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Reflectivity - an alternative approach to teaching multiple-effect evaporator sizing to chemical engineering students

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ABSTRACT: Multiple-effect evaporators are applied extensively in chemical processes to remove relatively large amounts of solvent from solid-liquid or liquid-liquid mixtures. A common procedure to determine the heat transfer surface area requires an iterative procedure, which has the disadvantage of being lengthy and time-consuming. A new approach is suggested to reduce calculation. It involves solving a system of equations without any need for advanced computer programming skills. Chemical engineering students at Mangosuthu University of Technology (MUT) in Durban, South Africa, responded to an evaluation survey after learning both approaches. The new approach improved the learning experience of students. Highlighted by this study is the need for critical reflectivity to improve instructional delivery.

Keywords: Chemical engineering, engineering education, multiple-effect evaporator, reflectivity

INTRODUCTION

In an evaporator, a mixture containing a liquid-liquid or solid-liquid solution is subjected to heat to remove, through evaporation, a substantial amount of solvent. The effect of this is an increased concentration of the resultant solution. Examples where evaporation is used include sugar refining and fruit juice concentration. Efficient evaporation is characterised by a large amount of evaporated solvent per unit mass of steam [1]. Multiple-effect evaporators are used instead of single-effect evaporators, to improve economy. In relation to multiple-effect evaporators, various procedures [1][2] and models [3-5] have been proposed in the literature for material and energy balance, as well as heat transfer area calculations.

In chemical engineering departments, evaporators are taught as unit operations, and in mass transfer and heat transfer subjects. At Mangosuthu University of Technology (MUT), the modelling and analysis of multiple-effect evaporators are covered in the Unit Operations subject, at the Bachelor of Technology level (fourth year of study). The pass rate consistently was below the average pass rate of all subjects offered at the Bachelor of Technology level during the first semester, fourth year. This situation negatively affected the throughput rate (i.e. ratio of the number of students from the cohort who graduate).

As part of efforts to improve the programme throughput, lecturers were tasked with identifying problem areas and implementing necessary interventions. In response, the teaching practice and teaching and learning environment was scrutinised for Unit Operations, from 2011 to 2016. The topic covering multiple-effect evaporators was identified as an *issue* to be addressed.

An *issue* in this context is a point in a course where the learning process for most students is interrupted [6]. The new approach presented in this article is a response to the issue of multiple-effect evaporators characterised by unsatisfactory student success in the Unit Operations subject. Students' evaluation and assessment results were instrumental in identifying the cause of students' poor performance. In fact, these are two of the four lenses (students' eyes, colleagues' perceptions, educational literature and teachers' autobiographical experiences), through which to reflect on teaching and learning [7]. Student evaluation and assessment results were incorporated in the reflectivity and criticality processes. Publications related to teaching and learning emphasise criticality, reflectivity, student evaluation and assessment as triggers for improved teaching practices [8].

In this article, a well-established teaching approach for multiple-effect evaporators is critically examined. This method is provided in the recommended textbook in use at most South African universities, where chemical engineering is taught. The weaknesses are highlighted before an alternative procedure is proposed. The aim is to introduce an alternative teaching approach for multiple-effect evaporator calculation, while showing how reflectivity can trigger improved learning experience in chemical engineering education. Engineering educators may be encouraged by the results to incorporate reflectivity as a regular feature of their teaching practice.

PREVIOUS PRACTICE

At most South African chemical engineering departments, including MUT, the book, *Separation Process Principles,* is prescribed for students [1]. It represents the primary source of information for topics covered in the third and fourth years of undergraduate studies. These generally include a wide range of separation processes. At MUT, topics for Bachelor of Technology students enrolled for Unit Operations IV include crystallisation, multiple effect evaporation, the Ponchon-Savarit method for binary distillation, multicomponent distillation and absorption. An example in the textbook was provided to illustrate the calculation for the heat transfer area of each effect, along with material and energy balances for a triple-effect forward feed evaporator by which to concentrate an aqueous solution containing colloids.

Textbook Example

The total flow rate of the feed, the feed composition, the final concentrate composition, the feed temperature, the last effect pressure, saturated steam pressure (service stream) and the specific heat of the colloids were provided. Enthalpy values of water at different temperatures could be obtained from steam tables in handbooks or through correlations found in the literature [9-12].

