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Simple and rapid determination of effective Murphree component efficiencies for operating absorbers, strippers and distillation columns filled with any type of trays

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ABSTRACT

Estimating efficiency of an *operating* column has to be distinguished from that of a column being *designed*. This crucial point has been totally overlooked in the literature. All the methods and models available for predicting the Murphree efficiencies of tray columns have been developed for the design case. They generate their own mass and heat transfer rates and empirical parameters rather than produce true transfer rates by using *operating* column (realistic) data, especially the specifications of outlet streams. In addition, most of these methods are limited in application and insufficient in accuracy, especially if applied outside the range of conditions under which they were formulated.

The present work introduces a general and applicable method for determining the overall Murphree component efficiencies of an *operating* tray column. This method uses the specifications of both inlet (feed) and outlet (product) streams of an *operating* column to back-calculate realistic mass and heat transfer rates for Murphree efficiency estimation. The presented method is usable to operating tray columns with any amount of flow rates and diameter as well as with any number of components and trays. Overall, it can be usable to the gas–liquid *operating* columns filled with any type of trays.

1. Introduction

Efficiency estimation of an *operating* (existing) column is more difficult than, and has to be distinguished from, that of a column being designed. Operating conditions and the specifications of both inlet (feed) and outlet (product) streams of an operating column have to be directly employed for determining *true* mass and heat transfer rates and subsequently, the tray efficiency. The calculated transfer rates and efficiency if applied to the column-describing equations have to lead to the same specifications of the outlet streams. However, this is not the case with available (especially empirical) models, which have been originally developed for *designing* columns but are also used for *operating* (existing) columns. Once empirical mass transfer models are applied to an *operating* column, they generate their own mass and heat transfer rates and parameters instead of using the column (realistic) data, especially the specifications of outlet streams. As a result, there is a need to have an efficiency estimation method applicable directly to *operating* (existing) columns.

The most common definition for a tray (stage) efficiency is the vapor phase Murphree tray efficiency [1,2] that is defined as (for component i on tray number j):

$$E_{i,j} = \left(\frac{y_{i,j} - y_{i,j+1}}{y^*_{i,j} - y_{i,j+1}} \right) \tag{1}$$

Murphree efficiencies vary from tray to tray and from component to component within a column (see [1,2]). The objective of this research is to develop an accurate and unique method for predicting overall Murphree efficiencies. The approach is to modify the traditional MESH equations and incorporate the Murphree component efficiency into the equilibrium stage model (**MESH** is the acronym referring to the different types of equations: **M** = Component **M**aterial balances, **E** = phase **E**quilibrium, **S** = **S**ummation equations, **H** = **H**eat balances). In fact, the phase **E**quilibrium equations (in the M**E**SH equations) will be replaced by the **M**urphree efficiency equations and, therefore, the method is named "M**M**SH method". A backward approach is taken to reach

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Nomenclature

Symbol	description
Roman symbols	
c	number of components (–)
$E_{i,j}$	Murphree efficiency for component i on tray number j (–)
$E_{i\text{eff}}$	effective Murphree efficiency for component i ($\equiv E_{iave}$) (–)
h	enthalpy (J kmol^{-1})
K	equilibrium constant (k value) (–)
l	liquid component flow rate (kmol h^{-1})
L	liquid flow rate (kmol h^{-1})
L_j	flow rate of liquid phase leaving the j-th tray (stage) (kmol h^{-1})
L_0	flow rate of liquid phase entering the 1-th tray (stage) (kmol h^{-1})
N	number of trays (stages) (–)
P	pressure (atm)
Q_j	heat rate transferred from (−) or to (+) tray (stage) j (J h^{-1})
T	Temperature (K)
v	vapor (gas) component flow rate (kmol h^{-1})
V	vapor (gas) flow rate (kmol h^{-1})
V_j	flow rate of vapor (gas) phase leaving the j-th tray (stage) (kmol h^{-1})
V_{N+1}	flow rate of vapor (gas) phase entering the N-th tray (stage) (kmol h^{-1})
y	vapor mole fraction (–)
y^*	mole fraction in vapor in equilibrium with liquid leaving the tray (–)
Subscript	
1, 2,…, N	stage number (from the top of the column)
eff	effective
i	component i
j	tray or stage j
L	liquid phase
V	vapor (gas) phase

the overall mass and heat transfer rates inside the operating column so that all the MMSH equations and outlet streams are satisfied. This new approach taken here is applicable only to operating columns where outlet streams are known.

