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Review

Assessment of separation efficiency modeling and visualization approaches pertaining to flow and mixing patterns on distillation trays

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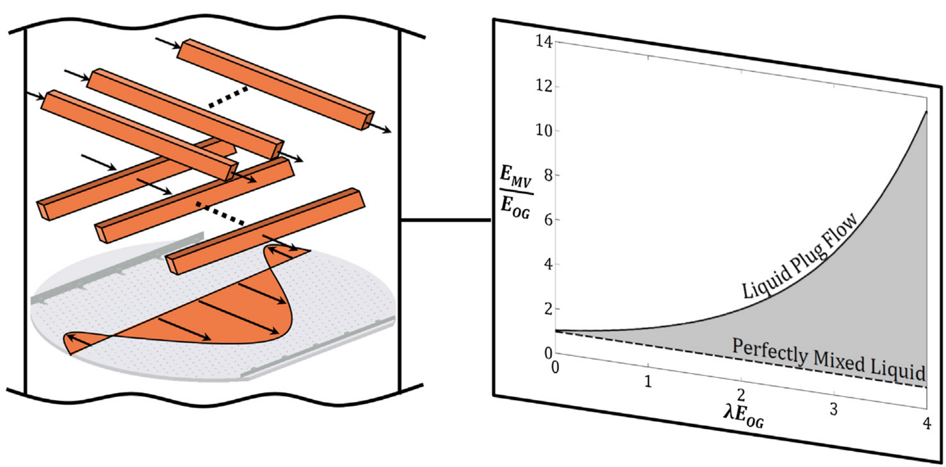
HIGHLIGHTS

- Flow and mixing patterns on distillation trays strongly dictate their efficiency.
- Existing experimental and CFD approaches for tray flow visualization are reviewed.
- The existing mathematical models for tray efficiency prediction are examined.
- A strategy on how to extract the fluid dynamics data from experiments is discussed.
- Tray efficiency predictions using the data extracted from experiments are shown.
- Hybrid (CFD and efficiency prediction) models could be used together in the future.

GRAPHICAL ABSTRACT



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ABSTRACT

Distillation columns are essential to chemical process industries, and most of them are fitted with cross-flow trays due to their versatility. Since these columns are expensive in terms of cost and energy consumption, an accurate determination of their separation efficiency is a prerequisite to optimization of their performance by design modification and revamping. This would further reduce the extra trays, added to account for the uncertainties, during the column design. There have been several attempts in the past to understand the nature of liquid mixing and flow patterns on the trays through experiments and CFD simulations, and to relate them with their separation efficiency through CFD, empirical and theoretical models. The present work aims at reviewing the experimental and the simulational studies accomplished to characterize the flow and the mixing patterns on column trays. In particular, a comprehensive review of the existing theoretical efficiency prediction models along with the critical analysis of their strengths and weaknesses is presented. The dependence of the tray efficiency on system and flow properties is also discussed. In addition, a concise strategy on how to process and utilize the experimental data in tandem with mathematical models is proposed. The future of the tray efficiency modeling is anticipated to feature hybrid approaches, i.e. using theoretical models supplemented with fluid dynamics information from experimentally validated CFD models. Thus, knowledge of the existing theoretical approaches is imperative for their improvement and development of the new ones for better tray efficiency predictions.

