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The present paper reports revision of the design model previously developed by the authors for the cryogenic falling liquid film helium separator. The revised design procedure is composed of three steps : 1) calculation of distributions of phase flow rates, temperature and phase compositions within the refrigerated section and the packed section ; 2) calculation of more detailed distributions of these variables within the refrigerated section ; and 3) estimation of column dimensions and determination of operating conditions. It is assumed that the vacant refrigerated section has two theoretical stages for hydrogen isotope separation. The mixture within the refrigerated section is considered in step 2) as two component system of He-HD.

KEYWORDS : Design Model, Cryogenic Temperature, Falling Liquid Film, Helium Separator, Refrigerated Section, Packed Section, Isotope Separation, Hydrogen Isotopes

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流下液膜式ヘリウム分離塔の設計モデルの改訂

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（1983年4月13日受理）

本報告は，著者らがすでに流下液膜式ヘリウム分離塔用に開発した設計モデルの改訂について述べたものである。改訂された設計手順は次の3つのステップから成る：1）冷凍部及び充塡部における気液流量，温度，及び気液組成の計算；2）冷凍部におけるこれらの変数のより詳細な解析；3）設計変数および操作変数の決定。

空の冷凍部は，水素同位体分離用には2理論段を有しているものと仮定されている。ステップ2）では，混合物はHe－HDの2成分系として取り扱われている。

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1. INTRODUCTION

The authors[(1)(2)] have developed a preliminary design model for a cryogenic falling liquid film helium separator for removing helium from hydrogen isotopes. The column is composed of two sections, a refrigerated section and a packed section. The computer code, FLFC,[(1)-(3)] allowed us to analyze the separation characteristics of the column. A significant amount of information was revealed by our previous studies. However, the estimation method for dimensions of the refrigerated section is not absolutely the best one, so we have to try to revise the design model. In the previous model, hydrogen isotope separation was assumed to be promoted even within the refrigerated section to some extent. In addition, the molecular species, D_2, was chosen for calculating the transfer coefficients.

Yamanishi & Kinoshita[(4)-(6)] have performed an experimental work for a cryogenic distillation column with a small inner diameter separating N_2 and Ar. The results indicate that the HETP value is approximately 5 cm if the column is packed with the packing materials, while it is about 50 cm if the column is vacant. Therefore, unless the column is packed with the packing materials, the vapor/liquid interface area is not adequately large with the result that the separation is very poor. For this reason, if the refrigerated section of the falling liquid film condenser is vacant, it should have only a few theoretical stages because its height is ~ 1 m. Additionally, the predominant molecular species within the refrigerated section is not D_2 but HD.

The present report describes a revised design model for overcoming these problems. The refrigerated section can also be packed with the packing materials, but it is assumed to be vacant in the present study.

2. DESCRIPTION OF REVISED DESIGN MODEL

The revised design model for estimation of column dimensions requires three steps of calculations : 1) calculation of distributions of temperature, liquid and vapor flow rates, and compositions of the two phases within the two sections ; 2) investigation of more detailed distributions of temperature, phase flow rates and helium concentration within the refrigerated section ; and 3) estimation of specifications of the refrigerated section (specifications of the packed section can readily be estimated because a significant amount of information has been obtained by experimental studies at the Los Alamos National Laboratory[7][8]). More details are described as follows.

2.1 Step (1)

The calculation can be performed by means of our previous computer code, FLFC. A total of seven components (He, H_2, HD, not D_2 but HD.

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2.1 Step (1)

The calculation can be performed by means of our previous computer code, FLFC. A total of seven components (He, H_2, HD, HT, D_2, DT and T_2) must be considered in the calculation. The model column for mathematical simulation in this step is illustrated in Fig. 1. The refrigerated section is postulated to have two theoretical stages, while the packed section has many stages. The input and output variables for the step (1) calculation are listed in Table 1. Significant parameters which are used as input variables for the step (2) calculation are the flow rate of the vapor stream entering the refrigerated section and the composition of this vapor flow. An example calculation is made under the conditions given in Table 2. The calculational results (listings of the final results) are given in Tables 3 - 5. As observed from these tables, the information concerning the temperature and composition profiles within the refrigerated section is not adequate. Hence, we have to further analyze these profiles in step (2). We rename the computer code used here 'FLFC1'.

2.2 Step (2)

The model column to be analyzed in this step is illustrated in Fig. 2. The vapor flow entering the refrigerated section is considered as the feed. The feed can be considered as a mixture of He and HD. The section is separated into many elemental stages for calculating more detailed temperature and helium concentration profiles. It should be noted that the elemental stage introduced here is quite different in the concept from the usual theoretical stage. The number of total elemental stages has no effect on the separation performance. A larger number results in a more accurate analysis. The input and output variables for the step (2) calculation are listed in Table 6. The calculation is performed by means of a new computer code, FLFC2. An example calculation is made under the conditions given in Table 7. The listings of the final results are given in Tables 8 and 9. By using distributions of phase flow rates, temperature and helium concentration calculated here, the dimensions of the refrigerated section are estimated by means of FLFC3, in accordance with the following procedure.[1][2]

2.3 Step (3)

The components which are present within the refrigerated section are He and HD. We apply the method proposed by Colburn and Hougen[9] to the j-th stage of the refrigerated section as illustrated in Fig. 3. The heat transfer equation is expressed by

$$\theta_{Gj}(T_{Gj} - T_{Cj}) + \kappa_j \lambda_j (p'_{Cj} - p'_{Gj}) = \theta_{Oj}(T_{Cj} - T_{Rmj}), \qquad (1)$$

where

$$p'_{Cj} = P_j - p(T_{Cj})x_j, \; p'_{Gj} = P_j - p(T_{Gj})x_j. \qquad (2)$$

The overall conductance is made up of the conductance of the gas film, condensate (liquid film), metal wall and the refrigerant gas film. In Eq.(1), all except the gas conductance are grouped together as a single conductance. Since the distributions of temperature, phase flow rates and helium concentration are calculated in step (2), the transfer coefficients can be estimated.

