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ASSESSMENT OF MODELS IN COBRA-TF CODE FOR LIQUID ENTRAINMENTS IN FILM-MIST FLOW

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Assessment of Models in COBRA-TF Code

for Liquid Entrainments in Film-mist Flow

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Assessment calculations on the liquid entrainment and deposition models in the film-mist flow of the COBRA-TF code have been performed, prior to apply the code to the analyses on the film dryout phenomenon. Concerned experiments are basic ones conducted with a single tube test section under the adiabatic conditions. Although the calculated results of the liquid entrainment mass flow rates at the exit of the test section are in good agreements with the experimental data for the high pressures of 3.4 and 6.9 MPa, the results showed large discrepancies at the low pressures of 0.24 ∿ 0.45 MPa.

In this report, calculational results are presented with detailed investigation on the entrainment/deposition models used in COBRA-TF. In COBRA-TF, an entrainment correlation proposed by Würtz is used. This correlation was developed mainly based on his experimental data conducted at the high pressure range of 3 ∿ 9 MPa. This is considered to be the reason for the good agreements at the high pressures but the discrepancies at the low pressures described above. At the low pressures, its effect on fluid densities, especially the vapor density, is expected

* An STA fellow during May, 1992 ∿ May, 1993

to become significant and should be included in the correlation. Therefore, an alternative set of Sugawara's entrainment and deposition correlations, which show good agreements at the low pressures, is also investigated by comparing to that of COBRA-TF. Those correlations include additional factors on the pressure effects, and hence, are considered to be promising ones to improve the capability of COBRA-TF.

Although the practical applications to nuclear reactors may be considered to be in the high pressure range, many experiments utilized for the thermo-hydrodynamic model development are conducted in the low pressure range. Therefore, more efforts on the improvements of the models to get a good agreement at the low pressures are considered to be necessary.

COBRA-TF コードの液膜噴霧流に対する

エントレインメントモデルの検証

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　　COBRA-TF コードを液膜ドライアウト現象の解析に利用するに先だって、本コードの液膜噴霧流におけるエントレインメント発生および沈着のモデルに対する検証計算を実施した。対象とした実験は、断熱条件下で実施された単管のテスト部を用いた基礎的な実験である。テスト部出口におけるエントレインメント流量の計算値は、3.4および6.9MPa の高圧条件下での実験データとは良い一致を示したものの、0.24〜0.45MPa の低圧条件下での実験データとは大きな相違を示した。

　本報告書では、計算結果とともにCOBRA-TF コードで使用されているエントレインメント発生および沈着モデルについての詳細な検討を示す。COBRA-TFでは、Würtz によって提案された相関式が使用されている。この相関式は、主として3〜9 MPa という高圧領域で実施された彼の実験のデータに基づいて開発された。このことが上述の高圧領域で良い一致を与えるものの低圧領域で相違を生ずる理由と考えられる。低圧領域では、圧力が流体の密度特に蒸気密度に与える影響が極めて大きいと予想され、その効果を相関式に含むべきであると思われる。そこで、低圧領域でも良い一致を示すエントレインメントの発生および沈着に関する菅原の相関式を取り上げてCOBRA-TF のものと比較検討を行った。これらの相関式には、圧力の効果に関する因子が付加されており、これらの使用によりCOBRA-TF の予測能力を改善することができると期待できる。

　　原子炉への実際の適用は高圧状況下においてなされると考えられるが、熱流体力学的モデルの開発に利用される多くの実験は低圧領域で行われている。従って、低圧領域でも良い一致を得るためのモデルの改良に関する努力が必要であると考える。

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1. Introduction

The COBRA-TF (Coolant Boiling in Rod Arrays, Two-Fluid) computer code[1] was developed at the Pacific Northwest Laboratory to provide best estimate thermal hydraulic analysis of a Light Water Reactor (LWR) core for design basis accidents and anticipated transients. It is the final version of the COBRA family subchannel analysis codes[2],[3].

The most important feature of COBRA-TF is it provides a two-fluid three-field representation of two-phase flow, instead of the homogeneous representation used in the previous versions of the COBRA codes, such as COBRA-IV-I[2]. The three fields are : continuous vapor, continuous liquid and entrained liquid. Therefore, the code is appropriate to be utilized to analyze the film-mist flow behavior, which we are interested in from the point of view of the prediction of the film dryout phenomenon expected in the reactor core. The code also features extremely flexible noding for both the hydrodynamic and the heat transfer solution. This flexibility provides the capability to model the wide variety of geometries encountered in components of nuclear reactors primary system. Furthermore, COBRA-TF can be used with either subchannel or rectangular cartesian coordinates, which allows a fully three dimensional treatment.

To close the equation set for the two-phase flow, some physical models are needed for the mass and momentum exchange among the three fields at the phase interfaces, the drag forces at solid boundaries, knowledge of the turbulence terms in the continuous fields, the entrainment rate and so forth. Since we are particularly interested in the precise prediction of the critical heat flux or the film dryout phenomenon in the core, the physical models related to the liquid entrainments in the film-mist flow used in the COBRA-TF code have been investigated and assessed with some basic experimental data in order to clarify the predictive capability of COBRA-TF for the basic entrainment/deposition phenomenon in the film-mist flow. The essential features of the film-mist flow are that the vapor travels in the center of the flow channel, *i.e.* the subchannel, the liquid film travels on the fuel rod surfaces and the liquid droplets are carried along with the vapor flow. These droplets are continually torn off the liquid film by the break-up of the crests of disturbance waves at the vapor-liquid interface[4]. When the liquid film flow rate approaches zero due to heat release from the fuel rods and it finally vanishes, the dryout occurs.

In this report, analyses of the basic entrainment/deposition experiments with COBRA-TF are presented. The experiments referred to are ones conducted by Hewitt *et al.*[5],[6] with the steam-water two-phase flow flowing in a simple tube under adiabatic conditions.

2. Physical Models for Entrainment and Deposition for Film-Mist Flow

2.1 General Description for Two-Phase Flow Models in COBRA-TF

The two-fluid three-field representation is considered to be the most convenient and physically reasonable way to handle flows where the liquid coexists in both continuous (film) and discrete (droplet) forms as appears in the film-mist flow. This formulation uses a separate set of conservation equations (Mass, Energy, and Momentum) for each field. Therefore, this two-fluid three-field description of two-phase flow results in a set of nine equations in general. In addition, the COBRA-TF code can treat the noncondensible gas mixture such as air, nitrogen and so forth. In the COBRA-TF code, four mass conservation equations are used for the vapor, continuous liquid, entrained liquid and noncondensible gas mixture. Three momentum equations are solved allowing the two liquid fields to flow with different velocities relative to the vapor phase. They are described in either the three-dimensional form or the subchannel form. Two energy conservation equations, in which the continuous liquid and the entrained liquid are assumed to be at the same temperature, are specified for the vapor-gas mixture and the combined liquid fields. These conservation equations are solved using a semi-implicit finite-difference numerical technique on an Eulerian mesh.

In the COBRA-TF code, two types of flow regimes are considered[1]. One is named "normal" flow regime and is illustrated in Fig. 2.1. The other is named "hot wall" flow regime and illustrated in Fig. 2.2. The latter is prepared for a detailed analysis of reflooding phenomena expected to appear during the large-break loss-of-coolant accident and is automatically selected in the calculation when a mesh cell contains a solid surface with a temperature greater than 750 °F (672 K).

In the present study, only the "normal" flow regime is concerned. Figure 2.3 summarize the detailed flow regime selection logic for the "normal" flow regime. As presented in Figs. 2.1 and 2.2, entrainment is possible to exist at the void fraction over 0.5, where the flow regime is referred to as churn-turbulent flow. This flow regime is actually defined as a linear interpolation area between the slug flow and the film-mist flow. Transition from the churn-turbulent flow to the film-mist flow is defined as that the void fraction is over a critical value presented in the following :

$$\alpha_{v_{crit}} = \max(\, 1 - \alpha_{l_{crit}} \,,\, 0.8\,)$$

(1)

$\alpha_{l_{crit}}$: critical liquid volume fraction defined in Eq.(6)

As described in the following, liquid film is considered to be stable in the film-mist flow and to be unstable in the churn-turbulent flow.

In the following, physical models used in COBRA-TF for the liquid entrainment and deposition in the film-mist flow are presented. They are exactly based on the information obtained from the FORTRAN statements for COBRA-TF and presented in British units expression as in the code. Therefore, "nomenclature" of this report is also given in British units.

2.2 Entrainment Model for Film-Mist Flow

The entrainment generation rate S_E is calculated in COBRA-TF by using Würtz empirical correlation[7] and it is expressed as follows :

$$S_E = 0.41 \left(\frac{k_s \times \tau_i}{\sigma} \right) \left(\frac{u_v \times \mu_l}{\sigma \times g} \right) P_w \times \Delta x \tag{2}$$

k_s : equivalent sand roughness
τ_i : shear stress at vapor-liquid interface
u_v : vapor axial velocity
μ_l : liquid dynamic viscosity
σ : surface tension of liquid
g : gravitational acceleration
P_w : wetted perimeter
Δx : axial mesh length

where, k_s is expressed in the form :

$$k_s = 0.57 \, \delta_{th} + 6.625 \times 10^3 \, \delta_{th}^2 - 3.56 \times 10^6 \, \delta_{th}^3 + 1.5736 \times 10^9 \, \delta_{th}^4 \tag{3}$$

where, theoretical film thickness δ_{th} is defined as :

$$\delta_{th} = \frac{D_h \times \alpha_l}{4} \tag{4}$$

D_h : hydraulic diameter
α_l : liquid volume fraction

The shear stress at the vapor-liquid interface is calculated as follows :

$$\tau_i = f_i \times \rho_v \times u_{vl}^2 / (2 \times g) \tag{5}$$

ρ_v : vapor density
u_{vl} : relative velocity between vapor and liquid fields

where the friction factor f_i is given as in the following depending on whether the film flow is stable or unstable. In the code, the liquid film is assumed to be stable when :

$$\alpha_l < \alpha_{l_{crit}} = \frac{2 \times \sigma \times g}{D_h \times \rho_v \times u_{vl}^2}$$

(6)

Otherwise, the liquid film is assumed to be unstable. For the stable film flow, friction factor f_i is given by Wallis correlation[8] as follows :

$$f_{iW} = 0.005 \times \left(1 + 75 \times \alpha_l\right)$$

(7)

This correlation is used in the code not only for the stable film but also for the unstable film flow when solving the transverse momentum equations. When solving the vertical momentum equations for the unstable film flow, the friction factor is given as follows :

$$f_i = \max\left(f_{iH}, 5 \times f_{iW}\right)$$

(8)

where, f_{iW} is given by Eq. (6) above and f_{iH} is given by Henstock and Hanratty correlation[9], which is expressed as follows :

$$f_{iH} = f_s \times \left(1 + 1400 \times F \times \left\{1 - \exp\left[-\frac{1}{G} \times \frac{(1 + 1400 \times F)^{3/2}}{13.2 \times F}\right]\right\}\right)$$

(9)

$$G = \frac{\rho_l \times g \times D_H}{\rho_v \times u_v^2 \times f_s}$$

(10)

$$F = \frac{m^+}{Re_v^{0.9}} \times \frac{\mu_l}{\mu_v} \times \left(\frac{\rho_v}{\rho_l}\right)^{\frac{1}{2}}$$

(11)

$$m^+ = \left[\left(0.707 \times Re_l^{0.5}\right)^{2.5} + \left(0.0379 \times Re_l^{0.9}\right)^{2.5}\right]^{0.40}$$

(12)

$$f_s = 0.25 \times \max\left(1.691 / Re_v^{0.43}, 0.117 / Re_v^{0.14}, 64 / Re_v\right)$$

(13)

ρ_l : liquid density
Re : Reynolds number

The size of droplets formed by entrainment from liquid films has been characterized by Tattarson et al.[10]. His results are used in the code and the diameter of droplets is given

by

$$d = 0.0112 \left(\frac{D_h \times \sigma \times g}{\frac{f_s}{2} \times \rho_v \times u_{vl}^2} \right)^{0.5} \tag{14}$$

$$f_s = 0.046 \, Re_v^{-0.20} \tag{15}$$

2.3 Deposition Model for Film–Mist Flow

The deposition of liquid droplets on the liquid film is due to random turbulent motions that impart transverse velocity to the drops, bringing them into contact with the liquid film. The code uses Cousin's expression[11] to determine the deposition rate S_{DE} :

$$S_{DE} = k_D \times C \times P_w \times \Delta x \tag{16}$$

where, C is the mean droplet concentration in the vapor core as given by the expression :

$$C = \frac{\alpha_e \times \rho_l}{\alpha_e + \alpha_v} \tag{17}$$

α_e : entrainment volume fraction

α_v : vapor volume fraction (normally, void fraction)

and k_D is the mass transfer coefficient, which has been found[12] to be a function of surface tension and is expressed in the code as :

$$k_D = \max \left(3.0491 \times 10^{12} \times \sigma^{5.3054}, \, 12.491 \times \sigma^{0.8968} \right) \tag{18}$$

In the equilibrium situation, the rate of entrainment of the droplets from the liquid film is equal to the rate of deposition of droplets back into the film. That is,

$$S_E = S_{DE} = k_D \times C_{eq} \times P_w \times \Delta x \tag{19}$$

Film / film-mist flow

↑ Stable film flow

$\alpha_v = \alpha_{v_{ei}}$

↓ Unstable film flow

Churn-turbulent flow
(linear interporation area)

$\alpha_v = 0.5$ Onset of entrainment
generation

Small bubbles dispersed in
liquid at a volume fraction of 0.2

Slug flow

$\alpha_v = 0.2$

Dispersed bubbly flow

Fig. 2.1 Normal two-phase flow regimes

Falling film regime

Quench front location

Dispersed droplet flow

Drops de-entrain and break up on grid spacer

Liquid chunk (liquid saturated)

Inverted annular flow (liquid subcooled)

Quench front location
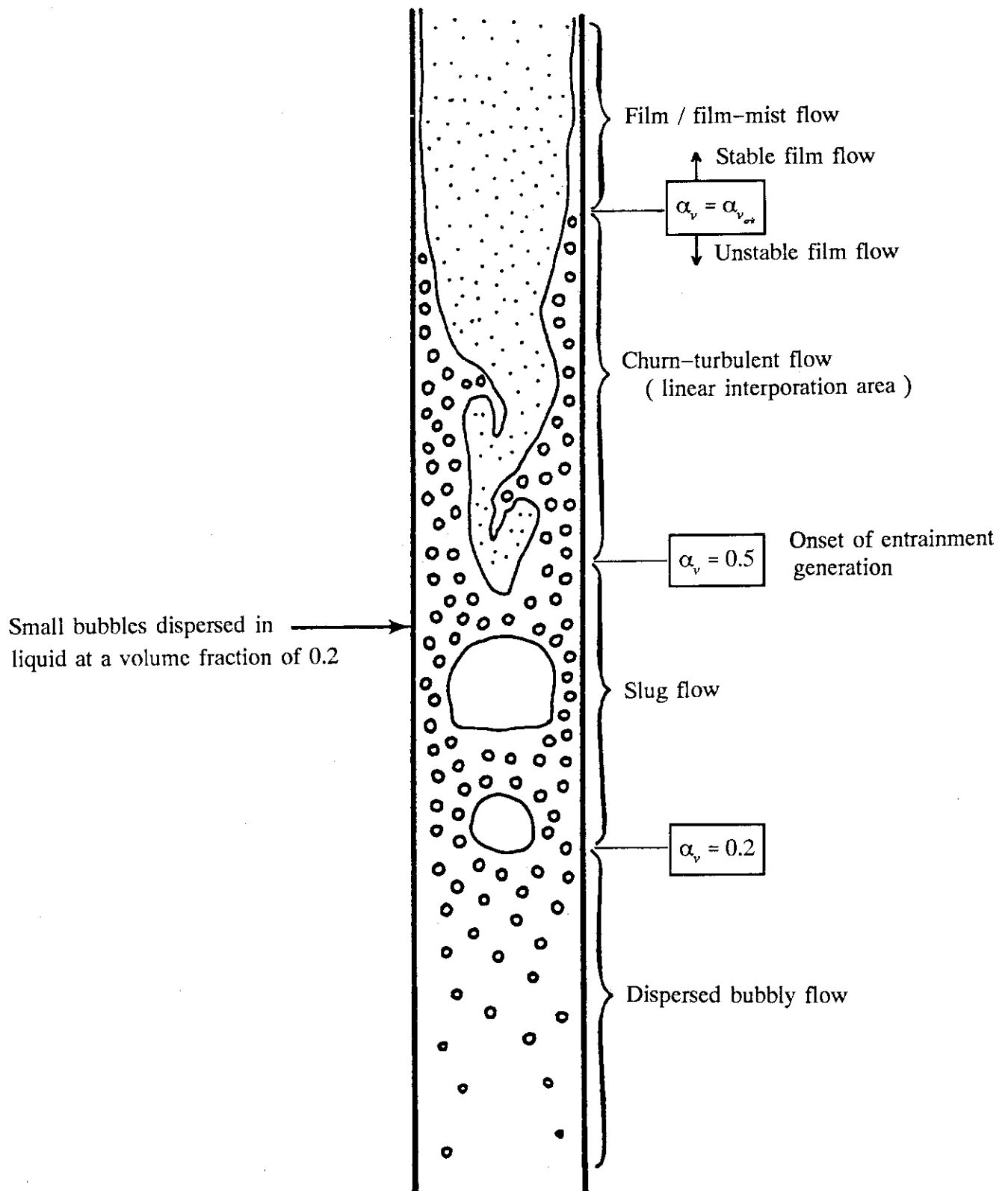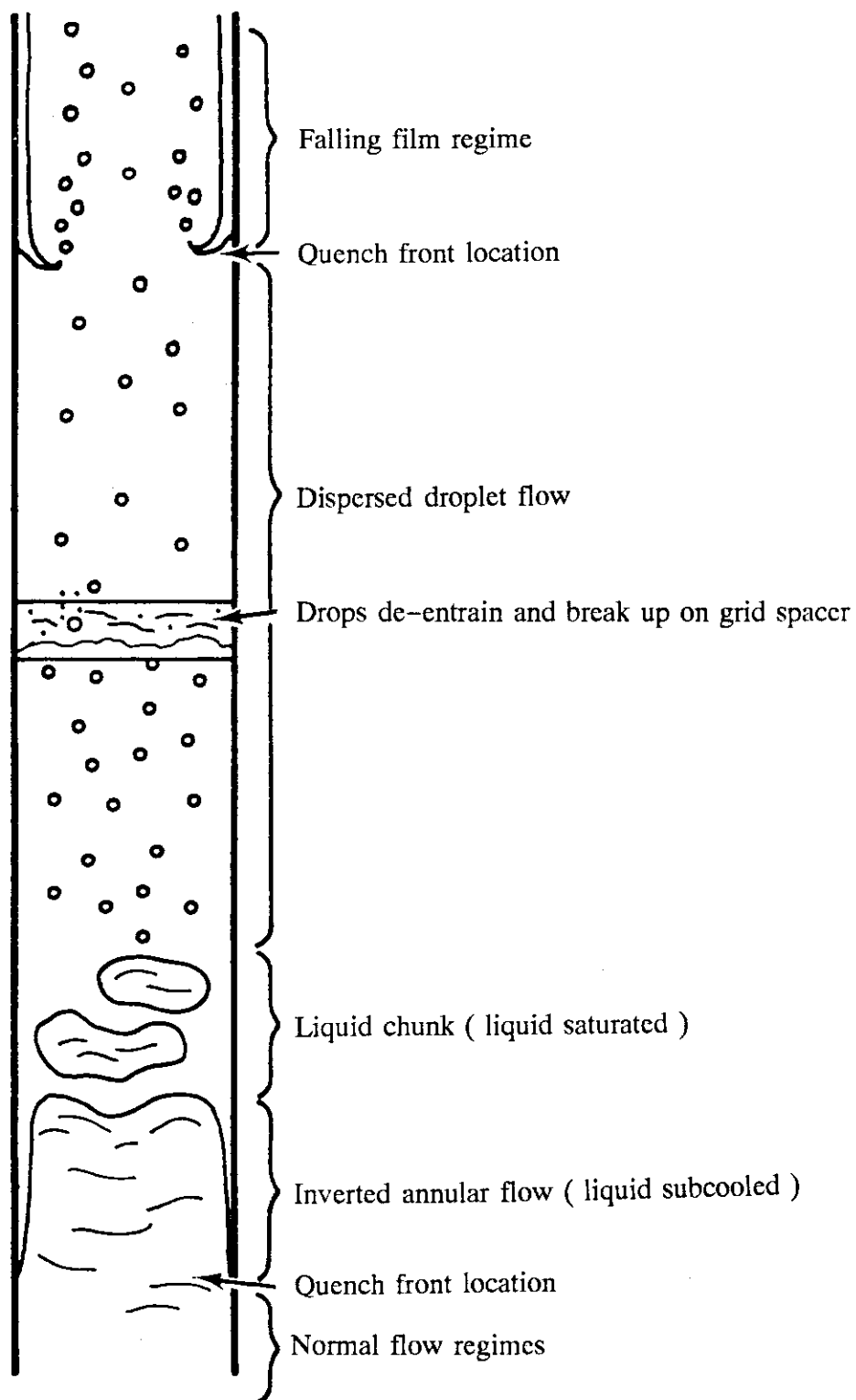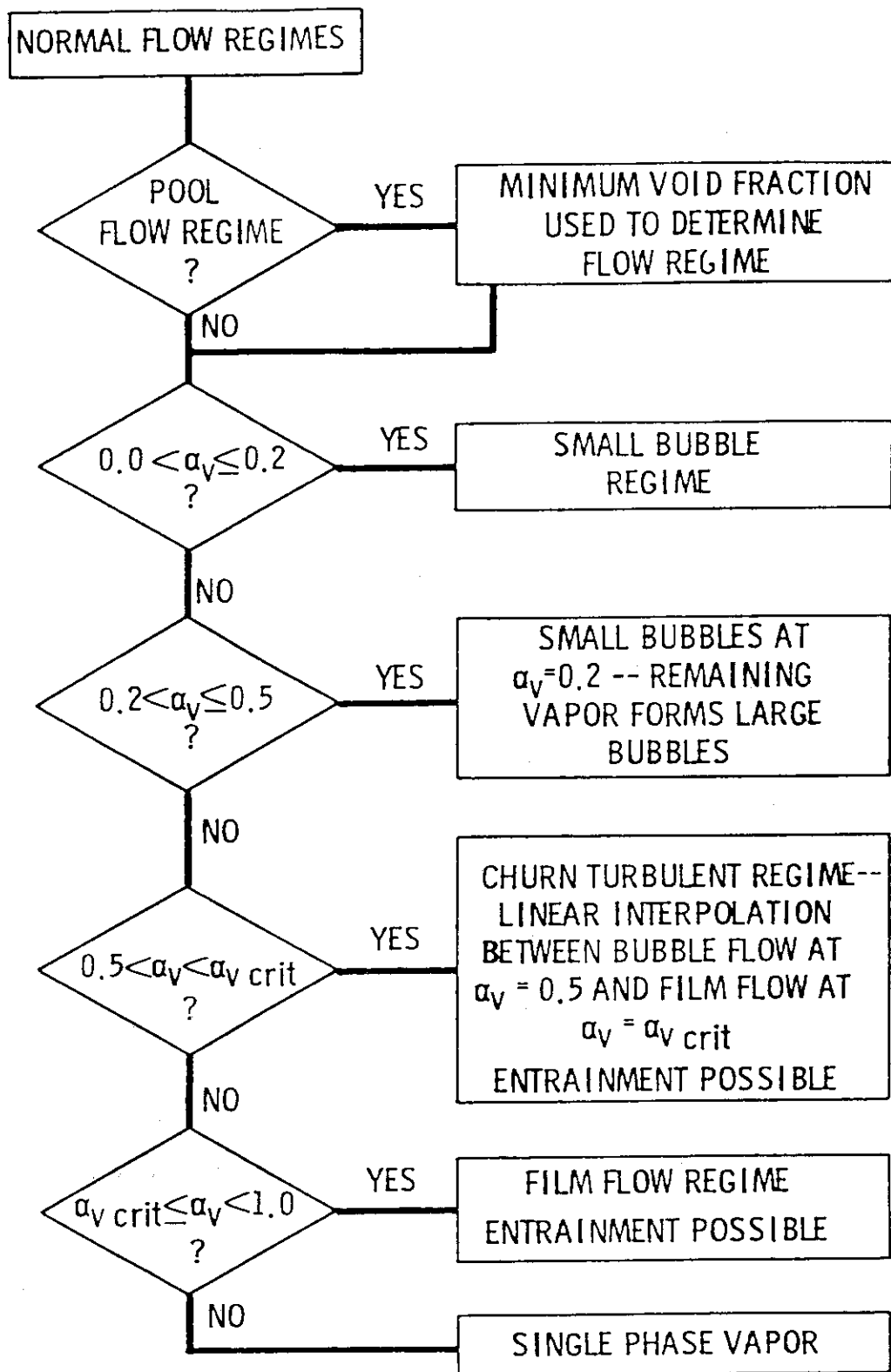
Normal flow regimes

Fig. 2.2 Hot wall flow regimes

Fig. 2.3 Normal flow regime selection logic

3. Calculational Results

3.1 Description of Experiments Analyzed with COBRA-TF

As previously mentioned, basic entrainment/deposition experiments conducted by Hewitt et al.[5],[6] are analyzed with COBRA-TF. They are steam-water two-phase flow experiments with a simple tube test section under adiabatic conditions. The tube inner diameter is around 10 mm and its vertical length is 3.66 m (12 ft).

