Technology

Simulation of Mixing Column for Cryogenic Air Separation Unit

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1. Introduction

Oxygen is used in a wide variety of industries, including iron and steel, chemicals, and food, with an annual domestic production of approximately 10 billion m^3 , most of which is produced by cryogenic air separation units that distill and separate oxygen from atmospheric raw materials at very low temperatures.

In recent years, from the point of view of energy conservation, the spotlight has been on low purity oxygen (97% or lower) that requires less production power than general high purity oxygen (99.5% or higher). Several air separation processes have been proposed to produce low-purity oxygen[1]. Among them, processes using mixing columns (Figure 1) are often applied to reduce facility costs and save energy. A mixing column is a packed column with structured packing. In a mixing column, liquid oxygen supplied from the top of the column and air from the bottom of the column come into contact, but the concentration of oxygen, a less volatile component, is higher at the top of the column, and its separation behavior is different from that of ordinary distillation.

This paper introduces a simulation technique for predicting and designing the separation behavior of mixing columns used in the low-purity oxygen production process.

2. Simulation

2.1 Model

Figure 2 models the gas-liquid contact in a mixing column as a heat and mass transfer phenomenon through the gas-liquid interface. The liquid phase flows down along the packing and the vapor phase rises in countercurrent contact with it. This causes concentration and temperature differences near the gas-liquid interface, which are the driving forces for diffusion J and sensible heat transfer q. As shown in the figure, oxygen, a less volatile component, is contained more in the liquid phase

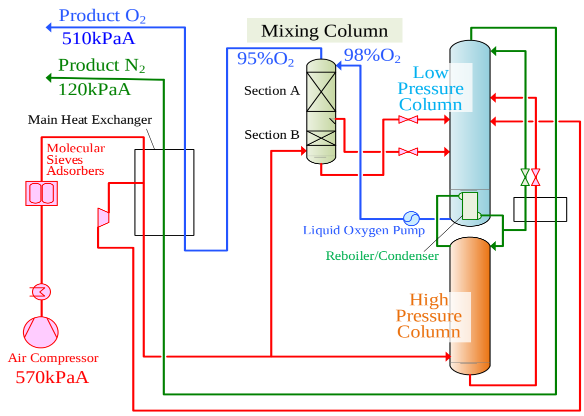
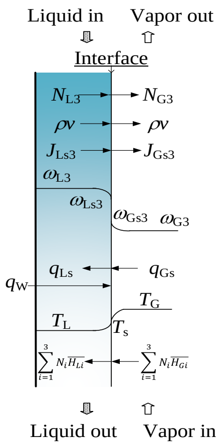


Fig 1. Cryogenic Air Separation Process with a Mixing Column



Nomenclature		
$\bar{H}$	partial specific enthalpy	[kJ/kg]
J	diffusion flux	[kg/(m^2·s)]
N	mass flux	[kg/(m^2·s)]
q	sensible heat flux	[kW/m^2]
q_w	heat leak through wall	[kW/m^2]
T	temperature	[K]
v	surface velocity	[m/s]
ρ	density	[kg/m^3]
ω	mass fraction	[-]
Subscripts		
G	vapor phase	
i	i -th component	
L	liquid phase	
s	vapor-liquid interface	
3	oxygen	

Fig 2. Simultaneous Heat and Mass Transfer Phenomena

than in the vapor phase, and moves from the liquid phase to the vapor phase through the interface by diffusion. On the other hand, if distillation is modeled as a heat and mass transfer phenomenon, oxygen is contained more in the vapor phase and moves from the vapor phase to the liquid phase through the interface.

Thus, if we look at the phenomena in a mixing column as heat and mass transfer, the direction of heat and mass transfer differs only from that of distillation. We have simulation technology[2) 3)] for distillation columns based on heat and mass transfer phenomena, and we believe that this simulation technology can be applied to mixing columns.

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2.2 Calculation method

The basic equations based on the above model were written in MODEL of gPROMS ModelBuilder® (PSE, UK), and simulation was performed. gPROMS ModelBuilder connects each modeled device (MODEL) by ports and calculates the entire process. It is a simulator that allows users to create their own MODELs. In the design of a mixing column, the amount of liquid oxygen and other substances to be supplied and discharged are calculated according to the product specifications of the air separation unit, and the column diameter, packed height, and other factors are determined to satisfy these specifications.

3. Comparison of simulation with observed data by pilot-scale experimental apparatus

3.1 Pilot scale experimental apparatus

Figure 3 shows a schematic of the pilot-scale experimental apparatus. The apparatus mainly consists of a mixing column R17 (column diameter 400 mm, packed height 1456 mm, structured packing 750Y:t=0.1 mm) and an oxygen concentration distillation column R18.

