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Cyclic distillation – Design, control and applications

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ABSTRACT

Cyclic distillation can bring new life in old distillation columns, by using a periodic operation mode that leads to significant benefits, such as: increased column throughput, lower energy requirements and much higher separation performance. The literature reveals experimental and theoretical studies carried out so far, including models for simulating cyclic distillation. However, the accuracy of these models is limited due to the assumption of linear thermodynamic vapor–liquid equilibrium (VLE) and these models can be used only for rating studies. Moreover, no design method has been reported so far for the general case of multi-component mixtures and nonlinear equilibrium.

This paper fills this gap by presenting a novel rigorous model, an intuitive graphical representation and an insightful comparison against conventional distillation. The design problem is formulated as a set of delay-differential equations with events and discontinuities. Several case studies involving ideal and non-ideal mixtures (e.g. benzene/toluene/o-xylene, methanol/water and ethanol/n-propanol separations) illustrate the process design and demonstrate the high flexibility and good controllability of cyclic distillation.

1. Introduction

Process intensification in distillation systems received much attention during the last decades, with the aim of increasing both energy and separation efficiency. Various techniques, such as internal heat-integrated distillation, membrane distillation, rotating packed bed, dividing-wall columns and reactive distillation were studied [5,17,7,36,16,13,14]. Cyclic operation is considered as an innovative method for operating separation columns, leading to higher throughput, lower energy requirements and higher separation performance.

The cyclic operating mode consists of two parts: (1) a vapor-flow period, when vapor flows upward through the column, while liquid remains stationary on each plate, and (2) a liquid-flow period, when vapor flow is stopped, reflux and feed are supplied to the column, while the liquid holdup is dropped from each tray to the tray below [21]. Fig. 1 schematically illustrates the principle of cyclic operation. This mode of operation can be achieved by using perforated trays, without downcomers, combined with sluice chambers located under each tray. If the vapor velocity exceeds the weeping limit, the liquid does not overflow from tray to tray during vapor-flow period (Fig. 1a). When the vapor supply is interrupted, the liquid drops down by gravitation to the sluice chamber (Fig. 1b). When the vapor supply is started again, the sluice chambers open and the liquid is transferred by gravity to the tray below (Fig. 1c). Note that the feed is added to stage *NF*, mixes with the liquid on the stage and flows to the sluice chamber below. Hence, when the new vapor-flow period begins, the feed will be found on the stage $NF + 1$.

Although the advantages of cyclic operation have been demonstrated experimentally, the information about modelling and designing cyclic distillation columns is rather limited. The idea of cyclic operation in distillation, liquid–liquid extraction and particle separation was introduced by Cannon [4] and tested in trays [11] and packed columns [26]. Afterward, Sommerfeld et al. [32] used computer simulation to investigate the theoretical effects of various parameters on the separating ability of a controlled cycling column. Analytical results were also presented for certain simplified cases assuming constant composition in the reboiler and a linear thermodynamic vapor–liquid equilibrium relationship of the form $y = m \cdot x$. An analogy with classic distillation was also developed. Analytical expressions describing the dynamics of a distillation column operated in controlled cyclic fashion were derived for linear equilibrium assumption and considering an average value for the liquid composition during one operating cycle. Also, an iterative procedure was proposed to handle the case of nonlinear

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Nomenclature

B	bottoms (kmol/cycle)
D	distillate (kmol/cycle)
d_h	hole diameter (mm)
F	feed (kmol/cycle)
K	constant that depends on liquid height on tray
L	reflux (kmol/cycle)
M	holdup (kmol)
NF	feed stage (–)
NT	total number of stages (–)
NS	number of trays in the stripping section (–)
P	pressure (Pa)
P^{vap}	vapor pressure (Pa)
t	time (s)
t_{vap}	duration of the vapor-flow period (s)
T	temperature (K)
u	manipulated variable
V	vapor flow rate (kmol/s)
v	minimum vapor velocity (m/s)
x	mole fraction, liquid phase (–)
y	mole fraction, vapor phase (–)

Greek letters

α	control tuning parameter
β	control tuning parameter
γ	activity coefficient (-)
ε	control error
λ	heat of vaporization (J/kmol)
ρ_v	vapor density (kg/m^3)

Superscripts

(V)	end of the vapor-flow period
(L)	end of the liquid-flow period

Subscripts

k	stage number (1 – condenser, NT – reboiler)
F	feed
D	distillate
B	bottoms

equilibrium [6]. Based on a model assuming linear thermodynamic vapor–liquid equilibrium and straight operating line, Robinson and Engel [28] suggest replacing the distance-axis composition profiles found in a conventional column with a composition profile along the time axis.