The experiments are divided into two groups depending on their conditions. One was conducted by Hewitt et al.[5] under lower pressures and mass flux. The pressure for them ranges from 0.24 to 0.45 MPa (20 ~ 50 psig) and the mass flux is fixed around 297 kg/m²s. The steam quality ranges from 15 to 90 %. The other was conducted by Keeys et al.[6] under higher pressures and mass fluxes. The range for the pressure is 3.4 and 6.9 MPa (500 and 1000 psia) and that for the mass flux is 1,360 ~ 2,720 kg/m²s. This condition range almost covers that for a BWR. The steam quality ranges from 25 to 70 %.

Figure 3.1 shows a schematic diagram of the apparatus used in these experiments. In these experiments the annular-mist flow was established and the flow was judged to be in the equilibrium situation at the exit of the test section. Therefore, the rates of the entrainment and the deposition are the same at the exit. Output from these experiments are liquid entrainment mass flow rate at given pressure, mass flux and exit steam quality.

3.2 Description of Input

To analyze the above experiments with COBRA-TF, only the test section was modeled in a single subchannel treatment with some appropriate boundary conditions given at the inlet and the outlet of the test section. That is, the total mass flow rate and the fluid enthalpy are given at the inlet and the pressure is given at the outlet. The steam quality at the inlet is determined based on the enthalpy assuming a saturated equilibrium flow situation.

The channel noding diagram employed in the present calculations is given in Fig. 3.2. It consists of 48 nodes of the same size, with two additional boundary nodes. Since the total length of the test section is 3.66 m, each node is 76.2 mm high. Simulated inner diameters for Hewitt and Keeys experiments are 9.30 and 12.6 mm, respectively. The geometrical parameters, which are needed in the input to define the subchannel, are given in Table 3.1 for each of the experiments. The thermal hydraulic parameters used in the calculations are given in Tables 3.2 and 3.3 for each experiment, respectively. The steam quality was varied over the range of 10 ~ 90 % at the inlet. The ambient temperature is assumed to be the saturation temperature at each pressure.

Calculation times were set to be in between 5 and 10 s. For the analyses of the Hewitt experiments, calculations were performed from 0 s to the termination time with the constant boundary conditions. Calculated results tended to approach to the converged values within the termination time. For the analyses of the Keeys experiments, *i.e.* the higher pressure and mass flow cases, some transient asymptotic boundary conditions were used instead of the constant conditions. In the concrete, a reduced mass flow rate of 10 % of the experimental value was specified at 0 s and the mass flow rate was linearly increased to the experimental value in 5 s. Then the value was kept constant to the termination time. This kind of transient boundary conditions were necessary to run the calculations, otherwise the calculation was stopped in a short time. A sample of the input is given in Table 3.4. Detailed input description for COBRA-TF is presented in Appendix C.

3.3 Calculational Results

Many calculations of about 150 cases have been performed to cover condition ranges of Hewitt *et al.* and Keeys *et al.* experiments. In addition, experimental data from Saint Pierre *et al.*[13] were also covered. These data are presented in the report of Keeys *et al.* with their original data, probably because they are good data to extend the range of the mass flux of the Keeys' experiments conducted at 6.9 MPa (1000 psia). That is, although the range of mass flux in Keeys' experiments was 1,356 ~ 2,645 kg/m^2s, Saint Pierre conducted experiments at the lower mass flux of 949 kg/m^2s.

Calculated results were summarized in Appendices A and B, for the lower and the higher pressures, respectively. The values presented in these tables are the entrained water mass flow rate and the percentage of the entrainment out of the total flow, as functions of exit quality, pressure and total mass flow rate. These values are the same information as presented in their experimental reports.

Figure 3.3 shows calculated entrainment mass flow rates for the case of the lower pressures and the lower mass flux plotted to the exit steam quality. The entrainment mass flow rate passes through a maximum with increasing the steam quality for each pressure, and it gradually decreases with increasing pressure. These tendencies are qualitatively the same as observed in the experiment. The results of Hewitt *et al.* experiments are shown in Fig. 3.4. These figures indicate the quantitative agreements are not good between the calculational results and the experimental data. Comparisons between them are presented in Fig. 3.5 for three pressures. In the figure, symbols show the data points from calculations or experiments, and lines give the polynomial approximations with the least square method. This figure indicates the maximum value of the entrainment mass flow rate for the calculation is around

one half of that for the experiment at each pressure. Also, the value of the steam quality, at which the entrainment mass flow rate has the maximum, is around 50 % in the calculation, whereas it was around 30 ~ 40 % in the experiments.

For the higher pressure and higher mass flux case, experimental data are shown in Fig. 3.6. In this figure, the liquid entrainment percentages out of the total mass flow are plotted as a function of the steam quality. This figure shows not only the effect of pressure but that of the total mass flow rate and indicates the entrainment is larger for lower pressure or higher mass flow rate. The effect of the pressure is in the same tendency as observed for the lower pressure case. Comparisons between the calculation and the experiment are presented in Figs. 3.7 and 3.8 for the pressure of 3.4 MPa (500 psia) and 6.9 MPa (1000 psia), respectively. Again, symbols show the data points from calculations or experiments, and lines give the polynomial approximations with the least square method. For 3.4 MPa case, calculations at six mass flow rate were performed. This is because they were actual mass flow rates established in the experiments, although the nominal mass flow rate is 0.3742 (lb/s), *i.e.* 1×10^6 (lb/h ft^2). Even though there are only six data points available and the quality range is rather small in between 25 and 50 %, calculated results are in good agreement with the experimental data. Also, for 6.9 MPa case, the agreement between the calculation and the experiment is fairly good for all four mass flow rate concerned.

Therefore, COBRA-TF can give good predictions for the basic entrainment/deposition phenomenon in a tube at the high pressures of 3.4 and 6.9 MPa, whereas it cannot at the low pressures of 0.24 ~ 0.45 MPa. This shortage will be discussed in the next Chapter.

Table 3.1   Geometrical parameters for Input

Geometrical parameters		Hewitt *et al.*	Keeys *et al.*
Nominal channel flow area	(in²)	0.1052	0.1940
Channel wetted perimeter	(in)	1.150	1.561
Intside diameter of tube	(in)	0.366	0.497
Total lenght of tube	(in)	144.0	144.0

Table 3.2   Thermal hydraulic parameters for Hewitt *et al.* experiments

X	Inlet Fluid Enthalpy (Btu/lb)						
	P=20	P=25	P=30	P=35	P=40	P=45	P=50
10	321.43	329.05	335.93	342.21	348.01	353.42	358.59
20	415.38	422.44	428.81	434.63	439.99	444.98	449.64
30	509.32	515.82	521.69	527.04	531.96	536.54	540.81
40	603.27	609.21	614.57	619.45	623.94	628.10	631.98
50	697.21	702.60	707.46	711.87	715.91	719.65	723.15
60	791.16	795.98	800.34	804.27	807.89	811.21	814.31
70	885.09	889.39	893.23	896.70	899.85	902.77	905.49
80	979.03	982.76	986.10	989.10	991.83	994.33	996.66
90	1072.98	1076.15	1078.41	1081.52	1083.81	1085.89	1087.83

X   : Inlet quality (%)
P   : Outlet pressure (psig)
G   : Total mass flow rate = 0.04445 (lb/s)

Table 3.3　Thermal hydraulic parameters for Keeys *et al.* experiments

X	Inlet Fluid Enthalpy (Btu/lb)									
	P = 500 psia, T = 435.6 °F						P = 1000 psia, T = 545.0 °F			
	G=0.3736	G=0.3756	G=0.3775	G=0.3833	G=0.3847	G=0.3944	G=0.2600	G=0.3742	G=0.5614	G=0.7300
20	570.84	544.16	528.96	578.36	533.84	568.24	603.60	630.64	648.52	618.72
30	687.86	637.89	619.09	666.94	625.11	653.96	693.40	707.06	724.08	695.88
40	744.88	731.62	709.22	755.52	716.38	739.68	773.20	783.48	799.64	773.04
50	831.90	825.10	799.35	844.10	807.65	825.40	853.00	859.90	875.20	850.20
60	918.92	919.08	889.48	932.68	898.92	911.12	932.80	936.32	950.76	927.36
70	1005.94	1012.81	979.61	1021.26	990.19	995.94	1012.60	1012.74	1026.32	1004.52
80	1092.96	1106.54	1069.74	1109.84	1081.46	1082.56	1092.40	1089.16	1101.88	1081.68
90	1179.98	1200.27	1159.87	1198.42	1172.73	1168.28	1172.20	1165.58	1177.44	1158.84

X : Inlet quality (%)
P : Outlet pressure (psia)
T : Saturation temperature (°F)
G : Total mass flow rate (lb/s)

Table 3.4 A sample of input for calculation

```
            0
            0              0.0
      1.0E-3            10              40
          1      *****  ENTRAINMENT EXP. AERE-R 5374, 12FT-50PSIG-X40  *****
    1    1
   64.692     631.98        0.0       0.0     631.98 3.897E-03     .9999  1.0
AIR        0.0001
    2    1
   1.10521.150
    4    1    1
    1    1   48    3.0
    1    1                               1
    1
   48
    7

    8    1    0    1    1
    1    1    1    0                      1.0       1.0            1  0. 297.7
    1  1.0
    1    1    0    2
    1
       0.0     297.7     144.     297.7
    9    1
    1 HROD      0.366       0.0    2    1    1
    1    1 .1     1.0      1    1 .083  1.0
   10    1
    1    9     525.0                      S.S.
   32.       0.2     10.11     400.      .116     10.11
  600.       .121     11.10     800.      .126     12.1
 1000.       .132     13.2    1200.      .14      14.3
 1400.       .145     15.5    1600.      .149     16.7
 2500.       .167     22.1
   11    1
    1    2
       0.0       1.0     144.       1.0
   12
   13    2
    1    1    2    0    0  0.04444     631.98     95.00
 631.9.0039.9999.0001

    1   50    1    0    0   64.692     631.98
 631.9.0039.9999.0001

   14    5


  030
        .0002       .015       5.0       1.0    10800.0
           1.          5.      800.      800.0
       -.0002       .015      20.0       1.0    10800.0
          10.        900.      800.      800.0
       -.001       0.005       5.0       1.0      200.0
```
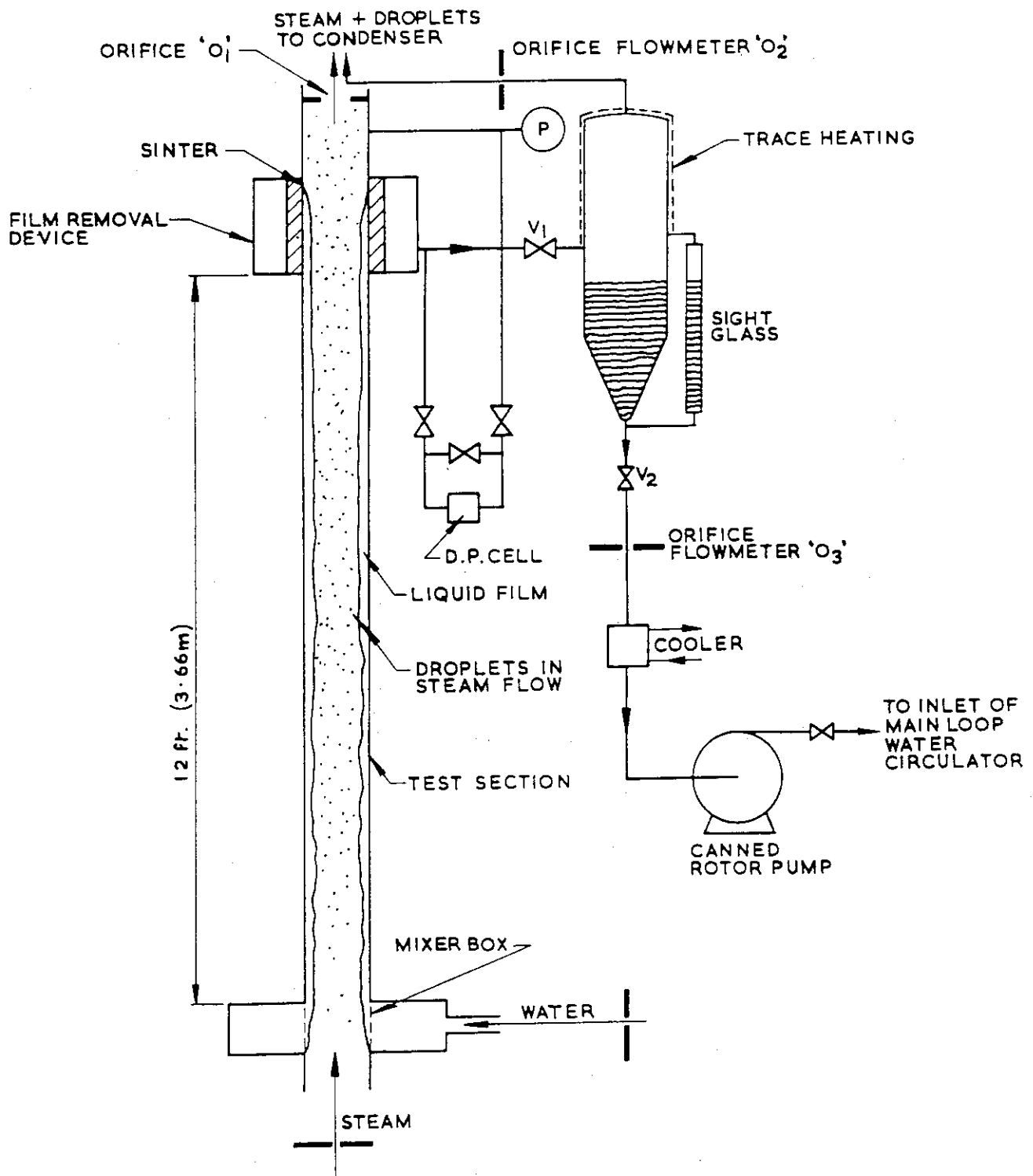
Fig. 3.1 Schematic diagram of experimental apparatus[6]
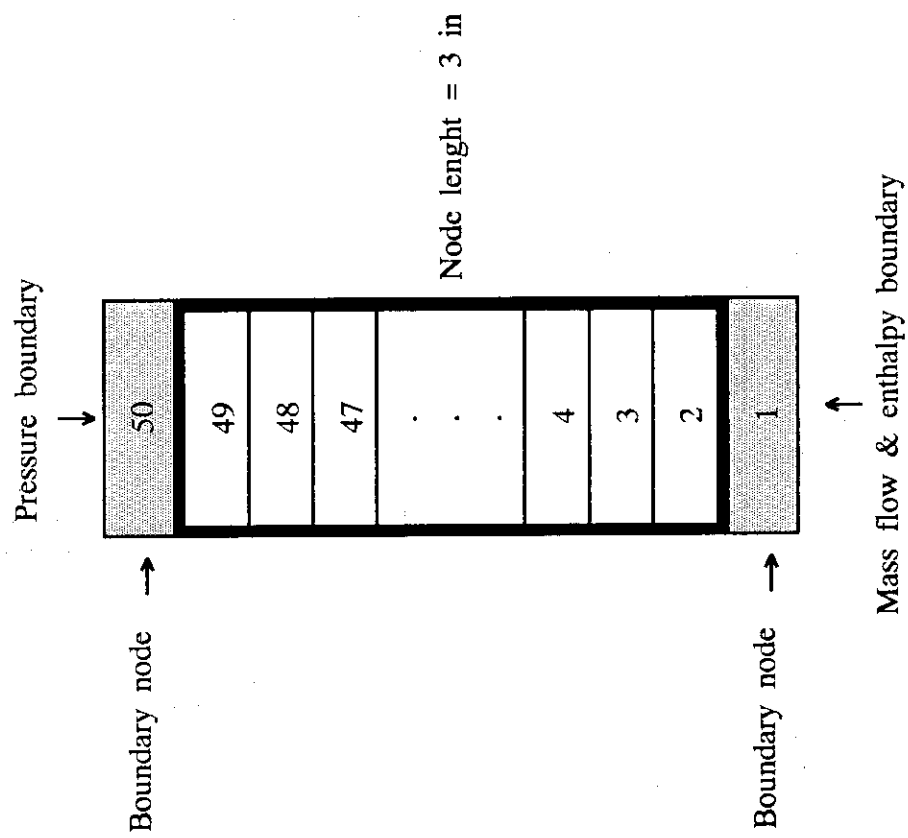
Fig. 3.2 Noding diagram for entrainment experiments
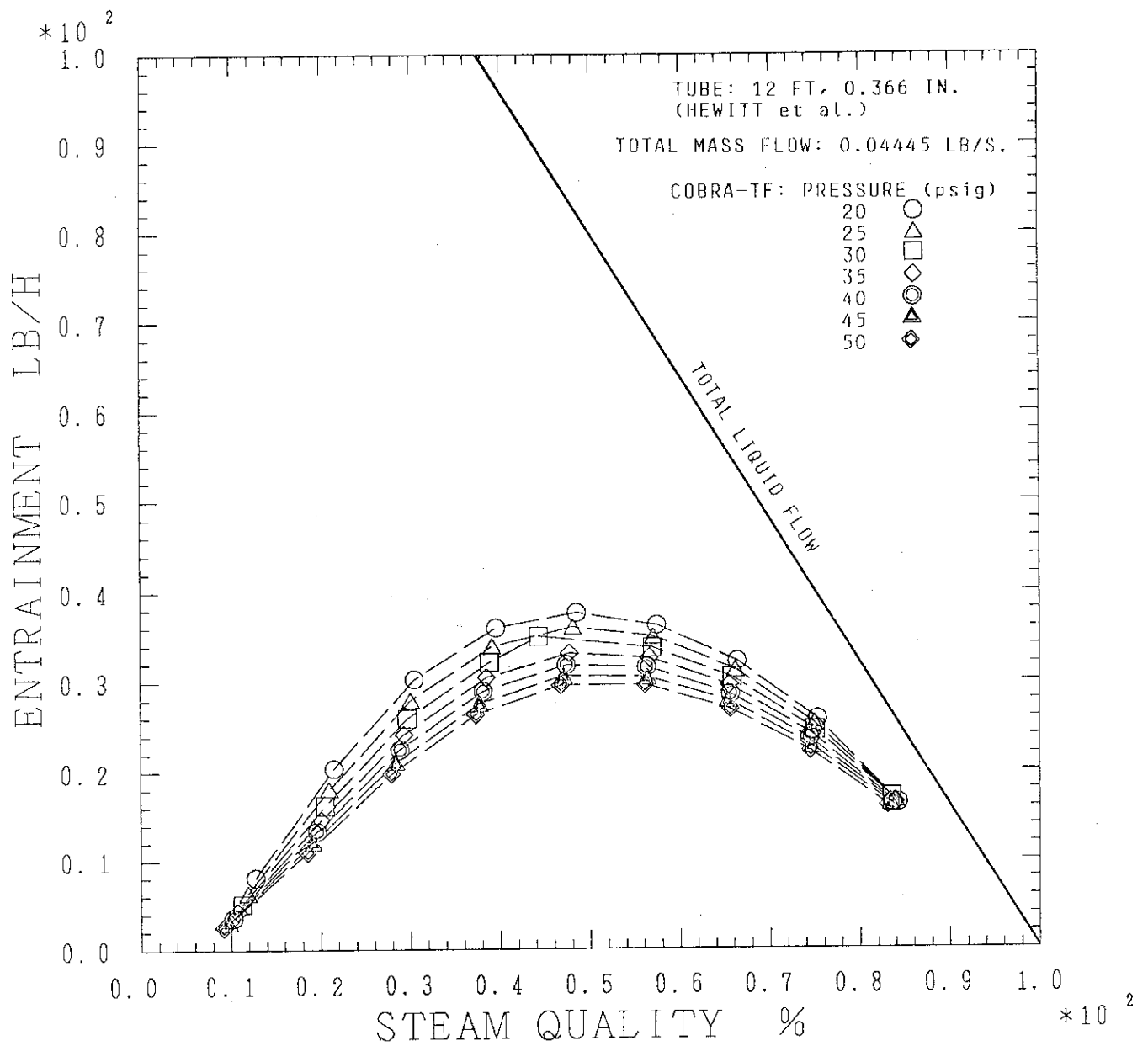
Fig. 3.3 Calculated entrainment mass flow rates for lower pressure cases
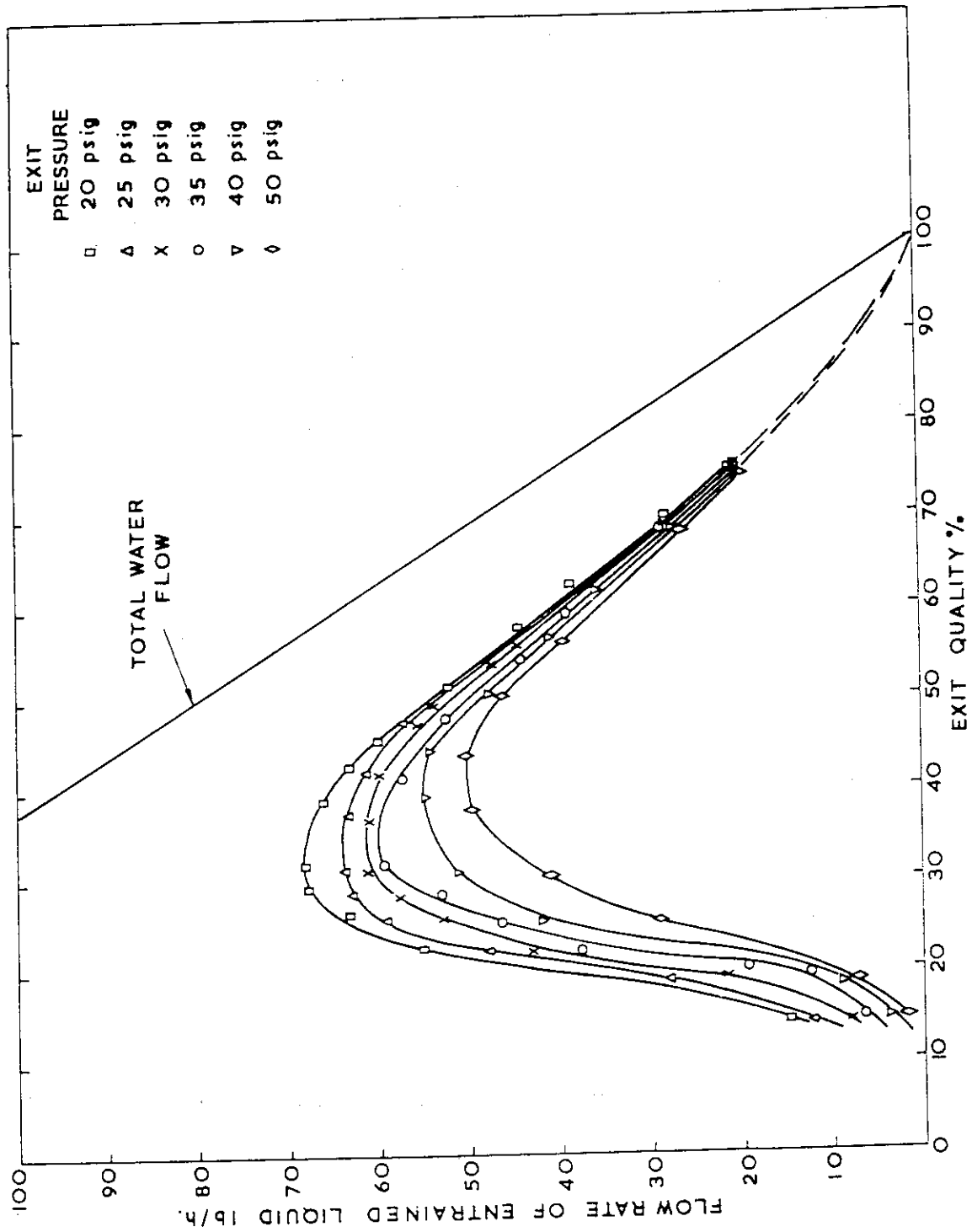
Fig. 3.4 Entraiment mass flow rates from Hewitt *et al.* experiments at lower pressures[5]
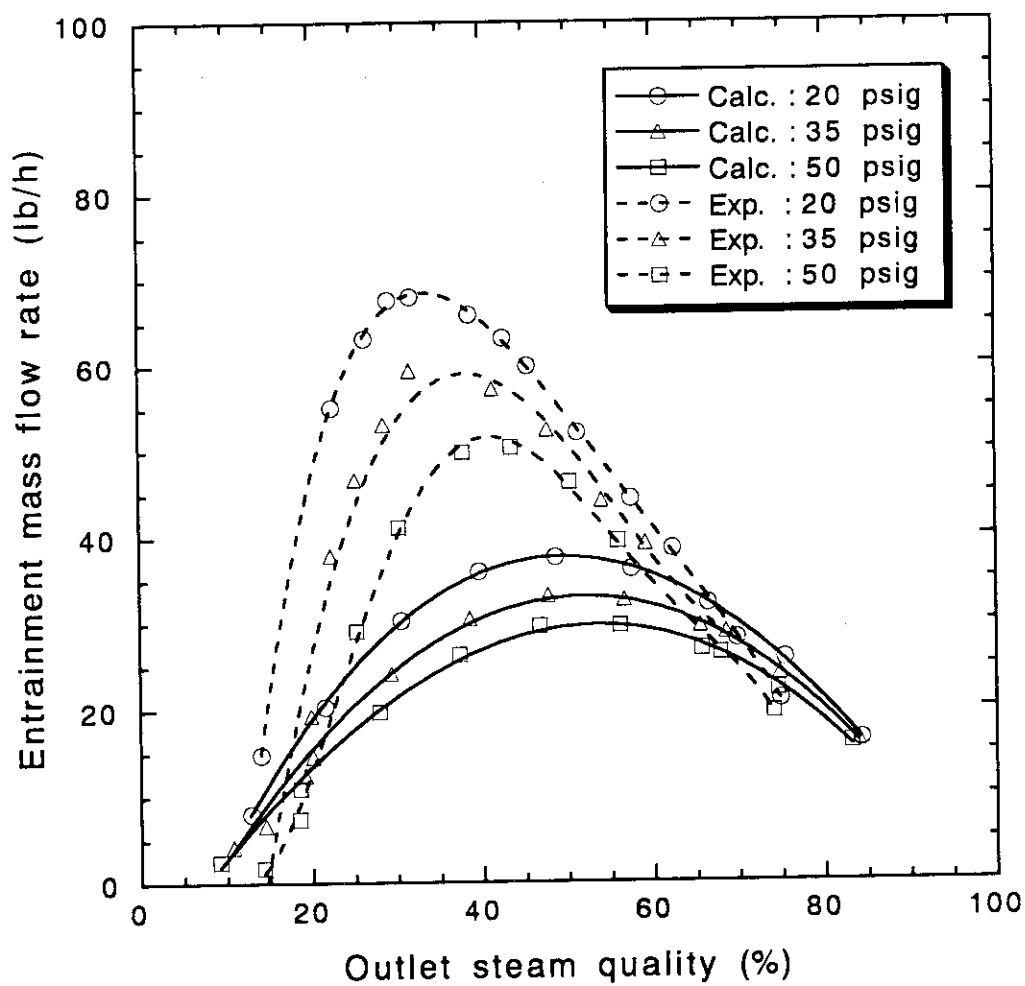
Fig. 3.5 Comparisons between calculation and experiment for lower pressures
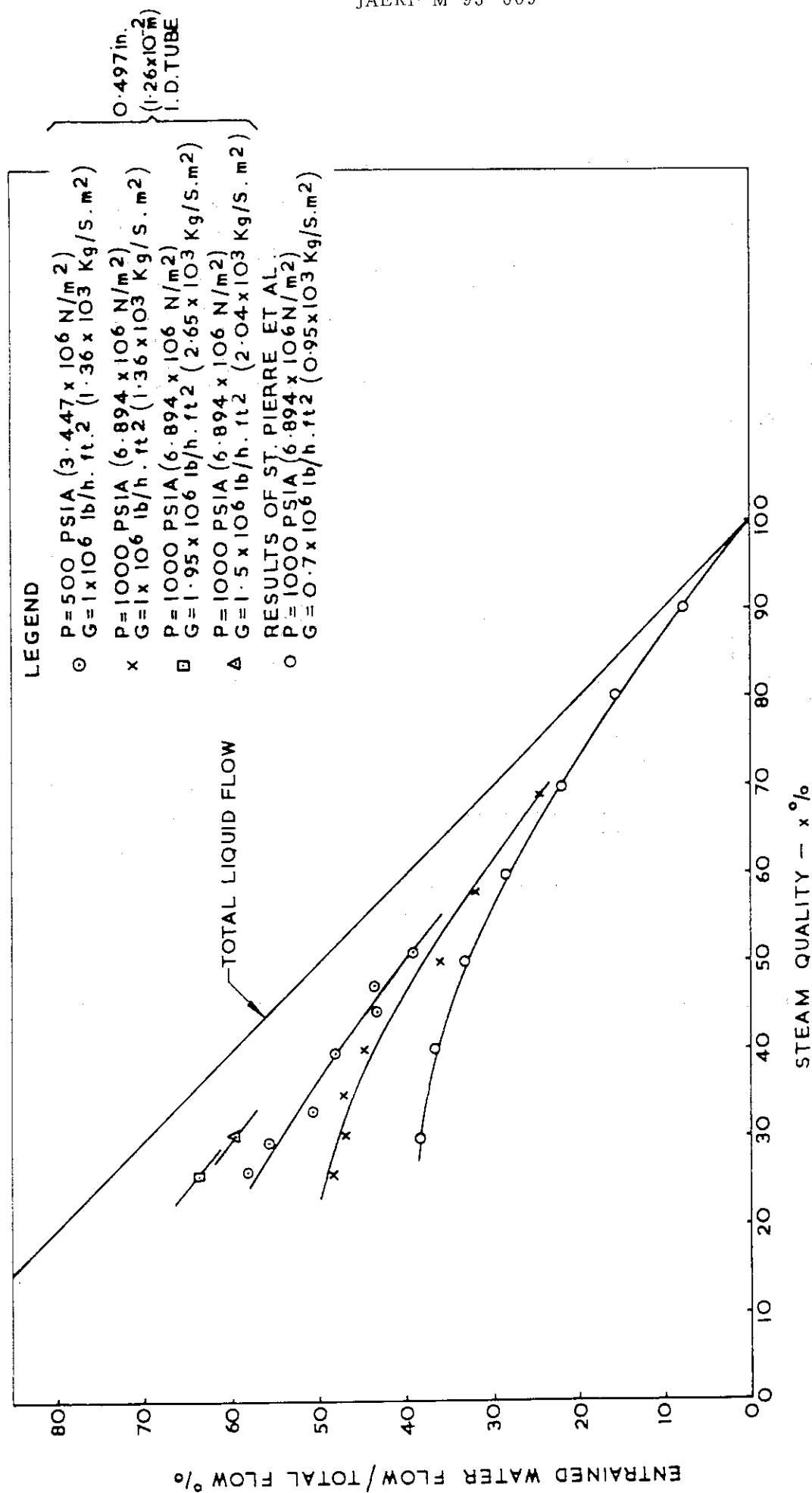
Fig. 3.6 Entrainment ratios to total flow rates from experiments at higher pressures[6]

