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A control method was proposed for a two-column cascade composed of cryogenic distillation columns with feedback streams. The lead column process the exhaust gas from a plasma, and produces high purity tritium. The second column process the top stream from the lead column and hydrogen gases containing tritium from water detritiation and blanket systems. The top and bottom flow rates of the columns are adjusted against variations of feed compositions to control product purity. The method of parameter setting for the proportional-integral (PI) controller was proposed for step changes of the feed compositions. For the lead column, either the mole fraction of DT at top or the atom fraction of T at bottom can be chosen as the controlled variable. The mole fraction of DT is more favorable as the controlled variable than the atom fraction of T from the viewpoint of promptness of the control. However, only a short time lag in the measurement of the controlled variable is permissible. It is required to decrease the value for the proportional sensitivity to relax this restrict. The successful control is obtained for the second column to choose the mole fraction of HT at top. A considerably long time lag is permitted for the second column in contrast to the lead column.

Keywords: Cryogenic Distillation, Feedback, Column Cascade, Control, Hydrogen Isotopes, Tritium, Transfer Function, Time Lag, Proportional Sensitivity, Integral Time

フィードバック流れを持つ深冷蒸留塔から構成される塔カスケードの制御特性

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フィードバック流れを持つ深冷蒸留塔から構成される2塔カスケードの制御手法を提案した。先頭の塔は，プラズマからの排出ガスを処理し，高純度のトリチウムを塔底から精製する。2番目の塔は，先頭の塔の塔頂流と，ブランケット及び水処理システムからのトリチウムを含んだ軽水素ガスを処理する。塔の塔頂及び塔底流量は，フィード組成の変化に対して，製品純度を保つように調整する。フィード組成のステップ変化に対する，比例積分（PI）コントローラのパラメータ設定手法を提案した。先頭の塔では，塔頂流中のDTモル分率あるいは塔底流中のTの原子分率が制御因子となりうる。制御の迅速性からは，塔頂流中のDTモル分率を制御因子として選ぶことが望ましい。しかしながら，この場合，制御因子の測定のための遅れ時間は極めて短くなければならない。この制限を緩和するためには，PIコントローラの比例感度を小さくする必要があり，制御の迅速性が失われる。2番目の塔に対しては，塔頂流中のHTモル分率を制御因子として選択することで，安定した制御特性を得ることができる。また先頭の塔とは対照に，大きな測定遅れ時間も許される。

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Contents

目次

I. Introduction

In the fuel cycle of fusion reactors, an isotope mixture of six molecular species is required to separate into three streams: H_2-HD, D and T. In this hydrogen isotope separation, a major concern must be made how do we treat the molecular species of DT and HT. A single cryogenic distillation column having a feedback stream can separates D and T (H and T), since the molecular species of DT (HT) is decomposed to D_2 and T_2 (H_2 and T_2) at an equilibrator. The molecular species of HT can also be decomposed to HD and DT with D_2 ($HT + D_2 \rightarrow HD + DT$) in the column having a feedback stream. For these reasons, the column having a feedback stream has been applied in recent design of isotope separation system of ITER[1,2]. Kinoshita et al. have studied characteristics of the column having a feedback stream in their theoretical works[3~5]. The authors have carried out experimental studies for the column having a feedback stream[6~9]. The effect of the feedback stream was experimentally verified. These studies allow us to design a column cascade composed of the columns having the feedback streams for a fusion reactor.

The column cascade is designed for a set of input and output conditions. Hence, it is required to examine the behavior of the cascade against the disturbances such as changes of feed composition and feed flow rate: control characteristics of the cascade. However, there are only a few studies that have reported on the control characteristics of the cascade. Davis et al.[10] studied dynamic and control characteristics of a single column. They used the PRC (process reaction curve) method to determine the parameters of the PI (proportional-integral) control. Kinoshita et al.[11,12] proposed a simple parameter setting method, which has two principal features: The strong non-linearity of the process is accounted for, and the unstable region under the PI control can be predicted. These features are not inherent in such conventional methods as the PRC method. These studies provide useful information on the design of the control systems of the ordinary columns. The column with a feedback stream has several features: the flow rate of feedback stream is also a manipulated variable of the control system; and the overall mass balance around the column is valid for each atomic species only. The authors have proposed a control method for the column having a feedback stream, considering these features[13].

The principal objective of the present paper is to complement the previously reported work by the authors[13] for the control of the column having a feedback stream. It is also a significant objective to extend the understanding for the control of the column having a feedback stream to the design of the control system of cascades. The behavior of the cascade is discussed for manipulated variables of the control system chosen for each column.

2. Mathematical simulation procedure

The stage model is used for mathematical simulation of the column having a feedback stream: The column is composed of N theoretical stages; and the first stage is condenser. For the simulation at the steady state, we used a simulation code especially developed for the column having a feedback stream. The simulation can be carried out by solving two nonlinear simultaneous equations. The atom fractions of hydrogen and deuterium in the feedback stream are independent variables. All the factors such as nonideality of hydrogen isotope solution, differences in the latent heat of vaporization among the six isotopic species, and decay heat of tritium are taken into account for the code: liquid flow rate within the column and activity coefficients of the solutions are recalculated in an outer loop of the main distillation calculation. The main distillation calculation can be made by finding out the solutions of nonlinear simultaneous equations by the Newton-Raphson method, where the temperatures at manipulated variable of the control system; and the overall mass balance around the column is valid for each atomic species only. The authors have proposed a control method for the column having a feedback stream, considering these features[13].

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A simplified model neglecting the above-mentioned factors is used for the dynamic simulation of the column in the present study. It is expected that the qualitative aspects of the conclusion described later are not vitiated at all even if the simplified model is used. A further assumption is used in the simulation model: The liquid holdup within the column remains unchanged along the time trajectory. Consequently, simultaneous ordinary differential equations are derived in accordance with the model. We apply the Ballard-Brosilow algorithm to solve these equations. The basic equations and calculation procedure are described in Ref. 6, 11, and 14.

