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ANDES : A COMPUTER CODE FOR FUEL/COOLANT INTERACTION ANALYSIS UNDER LWR AND LMFBR CONDITIONS
—ANALYTICAL MODEL AND CODE MANUAL—

February 1981

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ANDES : A Computer Code for Fuel/ Coolant Interaction Analysis under LWR and LMFBR Conditions

- Analytical Model and Code Manual -

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A theoretical model for the analysis of transient behavior in fuel coolant interaction has been developed. The program is applicable for the combination of UO_2 fuel and water (LWR cases) and that of UO_2 and sodium coolant (LMFBR cases).

It is assumed that the hot fuel fragments mix with the coolant in a mixing region homogeneously, and results in prompt heat up and vapor generation of the coolant. The expansion of the mixing region is treated as being one dimensional along the coolant channel constrained acoustically at first till bulk boiling initiation and then constrained inertially by the coolant slugs upstream and downstream of the mixing region. Inertial constraint model can be chosen from the beginning of the transient by bypassing the acoustic constrained model calculation.

The effects of a fuel particle size distribution, mixing time, fuel-coolant ratio, coolant channel dimensions, fuel and coolant initial conditions and heat transfer coefficient at fuel-coolant interface can be taken into consideration by the input. Temperature, pressure and void fraction in the mixing region, temperature profile in the fuel particles, energy transfer rate, and ejection speed of coolant slugs are given as a major output at a specified time step. Plotting subroutine is also accommodated in the program.

Keywords: Fuel-Coolant Interaction, Fuel Failure, Destructive Pressure, vapor Explosion, Pressure Pulse, Acoustic Pressure Wave, Void Fraction, Computer Code

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ANDES： 軽水炉および高速炉条件下での燃料・冷却材相互作用解析コード
── 解析モデルおよびコードマニュアル ──

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（1981年1月12日受理）

本解析コードは燃料・冷却材相互作用の過渡挙動解析のため開発されたものであり，UO_2 燃料・軽水の組合せ（軽水炉条件）およびUO_2燃料・ナトリウムの組合せ（高速炉条件）に適用できる。解析モデルは，破損して冷却材中に細片化して飛散した高温燃料片が混合領域内で冷却材と均一に混合し，冷却材を急加熱し蒸気を発生するものとし，混合領域は流路に沿って一次元的に膨張するものとしている。混合領域の拘束条件は，バルク沸騰開始までは音響的拘束とし，沸騰開始後は，混合領域の上，下流の冷却材スラグによる慣性拘束としている。但し，最初から慣性拘束条件として計算できるように音響拘束条件をバイパスできるオプションも付加されている。入力により燃料粒子径分布，混合時間，燃料・冷却材比，冷却流路形状・寸法，燃料および冷却材の初期条件，燃料粒子・冷却材境界面での熱伝達率等を指定でき，これら種々のパラメータの影響を評価することができる。計算結果としては，混合領域内の温度，圧力およびボイド率，燃料粒子内温度分布，燃料から冷却材への伝熱量，冷却材スラグの噴出速度等が時間ベースで出力される。なお，本コードにはプロッターサブルーチンも備えており，出力をプロッタに書くことができる。

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1. Introduction

In a postulated severe reactore core damage accident, generation of destructive forces such as pressure pulses and ejection of liquid coolant are expected to occur by rapid thermal expansion of coolant or prompt steam generation in the destroyed core region.

This phenomenon which is generally called as fuel coolant interaction (FCI) was first experienced in SL-1 accident[1], and were observed in in-pile fuel destructive experiments of SPERT[2] and TREAT[3]. The in-pile studies are now continueing in NSRR[4] and PBF[5] projects in which LWR fuel rods are irradiated by a large pulse power simulating prompt power burst in a reactivity initiated accident (RIA).

In FBR field, destructive energy generation by contact of molten fuel and sodium (Molten Fuel/Sodium Interaction) is regarded as one of very important aspects of postulated severe core damage accidents. The in-pile experiments for FBR conditions are being conducted in ACRR in Sandia Laboratories[6].

The analysis code ANDES calculates the pressure pulse generation and liquid coolant ejection process during fuel failure both in LWR and LMFBR conditions mentioned above. The calculation model is based on homogeneous mixing of fragmented fuel and coolant at destructed core region and on one dimensional expansion of the heated region along the flow channel. As this situation of the model does basically simulate the fuel disintegration by prompt power increase, the code is most suited to analyze the destructive energy generation during an RIA. By setting a suitable boundary conditions by the input, however, the code can be applied to a case of molten core drop into the coolant pool.

The ANDES has been developed by combining two FCI codes PULSE-2[7] and BREEZE[8]. Acoustic constraint model of BREEZE was used for pressure pulse calculation before boiling incipience and inertial constraint model of PULSE-2 was applied for pressure accumulation and liquid coolant ejection dynamics after boiling. In combining the codes, the program was reassembled to a modular system for the convenience of future modification, and free format input subroutine was introduced.

This report describes the analytical models, numerical solution procedure in section 2 and 3, respectively. Input and output descriptions are in section 4 and 5. Numerical methods applied are shown in the Appendix.

2. Description of Analytical Models

2.1 Assumptions

The analysis models are based on the following assumptions.

(1) The destroyed reactor core system can be simulated by one dimensional arrangement of interaction region and upper and lower intact coolant channels connected to it as illustrated in Figure 1.

(2) Fragmented fuel particles mix homogeneously with the coolant in the interaction region. Particle size distribution and mixing ratio as a function of time are considered.

(3) The state of coolant in the interaction region is defined by average values.

(4) The constraint condition to the interaction region is divided into two phases; i.e. acoustic constraint before boiling occurrence (Phase A) and inertial and frictional constraint after boiling initiation (Phase B).

(5) In phase B calculation coolant vapor is assumed to keep thermohydraulically equilibrium with the liquid coolant.

2.2 Heat Transfer from Fuel Particles to the Coolant

2.2.1 Temperature inside the Fuel Particles

As the time scale of the destructive energy generation process is of the order of milliseconds to scores of milliseconds, thermal registance inside the fuel particles has considerable influence on heat transfer to the coolant. Especially in the case of sodium/UO_2 interaction of FBR's, major resistance to heat transfer from fuel to coolant is in the fuel side. Thus, the transient heat conduction calculation in the fuel particle is conducted by treating a fuel particle as an exact sphere.

$$\frac{\partial T_f(r,t)}{\partial t} = \frac{\lambda_f}{\rho_f C_f} \frac{1}{r^2} \frac{\partial}{\partial r}\left(r^2 \frac{\partial T_f(r,t)}{\partial r}\right) \tag{1}$$

The boundary conditions are given as follows.

$$\left.\frac{\partial T_f(r,t)}{\partial r}\right|_{r=0} = 0 \tag{2}$$

$$T_f(r,t)\big|_{r=r_0} = T_{f,s}(t) \tag{3}$$

$$T_f(r,t)\big|_{t=0} = T_{f,0} \tag{4}$$

where,

$T_f(r,t)$: Fuel temperature as functions of radius and time
$T_{f,s}(t)$: Fuel surface temperature
$T_{f,0}$: Initial fuel temperature
λ_f : Fuel thermal conductivity
ρ_f : Fuel density
C_f : Fuel specific heat

Surface temperature $T_{f,s}$ of the fuel particle of radius r_0 is obtained by solving Eqs. (1) through (4). Then the heat transfer from the fuel particle to the coolant is calculated based on the temperature difference between $T_{f,s}$ and bulk coolant temperature T_c. The effects of particle size distribution are realized by classifying the fuel particles into particle groups of different radius, and solving the heat conduction equations for each group independently.

When the fragmentation process is introduced into the calculation, Equation (1) is solved for each group of fuel particles which starts to interact with coolant at different time. In this case, time t in Equation (1) is rewritten as $(t - \tau_n)$, where τ_n is the delay time of the contact for n-th group of fuel particles from the first contact of fuel particles with coolant.

2.2.2 Heat Transfer from Fuel to Coolant

The heat transfer from fuel particle to coolant is one of the difficult problems to be solved in FCI analysis. There are a few experimental results which have been done in the field of transient heat transfer between a small hot particle and liquid. Experimental study of forced conduction heat transfer from sphere to water was performed by J.C. Hessen and W. Bloom[9]. They measured heat transfer rate from 1/4 inch dia. silver sphere to water by Swinging-Arm experiment. Figure 2 shows their test results at the sphere velocity of 13.9 ft/sec. Each group of data constitutes a boiling curve depending on the water temperature and pre-test treatment. The comparison of the boiling curves indicate that DNB (Departure from Nucleate Boiling) and heat transfer rate in the film boiling region are strongly influenced by the water temperature and by degassing treatment of water by boiling. The following equation for heat transfer rate before DNB

was proposed.

$$q/A = 1.13 \left(\frac{U_\infty \rho_\ell C_{p\ell} \lambda_\ell}{D}\right)^{\frac{1}{2}} (T_w - T_B) \quad (5)$$

or $$Nu = 1.13 (Re\ Pr)^{0.5} \quad (6)$$

where

q/A : heat transfer rate

U_∞ : velocity of the sphere

ρ_ℓ : density of water

$C_{p\ell}$: specific heat of water

λ_ℓ : thermal conductivity of water

T_w : surface temperature of sphere

T_B : coolant bulk temperature

$Nu \equiv (h\,D)/k$: Nusselt number

$Re \equiv (\rho V_\infty D)/\mu$: Reynolds number

$Pr \equiv (C_p\,\mu)/k$: Prandtl number

h : heat transfer coefficient

μ : viscosity of water

Similar equations are developed by Hsu[10], Eq.(7), and by Vliet and Leppert[11], Eq.(8) as follows.

$$Nu = 0.921(Re\ Pr)^{0.5} \quad (7)$$

$$Nu(Pr)^{-0.5} = 2.7 + 0.12(Re)^{0.66} \quad (8)$$

Heat transfer rate from a metal sphere to sodium was measured by Witte[12] in atmospheric sodium using small tantalum sphere.

