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Research paper

Performance investigation of vapour recompressed batch distillation for separating ternary wide boiling constituents☆

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ABSTRACT

The vapour recompression scheme (VRC) has been very effective in continuous distillation for energy intensification. The applicability of this scheme for the separation of multicomponent wide boiling constituents in batch distillation is a major challenge, because of the unsteady nature of the batch. In this study, the vapour recompression scheme has been implemented for the separation of multicomponent wide boiling constituents in the batch distillation. For the optimal usage of energy from compressed vapours manipulation of top tray vapour or external energy is done. A comparative study of the vapour recompressed batch distillation having a variable speed single compressor (SVRBD) and double stage compressor (DVRBD) with conventional batch distillation in terms of energy savings and total annualized cost is done. The VRC schemes achieve an energy savings of 50% and 10.03% total annualized cost (TAC) for SVRBD and DVRBD achieve 52% energy savings and 12.21% TAC with a payback period of 10 years.

1. Introduction

The overexploitation of fossil fuels has enhanced the concentration of greenhouse gases in the atmosphere. It has increased the natural greenhouse effect, global warming. Its adverse effects are melting of glaciers, rise in sea levels, changes in patterns and amount of precipitations, droughts, floods, epidemics, malignancy, etc. This demands an urgent need for reduction in usage of fossil fuels.

Distillation is one of the major separation technology used in chemical and allied industries. It consumes an estimate of 60% of energy in chemical industries [1]. The thermodynamic efficiency of conventional distillation is very low around 5–20% [2]. Since distillation is an energy consumer of fossil fuels, the need for energy intensification of the process is severe. To improve the energy efficiency of distillation processes, several energy integration techniques have been proposed.

Coupling of condenser and reboiler using a heat pump is an effective method for energy intensification of distillation. The most frequently used heat pumps for distillation columns are electrically driven vapour recompression types. They include the direct vapour recompression, closed cycle heat pump and bottom flashing. In the direct vapour recompression column (VRC), the overhead vapour is compressed in a compressor and then it is used as an internal source of energy in liquid reboiling. In the closed cycle heat pump, an external refrigerant is used to facilitate the energy transfer between the top vapour stream and the bottom liquid stream. In bottom flashing, the bottoms product is expanded and used as a coolant in the condenser, where after it is compressed and returned to the column. Among these three heat pumping arrangements, VRC is the most popular and commonly used configuration and is suitable for close boiling constituents [3].

Since 1960 s, the application of vapour recompression heat pump system is observed in continuous columns [4–6] because of its ability to greatly improve the energy and economic performance of the system. The use of this heat pumping system in batch column, unlike the continuous distillation, is not so straightforward mainly because of unsteady state nature of the batch processing.

Batch processing has continued to be an important technology owing to the operational flexibility that it offers. This operational flexibility of batch distillation processes makes them particularly suitable for smaller, multiproduct or multipurpose operations. Manufacturing in the pharmaceutical and specialty fine chemical industries are examples of small, multiproduct operations, where products are typically required in small volumes, and subject to

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Nomenclature

L_1	Flow rate of liquid leaving 1st tray,
V_B	Vapour boil-up rate and
V_{n_T}	Overhead vapour rate
C	Total number of components,
D	Distillate rate,
H_n^L	Enthalpy of a liquid stream leaving nth tray,
H_n^V	Enthalpy of a vapour stream leaving nth tray,
$k_{n,j}$	Vapour-liquid equilibrium coefficient with respect to nth tray and jth

Component

L_n	Flow rate of a liquid stream leaving nth tray,
m_n	Liquid holdup on nth tray,
$P_{n,j}^0$	Vapour pressure of component j in nth tray,
P_T	Total pressure,
Q_R	Reboiler duty,
R	Reflux rate,
V_n	Flow rate of a vapour stream leaving nth tray,
$x_{n,j}$	Mole fraction of component j in a liquid stream leaving nth tray,
$y_{n,j}$	Mole fraction of component j in a vapour stream leaving nth tray
$\gamma_{n,j}$	Activity coefficient of component j in nth tray.

short product cycles and fluctuating demand. The thermodynamic disadvantage of batch distillation over continuous fractionation, which results in lower energy efficiency, has long been known.