3. Computer analyses on dynamics and control

3.1 Basic philosophy of control method

The cascade shown in Fig. 1 is chosen as an example case. The lead column (Column 1) processes a feed of 16 mol/h of H:D:T = 0.01:0.495:0.495 similar to what might be expected from the exhaust gas from a Tokamak fusion energy device[2]. High purity tritium (~90%) can be obtained from the bottom of the column because of a feedback stream ($2DT \rightarrow D_2 + T_2$). The second column (Column 2) processes the top product of the lead column and the hydrogen gases containing tritium from the water detritiation and breeder blanket systems. The feedback stream of Column 2 produces an essential tritium free stream: $HT + D_2 \rightarrow HD + DT$. The flow rates and compositions of these feed streams of Column 2 are presented in Fig.1[1,2]. The optimum design specifications of the columns (N, R, N_S, W_S) were determined by the method proposed in our previous study[8,9]. To estimate the liquid holdups, the

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After the column was designed for an input condition, product purity must be maintained at desirable values against the disturbances, which would be a change of feed flow rate or a change of feed composition. Possible manipulated variables are the top and bottom flow rates, vapor flow rate from the reboiler, flow rate of side stream. The feedback and side stream locations affect the column performance[9]. As discussed in the precede section, the feedback stream has the function of changing the external feed composition. Hence, the feedback stream at least can meet this function in the case where the side stream is recycled to the external feed stream as the feedback stream. The location of the side stream is a complicated function of the external feed composition, top and bottom flow rates, and vapor flow rate from the reboiler (reflux ratio); however, an appropriate location would present a narrow range as long as the external feed composition does not vary extensively. The authors carry out the simulation, changing the external feed composition for Column 1: $z_D = 0.445$; and $z_D = 0.545$. The calculated results are shown in Table 2. The product purity can be maintained by adjusting the flow rates of top and bottom streams only (The reflux ratios are consequently changed because of variation of the top flow rate.). The effect of the flow rate of the external feed stream is then examined for Column 1. The flow rate of the external feed stream is increased to 30%, and the calculated result is in Table 2. The flow rates of top and bottom streams are increased with the corresponding increase in the external feed stream. The vapor flow rate from the reboiler is also increased with the corresponding increase in the top stream to make the reflux ratio constant. We can maintain the product purity by the flow rate of the side stream. This result is quite understandable if we recall the requirement that the amount of DT decomposed at the equilibrator be almost equal to that supplied to the column by the external feed stream.

The main function of Column 2 is to produce a tritium free and a hydrogen free streams. It is essential for Column 2 to discuss the effect of amount of HT supplied to the column. The molecular species of HT is mainly supplied by the feed stream from the breeder blanket. Calculations are carried out by changing the atom fraction and flow rate of the feed stream from the breeder blanket, and the results are presented in Table 2. Against the change of feed composition, the concentration of HT can be maintained by just adjusting the top and bottom flow rates of the column. The reflux ratio is consequently changed because of variation of the top flow rate similar to the case of Column 1. For the change of feed flow rate, only the flow rates of top and bottom streams are increased with the corresponding increase in the external feed stream; and the concentrations of HT in the product streams are maintained at desirable values as seen in Table 2.

From these calculated results, we propose a control method shown in Fig. 2. The top flow rate is controlled by the composition of top or bottom product stream. The bottom flow rate is controlled by the liquid level in the reboiler: the bottom flow rate is increased or decreased with the corresponding decrease or increase in the top and external feed flow rates. The flow rate of the side stream and the power of reboiler heater (vapor flow rate from the reboiler) are proportionally adjusted with a change of flow rates of the external feed streams. The column pressure is controlled by the heater power at the refrigerant helium gas. The product purity should be maintained against the change of flow rates and compositions of the external feed streams by this control method.

3.2 Determination of process transfer function and tuning PI controller

The assumed upset for Column 1 is the first disturbance in Table 2: a step change in z_D from 0.495 to 0.545. For Column 2, a step change in z_T of F_2 is assumed as the upset. For Column 1, the molecular species of H_2, HD, HT, and D_2 are recovered at the top while DT and T_2 are recovered at the bottom. The key component can be considered as DT in the top stream: The mole fraction of DT in the top stream is the controlled variable. Since the function of Column 1 is to produce a high purity tritium, the atom fraction of T in the bottom stream can also be a controlled variable. For Column 2, the mole fraction of HT in the top stream is the controlled variable. Table 3 summarizes the disturbance of the external feed stream, and controlled and manipulated variables of the column:

Case 1, for Column 1, the mole fraction of DT in the top stream is the controlled variable;

Case 2, for Column 1, the atom fraction of T in the bottom stream is the controlled variable;

Case 4, for Column 2, the mole fraction of HT in the top stream is the controlled variable.

For column 1, we examine an additional case, case 3, where the flow rate of external feed stream is increased to 50 mol/h. The flow rates of top, bottom, and side streams are increased with the corresponding increase in the external feed stream. The liquid holdup in the packed section, H_L, is also increased with the corresponding increase in the external feed stream. The controlled values, DT mole fraction in the top stream of Column 1, T atom fraction in the bottom stream of Column 1, HT mole fraction in the top stream of Column 2, in Table 3 differs from that in Table 2; this is because the computer code simulating dynamic behavior of the column does not consider the factors such as the nonideality of hydrogen isotope solutions and the heat balance between isotopic species.

The response curves of the controlled variable to the step changes in the external feed composition and in the manipulated variable (ΔD) were first calculated. The value of ΔD is chosen -1 mol/h for Cases 1, 2, and 4, and is -3 mol/h for Case 3, from the calculated results in Table 2. The mean delay times for the response curves of the controlled variable were adequately longer for the step change in the external feed composition than for the step change in the manipulated variable. This means that the negative feedback control is quite satisfactory. To eliminate the offset, the PI action is chosen for the controller. Selection of the proportional-integral-derivative action is not necessary because of the sufficiently long response time to the disturbance.