To simulate a multiple-effect evaporator, a set of equations (model) is used. The textbook [1] proposes the following equations for *n* effects, as illustrated in Figure 1:

$$m_1 w_1 = m_n w_n \tag{1}$$

$$Q_1 = \left(m_f - m_1\right)H_{v1} + m_1 H_1 - m_f H_f \tag{2}$$

$$Q_2 = \left(m_1 - m_2\right)H_{v2} + m_2 H_2 - m_1 H_1 \tag{3}$$

$$Q_3 = \left(m_2 - m_3\right)H_{v3} + m_3 H_3 - m_2 H_2 \tag{4}$$

$$Q_{n-1} = \left(m_{n-2} - m_{n-1}\right)H_{v(n-1)} + m_{n-1} H_{n-1} - m_{n-2} H_{n-2} \tag{5}$$

$$Q_n = \left(m_{n-1} - m_n\right)H_{vn} + m_n H_n - m_{n-1} H_{n-1} \tag{6}$$

$$Q_1 = m_s \Delta H_s^{vap} \tag{7}$$

$$Q_2 = (m_f - m_1)\Delta H_2^{vap} \tag{8}$$

$$Q_3 = (m_1 - m_2)\Delta H_3^{vap} \tag{9}$$

$$Q_{n-1} = (m_{n-3} - m_{n-2})\Delta H_{n-1}^{vap} \tag{10}$$

$$Q_n = (m_{n-2} - m_{n-1})\Delta H_n^{vap} \tag{11}$$

$$Q_1 = U_1 A_1 \left(T_s - T_1\right) \tag{12}$$

$$Q_2 = U_2 A_2 \left(T_1 - T_2\right) \tag{13}$$

$$Q_3 = U_3 A_3 \left(T_2 - T_3\right) \tag{14}$$

$$Q_{n-1} = U_{n-1} A_{n-1} \left(T_{n-2} - T_{n-1}\right) \tag{15}$$

$$Q_n = U_n A_n \left(T_{n-1} - T_n\right) \tag{16}$$

Furthermore, the following equation for the overall temperature-driving force can be assumed:

$$\Delta T = TS - T1 + T1 - T2 + T2 - T3 + ... + T_n - 1 - T_n = TS - T_n \tag{17}$$

The various notations in Figure 1, as well as the equations above, are explained in Table 1. Equation (1) describes the solute mass balance, while energy balances are given by Equations (2) to (11).

Heat transfer rates are represented by Equations (12) to (16). The model was derived on the basis of the following assumptions: the feed contains only one volatile solvent; the solution is heated and vaporised by the latent heat of vaporisation of steam only; the vapour and liquid phases are in thermodynamic equilibrium in each effect; the overall temperature-driving force (ΔT) for heat transfer is given by T_S - T_n; the overall temperature-driving force is appropriate to achieve nucleate boiling while avoiding any undesirable film boiling; the presence of the solute does not lead to a rise in boiling temperature; heat lost from the evaporator is negligible.

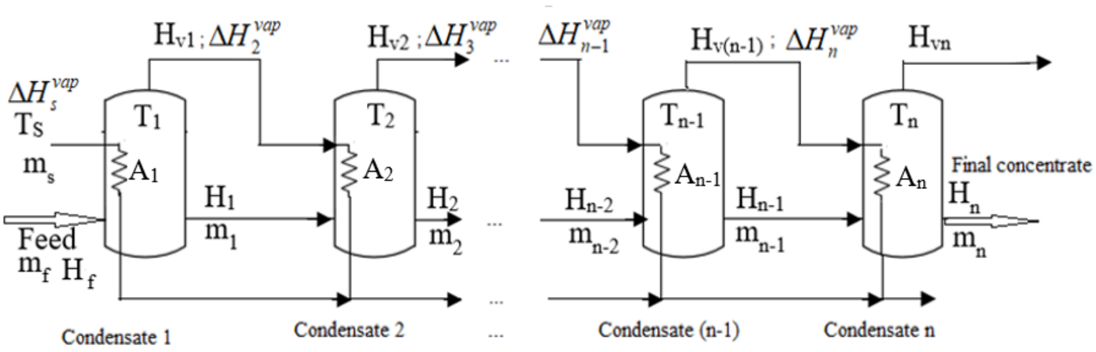

Figure 1: Feed forward multiple-effect evaporator with *n* effects.