The following equation was proposed based on the experimental data.

$$q = 4\pi\, r_f^2\, c\, (T_{f,s} - T_{Na})^n \quad (9)$$

where

r_f : radius of particle

$T_{f,s}$: surface temperature of particle

T_{Na} : sodium bulk temperature

c,n : constants

The empirical constants c and n obtained by Witte's experiment are shown in Table 1. As these constants depend on sphere speed and

sodium temperature, other combinations of c and n may have to be introduced for the different conditions.

In the present analysis the following equation was adopted as the heat transfer correlation at fuel surface.

$$q(r_f,t) = 4\pi\, r_f^2\, c(T_{f.s} - T_c)^n \tag{10}$$

where T_c is bulk coolant temperature, and constants c, n are specified by input. Further, it is modified in the code to be able to switch the constants at a specified temperature Tc.

The effect of vapor void is considered after bulk boiling initiation by introducing the influence factor $f(\alpha)$ as follows.

$$q(r_f,t) = 4\pi\, rf^2\, c(T_{f.s} - T_c)^n \cdot f(\alpha) \tag{11}$$

$$f(\alpha) = \frac{1}{\lambda_\ell}\left[(1-\alpha)\lambda_\ell + \alpha\lambda_v\right] \tag{12}$$

where

λ_ℓ : thermal conductivity of liquid coolant

λ_v : thermal conductivity of coolant vapor

α : void ratio in the interaction region

The total energy transferred to the coolant from the fuel particles of various sizes can be otained by summing up the heat transfer rate for all particle sizes.

$$Q(t) = \sum_{i=1}^{imax} q_i(r_{f,i},\ t-\tau_i) \cdot n(r_{f,i}) \tag{13}$$

where

$q_i(r_{f,i},\ t-\tau_i)$: heat transfer rate from a particle of i-th particle group at time t

$n(r_{f,i})$: number of fuel particles of radius $r_{f,i}$

imax : total number of groups into which fuel particles are classified by the radius.

2.3 Pressure Accumulation in the Reaction Region

It is assumed that the coolant in the reaction region is heated homogeneously by the fuel particles and keeps thermodynamic equilibrium throughout the region.

If the average coolant temperature is lower than the saturation

temperature at the pressure of the interaction region, the coolant is treated as a solid liquid which expands only by thermal expansion. The pressure accumulation during this period is calculated by one dimensional expansion of the interaction region against acoustic constraint at the region boundary. (Phase A mode) When the coolant temperature exceeds the saturation point, vapor-generation is initiated, and the pressure generation is calculated by the different model (Phase B). It is assumed that the pressure is governed by the vapor pressure, and that the vapor bubbles mix homogeneously with the coolant keeping thermodynamic equilibrium. The vapor pressure is estimated by the saturation pressure at the average coolant temperature in the interaction region, and all other properties are calculated by the average value.

The equations to describe the above models are as follows.

2.3.1 Acoustic Constraint Model[8)]

The temperature rise of liquid coolant in the interaction region is given by

$$\rho_c \, C_p \, V_c \frac{d \, T_c}{dt} = Q + V_c \, \alpha_p \, T_c \frac{dP}{dt} \tag{14}$$

where

ρ_c : density of coolant

C_p : specific heat of coolant

V_c : volume of coolant in the interaction region

T_c : coolant temperature in the interaction region

α_p : thermal expansion coefficient of coolant

$$= \frac{1}{V_c} \left(\frac{\partial V_c}{\partial T_c}\right)_p$$

p : pressure in the interaction region

The equation of state for liquid coolant is given by

$$\frac{d \, V_c}{dt} = \alpha_p \, V_c \, \frac{d \, T_c}{dt} - \beta_T \, V_c \, \frac{dp}{dt} \tag{15}$$

where

β_T : isothermal compressibility of coolant

$$= - \frac{1}{V_c} \left(\frac{\partial V_c}{\partial P}\right)_{T_c}$$

In order to incorporate the effect of noncondensable gases such as helium and various fission gases, which were stored in the fuel rod

before the rupture, noncondensable ideal gas of volume V_g is assumed to undergo an adiabatic change in the interaction region.

Then the total volume of the interaction region and its change are written as

$$V_t = V_c + V_g + V_F \tag{16}$$

$$\frac{dV_t}{dt} = \frac{dV_c}{dt} + \frac{dV_g}{dt} \tag{17}$$

where

V_t : total volume of the interaction region

V_c, V_g, V_F : volume of coolant, noncondensable gas and the fuel, respectively.

The adiabatic change of noncondensable gas is described as

$$p V_g^n = p_o V_{go}^n = \text{const.} \tag{18}$$

where

n : adiabatic constant.

By differentiating Eq.(18) with respect to time, volume change of the noncondensable gas is written as

$$\frac{dV_g}{dt} = - \frac{p_0^{\frac{1}{n}} V_{go}}{np^{(1+1/n)}} \cdot \frac{dp}{dt} \tag{19}$$

Substitution of Eq.(19) into Eq.(17) gives

$$\frac{dV_t}{dt} = \frac{dV_c}{dt} - \frac{p_0^{\frac{1}{n}} V_{go}}{np^{(1+1/n)}} \cdot \frac{dp}{dt} \tag{20}$$

The acoustic pressure generation caused by the expansion of the interaction region boundary is approximated by the following equation.

$$p(t) - P_0 = \rho_0 c_0 \frac{dz(t)}{dt} \tag{21}$$

where

$p(t)$: pressure at time t

P_0 : initial pressure

ρ_0 : density of liquid coolant column

c_0 : sonic velocity in liquid coolant column

$z(t)$: position of the interface between the interaction region

and the liquid coolant column measured relative to the stationary midplane.

(see Fig.3)

The expansion velocity of region boundary dz/dt is related to the total volume change of the interaction region by

$$\frac{dV_t}{dt} = (S_1 + S_2)\frac{dz}{dt} \tag{22}$$

where

S_1, S_2 : flow area at upper and lower boundary of interaction region

Substituting Eq.(22) into (21), we have

$$p(t) - p_0 = \frac{\rho_0 c_0}{S_1 + S_2}\frac{dV_t}{dt} \tag{23}$$

The pressure history in the interaction region will be obtained by solving the Equations (14), (15), (20) and (23) if the heat input Q is given as a function of time.

The sonic velocities for sodium and water are calculated by the following equations.

(1) Sodium

$$c_0 = 2526.0 - 0.524 \times (T - 97.6) \quad \text{(m/s)} \tag{24}$$

where

T : sodium temperature (°C)

(2) Water

$$c_0 = \sqrt{\frac{2.07 \times 10^8 \times 9.8}{\rho_0}} \quad \text{(m/s)} \tag{25}$$

where

ρ_0 : density of coolant (kg/m^3)

2.3.2 Inertial Constraint Model[7)]

The upper and lower boundaries of the interaction region are considered as the control surfaces. The equations of mass and energy conservation are described as

$$\frac{d}{dt}[(1-\alpha)\rho_\ell h_\ell + \alpha\rho_v] - \frac{S}{V}[(1-\alpha)\rho_\ell h_\ell + \alpha\rho_v](u_1 - u_2) = 0 \tag{26}$$

$$\frac{d}{dt}[(1-\alpha)\rho_\ell h_\ell + \alpha\rho_v h_v] - \frac{S}{V}[(1-\alpha)\rho_\ell h_\ell + \alpha\rho_v h_v](u_1 - u_2) = \frac{Q}{V} \quad (27)$$

where

α : void ratio in the interaction region

ρ_ℓ, ρ_v : densities of liquid and vapor

h_ℓ, h_v : enthalpy of liquid and vapor

S : flow area of coolant

V : volume of interaction region

u_1, u_2 : coolant velocity at the lower and upper boundary of the interaction region

The movement of lower and upper liquid coolant slugs is calculated by the following one-dimensional momentum equations.

