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Advances in heat pump assisted distillation column: A review

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ABSTRACT

Progressive depletion of conventional fossil fuels with increasing energy demand and federal laws on environmental emissions have stimulated intensive research in improving energy efficiency of the existing fractionation units. In this light, the heat pump assisted distillation (HPAD) scheme has emerged as an attractive separation technology with great potential for energy saving. This paper aims at providing a state-of-the-art assessment of the research work carried out so far on heat pumping systems and identifies future challenges in this respect. At first, the HPAD technology is introduced with its past progresses that have centered upon column configuration, modeling, design and optimization, economic feasibility and experimental verification for steady state operation. Then the focus is turned to review the progress of a few emerging heat integration approaches that leads to motivate the researchers for further advancement of the HPAD scheme. Presenting the recently developed hybrid HPAD based heat integrated distillation configurations, the feasibility of heat pumping in batch processing is discussed. Finally the work highlights the opportunities and future challenges of the potential methodology.

1. Introduction

There is a steep rise in global energy consumption mainly because of the increasing industrialization and motorization of the world. Fossil fuels meet 80 percent of our primary energy demands and they are responsible for the major production of greenhouse gases, leading to a number of negative effects, such as climate change, receding of glaciers, rise in sea level and loss of biodiversity [1]. Increasing energy consumption, negative growth of fossil resources and greenhouse gas emissions have led to a move towards the improvement of thermodynamic efficiency of the well established processes, along with the development of new energy efficient and cost-effective process technology.

Distillation is the most mature and widely used separation process in the chemical and allied industries, accounting for 95% of all separations in chemical process industries [2], and for an estimated 10% of the US industrial energy consumption [3]. Furthermore, it is reported [4] that 40% of the energy used by a chemical plant is for distillation alone. Because of low thermodynamic efficiency, which is typically in the range of 5 to 20%, and high energy consumption, the distillation has become a potential candidate for thermal intensification.

After the oil crises in the 1970s, the interest in thermal intensification appears to have been resurrected. In separation processes, the major energy costs are associated with compressors, reboilers and condensers cooled with refrigerant. Proposing thermal integration in fractionation units leads to additional equipment costs that are more than offset savings in utility costs. However, because of increasing utility costs at a faster rate than equipment costs, along with the environmental alarm due to the greenhouse gas emissions, the heat integration approach has received considerable research attention in literature and appears to be economically feasible for distillation processes.

Among various heat integrated distillation techniques, the heat pumping system has emerged as one of the widely accepted schemes for continuous flow distillation columns. In fact, practical studies have shown the potential of this strategy to drastically reduce the net energy consumption and hence emissions of greenhouse gases. However, continuous efforts need to be devoted to make the heat pump assisted distillation (HPAD) scheme more attractive compared to its close competitors. Although a considerable progress on heat pumping systems is noticed for continuous flow operations, there is almost no research attention paid for batch processing. It is fairly true that the unsteady state behavior of the batch operation makes the heat integration more challenging. The objective of this article is to present the recent developments in the field of heat pump assisted distillation technology, particularly vapor recompression column (VRC) and its hybrid configurations, and to identify uncovered gaps in this respect.

2. Heat pump assisted distillation (HPAD) columns

As the cost of energy continues to rise, it becomes imperative to improve overall energy performance of the chemical process units. With this objective, various energy integration techniques for

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distillation columns have been explored so far seeking lower energy consumption and better profitability. Heat pump assisted distillation (HPAD) column is one of the most promising alternatives for the conventional distillation column (CDiC) since HPAD has the potential to separate a mixture with smaller energy consumption compared to CDiC.

In a conventional distillation column, the heat is supplied at the bottom reboiler by a hot utility and that is wasted to a cold utility at the overhead condenser, thus causing a substantial energy degradation. An obvious way to reduce the energy consumption is to couple the condenser and the reboiler which represent the major source and sink of energy, respectively. In this light, the integration between a heat pump and the distillation column is well-known as an attractive terminology.

The heat pumping systems, which can be operated in conjunction with the distillation columns, can be conveniently lumped into two categories: mechanical heat pump and absorption heat pump. In the mechanical heat pumps, instead of using a separate overhead condenser and bottom reboiler, the vapor stream leaving the top tray is compressed to a higher pressure and then used to heat the bottom liquid, or the liquid stream leaving the bottom tray is flashed in a pressure reducing valve and then used to cool the overhead vapor. On the other hand, the later scheme uses a separate closed loop fluid system to transfer the heat up the temperature scale by means of heat of mixing. In this article, at first, selected works on both of these heat pump assisted distillation columns and their impact on energy efficiency as well as cost are reviewed. Subsequently, we turn our special attention on the recent developments of mechanically heat pump assisted VRC scheme for finding the further research possibilities.