For all the Cases 1 through 4, the response curves had inflection points, and the first-order lag system could not be applied. It was also observed that the dead time was negligible for all the Cases. As an example, the response curve for Case 2 is shown in Fig. 3. The second-order lag system, $G_p(s) = M/\{(1+T_1 s)(1+T_2 s)\}$, was assumed for both the columns and the optimum values of the parameters in the transfer function were searched by using the Simplex Method.[16] The results are given in Table 4. The process transfer function is approximately expressed by the second-order lag system, and the controller has the PI action. From the open loop transfer function, the two criteria for tuning PI controller parameters are derived as follows[13]:

$$T_i \geq \frac{KMT_1T_2}{(1+KM)(T_1+T_2)} \quad \text{and} \quad \omega^2 = \frac{KM}{T_i(T_1+T_2)} \qquad ; \qquad (1)$$

$$Y = -20\log_{10}|G(j\omega)|, \quad \text{and} \quad \angle G(j\omega) = -\pi \qquad ; \qquad (2)$$

where

$$|G(j\omega)| = \frac{KM\sqrt{(1-T_1T_2\omega^2-\mu)^2+\left[T_1T_2\omega/T_i-1/(T_i\omega)-\mu T_i\omega\right]^2}}{(1+T_1^2\omega^2)(1+T_2^2\omega^2)} \quad , \qquad (3)$$

$$\mu = (T_1+T_2)/T_i \quad , \qquad (4)$$

$$\angle G(j\omega) = \tan^{-1}\left[\frac{T_1T_2\omega^2 - 1 - (T_1 + T_2)T_i\omega^2}{(T_i - T_1 - T_2)\omega - T_1T_2T_i\omega^3}\right] \tag{5}$$

The order of magnitude of K can be estimated from the following equation representing the proportional-integral action[13].

$$-\Delta D(t) = K\Delta C + \frac{K}{T_i}\int_0^t \Delta C(t)dt \tag{6}$$

For Cases 1 and 3, the initial controlled variable, $y_{DT,1}$, is ~7.2×10^{-3}. It is desired that ΔC be approximately one order of magnitude smaller than the initial value. The order of magnitude value of ΔD is 10^0. Hence, the approximate value of K is expected to be ~1.4×10^3 mol/h. The value of ΔC for Case 4 should be ~2.4×10^{-11}, since $y_{HT,1}$ is ~2.4×10^{-10}; and K is ~3×10^{10}. The initial controlled variable for Case 2 is ~0.92. To keep the atom fraction of T in the bottom steam around ~0.9, we set the value of ΔC to 0.02. The value of K is consequently ~50. Substituting these K values into Eq. (1), we can obtain the minimum values of T_i. A favorable value of Y is ~10 dB, and the values of T_i at Y = 10 dB can be calculated from Eqs (2)~(5). Table 4 shows these values thus obtained.

3.3 Stability of control method

The response curves of the mole fraction of DT at the top and atom fraction of T at the bottom under the PI control are calculated for Cases 1 and 2. The proportional sensitivity is 1.4×10^3 mol/h for Case 1 and is 50 mol/h for Case 2. The value of T_i must be larger than ~0.04 h as indicated in Table 4. We set T_i to 0.1 h for both the Cases. The results are shown in Figs. 4 and 5. For both the cases, oscillatory lines are obtained, the overshoot are sufficiently small: The control is successful. For

Case 1, the atom fraction of T in the bottom stream is maintained at a slightly lower level (~0.91) than the initial value, however, the control method of Case 1 is more prompt than Case 2 as seen in Figs. 4 and 5. If this slightly lower value for the atom fraction of T is acceptable, Case 1 should be chosen as the control method for Column 1.

The response curves of the mole fraction of HT at the top under the PI control are calculated for Case 4. The proportional sensitivity is 3×10^{10} mol/h. We set T_i to 0.1 h for Case 4 also because of the calculated results in Table 4. The response curve is shown in Fig 6. The set of parameters of the PI controller gives us successful control. In comparison with Cases 1 and 2, the oscillatory line in Fig. 6 is appreciably slower. This would be due to the larger liquid holdup within Column 2.

3.4 Effect of time lag in measurement of controlled variable

As analysis instruments of hydrogen isotopes, we can mention ion chamber, gas chromatography, and Raman spectroscopy. For Cases 1 through 3, the Raman spectroscopy can be used to measure the mole fraction of DT in the top stream or the atom fraction of T in the bottom stream of Column 1[17]. The ion chamber is appropriate for Case 4 to measure the mole fraction of HT in the top stream of Column 2. The ion chamber and Raman spectroscopy can detect HT or DT within a negligible time. However, a few minutes would consequently be required to withdraw sample gases, to convert signals into mole fractions, and to send them to the PI controller. The stability of the control would greatly be affected, if the measurement of the controlled variable is accompanied by a time lag. Expressing the time lag by τ (h), we obtain the following simultaneous equations[13]:

$$T_{ic}\omega_c + KMT_{ic}\omega_c\cos(\tau\omega_c) - KM\sin(\tau\omega_c) - T_iT_1T_2\omega_c^3 = 0 \quad , \tag{7}$$

$$-T_{ic}T_2\omega_c^2 + KMT_{ic}\omega_c\sin(\tau\omega_c) + KM\cos(\tau\omega_c) - T_iT_1\omega_c^2 = 0 \ , \qquad (8)$$

If K, M, T_1, T_2, and τ are given; the lower limit of the integral time, T_{ic}, can be calculated by solving these equations by the Newton-Raphson method, where T_{ic} and ω_c are the independent variables.