For the lower slug,

$$\rho_\ell \int_{z_{in}}^{z_1} \left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial z}\right)dz + [\rho_\ell gz]_{z_{in}}^{z_1} + \frac{\rho_\ell}{2}\left[\int_{z_{in}}^{z_1} \frac{f}{d} u|u|dz + \sum^{j} \xi_{1j} \cdot u_{1j} \cdot |u_{1j}|\right] = p_{in} - p_c \quad (28)$$

for the upper slug

$$\rho_\ell \int_{z_2}^{z_{out}} \left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial z}\right)dz + [\rho_\ell gz]_{z_2}^{z_{out}} + \frac{\rho_\ell}{2}\left[\int_{z_2}^{z_{out}} \frac{f}{d} u \cdot |u| \cdot dz + \sum^{j} \xi_{2j} \cdot u_{2j} \cdot |u_{2j}|\right] = p_c - p_{out} \quad (29)$$

where,

ρ_ℓ : density of coolant

u : coolant velocity

z_1, z_2 : axial positions of lower and upper boundary of the interaction region

z_{in}, z_{out} : axial positions of channel inlet and outlet

f : friction factor

d : hydraulic diameter of coolant channel

ξ : pressure loss factor for flow area change

P_c : pressure at interaction region

p_{in}, p_{out} : pressures at inlet and outlet of the channel

As the coolant velocity changes depending on the cross sectional area of the coolant channel, velocity at position z is given by the following

correlations.

For lower slug,

$$u(z) = \frac{S(z_1)}{S(z)} u_1 \tag{30}$$

for upper slug

$$u(z) = \frac{S(z_2)}{S(z)} u_2 \tag{31}$$

where

$S(z)$: cross sectional area of coolant channel at position z

Substituting Eqs. (30) and (31), Eqs.(26) and (27) are rewritten as

$$\frac{du_1}{dt} = \frac{1}{\rho_\ell L_1'}(P_{in} - P_c) - g\frac{L_1}{L_1'} - \frac{Z_1}{2L_1'} u_1 \cdot |u_1| - \frac{1}{2L_1'}(u_1 \cdot |u_1| - u_{in} \cdot |u_{in}|) \tag{32}$$

$$\frac{du_2}{dt} = \frac{1}{\rho_\ell L_2'}(P_c - P_{out}) - g\frac{L_2}{L_2'} - \frac{Z_2}{2L_2'} u_2 \cdot |u_2| - \frac{1}{2L_2'}(u_{out} \cdot |u_{out}| - u_2 \cdot |u_2|) \tag{33}$$

where

$$L_1 = z_1 - z_{in} \tag{34}$$

$$L_2 = z_{out} - z_2 \tag{35}$$

$$L_1' = \int_{z_{in}}^{z_1} \frac{S(z_1)}{S(z)} dz = \sum^{j} \frac{S(z_1)}{S(z_{1j})} \cdot \Delta z_{1j} \tag{36}$$

$$L_2' = \int_{z_2}^{z_{out}} \frac{S(z_2)}{S(z)} dz = \sum^{j} \frac{S(z_2)}{S(z_{2j})} \cdot \Delta z_{2j} \tag{37}$$

$$Z_1 = \int_{z_{in}}^{z_1} \frac{f}{d}\left\{\frac{S(z_1)}{S(z)}\right\}^2 dz + \sum^{j} \xi_{1j}\left\{\frac{S(z_1)}{S(z_{1j})}\right\}^2 = \sum^{j}\left(\frac{f_{1j}}{d_{1j}} \Delta z_{1j} + \xi_{1j}\right)\left\{\frac{S(z_1)}{S(z_{1j})}\right\}^2 \tag{38}$$

$$Z_2 = \int_{z_2}^{z_{out}} \frac{f}{d}\left\{\frac{S(z_2)}{S(z)}\right\}^2 dz + \sum^{j} \xi_{2j}\left\{\frac{S(z_2)}{S(z)}\right\}^2$$

$$= \sum^{j} \left(\frac{f_{2j}}{d_{2j}} \cdot \Delta z_{2_j} + \xi_{2j} \right) \left\{ \frac{S(z_2)}{S(z_{2j})} \right\}^2 \tag{39}$$

ξ_{ij} : pressure loss factor at the boundary of flow channel segment j

f_{ij} : friction factor for flow channel segment j

d_{ij} : hydraulic diameter for channel segment j

Δz_{ij} : length of flow channel segment j

the friction factor f is calculated by

$$f = 64\ Re^{-1} \qquad (Re \leq 3.2 \times 10^6) \tag{40}$$

$$f = 0.316\ Re^{-0.25} \qquad (Re > 3.2 \times 10^6) \tag{41}$$

where

$Re = \frac{ud}{\nu}$: Reynolds number

u : velocity

d : hydraulic diameter

ν : kinematic viscosity

2.4 Physical Properties

2.4.1 Coolant Properties

(1) Water

Density, specific heat and enthalpy for water and steam are calculated by physical property subroutine WATER and STEAM, respectively, which are programmed for EUREKA code[13] based on the JSME Steam Table. The relation between saturation vapor pressure and temperature are also given by subroutine STEAM. As the physical properties have to be recalculated at each time step in transient calculation, the relations are rewitten into quadratic expressions of temperature to save computation time. Nine sets of equations corresponding to nine temperature ranges covering from room temperature to critical point are prepared by least square approximation based on ten data sets for each temperature range.

(2) Sodium

Physical properties of sodium are calculated by subroutine SODIUM[14]. For use in transient calculation, the property

equations are also rewritten by quadratic expression of temperature. A single equation is used for all temperature range. The saturation vapor pressure is calculated by the following equations.

For 97.81 < T < 976.7°C

$$\log_{10}P(\text{atm}) = -\frac{10020.6}{1.8T+491.7} - 0.5\log_{10}(1.8T+491.7) + 6.4818 \quad (42)$$

(Ditchbarn and Gilmour's equation)[15]

For 976.7°C < T

$$\log_{10}P(\text{atm}) = -\frac{9980.94}{1.8T+491.7} - 0.61344\log_{10}(1.8T+491.7) + 6.8377 \quad (43)$$

(Stone's equation)[16]

2.4.2 Fuel and Cladding Properties

Thermodynamic properties of UO_2 fuel and cladding are calculated by the following equations.

Thermal Conductivity :

$$\lambda_f = 1.0907\times10^{-3} - 0.9311\times10^{-6}T + 0.31542\times10^{-9}T^2 + \frac{0.243786}{(T+200)} \quad (44)$$

$$\lambda_{sus} = 3.602\times10^{-3} + 1.096\times10^{-6} \quad (45)$$

$$\lambda_{zry} = 10.5462 + 0.010962\times T \quad (46)$$

where

$\lambda_f, \lambda_{sus}, \lambda_{zry}$: thermal conductivities of fuel, stainless steel and zircaloy (kcal/m hr °C)

T : temperature (°C)

Density :

$$\rho_f = 1.04\times10^4 - 0.312T \quad (47)$$

$$\rho_{sus} = 7.82\times10^2 - 0.42228T \quad (48)$$

$$\rho_{zry} = 6.55\times10^3 \quad (49)$$

where

$\rho_f, \rho_{sus}, \rho_{zry}$: densities of fuel, stainless steel and zircaloy (kg/m^3)

T : temperature (°C)

Specific heat :

$$C_f = 0.0657 - 0.9556 \times 10^{-6}T + 0.8123 \times 10^{-8}T^2 \quad (50)$$

$$C_{sus} = 0.12068 + 2.0053 \times 10^{-5}T \quad (51)$$

$$C_{zry} = 0.06805 + 2.3872 \times 10^{-5}T \quad (52)$$

where

C_f, C_{sus}, C_{zry} : specific heat of fuel, stainless steel and zircaloy (kcal/kg °C)

T : temperature (°C)

Latent heat :

Latent heat of melting or phase transformation is considered as follows.

for UO_2 L = 64.8 kcal/kg at T = 2800°C (53)

for stainless steel

L = 65.0 kcal/kg at T = 1410°C (54)

for zircaloy*

L = 10.0 kcal/kg at T = 900°C (55)

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* Latent heat for α-β phase transformation. Due to lack of data, latent heat is not considered at melting point for zircaloy.

Table 1 Witte's Experimental Results

Sphere speed (ft/sec.)	Sodium temperature (°F)	c	n
10.0	572	2.98×10^4	0.88
6.0	572	2.23×10^4	0.88
10.0	842	4.94×10^4	0.77

(The unit of q becomes Btu/hr.)

