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DESIGN CONCEPT OF CONTROL SYSTEM FOR
CRYOGENIC DISTILLATION COLUMNS OF
FUSION REACTOR

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Toshihiko YAMANISHI and Kenji OKUNO

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Design Concept of Control System for Cryogenic
Distillation Columns of Fusion Reactor

Toshihiko YAMANISHI and Kenji OKUNO

Department of Fusion Engineering Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

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Control systems were designed for cryogenic distillation columns in the main fuel cycle and the breeder blanket interface systems of fusion reactors. Three basic control modes were proposed for the column whose top product was more important; the column whose bottom product is more important; and the column having a feed back stream. The key component in the important product stream was selected for each column, and the analysis method for measurement of this key component was discussed. Some of the columns need the gas chromatography as the analysis instrument of the control system. The time required for the measurement of product purity by the gas chromatography considerably affects the stability of the control system. A significant conclusion is that permissible time is about 20 min. It is possible to complete the measurement within 20 minute by the gas chromatography. The gas chromatography is applicable for the control system of the column.

Key words: Cryogenic Distillation, Control System, Fuel Cycle,
Breeder Blanket, Hydrogen Isotopes, Gas Chromatography,
Time Lag, Feed Back

核融合炉における深冷蒸留塔制御システムの概念設計

日本原子力研究所那珂研究所核融合工学部

山西 敏彦・奥野 健二

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核融合炉燃料給排気系及びブランケット系の深冷蒸留塔に対して制御システムを設計した。3つの基本的制御モードを、塔頂製品流がより重要な塔、塔底製品流がより重要な塔、フィードバック流れを持つ塔に対し、それぞれ提案した。各々の塔に対し、製品流中の鍵となる成分を選択し、その鍵成分の分析に適した分析方法を検討した。幾つかの塔は、制御システムの分析手段として、ガスクロマトグラフを必要とする。ガスクロマトグラフによる分析はある程度の時間を要するが、その時間が、制御システムの安定性にかなりの影響を与える。1つの重要な結論として、ガスクロマトグラフに許される分析時間は約20分であることが判明した。ガスクロマトグラフにより、約20分以内に、分析を終了することは可能である。ガスクロマトグラフによる分析手段は、深冷蒸留塔の制御システムに適用可能である。

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1. Introduction

Hydrogen isotope separation by cryogenic distillation is expected to be best suited to the needs in the fuel circulation system of fusion reactors: a comparatively large flow rate can be processed even with a compact scale; and it has relatively high separation performance in comparison with other methods such as thermal diffusion and metal bed sorption^{(1),(2)}. In the main fuel cycle of the fusion reactor, an isotope mixture of the six molecular species is separated into four streams: H₂-HD, D₂, DT and T₂⁽¹⁾. In the breeder blanket interface (BBI), hydrogen is removed from a mixture of H and T⁽³⁾. Purity of these product streams is considerably high⁽¹⁾, so that control method of the cryogenic distillation column in the fusion reactor should be carefully designed.

For the distillation columns used in the hydrocarbon processing, purity of product stream can be expected from temperature at top or bottom of the column⁽⁴⁾. However, for the cryogenic distillation columns, it is difficult to know the purity of product from the temperature of the column. Exact measurement of the temperature is not easy task at a cryogenic temperature range (~ 20 K). In addition, the temperature of product stream hardly varies even if the purity of product deteriorates to some extent. For instance, tritium concentration in a hydrogen waste gas should be maintained at extremely low values (Atom fraction of T should be less than $\sim 1 \times 10^{-6}$.)⁽¹⁾. If the tritium concentration in the waste gas increases to $\sim 1 \times 10^{-5}$, it would cause a serious problem from the view point of tritium release to environment; however, the temperature is almost the same. Hence, it is a significant subject for the design of control system what analysis method should be applied. Only a report for the control system of the cryogenic distillation column has been published by Kinoshita et al⁽⁵⁾. However, their attention was focused on the stability of the control system of the column when the proportional-integral control mode was applied.

The present paper describes the control system of the cryogenic distillation columns in the fusion reactor. The control method for inventory and pressure of the column is first discussed. For the cryogenic distillation columns in the fusion reactor,

either top or bottom product is more important. A key component whose concentration should be controlled differs in each column. An appropriate analysis method and a key component are then discussed for each column. The gas chromatography is an attractive analysis method for the control system of the column, since it can measure the concentrations of all the hydrogen isotope species. Combination of a gas chromatograph and an ion chamber allows us to measure extremely low concentration for HT, DT and T₂⁽⁶⁾. However, it has a disadvantage that appreciable time is required to measure composition of a sample (15~20 minute). Application of the gas chromatography to the control system is also discussed as a major objective of the present study.

2. Design of Control System for Cryogenic Distillation Columns

2.1 Basic philosophy of design of control system

The column parameters which must be controlled are the purity of product, liquid level of the reboiler, and pressure. Both the temperature and flow rate of refrigerant helium gas can control the column pressure; the temperature of refrigerant helium gas more strongly affects the column pressure. For this reason, the temperature of refrigerant gas is applied as the manipulated variable for the control of column pressure⁽⁷⁾.

Figure 1 shows a typical control system in the case where the top product is more important. The column pressure is controlled by adjusting the heater power installed at refrigerant helium gas: temperature of the refrigerant helium gas. As the manipulated variable for the control of top product, the flow rate of top stream is selected. Although the vapor velocity within the column (reflux ratio) can also be a manipulated variable for the control of the product purity, it has an upper limit⁽⁸⁾; since the larger vapor velocity would cause the flooding. The flow rate of the top stream is the most excellent manipulated variable for the control of top product in this case⁽⁵⁾. The liquid level in the reboiler is controlled by the heater power at the reboiler and the flow rate of bottom

either top or bottom product is more important. A key component whose concentration should be controlled differs in each column. An appropriate analysis method and a key component are then discussed for each column. The gas chromatography is an attractive analysis method for the control system of the column, since it can measure the concentrations of all the hydrogen isotope species. Combination of a gas chromatograph and an ion chamber allows us to measure extremely low concentration for HT, DT and T₂⁽⁶⁾. However, it has a disadvantage that appreciable time is required to measure composition of a sample (15~20 minute). Application of the gas chromatography to the control system is also discussed as a major objective of the present study.

