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Control of a recuperative vapor- recompression air separation process

William L. Luyben

Department of Chemical Engineering, Lehigh University, Bethlehem, PA 18015, USA

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ABSTRACT

The use of oxy-combustion for producing furnace stack gases with low nitrogen and high carbon dioxide concentrations is a potential method for economical sequestration of green house gases. A conventional air separation unit to provide oxygen compresses all the air feed and operates with one of the two cryogenic distillation columns at elevated pressure so heat integration can be employed.

The use of recuperative vapor recompression has been recently proposed in which only a portion of a nitrogen stream is compressed to provide liquid reflux to two columns, which both operate at low pressure where the separation is easier. Steady-state designs have been developed and economically optimized.

The purpose of this paper is to explore the dynamic controllability of this type of vapor recompression system for air separation.

1. Introduction

The sequestration of carbon dioxide has been studied for many years. Much of the carbon dioxide emitted comes from the combustion of fossil fuels using air in furnaces or in combustion turbines. The resulting stack gas has a high nitrogen composition, which makes the recovery of the carbon dioxide difficult and expensive. If the carbon dioxide concentration could be increased, its recovery would be easier and less expensive.

One way to achieve this objective is to use oxygen instead of air for the combustion. Oxy-combustion power plants need only moderate-purity oxygen (96 mol%) instead of the typically high-purity oxygen (99.5 mol%) produced in conventional air separation units (ASU). In addition they do not need to produce high-purity nitrogen since it is not recovered as a product but simply vented. Under these conditions, it is possible to modify the conventional ASU design in a number of ways.

Several possible flowsheets are discussed by Fu and Gundersen [1] in a very insightful paper. They develop a "recuperative" vapor recompression system that uses two low-pressure cryogenic distillation columns and does not compress the air feed but compresses a nitrogen recycle stream to produce liquid for reflux. They clearly explain the fundamental engineering reasons why these modifications result in lower compressor power demand than a conventional ASU. Low pressure improve the relative volatility between nitrogen and oxygen, so reflux ratios are lower, which requires less liquid to be generated in the cryogenic process by compression work. In addition, the air feed does not have to be compressed to high pressure. The flowrate of nitrogen used in the vapor recompression is smaller than the air feed flowrate, which means less compressor work.

The term "recuperative" refers to the heating of the nitrogen gas before compression by cooling a process stream so compression is done at ambient conditions, not at cryogenic conditions. The heat produced in the compressors can then be rejected to inexpensive cooling water.

There is no discussion of dynamic control in the Fu and Gundersen [1] paper. No control valves are considered. These are essential components in any practical control structure. It appears that very small pressure drops are assumed through exchangers and columns. In addition, very small differential temperature driving forces for heat transfer (1 K) are used. More practical and realistic values for these parameters are used in this paper.

Many papers have discussed conventional high-purity oxygen processes. A small sampling is listed in the Refs. [2,3,4]. Conventional vapor-recompression applications in distillation have also been presented [5,6].

2. Process studied

The process developed is based on the flowsheet given by Fu and Gundersen [1] called "Cycle 2" in their paper, There are several differences, mainly due to taking into consideration the important issues of pressure drops through control valves that are required for control. Aspen Plus and Aspen Dynamics (Version 8.8) simula-

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E-mail address: WLL0@Lehigh.edu

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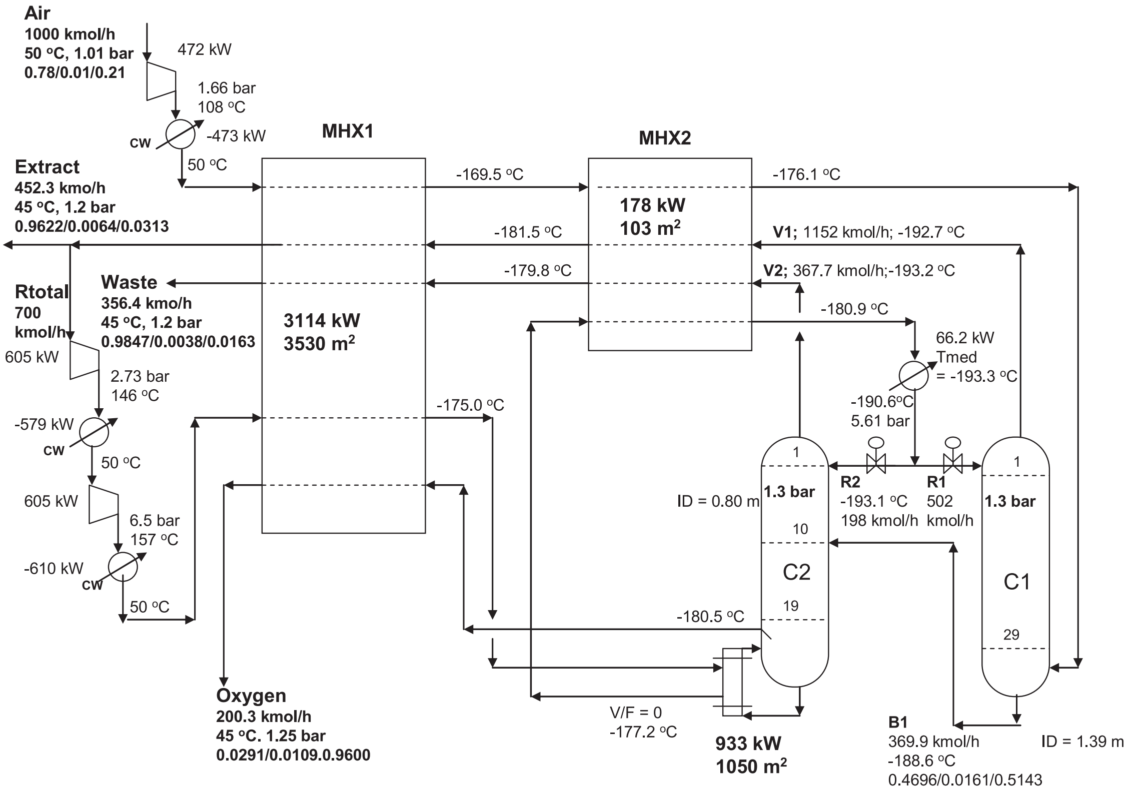