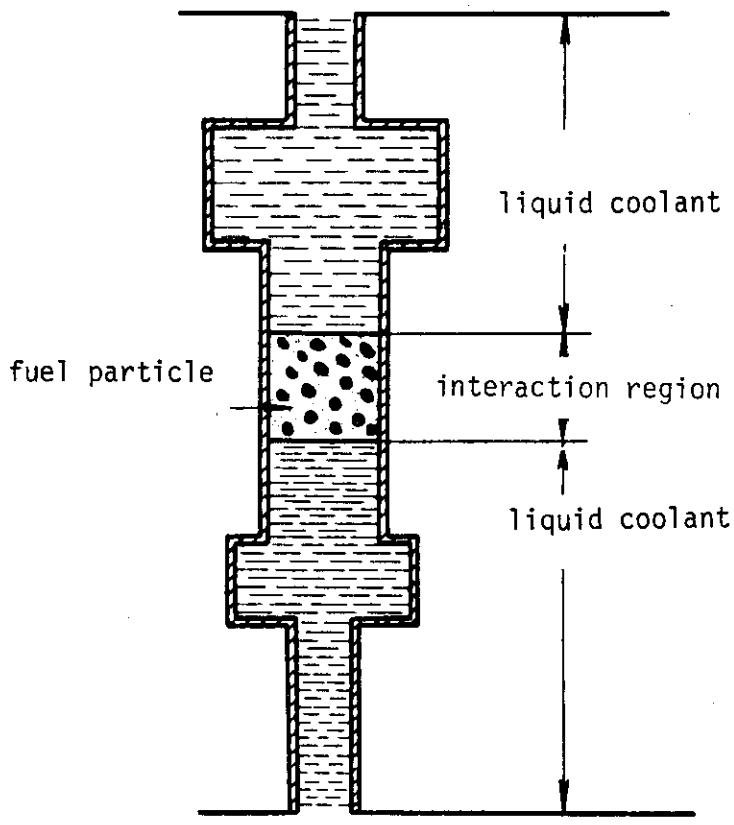

Fig. 1 Schematic fuel-coolant interaction model

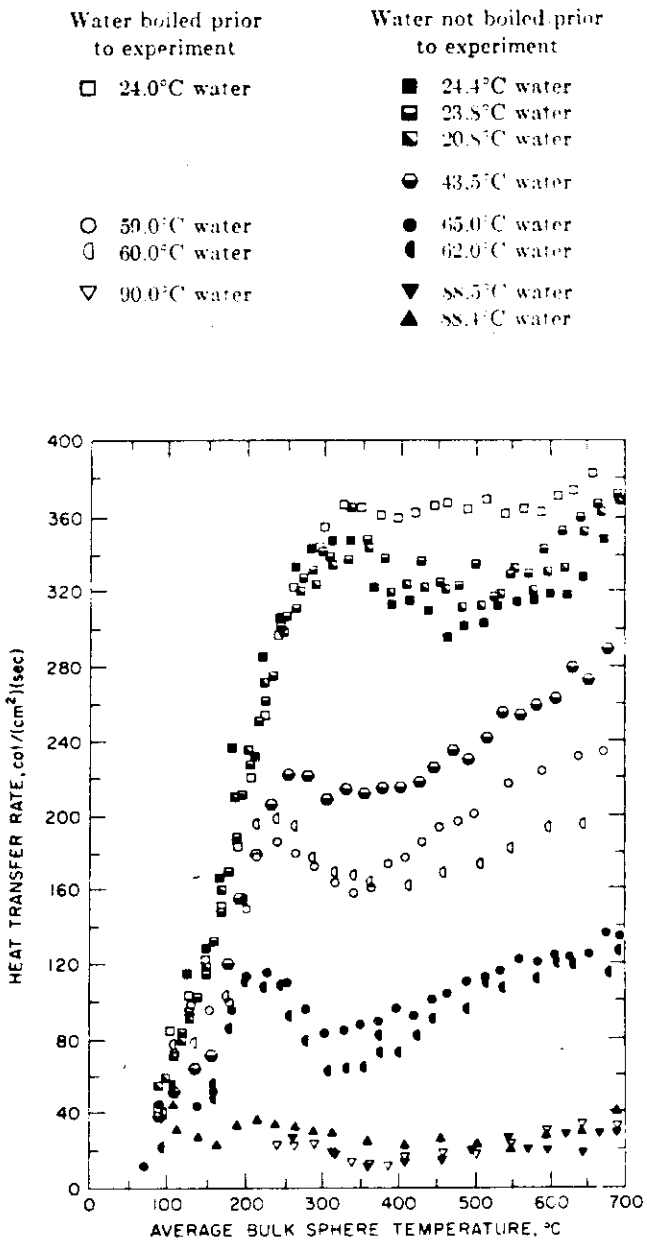

Fig. 2 Heat flux versus average bulk sphere temperature from Swinging-Arm Experiment with 1/4 in dia silver sphere moving through water at 13.9 Ft/sec [9)]

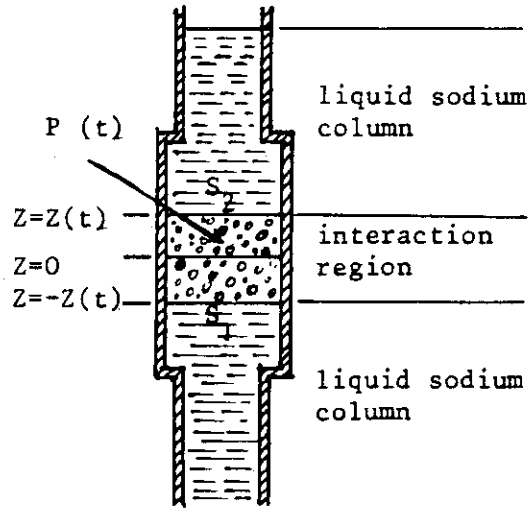

Fig. 3 Calculational model for acoustic constraint

3. Numerical Solution Procedure

Flow chart of numerical solution procedure is shown in Figure 4. In the preliminary calculation, quadratic equations of physical properties are prepared either for water or for sodium depending on coolant selection. The time mesh size specified by input is examined by the following stability criterion. If the specified time mesh does not satisfy Equation (56), it is halved until it satisfies the criterion.

Stability Criterion

$$\frac{\lambda_f \Delta t}{\rho_f C_f (\Delta r_{min})^2} < 0.5 \qquad (56)$$

where

λ_f : thermal conductivity of fuel

ρ_f : density of fuel

C_f : specific heat of fuel

Δt : time mesh size

Δr_{min}: minimum dimensional mesh size in fuel particles

Since a simultaneous solution of all the equations governing the FCI phenomena is not possible, heat transfer process from fuel particles to the coolant and the hydrodynamic procedure in the coolant are solved separately. At first, temperature profile in the fuel particle and the heat transferred from fuel particles to the coolant are calculated based on the environmental conditions at the preceding time step. Then thermo-hydrodynamic calculation of coolant is performed using the heat transferred to the coolant from the fuel particles as the input.

Before starting the hydrodynamic calculation, selection of phase A or phase B model is decided based on boiling initiate condition. As this code has a plotter subroutine, the calculated results can be plotted as a function of time.

Total construction of ANDES is summarized in Figure 5. The definition of subcodes shown in Figure 5 is listed in Table 2.

Table 2 Definition of Subcodes

ANDES	:	Main routine to control the total calculation procedure
BLKDT1	:	Subcode which sets data in common blocks
CLEAR	:	Subcode which sets all the data in common blocks to zero
CLR	:	Zero clear subroutine
CNTRL	:	Subcode which determines calculation time step
COEF	:	Subcode which determines coefficients of quadratic expression to represent sodium or water physical properties
CWATER	:	Subcode which gives physical properties of compressed water
EDIT	:	Subcode which prints minor and/or major edit, called from TRAN
ESUF	:	Function subroutine which gives enthalpy of steam for given temperature and pressure
FLUID	:	Subcode which calculates coolant hydrodynamics, called from TRAN
FUEL	:	Subcode which determines fuel particle geometries, called from PRECAL
HTRC	:	Subcode which defines coefficients for heat transfer equation, called from TRAN
IDENT	:	Subcode for identification of line in data plotting
INCHNL	:	Subcode which reads upper and lower channel geometry data, called from INPUT
INDIM	:	Subcode which reads miscellaneous control data (1000), called from INPUT
INDSTR	:	Subcode which reads destruction region data (1300), called from INPUT
INFORM	:	Subcode which sets information for axis plot
INHTC	:	Subcode which reads heat transfer data (1500) and (1550), called from INPUT
ININIT	:	Subcode which reads initial condition data (1400), called from INPUT
INISET	:	Subcode which determines initial conditions
INP	:	Subcode which constructs a data array from input cards
INPART	:	Subcode which reads fuel particle data (16xx), called from INPUT
INPLOT	:	Subcode which reads plot information data (1700, 1800, 19xx), called from INPUT

(continued)

Table 2 (continued)

INPUT	:	Subcode which controls input procedure, called from MAIN
INP2	:	Subcode to transfer data from input card buffer to designated storage area in core
INTSTP	:	Subcode which reads time step control data (1001), called from INPUT
INTVAL	:	Subcode which defines minimum and maximum data
IRANGE	:	Function subcode which sets temperature range
LINES	:	Subcode which updates line counter
LOCAL	:	Subcode which calculates local velocity and pressure, called from PRTINI and FLUID
NORMLZ	:	Subcode which normalizes data for plotting
PLLINE	:	Subcode for line plotting
PLOSS	:	Subcode which calculates friction pressure loss, called from PRTINI and FLUID
PLOTER	:	Subcode which controls figuire plotting
PRECAL	:	Subcode which controls preliminary calculation, called from MAIN
PRTINI	:	Subcode which prints physical properties and the coefficients for quadratic expression, called from PRECAL
PVT	:	Subcode which gives thermodynamic properties of water or steam for a given temperature and pressure
QUAFIT	:	Subcode which determines the coefficients for quadratic expression using least square approximation method
READIN	:	Subcode which reads plot data from MT and generates the files for figure plot
SEARCH	:	Subcode which searches minimum and maximum data of series ID
SETFCT	:	Subcode which determines minimum data and delta x or y for plotting
SETPDT	:	Subcode to set plot data to common working are for plotting
SETUNT	:	Subcode to determine coefficient for unit plotting
SLUGL	:	Subcode which calculates coolant slug length, called from FLUID
SODIUM	:	Subcode which gives sodium thermodynamic and physical properties
SSATT	:	Subcode which gives temperature of saturated steam as a function of pressure