LEGEND

⊙ P=500 PSIA (3.447 × 10⁶ N/m²)
   G=1×10⁶ lb/h.ft.2 (1.36 × 10³ Kg/S.m²)

× P=1000 PSIA (6.894 ×10⁶ N/m²)
   G=1x 10⁶ lb/h.ft2 (1.36×10³ Kg/S.m²)

□ P=1000 PSIA (6.894 × 10⁶ N/m²)
   G=1.95 × 10⁶ lb/h.ft2 (2.65 × 10³ Kg/S.m²)

△ P=1000 PSIA (6.894 × 10⁶ N/m²)
   G=1.5 × 10⁶ lb/h.ft2 (2.04×10³ Kg/S.m²)

RESULTS OF ST. PIERRE ET AL.
○ P=1000 PSIA {6.894×10⁶N/m²)
   G=0.7×10⁶ lb/h.ft2 (0.95×10³ Kg/S.m²)

0.497 in.
(1.26×10⁻² m)
I.D.TUBE

Fig. 3.7 Comparison between calculation and experiment for 3.4 MPa (500 psia) case
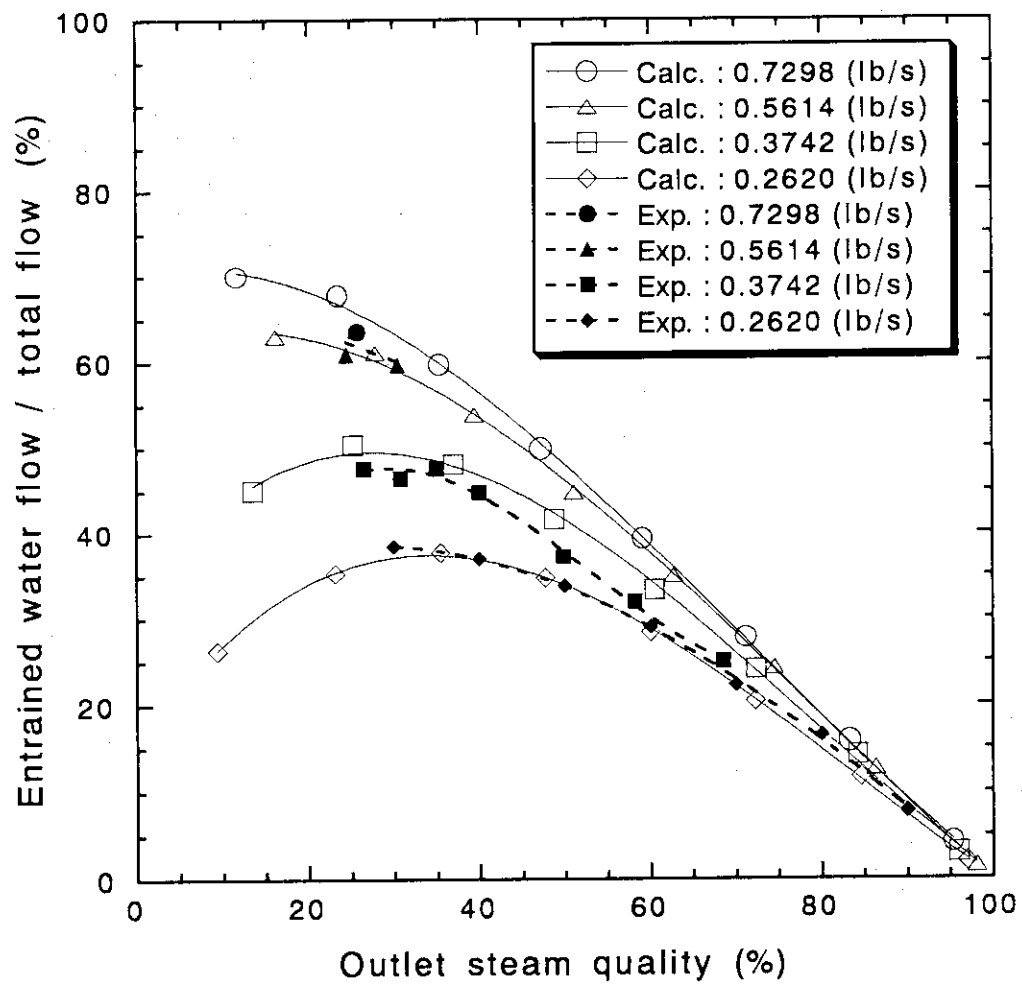
Fig. 3.8 Comparison between calculation and experiment for 6.9 MPa (1,000 psia) case

4. Discussion

4.1 Axial Change in Mass Flow Rate of Each Field

Although the data from the experiments are almost limited to the mass flow rates at the exit of the test section, the calculations can offer much more detailed information on the thermo-hydrodynamic variables in the test section. One important information is the axial changes in the mass flow rate of the three fields.

In the report[5] of Hewitt *et al.*, a short discussion on this information was made focusing on establishment of the equilibrium entrainment situation at the exit of the test section. Figure 4.1 shows their data discussed in their report. This is a comparison of the entrainment mass flow rate at the exit of the test section between 6 ft and 12 ft length cases. The figure indicates the entrainment mass flow rates are nearly the same between the two lengths except for the lower pressure cases in the steam quality region near the maximum entrainment. They concluded that at least 99 % of the equilibrium figure was attained after 12 ft, by estimating the equilibrium entrainment assuming the exponential function with respect to the length from the inlet.

The calculated mass flow rates with COBRA-TF for the three fields are plotted along the axial position in Fig. 4.2 at the pressure of 35 psig and the steam quality of 40 % case. It is seen that the entrainment mass flow rate increases along the channel, resulting in decreasing in the film flow rate, while vapor flow rate is nearly constant. In this case at the lower pressure, the hydrodynamic equilibrium situation is not yet attained in the calculation, although the equilibrium situation is expected to be established in the experiment as described above. Figure 4.3 shows the same kind of data for the pressure of 50 psig and the steam quality of 40 %. Even in this case, the equilibrium situation is not attained at the exit. Judging from the gradient of the curve, however, the value of entrainment mass flow rate at the exit is much closer to the equilibrium one in this case of 50 psig than the other. This dependency of the asymptotic behavior on the pressure is the same as observed in the experiments. Figure 4.4 also shows the same kind of data for the pressure of 50 psig and the steam quality of 20 %. In this case, the value at the exit is fairly close to the equilibrium one even at the lower pressure of 50 psig.

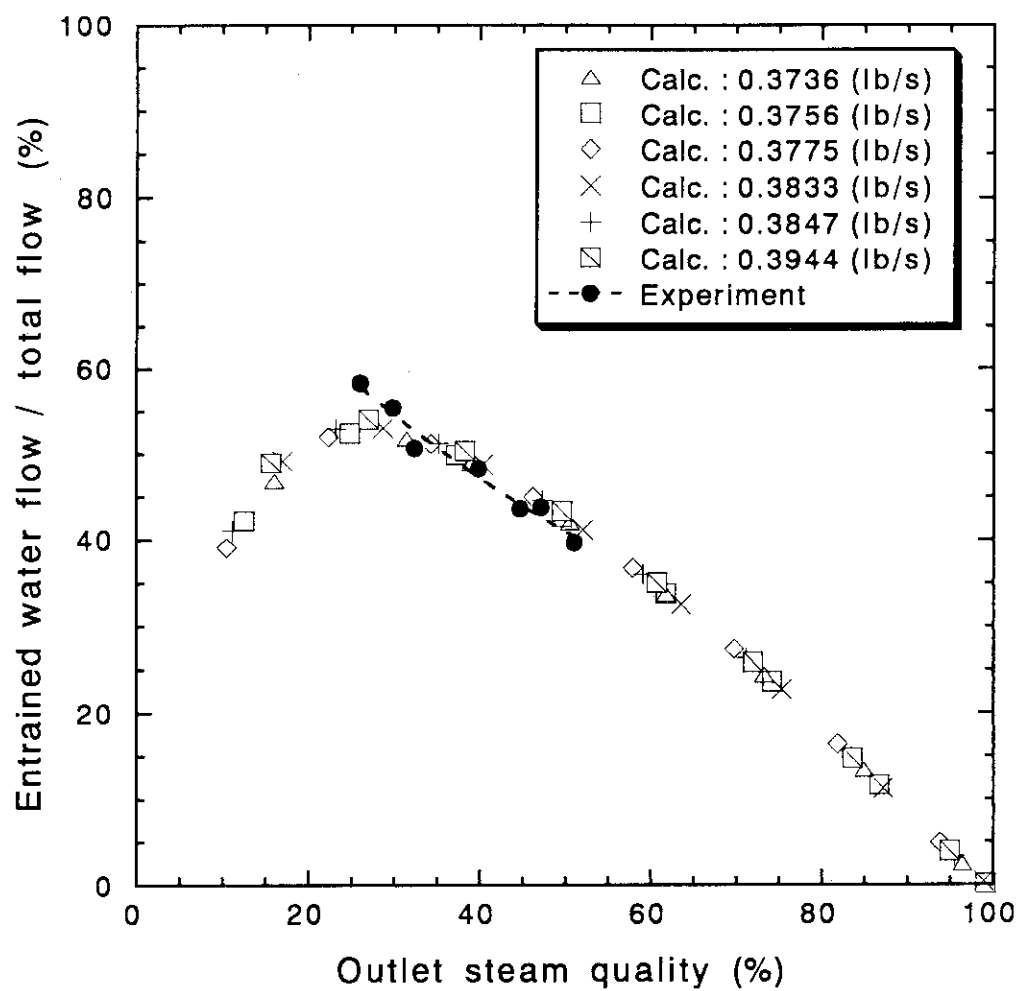The reason for these characteristics on the asymptotic behavior to the equilibrium is considered to be as follows. The equilibrium values for the steam quality of 40 % are much higher than the calculated at the lower pressures as shown in Fig. 3.5. In other words, the equilibrium is not attained in these calculations. For the pressure of 50 psig and the steam quality of 20 % case, however, the calculated value is in good agreement with the

experimental data, *i.e.* the equilibrium value. Therefore, the equilibrium is considered to be attained in this calculation.

At the higher pressures, the equilibrium situation is generally attained at the exit as shown in Figs. 4.5 and 4.6. This is considered to be corresponding to the good agreement between the calculations and the experiments at the higher pressures as shown in Figs. 3.7 and 3.8.

4.2 Detailed Discussion on Calculated Results

As described in Sec. 3.3, the calculated results with COBRA-TF are in good agreement with the experimental data for the higher pressures of 3.4 and 6.9 MPa (500 and 1,000 psia), whereas not for the lower pressures of 0.24 ~ 0.45 MPa (20 ~ 50 psig). One possible reason for this discrepancy is the entrainment correlation used in COBRA-TF is one developed by Würtz based mainly on his experimental data obtained at high pressures of 3 to 9 MPa[7]. The mass fluxes are also different a lot between the experiments by Würtz and by Hewitt *et al.* That is, the mass flux ranges from 500 ~ 3,000 kg/m²s for Würtz, which covers the range for Keeys *et al.*, whereas the mass flux was fixed at 297 kg/m²s for Hewitt *et al.* Concerning to the difference in the pressure range, the effects of the material properties on the thermo-hydrodynamic behavior are dominant. Especially, the effect of the fluid density, which is not directly taken into account in the Würtz's correlation, is expected to be significant when the correlation is applied to the lower pressures as in the above case. For instance, the ratio of the liquid density to the vapor is about 10 times larger in the lower pressures than the higher pressures and this seems to have a significant effect on the entrainment/deposition phenomena. This will be discussed more in detail in the next section.

Tables 4.1 and 4.2 summarize detailed information of the calculated values at 6 and 12 feet elevations for 50 psig and 500 psia cases, respectively. One point to be noted is the void fractions (*i.e.* vapor volume fractions) are lower than the critical void fractions for both cases. The critical void fraction is defined by Eq.(1) and the calculated values are very high numbers over 0.996. Therefore, in the calculations, the film flow is regarded as the unstable film flow rather than the stable. According to the Tables 4.1 and 4.2, the interfacial friction factors for these unstable cases are calculated to be five times values obtained with the Wallis correlation. This multiplication factor of five is directly reflected to the entrainment rate as recognized by Eqs.(2) and (5). The calculated entrainment is nevertheless much smaller than the experimental data for the lower pressures. The reason for this is under investigation.

Although the practical application with COBRA-TF may be considered to be in the pressure and mass flux ranges covered by the Würtz's correlation, many experiments utilized

for the thermo-hydrodynamic model development are conducted in the lower pressure and mass flux range. Therefore, more efforts to get a good agreement are necessary for the future improvements of the models in the code, such as for the film dryout prediction, the spacer effect prediction and so forth.

4.3 Discussion on Entrainment/Deposition Models

On the entrainment/deposition modeling, many researchers have put their efforts during passed two decades. Among them, Sugawara seems to be most successful judging from literatures published as shown in Fig. 4.7[14]. He developed an entrainment/deposition correlations for his subchannel analysis code FIDAS[15]. The code is based on the three-field modeling of the two phase flow, as is in COBRA-TF. Therefore, it is useful to study his entrainment/deposition modeling to improve the COBRA-TF calculation for the lower pressures. His correlations are presented briefly in the following in the British units.

The entrainment generation rate m_E is as follows :

$$m_E = 0.219 \left(\frac{\Delta h_{eq} \times \tau_i}{\sigma} \right) \left(\frac{u_v \times \mu_l}{\sigma \times g} \right) \left(\frac{\rho_l}{\rho_v} \right)^{0.4} \tag{20}$$

Δh_{eq} : hydrodynamic equivalent wave height

where, Δh_{eq} is expressed with the equivalent sand roughness k_s defined in Eq.(3) :

$$\Delta h_{eq} = k_s \qquad\qquad\qquad \left(Re_v > 1 \times 10^5 \right),$$
$$= k_s \left[2.136 \log_{10} (Re_v) - 9.68 \right] \quad \left(Re_v \leq 1 \times 10^5 \right), \tag{21}$$

Interfacial friction factor f_i is given by the Wallis correlation, but in a different expression from Eq.(7) as in the following :

$$f_{iw'} = \frac{1}{4} \left(\frac{0.316}{Re_v^{0.25}} \right) \left(1 + 300 \frac{\delta_{th}}{D} \right) \tag{22}$$

D : diameter

Although this expression has a dependency on the vapor Reynolds number, values are almost the same for Eqs.(7) and (22) around the Reynolds number of 1×10^5.

The deposition rate m_{DE} is expressed as follows :

$$m_{DE} = k_D \times C \tag{23}$$

and the mass transfer coefficient k_D is expressed as follows :

$$\frac{k_D}{u_v} = 9.0 \times 10^{-3} \left(\frac{C}{\rho_v}\right)^{-0.5} Re_v^{-0.2} \times Sc^{-2/3} \tag{24}$$

Sc : Schmidt number

Comparing the entrainment correlation of Eq.(20) with that for COBRA-TF, i.e. Eq.(2), it is recognized the Sugawara's correlation is based on the Würtz's correlation and two additional factors are introduced. One is effect of the density ratio and is considered to be the representative of the pressure effect mentioned above. The other is the effect of the vapor Reynolds number and is considered to include both the pressure and the mass flux effects. As discussed above in the previous section, these two modifications on the Würtz's correlation are considered to be appropriate and to improve calculational results for the lower pressure cases. In the FIDAS code, however, the interfacial friction factor expressed with Eq.(22) is always used for the film-mist flow[15], whereas five times larger values are usually used in the COBRA-TF calculations as described in the previous section. The effect of this difference in the interfacial friction factor should be also included in the future investigation.

For the deposition correlation, Sugawara developed a new one based on the wide ranges of experimental data, i.e. air-water data at low pressures and steam-water data at high pressures. This is summarized in Fig. 4.8[14]. Although the deposition correlation used in COBRA-TF is based on a Whalley's suggestion[12] that the mass transfer coefficient can be expressed with the surface tension, no information is presented on the formation of the correlation expressed in Eq.(18).

Based on the above consideration, it may be reasonable to use Sugawara's correlations in COBRA-TF code to improve its predictive capability of the entrainment/deposition phenomena at the low pressures.