The film coefficient of heat transfer θ_{Gj} and the molar mass transfer coefficient κ_j are calculated for the gas film from the following equations :

$$\theta_{Gj} = 4J_j c_{Gj} V_{mj}/Pr_j^{2/3}/\pi d_j^2 \tag{3}$$

and

$$\kappa_j = 4J_j V_{mj}/p'_{ln.j}/Sc_j^{2/3}/\pi d_j^2 \ , \tag{4}$$

where

$$Pr_j = c_{Gj}\mu_{Gj}/k_{Gj} \ , \quad Sc_j = \mu_{Gj}/\rho_{Gj}/\Xi_j \ ,$$

$$J_j = J_j(Re_j), \ Re_j = 4V_{mj}/\pi/\mu_{Gj}/d_j$$

$$\text{and } p'_{ln.j} = (p'_{Gj} - p'_{Cj})/\ln(p'_{Gj}/p'_{Cj}) \ . \tag{5}$$

These equations are derived assuming that two components are present and the diffusion of the condensible component occurs in one direction.[10] The Chilton and Colburn's j-factor, J_j, is given as a function of Reynolds Number in Fig. 1 of Ref.(10). The combined coefficient of heat transfer θ_{0j} is calculated from the following equations[11]:

$$\theta_{Cj} = 1.47(\mu_{Cj}^2/k_{Cj}^3/\rho_{Cj}^2/g)^{-1/3}(4\Gamma_j/\mu_{Cj})^{-1/3},$$

$$\Gamma_j = L_j/\pi/d_j \ ,$$

$$\theta_{Rj}D_{ej}/k_{Rj} = 0.023(G_jD_{ej}/\mu_{Rj})^{0.8}(c_{Rj}\mu_{Rj}/k_{Rj})^{0.4},$$

$$D_{ej} = (D_{2j}^2 - D_{1j}^2)/D_{1j} \ ,$$

$$1/\theta_{0j} = (1/\theta_{Rj})(d_j/D_{1j}) + (\delta_j/k_{Mj})(d_j/D_j) + 1/\theta_{Cj} \ ,$$

$$\delta_j = (D_{1j} - d_j)/2 \ , \quad \text{and } D_j = (D_{1j} + d_j)/2 \ . \tag{6}$$

Under usual conditions, the liquid film resistance can be neglected in comparison with the other two resistances.
The equivalent height l_j for each elemental stage is estimated from the following procedure.

1) Assume the diameters, d_j, D_{1j} and D_{2j}.
2) Assume the inlet and outlet temperatures of the helium refrigerant gas, T_{Rin} and T_{Rout}, for calculating the required flow rate V_R and the mean temperature on the j-th stage T_{Rmj} from

$$V_R = Q_T/c_{Rm}/(T_{Rout} - T_{Rin}),$$

$$T_{Rj+1} = Q_j/V_R/c_{Rm} + T_{Rj}, \quad T_{Rin} = T_{R1},$$

$$\text{and } T_{Rmj} = (T_{Rj+1} + T_{Rj})/2, \ (\ j = 1, \ \ldots, \ M \ ). \tag{7}$$

3) Calculate the transfer coefficients.
4) Solve the following nonlinear equation for T_{Cj} by using the Newton method :

$$\theta_{Gj}(T_{Gj} - T_{Cj}) + \kappa_j\lambda_j(p'_{Cj} - p'_{Gj}) - \theta_{Oj}(T_{Cj} - T_{Rmj})$$
$$= 0 , \qquad (8)$$

where T_{Gj} is the temperature calculated in step (2).

5) Calculate the equivalent height l_j from

$$l_j = Q_j/\theta_{Oj}/(T_{Cj} - T_{Rmj})/\pi/d_j . \qquad (9)$$

6) Verify that the following material balance equation is approximately satisfied :

$$\kappa_j(p'_{Cj} - p'_{Gj})\pi d_j l_j = L_j - L_{j-1} . \qquad (10)$$

In the region of small Reynolds Number, it is needed to allow for effects of the natural convection. As a consequence, the j-factor depends upon l_j requiring a cumbersome calculational procedure. Although the order of magnitude of the parameter $l_j/d_j/\phi_j$ (the physical meaning of this parameter is given in Ref.(10)) is in the range from 10^0 to 10^1, we set the value of the parameter at unity. Hence, in the design, the calculated values of the transfer coefficients must be divided by a certain value larger than unity to compensate for the uncertainty. The thermal conductivity, density, specific heat at constant pressure and viscosity of the HD gas are calculated by using the equations proposed by Souers.[12] These physicochemical parameters for He and the diffusion coefficient of the He-HD system are calculated by using the equations derived by the rigorous kinetic theory of gases.[13]

The inlet temperature of the refrigerant should carefully be controlled to meet the following requirements : 1) the inlet temperature of the refrigerant must be lower than the temperature of the top of the column ; 2) the inlet temperature of the refrigerant must be adequately high for preventing hydrogen isotopes from freezing ; and 3) the difference between the column temperature and the refrigerant temperature should be sufficiently large. The hydrogen isotopes (10 % H_2 and 90 % HD) freezes at ~ 16.5 K. Hence, 18 K is chosen for the inlet temperature in the present design.

An example design is made and the results are summarized in Tables 10 and 11. The coefficients, θ_{Gj}, κ_j and θ_{0j} are divided by 2 in the calculation. The equivalent height for the first elemental stage is significantly higher than those for the other stages. The reasons are as follows : 1) the gas velocity is very low, and the rates of mass and heat transfers are also very low ; 2) the partial pressure of He is large with the result that the mass transfer coefficient for HD is small ; and 3) the temperature difference between the liquid film and the refrigerant is not large. The problem of the low gas velocity could be eliminated by decreasing the inner diameter, but it is already very small.

3. CONCLUSION

The design model for the cryogenic falling liquid film helium separator has been revised. The design procedure is composed of three steps : 1) calculation of distributions of phase flow rates, temperature and phase compositions within the refrigerated section and the packed section ; 2) calculation of more detailed distributions of these variables within the refrigerated section ; and 3) estimation of column dimensions and determination of operating conditions. The three computer codes, FLFC1, FLFC2 and FLFC3 are now available for these steps.

A rigorous dynamic simulation code, FLFC4, is under development for design of the control system. These four computer codes are very useful for analyses on both the steady state and dynamic characteristics of the falling liquid film condenser.

NOMENCLATURE

c = specific heat at constant pressure (cal/g-mol/K)

G = mass velocity of refrigerant (g-mol/cm^2/h)

g = acceleration of gravity (cm/h)

J = Chilton and Colburn's j-factor

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k = thermal conductivity (cal/h/cm/K)

L_j = flow rate of liquid stream leaving j-th stage (g-mol/h)

M = number of total elemental stages

N = number of total theoretical stages

N_F = feed stage number

N_R = number of total refrigerated stages

P_j = total pressure on j-th stage (atm)

$p(T_j)$ = vapor pressure of condensible component at T_j K (atm)

p' = partial pressure of inert component (atm)

Pr = Prandtl Number

Q_j = heat subtraction rate on j-th stage (j = 1, 2)

Q_T = total heat subtraction rate (cal/h)

q_j = heat subtraction rate on j-th stage (j = 1, ..., M) (cal/h)

Re = Reynolds Number

Sc = Schmidt Number

T_j = temperature on j-th stage (K)

V_j = flow rate of vapor stream leaving j-th stage (g-mol/h)

x_j = mole fraction of condensible component in liquid stream leaving j-th stage

δ = wall thickness (cm)