The first configured thermally integrated batch distillation scheme consisted of a rectification tower surrounded by a jacketed reboiler (or still pot) [7]. The advantages of this internally heat integrated scheme was systematized and clarified through numerical simulations after a decade [8]. Even though the capital cost is higher compared to conventional batch distillation (CBD), it achieves a total annualized savings of 27.93% in 1.38 years payback period. A VRBD scheme which is a combination of internally heat integrated distillation with concentric reboiler (IHIBDCR) and VRC for the separation of wide boiling constituents was developed [9]. The scheme was illustrated using binary wide boiling constituents of methanol and water features the advantages of (IHIBDCR) and the hybrid scheme in reducing operating costs. The impacts of heat integration by performance indicators such as energy consumption, total annualized cost and CO_2 emissions was studied and simulated using a binary mixture of benzene and toluene [10]. The three parameters were compared with the CBD. The proposed VRBD secured significant reduction in the performance indicators. The investigation of vapour recompression scheme in batch distillation in separation of binary wide boiling constituents (acetone/water) found 68.89% reduction in energy use and around a 67.58% reduction in operating cost [11].

Few papers have been published on application of vapour recompression in batch distillation (VRBD) with close boiling constituents [12–16]. The traditional vapour recompressed continuous distillation is not an economically attractive option for wide boiling constituents. In this paper vapour recompression technique in batch distillation is explored for the separating of ternary wide boiling constituents in terms of energy and cost savings.

In the present work, introduce the vapor recompression technique in a batch distillation column. The proposed VRBD arrangement consists an isentropic compressor that runs at a fixed as well as variable speed. It is noticing the variable speed VRBD additionally involves the manipulation of compression ratio (CR). The Objective is to ensure the optimal use of internal heat energy, an open-loop control policy is proposed for the VRBD that adjusts either the heat supply from external source to the reboier or top vapor splitting. Developing two alternative configurations of the VRBD column, i.e., Variable speed Single stage compressor (SVRBD) and Variable speed Double stage compressor (DVRBD) to identify the best heat integrated scheme in terms of energy and total annualized cost (TAC) savings.

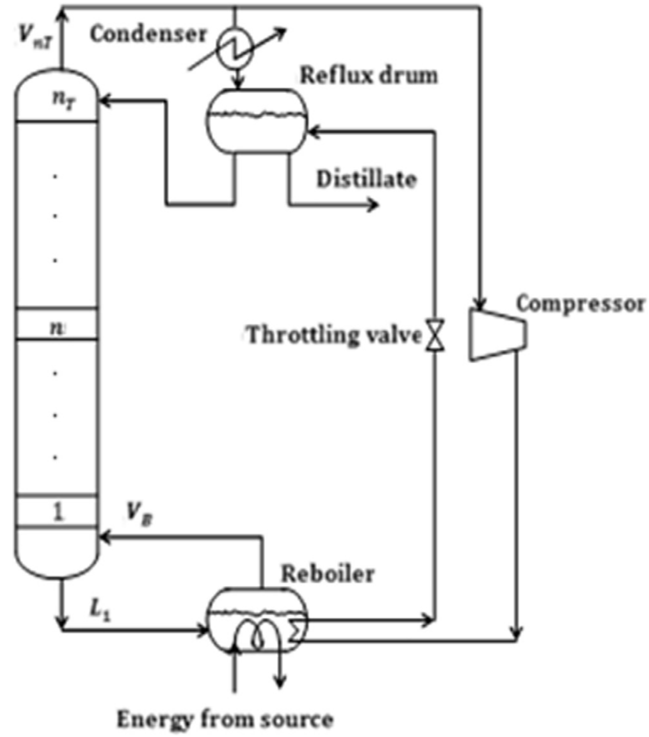

Fig 1. Schematic representation of Single Stage Vapour Recompressed Batch Distillation (SVRBD).

2. Principle and configurations of vapour recompressed batch distillation

The conventional batch column that consists of a rectification tower consists of reboiler at the bottom and total condenser at the top. The trays are numbered from bottom-up, indicating the bottom tray as the 1st Stage and the topmost tray as the n_Tth Stage. The batch operation in a distillation column operated in two phases, the startup phase and the production phase [17].

The SVRBD consists of electrically driven Single stage Variable speed compressor and a throttling valve [15]. Schematic representation of SVRBD is shown in Fig 1. In SVRBD, vapour leaving the top tray of the column is compressed to a desired pressure using a single stage isentropic compressor The work done by the compressor is an energy expense. In order to reduce it, instead of a single stage compressor, a double stage compressor is used to make a Double stage vapour recompressed batch distillation (DVRBD). Compression at high temperature with energy expense causes evaporation of lubricating oil and thereby increasing wear and tear in the compressor. In order to prevent that double stage compressor is used. DVRBD consists of two electrically driven Variable speed compressors, an intercooler and a throttling valve. Intercooler cools down vapour to low temperature. It cools down the compressed vapour from first compressor to the inlet temperature of the first compressor without any pressure drop and supplies vapour to the second compressor. The intercooler is assumed as ideal one. Intercooling helps to reduce the work done by the