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Recuperative vapor recompression heat pumps in cryogenic air separation processes

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ABSTRACT

Vapor recompression heat pumps are used in distillation processes to reduce energy consumption. For sub-ambient distillation, one of the largest difficulties is to produce liquid reflux since the condensation of highly volatile components requires expensive refrigeration energy. Thermally coupled distillation columns have been commonly applied to produce reflux in cryogenic air separation processes. In order to condense the nitrogen vapor for reflux by the oxygen liquid, all the air feed has been compressed to a pressure considerably above ambient pressure. In cases where the oxygen product does not have to be at elevated pressure, this causes unnecessary compression of the oxygen in the air feed. One such large scale application is oxy-combustion in coal based power plants. A scheme of recuperative vapor recompression heat pumps is developed to substitute the thermally coupled distillation columns, and this scheme is applied in cryogenic air separation processes in this paper. A portion of the vapor nitrogen is compressed and condensed for reflux, thus the mass flow through the compression stages is reduced. The power consumption has been significantly reduced compared to conventional double-column distillation cycles, and further reduced when the principle of distributed reboiling is applied to reduce irreversibilities in distillation columns.

1. Introduction

Distillation technology is commonly applied to separate mixtures of chemical components. In a distillation column, the descending liquid and ascending vapor are flowing in a counter current way. Heat and mass are transferred due to the differences in temperature and chemical potential between the liquid and vapor streams. The descending liquid is referred to as “reflux”, and is an important parameter related to the capital cost and operating cost of distillation processes. For above-ambient distillation, reflux is usually produced in a condenser where the top vapor product is partially or fully condensed by cooling water. However, the production of reflux is a considerable challenge for sub-ambient distillation, since low temperature cooling sources are not available in the environment, thus refrigeration cycles are generally applied to produce reflux in such distillation processes. The reflux represents expensive compression work (operating cost). The amount of reflux used in distillation processes can be reduced by using more distillation stages, thus the capital cost increases. Compared to above-ambient distillation processes, many more distillation stages are used in sub-ambient cases. In cryogenic air separation processes which separate air into oxygen and nitrogen, 70–150 theoretical stages in total are commonly used [1].

1.1. Heat pump distillation

From the viewpoint of exergy analysis, the chemical exergy will increase when a mixture of components is separated into more or less pure components [2]. A detailed classification of the various forms of exergy is discussed by many authors, among these Aspelund et al. [3]. For above-ambient distillation, heat (thermal exergy) is usually consumed and converted into chemical exergy of the substances; while in sub-ambient cases, work is used in refrigeration cycles and finally converted into chemical exergy. Work always has a higher quality than heat at above-ambient temperatures, thus work is normally not used in above-ambient distillation processes. One exception is the use of heat pump technology in distillation [4–6].

Fig. 1(a) shows a closed heat pump applied to a distillation column. The feed mixture is separated into two products: B (bottoms product) and D (distillate product). The temperature of the condensation heat is lifted by the heat pump and the resulting heat is used as heat source in the reboiler. Instead of using substances different from the distillation products as working fluid in a closed

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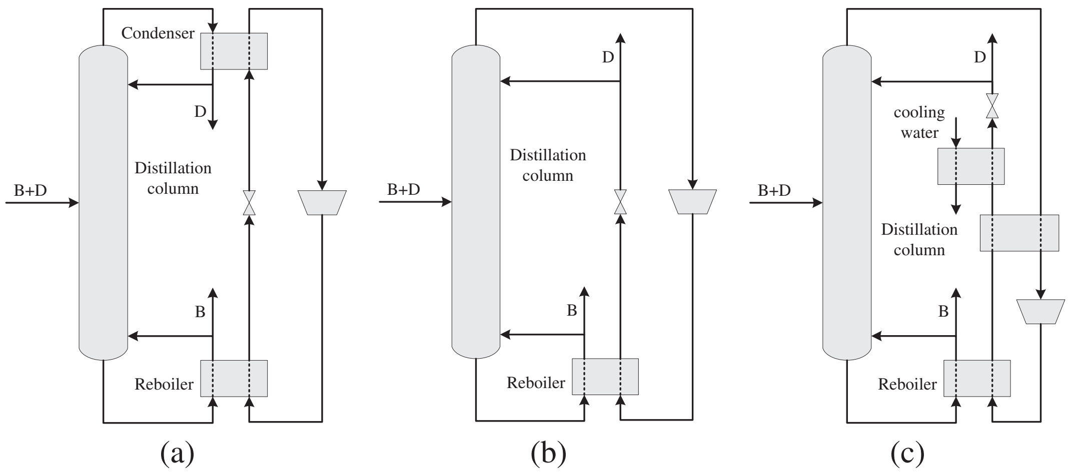