θ = film coefficient of heat transfer (cal/h/cm^2/K)

κ = molar mass transfer coefficient (g-mol/h/cm^2/atm)

λ = latent heat of vaporization of condensible component (cal/g-mol)

μ = viscosity (g-mol/cm/h)

Ξ = diffusion coefficient of He-HD system (cm^2/h)

ρ = density (g-mol/cm^3)

(Subscript)

C : condensate film (liquid film)

G : gas (main body)

j : stage

M : metal wall

m : mean value

R : refrigerant gas

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Table 1 Input and Output Variables for Step (1) Calculation

<u>Input Variables</u>
Number of total theoretical stages (N)
Number of total refrigerated stages (N_R = 2)
Feed stage number (N_F)
Feed specifications (flow rates, temperature, composition)
Operating pressure (P)
Flow rate of top gas (FD)
Heat subtraction rate on refrigerated stages (Q_j, j = 1, 2)
<u>Output Variables</u>
Flow rate of gas stream leaving each stage
Flow rate of liquid stream leaving each stage
Temperature on each stage
Composition of gas stream leaving each stage
Composition of liquid stream leaving each stage
Reboiler duty

The molecular species to be considered are He, H_2, HD, HT, D_2, DT and T_2.

Table 2 Calculational Conditions of Step (1)

Feed flow rate = 15 g-mol/h		
Feed temperature = 31.5 K		
Feed composition* :		
H_2 = 0.5162D-3	HD = 0.1963D-1	HT = 0.1734D-1
D_2 = 0.2307	DT = 0.4499	T_2 = 0.2319
He = 0.5000D-1		
(H : D : T = 2 : 49 : 49)		
Top gas flow rate = 0.83 g-mol		
Operating pressure = 5 atm		
$Q_1 = Q_2$ = 20000 cal/h		
N = 60		

*) The original feed is an equimolar mixture of D-T containing 1 atom% H. However, protium is added to this original feed for decreasing the tritium concentration in the top gas and for assuring an adequate flow rate from the top of column (2) in the Isotope Separation System.

Table 3 Final Results of Step (1) Calculation

***** FINAL RESULT *****

***** VAPOR FLOW RATES (G-MOL/H) *****

1	0.830000	2	74.7206	3	190.829	4	191.748	5	191.641
6	191.540	7	191.465	8	191.409	9	191.367	10	191.336
11	191.313	12	191.296	13	191.283	14	191.273	15	191.266
16	191.260	17	191.255	18	191.251	19	191.248	20	191.244
21	191.241	22	191.237	23	191.233	24	191.228	25	191.223
26	191.215	27	191.206	28	191.194	29	191.179	30	191.160
31	191.134	32	191.100	33	191.055	34	190.996	35	190.916
36	190.810	37	190.666	38	190.474	39	190.214	40	189.865
41	189.397	42	188.772	43	187.946	44	186.865	45	185.476
46	183.727	47	181.587	48	179.050	49	176.158	50	172.995
51	169.686	52	166.375	53	163.196	54	160.252	55	157.605
56	155.275	57	153.248	58	151.495	59	134.842	60	133.870

***** LIQUID FLOW RATES (G-MOL/H) *****

1	73.8906	2	189.999	3	190.918	4	190.811	5	190.710
6	190.635	7	190.579	8	190.537	9	190.506	10	190.483
11	190.466	12	190.453	13	190.443	14	190.436	15	190.430
16	190.425	17	190.421	18	190.418	19	190.414	20	190.411
21	190.407	22	190.403	23	190.398	24	190.393	25	190.385
26	190.376	27	190.364	28	190.349	29	190.330	30	190.304
31	190.270	32	190.225	33	190.166	34	190.086	35	189.980
36	189.836	37	189.644	38	189.384	39	189.035	40	188.567
41	187.942	42	187.116	43	186.035	44	184.646	45	182.897
46	180.757	47	178.220	48	175.328	49	172.165	50	168.856
51	165.545	52	162.366	53	159.422	54	156.775	55	154.445
56	152.418	57	150.665	58	149.012	59	148.040	60	14.1700

***** TEMPERATURES (K) *****

1	19.7755	2	28.9762	3	29.0490	4	29.0650	5	29.0760
6	29.0843	7	29.0904	8	29.0951	9	29.0985	10	29.1012
11	29.1031	12	29.1047	13	29.1058	14	29.1068	15	29.1076
16	29.1082	17	29.1088	18	29.1094	19	29.1100	20	29.1106
21	29.1112	22	29.1120	23	29.1128	24	29.1138	25	29.1149
26	29.1162	27	29.1178	28	29.1197	29	29.1220	30	29.1248
31	29.1282	32	29.1325	33	29.1377	34	29.1442	35	29.1525
36	29.1628	37	29.1760	38	29.1929	39	29.2144	40	29.2421
41	29.2775	42	29.3226	43	29.3797	44	29.4511	45	29.5387
46	29.6438	47	29.7662	48	29.9039	49	30.0530	50	30.2079
51	30.3626	52	30.5114	53	30.6501	54	30.7762	55	30.8890
56	30.9890	57	31.0775	58	31.1561	59	31.2427	60	31.3025