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stream. Increase of the heater power at the reboiler means that of the vapor velocity within the column. The liquid holdup within the packed section increases with the vapor velocity, so that the liquid level in the reboiler decreases⁽⁹⁾. As described above, the vapor velocity has an upper limit. Hence, in the case where the liquid level in the reboiler still increases in spite of adjustment of the vapor velocity; the flow rate of the bottom stream is increased. We call this control mode here in after mode 1.

Figure 2 shows a typical control system where the purity of bottom product is more important. The bottom flow rate is chosen as the manipulated valuable for the control of product purity in place of the top flow rate. The liquid level in the reboiler is adjusted by the heater power at the reboiler and flow rate of top steam similar to the control concept of the mode 1. We call this control mode here in after mode 2.

The column having a feed back stream plays an important role of the isotope separation system in the breeder blanket interface (BBI)⁽³⁾. In the BBI, hydrogen must be removed from a H-T mixture. High purity tritium must be recovered from the mixture. The molecular specie of HT must not be contained both in the hydrogen stream and in the tritium stream. The feed back stream decomposes the HT supplied into the column to H₂ and T₂ through a equilibrators⁽¹⁰⁾. Figure 3 shows a control system of this column having a feed back stream. The bottom product purity is considered to be more important. The pressure, liquid level in the reboiler, and purity of bottom product are controlled by the same concept of the mode 2. A major concern should be made how do we choose the flow rate of the feed back stream. The feed back stream has a function of decomposition of HT. Its flow rate depends on the amount of HT supplied to the column. A feed forward control loop can be considered to be the best appropriate method: the flow rate of the feed back stream is controlled by the analysis result for the concentration of HT in external feed streams. Ideally, the feed back stream is withdrawn from the portion of the column where concentration of HT is the highest. About 20-30% of HT is expected to be decomposed into H₂ and T₂ through the equilibrators⁽¹⁰⁾. The flow rate of the feed back stream can be determined by

$$\begin{aligned} (\text{Flow rate of the feed back stream}) &= (\text{Flow rate of the external feed stream}) \times \\ (\text{Concentration of HT}) &\times 3\sim 4. \end{aligned} \quad (1)$$

As long as the flow rate of the feed back stream is set an appropriate value for the amount of HT supplied into the column, we can regard the column having the feed back stream as the ordinary column separating H_2 and T_2 . Hence, the mode 2 can be applied for controlling other valuables. We call this control mode here in after mode 3.

2.2 Control system of cryogenic distillation columns in main fuel cycle

The column cascade at TSTA is chosen in this section. The TSTA cascade composed of four columns. Since pure tritium is not necessarily required for the fusion reactor, the four-column cascade can be reduced to a three-column cascade⁽¹¹⁾. Figure 4 shows the configuration of this three-column cascade. In the following section, we discuss the control system for each column.

(i) Column (1)

The control of the tritium concentration in the top product from Column (2) to keep it below a set point level is a most critical task. To keep the tritium concentration adequately low, the total amount of tritium leaving Column (1) needs to be kept within an adequately small range. This requires the control of the total amount of tritium in the top product from the Column (1). For this column, H_2 , HD, HT and D_2 are recovered at the top, while DT and T_2 are recovered at the bottom. The four molecular species (H_2 , HD, HT, and T_2) can be considered to be recovered almost completely under the normal condition. Hence, the mole fraction of DT in the top product is the most significant variable to be controlled by manipulating the top product flow rate. For these reasons, we apply the mode 1 for this column, and consider a key component is DT in the top product as presented in Tables 1 and 2.

The designed values for the top composition are also seen in Table 1. As analysis instruments of hydrogen isotopes, we can mention ion chamber, gas chromatograph, and raman. The raman method is an attractive, since it requires only a few minutes for measurement of a sample, and does not produce waste gas. However, the concentration of DT is lower than limitation of analysis of the raman⁽¹²⁾, so that the raman method can not be used. Since the concentration of HT is higher than that of DT, it is not possible to measure the concentration of DT by the ion chamber only. The most appropriate analysis instrument for the Column (1) is therefore a combination of the ion chamber and the gas chromatograph (See Table 2).

(ii) Column (2)

The most critical task for Column (2) is to keep the tritium concentration in the top product within an adequately small range. Hence, the mode 1 can be chosen for the Column (2). The key component of the top product is HT; its concentration is extremely low as seen in Table 1. In addition, concentrations of DT and T₂ are negligible in comparison with that of HT. The ion chamber is sufficient to measure the concentration of HT in the top product of the Column (2).

(iii) Column (3)

This column has a function of production of high purity D₂. The HT and D₂ are recovered at the top while DT is recovered at the bottom. Hence, the mode 1 is appropriate for the Column (3). The key component is DT in the top product. The concentration of HT is appreciably lower than that of DT, so that the ion chamber is the best choice as the analysis instrument.

In the case where the atom fraction of HT in the raw fuel input supplied to the Column (1) is higher than the design value (See Fig. 4), there is possibility that an appreciable amount of HT is fed to the Column (3)⁽¹³⁾. It is expected that the concentration of HT in the top product of the Column (3) is comparative to that for DT. The combination of the ion chamber and the gas chromatograph should be applied as the

analysis instrument for this case.

Design concept for the control system of each column in the main fuel cycle discussed above are summarized in Table 2.

2.3 Control system of cryogenic distillation column in Breeder blanket interface

Kinoshita et al. have proposed a two-column cascade for the BBI⁽³⁾. Figure 5 shows this cascade configuration. The cascade composed of one ordinary column and one column having a feed back stream. One column having a feed back stream can fulfill the function as same as that of this two-column cascade. However, the two-column cascade is more excellent than the one column system; since its tritium inventory is smaller and higher purity tritium is obtained. In addition, one more disadvantage of the one column system can be pointed out. In the case where the mixture of H-T in the BBI is separated by the one column having the feed back stream, both the top and bottom products are significant. Essentially tritium free stream is recovered at the top, while high purity tritium is recovered at the bottom. It is not easy task to maintain the purity of both top and bottom products against disturbances for the feed flow rate and feed composition. From the view point of easiness of the control also, the one column system should be avoided.