Figure 7 shows the curves of T_{ic} plotted against τ. A longer time lag requires a larger integral time to avoid the instability of the control. For Cases 3 and 4, the effect of the time lag in measurement is not serious. A relatively large time lag is permissible. Especially for Case 4, even a considerably long time lag is acceptable as seen in the figure. This result does not contradict with one of the conclusions obtained in our previous study[13] that the effect of time lag is more serious for the smaller column that processes a smaller feed flow rate. In comparison between Cases 1 and 2, a longer time lag is allowable for Case 2. From viewpoint of the effect of time lag, the atom fraction of T in the bottom stream is the favorable controlled variable for Column 1. Only a short time lag (~0.05 h) is allowable with K = 1400 mol/h for Case 1. To relax this restriction, we should decrease the value of K. The calculated result for K = 400 mol/h is also presented in Fig. 7. The allowable time lag is appreciably increased. For verification, the response curves of the controlled variable to the step change in the external feed composition are calculated under the PI control incorporating the time lag of 0.1 h: the controlled variable is the mole fraction of DT in the top stream, K = 400 mol/h, and T_i = 0.3 h; the controlled variable is the atom fraction of T in the bottom stream, K = 50 mol/h, and T_i = 0.3 h. The results are shown in Figs. 8 and 9. Successful control is obtained for both the sets of parameters; although the overshoots are considerably increased in comparison with the cases without the time lag (Figs. 5 and 6). There is no significant difference between Figs. 8 and 9 concerning the overshoot and stability of the control. If it is the most significant task that the tritium purity in the product is stabilized, the atom fraction of T in the bottom stream should be chosen as the controlled variable. If a variation of the tritium purity (0.90~0.92) is allowable, the mole fraction of DT in the top stream should be chosen; where the values of K and T_i can be decreased with decreasing the time lag in measurement, and more prompt control can be obtained.

4. Conclusion

A two-column cascade composed of the columns having feedback streams is proposed for a fusion reactor. The lead column produces high purity tritium from the exhaust gas from a plasma. The second column produces a tritium-free and a hydrogen-free stream from the top stream of the lead column and hydrogen gases from the water detritiation and blanket systems.

The method of parameter setting for the PI controller was proposed for each column of the cascade. For the change of external feed composition, the column with a feedback stream can maintain the product purity by just adjusting the flow rates of top and bottom streams. The mole fraction of DT at top or the atom fraction of T can be the controlled variable for the lead column. The mole fraction of HT at top is the controlled variable for the second column.

The mole fraction DT is the more favorable controlled variable than the atom fraction of T because of promptness of the control; though there is possibility that the tritium purity is maintained at a slightly lower level than the initial value. However, only a short time lag in the measurement of the controlled variable is permissible than the other case. The value for the proportional sensitivity must be decreased to relax this restrict. For the second column, successful control is obtained to choose the mole fraction of HT at top as the controlled variable. In addition, a considerably long time lag is acceptable than the lead column. This result is quite understandable if we recall values of K and T_i can be decreased with decreasing the time lag in measurement, and more prompt control can be obtained.

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The time lag in the measurement depends on selected analysis instruments such as the ion chamber and Raman spectroscopy. The results of the present study allow us to determine a set of parameters of the PI controller which can avoid unstable region of the control. The information given here would be useful for the design of control systems of other cascades composed of the columns having feedback streams.

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Nomenclature

B = flow rate of bottom stream (mol/h)

ΔC = magnitude of controlled variable (-)

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

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

F = flow rate of external feed stream (mol/h)

$G(s)$ = process transfer function

H_L = liquid holdup for a theoretical stage in packed section (mol)

K = proportional sensitivity (mol/h)

M = static gain (h/mol)

N = number of total theoretical stages (-)

$N_{F,ex}$ = external feed stream stage number (-)

$N_{F,fb}$ = feedback stream stage number (-)

N_S = side stream stage number (-)

P = pressure (kPa)

R = reflux ratio (-)

T_1, T_2 = time constants for second-order lag system (h)

T_i = integral time (h)

t = time (h)

W_S = flow rate of side stream (mol/h)

Y = gain margin (dB)

z = atom fraction in external feed stream (-)

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

ω = angular frequency (1/h)

Subscript

c = critical value

D = deuterium

H = hydrogen

Table 1 Column parameters for a representative case

	Column 1	Column 2
N	83	120
$N_{F,ex}$	40	F_1=30, F_2 =60, F_3 =90
$N_{F,fb}$	40	60
N_S	50	95
F (mol/h)	16	F_1=552, F_2=105, F_3=7.5
D (mol/h)	7.5	657
B (mol/h)	8.5	7.5
W_S (mol/h)	96	300
R	20	5
P (kPa)	101.3	101.3
H_L (mol)	0.12	1.7
Top		
H_2, HD	2.79×10^{-4}, 2.53×10^{-2}	0.990, 9.62×10^{-3}
HT, D_2	1.68×10^{-2}, 0.908	1.53×10^{-9}, 0.0
DT, T_2	4.99×10^{-2}, 2.05×10^{-5}	0.0, 0.0
Bottom		
H_2, HD	0.0, 0.0	0.0, 8.16×10^{-7}
HT, D_2	2.22×10^{-9}, 2.51×10^{-4}	2.90×10^{-5}, 0.654
DT, T_2	0.195, 0.805	0.342, 4.06×10^{-3}

Table 2 Effect of flow rate and composition of the external feed stream on column performance

	Column 1	Column 1	Column 1	Column 2	Column 2
Disturbance	$z_D = 0.545$ $z_T = 0.445$	$z_D = 0.445$ $z_T = 0.545$	F=20.8 mol/h	z_H =0.9799 $z_T = 0.02$	$F_2 = 205$ mol/h
Change of operational conditions*1	D = 8.4 B = 7.6 R = 18.5*2	D = 6.6 B = 9.4 R = 22.5*2	D = 9.75 B = 11.05 W_S =124.8	D = 656 B = 8.5 R = 5.01*2	D = 756 B = 8.5
Top	D_2 = 0.925 DT = 3.76×10^{-2}	D_2 = 0.901 DT = 5.10×10^{-2}	D_2 = 0.913 DT = 4.45×10^{-2}	HT = 1.80×10^{-9}	HT = 1.91×10^{-10}
Bottom	DT = 0.182 T_2 = 0.817	DT = 0.195 T_2 = 0.805	DT = 0.190 T_2 = 0.810	HT = 4.38×10^{-5}	HT = 3.43×10^{-5}

* 1: Other calculated conditions are identical to those in Table 3.