Table 4　Final Results of Step (1) Calculation

***** VAPOR MOLE FRACTIONS *****

	H2	HD	HT	D2	DT	T2	HE
1	0.901905D-02	0.873487D-01	0.177873D-04	0.184434D-07	0.938160D-11	0.104973D-14	0.903614
2	0.536713D-01	0.931785	0.252173D-03	0.342390D-06	0.235767D-09	0.369171D-13	0.142914D-01
3	0.406577D-01	0.954769	0.299344D-03	0.477057D-06	0.377839D-09	0.681945D-13	0.427318D-02
4	0.304358D-01	0.965199	0.350359D-03	0.655004D-06	0.596280D-09	0.123971D-12	0.401433D-02
5	0.227327D-01	0.972848	0.408789D-03	0.896408D-06	0.937819D-09	0.224573D-12	0.401013D-02
6	0.169578D-01	0.978553	0.475936D-03	0.122404D-05	0.147154D-08	0.405827D-12	0.401196D-02
7	0.126424D-01	0.982789	0.553219D-03	0.166862D-05	0.230499D-08	0.732048D-12	0.401344D-02
8	0.942549D-02	0.985915	0.642273D-03	0.227184D-05	0.360579D-08	0.131871D-11	0.401455D-02
9	0.703167D-02	0.988205	0.744986D-03	0.309023D-05	0.563517D-08	0.237312D-11	0.401536D-02
10	0.525273D-02	0.989864	0.863535D-03	0.420048D-05	0.880027D-08	0.426738D-11	0.401597D-02
11	0.393204D-02	0.991045	0.100043D-02	0.570660D-05	0.137356D-07	0.766925D-11	0.401642D-02
12	0.295229D-02	0.991865	0.115858D-02	0.774963D-05	0.214296D-07	0.137771D-10	0.401676D-02
13	0.222586D-02	0.992405	0.134131D-02	0.105209D-04	0.334229D-07	0.247409D-10	0.401700D-02
14	0.168748D-02	0.992728	0.155251D-02	0.142797D-04	0.521154D-07	0.444184D-10	0.401719D-02
15	0.128859D-02	0.992878	0.179661D-02	0.193777D-04	0.812457D-07	0.797296D-10	0.401733D-02
16	0.993117D-03	0.992884	0.207878D-02	0.262916D-04	0.126638D-06	0.143088D-09	0.401743D-02
17	0.774289D-03	0.992767	0.240493D-02	0.356675D-04	0.197363D-06	0.256757D-09	0.401751D-02
18	0.612247D-03	0.992540	0.278192D-02	0.483811D-04	0.307549D-06	0.460663D-09	0.401758D-02
19	0.492265D-03	0.992206	0.321764D-02	0.656189D-04	0.479191D-06	0.826400D-09	0.401763D-02
20	0.403432D-03	0.991768	0.372118D-02	0.889880D-04	0.746536D-06	0.148232D-08	0.401767D-02
21	0.337664D-03	0.991220	0.430301D-02	0.120665D-03	0.116289D-05	0.265851D-08	0.401771D-02
22	0.288972D-03	0.990553	0.497517D-02	0.163597D-03	0.181120D-05	0.476729D-08	0.401775D-02
23	0.252921D-03	0.989753	0.575151D-02	0.221771D-03	0.282051D-05	0.854743D-08	0.401780D-02
24	0.226227D-03	0.988803	0.664792D-02	0.300582D-03	0.439151D-05	0.153222D-07	0.401786D-02
25	0.206455D-03	0.987679	0.768261D-02	0.407322D-03	0.683616D-05	0.274610D-07	0.401792D-02
26	0.191806D-03	0.986351	0.887640D-02	0.551841D-03	0.106392D-04	0.492043D-07	0.401801D-02
27	0.180944D-03	0.984784	0.102530D-01	0.747437D-03	0.165532D-04	0.881383D-07	0.401813D-02
28	0.172882D-03	0.982931	0.118396D-01	0.101204D-02	0.257461D-04	0.157825D-06	0.401828D-02
29	0.166886D-03	0.980738	0.136666D-01	0.136979D-02	0.400284D-04	0.282492D-06	0.401849D-02
30	0.162412D-03	0.978134	0.157685D-01	0.185315D-02	0.622035D-04	0.505379D-06	0.401877D-02
31	0.159057D-03	0.975035	0.181838D-01	0.250567D-02	0.966066D-04	0.903574D-06	0.401916D-02
32	0.156520D-03	0.971331	0.209554D-01	0.338563D-02	0.149929D-03	0.161430D-05	0.401968D-02
33	0.154576D-03	0.966889	0.241297D-01	0.457074D-02	0.232477D-03	0.288142D-05	0.402039D-02
34	0.153056D-03	0.961539	0.277568D-01	0.616424D-02	0.360080D-03	0.513726D-05	0.402136D-02
35	0.151829D-03	0.955068	0.318890D-01	0.830241D-02	0.556956D-03	0.914611D-05	0.402268D-02
36	0.150795D-03	0.947206	0.365785D-01	0.111639D-01	0.859995D-03	0.162541D-04	0.402449D-02
37	0.149873D-03	0.937615	0.418739D-01	0.149804D-01	0.132503D-02	0.288209D-04	0.402697D-02
38	0.148995D-03	0.925870	0.478146D-01	0.200488D-01	0.203590D-02	0.509568D-04	0.403036D-02
39	0.148099D-03	0.911446	0.544217D-01	0.267418D-01	0.311715D-02	0.897648D-04	0.403499D-02
40	0.147131D-03	0.893701	0.616861D-01	0.355162D-01	0.475119D-02	0.157389D-03	0.404133D-02
41	0.146033D-03	0.871868	0.695509D-01	0.469105D-01	0.720017D-02	0.274306D-03	0.404996D-02
42	0.144749D-03	0.845073	0.778892D-01	0.615255D-01	0.108313D-01	0.474424D-03	0.406168D-02
43	0.143222D-03	0.812372	0.864788D-01	0.799742D-01	0.161415D-01	0.812569D-03	0.407746D-02
44	0.141399D-03	0.772850	0.949774D-01	0.102786	0.237722D-01	0.137470D-02	0.409854D-02
45	0.139238D-03	0.725781	0.102908	0.130257	0.344980D-01	0.229037D-02	0.412628D-02
46	0.136717D-03	0.670863	0.109670	0.162253	0.491694D-01	0.374517D-02	0.416216D-02
47	0.133853D-03	0.608490	0.114590	0.197999	0.685907D-01	0.598887D-02	0.420750D-02
48	0.130706D-03	0.539976	0.117023	0.235940	0.933334D-01	0.933270D-02	0.426315D-02
49	0.127389D-03	0.467619	0.116493	0.273779	0.123523	0.141304D-01	0.432915D-02
50	0.124051D-03	0.394487	0.112824	0.308743	0.158675	0.207432D-01	0.440440D-02
51	0.120855D-03	0.323945	0.106220	0.338070	0.197662	0.294961D-01	0.448662D-02
52	0.117944D-03	0.259039	0.972367D-01	0.359543	0.238849	0.406419D-01	0.457258D-02
53	0.115413D-03	0.201980	0.866620D-01	0.371881	0.280360	0.543425D-01	0.465868D-02
54	0.113301D-03	0.153898	0.753474D-01	0.374858	0.320369	0.706722D-01	0.474162D-02
55	0.111595D-03	0.114889	0.640602D-01	0.369166	0.357319	0.896353D-01	0.481892D-02
56	0.110250D-03	0.842734D-01	0.533910D-01	0.356114	0.390037	0.111185	0.488918D-02
57	0.109202D-03	0.609185D-01	0.437250D-01	0.337313	0.417743	0.135240	0.495196D-02
58	0.108387D-03	0.435284D-01	0.352599D-01	0.314410	0.440000	0.161686	0.500756D-02
59	0.623592D-04	0.320904D-01	0.292384D-01	0.295398	0.457388	0.185761	0.621409D-04
60	0.345962D-04	0.228759D-01	0.235362D-01	0.271350	0.468980	0.213223	0.756149D-06