Table 4.1 Detailed calculational results for 50 psig and 40 % quality case

Variable	Notation	Unit	6ft elevation	12ft elevation
Pressure	P	lb_f/in^2	81.59	65.44
Vapor velocity	u_v	ft/s	125.68	155.81
Film velocity	u_l	ft/s	18.50	19.60
Entrainment velocity	u_e	ft/s	92.71	114.43
Vapor volume fraction	α_v	−	0.9692	0.9731
Film volume fraction	α_l	−	0.0294	0.0255
Entrainment volume fraction	α_e	−	0.0014	0.0015
Vapor mass flow rate	m_v	lb_m/s	0.01651	0.01667
Film mass flow rate	m_l	lb_m/s	0.02257	0.02088
Entrainment mass flow rate	m_e	lb_m/s	0.00539	0.00698
Critical void fraction	$\alpha_{v\ crit}$	−	0.9968	0.9975
Vapor density	ρ_v	lb_m/ft^3	0.1855	0.1504
Liquid density	ρ_l	lb_m/ft^3	56.879	57.296
Interfacial friction factor (Wallis)	f_{iw}	−	7.992×10^{-3}	7.272×10^{-3}
Interfacial friction factor (Henstock–Hanratty)	f_{iH}	−	1.997×10^{-2}	1.721×10^{-2}
Interfacial friction factor (Unstable flow)	f_i	−	3.996×10^{-2}	3.636×10^{-2}
Relative velocity between vapor and film	u_{vl}	ft/s	107.18	136.21
Film thickness	δ_{th}	ft	2.239×10^{-4}	1.940×10^{-4}
Vapor Re	Re_v	−	7.2284×10^4	7.476×10^4
Interfacial shear	τ_i	lb_f/ft^2	2.634	3.150
Equivalent sand roughness	k_s	ft	4.236×10^{-4}	3.362×10^{-4}
Entrainment rate	S_E	lb_m/s	4.776×10^{-4}	5.493×10^{-4}
Vapor Pr	Pr_v	−	1.108	1.095
Mean droplet concentration	C	lb_m/ft^3	8.193×10^{-2}	8.572×10^{-2}
Mass transfer coefficient	k_D	ft/s	0.1909	0.2314
Deposition rate	S_{DE}	lb_m/s	3.747×10^{-4}	4.753×10^{-4}

Table 4.2 Detailed calculational results for 500 psia and 40 % quality case

Variable	Notation	Unit	6ft elevation	12ft elevation
Pressure	P	lb_f/in^2	526.3	501.0
Vapor velocity	u_v	ft/s	103.04	108.82
Film velocity	u_l	ft/s	33.58	32.35
Entrainment velocity	u_e	ft/s	98.81	106.37
Vapor volume fraction	α_v	–	0.9462	0.9531
Film volume fraction	α_l	–	0.0283	0.0211
Entrainment volume fraction	α_e	–	0.0255	0.0258
Vapor mass flow rate	m_v	lb_m/s	0.14936	0.15113
Film mass flow rate	m_l	lb_m/s	0.06437	0.04652
Entrainment mass flow rate	m_e	lb_m/s	0.16933	0.18705
Critical void fraction	$\alpha_{v\,crit}$	–	0.9995	0.9995
Vapor density	ρ_v	lb_m/ft^3	1.1369	1.0815
Liquid density	ρ_l	lb_m/ft^3	50.344	50.593
Interfacial friction factor (Wallis)	f_{iw}	–	7.745×10^{-3}	6.455×10^{-3}
Interfacial friction factor (Henstock–Hanratty)	f_{iH}	–	1.346×10^{-2}	1.040×10^{-2}
Interfacial friction factor (Unstable flow)	f_i	–	3.873×10^{-2}	3.228×10^{-2}
Relative velocity between vapor and film	u_{vl}	ft/s	69.47	76.47
Film thickness	δ_{th}	ft	2.927×10^{-4}	2.185×10^{-4}
Vapor Re	Re_v	–	3.956×10^5	4.033×10^5
Interfacial shear	τ_i	lb_f/ft^2	6.59	6.339
Equivalent sand roughness	k_s	ft	6.569×10^{-4}	4.072×10^{-4}
Entrainment rate	S_E	lb_m/s	3.794×10^{-3}	2.303×10^{-3}
Vapor Pr	Pr_v	–	1.184	1.181
Mean droplet concentration	C	lb_m/ft^3	1.322	1.333
Mass transfer coefficient	k_D	ft/s	4.490×10^{-2}	4.588×10^{-2}
Deposition rate	S_{DE}	lb_m/s	4.437×10^{-3}	1.190×10^{-3}
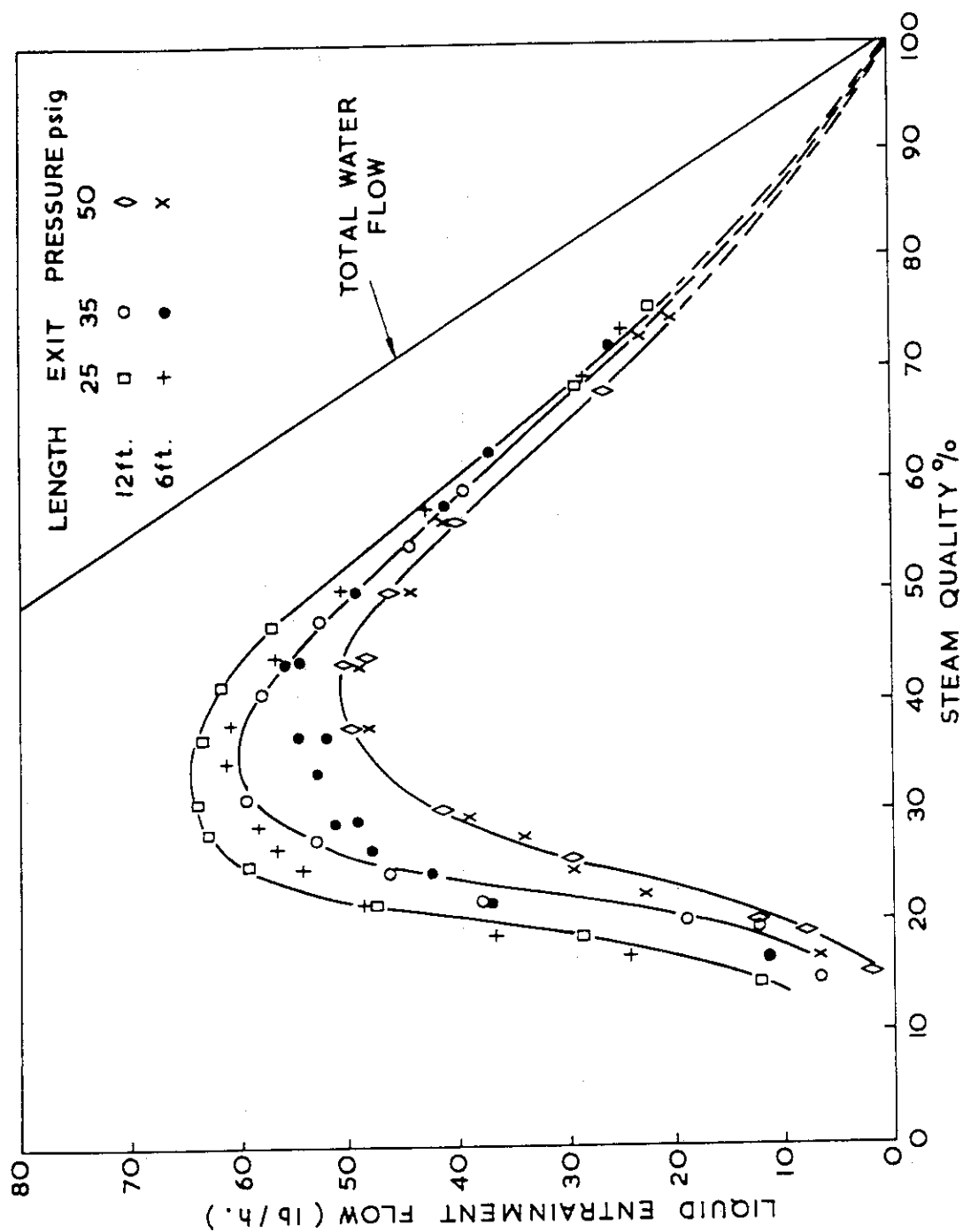
Fig. 4.1　Comparison of measured entrainment mass flow rates between 6 ft and 12 ft lengths[5]
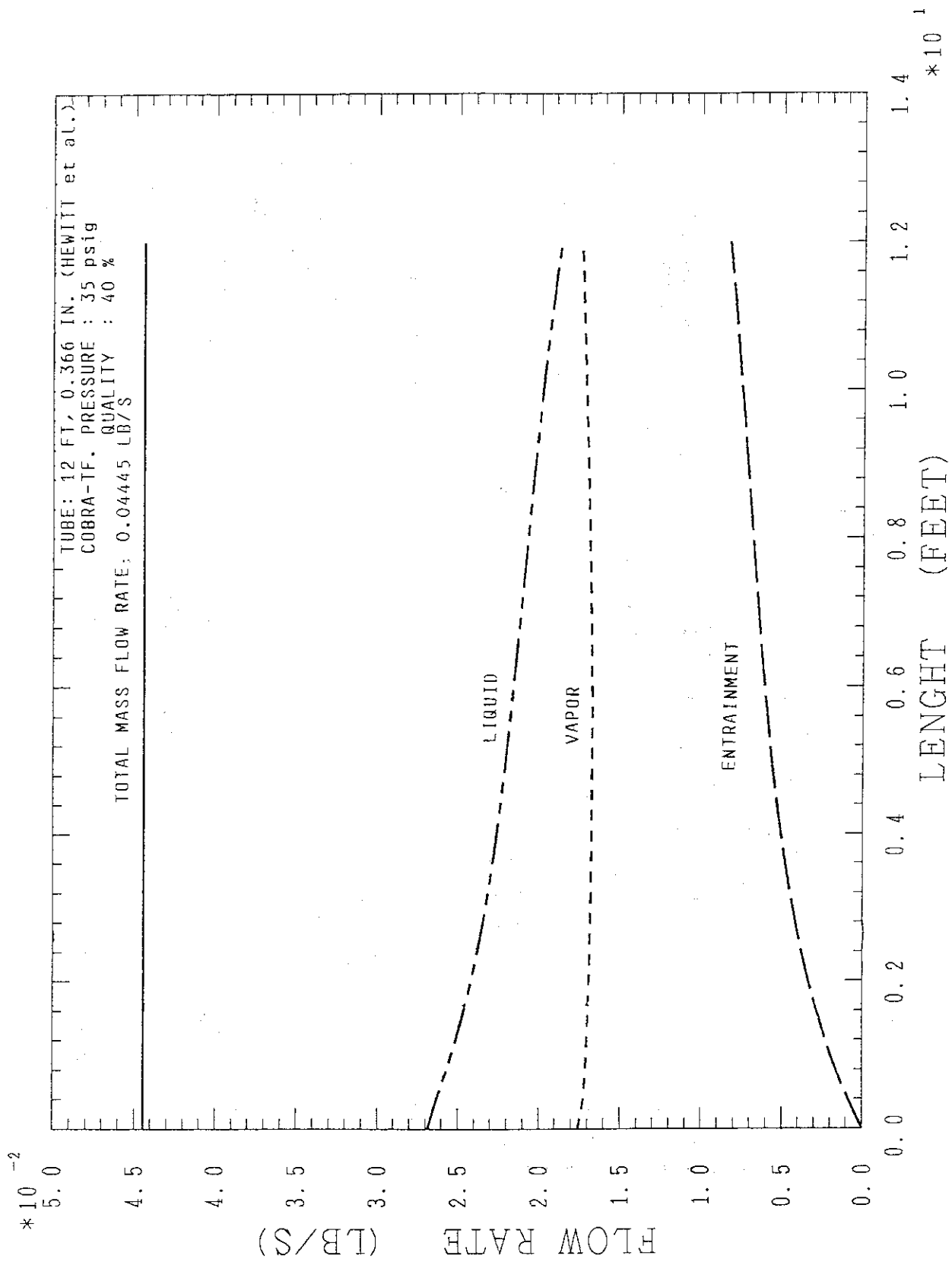
Fig. 4.2   Axial changes in mass flow rate of three fields at 35 psig and 40 % quality
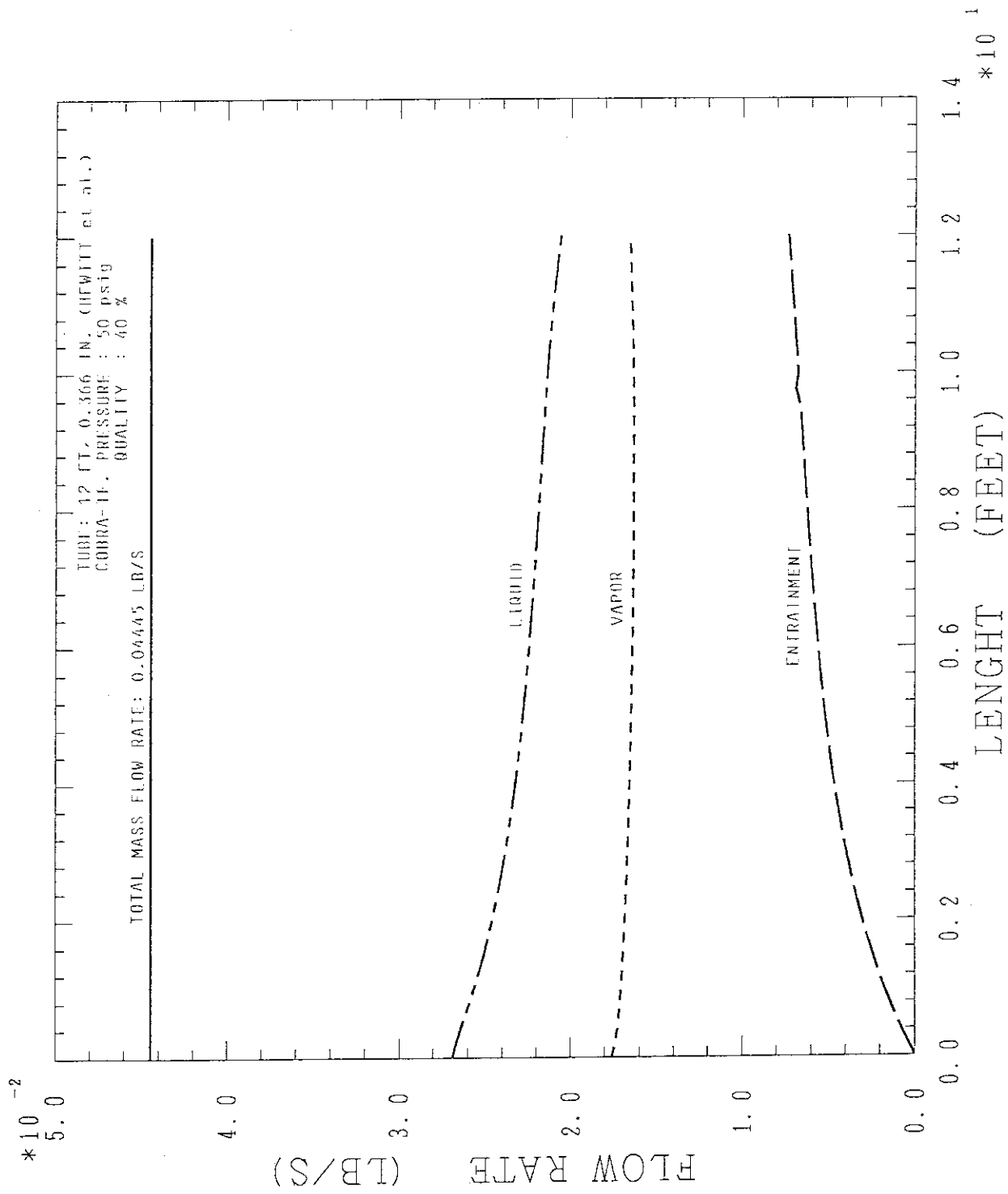
Fig. 4.3 Axial changes in mass flow rate of three fields at 50 psig and 40 % quality
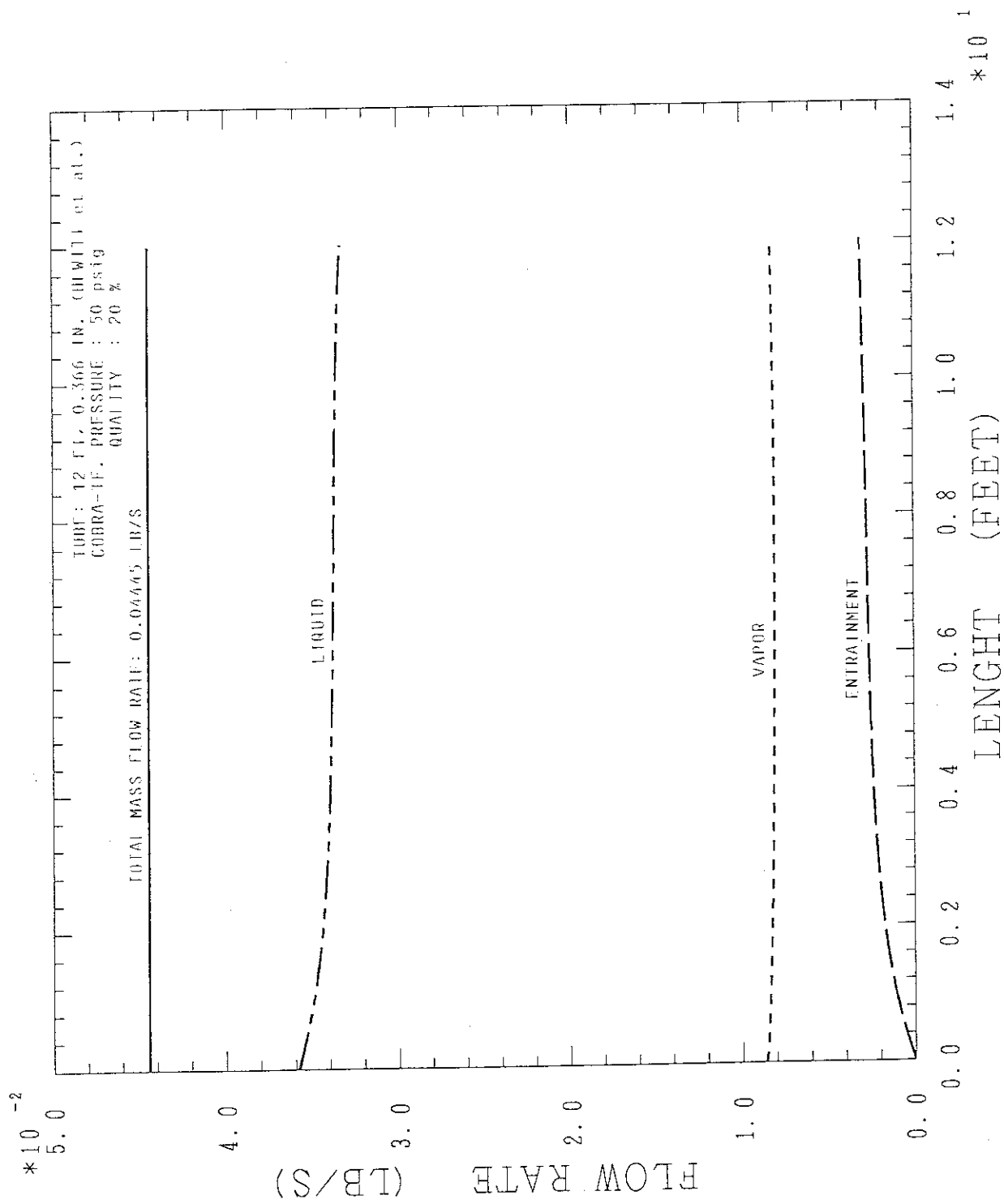
Fig. 4.4 Axial changes in mass flow rate of three fields at 50 psig and 20 % quality
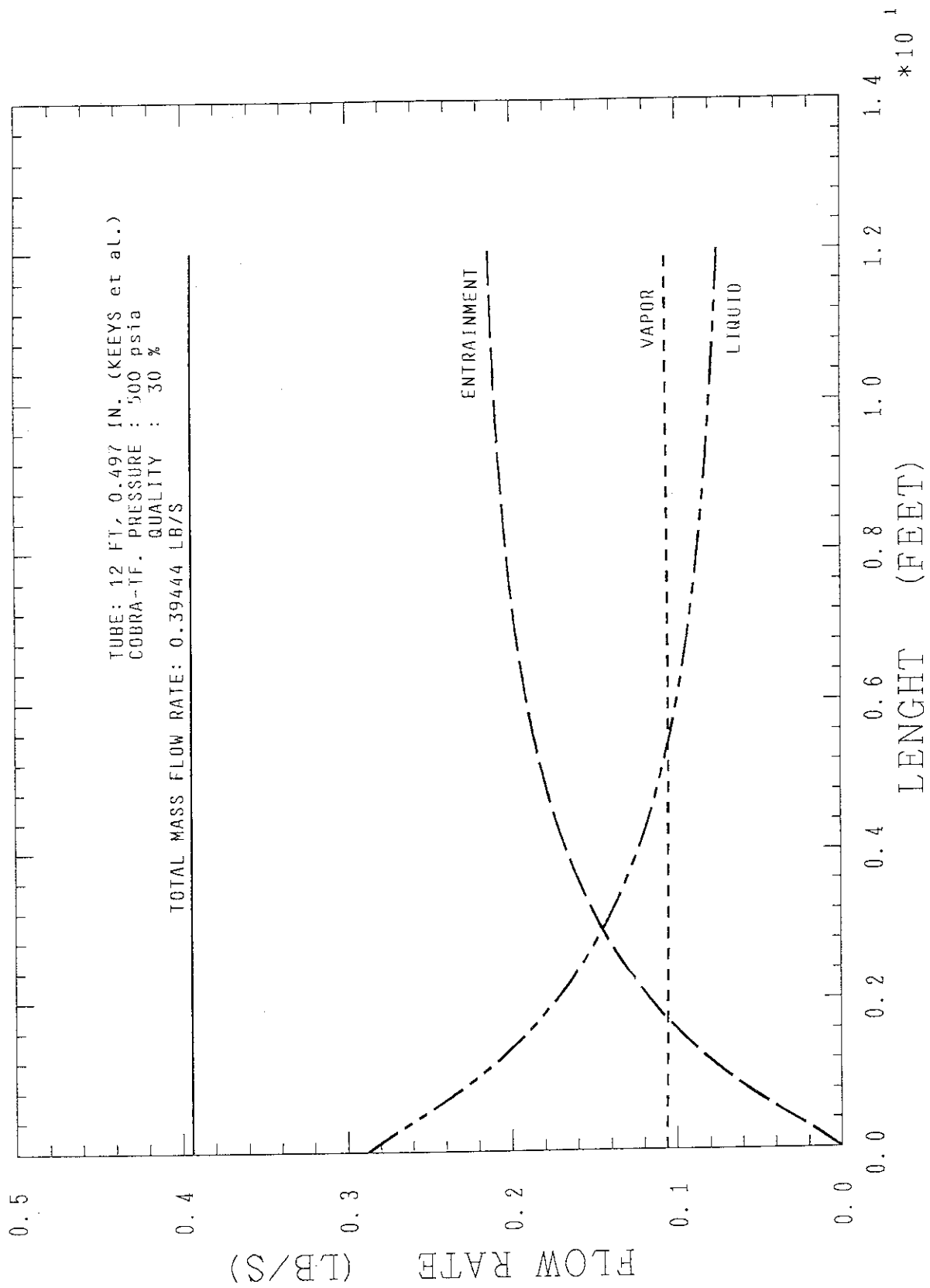
Fig. 4.5 Axial changes in mass flow rate of three fields at 500 psia and 30 % quality
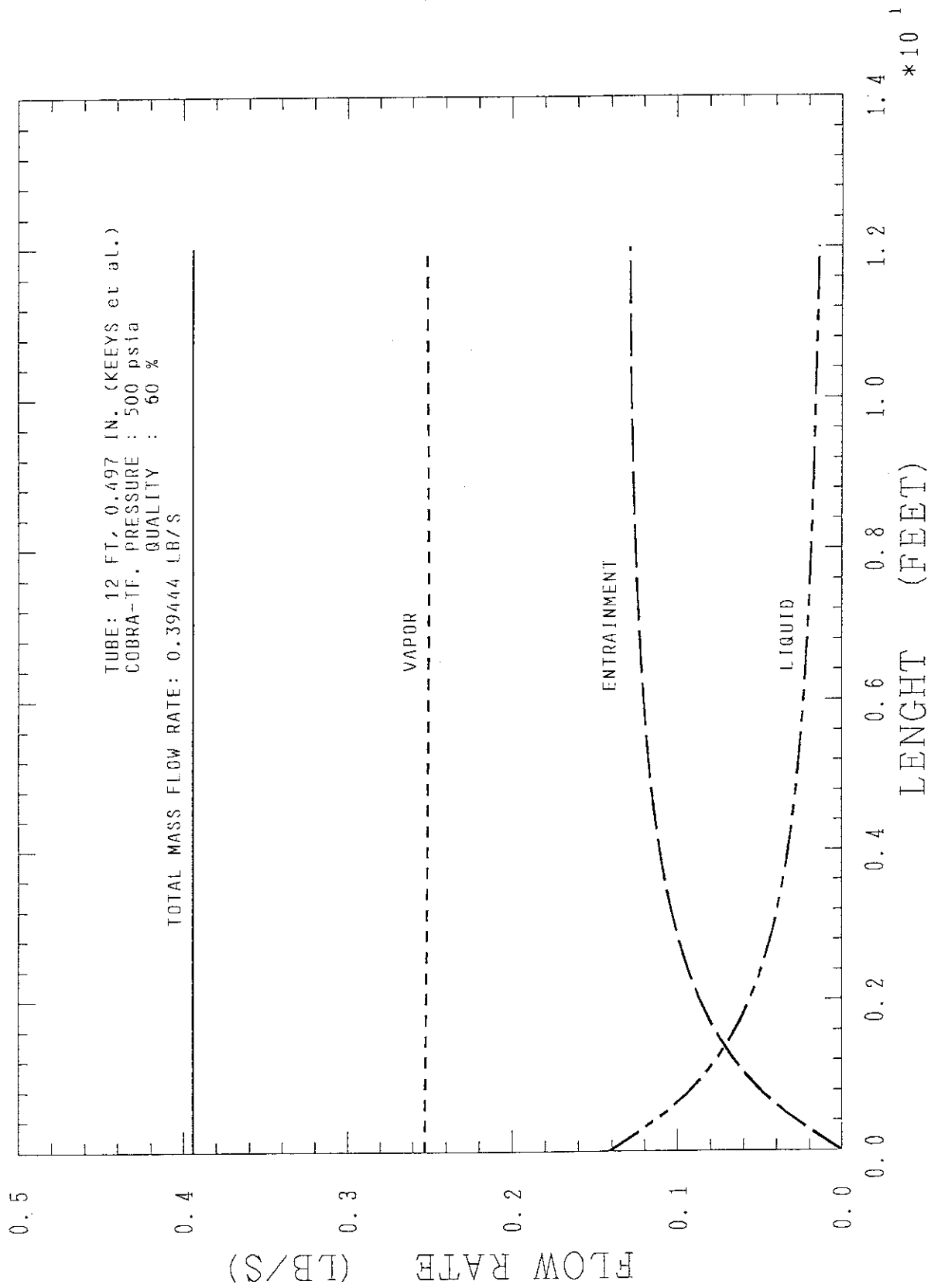
Fig. 4.6 Axial changes in mass flow rate of three fields at 500 psia and 60 % quality
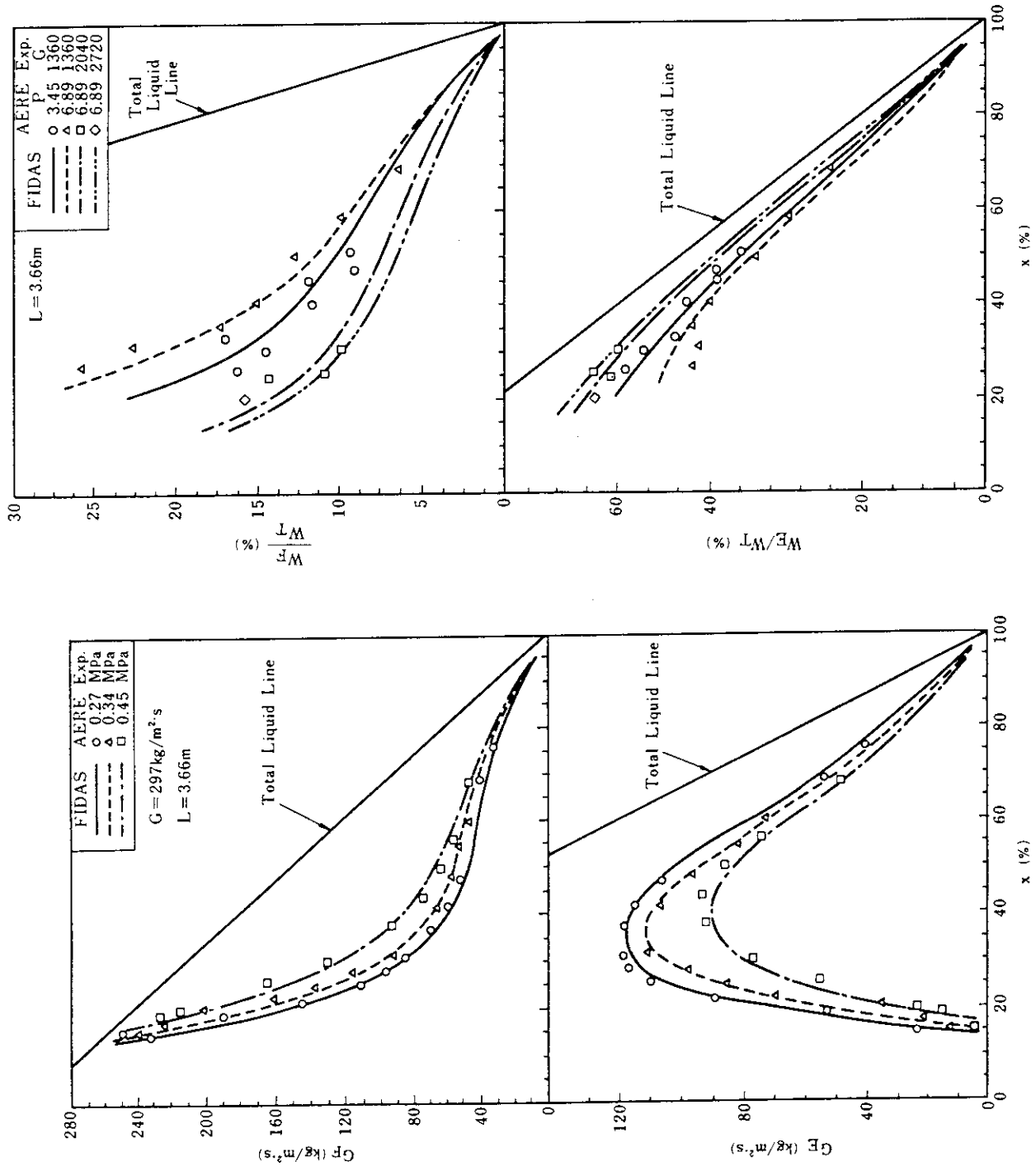
Fig. 4.7 Comparisons between experiment and calculation with FIDAS[14]
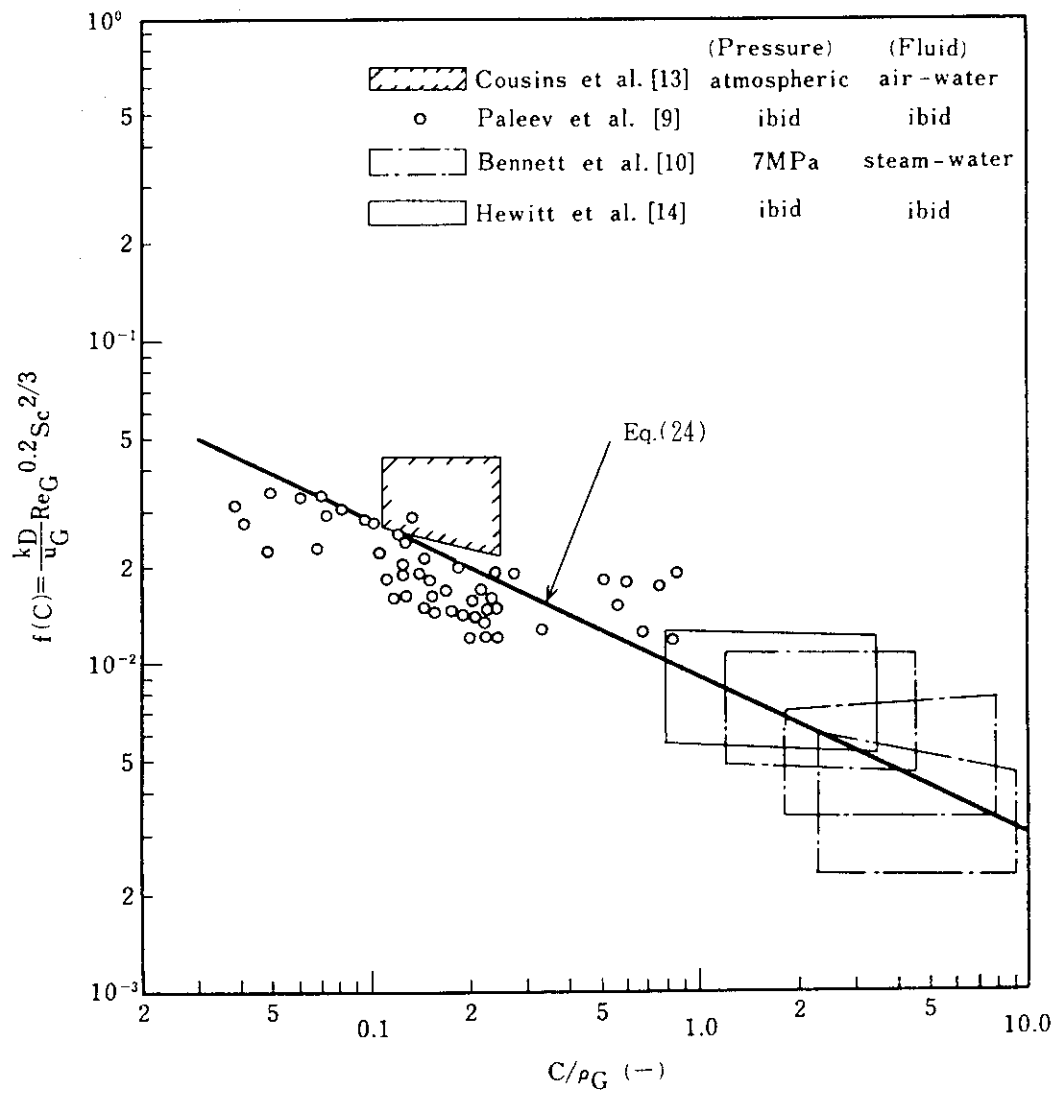
Fig. 4.8 Comparisons between experiments and Sugawara's deposition correlation[14]