(continued)

Table 2 (continued)

STEAM	:	Subcode which gives thermodynamic properties of steam as a function of temperature and pressure
STEAMP	:	Subcode which gives pressure of saturated steam as a function of temperature by S. Sugawara's equation
STEAMT	:	Subcode which gives temperature of saturated steam as a function of pressure by S. Sugawara's equation
TEMP	:	Subcode which calculates heat conduction in fuel particles, called from TRAN
TRAN	:	Subcode which controls transient calculation, called from MAIN
TSAT	:	Subcode which calculates saturation temperature of sodium vapor for a given pressure
TSTP	:	Subcode which turns over time step data, called from TRAN
WAKU	:	Subcode which controls X and Y axis plot
WATER1	:	Subcode which calculates coefficients for combined physical properties of water
WATER2	:	Subcode which replaces coefficients for combined physical properties of water for use in transient calculation
XAXIS	:	Subcode which executes X-axis plotting
YAXIS	:	Subcode which executes Y-axis plotting

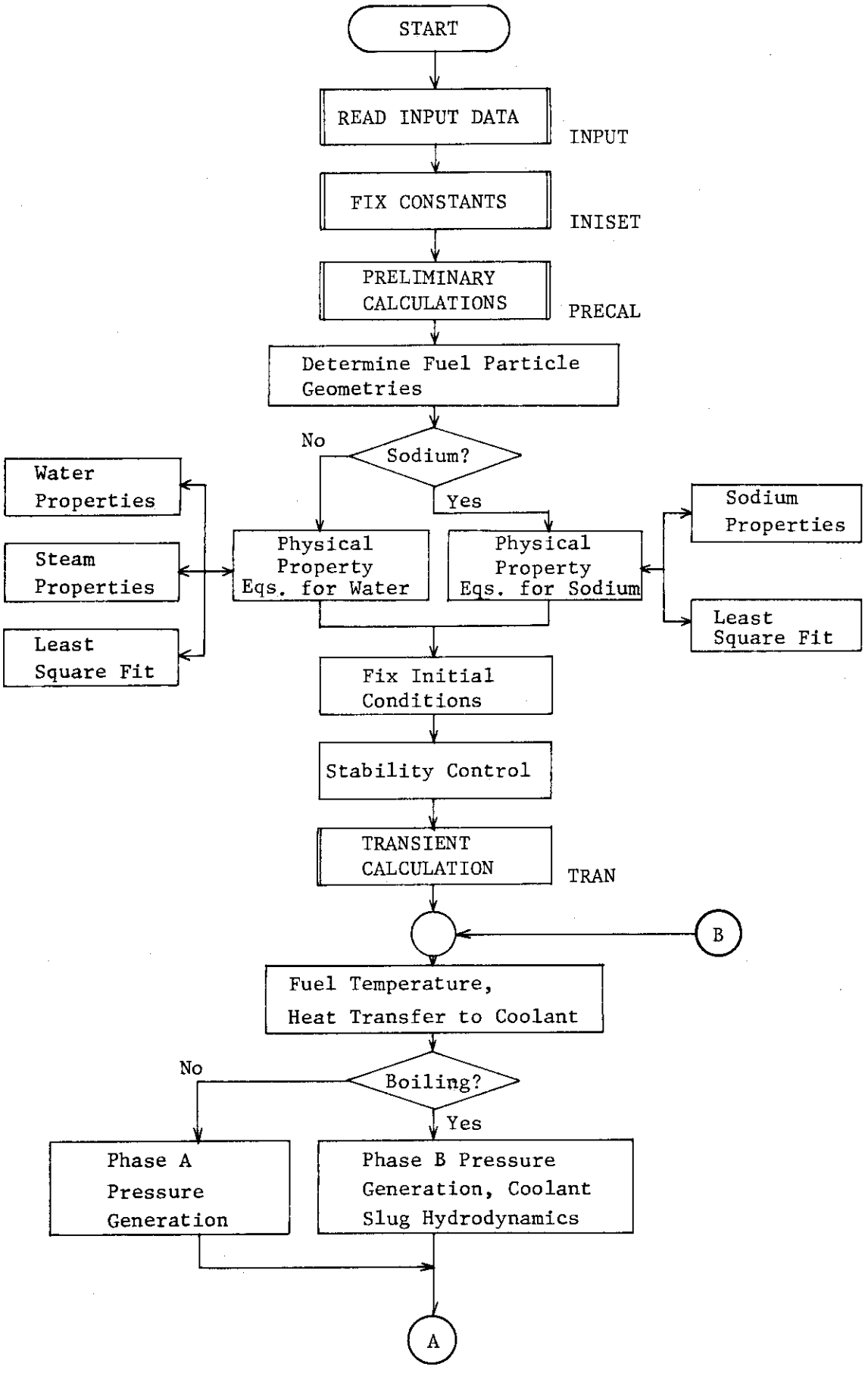

Fig. 4-a Solution procedure flow chart

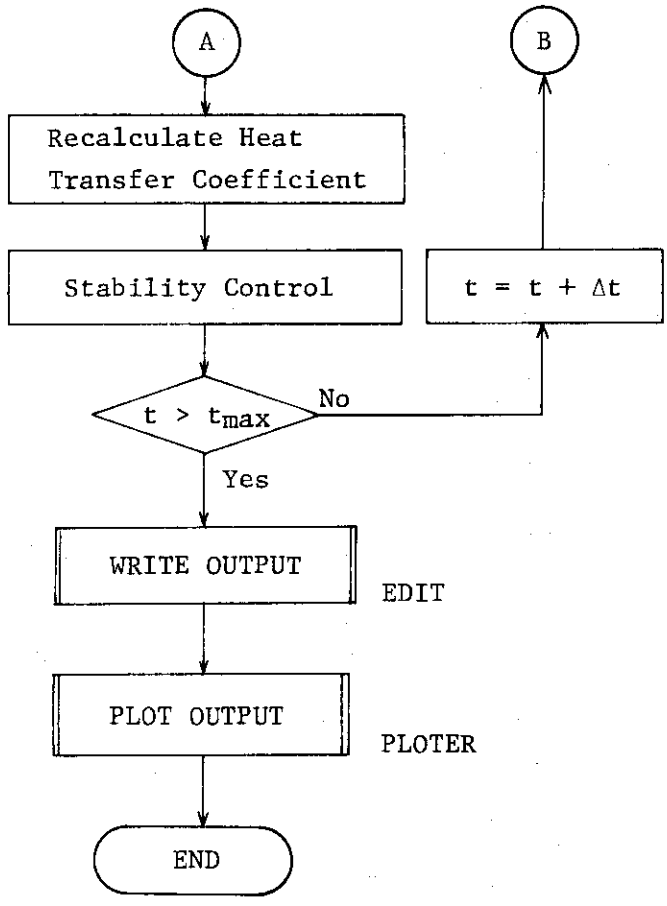

Fig. 4-b　Solution procedure flow chart

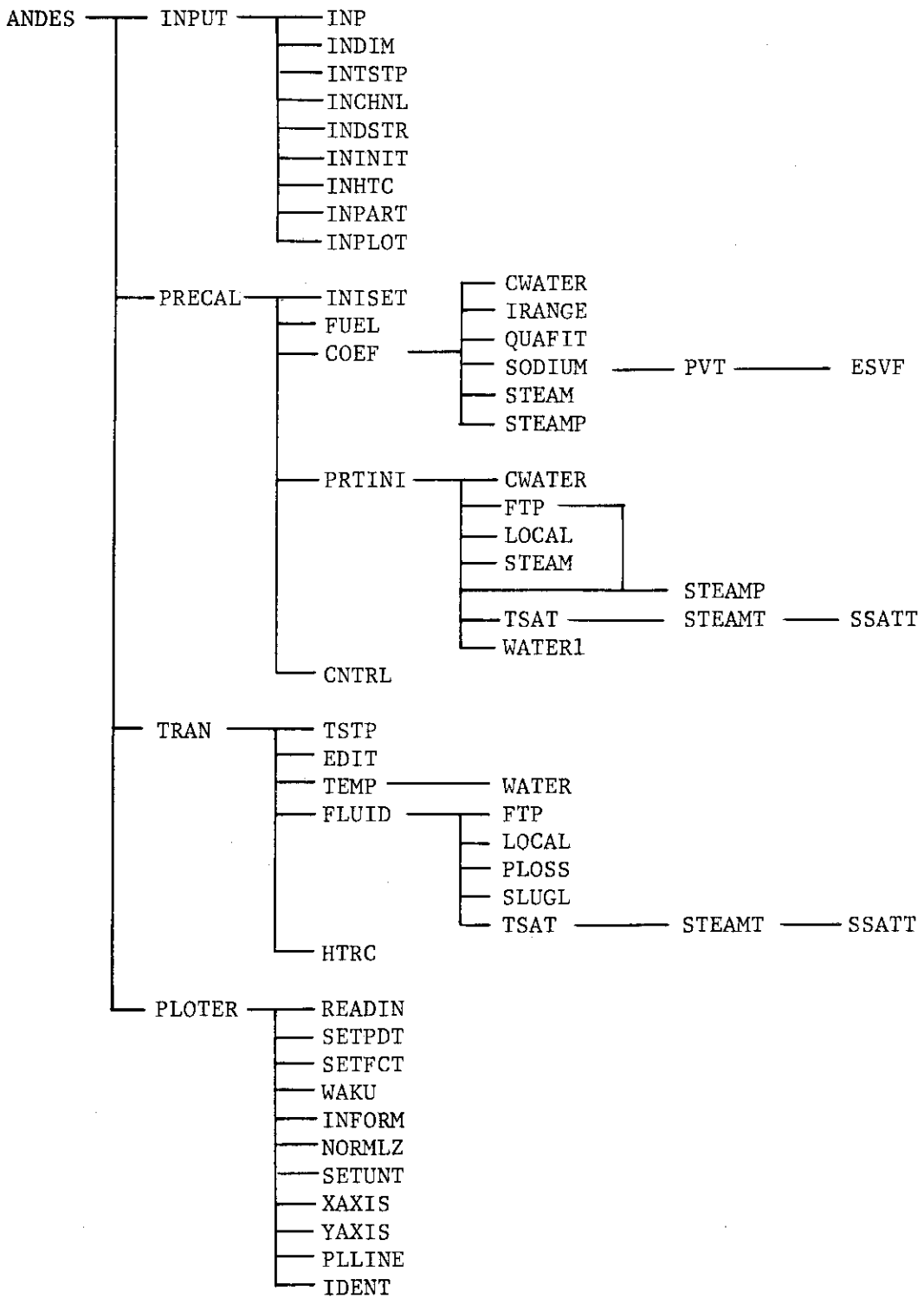

Fig. 5 Construction of ANDES code

4. Input Description

This code incorporates "Free Format" input routine, i.e. each input datum in a card is identified only by the order. Consequently, word number is specified in stead of column number in the following description.

Input data have to be in metric unit which is specified for each data. Input format is indicated by I and R. An I denotes that integer numbers are to be input. No decimal point or an exponent can be present. R denotes no restriction. Both floating point numbers and integers are allowed. Each piece of input data must be separated on both sides by at least one blank card column or a comma.

The input data deck starts from a title card which must have a " = " as the first non-blank character. Comment cards are allowed and are identified by a "*" as the first non-blank character. All the input data cards must have a four digit card number as the first entry on the card, since the data are identified by the card number and the order in the card. Data on a card may be continued on a following card by entering a plus sign as the first non-blank character on the continuation card.

The last card in the data deck must have a "." character in column 1.

Card 1 Title Card

This card must have the "=" symbol as the first non-blank character, usually placed in column 1. The remainder of the card is used to specify the problem title, which will be printed at the top of each page of computer printout.

Card 2 Dimensional Data - Card number 1000

Data Field	Format	Name	Quantity
1	I	IFLG	Coolant specification If IFLG = 0, Sodium is selected. If IFGL ≠ 0, Water is selected.
2	I	IPLT	If IPLT = 0, plotting is omitted. Input for data plot, card number 1700 to 19xx, are not needed. If IPLT ≠ 0, output data are plotted according to the specification given by the card 1700 to 19xx.

Data Field	Format	Name	Quantity
3	I	NTC	Number of time step cards (NTC ≤ 10)
4	I	K1MAX	Number of axial nodes in the coolant slug at upstream of the interaction region (K1MAX ≤ 40)
5	I	K2MAX	Number of axial nodes in the coolant slug at downstream of the interaction region (K2MAX ≤ 40)