Table 5 Final Results of Step (1) Calculation

***** LIQUID MOLE FRACTIONS *****

	H2	HD	HT	D2	DT	T2	HE
1	0.541729D-01	0.941270	0.254806D-03	0.346029D-06	0.238310D-09	0.373200D-13	0.430181D-02
2	0.407959D-01	0.958559	0.300574D-03	0.479061D-06	0.379448D-09	0.684878D-13	0.344461D-03
3	0.305289D-01	0.969015	0.351805D-03	0.657771D-06	0.598831D-09	0.124505D-12	0.103407D-03
4	0.227923D-01	0.976699	0.410490D-03	0.900227D-06	0.941858D-09	0.225545D-12	0.969802D-04
5	0.169923D-01	0.982432	0.477930D-03	0.122929D-05	0.147791D-08	0.407589D-12	0.967452D-04
6	0.126582D-01	0.986688	0.555550D-03	0.167581D-05	0.231499D-08	0.735230D-12	0.966887D-04
7	0.942726D-02	0.989829	0.644993D-03	0.228166D-05	0.362145D-08	0.132445D-11	0.966483D-04
8	0.702301D-02	0.992129	0.748154D-03	0.310361D-05	0.565968D-08	0.238346D-11	0.966168D-04
9	0.523632D-02	0.993796	0.867220D-03	0.421870D-05	0.883857D-08	0.428596D-11	0.965915D-04
10	0.390988D-02	0.994983	0.100471D-02	0.573138D-05	0.137954D-07	0.770266D-11	0.965706D-04
11	0.292585D-02	0.995806	0.116355D-02	0.778332D-05	0.215230D-07	0.138371D-10	0.965525D-04
12	0.219626D-02	0.996350	0.134708D-02	0.105666D-04	0.335685D-07	0.248487D-10	0.965361D-04
13	0.165553D-02	0.996674	0.155920D-02	0.143418D-04	0.523424D-07	0.446120D-10	0.965205D-04
14	0.125490D-02	0.996825	0.180437D-02	0.194620D-04	0.815998D-07	0.800771D-10	0.965050D-04
15	0.958135D-03	0.996831	0.208776D-02	0.264061D-04	0.127190D-06	0.143711D-09	0.964888D-04
16	0.738353D-03	0.996714	0.241534D-02	0.358229D-04	0.198224D-06	0.257876D-09	0.964713D-04
17	0.575603D-03	0.996485	0.279397D-02	0.485919D-04	0.308889D-06	0.462671D-09	0.964521D-04
18	0.455098D-03	0.996150	0.323159D-02	0.659048D-04	0.481280D-06	0.830002D-09	0.964305D-04
19	0.365877D-03	0.995710	0.373732D-02	0.893758D-04	0.749790D-06	0.148878D-08	0.964059D-04
20	0.299822D-03	0.995160	0.432169D-02	0.121191D-03	0.116796D-05	0.267010D-08	0.963776D-04
21	0.250917D-03	0.994490	0.499678D-02	0.164310D-03	0.181909D-05	0.478807D-08	0.963449D-04
22	0.214708D-03	0.993687	0.577651D-02	0.222738D-03	0.283281D-05	0.858469D-08	0.963068D-04
23	0.187896D-03	0.992733	0.667682D-02	0.301893D-03	0.441065D-05	0.153890D-07	0.962624D-04
24	0.168038D-03	0.991604	0.771602D-02	0.409097D-03	0.686596D-05	0.275807D-07	0.962104D-04
25	0.153323D-03	0.990271	0.891502D-02	0.554247D-03	0.106856D-04	0.494188D-07	0.961493D-04
26	0.142412D-03	0.988696	0.102977D-01	0.750696D-03	0.166254D-04	0.885226D-07	0.960772D-04
27	0.134312D-03	0.986836	0.118911D-01	0.101645D-02	0.258584D-04	0.158513D-06	0.959918D-04
28	0.128287D-03	0.984634	0.137261D-01	0.137576D-02	0.402030D-04	0.283723D-06	0.958904D-04
29	0.123789D-03	0.982019	0.158372D-01	0.186123D-02	0.624748D-04	0.507583D-06	0.957695D-04
30	0.120415D-03	0.978906	0.182631D-01	0.251660D-02	0.970279D-04	0.907515D-06	0.956245D-04
31	0.117860D-03	0.975187	0.210467D-01	0.340039D-02	0.150583D-03	0.162135D-05	0.954500D-04
32	0.115899D-03	0.970727	0.242349D-01	0.459069D-02	0.233492D-03	0.289399D-05	0.952387D-04
33	0.114359D-03	0.965355	0.278779D-01	0.619115D-02	0.361651D-03	0.515968D-05	0.949816D-04
34	0.113111D-03	0.958857	0.320282D-01	0.833866D-02	0.559388D-03	0.918604D-05	0.946670D-04
35	0.112051D-03	0.950963	0.367382D-01	0.112127D-01	0.863753D-03	0.163251D-04	0.942801D-04
36	0.111095D-03	0.941332	0.420569D-01	0.150459D-01	0.133083D-02	0.289469D-04	0.938019D-04
37	0.110174D-03	0.929540	0.480238D-01	0.201365D-01	0.204481D-02	0.511799D-04	0.932087D-04
38	0.109221D-03	0.915058	0.546601D-01	0.268590D-01	0.313082D-02	0.901582D-04	0.924714D-04
39	0.108177D-03	0.897241	0.619569D-01	0.356721D-01	0.477206D-02	0.158080D-03	0.915552D-04
40	0.106977D-03	0.875321	0.698569D-01	0.471169D-01	0.723186D-02	0.275514D-03	0.904206D-04
41	0.105557D-03	0.848419	0.782331D-01	0.617972D-01	0.108791D-01	0.476519D-03	0.890264D-04
42	0.103851D-03	0.815588	0.868624D-01	0.803289D-01	0.162131D-01	0.816174D-03	0.873356D-04
43	0.101791D-03	0.775908	0.954011D-01	0.103245	0.238783D-01	0.138084D-02	0.853249D-04
44	0.993219D-04	0.728651	0.103371	0.130843	0.346530D-01	0.230066D-02	0.829971D-04
45	0.964087D-04	0.673511	0.110168	0.162989	0.493925D-01	0.376216D-02	0.803932D-04
46	0.930537D-04	0.610883	0.115116	0.198908	0.689057D-01	0.601637D-02	0.775980D-04
47	0.893117D-04	0.542084	0.117568	0.237039	0.937681D-01	0.937616D-02	0.747340D-04
48	0.852956D-04	0.469419	0.117044	0.275075	0.124108	0.141973D-01	0.719399D-04
49	0.811682D-04	0.395968	0.113367	0.310231	0.159440	0.208432D-01	0.693403D-04
50	0.771164D-04	0.325108	0.106742	0.339732	0.198633	0.296411D-01	0.670195D-04
51	0.733156D-04	0.259900	0.977242D-01	0.361346	0.240046	0.408457D-01	0.650084D-04
52	0.698978D-04	0.202566	0.871049D-01	0.373782	0.281794	0.546203D-01	0.632892D-04
53	0.669345D-04	0.154245	0.757396D-01	0.376810	0.322037	0.710401D-01	0.618124D-04
54	0.644374D-04	0.115035	0.643993D-01	0.371120	0.359211	0.901098D-01	0.605172D-04
55	0.623732D-04	0.842569D-01	0.536778D-01	0.358028	0.392133	0.111783	0.593471D-04
56	0.606829D-04	0.607746D-01	0.439630D-01	0.339149	0.420018	0.135976	0.582594D-04
57	0.592987D-04	0.432870D-01	0.354541D-01	0.316142	0.442423	0.162577	0.572261D-04
58	0.581558D-04	0.305279D-01	0.282037D-01	0.290534	0.459182	0.191438	0.562325D-04
59	0.330225D-04	0.221852D-01	0.230404D-01	0.268756	0.469676	0.216309	0.684552D-06
60	0.181555D-04	0.156594D-01	0.183573D-01	0.244250	0.476256	0.245459	0.813834D-08