5. Conclusions

Some assessment calculations on the liquid entrainment and deposition models in the film-mist flow of the COBRA-TF code have been performed. Concerned experiments are basic ones conducted with a single tube test section under the adiabatic conditions. Although the calculated results of the liquid entrainment mass flow rates at the exit of the test section are in good agreements with the experimental data for the high pressures of 3.4 and 6.9 MPa, the results showed large discrepancies at the low pressures of 0.24 ~ 0.45 MPa.

In COBRA-TF, an entrainment correlation proposed by Würtz is used. This correlation was developed mainly based on his experimental data conducted at the high pressure range of 3 ~ 9 MPa. This is considered to be the reason for the good agreements at the high pressures but the discrepancies at the low pressures described above. At the low pressures, its effect on fluid densities, especially the vapor density, is expected to become significant and should be included in the correlation. An alternative set of Sugawatra's entrainment and deposition correlations, which show good agreements at the low pressures, is investigated by comparing to that of COBRA-TF. Those correlations include additional factors on the pressure effects, and hence, are considered to be promising ones to improve the capability of COBRA-TF.

Although the practical applications to nuclear reactors may be considered to be in the high pressure range, many experiments utilized for the thermo-hydrodynamic model development are conducted in the low pressure range. Therefore, more efforts on the improvements of the models to get a good agreement at the low pressures are considered to be necessary.

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Acknowledgements

References

1.   Thurgood, M.J. *et al.* : "COBRA/TRAC – A Thermal–Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Coolant Systems", NUREG/CR–3046 (1983).

2.   Wheeler, C.L. *et al.* : "COBRA–IV–I An Interim Version of COBRA for Thermal–Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements and Cores", BNWL–1962 (1976).

3.   Rowe, D.S. : "COBRA–IIIC A Digital Computer Program for Steady–State and Transient Thermal–Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements", BNWL–1695 (1973).

4.   Hewitt G.F., Hall–Taylor N.S. : "Annular Two–Phase Flow", Pergamon Press, Oxford, (1970).

5.   Hewitt, G.F., Pulling, D.J. : "Liquid Entrainment in Adiabatic Steam–Water Flow", AERE–R 5374 (1969).

6.   Keeys, R.K.F. *et al.* : "Liquid Entrainment in Adiabatic Steam–Water Flow at 500 and 1000 p.s.i.a (3.447 and 6.894 x 10^6 N/m^2)", AERE–R 6293 (1970).

7.   Würtz, J. : "An Experimental and Theoretical Investigation of Annular Steam–Water Flow in Tubes and Annuli at 30 to 90 Bar", RISO Report No. 372 (1978).

8.   Wallis G.B. : "One–Dimensional Two–Phase Flow", McGraw–Hill, New York, (1969).

9.   Henstock, W.H., Hanratty, T.J. : "The Interfacial Drag and the Height of the Wall Layer in Annular Flows", *AIChE J.*, **22**[6], 990–1000 (1976)

11.   Cousins L.B. *et al.* : "Liquid Mass Transfer in Annular Two–Phase Flow", AERE–R 4926 (1965).

12.   Whalley P.B. : "The Calculation of Dryout in a Rod Bundle", *Int. J. Multiphase Flow*, **3**, 501–515 (1977).

13.   Singh K. *et al.* : "Liquid Film Flow Rates in Two–Phase Flow of Steam and Water at 1000 Lb./Sq.In.Abs.", *AIChE J.*, **15**[1], 51–56 (1969).

14.   Sugawara, S. : "Droplet Deposition and Entrainment Modeling Based on the Three–Fluid Model", *Nucl. Eng. Des.*, **122**, 67–84 (1990).

15.   Sugawara, S., Miyamoto, Y. : "FIDAS : Detailed Subchannel Analysis Code Based on the Three–Fluid and Three–Field Model", *Nucl. Eng. Des.*, **120**, 147–161 (1990).

Nomenclature

d : droplet diameter (ft)

f : friction factor

g : acceleration of gravity (ft/s^2)

k_D : mass transfer coefficient (ft/s)

k_s : equivalent sand roughness (ft)

m_{DE} : deposition rate (lb/ft^{2}s)

m_E : entrainment generation rate (lb/ft^{2}s)

C : mean droplet concentration (lb/ft^3)

D_h : hydraulic diameter (ft)

P_w : wetted perimeter (ft)

Re : Reynolds number

S_{DE} : deposition rate (lb/s)

S_E : entrainment generation rate (lb/s)

Sc : Schmidt number

u : axial velocity (ft/s)

α : volume fraction

δ_{th} : theoretical film thickness (ft)

μ : dynamic viscosity (lb/ft·s)

σ : surface tension of water (lb$_f$/ft)

τ : shear stress (lb$_f$/ft^2)

ρ : density (lb/ft^3)

Δh_{eq} : hydrodynamic equivalent wave height (ft)

Δx : axial mesh length (ft)

subscript

e : entrainment

eq : equilibrium

i : vapor–liquid interface

l : liquid

v : vapor

vl : relative value between vapor and liquid

Appendix A

Calculational results for Hewitt *et al.* experiments

Table A.1 Outlet pressure : <u>20</u> (psig) , Total mass flow rate : <u>0.04445</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
12.76	0.00225	5.06
21.51	0.00566	12.73
30.44	0.00842	18.94
39.53	0.00999	22.48
48.49	0.01045	23.51
57.42	0.01006	22.63
66.37	0.00894	20.11
75.26	0.00715	16.09
84.21	0.00454	10.21

Table A.2 Outlet pressure : <u>25</u> (psig) , Total mass flow rate : <u>0.04445</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
11.90	0.00176	3.96
20.97	0.00501	11.27
30.04	0.00777	17.48
39.10	0.00942	21.19
48.08	0.01001	22.52
57.04	0.00971	21.85
66.17	0.00869	19.55
74.92	0.00703	15.82
83.90	0.00462	10.39

Table A.3   Outlet pressure : <u>30</u>   (psig) ,   Total mass flow rate : <u>0.04445</u>   (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
11.27	0.00143	3.22
20.52	0.00450	10.12
29.68	0.00721	16.22
38.79	0.00893	20.09
44.28	0.00972	21.87
56.90	0.00936	21.06
65.83	0.00845	19.01
74.99	0.00681	15.32
83.49	0.00472	10.62

Table A.4   Outlet pressure : <u>35</u>   (psig) ,   Total mass flow rate : <u>0.04445</u>   (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
10.73	0.00119	2.68
20.09	0.00406	9.13
29.29	0.00671	15.10
38.47	0.00846	19.03
47.68	0.00920	20.70
56.58	0.00905	20.36
65.50	0.00821	18.47
74.70	0.00668	15.03
83.88	0.00454	10.21

Table A.5   Outlet pressure : <u>40</u>   (psig) ,   Total mass flow rate : <u>0.04445</u>   (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
10.26	0.00100	2.25
19.62	0.00370	8.32
28.87	0.00625	14.06
38.09	0.00804	18.09
47.36	0.00884	19.89
56.27	0.00877	19.73
65.63	0.00793	17.84
74.38	0.00656	14.76
83.63	0.00454	10.21

Table A.6   Outlet pressure : <u>45</u>   (psig) ,   Total mass flow rate : <u>0.04445</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
9.76	0.00085	1.91
19.12	0.00336	7.56
28.39	0.00585	13.16
37.69	0.00766	17.23
47.02	0.00851	19.15
56.38	0.00847	19.06
65.32	0.00774	17.41
74.72	0.00631	14.20
83.34	0.00452	10.17

Table A.7 Outlet pressure : $\underline{50}$ (psig) , Total mass flow rate : $\underline{0.04445}$ (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
9.20	0.00071	1.60
18.54	0.00304	6.84
27.90	0.00549	12.35
37.28	0.00732	16.47
46.71	0.00822	18.49
56.11	0.00823	18.52
65.61	0.00747	16.81
74.50	0.00618	13.90
83.09	0.00446	10.03

Appendix B

Calculational results for Keeys *et al.* experiments

Table B.1   Outlet pressure : <u>500</u> (psia) ,   Total mass flow rate : <u>0.3736</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
16.06	0.1750	46.84
31.46	0.1935	51.79
38.98	0.1827	48.91
50.46	0.1568	41.98
61.74	0.1260	33.73
73.27	0.0912	24.42
84.90	0.0501	13.42
96.39	0.0094	2.52

Table B.2   Outlet pressure : <u>500</u>   (psia) ,   Total mass flow rate : <u>0.3756</u>   (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
12.51	0.1587	42.26
24.87	0.1969	52.43
37.23	0.1872	49.85
49.57	0.1602	42.67
61.76	0.1268	33.77
74.18	0.0889	23.67
86.71	0.0438	11.67
99.14	0.0008	0.20

Table B.3 Outlet pressure : 500 (psia) , Total mass flow rate : 0.3775 (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
10.50	0.14767	39.12
22.39	0.19634	52.01
34.28	0.19322	51.18
46.16	0.16984	44.99
57.86	0.13881	36.77
69.77	0.1035	27.42
81.80	0.0620	16.43
93.76	0.0187	4.95

Table B.4 Outlet pressure : 500 (psia) , Total mass flow rate : 0.3833 (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
17.02	0.1883	49.12
28.70	0.2034	53.05
40.38	0.1866	48.69
52.06	0.1579	41.20
63.55	0.1249	32.51
75.32	0.0872	22.75
87.16	0.0431	11.25
98.91	0.0018	0.46

Table B.5   Outlet pressure : 500 (psia) , Total mass flow rate : 0.38472 (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
11.14	0.1583	41.13
23.18	0.2037	52.94
35.22	0.1972	51.26
47.25	0.1715	44.58
59.10	0.1387	36.05
71.17	0.1015	26.37
83.38	0.0574	14.92
95.47	0.0131	3.40

Table B.6   Outlet pressure : 500 (psia) , Total mass flow rate : 0.3944 (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
15.68	0.1931	48.97
26.98	0.2133	54.07
38.28	0.1986	50.35
49.58	0.1709	43.34
60.70	0.1383	35.07
71.94	0.1021	25.88
83.53	0.0584	14.79
94.91	0.0156	3.95

Table B.7 Outlet pressure : <u>1000</u> (psia) , Total mass flow rate : <u>0.26196</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
9.39	0.0690	26.36
23.19	0.0925	35.31
35.46	0.0989	37.76
47.72	0.0910	34.73
60.00	0.0745	28.44
72.29	0.0535	20.41
84.61	0.0307	11.73
96.94	0.0053	2.03

Table B.8 Outlet pressure : <u>1000</u> (psia) , Total mass flow rate : <u>0.37423</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
13.54	0.1689	45.14
25.28	0.1887	50.42
37.02	0.1802	48.15
48.77	0.1561	41.70
60.53	0.1248	33.34
72.33	0.0903	24.12
84.18	0.0533	14.25
96.02	0.0115	3.07

Table B.9 Outlet pressure : <u>1000</u> (psia) , Total mass flow rate : <u>0.56135</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
16.26	0.3539	63.04
27.87	0.3429	61.08
39.47	0.3024	53.87
51.08	0.2515	44.80
62.74	0.1962	34.96
74.49	0.1366	24.34
86.28	0.0714	12.71
98.06	0.0085	1.52

Table B.10 Outlet pressure : <u>1000</u> (psia) , Total mass flow rate : <u>0.72975</u> (lb/s)

Outlet Quality (%)	Entrainment Mass Flow (lb/s)	Entraiment Percentage of Total Flow
11.68	0.5110	70.03
23.51	0.4951	67.85
35.33	0.4361	59.75
47.18	0.3644	49.93
59.08	0.2878	39.44
71.12	0.2032	27.85
83.22	0.1158	15.87
95.31	0.0312	4.28

Appendix C

Input description for COBRA-TF

(Ver. 2.1)

Contents

Main Problem Control Data, read by subroutine INPUT

Input Unit Option:
INPUT. 1 ICOBRA   FORMAT (I14)

Columns	Variable	Description
1-14	ICOBRA	Enter vessel input units option: 0 = Use English units (default). 1 = Use metric units; code will convert the data to English units.

Restart Data:
INPUT. 2 DSTEP, TIMET   FORMAT (I14, E14. 0)

Columns	Variable	Description
1-14	DSTEP	Enter the time step number of the dump to be used for restarting. Enter zero (0) if this is no a restart.
15-28	TIMET	Enter the restart time for the problem. Enter zero (0. 0) if this is not a restart.

Iteration Control:
INPUT. 3 EPSO, OITMAX, IITMAX   FORMAT (E14. 0, 2I14)

Columns	Variable	Description
1-14	EPSO	Enter the outer iteration convergence criterion; suggested value = 0. 001.
15-28	OITMAX	Enter the maximum number of outer iterations; suggested value = 5.
29-42	IITMAX	Enter the maximum number of vessel iterations; suggested value = 40.

Title Card, read by subroutine COBRAI

COBRA.1   MAXT, INIT, TEXT   FORMAT (2I5, A68)

Columns	Variable	Description
1-5	MAXT	
6-10	INIT	Enter the vessel initialization option. Valid entries are:
		1 = initial start
		4 = fill vessel arrays with data obtained from a restart file
11-80	TEXT	Enter alphanumeric information to identify the simulation.

Title Card, read by subroutine COBRAI

VESSEL Group 1: Calculation Variables and Initial Conditions, read by subroutine
                                                                    SETIN

VESSEL1. 1   NGROUP, NGAS   FORMAT (2I5)

Columns	Variable	Description
1-5	NGROUP	Enter one (1).
6-10	NGAS	Number of noncondensible gases (minimum of one. JGDIM).

VESSEL1. 2   PREF, HIN, GIN, AFLUX, HGIN, VFRAC (1), VFRAC (2)   FORMAT (8F10. 0)

Columns	Variable	Description
1-10	PREF	Enter the initial vessel operating pressure in psi (if ICOBRA = 0) or N/m² (if ICOBRA = 1).
11-20	HIN	Enter the enthalpy for fluid initialzation, in Btu/lbm (if ICOBRA = 0) or J/kg (if ICOBRA = 1).
21-30	GIN	Not used.
31-40	AFLUX	Enter the initial average linear heat rate per active rod kw/ft (if ICOBRA = 0) or kw/m (if ICOBRA = 1).
41-50	HGIN	Enthalpy of noncondensible gas mixture.
51-60	VFRAC (1)	Volume fraction of liquid (≠ 0.0 or 1.0).
61-70	VFRAC (2)	Volume fraction of vapor in gas mixture (≠ 0.0 or 1.0).
71-80	RBSF	Rod bundle scaling factor. Enter 1.0 for ideal subchannel; see NUREG/CR-4166 paragraph A-12. (Do not enter zero for reflood calculation, or reflood entrainment is forced to be nothing.)

VESSEL1. 3   (GTYPE (I), VFRAC (I+2), I=1, NGAS)   FORMAT (4 (8A, 2X, F10. 0))

Columns	Variable	Description
1-8, 21-28...	GTYPE (I)	Name of gas (left justified) Examples: air, argon, helium, hydro, kryto, nitro, oxyge, xneno.
10-20, 30-40...	VFRAC (I+2)	Volume fraction of gas (I) in mixture (> 0.0).

VESSEL Group 2: Channel Description, read by subroutine SETIN

VESSEL2.1   NGROUP, NCHANL, NCHANR   FORMAT (3I5)

Columns	Variable	Description
1-5	NGROUP	Enter two (2).
6-10	NCHANL	Enter the number of channels in the problem. (MCDIM)
11-15	NCHANR	Not used

Cards VESSEL2.2 and VESSEL2.3 are read in pairs, NCHANL times.

VESSEL2.2   I, AN (I), PW (I), ABOT (I), ATOP (I), NAMGAP (I), PWI (I)
             FORMAT (I5, 4F5.0, I5, F5.0)

Columns	Variable	Description
1-5	I	Enter the channel identification number. (Note: Channel index numbers must be unique, but they do not have to be sequential. Skipping numbers is permitted, so long as exactly NCHANL channels are identified.)
6-10	AN (I)	Enter the nominal channel area, in in.^{2} (if ICOBRA = 0) or m^2 (if ICOBRA = 1). (Do not enter zero.)
11-15	PW (I)	Enter the channel wetted perimeter, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). (Do not enter zero.)
16-20	ABOT (I)	Enter the area of the bottom of the channel for use in the momentum equation. Units are in.^{2} (if ICOBRA = 0) or m^2 (if ICOBRA = 0). If ABOT (I) is entered as zero (0.0), it is set to AN (I).
21-25	ATOP (I)	Enter the area on the top of the channel for use in the momentum equation. Units are in.^{2} (if ICOBRA = 0) or m^2 (if ICOBRA = 1). If ATOP (I) is entered as zero (0), it is set to AN (I).
26-30	NAMGAP (I)	Enter the number of gaps for which the vertical velocity of channel I convects transverse momentum between sections. (MYDIM-1)
31-35	PWI (I)	Enter the inside channel wetted perimeter, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).

<u>VESSEL2. 3</u>   (INODE (I, N), KGAPB (I, N), KGAPA (I, N), N=1, NAMGAP)   FORMAT (15I5)

Omit this card if NAMGAP < 1 for channel I.

Columns	Variable	Description
1-5, 16-20, 31-23, 46-50, 61-65	INODE (I, N)	Enter the index number of the node where the vertical velocity of channel I convects transverse momentum across a section boundary. (Note: INODE will be either at the bottom of the channel (INODE (I, N) =1), or the top of the channel, (INODE (I, N) =NONODE+1), where NONODE is the number of axial levels in the section containing channel I. INODE is defined in the section where the vertical momentum equation is solved.
6-10, 21-25, 36-40, 51-55, 66-70	KGAPB (I, N)	Enter the index number of the gap below the section boundary. Enter zero if there is no gap below the section boundary. (Note: If KGAPB is not zero, the positive velocity of channel I at INODE (I, N) convects transverse momentum out of KGAPB into KGAPA. The negative velocity of channel I at INODE (I, N) convects transverse momentum from KGAPA into KGAPB; but if KGAPB is zero, this momentum is dissipated.)
11-15, 26-30, 41-45, 56-60, 71-75	KGAPA (I, N)	Enter the index number of the gap above the section boundary. Enter zero if there is no gap above the section boundary. Note: If KGAPA is not zero, the positive velocity of channel I at INODE (I, N) convects transverse momentum from KGAPB (if KGAPB ≠ 0) into KGAPA. (If KGAPA is zero, this momentum is dissipated.) The negative velocity of channel I at INODE (I, N) convects transverse momentum from KGAPA to KGAPB, (if KGAPB ≠ 0; if KGAPB is zero, this momentum is dissipated.)