(i) Column (1)

Basic philosophy for the control of this column is the same as that for the Column (2) in the main fuel cycle. The purity of top product is more important. The concentration of HT in the top product is the key variable. The concentration of HT should be very low. The concentrations for DT and T₂ are negligible in comparison with that of HT (See Table 3). The mode 1 is applied for this column. The ion chamber is appropriate as the analysis instrument.

(ii) Column (2)

As discussed in section 2.1, the mode 3 should be applied for this column. The key component is DT in the bottom product. If the purity of tritium is restrict (99.8~99.9%), the concentration of DT must be maintained at an extremely low value (See Table 3). The trace amount of DT in T₂ must be measured, and the combination of the ion chamber and the gas chromatograph is the only analysis instrument that satisfies this condition. In the case where the purity of tritium required is relatively low (~99%), the raman method can be applied. To control the flow rate of the feed back stream, it is required to know the concentration of HT in the external feed stream. The concentration of HT in the feed stream is expected to be appreciably large as indicated in Table 3, so that the raman method is the most appropriate.

The design concepts for the control system of the columns in the BBI are summarized in Table 4.

3. Application of Gas Chromatography as Analytical Method of Control System

Basically, the gas chromatography is not desirable analysis method for the control of the column, since it needs 15~20 minutes for the measurement of a sample. This time lag for the measurement possibly deteriorates the stability of the control system. However, as discussed in chapter 2, we must use the gas chromatography as the analysis method for several columns. Kinoshita et al. reported the proportional-integral (PI) control mode for the Column (1) in detail⁽⁵⁾. They discussed the stability of this control system in the case where the measurement of the controlled variable is accompanied by a long time lag also. In this chapter, we summarize their simulation results and discussed the applicability of the gas chromatography for the control system.

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3.1 Parameter setting method for proportional-integral control⁽⁵⁾

The design concept of control system of the Column (1) is presented in Table 1 and 2. The detailed design specifications of the Column (1) are listed in Table 5. The assumed upset is a step increase of 5% in the molar flow rate of D-T fed to the column. To keep the total feed flow rate, molar flow rate of D₂ is decreased for the corresponding value. Table 6 shows the assumed upset feed composition and the controlled and manipulated variables of the column.

The parameter setting method is summarized as follows.

- (i) Estimate the approximate value of the change in the manipulated variable needed for a successful control, ΔD .
- (ii) Calculate the response curves of the controlled variable assuming several different magnitudes of step change in the manipulated variable (e.g., $\Delta D/4$, $\Delta D/2$, and ΔD). This step accounts for the nonideality of the column.
- (iii) Check the curves to see whether the curves have inflection points or not. If they do not have an inflection point, the usual first-order lag approximation is adequate for the transfer function. If they have those points, the second-order lag approximation must be used. The dead time is usually negligible.
- (iv) Determine the optimum set of parameters in the transfer function, which represents the best fit to each calculated response curve. These parameters are functions of the magnitude of the manipulated variable upset assumed because of the nonideality of the column.
- (v) Derive the criteria for successful parameter settings. This can be achieved by using the classical control theory.
- (vi) Draw a graph of the integral time plotted against the proportional sensitivity including the magnitude of the manipulated variable upset assumed as the third parameter, to illustrate the parameter settings, which bring instability, oscillatory behavior, or proportional-only control behavior.

The response curves of the controlled variable to the step changes in the

manipulated variable were first calculated. Kinoshita et al. reported that all the response curves had no inflection points and hence the first-order lag system can be assured. We now consider the negative feedback control scheme illustrated in Fig. 6. Since the process transfer function is expected by the first-order lag system, the open loop transfer function is written by

$$G(s) = \frac{KM \left[1 + \frac{1}{T_i s} \right]}{1 + Ts} \quad (2)$$

The characteristics equation is expressed by

$$T_i Ts^2 + T_i(1 + KM)s + KM = 0 \quad (3)$$

In this case, the control never brings instability because the above equation has only real negative roots or imaginary roots whose real parts are negative. However, to obtain oscillatory behavior, it must have imaginary roots:

$$T_i \leq \frac{4KMT}{(1 + KM)^2} \quad (4)$$

The order of magnitude of K can be estimated from the following equation representing the PI action.

$$-\Delta D(t) = K\Delta y_{DT,1} + \frac{K}{T_i} \int_0^t \Delta y_{DT,1}(t) dt \quad (5)$$

The initial value of the controlled variable, $y_{DT,1}$, is -2.0×10^{-4} . It is desired that $\Delta y_{DT,1}$ be approximately one order of magnitude smaller than the initial value. The approximate value of K is expected to be -5×10^{-4} mol/h. Substituting this K value into Eq. (4), we can obtain the maximum value of T_i .

The maximum value of T_i thus obtained for the selected K value are shown in Fig. 7. Figure 8 shows an example of the response of the controlled variable to the step change in the feed composition.

If the measurement of the controlled variable is accompanied by a long time lag, the great stability of the control is no longer inherent in this control mode. Expressing the time lag by τ (h), the open loop transfer function is written by

$$G(s) = KM \left[1 + \frac{1}{T_i s} \right] \frac{\exp(-\tau s)}{1 + Ts} \quad (6)$$

The characteristics equation is then written by

$$T_i s(1 + Ts) + KM(1 + T_i s) \exp(-\tau s) = 0 \quad (7)$$

Substituting $s = j\omega_c$ in the above equation yields the following nonlinear simultaneous equations:

$$T_{ic} \omega_c + KMT_{ic} \omega_c \cos(\tau \omega_c) - KM \sin(\tau \omega_c) = 0 \quad (8)$$

$$-T_{ic} T \omega_c^2 + KMT_{ic} \omega_c \sin(\tau \omega_c) + KM \cos(\tau \omega_c) = 0 \quad (9)$$

$$\tau \omega_c \leq \frac{\pi}{2} \quad (10)$$

If K , M , T , and τ are given, the lower limit of the integral time, T_{ic} can be calculated by solving the above equations by use of the Newton-Raphson method where T_{ic} and ω_c are the independent variables.