Table 6 Input and Output Variables for Step (2) Calculation

<u>Input Variables</u>
Number of total elemental stages (M)
Flow rate, temperature and composition of gas stream entering refrigerated section
Flow rate of top gas (FD)
Operating pressure (P)
Heat subtraction rates on elemental stages*(q_j, $j = 1, \ldots, M-1$)
<u>Output Variables</u>
Distributions of gas flow rate, liquid flow rate, temperature and helium concentration
Heat subtraction rate on M-th stage (q_M)

*) $\sum_{j=1}^{2} Q_j \sim \sum_{j=1}^{M} q_j$. The values of q_j's for stages whose numbers are small (e.g. $j = 1, 2, 3$) should be adequately small for obtaining a more accurate temperature profile within these stages.

The molecular species to be considered are He and HD.

Table 7 Calculational Conditions of Step (2)

Number of total elemental stages = 20

Feed flow rate = 190.83 g-mol/h

Feed composition : He = 0.4050D-2 HD = 0.9960

Feed temperature = 29.0 K

Operating pressure = 5 atm

Heat subtraction rate : q_1 = 100 cal/h, q_2 = 200 cal/h,
q_3 = 500 cal/h, q_4 = 1000 cal/h,
q_5 = 2000 cal/h, q_6 ~ q_{15} = 2400 cal/h,
q_{16} ~ q_{20} = 2440 cal/h.

(q_{20} is calculated to be 2290 cal/h as an output value)

Table 8 Final Results of Step(2) Calculation

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***** FINAL RESULT *****

***** VAPOR FLOW RATES (G-MOL/H) *****
  1   0.830000      2   1.16275      3   1.86938      4   3.89815      5   8.48219
  6   17.9758       7   29.6155      8   41.1860      9   52.6925     10   64.1761
 11   75.6496      12   87.1178     13   98.5828     14   110.046     15   121.507
 16   132.968      17   144.618     18   156.269     19   167.919     20   179.568

***** LIQUID FLOW RATES (G-MOL/H) *****
  1   0.332745      2   1.03938      3   3.06815      4   7.65219      5   17.1458
  6   28.7855       7   40.3560      8   51.8625      9   63.3461     10   74.8196
 11   86.2878      12   97.7528     13   109.216     14   120.677     15   132.138
 16   143.788      17   155.439     18   167.089     19   178.738     20   189.999