VESSEL Group 3: Transverse Channel Connection (Gap) Data, read by subroutine
SETIN

This group is omitted if there are no transverse connections between channels.

VESSEL3.1   NGROUP, NK   FORMAT (2I5)

Columns	Variable	Description
1-5	NGROUP	Enter three (3).
6-10	NK	Enter the number of transverse connections ("gaps". MGDIM).

Cards VESSEL3.2 and VESSEL3.3 are read in pairs NK times.

VESSEL3.2   K, IK (K), JK (K), GAPN (K), LENGTH (K), WKR (K), FWALL (K), IGAPB (K), IGAPA (K),
             FACTOR (K), (IGAP (K, N), JGAP (K, N), N=1, 3)
                    FORMAT (3I5, 4F5.0, 2I5, F5.0, 6I5)

Columns	Variable	Description
1-5	K	Enter the gap identification number. (Note: Gap numbers must be unique but they do not have to be sequential. NK gaps must be input.)
6-10	IK (K)	Enter the identification number of the lower-numbered channel of the pair that connects through gap K.
11-15	JK (K)	Enter the identification number of the higher-numbered channel of the pair that connects through gap K.
16-20	GAPN (K)	Enter the nominal gap width, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
21-25	LENGTH (K)	Enter the distance between the center of channel IK (K) and the center of channel JK (K), in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
26-30	WKR (K)	Enter the loss coefficient (velocity head) for gap K.
31-35	FWALL (K)	Enter the wall friction factor for the gap. Valid entries are: 0.0 = no walls

0. 5 = one wall

1. 0 = two walls

36-40	IGAPB (K)	Enter the index number of the gap below gap K. Enter zero if there is no gap below gap K. (The velocity of IGAPB(K) convects vertical momentum at node 1 into (or out of) channel IK(K) out of (or into) JK(K).)
41-45	IGAPA (K)	Enter the index number of the gap above gap K. (The velocity of IGAPA(K) convects vertical momentum at the top node of the section into (or out of) channel IK(K) out of (or into) JK(K).) Enter zero if there is no gap above gap K.
46-50	FACTOR (K)	Enter 1.0 if gap positive flow (from channel IK(K) to channel JK(K)) is in the same direction as positive flow for the global coordinate system. Enter -1.0 if gap positive flow is opposote to positive flow for the global coordinate system. (Default = 1.0).
51-55 61-65, 71-75	IGAP (K, N)	Enter the index numbers of gaps facing the IK(K) side of gap K. If the gap faces a wall, enter -1. If the gap faces a vessel connection to a one-dimensional component, enter -2.
56-60 66-70, 76-80	JGAP (K, N)	Enter the gap numbers facing the JK(K) side of gap K. If the gap faces a wall, enter -1. If the gap faces a vessel connection to a one-dimensional component, enter -2. Up to three (3) sets of (IGAP, JGAP) may be entered.

Note: The input for FACTOR, IGAP and JGAP is required only if the three-dimensional form of the transverse momentum equation is desired.

<u>VESSEL3. 3</u>   GMULK (K), ETANR (K)   FORMAT (2F5. 0)

Columns	Variable	Description
1-5	GMULT (K)	Enter the number of actual gaps modeled by gap K.
6-10	ETANR (K)	Enter the crossflow deentrainment fraction.

VESSEL3. 4   NLMGAP   FORMAT (I5)

Columns	Variable	Description
1-5	NLMGAP	Enter the number of gaps that convect orthogonal transverse momentum. (This is required only for the three-dimensional form of the transverse momentum equation. MDDIM) Enter zero if the three-dimensional form of the transverse momentum equation is not desired.

Card <u>VESSEL3. 5</u> is read NLMGAP times.   Read only if NLMGAP > 0.

VESSEL3. 5   (KGAP1 (N), KGAP2 (N), KGAP3 (N), N=1, NLMGAP)   FORMAT (12I5)

Columns	Variable	Description
1-5, 16-20, 31-35, 46-50	KGAP1 (N)	Enter the index number of a gap whose velocity transports transverse momentum from one gap to another.
6-10, 21-25, 36-40, 51-55	KGAP2 (N)	Enter the index number of the gap that receives the transverse momentum convected by the positive velocity of gap KGAP1. A nonzero value must be entered.
11-15, 26-30, 41-45, 56-60	KGAP3 (N)	Enter the index number of the gap that the positive velocity of KGAP1 transports transverse momentum out of. (The positive velocity of KGAP1 transports momentum from KGAP3 to KGAP2. Note: The negative velocity of KGAP1 will transport transverse momentum in the opposite direction; i.e., from KGAP2 into KGAP3.) A nonzero number must be entered.

Up to four sets of (KGAP1, KGAP2, KGAP3) entries are specified per card.   If NLMGAP > 4, repeat this card until all NLMGAP sets have been entered.

VESSEL Group 4: Vertical Channel Connection Data, read by subroutine SETIN

VESSEL4.1   NGROUP, NSECTS, NSIM, IREBAL   FORMAT (4I5)

Columns	Variable	Description
1-5	NGROUP	Enter four (4).
6-10	NSECTS	Enter the number of sections in this problem. (NODIM)
11-15	NSIM	Enter the number of simultaneous solution groups.
16-20	IREBAL	Enter the rebalancing option. Valid entries are: 1 = rebalance 0 = no rebalancing

Cards VESSEL4.2 and VESSEL4.3 are read in a group NSECTS times.

VESSEL4.2   ISEC, NCHN, NONODE, DXS (ISEC, 1), IVARDX   FORMAT (3I5, F10.0, I5)

Columns	Variable	Description
1-5	ISEC	Enter the section number. Begin with section number 1 on the bottom of the vessel and proceed toward the top, incrementing ISEC by 1.
6-10	NCHN	Enter the number of channels in section ISEC. (MBDIM)
11-15	NONODE	Enter the number of vertical levels in section ISEC. (MXDIM-2)
16-25	DXS (ISEC, 1)	Enter the vertical node length in this section, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
26-30	IVARDX	Flag for variable node length in this section. For constant node length, IVARDX=0 (default). If IVARDX>0, read IVARDX pairs in variable ΔX table.

Card <u>VESSEL4.3</u> is read only if IVARDX > 0.

<u>VESSEL4.3</u>   (JLEV(I), VARDX(I), I=1, IVARDX)   FORMAT (5 (I5, F10. 0))

Columns	Variable	Description
1-5, 16-20...	JLEV(I)	Last axial level in section to have a node length of VARDX(I). JLEV(IVARDX) must be greater than or equal to NONODE+1.
6-15, 21-30...	VARDX(I)	Axial node length, in inches (ICOBRA=0) or meters (ICOBRA=1)

Card <u>VESSEL4.4</u> is read NCHN times for each section.

<u>VESSEL4.4</u>   I, (KCHANA(I, J), J=2, 7), (KCHANB(I, J), J=2, 7)   FORMAT (13I5)

Columns	Variable	Description
1-5	I	Enter the identification number of a channel in section ISEC.
6-10, 11-15, 16-20...	KCHANA(I, J)	Enter the indices of channels in the section above ISEC that connect to channel I. If channel I does not connect to any channels above, enter I in KCHANA(I, 2).
36-40 41-45, 46-50...	KCHANB(I, J)	Enter the indices of channels in the section below ISEC that connect to channel I. If channel I dose not connect to any channels below, enter I in KCHANB(I, 2).

<u>VESSEL4.5</u>   IWIDE   FORMAT (I5)

Columns	Variable	Description
1-5	IWIDE	Enter the maximum difference between the index numbers of adjacent cells in a simultaneous solution group. ((NEDIM-1)/2)

<u>VESSEL4. 6</u>   (MSIM(I), I=1, NSIM)   FORMAT (12I5)

Columns	Variable	Description
1-5	MSIM(I)	Enter the last cell number in each simultaneous solution group. (Note that this input asks for cell number, not vertical level number.)

Twelve values are entered per card.   If NSIM is greater than 12, repeat card <u>VESSEL4. 6</u> until NSIM values have been entered.

VESSEL Group 5: Geometry Variation Data, read by subroutine SETIN

The input for this group allows the user to specify vertical variations in the continuity area, momentum area, or wetted perimeter for channels, and in the transverse width for gaps. It can be omitted if such variations are not needed.

VESSEL5. 1   NGROUP, NAFACT   FORMAT (2I5)

Columns	Variable	Description
1-5	NGROUP	Enter five (5).
6-10	NAFACT	Enter the number of geometry variation tables to be entered. (MLDIM)

Cards VESSEL5. 2 and VESSEL5. 3 are read in a group NAFACT times.

VESSEL5. 2   NAXL (I)   FORMAT (I5)

Columns	Variable	Description
1-5	NAXL (I)	Enter the number of points in this variation table. (MADIM)

VESSEL5. 3   (JAXL (I, N), AFACT (I, N), N=1, NAXL (I))   FORMAT (8 (I5, F5. 0))

Columns	Variable	Description
1-5, 11-15, 21-25...	JAXL (I, N)	Enter the node number at which to apply the area variation factor for table I, point N.
6-10, 16-20, 26-30...	AFACT (I, N)	Enter the variation factor for table I, point N. Area = AFACT (I, N) *AN (I), or Gap width = AFACT (I, N) *GAPN (K)

Eight pairs of (JAXL, AFACT) are entered per card. Repeat card VESSEL5. 3 until NAXL pairs have been entered. The tables are numbered sequentially in the code, in the order they are read in on cards VESSEL5. 2 and VESSEL5. 3.

<u>VESSEL Group 6: Channels and Gaps Affected by Variation Tables</u>, read by subroutine
SETIN

This group is read only if vertical variation tables have been specified in group 5.

<u>VESSEL6. 1</u>   NGROUP, N1   FORMAT (2I5)

Columns	Variable	Description
1-5	NGROUP	Enter six (6).
6-10	N1	Enter the total number of channel and gap variation table cards to be read.

Card <u>VESSEL6. 2</u> is read N1 times.

<u>VESSEL6. 2</u>   IACT, IAMT, IPWT, (ICRG (M), M=1, 12)   FORMAT (16I5)

Columns	Variable	Description
1-5	IACT	Enter a positive integer corresponding to a variation table number, for channel continuity area variation.
		Enter a negative integer, whose absolute value corresponds to a variation table number, for gap width variation.
6-10	IAMT	Enter a variation table number for channel momentum area variation.
		Enter zero (0) if IACT is negative.
11-15	IPWT	Enter a variation table number for wetted perimeter variation.
		Enter zero (0) if IACT is negative.
16-20	ICRG (M)	Enter the index numbers of the channela (or gaps if IACT is negative) that the tables identified in IACT, IAMT and IPWT are to be applied to. (Up to 13 channels or gaps may be specified per card.)

VESSEL Group 7: Local Loss Coefficient and Grid Spacer Data, read by subroutine
SETIN

VESSEL7. 1   NGROUP, NCD, NGT, IFGQF, IFSDRP, IFESPV, IFTPE, IGTEMP, DUM1, NFBS
FORMAT (10I5)

Columns	Variable	Description
1-5	NGROUP	Enter seven (7).
6-10	NCD	Enter the number of loss coefficient specifications to be read. (These include vertical momentum losses only. Transverse losses are specified in group 3.)
11-15	NGT	Number of grid types to be read. (MJDIM)
16-20	IFGQF	Flag for grid quench front model (1=on, 0=off).
21-25	IFSDRP	Flag for small drop model (1=on, 0=off).
26-30	IFESPV	Flag for grid convective enhancement (1=on, 0=off).
31-35	IFTPE	Flag for two-phase enhancement of dispersed flow heat transfer (1=on, 0=off).
36-40	IGTEMP	
41-45	DUM1	Not Used.
46-50	NFBS	Number of flow blockages. (MNDIM)

Card VESSEL7. 2 is read NCD times and read at least once even if NCD < 1.

VESSEL7. 2   CDL, J, (ICDUM(I), I=1, 12)   FORMAT (F5. 0, 13I5)

Columns	Variable	Description
1-5	CDL	Enter the loss coefficient (velocity head).
6-10	J	Enter the node number where the loss coefficient is applied. (NOTE: The vertical node number is relative to the beginning of the section containing the channel (s) listed in ICDUM(I).)
11-15	ICDUM(I)	Enter the index number (s) of channel (s) the loss coefficient will be applied to at node J. (Up to twelve channels may use the specified loss coefficient CDL at vertical node J.)

Cards <u>VESSEL7.3</u> through <u>VESSEL7.5</u> are read NGT times.

<u>VESSEL7.3</u>   ING, NGAL (NG), NGCL (NG), IGMAT (NG), GLOSS (NG), GABLOC (NG),

   GLONG (NG), GPERIM (NG), SPBLOC (NG), TPROBE (NG)   FORMAT (4I5, 6F10.0)

Columns	Variable	Description
1-5	ING	Grid type number (must be sequential starting with 1)
6-10	NGAL (NG)	Number of axial locations for grid type ING (maximum = 16)
11-15	NGCL (NG)	Number of channels containing grid ING at levels NGAL (NG)
16-20	IGMAT (NG)	Grid material type index corresponding to material types in card group 10
21-30	GLOSS (NG)	Loss coefficient multiplier (suggest 1.0 for round edge grids; 1.4 for square edge grids)
31-40	GABLOC (NG)	Fraction of channel area blocked by grid
41-50	GLONG (NG)	Grid length, in inches (if ICOBRA=0) or meters (if ICOBRA=1)
51-60	GPERIM (NG)	Grid perimeter, in inches (if ICOBRA=0) or meters (if ICOBRA=1)
61-70	SPBLOC (NG)	$\geqq 0.0$
71-80	TPROBE (NG)	$\geqq 0.001$

<u>VESSEL7.4</u>   (NNGL (NG, NN), NN=1, NGAL (NG))   FORMAT (16I5)

Columns	Variable	Description
1-5, 6-10, 11-15...	NNGL (NG, NN)	Axial node number of momentum cells containing grid type ING

<u>VESSEL7.5</u>   NCNGL (NG, M), GMUL (NG, M) (NGROD (NG, M, L), NGSURF (NG, M, L), L=1, 6)
                   FORMAT (I5, F10.0, 12I5)   Repeat NGCL (NG) times.

Columns	Variable	Description
1-5	NCNGL (NG, M)	Channel ID number with grid type ING at axial levels NNGL (NG, NN) (specified above)
6-15	GMUL (NG, M)	Number of grids contained in channel NCNGL (NG, M)

16-20, 26-30, 36-40...	NGROD (NG, M, L)	Whole rod number with surface surrounding grid (maximum of six)
21-25, 31-35, 41-45...	NGSURF (NG, M, L)	Rod surface index of whole rod NGROD (NG, M, L) surrounding grid ING. (Note: average temperature of all surfaces surrounding grid is used to transport heat between grid and heater rods.)

Cards VESSEL7. 6 and VESSEL7. 7 are read NFBS times.

VESSEL7. 6   IBS, IFB (IB), JSFB (IB), NRFB (IB), SPOINT (IB), DSEP (IB), THROAT (IB), AFLBLK (IB),
             CDFB (IB), ABLOCK (IB)   FORMAT (4I5, 6F10. 0)

Columns	Variable	Description
1-5	IBS	flow blockage index number
6-10	IFB (IB)	channel index number
11-15	JSFB (IB)	axial node index number
16-20	NRFB (IB)	number of rods that block this channel
21-30	SPOINT (IB)	axial position of the flow separation point (in.)
31-40	DSEP (IB)	channel diameter at separation point (in.²), $(D = \sqrt{(4A/\pi)})$
41-50	THROAT (IB)	diffuser diameter at exit
51-60	AFLBLK (IB)	area for DBM (fraction of channel) x 0. 25
61-70	CDFB (IB)	loss coefficient (Rehme multiplier)
71-80	ABLOCK (IB)	blockage area ratio

VESSEL7. 7   NRODFB (IB, NRF), KRODFB (IB, NRF), ANGIHT (IB, NRF), ARAIHT (IB, NRF)
                       FORMAT (2I5, 2F10. 0)   Repeat NRFB (IB) times.

Columns	Variable	Description
1-5	NRODFB (IB, NRF)	index number of rod
6-10	KRODFB (IB, NRF)	surface number
11-20	ANGIHT (IB, NRF)	angle for impact heat transfer (˚)
21-30	ARAIHT (IB, NRF)	area for impact heat transfer (in.²/per rod)

<u>VESSEL7.8</u>   (TGRID(I),QFGRID(I),I=1,IGTEMP)   FORMAT(8F10.0)   Omit if IGTEMP < 1.

Columns	Variable	Description
1-10,	TGRID(I)	
21-30,		
41-50,		
61-70		
11-20,	QFGRID(I)	
31-40,		
51-60,		
71-80		

VESSEL Group 8: Rod and Unheated Conductor Data, read by subroutine SETIN

VESSEL8. 1   NGROUP, NRROD, NSROD, NC, NRTAB, NRAD, NLTYP, NSRAD, NXF   FORMAT (9I5)

Columns	Variable	Description
1-5	NGROUP	Enter eight (8).
6-10	NRROD	Enter number of rods. Minimum value is 1. (MRDIM)
11-15	NSROD	Enter number of unheated conductors ("slabs". NTDIM).
16-20	NC	Conduction model flag; 1: radial conduction only. 2: radial and axial conduction. 3: radial, axial, and azimuthal conduction.
21-25	NRTAB	Enter number of temperature initialization tables to be read. Minimum value is 1. (N4DIM)
26-30	NRAD	Enter number of radiation channels. (NDDIM)
31-35	NLTYP	Enter number of location types. (NDDIM)
36-40	NSRAD	Enter total number of rod or slab surfaces with radiation.
41-45	NXF	Enter number of time steps between radiation calculations (Default = 1).

ROD GEOMETRY DATA

These cards are read to define the geometry of structures that generate heat, including nuclear fuel rods. They are read NRROD times. Read only if NRROD > 0.

VESSEL8. 2   N, IFTYP (N), IAXP (N), NRENODE (N), DAXMIN (N), RMULT (N), RADIAL (N), HGAP (N),
             ISECR (N), HTAMB (N), TAMB (N)   FORMAT (4I5, 4F10. 0, I5, 2F5. 0)

Columns	Variable	Description
1-5	N	Enter rod identification number. (Note: Rod index numbers must be entered sequentially, from 1 to NRROD. Skipping numbers is not permitted.)
6-10	IFTYP (N)	Enter geometry type identification number. (Refer to group 9 for geometry type input data.)
11-15	IAXP (N)	Enter axial power profile table identification number. (Refer to group 11 for axial power profile input data.)

16-20	NRENODE (N)	Enter renoding flag for heat transfer solution for rod N
		= 0; no fine mesh renoding
		> 0; renoding every NRENODE (N) time steps ($\geq$ 1)
		< 0; renoding every	NRENODE (N)	time steps, based on inside surface temperatures ($\leq$ -1)
21-30	DAXMIN (N)	Enter minimum axial node size, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). ($\geq$ 0.05. This is used only if fine mesh renoding is used.)
31-40	RMULT (N)	Enter rod multiplication factor (number of rods modeled by rod N). (This number can contain fractional parts.)
41-50	RADIAL (N)	Enter radial power factor (normalized to average power).
51-60	HGAP (N)	Enter constant gap conductance, in Btu/hr-ft²-° F (if ICOBRA = 0) or W/m²-° C (if ICOBRA = 1). (This parameter is used only for nuclear fuel rods that do not have the dynamic gap conductance model specified by their geometry type.) Enter zero if rod N does not model a nuclear fuel rod.
61-65	ISECR (N)	Number of sections containing rod N ($\geq$ 1)
66-70	HTAMB (N)	Heat transfer coefficient for heat loss to ambient from surface not connected to a channel (Btu/hr-ft²-° F) or (W/m²-° C)
71-75	TAMB (N)	Sink temperature for ambient heat loss, (° F) or (K)

<u>VESSEL8. 3</u> (NSCHC (IS, K), PIE (N, K), K=1, 8) FORMAT (8 (I5, F5. 0))
Read ISECR (N) times (IS=1, ISECR (N)).

Columns	Variable	Description
1-5, 11-15,...	NSCHC (IS, K)	Channel number with thermal connections to rod N in section IS
6-10, 16-20,...	PIE (N, K)	Fraction of rod N thermally connected to channel NSCHC (IS, K).

<u>VESSEL8.4</u> (NISCHC (N, IS, K), K=1, 8)   Format (8 (I5, 5X))
          Omit if no inside surfaces exist for rod N.

Columns	Variable	Description
1-5,	NISCHC (N, IS, K)	Negative of channel number connected to the
11-15,		inside of fraction K of rod N
21-26...		

UNHEATED CONDUCTOR DATA

This card is read for each of the NSROD conductor rods (also called heat slabs).

<u>VESSEL8.5</u> N, ISTYP (N), HPERIM (N), HPERIMI (N), RMULS (N), NSLCHC, NOSLCH, HTAMBS (N),
          TAMBS (N)   FORMAT (2I5, 3F10.0, 2I5, 2F5.0)   Read only if NSROD $\geqq$ 1.

Columns	Variable	Description
1-5,	N	Enter unheated conductor identification number. (Note: Unheated conductor index numbers must be entered sequentially, from 1 to NSROD. Skipping numbers is not permitted.)
6-10	ISTYP (N)	Enter geometry type identification number. (Refer to group 9 for geometry type input data.)
11-20	HPERIM (N)	Enter wetted perimeter on outside surface, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
21-30	HPERIMI (N)	Enter wetted perimeter on inside surface, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). (Enter zero for a solid cylinder.)
31-40	RMULS (N)	Enter multiplication factor (number of elements modeled by unheated conductor N). (This number can contain farctional parts.)
41-45	NSLCHC	Channel number on inside of slab.
46-50	NOSLCH	Negative of channel number on outside of slab.
51-55	HTAMBS (N)	Heat transfer coefficient for heat loss to the ambient (Btu/hr-ft^2-$^\circ$F) or W/m^2-$^\circ$C)
56-60	TAMBS (N)	Sink temperature for ambient heat loss ($^\circ$F) or (K).

ROD TEMPERATURE INITIALIZATION TABLES

Cards VESSEL8. 6 through VESSEL8. 9 are read to specify which temperature tables apply to which rods and unheated conductors. The sequence is repeated NRTAB times, and all rods and conductors must be accounted for.

VESSEL8. 6   I, NRT1, NST1, NRAX1   FORMAT (4I5)

Columns	Variable	Description
1-5	I	Enter identification number of temperature table.
6-10	NRT1	Enter number of rods using table I.
11-15	NST1	Enter number of unheated conductors using Table I.
16-20	NRAX1	Enter number of pairs of elements in table I. (N5DIM)

VESSEL8. 7   (IRTAB (I, L), L=1, NRT1)   FORMAT (12I5)   Read only if NRT1 > 0.

Columns	Variable	Description
1-5,	IRTAB (I, L)	Enter identification numbers of rods using
6-10,		table I for temperature initialization.
11-15...		Enter the negative of the rod identification number if the temperature boundary is to be applied to the inside surface of the rod.

Note: The steady-state conduction equation is solved for these rods using the temperatures from table I as a boundary condition on the rod surface.

VESSEL8. 8   (ISTAB (I, L), L=1, NST1)   FORMAT (12I5)   Read only if NST1 > 0.

Columns	Variable	Description
1-5,	ISTAB (I, L)	Enter identification numbers of unheated
6-10,		conductors using table I for temperature
11-15...		initialization.

Note: A flat radial temperature profile is assumed initially in unheated conductors.

<u>VESSEL8. 9</u>   (AXIALT (I, L), TRINIT (I, L), L=1, NRAX1)   FORMAT (8F10. 0)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-10, 21-30, 41-50...	AXIALT (I, L)	Enter the vertical position relative to the bottom of the VESSEL, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
11-20, 31-40, 51-60...	TRINIT (I, L)	Enter the temperature to be applied at AXIALT (I, L), in °F (if ICOBRA = 0) or K (if ICOBRA = 1).

> Note: The vertical locations of the bottom and top of each rod or unheated conductor using table I must be contained within the range AXIALT (I, 1) to AXIALT (I, NRAX1).

Radiation Initialization Tables

Cards <u>VESSEL8. 10</u> through <u>VESSEL8. 11. 6</u> are read in to specify orientation and which location type tables apply to which fluid channels, rods, and unheated conductors. Read only if NRAD > 0 and NLTYP > 0.

Repeat <u>VESSEL8. 10</u> and <u>VESSEL8. 10. 1</u> NRAD times, until all radiation channels have been input.