3.2 Effect of time lag in measurement of controlled variable

The control mode proposed in the present study never becomes unstable as long as the controlled variable is measured with a negligible short time lag. The small value of T_i can be selected. However, if the measurement is accompanied by a long time lag, there is the lower limit of T_i as indicated in Eqs. (8)–(10). Figure 9 shows the curves of T_{ic} plotted against τ . A longer time lag requires a larger integral time to avoid the instability. In the case where $\tau = 0.3$ h and $\Delta D = -5$, Figs. 7 and 9 indicate that T_{ic} is -0.2 h while the maximum T_i is -0.6 h. For the case where $\tau = 0.3$ h and $\Delta D = -1$, Figs. 7 and 9 indicate that T_{ic} is -0.3 h while the maximum T_i is -1.3 h. Accordingly, we must set the value of T_i in the range of 0.3–0.6 h. Figure 10 shows the response curve of the controlled variable for the case: $K = 5 \times 10^{-4}$ mol/h, $T_i = 0.4$ h, $\tau = 0.3$ h. The concentration of DT is successfully controlled, although a relatively large overshoots is observed in comparison with Fig. 8. If $\tau = 0.5$ h, we can conclude from Figs. 7 and 9 that the value of T_i must be set in the range of 0.5–0.6 h. If the value of τ is larger than 0.5 h, there is possibility that an appropriate value of T_i no longer exists.

We must pay attention to another disadvantage of the gas chromatography that it can not continually provide the measurement results. For this case, Kinoshita has reported that the time lag for measurement must be considered to be 50% larger than actual time required for composition measurement⁽¹⁴⁾. For the above discussion, it can be concluded that the permissible time for the gas chromatography is about 20 min. It is possible to complete the measurement for a sample within 20 minutes by the gas chromatography⁽¹⁵⁾. In fact, some workers have performed the measurement of composition of hydrogen isotopes by the gas chromatography within 15 minutes⁽¹⁶⁾. In addition, for the control of

the columns, we need the concentration of HT or DT (See Tables 2 and 4). This means that complete separation of all the peaks of the six hydrogen isotopes in the gas chromatogram is not necessarily required. Thus, our final conclusion is that the gas chromatography is the applicable analysis method for the control system of the columns in the fusion reactor. To increase the stability of the control system, we must improve the gas chromatography. The shorter measurement time brings more stable control.

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NOMENCLATURE

D = flow rate of top product (mol/h)

ΔD = magnitude of top product flow rate upset assumed (mol/h)

$G(s)$ = process transfer function

j = imaginary unit

K = proportional sensitivity (mol/h)

M = static gain (h/mol)

T = time constant for first-order lag system (h)

T_i = integral time (h)

$y_{DT,1}$ = mole fraction of DT in top product (-)

$\Delta y_{DT,1}$ = magnitude of mole fraction of DT upset (-)

τ = time lag in measurement of controlled variable (h)

ω = angular frequency (1/h)

Subscript

c = critical value

Table 1 Important product stream and key component in the stream
for each column in main fuel cycle

	Column (1)	Column (2)	Column (3)
Important product	Top	Top	Top
Composition	$H_2 : 5.5 \times 10^{-4}$ $HD : 4.2 \times 10^{-2}$ $HT : 3.7 \times 10^{-2}$ $D_2 : 9.2 \times 10^{-1}$ $DT : 1.8 \times 10^{-4}$ $T_2 : 0.0$	$H_2 : 9.1 \times 10^{-3}$ $HD : 9.9 \times 10^{-1}$ $HT : 4.0 \times 10^{-7}$ $D_2 : 0.0$ $DT : 0.0$ $T_2 : 0.0$	$H_2 : 0.0$ $HD : 0.0$ $HT : 1.0 \times 10^{-6}$ $D_2 : 9.995 \times 10^{-1}$ $DT : 5.0 \times 10^{-4}$ $T_2 : 0.0$
Key component	DT	HT	DT

Table 2 Design concept for control system of each column in main fuel cycle

	Column (1)	Column (2)	Column (3)
Control mode	Mode 1	Mode 1	Mode 1
Analysis method	Gas chromatography + Ion chamber	Ion chamber	Ion chamber

Table 3 Important product stream and key component in the stream for each column in BBI

	Column (1)	Column (2)
Important product	Top	Bottom
Composition	$H_2 : 1.000$ $HD : 3.6 \times 10^{-6}$ $HT : 8.5 \times 10^{-7}$ $D_2 : 0.0$ $DT : 0.0$ $T_2 : 0.0$	$H_2 : 0.0$ $HD : 0.0$ $HT : 3.1 \times 10^{-6}$ $D_2 : 2.4 \times 10^{-7}$ $DT : 2.0 \times 10^{-3}$ $T_2 : 9.98 \times 10^{-1}$
Key component	HT	DT

Table 4 Design concept for control system of each column in BBI

	Column (1)	Column (2)
Control mode	Mode 1	Mode 3
Analysis method	Ion chamber	Gas chromatography + Ion chamber or Raman

Table 5 Design specifications of Column (1)

Feed flow rate	100 mol/h
Feed composition	H ₂ : 1.368x10 ⁻⁴ HD : 1.048x10 ⁻² HT : 9.248x10 ⁻³ D ₂ : 0.2481 DT : 0.4832 T ₂ : 0.2488
Number of total theoretical stages	80
Feed stage number	50
Flow rate of top product	25 mol/h
Reflux ratio	25
Pressure	101.3 kPa

The feed is equilibrated at 293 K by H₂ + D₂ = 2HD, H₂ + T₂ = 2HT, and D₂ + T₂ = 2DT.

Table 6 Controlled and manipulated variables

Controlled variable	Mole fraction of DT in top product $y_{DT,1} = \sim 2.0 \times 10^{-4}$
Disturbance	Increase of DT flow rate in feed composition (5%)
Upset feed composition*	H ₂ : 1.37x10 ⁻⁴ HD : 1.0x10 ⁻² HT : 9.2x10 ⁻³ D ₂ : 0.224 DT : 0.507 T ₂ : 0.249

* The feed is not equilibrated.