6	I	KFB	If KFB = 0, switching of heat transfer coefficient by DNB condition is not performed. Input data of card number 1550 is not read in this case. If KFB = 1, heat transfer coefficient at fuel surface is switched to a new value as specified by the card 1550.
7	I	IR	Number of fuel particle group (IR ≤ 20)
8	I	JFLG	If JFLG = 0, calculation by phase A model is omitted. If JFLG = 1, transient calculation starts from phase A and then switched to phase B.
9	R	HTIME	Time at which heat dissipation from fuel particles to the coolant is ended. [sec]
10	R	FINTIM	Final problem time [sec]

Card 3 Time Control Data - Card number 10xx

xx = card sequence number 1 ≤ xx ≤ NTC

Data Field	Format	Name	Quantity
1	I	NMIN(xx)	Number of calculation time steps at which interval minor output are printed.

Data Field	Format	Name	Quantity
			If NMIN = 0, NMIN is adjusted to 1.
2	I	NMAJ(xx)	Number of minor output printout at which interval major output are printed. If NMAJ = 0, NMAJ ix adjusted to 50
3	R	DELTT(xx)	Calculation time step [sec]
4	R	TLAST(xx)	Final calculation time [sec]

Card 4 Upstream Coolant Channel Dimensions - Card number 11xx

xx = card sequence number $1 \leq xx \leq K1MAX$

Coolant channel at upstream and downstream of the interaction region can be divided into flow channel segments which have different diameter and length. Pressure loss coefficient can be given at the boundary of the segments as shown in Figure 6.

Numbering of the segments is to be done in the order starting from the interaction region to upstream or downstream. Segment length CL1(01) and CL2(01) include half the length of the interaction region.

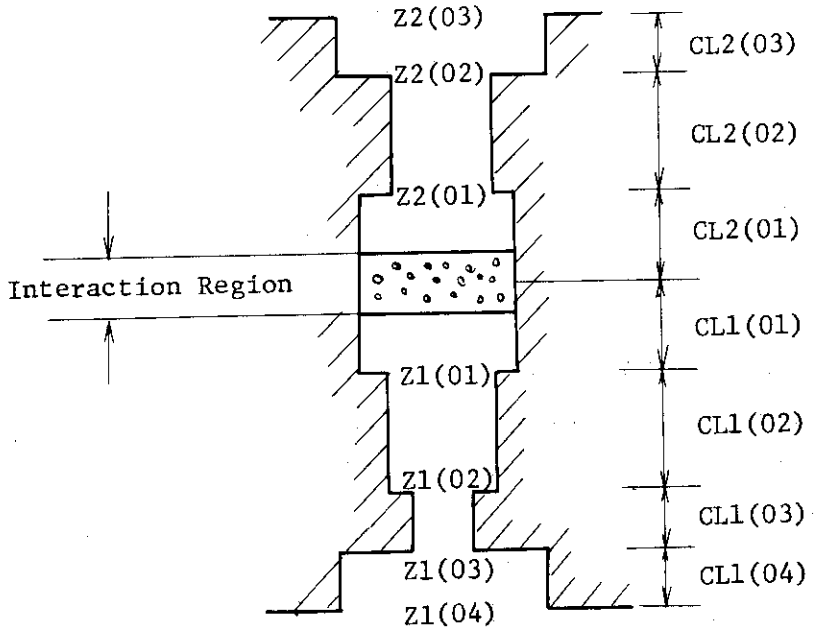

Fig.6 An example of flow channel configuration

Data Field	Format	Name	Quantity
1	R	CL1(xx)	Length of flow channel segment [m]
2	R	SC1(xx)	Cross-sectional area of flow channel segment [m^2]
3	R	DE1(xx)	Hydraulic dimaeter of flow channel segment [m]
4	R	Z1(xx)	Pressure loss factor of outer (lower) end of a flow channel segment
5	R	ZR1(xx)	Pressure loss factor at outer end of the flow channel segment at reversal flow

Card 5 Downstream Coolant Channel Dimensions - Card number 12xx

xx = card sequence number $1 \leq xx \leq$ K2MAX

Data Field	Format	Name	Quantity
1	R	CL2(xx)	Length of flow channel segment [m]
2	R	SC2(xx)	Cross-sectional area of flow channel segment [m^2]
3	R	DE2(xx)	Hydraulic diameter of flow channel segment [m]
4	R	Z4(xx)	Pressure loss factor at outer (upper) end of a flow channel segment
5	R	ZR2(xx)	Pressure loss factor at outer end of a flow channel segment at reversal flow

Card 6 Interaction Region Data - Card number 1300

Cross-sectional area of the interaction region is assumed to be equal to SC1(01), the area of innermost flow channel segment. The coolant volume is calculated by SC1(01) × CL0, where CL0 is the length of the interaction region. The amount of fuel and cladding is specified by the cross-sectional area. The length of the broken fuel rods is assumed to be the same as that of the interaction region, CL0. The volume of the fuel and the cladding is, then, given by multiplying CL0

to the cross-sectional area. In order to apply to a case of partial interaction, a factor which is defined as a volumetric ratio of effective to total fuel in the interaction region is to be specified.

