Applied Thermal Engineering 59 (2013) 405–413

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

A novel combination of internal and external heat integrations in batch distillation: Application to a reactive system

Debadrita Maiti, Amiya K. Jana*

Energy and Process Engineering Laboratory, Department of Chemical Engineering, Indian Institute of Technology, Kharagpur 721 302, India

HIGHLIGHTS

- We develop an internally energy integrated batch distillation.
- Vapor recompression scheme is further introduced to boost thermal efficiency.
- The hybrid mechanism is illustrated by a batch reactive distillation.

ARTICLE INFO

Article history:
Received 20 January 2013
Accepted 24 May 2013
Available online 4 June 2013

Keywords:
Heat integration
Batch distillation
Internal and external coupling
Energy
Economics

ABSTRACT

Studies on the thermal integration of batch rectifier have received almost no attention, although it is well-known for continuous distillation since the 1960s. In this contribution, we aim to develop an energy integration approach for batch distillation columns by thermally coupling the rectification tower with the concentric reboiler that surrounds the tower as a jackted. In this internally heat integrated batch distillation with a jacketed reboiler (IHIBDJR), the vapor produced in the concentric reboiler is compressed and then it enters the bottom of the rectifier. With the judicious use of internal heat source, the proposed IHIBDJR shows its attractiveness in terms of energy savings and payback time of excess capital. The pressure elevation from the jacketed reboiler to rectifying section generates a possibility of further intensification through the introduction of direct vapor recompression mechanism in the IHIBDJR. This novel combination of internal and external heat integrations can utilize the latent heat, an additional internal source, released by the compressed overhead vapor in vaporizing the reboiler liquid. After deriving the general form of this combined heat integrated structure, the mechanism is finally illustrated by a batch reactive distillation. This hybrid configuration shows promising energetic and economic potential over the IHIBDJR and its conventional counterpart.

1. Introduction

The steady increase of fossil fuel prices and the uncertainties of their long-term availability, along with the environmental alarm owing to the greenhouse gas emissions, have promoted research work on the improvement of process energy efficiency. It is well-known that the distillation, which is the workhorse of chemical process industries, is an energy intensive but not an energy efficient process. For the purpose of enhancing the thermodynamic efficiency, heat integration appears to be the most effective method and has already found wide applications in continuous distillation columns [1,2].

Broadly speaking, there are two ways to intensify the distillation processes. One is the external energy integration that includes the vapor recompression column (VRC) [e.g. Refs. [3–6]]. The other one classified as internal energy integration includes the internally heat integrated distillation column (HIDiC) [e.g. Refs. [7–15]] and the divided-wall column (DWC) [e.g. Refs. [16–21]]. The distillation assisted by a heat pump of the vapor recompression type is a well established technology and it is an economic way to conserve energy particularly when the temperature difference between the overhead and bottom of the column is small and the head load is high [6,22]. The Petlyuk column or DWC is already implemented in industry with 100 units all over the world [21]. On the other hand, the final phase of testing on HIDiC is going on in Japan and in the Netherlands [23]. Interestingly, all the aforementioned thermally coupled schemes are devised for continuous distillation systems. Therefore, we have undertaken this research project to explore the possibility of energy intensification in batch distillation columns.

A remarkable shift toward batch distillation technology has been noticed during the last two decades because of the exponential

* Corresponding author.
E-mail address: akjana@che.iitkgp.ernet.in (A.K. Jana).

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http://dx.doi.org/10.1016/j.applthermaleng.2013.05.039

growth of the fine-chemical, food and pharmaceutical industries. The operational flexibility of batch rectifiers makes them particularly suitable for smaller amounts of products with high added value, multi-product or multi-purpose operations. However, the batch distillation has long been known as a highly energy inefficient process, even compared to its continuous counterpart.

Takamatsu et al. [24] configure a thermally coupled scheme first time for a batch rectifier and after a long gap, Jana and his co-workers [25] have evaluated the energy saving and economical potentials of that internally heat integrated structure. Recently, an externally energy integrated batch rectifier is introduced by the same research group [26] showing sharp reduction in operating expenses and total annualized cost (TAC). Till now, only a little research work has been reported on the thermal coupling in batch distillation, so this area is only beginning to be explored.

For boosting further the thermodynamic and economic performance, this work proposes a novel combination of internal and external heat integrations introducing direct vapor recompression approach in the internally heat integrated batch distillation with a jacketed reboiler (IHIBDJR). In order to illustrate this hybrid VRC–IHIBDJR mechanism, a multicomponent batch distillation with esterification reaction is taken as a representative process. To our knowledge, no such heat integrated structure is reported in literature.