*2: The reflux ratio is established so that the vapor flow rate from the condenser (or equivalently, the liquid flow rate from the condenser) is equal to that in Table 3.

Table 3 Controlled and manipulated variables

	Case1 (Column 1)	Case 2 (Column 1)	Case 3 (Column 1)*1	Case 4 (Column 2)
Controlled	Mole fraction of DT at top $\sim 7.2\times10^{-3}$	Atom fraction of T at bottom ~0.92	Mole fraction of DT at top $\sim 7.2\times10^{-3}$	Mole fraction of HT at Top $\sim 2.4\times10^{-10}$
Disturbance	Decrease of atom fraction of T in feed stream $z_D = 0.545$ and $z_T = 0.445$*2	Same as Case 1	Same as Case 1	Increase of atom frcation of T in feed stream from blanket z_T=0.2*2
Manipulated	Flow rate of top stream	Same as Case 1	Same as Case 1	Same as Case 1

*1: F=50 mol/h, D=23.45 mol/h, B=26.55 mol/h, W_S=300 mol/h, H_L=0.36 mol, other conditions are the same as Cases 1 and 2.

*2: The feed is equilibrated.

Table 4 Optimum values of parameters in transfer function and proportional-integral controller

	ΔD (mol/h)	T_1 (h)	T_2 (h)	M (h/mol)	K (mol/h)	Mnimum T_i (h)	T_i at Y = 10 db (h)
Case 1	-1	0.480	0.0521	4.6×10^{-3}	1.4×10^{3}	0.041	0.046
					400	0.031	0.045
Case 2	-1	0.573	0.0447	6.5×10^{-2}	50	0.032	0.040
Case 3	-3	0.547	0.0494	1.5×10^{-3}	1.4×10^{3}	0.031	0.039
Case 4	-1	0.730	0.0565	4.8×10^{-11}	3.0×10^{10}	0.031	0.050

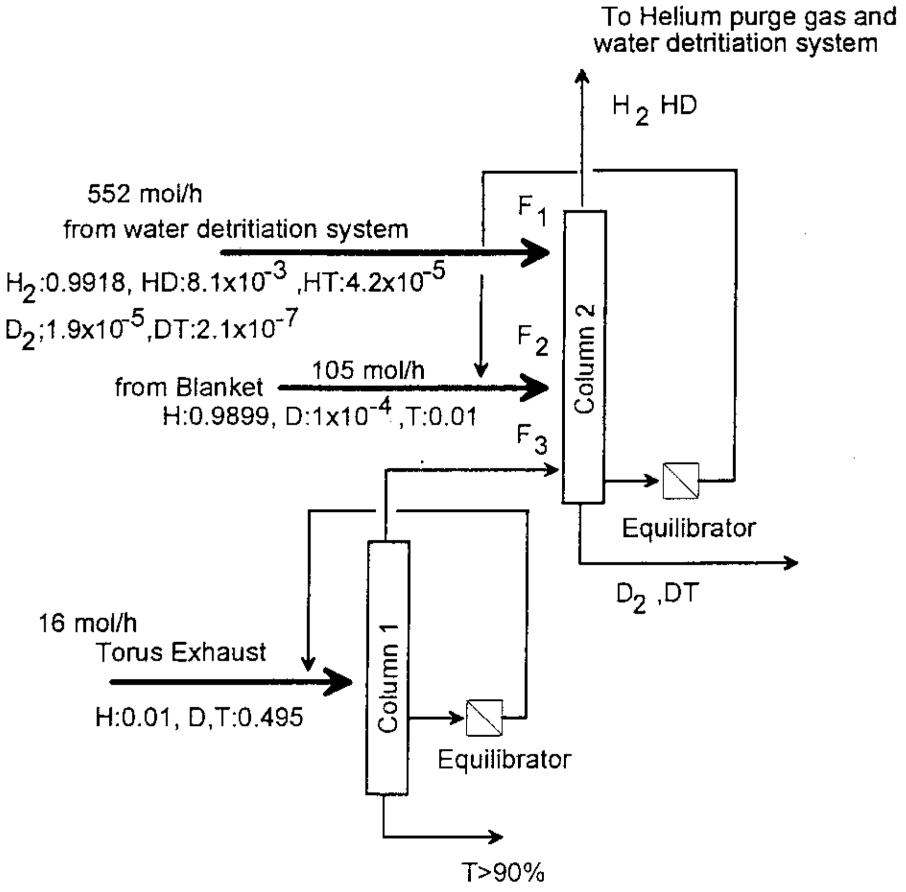
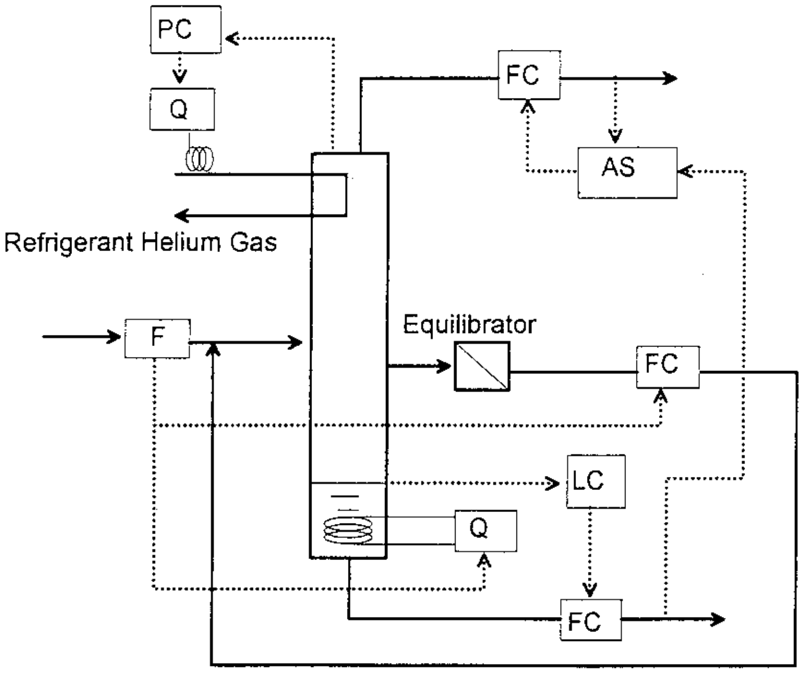


