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Using an internally heat-integrated distillation column for ethanol–water separation for fuel applications

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ABSTRACT

Distillation is widely used as a key process to concentrate ethanol from fermented broth in the Brazilian sugarcane industry. In this study, Aspen Plus® was used to compare the energy demand for a heat-integrated distillation column (HIDiC) both with and without heat panels with the energy demand for a conventional distillation column for a separation process that could be applied to the Brazilian bioethanol market. The overall convective heat transfer coefficient, area, and other parameter values were calculated and combined with the HIDiC simulation. The reboiler duty results showed that by assuming a fixed fraction of the fluids exchanged energy at the panels, energy savings of 77% were possible with the HIDiC column compared to the energy requirements of a conventional column. This approach also allowed a stage-by-stage calculation of the overall heat transfer coefficient instead of assuming a constant value.

1. Introduction

The instability of the oil price, the increasing greenhouse effect (global warming), and particularly, the finiteness of fossil fuels (oil, natural gas, and coal) have been fueling the search and production of renewable energy worldwide (Durre et al., 2013). Biofuels have been presented as an important option to overcome the problem of the depletion of fossil fuels. Among all biofuels currently in production across the world, ethanol from sugarcane is the most commercially successful, mainly because it has one of the lowest prices of production (Goldemberg, 2009; Macedo, 2007). In addition to this, Brazilian ethanol that uses sugarcane as raw material represents one of the most effective biofuels in terms of its capability to reduce CO_2 emissions (Macedo, 2007). The United States and Brazil are the world's largest producers of bioethanol, accounting for 87% of global biofuel production between them. Currently, Brazil is the largest global exporter and the second largest producer of fuel ethanol, producing approximately 30 billion liters per year (2008) (Bajpai, 2013).

The ethanol distillation process in Brazil is driven by steam produced by boilers, which are fueled by the combustion of sugarcane bagasse, to heat and concentrate the sugarcane juice and to separate the ethanol from the fermented broth. Besides of the ethanol case, distillation is a widely used separation process operation, mostly used in the chemical industry where it separates approximately 95% of all fluid mixtures (Humphrey and Siebert, 1992). According to various estimates, the energy requirement of most refining and chemical processes is consumed by distillation columns (Gadalla, 2009). Despite its wide use, distillation is known for its low thermodynamic efficiency (Huang et al., 2006), with the overall thermodynamic efficiency of a conventional distillation process in the range 5–20% (Humphrey et al., 1991; Jana, 2010).

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Nomenclature

A	available area for heatexchange (m^2)
A_1	Alhusseini equation constant (dimensionless)
A_2	Alhusseini parameter dependent on Reynolds number (dimensionless)
A_3	Alhusseini parameter dependent on Reynolds number (dimensionless)
B	Alhusseini parameter dependent on Reynolds and Kapitza numbers (dimensionless)
C_t	Alhusseini parameter dependent on Reynolds number (dimensionless)
g	gravitational constant ($m\,s^2$)
$\bar{h}_{int}$	convective heat transfer coefficient into rectifying section ($W\,m^{-2}\,K$)
$\bar{h}_{ext}$	convective heat transfer coefficient into stripping section ($W\,m^{-2}\,K$)
$\bar{h}_L$	convective heat transfer coefficient to falling film ($W\,m^{-2}\,K$)
$\bar{h}_{turbulent}$	convective heat transfer coefficient to falling film ($W\,m^{-2}\,K$)
k_L	thermal conductivity of liquid ($W\,m^{-1}\,K$)
K	thermal conductivity of the material ($W\,m^{-2}\,K^{-1}$)
Ka	Kapitza number (dimensionless)
Pr	Prandtl number (dimensionless)
Pr_L	Prandtl number for condensed liquid (dimensionless)
Q	heat load (kW)
$Q_{overall}$	total energy expended (kW)
$Q_{reb.}$	reboiler duty (kW)
$Q_{comp.}$	compressor duty (kW)
Re	Reynolds number (dimensionless)
Re_L	Reynolds number for condensed liquid (dimensionless)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
δ^+	Alhusseini parameter dependent on Reynolds number (dimensionless)
e	Thickness of the material (m)
ΔT_{stages}	temperature difference between stages (K)
T_R	rectifying temperature (K)
T_S	stripping temperature in a thermally coupled stage (K)