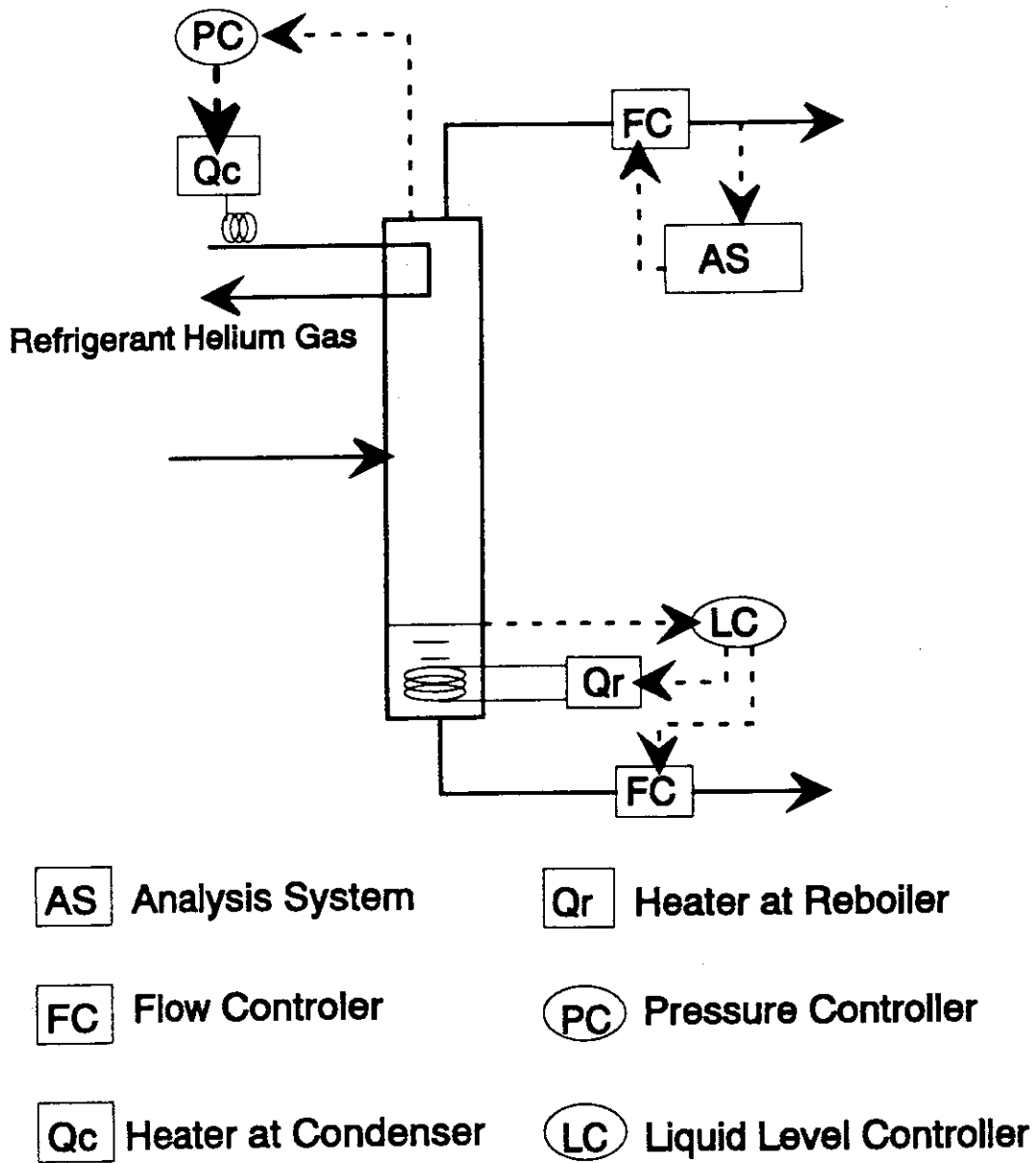


Fig. 1 Typical control system for the column whose top product is more important than bottom product.

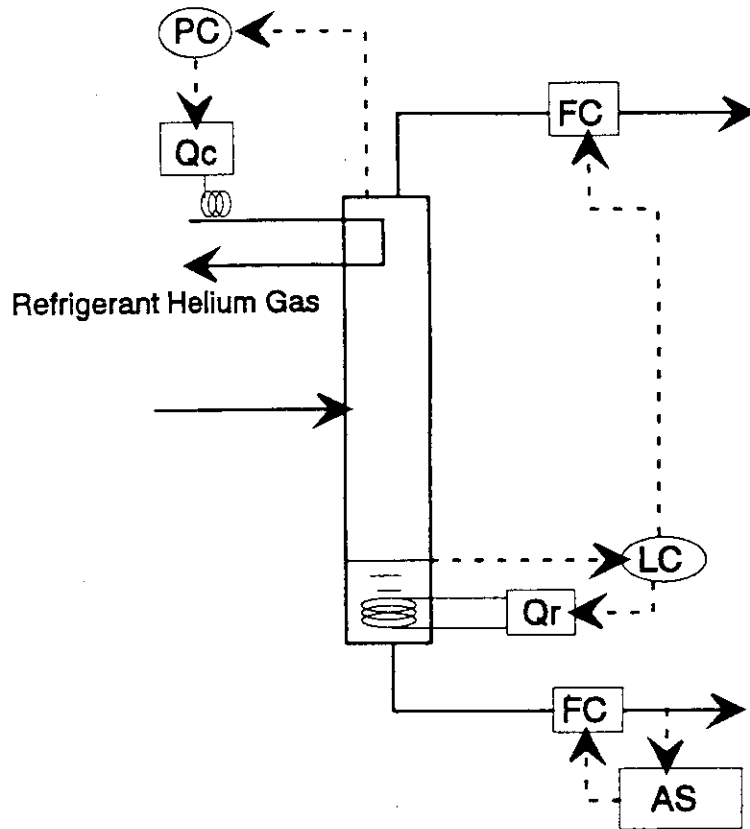


Fig. 2 Typical control system for the column where bottom product is important.