Schrodt et al. [30] describes a plant-scale cyclic column (19 in. diameter) for the separation of water–acetone mixture, proving that a 240% capacity increase is possible. Gel'perin et al. [12] created a cyclic regime using electromagnetic valves. A 200% efficiency increase proved again the beneficial effect of cycling regime. An empirical model was used to predict the performance. Shortly after, Rivas [27] derived simple analytical equations that can be used to calculate the ideal number of trays for cyclic counter-current processes such as cyclic distillation, absorption, and stripping. However, this applies better to absorption than to distillation, due to the assumption of linear vapor–liquid equilibrium. For a benzene/toluene mixture and 95% product purity, 50% fewer stages were needed as compared to conventional distillation.

However, experiments [30,9] and simulation [18] showed that, due to hydrodynamic problems, the tray design must be modified when over 12 trays are used. Practical solutions such as external pressure-equalizing manifolds [10] and composite schemes [24] were proposed. The importance of liquid plug-flow down the column was also emphasized by Baron et al. [1].

A breakthrough was recently achieved when a new type of trays especially designed for cyclic operation was invented [21,22] (www.maletacd.com). The special trays are provided with valves and sluice chambers located under the trays. The operation principle is the following: during the vapor-flow period, the valves are closed and the liquid stays on the tray. During the liquid-flow period, the valves open and the liquid flows from the tray to the sluice chamber below. When another vapor-flow period begins, the sluice

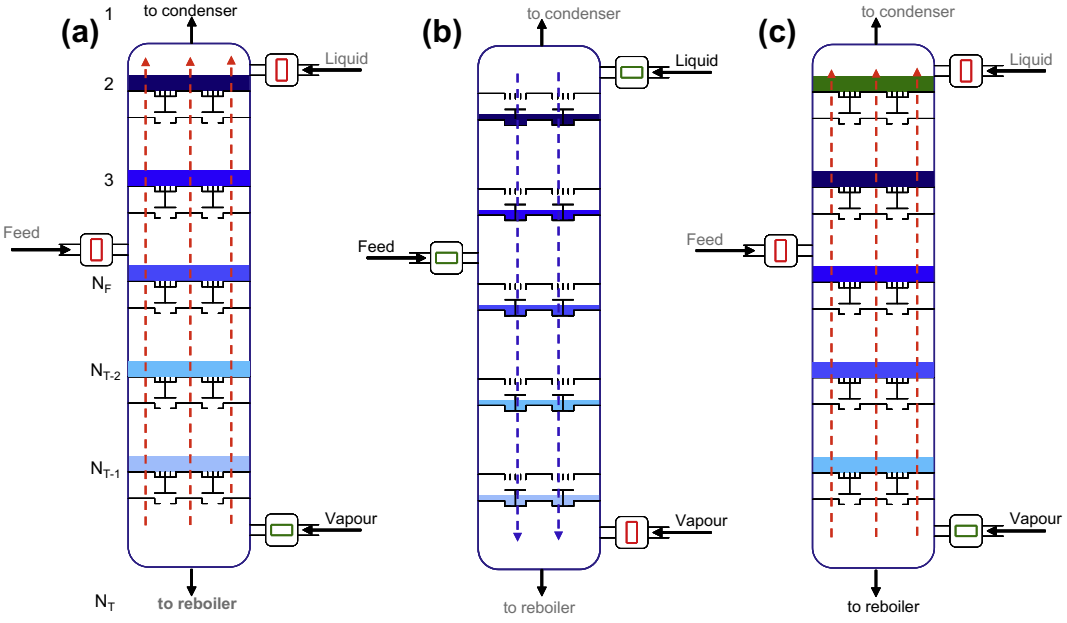

Fig. 1. Schematics illustrating the working principle of cyclic distillation: (a) vapor-flow period; (b) liquid flow-period; (c) beginning of a new vapor-flow period.