***** TEMPERATURES (K) *****
  1   19.7790       2   24.2629      3   26.5322      4   27.9875      5   28.6212
  6   28.8929       7   28.9878      8   29.0284      9   29.0507     10   29.0649
 11   29.0747      12   29.0819     13   29.0874     14   29.0918     15   29.0953
 16   29.0983      17   29.1007     18   29.1029     19   29.1047     20   29.1063
```

Table 9 Final Results of Step(2) Calculation

	***** VAPOR MOLE FRACTIONS *****			***** LIQUID MOLE FRACTIONS *****	
	HD	HE		HD	HE
1	0.925273D-01	0.907473	1	0.995796	0.420398D-02
2	0.351018	0.648982	2	0.992231	0.776909D-02
3	0.592764	0.407236	3	0.993025	0.697501D-02
4	0.801290	0.198710	4	0.995847	0.415341D-02
5	0.907455	0.925450D-01	5	0.997904	0.209626D-02
6	0.956100	0.439004D-01	6	0.998972	0.102815D-02
7	0.973568	0.264320D-01	7	0.999374	0.626216D-03
8	0.981099	0.189014D-01	8	0.999550	0.450002D-03
9	0.985263	0.147372D-01	9	0.999648	0.351806D-03
10	0.987916	0.120838D-01	10	0.999711	0.288955D-03
11	0.989758	0.102422D-01	11	0.999755	0.245210D-03
12	0.991111	0.888866D-02	12	0.999787	0.212988D-03
13	0.992149	0.785149D-02	13	0.999812	0.188260D-03
14	0.992969	0.703128D-02	14	0.999831	0.168682D-03
15	0.993634	0.636634D-02	15	0.999847	0.152795D-03
16	0.994184	0.581637D-02	16	0.999860	0.139644D-03
17	0.994653	0.534705D-02	17	0.999872	0.128415D-03
18	0.995052	0.494765D-02	18	0.999881	0.118853D-03
19	0.995396	0.460379D-02	19	0.999889	0.110617D-03
20	0.995695	0.430463D-02	20	0.999897	0.103449D-03

Table 10 Dimensions Estimated for Refrigerated Section

j	q_j(cal/h)	T_{Gj}(K)	T_{Cj}(K)	T_{Rmj}(K)	d_j(cm)	u_j(cm/sec)	Re_j	l_j(cm)
1	100	19.78	18.12	18.01	0.50	0.41	160	18.2
2	200	24.26	18.89	18.03	0.58	0.57	170	4.5
3	500	26.53	20.07	18.07	0.66	0.92	260	4.7
4	1000	27.99	22.07	18.16	0.74	1.67	480	4.7
5	2000	28.62	24.44	18.35	0.82	2.97	900	5.8
6	2400	28.89	26.49	18.63	0.89	4.49	1470	5.3