Fig. 1 Conceptual flow diagram of a cascade proposed for a fusion reactor.



AS : Analysis System F : Flow Meter
FC : Flow Controller Q : Heater
PC : Pressure Controller LC : Liquid Level Controller

Fig. 2 Control scheme of the column with a feedback stream.

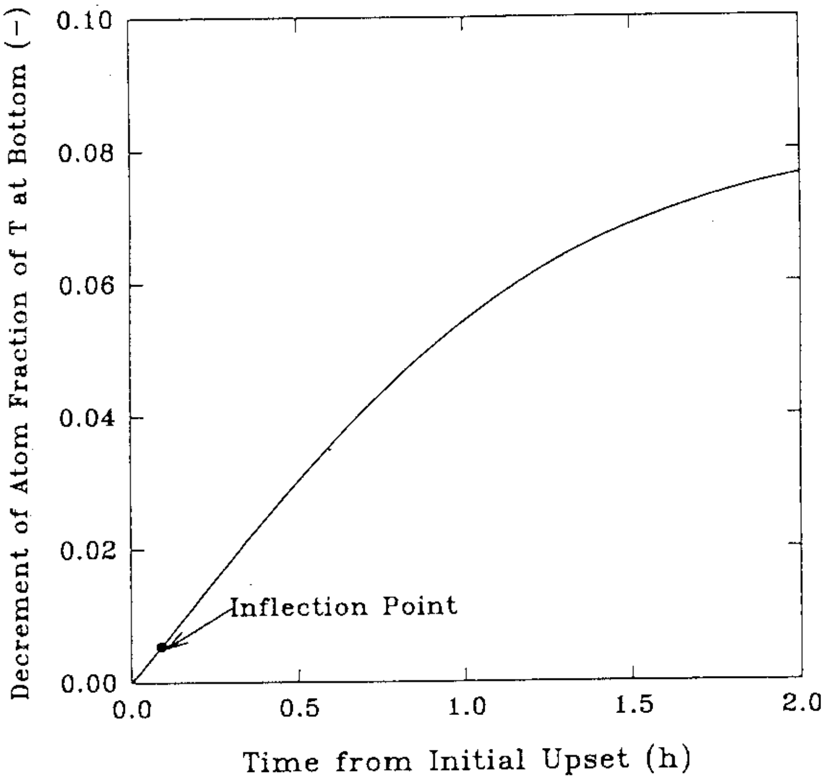


Fig. 3 Response of atom fraction of T at bottom (controlled variable) to a step change in manipulated variable ($\Delta D = -1$ mol/h) for Case 2.

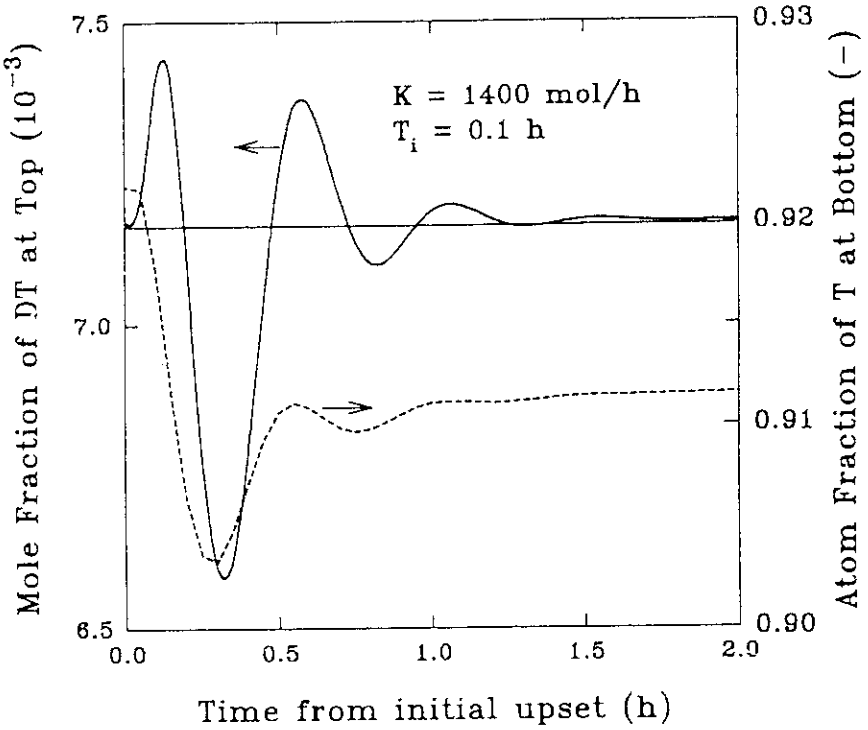


Fig. 4 Response of mole fraction of DT and atom fraction of T at bottom to a step change in external feed composition ($z_D = 0.495 \rightarrow 0.545$) under the PI control for Case 1 : K = 1400 mol/h and $T_i = 0.1$ h.