Table 1: Variables for multiple-effect evaporator modelling.

A_i	Heat transfer area of the i^{th} effect (i varies from 1 to n)	T_f	Feed temperature
H_f	Specific enthalpy of the feed	T_i	Temperature in effect *i*
H_i	Specific enthalpy of the concentrate for effect *i*	T_s	Steam temperature
H_{vi}	Specific enthalpy of the saturated vapour at effect *i*	U_i	Heat transfer coefficient for effect *i*
m_f	Mass flow rate of the feed	w_f	Mass fraction of the solute in the feed
m_i	Mass flow rate of the concentrate for effect *i*	w_i	Mass fraction of the solute in the concentrate for effect *i*
m_s	Steam mass flow rate	ΔH_i^{vap}	Latent heat of vaporisation for effect *i*
Q_i	Heat transferred to effect *i*	ΔH_s^{vap}	Latent heat of vaporisation for steam

Teaching the Textbook Example

The classroom was flipped to ensure that students were kept engaged, while working at their own pace. This approach allows the lecturer to provide more personalised attention to students. The 32 students in class were instructed to study the calculation procedure and to solve the worked example provided in the textbook before the contact 90-minute lecture. Students had the required information to undertake the calculation, as well as a short video recorded by the lecturer explaining the solution shown in Figure 2, which is the summary of the method explained in the textbook.

During the contact lecture, further engagement with concepts and theory takes place through interactions between the lecturer and the students. After going through all the steps of Figure 2 students were invited to solve a similar problem in class. Whenever necessary, students could get assistance from the lecturer while solving the problem. As part of the test, which contributes to the grading, students are given a question on multiple-effect evaporator calculations.

Correlations for enthalpies and latent heats of vaporisation were made available. Students were also invited to respond to a questionnaire, to evaluate their learning experience. It emerged that the calculation procedure of Figure 2 was found easy to use. However, more than 80% of students found the solution time-consuming. Students also held the view that the assumption in relation to vapour flow rates had no clear chemical engineering basis. Furthermore, they were concerned that the numerous iterative steps involved in the calculation procedure could be forgotten.

A critical examination of this current approach through students' opinion and the lecturing, allowed the following observations of its shortcomings:

- the method encourages rote learning and is time-consuming;
- students are compelled to memorise many steps;
- students failed the test because their memory failed them.

Some could easily forget an assumption or fail to remember which equations should be combined to eliminate Q_1 to Q_n, for example. The reliance on memory is inconsistent with recent research, which established that constructivism is the best approach through which knowledge is acquired in engineering [13][14].

Constructivist theories hypothesise that learning occurs better when students fit new information into existing cognitive structures. Learning is unlikely when no connection can be established between the new and existing knowledge [14]. The present method for multiple-effect evaporator calculations is time-consuming, because of a large number of iterations, particularly when the number of effects is high. The only advantage is that all equations in the procedure are linear and easy to solve - even through hand calculation. However, this advantage is moot as chemical engineers always will have access to computers regardless of their location.