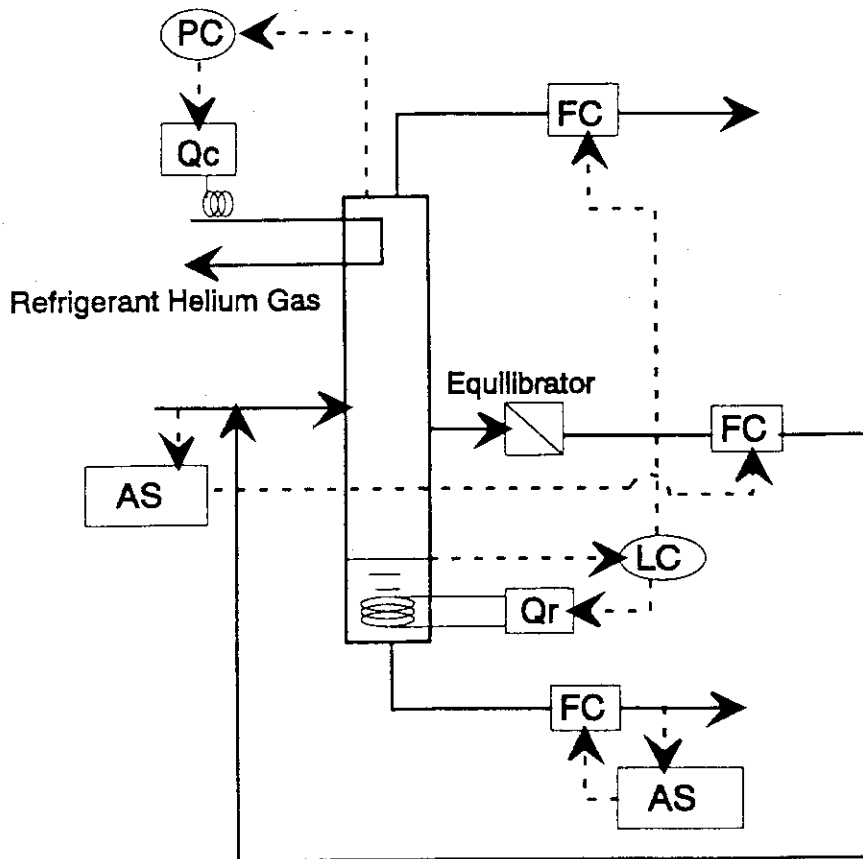


Fig. 3 Control system for the column having a feed back stream.

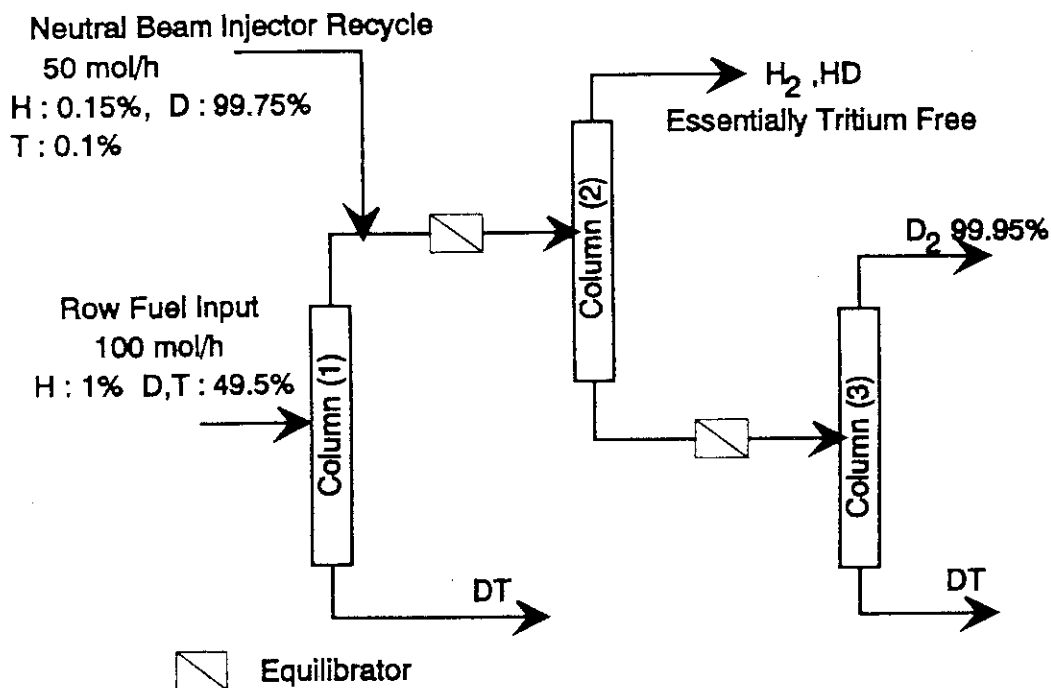


Fig. 4 Cryogenic distillation column cascade in the main fuel cycle chosen for the present study.

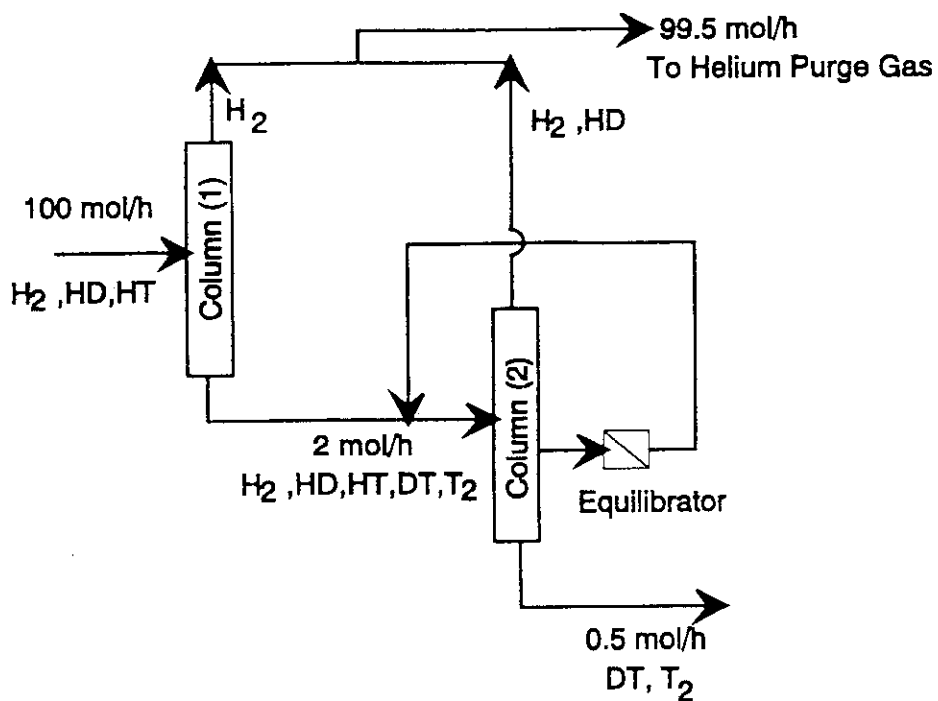


Fig. 5 Two-column cascade developed for the BBI by Kinoshita et al⁽³⁾.