In the experiment, liquid oxygen from the bottom of R18 was supplied to the top of mixing column R17 by a pump, and vapor with low oxygen concentration from the top of R18 was supplied to the bottom of R17, and vapor and liquid were contacted in the mixing column R17. After confirming the steady state, the flow rates, oxygen concentrations, and pressures of gas and liquid at the top and bottom of the mixing column were measured.

3.2 Comparison of simulation results with observed data

Figure 4 compares the observed and simulated oxygen concentration profiles in mixing column R17 under condition equivalent to the upper section A of the mixing column in Figure 1 (column top liquid oxygen concentration: 97%, column bottom gas oxygen concentration: 78%, vapor-liquid ratio: L/V 2.0, pressure: 500 kPaA).

Figure 4(a) shows the vapor phase nitrogen concentration along the vertical axis and the liquid phase nitrogen concentration along the horizontal axis. The operating line (solid line) acquired in the simulation and the observed data (dots) are plotted together with the Vapor-Liquid Equilibrium line of nitrogen-oxygen system. As is unique to mixing columns, the operating line is

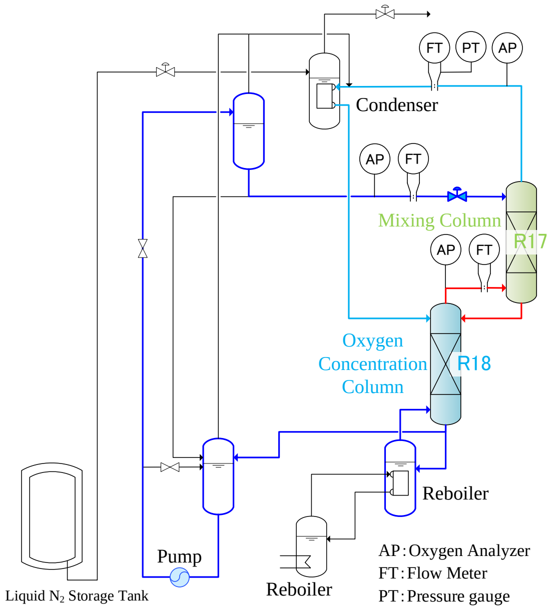

Fig 3. Schematic of Pilot-Scale Experimental Apparatus

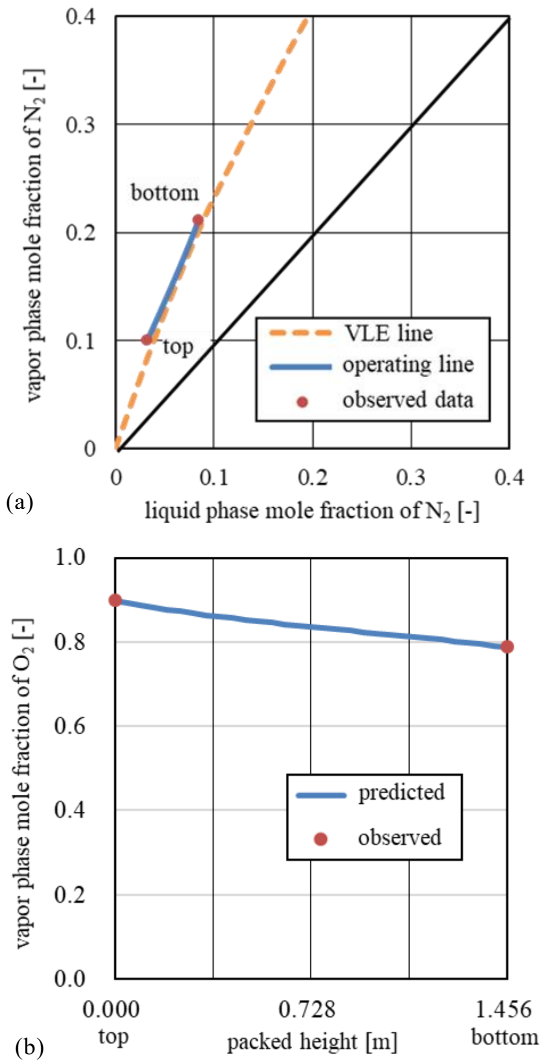

Fig 4. Comparison of predicted oxygen concentration profile with observed data (Section A equivalent conditions)

located outside the equilibrium line, and the operating line is almost parallel to the equilibrium line from the bottom of the column to the bottom of the column.

Figure 4(b) shows the vapor phase oxygen concentration along the vertical axis and packed height from the column top along the horizontal axis. The oxygen concentration profile (solid line) acquired from the simulation and the observed values (dots) are plotted.

These figures show that the predicted values from the simulation and observed data showed good agreement.