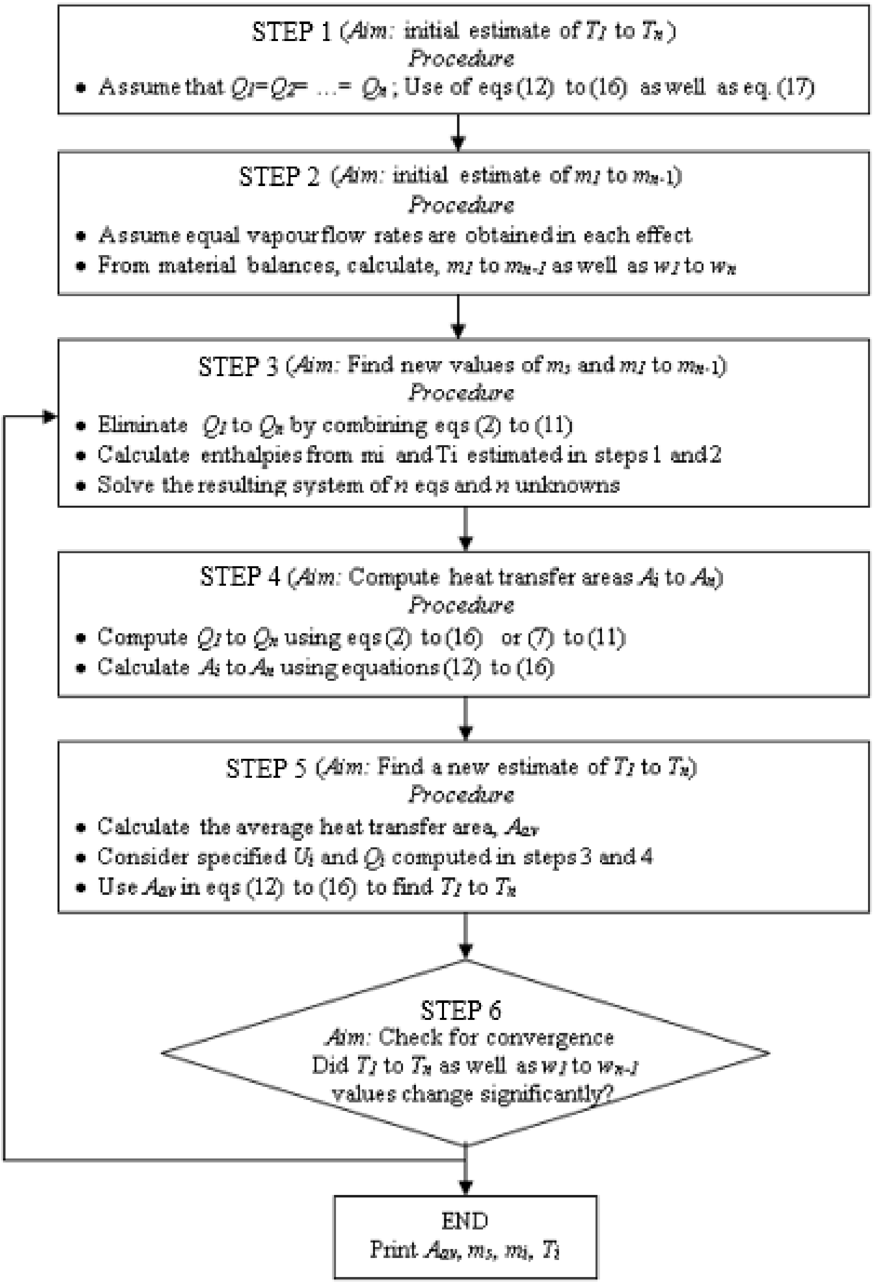

Figure 2: Calculation procedure for heat transfer area, mass and energy balances in multiple-effect evaporator.

PROPOSED APPROACH

In the new approach, the equations for modelling the multiple-effect evaporator, the instructional delivery, as well as evaluation, remain unchanged. The only modification is related to the way Equations (1) to (17) are applied to solve the problem.

One feature of the proposed procedure is the reliance on correlations for steam or vapour saturation temperatures, water enthalpies, as well as enthalpy change of vaporisation, which are readily available in the literature. Saturated temperatures were calculated as follows [9]:

$$T_s = \exp\left(\left(a + b\left(P_S / P_C\right) + c\left(P_S / P_C\right)^2 + d\left(P_S / P_C\right)^3 + e\left(P_S / P_C\right)^4 \right)^{-0.4} \right) \tag{18}$$

$$T_n = \exp\left(\left(a + b\left(P_n / P_C\right) + c\left(P_n / P_C\right)^2 + d\left(P_n / P_C\right)^3 + e\left(P_n / P_C\right)^4 \right)^{-0.4} \right) \tag{19}$$

where a = 9.37817 x 10^{-3}; b = 4.98951 x 10^{-4}; c = 1.11049 x 10^{-5}; d = 3.34995 x 10^{-7} and e = 3.44102 x 10^{-8}.