7	2400	28.99	27.56	18.93	0.97	5.65	2000	4.7
8	2400	29.03	28.09	19.23	1.05	6.42	2440	4.5
9	2400	29.05	28.38	19.53	1.13	6.93	2830	4.4
10	2400	29.07	28.56	19.83	1.21	7.24	3160	4.4
11	2400	29.08	28.68	20.13	1.29	7.43	3450	4.5
12	2400	29.08	28.77	20.43	1.37	7.53	3710	4.5
13	2400	29.09	28.83	20.74	1.45	7.57	3940	4.6
14	2400	29.09	28.88	21.04	1.53	7.55	4150	4.7
15	2400	29.10	28.92	21.34	1.61	7.51	4340	4.8
16	2440	29.10	28.95	21.64	1.68	7.44	4510	5.0
17	2440	29.10	28.98	21.95	1.76	7.36	4670	5.1
18	2440	29.10	29.00	22.25	1.84	7.26	4810	5.3
19	2440	29.11	29.01	22.56	1.92	7.16	4950	5.4
20	2440	29.11	29.03	22.86	2.00	7.04	5060	5.3

u = gas velocity

Table 11 Design Specifications of Falling Liquid Film Condenser

Total height of refrigerated section = 1.1 m

Inner diameter of refrigerated section = 2.0 cm tapering to 0.5 cm at the top

Inlet temperature of refrigerant gas = 18 K

Flow rate of refrigerant gas = 6.4 kg/h

Reboiler duty = 42 W

Total height of packed section = 2.9 m

Inner diameter of packed section = 2.0 cm

Wall*thickness = 0.3 cm

Operating pressure = 5 atm

$D_{2j} - D_{1j}$ = 0.4 cm

Flow rate of top product/Flow rate of feed = 0.055333

Composition of top product :	H_2 = 0.9019D-2	HD = 0.8735D-1
	HT = 0.1779D-4	D_2 = 0.1844D-7
	DT = 0.9382D-11	T_2 = 0.1050D-14
	He = 0.9036	
Composition of bottom product :	H_2 = 0.1816D-4	HD = 0.1566D-1
	HT = 0.1836D-1	D_2 = 0.2443
	DT = 0.4763	T_2 = 0.2455
	He = 0.8138D-8	

Flow rate of tritium lost from the top = 0.39 g/y

*) The wall of the refrigerated section is made of copper.

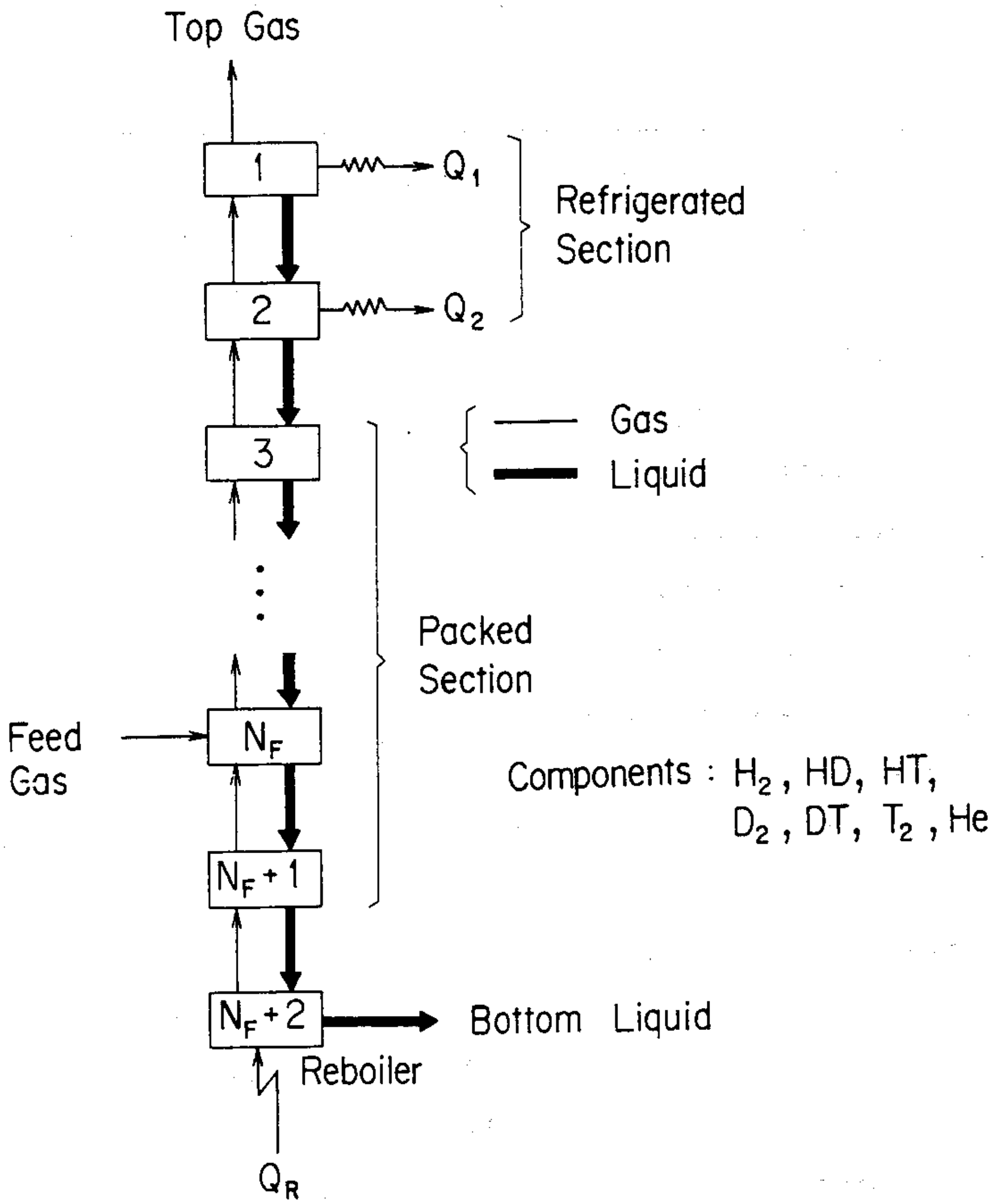
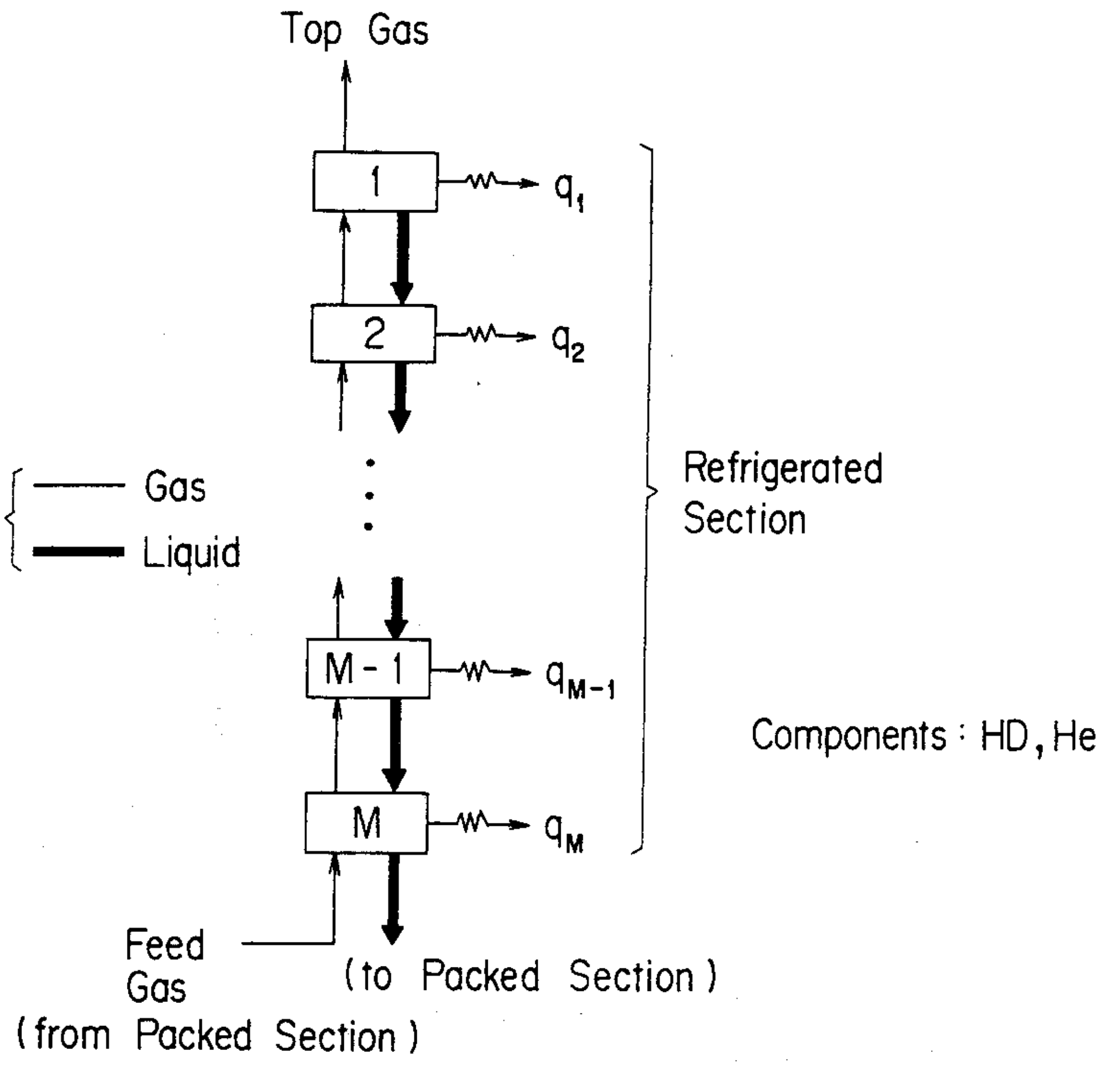


Fig. 1 Model Column for Mathematical Simulation in Step (1)



$$\sum_{j=1}^{M} q_j \sim Q_1 + Q_2$$

Fig. 2 Model Column to be Analyzed in Step (2)

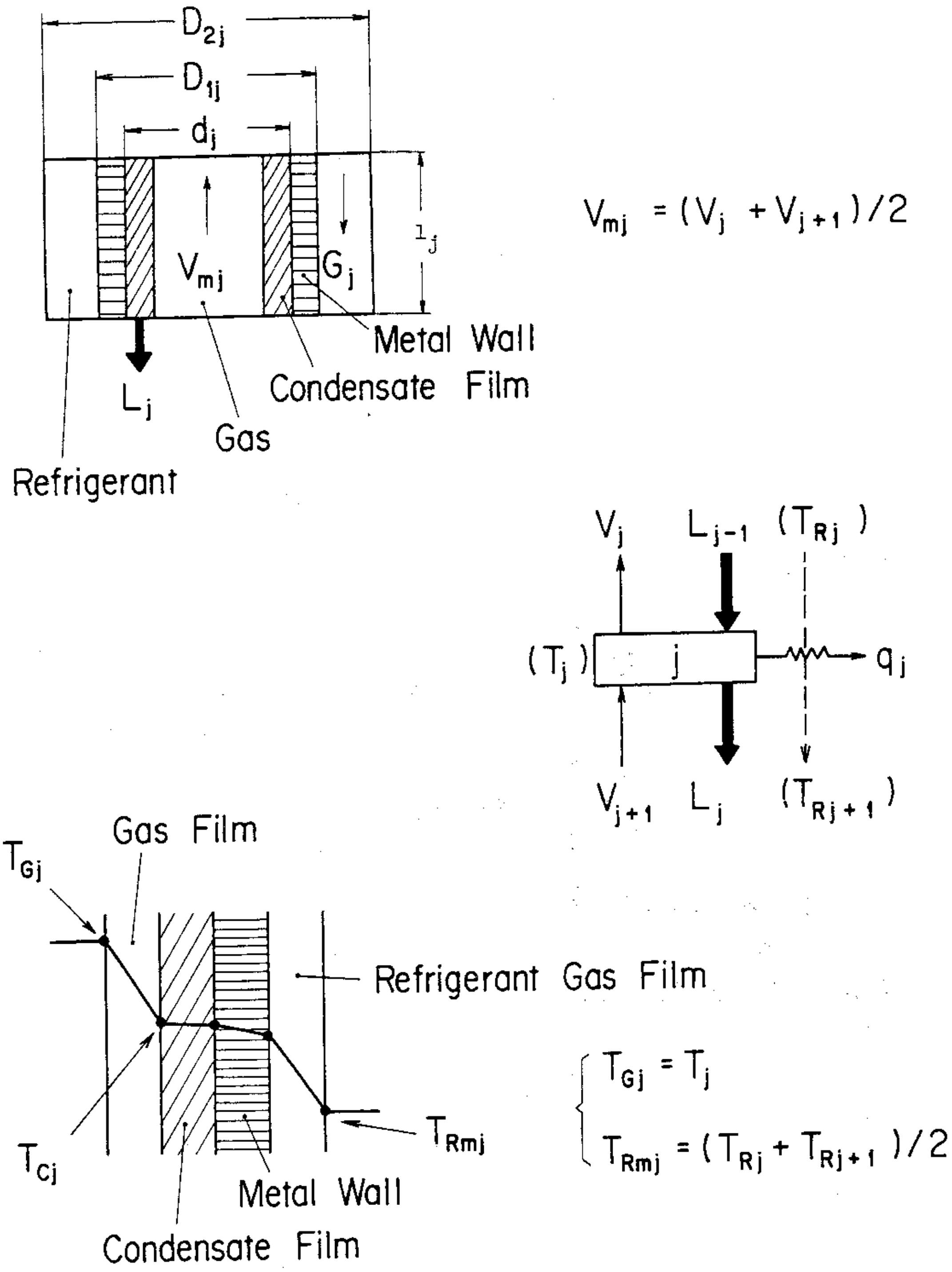


Fig. 3 Model Stage for Step (3) Calculation