Channel Orientation and Location Type Card

<u>VESSEL8. 10</u>   IDCRAD (IRAD), NSIDR (IRAD), LOCATE (IRAD), NRRAD (IRAD), NSYMF (IRAD),
MLTF (1, IRAD), MLTF (2, IRAD), MLTF (3, IRAD), MLTF (4, IRAD), VDMLT (IRAD)
FORMAT (5I5, 5F5. 0)   (MLTF (I, IRAD), I=1, 4) are real numbers)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	IDCRAD (IRAD)	Radiation channel ID number
6-10	NSIDR (IRAD)	Number of fluid channel which contains IDCRAD (IRAD)
11-15	LOCATE (IRAD)	Location type for rediation channel IDCRAD (IRAD) : < 0 contains no unheated conductors. > 0 has both rods and unheated conductors.
16-20	NRRAD (IRAD)	Number of contributing radiation surfaces for IDCRAD (IRAD) : = 20 location types 1, 2, 3, 7, 8 = 16 location types 4, 5

		= 9 location type 6
		= 14 location type 9
21-25	NSYMF (IRAD)	Enter flag for fluid channel or rod lumping.
		= 0 no lumping
		= 1 lumped fluid channels
26-35	MLTF (1, IRAD)	Enter surface lumping factor for surface position 1. Ratio of total calculated to actually modeled surface areas of this rod type contained in location type IDCRAD(IRAD) times the ratio of total surface areas in all channels of this rod type to this surface area (Default=1.0).
36-45	MLTF (2, IRAD)	Enter surface lumping factor for surface position 2. Ratio of total calaulated to actually modeled surface areas of this rod type contained in location type IDCARD(IRAD) times the ratio of total surface areas in all channels of this rod type to this surface area (Default=1.0).
46-55	MLTF (3, IRAD)	Enter surface lumping factor for surface position 3. Ratio of total calculated to actually modeled surface areas of this rod type contained in location type IDCRAD(IRAD) times the ratio of total surface areas in all channels of this rod type to this surface area (Default=1.0).
56-65	MLTF (4, IRAD)	Enter surface lumping factor for surface position 4. Ratio of total calculated to actually modeled surface areas of this rod type contained in location type IDCRAD(IRAD) times the ratio of total surface areas in all channels of this rod type to this surface area (Default=1.0).
66-75	VDMLT (IRAD)	Vapor/droplet multiplication factor. Total number of radiation channels being modeled by this location type (Default=1.0).

Radiation Channel Orientation Array
<u>VESSEL8. 10. 1</u> (LRAD (IRAD, J), J=1, NRRAD (IRAD)) FORMAT (1615)

Columns	Variable	Description
1-5	LRAD (IRAD, J)	Rod number in position "J" for appropriate
6-10		radiation channel IDCRAD (IRAD). Negative for
11-15...		inside surface.

·Note: See text for proper rod orientation.

Repeat <u>VESSEL8. 11</u> through <u>VESSEL8. 11. 4</u> NLTYP times, until all IDTYP (I)s are input for IDTYP (I) > 0.

Radiation Location Type Information
<u>VESSEL8. 11</u> IDTYP (I) FORMAT (I5)

Columns	Variable	Description
1-5	IDTYP (I)	Location type to be input
		> 0 manual input to follow.
		< 0 auto view factor routine to be used.

<u>Manual Location Type Input</u> If IDTYP (I) < 0 skip <u>VESSEL8. 11. 1</u> to <u>8. 11. 4</u>

<u>Area Input</u>
<u>VESSEL8. 11. 1</u> (ARAD (J), J=1, JTOT)) FORMAT (8F10. 0) JTOT=total number surfaces
for location type IDTYP (I)

Columns	Variable	Description
1-10	ARAD (J)	Surface area of position "J" for location type
11-20		IDTYP (I) in inches (if ICOBRA=0) or centimeters
21-30...		(if ICOBRA=1)

Emissivity Input

VESSEL8.11.2 (ERAD(J) J=1, JTOT) FORMAT(8F10.0)

JTOT=Total number of surfaces for location type IDTYP(I)

Columns	Variable	Description
1-10	ERAD(J)	Enter the emissivity of position "J" for
11-20		location type IDTYP(I).
21-30...		

View Factor Input

VESSEL8.11.3 ((FRAD(J,K), J=1, JL), K=J, JL)   FORMAT(8F10.0)

JL=Total number of radiant surface in location type IDTYP(I).

Columns	Variable	Description
Card Set 1		
1-10,	FRAD(1,K)	Enter radiation view factor between surface 1
11-20,		and surface "K".
21-30...		
Card Set 2		
1-10,	FRAD(2,K)	Enter radiation view factor between surface 2
11-20,		and surface "K".
21-30...		
Card Set "J"		
1-10,	FRAD(J,K)	Enter radiation view factor between surface "J"
11-20,		and surface "K", where "J" > "K".
21-30...		

Continue until all "J" surfaces have been input, starting each "J" surface group with a new card set.

Beam Length Input

<u>VESSEL8. 11. 4</u>   ((DRAD (J, K), J=1, JL), K=J, JL)   FORMAT (8F10. 0)

JL=Total number of radiant surfaces in location type IDTYP (I)

Columns	Variable	Description
Card Set 1		
1-10,	DRAD (1, K)	Enter beam length between surface 1 and surface "K" in inches (if ICOBRA=0) or centimeters (if ICOBRA=1).
11-20,		
21-30...		
Card Set 2		
1-10,	DRAD (2, K)	Enter beam length between surface 2 and surface "K" in inches (if ICOBRA=0) or centimeters (if ICOBRA=1).
11-20,		
21-30...		
Card Set "J"		
1-10,	DRAD (J, K)	Enter beam length between surface "J" and surface "K" in inches (if ICOBRA=0) or centimeters (if ICOBRA=1) where "J" > "K".
11-20,		
21-30...		

Continue until all "J" surfaces have been input, starting each "J" surface group with a new card set.

Auto View Factor Input

<u>VESSEL8. 11. 5</u> (APAR (III), III=1, 8)   FORMAT (8F10. 0)   Omit if IDTYP (I) > 0.

Columns	Variable	Description
1-10	APAR (1) d	Enter first parameter for auto view factor input according to location type. Enter nominal rod diameter in inches (if ICOBRA=0) or centimeters (if ICOBRA=1).
11-20	APAR (2) eml	Enter second parameter for auto view factor input according to location type. enter emissivity of rods

21-30	APAR (3)	Enter third parameter for auto view factor input. If location type
	d1	= 1 enter rod diameter of rod in oversized rod location.
	g	= 2, 3, 4, 5, 6, 7, 8, 9 enter gap width between rod and wall in inches (if ICOBRA=0) or centimeters (if ICOBRA=1).
31-40	APAR (4)	Enter fourth auto view factor input parameter.
	P	enter pitch of rods in inches (if ICOBRA=0) or in centimeters (if ICOBRA=1).
41-50	APAR (5)	Enter fifth auto view factor input parameter.
	rad	enter radius of curvature of wall in inches (if ICOBRA=0) or in centimeters (if ICOBRA=1).
51-60	APAR (6)	Enter sixth auto view factor input parameter. If location type
	disx	= 1, 2, 3, 4, 5, 7, 8, 9 enter displacement from centerline axis to rod position 1 in inches (if ICOBRA=0) or centimeters (if ICOBRA=1).
61-70	APAR (7)	Enter seventh auto view factor input parameter.
	em2	enter emissivity of the wall
71-80	APAR (8)	Enter eighth auto view factor input parameter. If location type
	d1	= 2, 3 enter rod diameter of rod in oversized rod location in inches (if ICOBRA=0) or in centimeters (if ICOBRA=1).
	fg	= 8, 9 enter

<u>VESSEL8. 11. 6</u> APAR (9)   FORMAT (F10. 0)

Columns	Variable	Description
1-10	APAR (9)	Enter ninth auto view factor input parameter. If location type
	d1	= 7 enter rod diameter of rod in oversized rod location in inches (if ICOBRA=0) or in centimeters (if ICOBRA=1).
	fw	= 8, 9 enter

VESSEL Group 9: Conductor Geometry Description, read by subroutine SETIN

The geometry types are read in this group. The geometry types are numbered sequentially in the order they are read in. Nuclear rod geometry types are read using cards VESSEL9.2 through VESSEL9.5. All other geometry types are read using cards VESSEL9.6 and VESSEL9.7.

VESSEL9.1   NGROUP, NFUELT, IRELF, ICONF   FORMAT (4I5)

Columns	Variable	Description
1-5	NGROUP	Enter nine (9).
6-10	NFUELT	Enter number of geometry types to be read in. (MFDIM)
		Note: A geometry type may be used by both rods and unheated conductors, but for the unheated conductor, any heat generation specified for the type will be ignored.
11-15	IRELF	Fuel relocation flag (1=on, 0=off) (This is used only for nuclear fuel rods using the dynamic gap conductance model).
16-20	ICONF	Fuel degradation flag (1=on, 0=off) (NOTE: if IRELF=1, then ICONF=1.)

NUCLEAR FUEL GEOMETRY TYPES

These data are read only for nuclear fuel geometry types. If FTYPE(I) is not entered as NUCL, the geometry data is interpreted by line VESSEL9.6.

VESSEL9.2   I, FTYPE(I), DROD, DFUEL(I), NFUEL, IMATF, IMATC, IMATOX(I), DCORE, TCLAD, FTDENS(I), IGPC(I), IGFORC, IRADP   FORMAT (I5, 1X, A4, 2F10.0, 4I5, 3F5.0, 3I5)
(Read only for nuclear geometry types.)

Columns	Variable	Description
1-5	I	Enter the geometry type identification number. (Note: Geometry type index numbers must be entered sequentially, from 1 to NFUELT. Skipping numbers is not permitted.)
7-10	FTYPE(I)	Enter NUCL.
11-20	DROD	Enter rod outside diameter, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).

21-30	DFUEL(I)	Enter fuel pellet diameter, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
31-35	NFUEL	Enter number of radial nodes in fuel pellet. (NNDIM-2)
36-40	IMATF	Fuel material properties flag: Enter zero (0) for built-in UO₂ properties. Enter a positive integer corresponding to the identification number of a material properties tables for user-input properties. (Refer to group 10 for material properties input data.)
41-45	IMATC	Clad material properties flag: Enter zero (0) for built-in zirconium properties. Enter a positive integer corresponding to the identification number of a material properties table for user-input properties. (Refer to group 10 for material properties input data.)
46-50	IMATOX(I)	Clad oxide property flag: Enter zero (0) for built-in zirconium dioxide properties. Enter a positive integer corresponding to the identification number of a material properties table for user-input properties (see group 10).
51-55	DCORE	Enter diameter of central void for cored fuel, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). Enter zero for uncored fuel.
56-60	TCLAD	Enter clad thickness, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
61-65	FTDENS(I)	Enter fuel theoretical density as a fraction (used only if built-in UO₂ properties have been flagged; i.e., if IMATF = 0). (Note: Do not enter zero.)
66-70	IGPC(I)	Gap conductance option flag; Enter zero (0) for constant gap conductance (as specified by HGAP(N) on card VESSEL8.2). Enter a positive integer for user-specified nonuniform gap conductance (entered on card

VESSEL9.4 in a table of IGPC(I) elements. NFDIM).
Enter a negative integer for the dynamic gap
conductance model. (| IGPC(I) | is the
number of entries in the cold gap width vs.
axial location table, read on card VESSEL9.4.)

71-75	IGFORC	Flag for temporal forcing function on gap conductance (valid only if IGPC(I) > 0:
		Enter zero (0) for constant gap conductance.
		Enter a positive integer for a temporal forcing function with IGFORC table entries.
76-80	IRADP	Enter number of entries in radial power profile table for the fuel pellet. (NODIM)
		Enter zero (0) for a uniform radial power profile.

VESSEL9.3   PGAS(I), VPLEN(I), ROUFF(I), ROUFC(I), (GSFRAC(L, 1), L=1, 6), OXIDET
            FORMAT (4F10.0, 6F5., F10.0)
            Read only if FTYPE(I) = NUCL and IGPC(I) < 0.

Columns	Variable	Description
1-10	PGAS(I)	Enter cold pin gas pressure for nuclear fuel rod geometry type 1, in psia (if ICOBRA = 0) or N/m^2 (if ICOBRA = 1).
11-20	VPLEN(I)	Enter gas plenum volume, in in^3 (if ICOBRA = 0) or m^3 (if ICOBRA = 1).
21-30	ROUFF(I)	Enter fuel pellet surface roughness in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
31-40	ROUFC(I)	Enter surface roughness of clad inner surface, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
		(Note: Fuel and clad surface roughness should correspond to those used in FRAPCON-2 since the correlation is empirical.)
		Fuel surface ROUFF = 0.000085 inches
		Clad surface ROUFC = 0.000045 inches
41-45	GSFRAC(1, 1)	Enter molar fraction of helium gas present.
46-50	GSFRAC(2, 1)	Enter molar fraction of xenon gas present.

51-55	GSFRAC (3, I)	Enter molar fraction of argon gas present.
56-60	GSFRAC (4, I)	Enter molar fraction of krypton gas present.
61-65	GSFRAC (5, I)	Enter molar fraction of hydrogen gas present.
66-70	GSFRAC (6, I)	Enter molar fraction of nitrogen gas present.

Note: $\sum_{L=1}^{6}$ GSFRAC (L, I) = 1.0

| 71-80 | OXIDET | Enter initial oxide thickness for the zircaloy metal-water reaction rate equation in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). (Used only if IMWR > 0.) |

VESSEL9. 4   (AXJ (L, I), AGFACT (L, I), L=1, | IGPC (I) |)   FORMAT (8F10. 0)
Read only if FTYPE (I) = NUCL and | IGPC (I) | > 0.

Columns	Variable	Description
1-10, 21-30, 41-50, 61-70	AXJ (L, I)	Enter topmost vertical position, measured from the bottom of the rod, at which the cold gap width (or gap conductance) AGFACT (L, I) is applied. (All vertical levels below AXJ (L, I) and above AXJ (L, I-1) will have AGFACT (L, I) for gap width or gap conductance.) Units on AXJ (L, I) are inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
11-20, 31-40, 51-60, 71-80	AGFACT (L, I)	Enter cold gap width if IGPC (I) is negative. Units are inches (if ICOBRA = 0) or meters (if ICOBRA = 1). Enter gap conductance if IGPC (I) is positive. Units are $Btu/hr\text{-}ft^2\text{-}°F$ (if ICOBRA = 0) or $W/m^2\text{-}°C$ (if ICOBRA = 1).

VESSEL9. 5   (RODP (L), POWR (L), L=IRADP)   FORMAT (8F10. 0)
Read only if FTYPE (I) = NUCL and IRADP > 0.

Columns	Variable	Description
1-10, 21-30, 41-50...	RADP (L)	Enter the relative radial location (r/r_o) where corresponding power factor (POWR (L)) is applied. $\dfrac{r}{r_o} = \dfrac{(radius - DCORE/2)}{\frac{1}{2}(DFUEL (I) - DCORE)}$

11-20,	POWR (L)	Enter the relative power factor (i.e., the
31-40,		ratio of local power at location RADP(L) to
51-60...		total rod power).

NONNUCLEAR GEOMETRY TYPES

These data are read for all geometry types that do not describe nuclear fuel.

VESSEL9. 6   I, FTYPE (I), DROD, DIN, NFUEL, IMATOX (I), IMATIX (I)   FORMAT (I5, 1X, A4, 2F10. 0, 3I5)
         Read only if FTYPE(I) ≠ NUCL

Columns	Variable	Description
1-5	I	Enter geometry type identification number.

7-10	FTYPE (I)	Enter four-character alphanumeric geometry type flag:
		    HROD = solid cylinder
		    TUBE = hollow tube
		    WALL = flat plate

11-20	DROD	Enter outside diameter for HROD or TUBE geometries, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). Enter the wetted perimeter for WALL geometries, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).
21-30	DIN	Enter inside diameter for TUBE geometries, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). Enter thickness for WALL geometries, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). Enter zero (0. 0) for (HROD) solid cylinder geometries.
31-35	NFUEL	Enter the number of regions within the conductor. (Each region has a uniform power profile and consists of one material. NNDIM)
36-40	IMATOX (I)	Enter material property table identification number for oxide on outside surface. (Default is zirconium oxide; IMATOX(I) = 0). Enter the index number of the material property table for material in region NFUEL if there is no oxide present.

41-45   IMATIX(I)   Enter material property table identification number for oxide on inside surface (Default is zirconium oxide; (IMATIX(I) = 0) ; applies only to TUBEs or WALLs.)
Enter the index number of the material property table for material in region 1 if there is no oxide present.

Data sets for the NFUEL regions of geometry type I are entered starting at the centerline for HROD types and at the inside surface for TUBE and WALL types. Data sets are entered in sequence moving radially toward the outside surface.

VESSEL9. 7   (NODER(L), MATR(L), TREG(L), QREG(L), L=1, NFUEL)   FORMAT (4 (2I5, 2F5. 0))
                Read only if FTYPE(I) ≠ NUCL.

Columns	Variable	Description
1-5, 21-25, 41-45...	NODER (L)	Enter the number of radial heat transfer nodes in region L.
6-10, 26-30, 46-50...	MATR (L)	Enter the materal property table identification number for region L.
11-15, 31-35, 51-55...	TREG (L)	Enter the thickness of region L, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1). Note: For TUBE and HROD geometry types, $\sum_{L=1}^{NFUEL} TREG(L) = 0.5 (DROD - DIN)$
16-20, 36-40, 56-60...	QREG (L)	Enter radial power factor for region L. (This profile is automatically normalized to unity.)

VESSEL Group 10: Material Properties Tables, read by subroutine SETIN

This input group is required only if user-supplied material properties were
flagged by input in group 9 (i.e., with nonzero values for IMATF, IMATC,
IMATOX(I), IMATIX(I) or MATR(L) for any geometry type).. If only default
material properties are used, (i. e, zircaloy and UO2), this group is omitted.

VESSEL10.1 NGROUP, NMAT   FORMAT (2I5)

Columns	Variable	Description
1-5	NGROUP	Enter ten (10).
6-10	NMAT	Enter number of material properties tables to be read in. (MTDIM)

Cards VESSEL10.2 and VESSEL10.3 are read in pairs NMAT times.

VESSEL10.2 N, NNTDP, RCOLD (N), IMATAN (N)   FORMAT (2I5, F10. 0, 20X, A10)

Columns	Variable	Description
1-5	N	Enter the material property table identification number.
6-10	NNTDP	Enter the number of entries in material properties table N. (NPDIM)
11-20	RCOLD (N)	Enter the cold density in lbm/ft³ (if ICOBRA = 0), or kg/m³ (if ICOBRA = 1) for material N. (This value is used to define the mass in the heat transfer nodes composed of material type N.)
41-50	IMATAN (N)	Alphanumeric label for material (e. g., stainless)

VESSEL10.3 (TPROP (I, N), CPF1 (I, N), THCF (I, N) I=1, NNTDP)   FORMAT (6F10. 0)

Columns	Variable	Description
1-10 31-40	TPROP (I, N)	Enter the temperature for entry I in material property table N. Units are °F (if ICOBRA = 0) or K (if ICOBRA = 1).

11-20 41-50	CPF1 (I, N)	Enter the specific heat for entry I in material property table N. Units are Btu/lb-° F (if ICOBRA = 0) or J/kg-° C (if ICOBRA = 1).
21-30 51-60	THCF (I, N)	Enter the thermal conductivity for entry I in material property table N. Units are Btu/hr-ft-° F (if ICOBRA = 0) or W/m-° C (if ICOBRA = 1).

VESSEL Group 11: Axial Power Tables and Forcing Functions, read by subroutine
SETIN

VESSEL11. 1　NGROUP, NAXP, NQ, NGPFF　FORMAT (4I5)

Columns	Variable	Description
1-5	NGROUP	Enter eleven (11).
6-10	NAXP	Enter number of axial power profile tables to be read.　(Minimum of one. N3DIM)
11-15	NQ	Enter number of pairs of elements in the power forcing function table. (NFDIM) Enter zero (0) if power is constant.
16-20	NGPFF	Enter number of pairs of elements in gap conductance forcing function table.　(NFDIM) Enter zero (0) if there is no forcing function on gap conductance.

Axial Power Tables

Cards VESSEL11. 2 and VESSEL11. 3 are read in pairs NAXP times.

VESSEL11. 2　I, NAXN (I)　　　　FORMAT (2I5)

Columns	Variable	Description
1-5	I	Enter axial power profile table identification number.
6-10	NAXN (I)	Enter number of pairs of elements in axial power profile table I.

VESSEL11. 3　(Y (I, N), AXIAL (I, N), N=1, NAXN (I))　　FORMAT (8F10. 0)

Columns	Variable	Description
1-10, 21-30, 41-50, 61-70	Y (I, N)	Enter vertical location, relative to bottom of the VESSEL, where axial power factor AXIAL (I, N) is applied.　Use inches (if ICOBRA = 0) or meters (if ICOBRA = 1).

11-20,	AXIAL (I, N)	Enter relative power factor (the ratio of local
31-40,		power to average power) at vertical location
51-60,		Y (I, N).
71-80		

All rods using the same table should start and end at the same vertical locations. In the table, Y(I,1) must be the vertical location of the beginning of the rods, and Y(I, NAXN(I)) must be the vertical location of the end of the rods.

Power Forcing Function

VESSEL11.4 (YQ(N), FQ(N), N=1, NQ)   FORMAT (8F10.0)   Read only if NQ > 0.

Columns	Variable	Description
1-10,	YQ (N)	Enter transient time (seconds).
21-30,		
41-50...		
11-20,	FQ (N)	Enter the power factor:
31-40,		$FQ(N) = \dfrac{\text{Power at time } YQ(N)}{\text{initial power}}$
51-60...		

Gap Conductance Forcing Function

VESSEL11.5 (YGPFF(N), FGPFF(N), N=1, NGPFF)   FORMAT (8F10.0)
          Read only if NGPFF > 0.

Columns	Variable	Description
1-10,	YGPFF (N)	Enter transient time (in seconds).
21-30,		
41-50...		
11-20,	FGPFF (N)	Enter conductance factor:
31-40,		$FGPFF(N) = \dfrac{\text{Power at time } YQ(N)}{\text{initial power}}$
51-60...		

VESSEL Group 12: Turbulent Mixing Data, read by subroutine SETIN

VESSEL12. 1   NGROUP, N1   FORMAT (2I5)

Columns	Variable	Description
1-5	NGROUP	Enter twelve (12).
6-10	N1	Enter number of sections in which turbulence will be applied.

Card VESSEL12. 2 is read N1 times.

VESSEL12. 2   I, BETA (I), AAAK (I)   FORMAT (I5, 2F5. 0)

Columns	Variable	Description
1-5	I	Section index number.
6-10	BETA (I)	Mixing coefficient ($\beta = w' / G \cdot S$)
11-16	AAAK (I)	Equilibrium distribution weighting factor in void drift model. Suggested value=1. 0.

<u>VESSEL Group 13: Boundary Condition Data,</u> read by subroutine SETIN

<u>VESSEL13.1</u>   NGROUP, NIBND, NKBND, NFUNCT, NGBND, NBCDMP, NBCRD   FORMAT (7I5)

Columns	Variable	Description
1-5	NGROUP	Enter thirteen (13).
6-10	NIBND	Enter the total number of vertical mesh cell boundary conditions. (MUDIM)
11-15	NKBND	Enter the total number of transverse momentum cells for which crossflow will be set to zero. (NLDIM)
16-20	NFUNCT	Enter the number of forcing functions for the boundary conditions. (MVDIM)
21-25	NGBND	Enter the number of groups of contiguous transverse momentum cells for which crossflows will be set to zero.
26-30	NBCDMP	$\leq$ 20.
31-35	NBCRD	$\leq$ 20.

<u>VESSEL13.2</u>   (NPTS (K), K=1, NFUNCT)   FORMAT (16I5)   Read only if NFUNCT > 0.

Columns	Variable	Description
1-5,...	NPTS (K)	Enter the number of points (pairs of values) in forcing function table K. (NFDIM)

Sixteen values are entered per card. Repeat card <u>VESSEL13.2</u> until NFUNCT values have been entered.

Card <u>VESSEL13.3</u> is read NFUNCT times.   Read only if NFUNCT > 0.

<u>VESSEL13.3</u>   (ABSCIS (K, I), ORDINT (K, I), I=1, NPTS (K))   FORMAT (5 (F5.0, F10.0))

Columns	Variable	Description
1-5, 16-20...	ABSCIS (K, I)	Enter the time, in seconds, the factor is applied. applied.
6-15, 21-30...	ORDINT (K, I)	Enter the forcing function factor to be applied at time ABSCIS (K, I).

Five pairs of (ABSCIS, ORDINT) are entered per card. Repeat card
VESSEL13.3 until NPTS(K) points have been entered for forcing function
table K. Continue entering data until NFUNCT tables have been specified.

Cards VESSEL13.4 through VESSEL13.6 are read NIBND times.   Read only if NIBND > 0.

VESSEL13.4   (IBOUND(L, N), L=1, 2), ISPEC(N), NPFN(N), NHFN(N), PVALUE(N), HVALUE(N),
              XVALUE(N), NXFN(N)   FORMAT(5I5, 3F10.0, I5)

Columns	Variable	Description
1-5	IBOUND(1, N)	Enter the index number of the channel boundary condition N applies to.
6-10	IBOUND(2, N)	Enter the vertical node number at which boundary condition N is applied. (NOTE: The node number is referenced to the beginning of the section that the channel identified in IBOUND(1, N) resides in.)
11-15	ISPEC(N)	Enter the boundary condition type. Valid options are:
		1 = pressure and enthalpy boundary condition
		2 = flow and enthalpy
		3 = flow only
		4 = mass source (flow rate and enthalpy)
		5 = pressure sink and enthalpy
16-20	NPFN(N)	Enter the index number of the forcing function table by which the first parameter of the boundary condition will be varied. (NOTE: The forcing function tables are numbered sequentially in the order they are read in on card VESSEL13.3.) For example: If ISPEC(N) = 1 and NPFN(N) = 3, the specified pressure will be adjusted according to the third forcing function entered on VESSEL13.3. Enter zero if the boundary condition is constant.
21-25	NHFN(N)	Enter the index number of the forcing function table by which the second parameter of the boundary condition will be varied. (For example: If ISPEC(N) = 1 and NHFN(N) = 6, the specified enthalpy will be adjusted according

to the 6th forcing function specified on
<u>VESSEL13. 3.</u>)
Enter zero if the boundary condition is
constant.