T_s is expressed in K, while P_c = 2.2064 x 10^7 Pa (critical temperature of water); P_s and P_n are the provided saturated vapour pressures in Pa for steam and the vapour at effect n, respectively. The specific enthalpies of saturated vapour at various effects (i) can be computed as follows [9]:

$$H_{vi} = \exp\left[\left(a'+b'[\ln(1/T_{ri})]^{0.35} + c'/T_{ri}^2 + d'/T_{ri}^3 + e'/T_{ri}^4\right)^{1/2}\right] \tag{20}$$

where a’ = 64.87678; b’ = 11.76476; c’ = -11.94431; d’ = 6.29015; and e’ = -0.99893; T_{ri} is the reduced temperature, given by:

$$T_{ri} = T_i/T_c \tag{21}$$

Specific enthalpies of vaporisation were calculated using the following equation [11]:

$$\Delta H_i^{vap} = a''(T_c - T_i)^{0.375} + b''(T_c - T_i)^{1.375} + c''(T_c - T_i)^{2.375} + d''(T_c - T_i)^{3.375} \tag{22}$$

where T_i is the temperature at effect i; T_c = 647, 096 K (water critical temperature); a’’ =2.67607 x 10^2; b’’ = 2.35577 x 10^{-1}; c’’ = -1.20281 x 10^{-3}, and d’’ = 1.60960 x 10^{-6}. The specific enthalpies of saturated liquid could be calculated as:

$$h_{li} = H_{vi} - \Delta H_i^{vap} \tag{23}$$

while the specific enthalpy of feed and concentrates at different effects were given by:

$$H_i = \left(1 - \frac{m_f \cdot \omega_f}{m_i}\right) \cdot h_{li} + \frac{m_f \cdot \omega_f}{m_i} C_{Pcol} \cdot (T_i - 273.15) \tag{24}$$

where C_{Pcol} is the solute heat capacity. The new calculation procedure is based on the elimination of Q_1 to Q_n by combining the Equations (2) to (6) with Equations (7) to (11) on the one hand, and Equations (12) to (16) with Equations (7) to (11) on the other hand. Hence, the following system of 2n simultaneous equations for heat transfer area, material and energy balances can be obtained:

$$(m_f - m_1)H_{v1} + m_1 H_1 - m_f H_f - m_s \Delta H_S^{vap} = 0 \tag{25}$$

$$(m_1 - m_2)H_{v2} + m_2 H_2 - m_1 H_1 - (m_f - m_1)\Delta H_2^{vap} = 0 \tag{26}$$

$$(m_2 - m_3)H_{v3} + m_3 H_3 - m_2 H_2 - (m_1 - m_2)\Delta H_3^{vap} = 0 \tag{27}$$

$$(m_{n-2} - m_{n-1})H_{v(n-1)} + m_{n-1}H_{n-1} - m_{n-2}H_{n-2} - (m_{n-3} - m_{n-2})\Delta H_{n-1}^{vap} = 0 \tag{28}$$

$$(m_{n-1} - m_n)H_{vn} + m_n H_n - m_{n-1}H_{n-1} - (m_{n-2} - m_{n-1})\Delta H_n^{vap} \tag{29}$$

$$U_1 A(T_S - T_1) - m_s \Delta H_S^{vap} = 0 \tag{30}$$

$$U_2 A(T_1 - T_2) - (m_f - m_1)\Delta H_2^{vap} = 0 \tag{31}$$

$$U_3 A(T_2 - T_3) - (m_1 - m_2)\Delta H_3^{vap} = 0 \tag{32}$$

$$U_{n-1}A_{n-1}(T_{n-2} - T_{n-1}) - (m_{n-3} - m_{n-2})\Delta H_{n-1}^{vap} = 0 \tag{33}$$

$$U_n A_n (T_{n-1} - T_n) - (m_{n-2} - m_{n-1})\Delta H_n^{vap} = 0 \tag{34}$$

It should be noted that in the above equations, w_f and w_n are known, m_n can be obtained from Equation (1), while T_s and T_n can be calculated from Equations (18) and (19). Hence, there are 2n unknowns (m_1 to m_{n-1}, m_s, T_1 to T_{n-1} and A) in the system of non-linear Equations (25) through (34). Any method can be used to solve this system of equations.