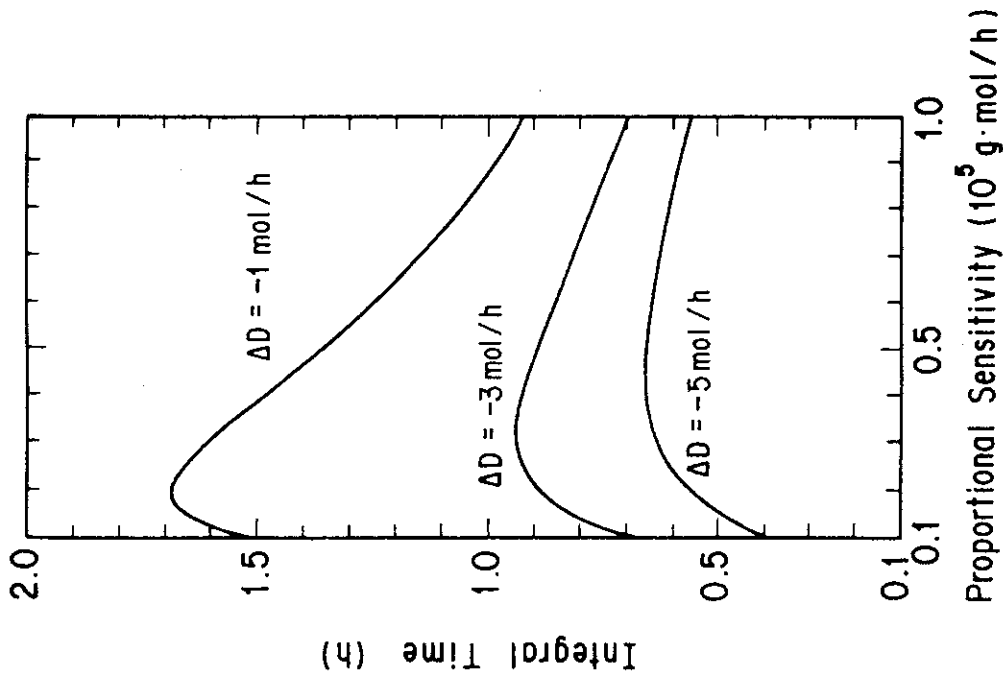


Fig. 7 Diagram for setting PI controller parameters (5).

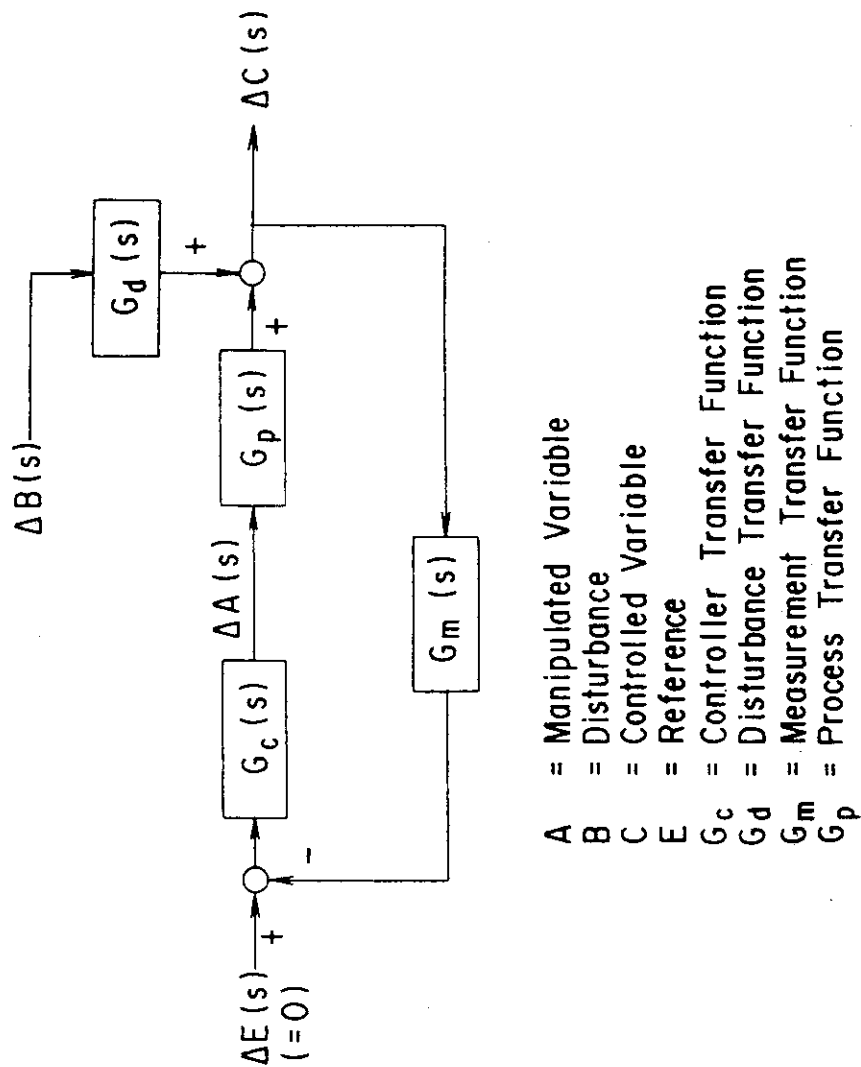


Fig. 6 Negative feedback control with PI controller.

