bi}}{F x_B} \right|$$

$$= \left| \frac{V_i x_{Ai}}{L_i x_{Ai} + V_i x_{Ai}} - \frac{V_i x_{Bi}}{L_i x_{Bi} + V_i x_{Bi}} \right| \quad (2)$$

The flows leaving the actual equipment, 2, have a degree of purification

$$P_{out} = \left| \frac{V_o x_{Ao}}{L_i x_{Ai} + V_i x_{Ai}} - \frac{V_o x_{Bo}}{L_i x_{Bi} + V_i x_{Bi}} \right| \quad (3)$$

We expect, as a result of the contacting process, that the degree of purification will increase,  $P_{out} > P_{in}$ . Its difference,  $\Delta P$ , is the working of the piece of equipment under study:

$$\Delta P = \left| \frac{V_o x_{Ao} - V_i x_{Ai}}{L_i x_{Ai} + V_i x_{Ai}} - \frac{V_o x_{Bo} - V_i x_{Bi}}{L_i x_{Bi} + V_i x_{Bi}} \right| \quad (4)$$

It is this number,  $\Delta P$ , in which the process engineer will be interested when he compares alter-

natives for separation.

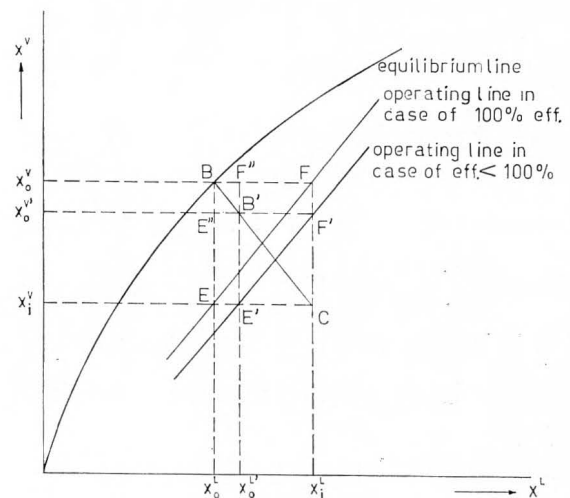
Note that, until now, nothing has to be known about the contacting process itself. The only tool used a *mass balance* over the equipment, or part of it.

### CONTACTING STAGE EFFICIENCY

**I**N MANY CONTACTING processes the equipment not necessarily has to be considered to be a black box. Contacting stages are so devised that the flows leaving the stages are more or less in physical equilibrium. This means that besides the mass balance an *equilibrium relationship* comes into the picture. A theoretical stage (theoretical plate) is a part of the equipment where the outgoing flows are in physical equilibrium. Its efficiency is taken to be 100%. However, the outgoing flows from practical stages are seldomly in equilibrium and then a problem arises. The efficiency of the stage then has to be expressed into flows and concentrations. The definition of the efficiency is often ambiguous as we will see. For only one definition, the efficiency can be shown to be consistent with the defined degree of purification.

The relation between the effects of a theoretical stage and a practical stage is elucidated by means of a graphical representation, figure 3.

Point C represents the compositions of the flows L and V entering the contacting stage. We took it that L and V do not change during the contacting process, a condition that is appropriate in many practical circumstances and in many other circumstances can be made appropriate by



**FIGURE 3. Composition diagram. Action of a contacting stage.**

choosing suitable units to express  $L$  and  $V$ .

Line CB then represents the mass balance for component A, since

$$L \cdot x_{Ai}^L + V \cdot x_{Ai}^V = L \cdot x_{AO}^L + V \cdot x_{AO}^V$$

and therefore

$$x_{AO}^V - x_{Ai}^V = -\frac{L}{V} [x_{AO}^L - x_{Ai}^L]$$

In the following the subscript A will be omitted since everywhere  $x$  will represent the concentration of A in the flow under study.

For a 100% efficiency, point B on the equilibrium line gives the compositions of the two flows leaving a theoretical contacting stage. Point F and E, as is well known, then represent the concentrations of A in the flows that pass each other in between the contacting stages in a multiple-stage-counter-current contacting process and are points of the so called operating line. The slope of the operating line has the opposite sign as the slope of the above mentioned mass balance plot:

$\frac{L}{V}$ , the flow ratio of the two contacting phases.