Fig. 1. Configurations of heat pumps: (a) closed heat pump; (b) vapor recompression heat pump; (c) vapor recompression heat pump with superheating.

heat pump, the products from the distillation column can be used as the working fluid. An example using the overhead vapor as the working fluid is shown in Fig. 1(b), resulting in an open heat pump solution known as vapor recompression. The overhead vapor is directly compressed and thereafter condensed in the reboiler before it is used as reflux. In some cases, in order to avoid condensation during compression, the overhead vapor is slightly superheated prior to compression [5], as shown in Fig. 1(c). In the drawings of Fig. 1(a–c), details such as reflux drums, pumps and trim coolers are not included in order to keep the flowsheets simple and thus focus on the main features. Compared to closed heat pumps, an obvious advantage of vapor recompression heat pumps is that heat transfer between the vapor product and the working fluid is avoided. Intermediate heat pumps (using heat sources and/or heat sinks with temperatures intermediate between the temperature of the distillate and the bottoms) can be used to reduce the irreversibilities of distillation columns [4,6]. Heat pump driven distillation is generally more profitable when the temperature difference between the top and bottom products is small [5]. The main advantage of using heat pumps in distillation is that the low temperature latent heat can be upgraded and utilized. Both the latent heat and sensible heat may be utilized in an efficient process design [7].

In sub-ambient distillation processes, heat pumping is commonly used in refrigeration cycles, e.g. in the cascade cycle of natural gas liquefaction [8]. For cryogenic distillation processes, several cascade cycles may be used to achieve a very low temperature, e.g. four cascade cycles in series are used to liquefy N_2 [8]. This process is thermodynamically efficient but difficult to operate due to its complexity. Thermally coupled distillation can be applied to substitute cascade cycles and produce the required reflux (liquefaction) in distillation processes. A typical thermally coupled distillation process at above-ambient temperature is shown in Fig. 2 [8,9]. The two distillation columns are operated at different pressures so that the overhead vapor product from the higher pressure (HP) column can be condensed by the bottom liquid from the lower pressure (LP) column. Instead of providing heat to both columns, steam is only consumed in the HP column.

Thermally coupled distillation can be regarded as a special type of heat pump. One example of sub-ambient application of thermally coupled distillation columns is the cryogenic cycle to recover carbon monoxide from syngas which is generated by steam reforming of natural gas or light oil [8]. In this process, the feed gas is compressed to around 2200–2800 kPa and partly condensed by the boiling methane liquid at around atmospheric pressure. Another well-known application of thermally coupled distillation is the cryogenic air separation process. An extensive review of cryogenic air separation processes is presented by Latimer [1].

1.2. Cryogenic air separation

Although various separation technologies have been developed for oxygen production, such as adsorption, membrane and water splitting, cryogenic distillation of air is the only commercially available technology for large scale industrial applications (up to 4200 tonnes/day O_2 production [10]). The first cryogenic air separation plant for O_2 production using a single column was developed by Linde in 1902, who also invented the double-column distillation system in 1910 [8]. The two processes are illustrated in Fig. 3 (the dashed lines refer to heat flow). In the single column cycle, the air feed is compressed and condensed by the boiling O_2 in the bottom of the distillation column. The O_2 recovery rate is very low since there is no rectification section (above the feed stage in a traditional distillation column). In the double-column distillation cycle, the two columns are operated at different pressures, termed as the HP column and the LP column. The overhead vapor (N_2) from the HP column is condensed by the boiling liquid (O_2) in the bottom of the LP column and then used as reflux for the two columns. Based on the double-column distillation cycle, various cryogenic air

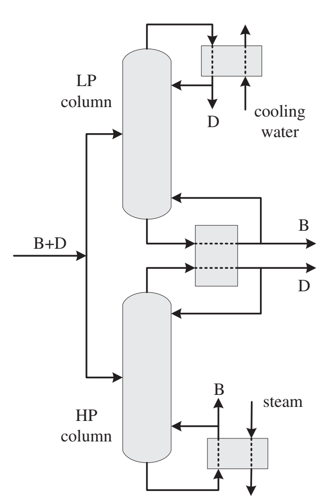

Fig. 2. Thermally coupled distillation.