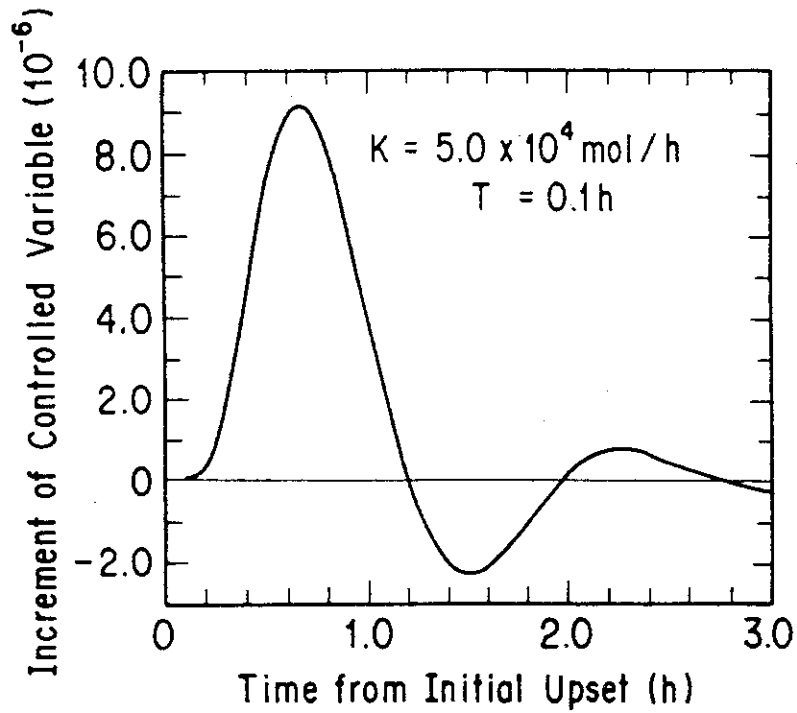


Fig. 8 Response of controlled variable to step change in feed composition under PI control⁽⁵⁾.

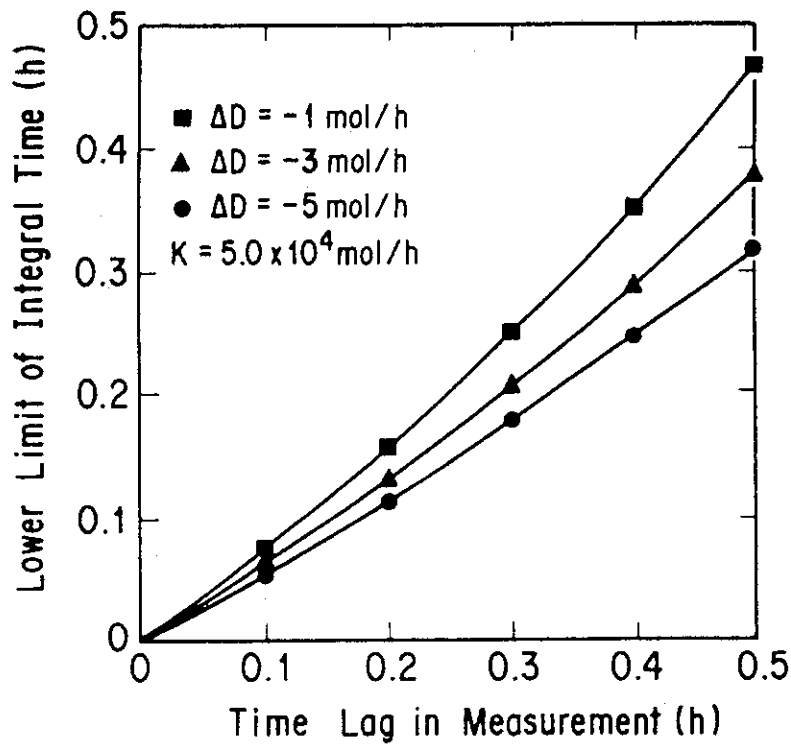


Fig. 9 Curve of lower limit of integral time plotted against time lag in measurement of controlled variable⁽⁵⁾.

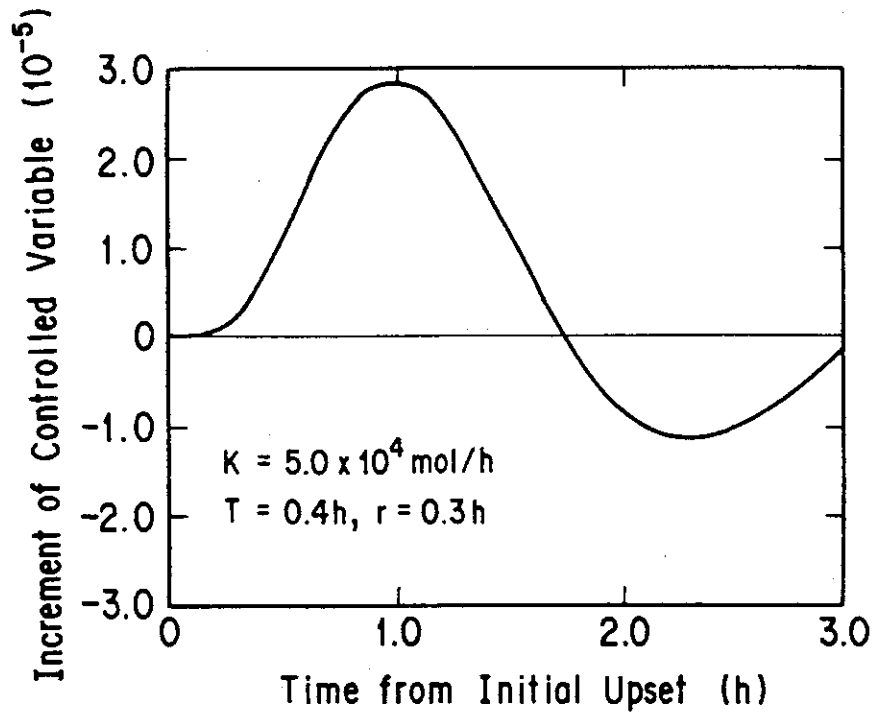


Fig. 10 Response of controlled variable to step change in feed composition under PI control accompanied by significant time lag in measurement of controlled variable.