In case the state of equilibrium is not reached, the concentrations of the flows leaving the practical stage are not given by B, but the process stops somewhere on the line CB, e.g. B' and consequently the operating line will shift to E'F'.

When we wish to compare the performance of the practical contacting stage to that of a theoretical one it is logical to relate its degree of purification to that of a theoretical stage and therefore we now express its efficiency as:

$$E = \frac{\Delta P_{\text{practical stage}}}{\Delta P_{\text{theoretical stage}}} = \frac{P_{\text{practical out}} - P_{\text{in}}}{P_{\text{theor. out}} - P_{\text{in}}}$$

If  $L/V$  is constant then:

$$E = \frac{\frac{V(x_0^{V'} - x_1^V)}{Lx_1^L + Vx_1^V} - \frac{V(1 - x_0^{V'} - 1 + x_1^V)}{L(1 - x_1^L) + V(1 - x_1^V)}}{\frac{V(x_0^V + x_1^V)}{Lx_1^L + Vx_1^V} - \frac{V(1 - x_0^V - 1 + x_1^V)}{L(1 - x_1^L) + V(1 - x_1^V)}}$$

$$\text{or: } E = \frac{x_0^{V'} - x_1^V}{x_0^V - x_1^V} = E_H$$

which is known as the Hausen efficiency [2] and represents in fig. 3 the fractional cut-off  $\frac{E''E}{BE}$

$$\text{or } \frac{F''F}{BF} \text{ or } \frac{B'C}{BC}$$

This definition of efficiency is the best one available in terms of a mathematical and physical

description of a contacting stage.

If  $L/V$  does not remain constant during the process of exchange the original equation (4) has to be inserted for both the theoretical as well as the actual contacting stage; then, however, the expression will be very complicated and does not reduce to simpler terms.

Standart [3] has tried to use a simplified equation for this situation, but although his definition of the efficiency comes down to an equal value irrespective whether it is related to gas phase parameters or to liquid phase parameters, the physical meaning of the numerical values which he obtained cannot be directly related to a degree of purification. Nevertheless in the limiting case, if  $L/V$  remains constant, Standart's definition also reduces to the Hausen efficiency.

However, The Hausen efficiency is seldom used in the profession, partly due to historical reasons, partly because the line CB, although it describes in mathematical terms the mass balance of the contacting stage, does seldom represent compositions of the two phases which are in near physical contact at certain points in the system.

## REPRESENTING EXISTING CONCENTRATIONS

WE MAY TRY TO represent in the concentration diagram sets of concentrations in the two phases that are in close contact with each other. For actual stages often the two phases are contacted in cross flow, e.g. gas bubbling through holes in a plate while liquid traverses the plate from one side to the other.

If the liquid on the plate is well mixed, as will be the case for even relatively large plate diameters, then it has everywhere the composition  $x_0^L$  and line a (E'B') in Fig. 4 describes the concentrations in the gas phase which will occur along the height.

If the gas flows in plug fashion through the liquid all points of line a represent actual occurring pairs of concentrations; if the gas is mixed to some extent, the line will not start at point E' but somewhat higher. In the case that the gas also would be completely mixed, point B' would represent the concentration pairs on all points of the plate.

In the same way it can be shown, that line b (F'B') represents processes in which the gas phase is well mixed and the liquid phase flows in more or less plug fashion through the stage. This may be true in a shallow spray-tower. Here line b shrinks in the direction of B' when also mixing



- Suppose that the gas flow is constant, while the liquid flow rate is varied, but
- the liquid height on the plate remains the same.

Now the real local liquid flow velocity will be made up by phenomena: a) the velocity induced by the overall liquid flow on the plate, and b) the statistical flow variations (mixing) caused by the action of the gas bubbles. It will be clear, that in most cases phenomena b) will be the one largely responsible for local fluid movement.

Therefore we may suppose, that a variation of the liquid flow rate on the plate will not influence directly the number of gas bubbles nor its dimensions, if the physical properties of the liquid on the plate remain the same (surface tension, viscosity, density). The physical properties are kept constant if the composition of the liquid on the plate is kept equal for different liquid flow rates,  $L$ , by adjusting the liquid feed composition. (from  $x_i^{L1}$  to  $x_i^{L2}$ ).