26-35	PVALUE (N)	Enter the first boundary value. If ISPEC (N) = 1 or 5, enter pressure, in psia (if ICOBRA = 0) or N/m² (if ICOBRA = 1). If ISPEC (N) = 2, 3 or 4, enter flow rate, in lbm/sec (if ICOBRA = 0) or kg/sec (if ICOBRA = 1).
36-45	HVALUE (N)	Enter enthalpy in Btu/lbm (if ICOBRA = 0) or J/kg (if ICOBRA = 1). Enter zero (0) if ISPEC (N) = 3.
46-55	XVALUE (N)	Pressure (psia) must be input for ISPEC (N) =2, 3 or 4.
56-60	NXFN (N)	

<u>VESSEL13. 5</u>   HMGA (N), (GVALUE (NGA, N), NGA=1, NGAS+2)   FORMAT (16F5. 0)
(read only if ISPEC (N) ≠ 3)

Columns	Variable	Description
1-5	HMGA (N)	Enthalpy of noncondensible gas mixture
6-10, 11-15...	GVALUE (NGA, N)	Volume fraction of gas in vapor-gas mixture (read in same order as in card group 1)

<u>VESSEL13. 6</u>   NHMFN (N), (NGFN (NGA, N), NGA=1, NGAS+2)   FORMAT (1215)

Columns	Variable	Description
1-5	NHMFN (N)	Index number of forcing function applied to gas mixture enthalpy
6-10, 11-15...	NGFN (NGA, N)	Index number of forcing function applied to volume fraction of each gas

Cards VESSEL13.7 or VESSEL13.8 are read NIBND times.

Card VESSEL13.7 is read only if some ISPEC(N) has been specified as 4 (i.e., a mass injection boundary condition). Card VESSEL13.7 is read once for each mass injection boundary condition, in the same order they are specified in the input for card VESSEL13.4.

VESSEL13.7 AINJT(K)   FORMAT (F5.0)   Read only if some ISPEC(N) = 4.

Columns	Variable	Description
1-5	AINJT(K)	Enter the flow area of the mass injection in in.^{2} (if ICOBRA = 0) or m^2 if (ICOBRA = 1).

Card VESSEL13.8 is read after cards VESSEL13.4 through VESSEL13.6 have been read NIBND times, and only if some ISPEC(N) has been specified as 5 (i.e., a pressure sink boundary condition). Card VESSEL13.8 is read once for each pressure sink, in the same order they are specified in the input for card VESSEL13.4.

VESSEL13.8 ASINK(K), SINKK(K), DXSINK(K)   FORMAT (3F5.0)
           Read only if some ISPEC(N) = 5.

Columns	Variable	Description
1-5	ASINK(K)	Enter the flow area of the pressure sink, in in.^{2} (if ICOBRA = 0) or m^2 (if ICOBRA = 1).
6-10	SINKK(K)	Enter the loss coefficient (velocity head) of the pressure sink.
11-15	DXSINK(K)	Enter the length of the momentum control volume for the sink, in inches (if ICOBRA = 0) or meters (if ICOBRA = 1).

VESSEL13.9   K, JSTART, JEND   FORMAT (3I5)   Read only if NGBND > 0.

Columns	Variable	Description
1-5	K	Enter the gap number to which a zero (0.0) crossflow is to be applied.
6-10	JSTART	Enter the continuity cell number at which to start applying the zero crossflow.
11-15	JEND	Enter the continuity cell number at which to stop applying the zero crossflow.

Note: The crossflow will be set to zero for gap K between nodes JSTART and JEND. The node numbers are given relative to the beginning of the section containing gap K.

This card may be repeated as many times as necessary for a given gap K, to identify all axial levels that have zero crossflow. The total number of transverse momentum cells with zero crossflow boundary conditions specified by card VESSEL13.8 must sum to NKBND.

Cards VESSEL13.10 and VESSEL13.11 are read only if NBCDMP ≧ 1

VESSEL13.10   BCDMPT   FORMAT (F10.0)

Columns	Variable	Description
1-10	BCDMPT	

VESSEL13.11   (IBCDMP (L), JBCDMP (L), L=1, NBCDMP)   FORMAT (16I5)

Columns	Variable	Description
1-5, 11-15, 21-25...	IBCDMP (L)	
6-10, 16-20, 26-30...	JBCDMP (L)	

Cards <u>VESSEL13. 12</u> and <u>VESSEL13. 13</u> are read only if NBCRD $\geqq$ 1

<u>VESSEL13. 12</u>   BCDMPT, TOLDBC   FORMAT (2F10. 0)

Columns	Variable	Description
1-10	BCDMPT	
11-20	TOLDBC	

<u>VESSEL13. 13</u>   (IBCRD (L, J), J=1, 2), L=1, NBCRD)   FORMAT (16I5)

Columns	Variable	Description
1-5, 6-10, 11-15...	IBCRD (L, J)	

VESSEL Group 14: Output Options, read by subroutine SETIN

VESSEL14.1   NGROUP, N1, NOUT1, NOUT2, NOUT3, NOUT4, IPROPP, IOPT   FORMAT (8I5)

Columns	Variable	Description
1-5	NGROUP	Enter fourteen (14).
6-10	N1	Enter the general vessel output option. Valid entries are: 1 = print channels only 2 = print channels and gaps only 3 = print rods and unheated conductors only 4 = print rods, unheated conductors, and channels only 5 = print channels, gaps, rods, and unheated conductors
11-15	NOUT1	Enter the number of channels to be printed (used if N1 = 1, 2, 4, or 5). If NOUT1 = 0, all channels will be printed. If NOUT1 > 0, an array of NOUT1 channel numbers. must be entered on card VESSEL14.2.
16-20	NOUT2	Enter the number of rods to be printed (used if N1 > 2). If NOUT2 = 0, all rods will be printed. If NOUT2 > 0, an array of NOUT2 rod numbers must be entered on card VESSEL14.4.
21-25	NOUT3	Enter the number of gaps to be printed (used if N1 = 2 or 5). If NOUT3 = 0, all gaps will be printed. If NOUT3 > 0, an array of NOUT3 gap numbers must be entered on card VESSEL14.3.
26-30	NOUT4	Enter the number of unheated conductors to be printed (used if N1 > 2). If NOUT4 = 0, all unheated conductors will be printed. If NOUT4 > 0, an array of NOUT4 unheated conductor numbers must be entered on card VESSEL14.5.
31-35	IPROPP	Enter the property table print option. Valid entries are: 0 = do not print the property table

		1 = print the property table
36-40	IOPT	Enter the debug print option. Valid entries are:
		0 = normal printout only
		2 = debug printout (print extra data for channels, rods and gaps)

VESSEL14.2 (PRINTC(I), I=1, NOUT1)   FORMAT (16I5)
Read only if N1 ≠ 3 and NOUT1 > 0.

Columns	Variable	Description
1-5,...	PRINTC(I)	Enter the index numbers of channels to be printed. Sixteen values are entered per card. Repeat this card until NOUT1 values have been entered.

VESSEL14.3 (PRINTG(I), I=1, NOUT3)   FORMAT (16I5)
Read only if N1 = 2 or 5 and NOUT3 > 0.

Columns	Variable	Description
1-5,...	PRINTG(I)	Enter the index numbers of gaps to be printed. Sixteen values are entered per card. Repeat this card until NOUT3 values have been entered.

VESSEL14.4 (PRINTR(I), I=1, NOUT2)   FORMAT (16I5)
Read only if N1 > 2 and NOUT2 > 0.

Columns	Variable	Description
1-5,...	PRINTR(I)	Enter the index numbers of rods to be printed. Sixteen values are entered per card. Repeat this card until NOUT2 values have been entered.

<u>VESSEL14.5</u>   (PRINTS(I), I=1, NOUT4)   FORMAT(16I5)   Read only if NOUT4 > 0.

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5,...	PRINTS(I)	Enter the index numbers of unheated conductors to be printed. Sixteen values are entered per card. Repeat this card until NOUT4 values have been entered.

<u>VESSEL14.6</u> NTINIT, TINIT, SAUT FORMAT (I5, 2F10. 0)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	NTINIT	
6-15	TINIT	
16-25	SAUT	

<u>VESSEL14.7</u> NDUMEND   FORMAT (I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	NDUMEND	Enter <u>zero (0)</u> to terminate VESSEL group control card input.

Graphics Options, read by subroutine IGRAF

GRAF. 1 MOVIE, TMOVIE   FORMAT (I5, F10. 2)

Columns	Variable	Description
1-5	MOVIE	Enter the movie process option. Valid entries are: 0 = no movie (recommended option) 1 = save data for particle tracker movie. Note: The COBRA/TRAC code has the capability to dump data that can be used to make particle-tracker movies of simulations. However, the software to actually make the particle-tracker movies is not part of the COBRA/TRAC package, and will be released and documented separately.
6-15	TMOVIE	Enter the time interval at which to save data for the movie. Valid only if MOVIE = 1.

Note: Movie option currently disabled.   Enter a blank card.

GRAF. 2 MXGDMP, IGRFOP, NLLR   FORMAT (3I5)

Columns	Variable	Description
1-5	MXGDMP	Enter the maximum number of time steps for which graphics data will be saved. (MIDIM). Enter zero and set GFINT on card TIME. 2 at a larger value than the time for calculation end, if graphics output is not required. (Note: This cannot be changed on a restart.)
6-10	IGRFOP	Enter the vessel graphics option, as follows: 0 for normal vessel dump (all variables saved for all vessel computational cells) N, where N is the number of user-selected vessel variables to be saved for graphics. (M5DIM)
11-15	NLLR	Enter the number of liquid level calculations. (Number of GRAF. 3 cards. Valid only if IGRFOP > 0. MZDIM)

Card <u>GRAF. 3</u> is read once for a liquid level calculation in channels that are all in the same section. If a liquid level calculation includes channels in different sections, <u>GRAF. 3</u> is read once for each section involved. Card <u>GRAF. 3</u> is read a total of NLLR times.

<u>GRAF. 3</u>   (NCHLL (N), JSLL (N), JCELL (N), (ICLL (I, N), I=1, NCHLL (N))   FORMAT (16I5)
               Read only if NLLR > 0.

Columns	Variable	Description
1-5	NCHLL (N)	Enter the number of channels in a section to be used for liquid level calculation N.
6-10	JSLL (N)	Enter the starting axial node number for the liquid level calculation. This value should be negative if continuing input from previous sections of a liquid level calculation that crosses section boundaries.
11-15	JCELL (N)	Enter the ending axial node number (in the section containing channels ICLL (I, N)) to be included in the liquid level calculation.
16-20 21-25...	ICLL (I, N)	Enter the index numbers of NCHLL (N) channels to use in the liquid level calculation. (Enter up to 13 values on the first line. If NCHLL (N) > 13, continue on the next line, entering values in the 16I5 format.)

<u>GRAF. 4</u>   ((IGRF (I, J), J=1, 2), GRFN (I), I=1, IGRFOP)   FORMAT (5 (2I5, F5. 0))
               Read only if IGRFOP > 0.

Columns	Variable	Description
1-5 16-20 31-35 46-50 61-65	IGRF (I, 1)	Enter a number signifying the vessel variable to be saved. Valid entries are: Channel variables-- 1 = pressure 2 = void fraction 3 = entrained liquid fraction 4 = liquid fraction 5 = liquid temperature 6 = vapor temperature 7 = liquid density

8 = vapor density

9 = vapor flow

10 = liquid flow

11 = entrained liquid flow

12 = vapor generation rate

13 = heat transfer rate to liquid

14 = heat transfer rate to vapor

15 = drop mass entrainment rate

16 = drop mass deentrainment rate

17 = drop interfacial area density

18 = ETAENP (dummy)

19 = HASHL

20 = HASCL

21 = HASHV

22 = flow regime

23 = boundary condition type

24 = interfacial drag coefficient (XK)

25 = interfacial drag coefficient (XKGE)

37 = mixture density; $(\alpha \rho_v + (1-\alpha) \rho_l)$

44 = Density of noncondensible gas mixrure

45 = Vapor partical pressure

46 = Vapor molar fraction

Gap variables--

26 = vapor crossflow

27 = liquid crossflow

28 = entrained liquid crossflow

Rod variables--

29 = heat transfer mode

30 = liquid temperature (seen by rod
     IGRF (I, 2))

31 = vapor temperature (seen by rod
     IGRF (I, 2))

32 = heat transfer coefficient to liquid

33 = heat transfer coefficient to vapor

34 = heat flux

35 = rod surface temperature

36 = peak temperature on rod identified in
     IGRF (I, 2) at Radial node GRFN (I)

Slab variables--

38 = slab heat transfer mode

39 = slab liquid temperature (seen by rod
      IGRF(I, 2))

40 = slab vapor temperature (seen by rod
      IGRF(I, 2))

41 = slab heat transfer coefficient to liquid

42 = slab heat transfer coefficient to vapor

43 = slab surface temperature

6-10	IGRF(I, 2)	Enter channel, rod, or gap number for which
21-25		selected variable will be saved. Parameters
36-40		1-25, 37 and 44-46 are channel variables; 26-28 are
51-55		gap variables; 29-36 are rod variables; 38-43 are slab
66-70		variables . If IGRF(I, 1) = 35 or 36 and the inside

surface temperature is desired, enter the negative of
the rod number.

(When any rod is divided into two or more
azimuthal surfaces, IGRF(I, 2) must be the rod
surface number rather than the whole rod
number. The surface number is determined by
counting the number of rod fractions in the
order read on card VESSEL 8. 3).

11-15	GRFN(I)	Enter the vertical node number for which the
26-30		selected variable will be saved.
41-45		For rod variables, enter the vertical elevation
56-60		in inches. (Must be within 1 inch of a
71-75		vertical node location.)

For IGRF(I, 1)=36, enter the radial node index.
(Node 1 is on the inside of the rod.)

<u>Time Domain Data</u>, read by subroutine TIMSTP

After all component data have been entered, the user mest define the time
domain for the simulation. The total time can be divided into several domains
of specified duration. Each time domain can have different minimum and
maximum time step sizes and different edit intervals. To terminate the
calculation, a time domain with a negative time step size is entered. Two
cards are required to specify the data for each time domain.

<u>TIME.1</u>   DTMIN, DTMAX, TEND, RTWFP, TMAX   FORMAT (5E14.6)

Columns	Variable	Description
1-14	DTMIN	Enter the minimum time step allowed for this domain, in seconds. Enter a <u>negative</u> value to terminate the calculation.
15-28	DTMAX	Enter the maximum time step allowed for this domain, in seconds.
29-42	TEND	Enter the end of this time domain, in seconds.
43-56	RTWFP	Enter the ratio of conduction solution and fluid solution time step sizes. (Used to obtain steady-state conditions. The conduction solution can generally take time steps greater than the fluid solution. For transient calculations, RTWFP should be one.)
57-70	TMAX	Enter the maximum CPU time allowed for this run. If this CPU limit is reached during this simulation time domain, the run will terminate. (Dump files will be written, so the calaulation can be restarted.)

<u>TIME.2</u>   EDINT, GFINT, DMPINT, SEDINT, TCKLEND   FORMAT (5E14.6)

Columns	Variable	Description
1-14	EDINT	Enter the print interval for this time domain. Output will be printed every EDINT seconds.
15-28	GFINT	Enter the graphics interval for this time domain. Data for graphics will be saved every

		GFINT seconds.
29-42	DMPINT	Currently not effective.

(NOTE: For larger problems, the restart dumps create relatively large files, and can become unmanageable if too many dumps are written during a simulation. Regardless of the value for input DMPINT, the dump logic automatically writes dumps at the end of a calculation and after every 60 minutes of CPU time during the calculation. This is usually quite sufficient, and DMPINT can be set to a large value.)

43-56	SEDINT	Enter the "short edit" interval for this time domain. (A "short edit" is an abbreviated print.) Short edits will be performed every SEDINT seconds.
57-70	TCLKEND	Enter the wall clock time (decimal, 24-hour clock) at which to stop the calculation and create a restart dump and edit. (This is useful for running the calculation during particular shifts; for example, TCLKEND can be entered as 7.5 to stop the calculation at 7:30 am.

Enter zero if this feature is not used.

Repeat cards TIME.1 and TIME.2 for each time domain desired. A final time domain with a negative value for DTMIN must be entered to terminate the calculation.

*** RESPEC Parameters ***

Parameter	Definition

MADIM   Maximum number of pairs of entries for the vertical variation tables. Each table will be dimensioned for MADIM pairs of elements. (This parameter should be equal to or greater than the maximum value of NAXL(I), entered on card VESSEL5. 2.)

MBDIM   Maximum number of channels per section. (This parameter should be equal to or greater than the maximum value for NCHN, entered on card VESSEL4. 2.)

MCDIM   Maximum number of channels. (This parameter should be equal to or greater than NCHANL, entered on card VESSEL2. 1.)

MDDIM   Number of gaps read to describe transverse orthogonal convection. (This parameter should be equal to or greater than NLMGAP, entered on card VESSEL3. 4.)

MFDIM   Maximum number of fuel geometry types. (This parameter should be equal to or greater than NFUELT, entered on card VESSEL9. 1.)

MGDIM   Maximum number of transverse connections between channels (i. e., gaps). (This parameter should be equal to or greater than the maximum value of NK, entered on card VESSEL3. 1.)

MIDIM   Maximum number of graphics dumps to be made. (This parameter should be equal to or greater than MXGDMP, entered on card GRAF. 2.)

MJDIM   Maximum number of grid types. (This parameter should be equal to or greater than NGT, entered on card VESSEL7. 1.)

MKDIM   Maximum number of grids. This parameter should be equal to or greater than the sum of all nodes containing any grid;

$$\sum_{NG=1}^{NGT} NGAL(NG) * NGCL(NG)$$

where NGAL(NG) = number of axial locations for grid type NG, entered on card VESSEL7. 3.

NGCL(NG) = number of channels containing grid NG at levels NGAL(NG), entered on card VESSEL7. 3.

MLDIM   Maximum number of vertical variation tables. (This parameter should be equal to or greater than NAFACT, entered on card VESSEL5. 1.)

Parameter	Definition
MNDIM	Maximum number of flow blockages. (This parameter should be equal to or greater than NFBS, entered on card VESSEL7.1.)
MRDIM	Maximum number of rods. (This parameter should be equal to or greater than NRROD, entered on card VESSEL8.1.)
MSDIM	Maximum number of pressure sink and mass source boundary condictions (i.e., up to MSDIM type 4 boundary condictions and up to MSDIM type 5 boundary condictions can be specified in input group 13. This parameter is not checked directly in the code. The user should make sure this parameter be equal to or greater than the maximum number of either type 4 or type 5 boundary condictions specified on card VESSEL13.4.)
MTDIM	Maximum number of material property tables. (This parameter should be equal to or greater than NMAT, entered on card VESSEL10.1.)
MUDIM	Maximum number of specified vertical boundary condictions. (This parameter should be equal to or greater than NIBND, entered on card VESSEL13.1.)
MVDIM	Maximum number of forcing functions on the specified cell boundary condictions. (This parameter should be equal to or greater than NFUNCT, entered on card VESSEL13.1.)
MXDIM	Maximum number of vertical nodes in a section. (This parameter should be equal to or greater than the maximum value of NONODE+2, entered on card VESSEL4.2.)
MYDIM	Maximum number of locations plus 1, in any one channel, where vertical velocities convect transverse momentum across section boundaries. (This parameter should be at least 1 greater than the maximum value of NAMGAP, entered on card VESSEL2.2.)
MZDIM	Maximum number of liquid level records to be read on card GRAF.3. This is the maximum number of groups of channels that can be considered in the liquid level graphics calculation. (This parameter should be equal to or greater than NLLR, entered on card GRAF.2.)
M5DIM	Number of variables dumped for short graphics dump. (This parameter should be equal to or greater than IGRFOP, entered on card GRAF.2.)

Parameter	Definition

NADIM   Maximum number of continuity cells. This paramrter should be equal to or greater than the sum of all nodes in all channels;

$$\sum_{N=1}^{NSECTS} NCHN(N) * NONODE(N)$$

where NSECTS = total number of sections, entered on card VESSEL4.1.

     NCHN(N) = number of channels in section N, entered on card VESSEL4.2.

     NONODE(N) = number of vertical levels in section N, entered on card VESSEL4.2.

NBDIM   Maximum number of flow connections to a cell (including all connections for vertical flow and transverse flow).

NCDIM   2 * NNDIM

NDDIM   Maxmum number of radiation channels or location types. (This parameter should be equal to or greater than NRAD or NLTYP, entered on card VESSEL8.1. Recommended value is 25.)

NEDIM   Maximum bandwidth of pressure solution matrix. Bandwidth for a given problem is (2*IWIDE+1), where IWIDE is specified on card VESSEL4.5. NEDIM must be equal to or greater than (2*IWIDE+1).

NFDIM   Maximum number of pairs of entries in tables of forcing functions on boundary conditions, rod power and gap conductance. Each forcing function may have up to NFDIM pairs of entries. (This parameter should be equal to or greater than the maximum of IGPC(I), entered on card VESSEL9.2, NPTS(K), entered on card VESSEL13.2, and NQ and NGPFF, entered on card VESSEL11.1.)

NGDIM   NNDIM + 2

NHDIM   NXDIM + 2

NIDIM   Maximum number of cells in any one simultaneous solution group. (This parameter should be equal to or greater than the maximum difference between adjacent elements of the MSIM(I) array, entered on card VESSEL4.6.)

NJDIM   NBDIM + 1

NKDIM   NBDIM + 6

NLDIM   Maximum number of transverse momentum cells that have crossflow set to zero. (This parameter should be equal to or greater than NKBND, entered on card VESSEL13.1.)

Parameter	Definition
NNDIM	Maximum number of radial nodes for conduction in a rod. (This parameter should be at last 2 greater than the maximum value of NFUEL, entered on card VESSEL9. 2 and greater then the number of nodes, also NFUEL, specified for a nonnuclear geometry type, entered on card VESSEL9. 6.)
NODIM	Maximum number of entries in radial power profile table for fuel pellets. (This parameter should be equal to or greater than IRADP, entcred on card VESSEL9. 2.)
NPDIM	Maximum number of entries in a material property table. (This parameter should be equal to or greater than the maximum value of NNTDP, entered on card VESSEL10. 2.)
NQDIM	Maximum number of sections. (This parameter should be equal to or greater than NSECTS, entered on card VESSEL4. 1.)
NRDIM	Maximum number of heat transfer surfaces on all rods, including both internal and external surfaces in contact with the fluid. (This parameter is not checked directly in the core. The user must check it aginst his input for the LR array.)
NTDIM	Maximum number of unheated conductors. (This parameter should be equal to or greater than NSROD, entered on card VESSEL8. 1.)
NVDIM	Maximum number of heat transfer surfaces on all unheated conductors, including both internal and external surfaces in contact with the fluid. (This parameter is not checked directly in the code. The user must check it against his input for the LS array. NVDIM must be equal to or greater than the maximum number of nonzero entries in the LS array. (2 * NTDIM) is the maximum for this value and recommended.)
NWDIM	25 + 5 * NBDIM
NXDIM	Maximum number of axial nodes in rods, including those created by fine mesh renoding. (Recommended value is 80 if renoding is used.)

Parameter	Definition

NYDIM   Maximum number of radial nodes for conduction in an unheated conductor. This parameter should be equal to or greater than the maximum value of the sum of all nodes in a non-nuclear geometry type;

$$\left[\sum_{L=1}^{NFUEL(I)} NODER(L) \right]_{max}$$

where NFUEL(I) = number of regions in geometry type I, entered on card <u>VESSEL9. 6.</u>

           NODER(L) = number of nodes in region L of geometry type I, entered on card <u>VESSEL9. 7.</u>

NZDIM   Maximum number of vertical levels in the VESSEL;

$$\left[\sum_{N=1}^{NSECTS} NONODE(N) \right] + 2$$

where NSECTS = total number of sections, entered on card <u>VESSEL4. 1.</u>

     NONODE(N) = number of vertical levels in section N, entered on card <u>VESSEL4. 2.</u>

N1DIM   NXDIM + 1

N3DIM   Maximum number of axial power profile tables. (This parameter should be equal to or greater than NAXP, entered on card <u>VESSEL11. 1.</u>)

N4DIM   Maximum number of rod or unheated conductor temperature initialization tables. (This parameter should be equal to or greater than NRTAB, entered on card <u>VESSEL8. 1.</u>)

N5DIM   Maximum number of entries in a given rod or unheated conductor temperature initialization table. (This parameter should be equal to or greater than the maximum value of NRAX1, entered on card <u>VESSEL8. 6.</u>)

N8DIM   Maximum number of nuclear fuel rods using the dynamic gap conductance model. (This parameter is not checked directly in the code. The user must check it against his input on card <u>VESSEL9. 2</u> by summing the number of heater rods using the dynamic gap conductance model.)

JGDIM   Maximum number of noncondensible gases. (This parameter should be equal to or greater than NGAS, entered on card <u>VESSEL1. 1.</u>)

J1DIM   JGDIM + 2