Low thermodynamic efficiency is directly related to the substantial energy wastage observed in the distillation process, which occurs due to large differences between reboiler and condenser temperatures. Furthermore, the thermal energy recovered at the condenser cannot be used to heat other flows in the same distillation column. These facts have prompted several studies that have resulted in new design configurations, such as direct vapor recompression (VRC) (Cambell et al., 2008; Olujic et al., 2006, 2008), diabatic distillation (LeGoff et al., 1992; Rivero, 2001), the multieffect column (Finelt, 1979; Emtir et al., 2001; Engelien and Skogestad, 2004) and the internally heat-integrated distillation column (HIDiC).

Energy savings are observed in all of the alternative designs mentioned, but often at the cost of product purity, which creates an economic barrier to implementation as energy use and product recovery must be balanced. It has been shown experimentally that the HIDiC configuration offers savings greater than those on a conventional alternative operation and also that HIDiC can increase the product recovery (Cambell et al., 2008).

Most simulation study with HIDiC, to validate experimental data or theoretically study different compound mixtures, is conducted using commercial simulation packages, such as ASPEN PLUS® and HYSYS®. In these, a generic approach to HIDiC is taken by creating an arrangement of calculation blocks.

Binary close-boiling mixtures and steady-state simulations are the main focus of numerous relevant studies (Nakaiwa et al., 2003; Olujic et al., 2006; De Rijke, 2007; Gadalla, 2009; Suphanit, 2010). Multicomponent distillation is well presented by Hourichi et al. (2006) and Iwakabe et al. (2006). Recently, Kim (2011) used HYSYS® to report a new design of HIDiC for a hydrocarbon mixture by using three columns with system heat integration.

Although research into HIDiCs has reached the stage of industrial-scale testing, only a few design methodologies have been developed, with this field not yet clearly established (Olujic et al., 2006).

Detailed methodologies to conduct simulations of HIDiC processes have been reported by Gadalla (2009), Suphanit (2010), and Hugill and Van Dorst (2005). Gadalla (2009) showed all of the hierarchy steps for a HIDiC procedure using a commercial software simulation process and also included a thermodynamic feasibility and area calculation step (initially presented in Gadalla et al., 2007). Suphanit (2010) intensified studies in the heat exchange procedure in Aspen Plus® using Radfrac® columns and highlighted important details that were of use in the present study. The heat exchange correlations coupled with HIDiC simulation were first presented by Hugill and Van Dorst (2005), which were based on correlations in the literature that were used to represent the heat exchange in hydrocanbons falling film systems.

Kaeser and Pritchard (2005) conducted heat exchange studies in diabatic columns with sieve trays to experimentally estimate the overall heat transfer coefficient. That study focused on horizontal heating and cooling for a methanol–water mixture, which is different to our present study on falling films. The results of the overall heat transfer coefficient were in the range 2.2–4 kW.

In the current study, a HIDiC was proposed to concentrate ethanol–water mixture to 92.6 wt% ethanol, as the product that is marketed as hydrated ethyl alcohol fuel (HEAF) or hydrous ethanol fuel which is used in flex-fuel vehicles launched in Brazilian market in 2003. Simulations were not performed to achieve dehydrated ethanol concentrations (>99, 1 wt%) in this study. This was mostly because contemporary technologies, such as adsorption with molecular sieves, with lower energy requirement are already replacing azeotropic and extractive distillation to produce dehydrated ethanol (Kiss and Suszwalak, 2012).

The design procedure of proposed HIDiC was explored and the performance comparison with the conventional distillation was conducted in terms of energy requirement. Also, a new approach to the prediction of the heat exchange behavior in HIDiC simulation was carried out without knowing an experimental estimate of the overall heat exchange coefficient value.

To calculate the heat exchange in HIDiC a spreadsheet with an overall heat transfer coefficient calculation, area, and other parameter values were combined with Aspen simulations to achieve suitable simulations results. The inclusion of