Figure 5 shows a comparison between the oxygen concentration profile and observed values in mixing column R17 and the calculated values from the simulation when the conditions near the top of B section at the bottom of the mixing column in Figure 1 (column top liquid oxygen concentration 85%, column bottom gas oxygen concentration 26%, gas-liquid ratio L/V 0.6, and pressure 500 kPaA) are simulated.

Figure 5(a) plots the simulated operating line (solid line) and the measured values (points) along with the equilibrium line (dashed line), as in Figure 4(a). It can be seen that the operating line is close to the equilibrium line at the bottom of the column.

Figure 5(b) plots the simulated oxygen concentration profile (solid lines) and the measured values (dots) against the packed height, as in Figure 4(b).

Similar to Figure 4, the predicted values from the simulation and observed data showed good agreement in Figure 5 so it was confirmed that the distillation column simulation can be applied to mixing columns.

4. Example of a Mixing Column Design by Simulation

Table 1 shows the simulated design of a mixing column for the process shown in Figure 1 which produces low-purity oxygen with a product volume of 35000 Nm3/h and an oxygen concentration of 95.5%.

The specific surface area of the packing used is different between Case 1 and Case 2. In Case 1, a structured packing with a large specific surface area (750 m2/m3) is used, and the packed height is lower because the gas-liquid contact area is larger than that of Case 2. However, it has larger column diameter due to smaller void fraction in the packing and the larger pressure drop. The selection of each case is made in consideration of layout of each component, such as the distillation columns and heat exchangers, so that the cold box that houses them is compact.

As we have shown, the simulation presented here has a wide range of application because it can use the knowledge accumulated in the distillation column design technology. In addition, effects of sheet thickness, inclination angles, and other factors of the structured packing can be theoretically considered, making it possible to optimize the design of air separation unit.

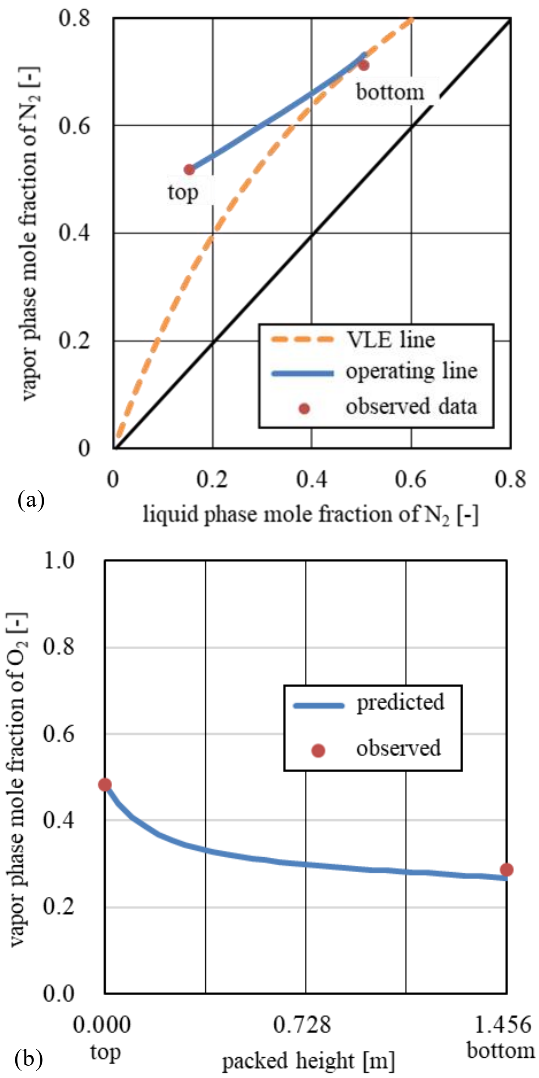

Fig 5. Comparison of predicted oxygen concentration profile with observed data (Section B equivalent conditions)

Table 1 Design of a Mixing Column*

			Case1	Case2
specific surface area of packing		[m^2/m^3]	750	350
column diameter		[mm]	2050	1700
packed height	section A	[mm]	3120	4576
	section B	[mm]	1872	2704

*Product oxygen 35,000Nm^3/h, purity 95.5%

5. Conclusion

Our air separation simulation technology is based on simultaneous heat and mass transfer phenomena, and can be applied to special processes such as mixing columns, which are different from ordinary distillation operations.

We can propose a compact and energy-saving air separation unit that meets user needs by making full use of process design technology as well as simulation technology for heat exchangers and other equipment.

References

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2) Egoshi, N., et. al.. Heat and Mass Transfer Model Approach to Prediction of Separation Performance of Cryogenic Air Separation Plant by Packed Columns with Structured Packing. *J. Chem. Eng. Japan*, 2001, 34(1), p 22-29.

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