Fig. 1. Flowsheet of RVCP Air Separation Unit.

tions are used in this study with the Aspen Peng-Robinson physical property package. A compressor efficiency of 85% is assumed (polytropic using ASTM method). An overall heat transfer coefficient of 0.15 kW m^{-2} K^{-1} is used since most of the heat transfer is between gas streams. Process pressure drop through exchangers of 0.1 bar and design pressure drop through control valves of 0.2 bar are assumed (with the valve 50% open).

Fig. 1 gives the flowsheet containing two distillation columns, several compressors and coolers and two multi-stream plate heat exchangers. The upstream units to remove water and impurities are not considered in this paper. The fresh air feed is 1000 kmol/h at 50 °C with a composition of 78 mol% nitrogen, 1 mol% argon and 21 mol% oxygen. It is compressed to 1.66 bar to provide pressure drop through the two heat exchangers before entering the first distillation column C1, which operates at 1.3 bar. The single-stage air compressor draws 472 kW of power and heats the air from 50 °C up to 108 °C. A water-cooled heat exchanger cools the air back down to 50 °C before it enters the first multi-stream heat exchanger in which it is cooled to −169.5 °C by cold product streams exiting the cryogenic distillation columns. The air is further cooled in the second multi-stream exchanger to −176.1 °C before entering the bottom of column C1 as a vapor feed below the bottom tray.

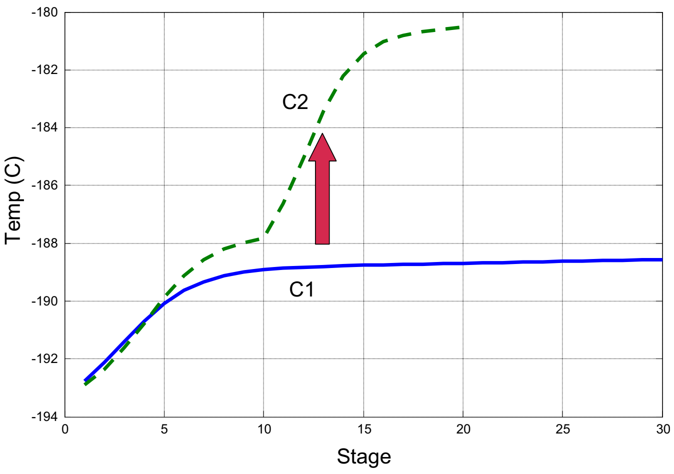

Fig. 2. Column temperature profiles.

Column C1 has 30 stages with a top pressure of 1.3 bar. Tray pressure drop is 0.002 bar per stage. Liquid weir height is 0.005 m. The column diameter is 1.39 m. Liquid reflux (502 kmol/h) is fed to the top tray. This liquid is 96.22 mol% nitrogen, 0.64 mol% argon and 1.63 mol% oxygen. It has been generated on the hot side of the reboiler of Column C2 in which vapor at −175 °C has been condensed to saturated liquid at −177.2 °C by boiling the liquid in the base of C2, which is at −180.5 °C. Note the very small differential temperature driving force that is typical of cryogenic processes. Capital investment in large heat-exchanger area is justified in order to reduce expensive compression costs.

The vapor V1 leaving the top of C1 (1152 kmol/h at −192.7 °C) passes counter-currently back through the two multi-stream exchangers (exiting at 45 °C). The liquid from the bottom of C1 is 369.9 kmol/h with a composition 46.96 mol% nitrogen, 1.61 mol% argon and 51.43 mol% oxygen. It is fed to Stage 10 of the second column C2.

Column C2 has 20 stages and operates with a top pressure of 1.3 bar. The column diameter is 0.80 m. Reflux is fed on the top tray at 198 kmol/h. A *vapor* oxygen-rich product is withdrawn from the bottom of the column. The vapor flowrate is 200.3 kmol/h at −180.5 °C with a composition 2.91 mol% nitrogen, 1.09 mol% argon and 96.0 mol% oxygen. This stream is heated to 45 °C in the first multi-stream exchanger.

The reboiler in the base of C2 transfers 933 kW of energy, which results in an overhead vapor stream V2 of 367.7 kmol/h.