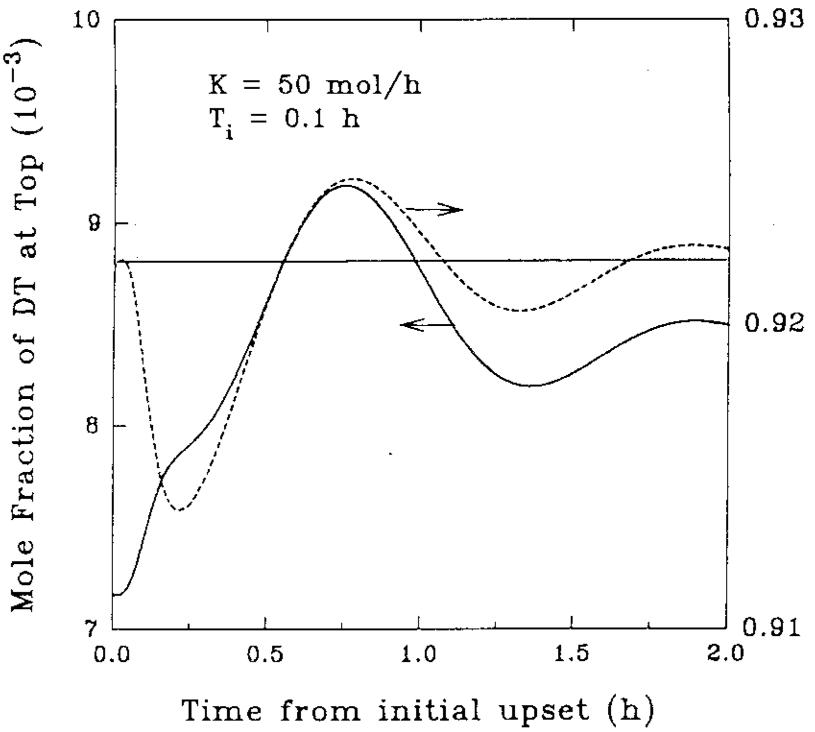


Fig. 5 Response of mole fraction of DT and atom fraction of T at bottom to a step change in external feed composition ($z_D = 0.495 \rightarrow 0.545$) under the PI control for Case 2 : K = 50 mol/h and $T_i = 0.1$ h.

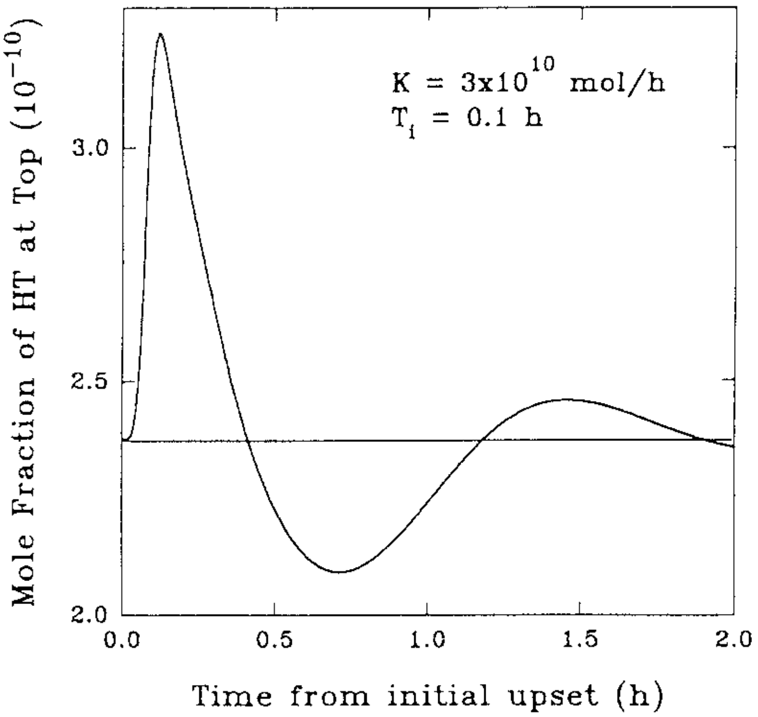


Fig. 6 Response of mole fraction of HT to a step change in the external feed composition from blanket ($z_t = 0.01 \rightarrow 0.02$) under the PI control for Case 4 : K = 3×10^{10} mol/h and $T_i = 0.1$ h.