Data Field	Format	Name	Quantity
1	R	CLO	Length of interaction region [m]
2	R	SFO	Cross-sectional area of fuel [m^2]
3	R	SKO	Cross-sectional area of cladding [m^2]
4	R	FACT	A volumetric ratio of effective to total fuel in the interaction region

Card 7 Initial Conditions - Card number 1400

Data Field	Format	Name	Quantity
1	R	TCO	Initial temperature of coolant [°C]
2	R	TF1	Initial temperature of fuel [°C]
3	R	TF2	Initial temperature of cladding [°C]
4	R	PO	Pressure at coolant flow channel exit [kg/cm^2]
5	R	UO	Initial flow velocity of coolant [m/s]

Card 8 Heat Transfer Coefficient - Card number 1500

Data Field	Format	Name	Quantity
1	R	TSP	Coolant superheat temperature at which phase A calculation is switched over to phase B.
2	R	HN	Constants for heat transfer equation $q/A = (HN) \times (T_{f.s} - T_c)^{(NH)}$ where q/A = heat flux [$kcal/m^2hr$] $T_{f.s}$ = surface temperature of a fuel particle [°C] T_c = average coolant temperature [°C]
3	R	HN	

Card 9 Heat Transfer Coefficient for Film Boiling Regime - Card number 1550

If a large change of heat transfer coefficient at fuel particle surface by film boiling initiation is to be assumed, the constants for heat transfer equation, HH and HN, which are specified by card 8, are replaced to HHF and HNF respectively. This replacement is initiated when the calculated bulk superheat temperature of the coolant exceeds a threshold value TFB.

If KFB = 0 in the card number 1000, this option is omitted.

Data Field	Format	Name	Quantity
1	R	HFN	New constants for heat transfer coef-
2	R	HNF	ficient equation to be replaced.
3	R	TFB	Threshold value of bulk superheat for the transition [°C]

Card 10 Fuel Particle Data Cards - Card number 16xx

xx = card sequence number $1 \leq xx \leq IR$

In order to give a fuel particle size distribution, the fuel and the cladding particles are divided into groups by the diameter. The distribution is specified by the typical diameter and the weight percentage of each group.

The mixing process between the fuel particles and the coolant is realized by giving a different contact time to each particle group. A complete set of particle data for one group must be placed on one card shown as follows.

Data Field	Format	Name	Quantity
1	I	NREG(xx)	If NREG = 0, particles are identified as fuel. If NREG = 1, particles are identified as stainless steel. If NREG = 2, particles are identified as zircaloy.
2	I	NR(xx)	Number of radial mesh in a particle ($NR \leq 9$)
3	R	R(xx)	Particle radius [m]
4	R	WF(xx)	Weight ratio of xx-th particle group
5	R	TPS(xx)	Contact time with the coolant [sec]

Card 11 Plot Selection and Figure Size - Card number 1700

If plots are not wanted, set IPLT = 0 in card number 1000, and omit the cards of number 1700 through 1900.

Data Field	Format	Name	Quantity
1 to 6	I	NFIG(1) to NFIG(6)	If Fig.K is wanted, set NFIG(K) ≠ 0. Fig.K will be omitted, if NFIG(K) = 0.
7	I	IAUTŌ	If IAUTŌ = 0, scale of X and Y axis will be adjusted automatically based on the maximum and minimum value of the data to be plotted. If IAUTŌ ≠ 0, scale of the axia should be specified by card 1800 and 1900.
8	I	NPARTI	Number of a fuel particle group whose temperature profile plot is wanted. ($1 \leq$ NPARTI $\leq$ IR)
9	I	LNGTHX	Length of X-axis* [cm]
10	I	LNGTHY	Length of Y-axis* [cm]

* If LNGTHX or LNGTHY $\leq$ 0, it is interpreted as LNGTHX or LNGTHY = 20.

Note that LNGTHX and LNGTHY have to be integer type input.

Card 12 X Axis Data - Card number 1800

If IAUTŌ = 0, omit this card.

Data Field	Format	Name	Quantity
1	R	XMIN(1)	Minimum time of phase A [sec]
2	R	XMAX(1)	Maximum time of phase A [sec]
3	R	XMIN(2)	Minimum time of phase B [sec]
4	R	XMAX(2)	Maximum time of phase B [sec]

Card 13 Y Axis Data - Card number 19yy

yy = card sequence number 00 $\leq$ yy $\leq$ 99

If IAUTŌ = 0, omit this card.

Data Field	Format	Name	Quantity
1	R	YMIN(1)	Minimum pressure in phase A (Fig.1) [kg/cm^2]
2	R	YMAX(1)	Maximum pressure in phase A (Fig.1) [kg/cm^2]
3	R	YMIN(2)	Minimum coolant temperature in phase A (Fig.1) [°C]
4	R	YMAX(2)	Maximum coolant temperature in phase A (Fig.1) [°C]
5	R	YMIN(3)	Minimum surface temperature of the fuel particle in phase A (Fig.1) [°C]
6	R	YMAX(3)	Maximum surface temperature of the fuel particle in phase A (Fig.1) [°C]
7	R	YMIN(4)	Minimum pressure in phase B (Fig.2) [kg/cm^2]
8	R	YMAX(4)	Maximum pressure in phase B (Fig.2) [kg/cm^2]
9	R	YMIN(5)	Minimum void ratio (Fig.2)
10	R	YMAX(5)	Maximum void ratio (Fig.2)
11	R	YMIN(6)	Minimum coolant temperature in phase B (Fig.2) [°C]
12	R	YMAX(6)	Maximum coolant temperature in phase B (Fig.2) [°C]
13	R	YMIN(7)	Minimum surface temperature of the fuel particle in phase B (Fig.2) [°C]
14	R	YMAX(7)	Maximum surface temperature of the fuel particle in phase B (Fig.2) [°C]
15	R	YMIN(8)	Minimum velocity of upper coolant slug (Fig.3) [m/sec]
16	R	YMAX(8)	Maximum velocity of upper coolant slug (Fig.3) [m/sec]
17	R	YMIN(9)	Minimum velocity of lower coolant slug (Fig.3) [m/sec]

Data Field	Format	Name	Quantity
18	R	YMAX(9)	Maximum velocity of lower coolant slug (Fig.3) [m/sec]
19	R	YMIN(10)	Minimum length of upper coolant slug (Fig.3) [m]
20	R	YMAX(10)	Maximum length of upper coolant slug (Fig.3) [m]
21	R	YMIN(11)	Minimum length of lower coolant slug (Fig.3) [m]
22	R	YMAX(11)	Maximum length of lower coolant slug (Fig.3) [m]
23	R	YMIN(12)	Minimum temperature in the fuel particle group which is specified by NPARTI in card 1700 to plot radial temperature profile (Fig.4) [°C]
24	R	YMAX(12)	Maximum temperature in the fuel particle group specified by NPARTI. (Fig.4) [°C]
25	R	YMIN(13)	Minimum pressure (Fig.5) [kg/cm^2]
26	R	YMAX(13)	Maximum pressure (Fig.5) [kg/cm^2]
27	R	YMIN(14)	Minimum pressure integration (Fig.5) [$kg.sec/cm^2$]
28	R	YMAX(14)	Maximum pressure integration (Fig.5) [$kg.sec/cm^2$]
29	R	YMIN(15)	Minimum specific work of fuel (Fig.5) [cal/g]
30	R	YMAX(15)	Maximum specific work of fuel (Fig.5) [cal/g]
31	R	YMIN(16)	Minimum specific work of coolant (Fig.5) [cal/g]
32	R	YMAX(16)	Maximum specific work of coolant (Fig.5) [cal/g]

Data Field	Format	Name	Quantity
33	R	YMIN(17)	Minimum coolant temperature (Fig.6) [°C]
34	R	YMAX(17)	Maximum coolant temperature (Fig.6) [°C]
35	R	YMIN(18)	Minimum surface temperature of fuel particle (Fig.6) [°C]
36	R	YMAX(18)	Maximum surface temperature of fuel particle (Fig.6) [°C]
37	R	YMIN(19)	Minimum heat flow rate from fuel to coolant (Fig.6) [cal/sec]
38	R	YMAX(19)	Maximum heat flow rate from fuel to coolant (Fig.6) [cal/sec]
39	R	YMIN(20)	Minimum heat flow rate to coolant from a fuel particle group which is specified by NPARTI in card 1700 (Fig.6) [cal/sec]
40	R	YMAX(20)	Maximum heat flow rate to coolant from a specified fuel particle group (Fig.6) [cal/sec]

5. Output Description

The output is done by the line printer. Besides it is possible to plot the data as the functions of time.

5.1 Line Printer Output

The line printer output is composed of parts A through D as follows.

A - listing of all the input data in one table

B - listing of the input data, one table for each data cards with the description of each datum and unit.

C - description of the quadratic expression of coolant physical properties, in which constants of each quadratic equation, list of data base for the least square fitting and a table of physical properties as a function of temperature produced by the quadratic equations are contained.