It should be noted that most of the methods developed for tray efficiency are limited in application, as they cannot estimate the efficiency with sufficient accuracy y over a wide range of operating conditions (see, e.g. Refs. [1–12]). These methods mainly include some empirical mass transfer and hydraulic relations. For a tray column, the relationship between mass transfer area, tray specifications, system physical properties, and operating conditions is complex and not yet understood well enough [13–17]. Even some of these methods give completely different estimates of a tray efficiency for a specified case [2,3,7,18,19] and can be off by 15–50% [6] or even more [9,20,21]. However, the MMSH method is a general method free of any empirical relations, developed for *operating* (existing) columns.

2. MMSH method (MMSH equations)

For efficiency estimation of an operating column, one should manipulate the Murphree efficiency to capture the realistic operating data of the column. The MMSH method is based on this principle. However, this method does not manipulate the Murphree efficiencies and, instead, calculates them directly. In the MMSH method, Murphree efficiencies of each component are considered as equal or average values for all trays. In fact, the *effective* Murphree efficiency is obtained for each component over the entire column.

Definition

Fig. 1 shows a simple nonequilibrium stage used in the MMSH method. A complete separation column is taken to be a sequence of these stages, where the stages are numbered down from the top (Fig. 2). The numbers of stages and components are the specified values N and c, respectively.

Relations

The equations that model these stages have been termed the MMSH equations. The first set of M equations is the component Material balances

$$(M_{i,j}) = v_{i,j+1} + l_{i,j-1} - v_{i,j} - l_{i,j} = 0 \quad \begin{array}{l}(i = 1,2,\ldots,c)\\(j = 1,2,\ldots,N)\end{array} \tag{2}$$

The second set of M equations is the relations of Murphree efficiencies defined by

$$(M_{i,j}) = E_{i,j} = \left(\frac{\frac{v_{i,j}}{V_j} - \frac{v_{i,j+1}}{V_{j+1}}}{K_{i,j}\frac{l_{i,j}}{L_j} - \frac{v_{i,j+1}}{V_{j+1}}}\right) \begin{array}{l}(i = 1,2,\ldots,c)\\(j = 1,2,\ldots,N)\end{array} \tag{3}$$

In this method, as mentioned earlier, the Murphree efficiency for each component is taken to be the same for all stages. Thus, the index j in $E_{i,j}$ can be replaced by notation "eff" (notation "eff" denotes the word "effective"). Therefore, the cN unknown Murphree efficiencies $E_{i,j}$ reduce to c unknown effective Murphree component efficiencies $E_{i\text{eff}}$.

The S or Summation equations are as (see [22])

$$(S_V)_j = \sum_{i=1}^{c} v_{i,j} = V_j \qquad (j = 1,2,\ldots,N) \tag{4}$$

$$(S_L)_j = \sum_{i=1}^{c} l_{i,j} = L_j \qquad (j = 1,2,\ldots,N) \tag{5}$$

Since for an operating column, the specifications of outlet streams are known, one of the two sets $l_{i,N}$ and $v_{i,1}$ is considered to be known (here $v_{i,1}$).

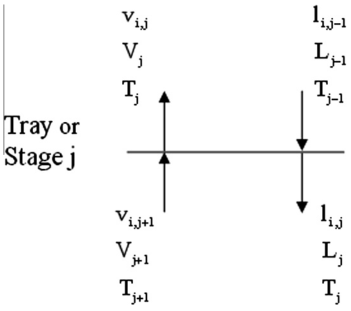

Fig. 1. A diagram of a simple non-equilibrium stage used in the MMSH method.