It should be pointed out here that the energetic and economic performances are somewhat case specific and therefore the percent savings shown throughout this paper for several example systems are intended to indicate trends rather than precise figures.

2.1. Absorption heat pump assisted distillation column

The first absorption heat pump machine was made by the LeCarre brothers in 1859 [5]. A historical review of this heat pump system dating back to the work of Nairne in 1777 is presented by Stephan [6]. Recently, Chua et al. [7] have provided a comprehensive update on recent developments in heat pump machines.

As illustrated in Fig. 1, a typical absorption heat pump includes four main components, namely absorber, desorber (usually called generator), evaporator and condenser. In the working fluid loop, the generator heats up the solution at high pressure and temperature, releasing vapor to the condenser. Subsequently, the condensate goes to the evaporator, in which, it evaporates using low temperature heat and then it is absorbed in the absorption column. Obviously, the system receives heat in the generator and the evaporator, and rejects heat in the condenser and the absorber. The rich solution is pumped from the absorber to the generator, where the cycle starts again. In a typical heat pump system, the pressure elevation and the corresponding higher boiling point of the working fluid are effected by an absorber, a generator and an additional fluid loop (absorbent loop) between these units.

Fonyo et al. [8] have evaluated six different variants of the heat pumping system with reference to the base case column with isomerization reactor. These six schemes include: three forms of mechanical heat pump system (vapor recompression, bottom flashing and closed cycle), and three modes of absorption heat pump system (single stage with parallel and sequential operations, and double stage parallel operation). It should be noted that the bottom liquid is boiled up with the use of heat exchangers arranged either in series (sequential operation) or parallel (parallel operation) mode. For the case of C_4 splitter, it is reported [8] that the lowest cost is reached by using the double stage scheme, although its operation is far more difficult. Heat pump assisted distillation research is also extended to absorption heat transformer (AHT) [9,10], the reverse operation of the absorption heat pump. In the transformer (Fig. 2), the absorber and evaporator operate at higher pressure, whereas the condenser at the lowest pressure. Tufano [10] has shown that the parallel heat pump – transformer allows one to exactly match the heat loads of most distillation columns and to reduce the consumption of primary energy by about 40%. A systematic comparison is also presented by Fonyo and Benko [11] between the different variants of the absorption and mechanical heat pumps with the transformer arrangement. For a C_4 splitter, their economic evaluations show that the AHT is the worst performer and the heat pump with sequential arrangement is the best one. For selecting a suitable scheme, however, a general guideline is proposed as: (1) larger heat load and smaller column temperature difference provide shorter payback time for heat pumping, and (2) the absorption heat transformation cycles have an even chance for implementation at larger temperature difference, when the other heat pump configurations are discarded. Ranade and Chao [12] have also detailed the guidelines for the use of different kinds of heat pumping arrangements. They have concluded that if the Carnot efficiency is taken into account, the vapor recompression approach is the most economical solution, but the simplest way of introducing a heat pump into an existing distillation unit is the closed cycle system with working fluid. However, it is fairly true to say that the performance of the heat pumps is mostly case specific.

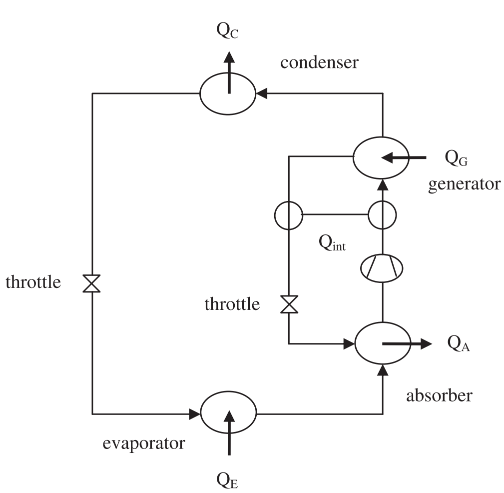

Fig. 1. A typical absorption heat pump arrangement.

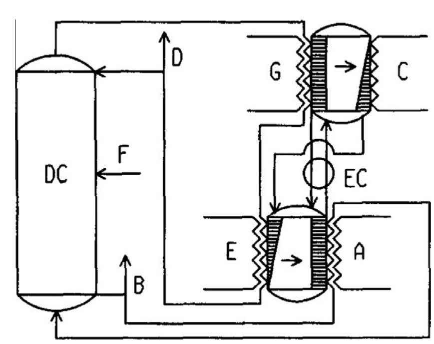

Fig. 2. Distillation column in conjunction with an absorption heat transformer [10] [A = absorber, B = bottoms, C = condenser, D = distillate, E = evaporator, EC = economizer, F = feed, G = generator].