2. Conventional batch distillation (CBD)

A conventional batch column consists of a rectification tower equipped with a reboiler (or still) at the bottom along with an overhead condenser. The batch distillation is inherently an unsteady state process and operated in two consecutive phases: startup phase (close operation mode) and production phase (open operation mode). Initially, the feed mixture is charged in the large reboiler, on the trays and in the reflux drum. The column starts running in close operation mode under total reflux condition, i.e. no distillate is withdrawn from the top. During this startup phase, the concentration of the lightest component in the reflux accumulator gradually increases until it reaches the steady state. In the subsequent stage (i.e. production phase), the column is operated in open mode and the product is collected under partial reflux condition. Note that we can start product withdrawal as soon as the lightest component met the composition specification, without waiting for the steady state to be attained. For brevity, more details of batch distillation, including the mathematical model and computer simulation, are not included here and available elsewhere [27].

As stated, the batch distillation provides operational flexibility and involves less capital investment than its continuous counterpart. In contrast, the batch scheme is relatively less energy efficient. Keeping this issue in mind, the present work attempts to improve the thermodynamic performance of the batch rectifiers through energy intensification route. The reduction of energy consumption leads not only to a more efficient and economical process but it also participates toward a cleaner environment by minimizing flue gas emissions.

3. Internally heat integrated batch distillation with a jacketed reboiler (IHIBDJR)

3.1. Principle and configuration

The schematic representation of a typical IHIBDJR structure is shown in Fig. 1. As can be seen, the rectification tower is surrounded with a concentric reboiler and the overhead condenser is placed, as usual, at the top. To accomplish internal heat transfer from the rectifying section to the reboiler, the rectifier is operated at a higher pressure (i.e. a higher temperature) than the still. For this, the vapor produced in the still is compressed and then it enters the bottom of the rectifier. This mechanism leads to the transfer of heat through the common wall by an indirect contact of the rectifying hot vapor stream with the reboiler liquid. As a consequence, continuous condensation of the vapor phase takes place along the rectifier and continuous evaporation, i.e. vapor generation, occurs in the reboiler.

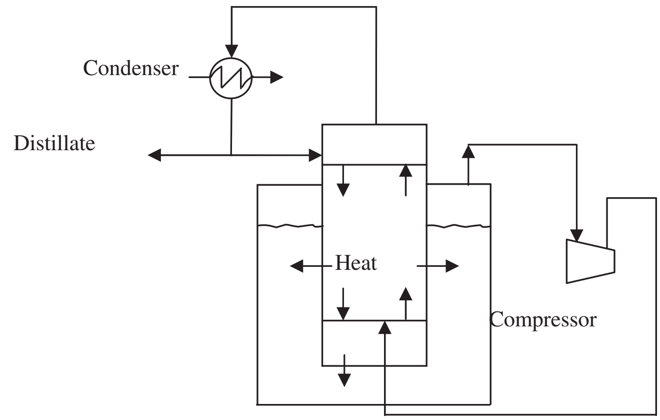

Fig. 1. The IHIBDJR scheme.

It is clear that this energy integration leads to the reduction of condenser and reboiler heat loads but at the expense of additional compressor duty. We are aware that the electricity for driving the compressor is several times more expensive than the thermal utility. Therefore, here we aim to develop a thermally coupled IHIBDJC scheme that should properly utilize the internal heat so that the overall performance is improved in terms of energy consumption and cost.

3.2. Mathematical model

The key assumptions adopted for introducing the energy integration in a batch distillation are:

- Internal heat transfer is estimated by $UA\Delta T$, where U is the overall heat transfer coefficient (kJ/hr.m^2.K), A the heat transfer area (m^2) and ΔT the temperature difference (K) between the coupled tray and jacketed still.
- The liquid feed occupies 70% volume of the still pot, which corresponds to a certain height in the rectifier, and remaining 30% is left for the vapor disengagement.
- In the jacketed reboiler, naturally the vapor phase is present just above the liquid phase. In comparison to the liquid phase, the vapor phase leads to an insignificant overall heat transfer coefficient. Hence, we neglect the internal heat transfer from the hot rectifier to the reboiled vapor.

As time progresses, the liquid height in the jacketed reboiler decreases and this happens because of the continuous vapor generation. Accordingly, the heat transfer area decreases and this, in turn, affects the rate of internal heat transfer.

In order to represent the heat integration, we develop the model of IHIBDJR in the following form.

3.2.1. Internal heat transfer through the common wall

The heat transfer from the high pressure rectifier to low pressure reboiler is calculated by using:

$$Q_N = UA_N(T_N - T_B) \quad (1)$$

Here, T represents the temperature (K), and Q the rate of internal heat transfer (kJ/hr). Subscripts N and B denote the Nth tray and reboiler, respectively.