EVALUATION OF THE NEW APPROACH

Compared to the previous approach, it is less time-consuming. Its implementation in a computer programme does not require advanced programming skills, although it incorporates non-linear equations. After instruction, the new approach was evaluated over a three-year period, from 2017 to 2019 by means of a survey questionnaire consisting of four questions (see Table 2).

Table 2: Students' survey questionnaire.

Rate the extent to which:	1. Poor 2. Average 3. Good 4. Excellent			
Q1. You were able to size multi-evaporators prior to this lecture (i.e. immediately after watching the video clip)	1	2	3	4
Q2. You are able to size multi-evaporators after the lecture	1	2	3	4
Q3. Could you explain the method to another student	1	2	3	4
Q4. Describe in less than 10 lines your experience with the procedure, comparing this approach with that described in the textbook				

The evaluation found that most students (55% to 67%) could understand the procedure, while 9% to 34 % of them rated their understanding as good and 3% to 7 % of respondents declared they had mastered the new procedure before the contact lecture. This response to Question 1 of the survey confirms the low level of complexity of the new method. In relation to Question 2, more than 70% of respondents described their proficiency in sizing multiple-evaporators as either good (40% to 71%) or excellent (18% to 31%). This is an indication that most students grasped the method.

This was also confirmed since 62% to 74% of respondents declared they could explain the sizing procedure to another student (Question 3). Hence, it can be implied that students were confident in their proficiency. Responses to Question 4 revealed the new procedure is superior to the current practice. Students unanimously indicated their preference for the proposed procedure. They held the view that the newly provided approach could be understood with minimum guidance from the lecturer.

In this study, the author opted for a multifaceted approach consisting of supplementing other evaluation tools applied to student ratings. This is referred to as triangulation, a technique that entails confronting outcomes obtained from different instruments to get a holistic view of the teaching process, as well as to check for validity and provide in-depth analysis of results [15].

The other two methods in this study were peer-evaluation (a colleague was asked to sit in on a lecture) and assessment results. The colleague gave a positive feedback, corroborating the view expressed by most students in responding to the fourth question (Q4) of the survey in relation to their experience with the new teaching approach. Students' success in the Unit Operations IV subject in terms of pass rates was also monitored from 2017 to 2019 and compared to the average pass rate of all chemical engineering Bachelor of Technology subjects offered at MUT in Semester 1.

The adoption of the new teaching approach in 2017 resulted in an improvement of the pass rate in Unit Operations IV. The new approach solved the problem it was meant to address, i.e. the consistently low pass rate in this subject with respect to other subjects taken by Bachelor of Technology students at MUT. All the three instruments indicated that the new approach contributed to improving the learning of the sizing of multiple-effect evaporators.

CONCLUSIONS

A well-established procedure for multiple-effect evaporator sizing and material and energy balance calculations was critically examined through reflectivity and students' opinion over seven years in a university of technology.

The shortcoming of this iterative method was addressed by proposing a two-step calculation procedure, which does not require advanced programming skills nor abstract paths. It is less time-consuming and more attractive to chemical engineering students, because it is based on solving a system of equations, rather than relying on a lengthy iterative procedure.

Although a slight modification of the well-established procedure, the new approach undoubtedly is a contribution towards improving the learning experience of chemical engineering students. The improved learning experience was a consequence of the constructivist nature of this new approach. This study is an illustration of the benefits to students of a critically reflective teacher.

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BIOGRAPHY

Kaniki Tumba graduated with a Bachelor of Science in chemical engineering from the University of Lubumbashi, Lubumbashi in the Democratic Republic of the Congo. He received his Master’s and PhD degrees in chemical engineering from the University of KwaZulu-Natal, Durban, South Africa, in 2010 and 2016, respectively. In 2020, he completed a Postgraduate Diploma in Higher Education at Rhodes University, Grahamstown in South Africa. He is employed as a Senior Lecturer and Researcher at Mangosuthu University of Technology in Durban, South Africa. Beyond his interest in engineering education, Dr Tumba carries out research in various areas, including thermodynamics, gas hydrates, separation processes, ionic liquid-based processes, bioprocessing and renewable energy.