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Nomenclature

A	cross-sectional area of froth perpendicular to the flow direction (m^2)
A_b	bubbling or perforated area of the tray (m^2)
b	slope of the VLE line (–)
$C_{in}(t)$	time-dependent tracer concentration at the tray (or WMS) inlet (mol/m^3)
$C_{out}(t)$	time-dependent tracer concentration at the tray (or WMS) outlet (mol/m^3)
$c(t)$	time-dependent tracer concentration (mol/m^3)
c_1, c_2	constants in Appendix B (–)
D	tray diameter (m)
D_E	eddy diffusion coefficient (m^2/s)
E_{ML}	liquid-side Murphree tray efficiency (–)
E_{MV}	vapor- or gas-side Murphree tray efficiency (–)
E_o	overall column efficiency (–)
E_{OG}	vapor- or gas-side point efficiency (–)
$f(t)$	residence time distribution function (s^{-1})
G	gas flow rate (kmol/s)
G'	gas flow rate per tray bubbling area ($kmol/(m^2 \cdot s)$)
h_F	froth height (m)
k	number of channels in Stichlmair's model (–)
K	diffusion coefficient based on the size of the fluid element in the RTD model ($kmol/(m^3 \cdot s)$)
L	liquid flow rate (kmol/s)
L'	liquid flow rate per unit weir length ($kmol/(m \cdot s)$)
m	tray number (–)
N_{ac}	actual number of trays in the column (–)
N_{eq}	number of equilibrium stages in the column (–)
n	number of pools in the flow direction (–)
$\dot{n}$	dimensionless distance normal to the column wall (–)
Pe	Péclet number ($= Z_1^2/(D_E \cdot \tau)$) (–)
$\dot{Pe}$	Péclet number denoting the three-dimensional eddy mixing (–)
p	arbitrary point on the tray (–)
Q	volumetric flow rate of liquid (m^3/s)
Q_L	volumetric flow rate of liquid per tray width (m^2/s)
q_s	normalized slip velocity at the wall (–)
$q(\xi)$	normalized velocity profile function (–)
$R(t)$	response function (s^{-1})
r_1, r_2	roots of the differential equation in Appendix B (–)
s	non-dimensional distance in the flow direction from the inlet weir (–)
T	parameter used in Appendix A (–)
t	time (s)
U	parameter used in Appendix A (–)
V_f	average froth velocity (m/s)
V_G	gas velocity (m/s)
W	weir length (m)
w	distance from the tray centerline perpendicular to the flow direction (m)
w'	normalized distance from the tray centerline perpendicular to the flow direction ($= w/D$) (–)
X	parameter used in Appendix B (–)
x	composition (mole fraction) of the volatile component in the liquid phase (–)
x'	composition (mole fraction) of the volatile component in the liquid phase in the side mixers (–)
x_e^*	liquid composition in equilibrium with the incoming vapor (–)
x_m	composition of liquid leaving the tray (–)
x_{+m}	liquid composition at the inlet weir (–)
x_{m1}	liquid composition at the inlet of the retrograde flow zone (–)
x_{m2}	mixing cup average composition of liquid leaving the retrograde flow zone (–)
x_m^*	liquid composition in equilibrium with vapor leaving the tray (–)
x_{m-1}	composition of liquid entering the tray (–)
$\bar{x}(z)$	space mean composition of liquid at point z (–)
y	composition (mole fraction) of the volatile component in the vapor phase (–)
y'	composition (mole fraction) of the volatile component in the vapor phase in the side mixers (–)
y_m	composition of vapor leaving the tray (–)
y_m^*	composition of vapor in equilibrium with liquid leaving the tray (–)
y_{in}	composition of vapor entering the tray (–)
y_p	composition of vapor at point p on the tray (–)
y_p^*	composition of vapor in equilibrium with liquid at point p on the tray (–)
y_2	composition of vapor leaving the froth element in the AIChE model (–)
Z_1	flow path length (m)
z	distance from inlet weir in the flow direction (m)
z'	normalized distance from inlet weir in the flow direction ($= z/D$) (–)

Subscripts

a	active region on the tray
d	stagnant or dead region on the tray
f	froth
h	hydraulic
i	channel index in the multi-channel plug flow model, index for main line mixers in the pool cascade model
in	inlet
j	index for pools and side mixers in the mixed stages model and the pool cascade model, respectively
m	m^{th} tray
$mean$	mean or average
w	w-direction
z	z-direction

Superscript

$*$	Equilibrium

Greek letters

β	fraction of liquid that circulates between main line mixer and side mixer (–)
β_o	empirical fitting parameter in the pool cascade model (–)
γ	parameter used in the plug flow model called as similarity ratio, i.e. the ratio of the difference between the vapor composition at any point on the tray and its outlet, on two adjacent trays (–)
δ	central tray area with forward flow per total tray area (–)
η	parameter used in the AIChE model (–)
θ	non-dimensional time ($= t/\tau$) (–)
λ	stripping factor (–)
ξ	non-dimensional distance from the tray centerline orthogonal to the flow direction (–)
ρ_L	clear liquid density ($kmol/m^3$)
ρ_F	froth density (= volume of liquid/froth volume) (–)
σ^2	variance of the RTD function (s^2)
τ	mean residence time of liquid on the tray (s)
τ_h	hydraulic or space time (= volume of the system/volumetric flow rate) (s)
ϕ_a	relative area of the active region in the pool cascade model (–)