In this case a gas bubble rising in the liquid will not observe any change in its surroundings and therefore will transfer the same amount of mass regardless of the magnitude of  $L$  and hence  $E_{MV}$  is predicted to be constant. From Fig. 5 it is obvious, however, that only  $E_{MV}$  will be constant,  $E_H$  and  $E_{ML}$  will change with  $L$ . Experimental confirmation is given elsewhere [4].

In the same way it can be shown, that if

- the gas "on the plate" is well mixed
- the liquid moves in plug flow through the gas
- the liquid flow rate is constant
- the length of the liquid trajectory is constant, that the Murphree liquid efficiency,  $E_{ML}$  will be constant for different vapour velocities, but not so  $E_{MV}$  or  $E_H$ .

This type of exchange will be expected in a shallow spray tower (Fig. 6) Cases in which  $E_H$  is constant are very difficult to be thought of. But,

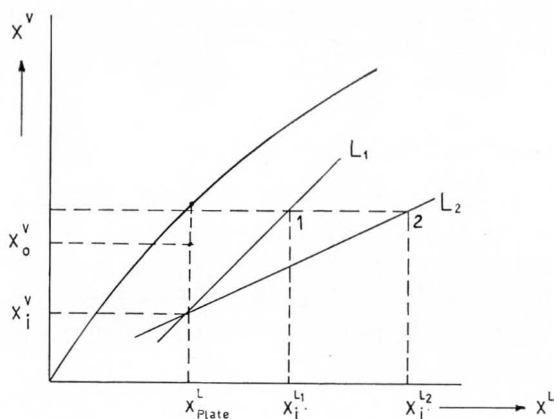


FIGURE 5. Constant  $E_{MV}$  as a function of  $L$ .  $x^L$  plate and  $V$  are constant.

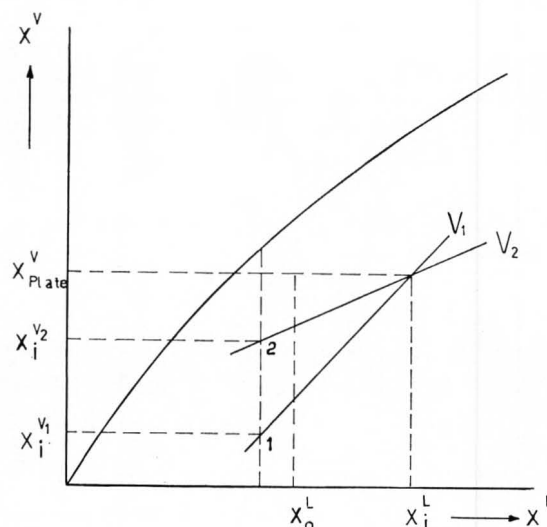


FIGURE 6. Constant  $E_{ML}$  as a function of  $V$ .  $x^V$  plate and  $L$  are constant.

then, the use of the Hausen efficiency, being consistent to a degree of purification, does not need further justification.

## CONCLUSIONS

There needs to be made a distinction between the degree of purification and the efficiency of a process. The degree of purification is derived on the basis of a mass balance, the efficiency must combine a mass balance with equilibrium relationship. The Hausen efficiency is based on a mass balance and an equilibrium relation and can readily be translated into a degree of purification. Numerical data on the Murphree vapour efficiency or the Murphree liquid efficiency, in general, do not provide complete quantitative information about the separation process. In certain circumstances the constancy of the Murphree vapour efficiency or the Murphree liquid efficiency may be expected on model considerations. □

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## NOMENCLATURE

- $x$  : concentration, consistent with the unit of flow rate.  
 $L$  : flow rate phase 1  
 $V$  : flow rate phase 2 consistent with  $x$   
 $P$  : degree of purification  
 $E$  : efficiency  
 $E_H$  : Hausen efficiency  
 $E_{MV}$  : Murphree efficiency, based on the vapour  
 $E_{ML}$  : Murphree efficiency, based on the liquid.