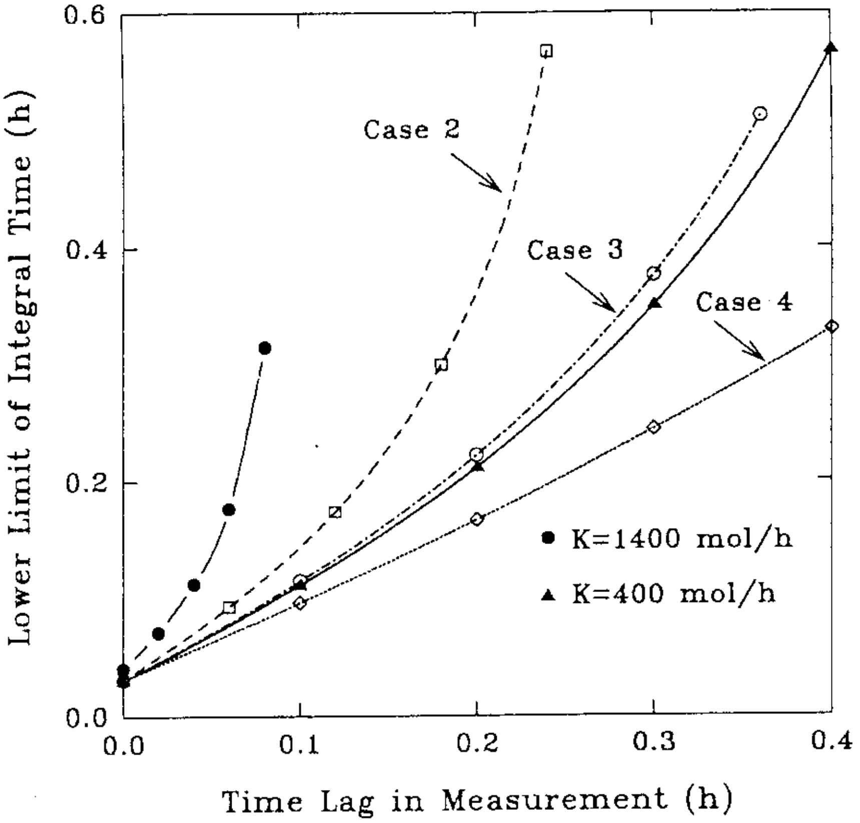


Fig. 7 Curve of lower limit of integral time plotted against the time lag in measurement of controlled variable, solid symbols and lines are Case 1.

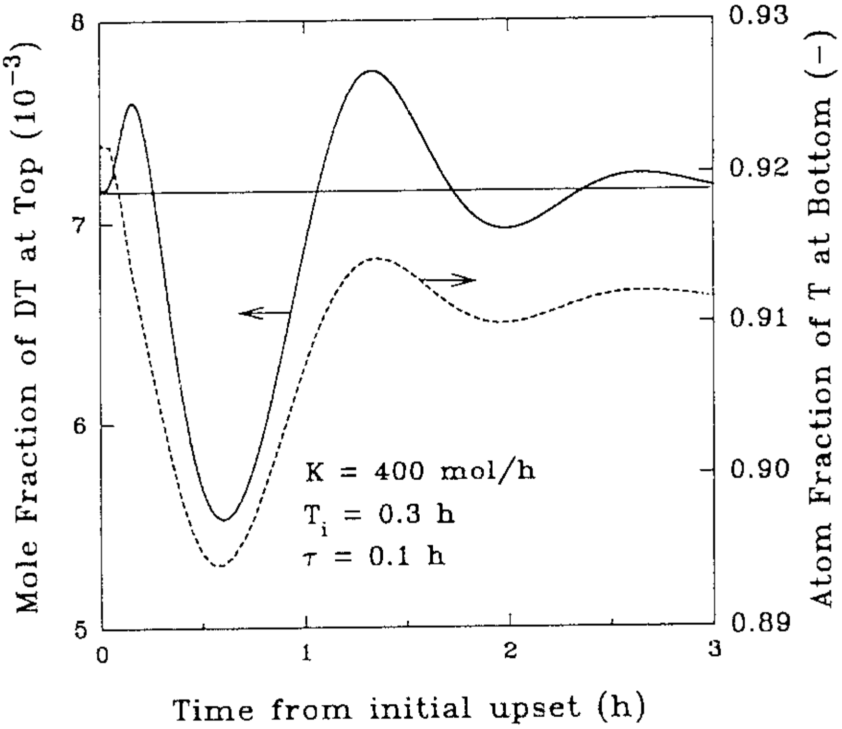


Fig. 8 Response of mole fraction of DT and atom fraction of T at bottom to a step change in external feed composition ($z_D = 0.495 \rightarrow 0.545$) under the PI control accompanied by the time lag in measurement of controlled variable for Case 1 : $K = 400$ mol/h, $T_i = 0.3$ h, and $\tau = 0.1$ h.

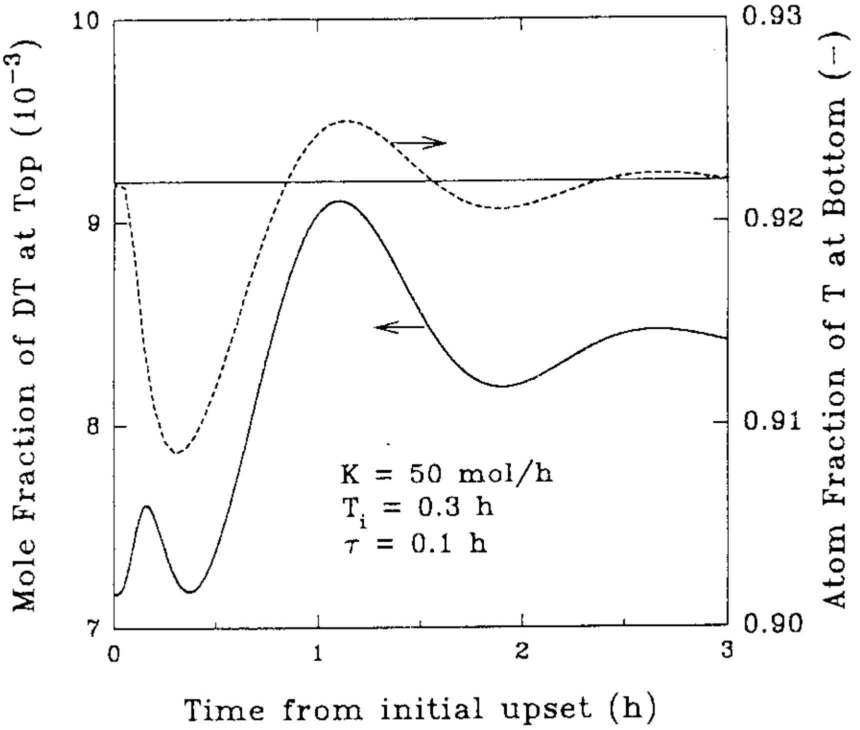


Fig. 9 Response of mole fraction of DT and atom fraction of T at bottom to a step change in external feed composition ($z_D = 0.495 \rightarrow 0.545$) under the PI control accompanied by the time lag in measurement of controlled variable for Case 2 : K = 50 mol/h, $T_i = 0.3$ h, and $\tau = 0.1$ h.