D - transient data output which consists of major and minor outputs

Major output contains the following data.

- time step number
- time (sec)
- time step (sec)
- time step size (sec)
- integral pressure ($kg\text{-}sec/cm^2$)
- pressure in the interaction region (kg/cm^2)
- coolant temperature in the interaction region (°C)
- energy transfer rate (kcal/sec)
- total energy transferred (kcal)
- void fraction in the interaction region
- upper region coolant slug velocity (msec)
- lower region coolant slug velocity (msec)
- upper region coolant slug displacement (m)
- lower region coolant slug displacement (m)
- fuel and cladding particle temperatures of each particle size group at energy radial nodes (°C)

Minor output is a listing of the following transient data as a function of time.

- pressure in the interaction region (kg/cm^2)
- coolant temperature in the interaction region (°C)

- energy transfer rate (kcal/sec)
- total energy transfered (kcal)
- void fraction in the interaction region
- upper and lower region slug velocities (m/s)
- upper and lower region slug displacements (m)

The intervals of the major and minor outputs are to be specified by the input.

5.2 Plot Output

The following six plots as a function of time can be selected.

1 - plot of following data during phase A period
- pressure in the interaction region (kg/cm^2)
- coolant temperature in the interaction region (°C)
- surface temperature of fuel particle of a specified group (°C)

2 - plot of following data during phase B period
- pressure in the interaction region (kg/cm^2)
- void ratio in the interaction region
- coolant temperature in the interaction region (°C)
- surface temperature of fuel particle of a specified group (°C)

3 -
- velocities of upper and lower coolant slugs (m/s)
- displacements of upper and lower coolant slugs (m)

4 -
- temperature distribution in a fuel particle of a specified group (°C)

5 -
- pressure in the interaction region (kg/cm^2)
- pressure integration ($kg.sec/cm^2$)
- specific work of fuel (cal/g)
- specific work of coolant (cal/g)

6 -
- surface temperature of fuel particle of a specified group (°C)
- total heat flow rate from fuel to coolant (cal/sec)
- heat flow rate from a specified fuel particle group (cal/sec)

6. Summary

This code is a first version of ANDES. The Analysis model is based on a simplified one dimensional arrangement of an interaction region and coolant slugs, and is solved by progressive method. Thanks to this simplification, the numerical calculation is quite stable and quick for wide range of input conditions. As the mixing process and the heat transfer rate between molten fuel and the coolant are not completely understood yet, these unknown parameters are to be specified by the input. Consequently, this first version is convenient to use for the sensitivity study of the FCI phenomena to various parameters. The analysis model has to be improved based on the sensitivity study and on the comparison with the experimental data.

The verification of the first version is progressing through the comparison with the data of inpile FCI experiments, such as NSRR, SPERT and Sandia PBE tests. The results will be published in a separate report.

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Appendix　　Numerical Method

A-1　Heat Transfer Calculation within a Fuel Particle

The transient temperature profile within a fuel (and/or cladding) particle is calculated by Eqs.(1) and (11) with the boundary and initial conditions represented by Eqs.(2) through (4). Finite difference equations for the numerical analysis are described in the following. Nodalization is shown in Figure A-1.

1)　Surface node

As the heat flux at the outer boundary of the surface node is given by Eq.(11), the finite difference form of the energy equation (1) is written as

$$\frac{4}{3}\pi\left\{r_1^3-\left(r_1-\frac{\Delta r}{2}\right)^3\right\}\rho_f C_f\frac{T_f(r_1,\,t+\Delta t)-T_f(r_1,\,t)}{\Delta t}$$

$$=4\pi\left(r_1-\frac{\Delta r}{2}\right)^2\lambda_f\frac{T_f(r_2,\,t)-T_f(r_1,\,t)}{\Delta r}-4\pi r_1^2\cdot q(t) \qquad (A.1)$$

This will be rewitten as

$$\frac{T_f(r_1,\,t+\Delta t)-T_f(r_1,\,t)}{\Delta t}=\frac{1}{1-\frac{\Delta r}{2r_1}+\frac{\Delta r^2}{12r_1^2}}\left[\frac{2K\left(1-\frac{\Delta r}{2r}\right)^2}{\Delta r^2}\right.$$

$$\left.\times\{T_f(r_2,\,t)-T_f(r_1,\,t)\}-\frac{2cf(\alpha)}{\Delta r\rho_f C_f}\{T_f(r_1,\,t)-T_c\}^n\right] \qquad (A.2)$$

where

$K:\dfrac{\lambda_f}{\rho_f C_f}$,　　thermal diffusivity

2)　Internal nodes

Eq.(1) will be rewritten as

$$\frac{T(r_i,\,t+\Delta t)-T_f(r_i,\,t)}{\Delta t}=\frac{K}{\left(1+\frac{\Delta r^2}{12r_i^2}\right)\Delta r^2}\left[\left(1+\frac{\Delta r}{2r_i}\right)^2\right.$$

$$\left.\times\{T_f(r_{i-1},\,t)-T_f(r_i,\,t)\}-\left(1-\frac{\Delta r}{2r_i}\right)^2\{T_f(r_i,\,t)-T_f(r_{i+1},\,t)\}\right] \qquad (A.3)$$

3)　Center node

The equation for the center node is written as

$$\frac{T_f(r_n, t+\Delta t) - T_f(r_n, t)}{\Delta t} = -\frac{6K}{\Delta r^2}\{T_f(r_n, t) - T_f(r_{n-1}, t)\} \tag{A.4}$$

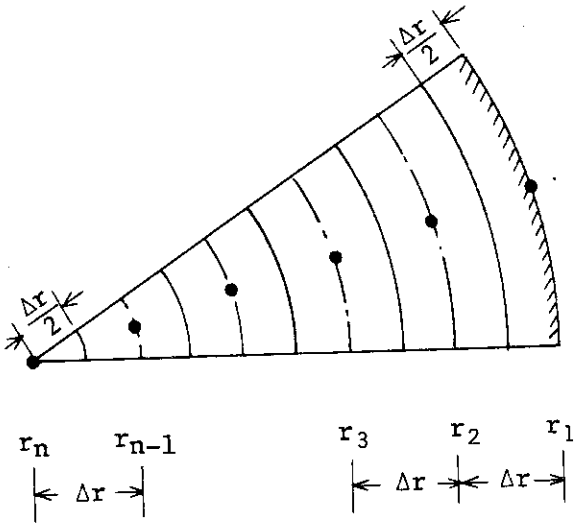

Fig. A.1

A-2 Temperature, Pressure and Volume Calculation of the Interaction Region

(1) Acoustic Constraint Mode (Phase A)

The coolant temperature, pressure and volume as a function of time are calculated by Eqs.(14), (15), (20) and (23).

Substituting Eq.(23) into Eq.(20), we have

$$\frac{S_1 + S_2}{\rho_0 c_0} (p(t) - p_0) = \frac{dV_c}{dt} - \frac{p^{1/n} V_{g_0}}{np^{(1+1/n)}} \cdot \frac{dp}{dt} \qquad (A.5)$$

Eqs.(14), (15) and (A.5) give the first derivatives of temperature, pressure and volume with respect to time.

$$\frac{dT_c}{dt} = \frac{BD + BF - CG}{AD + AF - CE} \qquad (A.6)$$

$$\frac{dp}{dt} = \frac{BE - AG}{AD + AF - CE} \qquad (A.7)$$

$$\frac{dV_c}{dt} = \frac{ADG + BEF - CEG}{AD + AF - CE} \qquad (A.8)$$

where

$$A = V_c \rho_c C_p$$

$$B = Q(t)$$

$$C = T_c V_c \alpha_p$$

$$D = \beta_T V_c$$

$$E = \alpha_p V_c$$

$$F = \frac{p_0^{1/n} V_{g0}}{n p^{(1+1/n)}}$$

$$G = \frac{S_1 + S_2}{\rho_0 C_0} (p(t) - p_0)$$

(2) Inertial Constraint Mode (Phase B)

The coolant conditions in the interaction region are calculated by Eqs.(26), (27), (32) and (33). As it is assumed that the thermodynamic state of liquid-vapor mixture in the interaction region changes along the saturation curve, the pressure, density and enthalpy of the coolant can be described as the functions of temperature only. Thus, the derivatives of density and enthalpy with respect to time can be written as

$$\frac{d\rho}{dt} = \frac{d\rho}{dT_c} \cdot \frac{dT_c}{dt} \tag{A.9}$$

$$\frac{dh}{dt} = \frac{dh}{dT_c} \cdot \frac{dT_c}{dt} \tag{A.10}$$

where

ρ : density

h : enthalpy

Using Eqs.(A.9) and (A.10), Eqs.(26) and (27) are rewritten as

$$A_1 = B_1 \frac{d\alpha}{dt} - C_1 \frac{dT_c}{dt} \tag{A.11}$$

$$A_2 = B_2 \frac{d\alpha}{dt} + C_2 \frac{dT_c}{dt} \tag{A.12}$$

where

$$A_1 = -\frac{S}{V_c}[(1-\alpha)\rho_\ell + \alpha\rho_v](u_1 - u_2)$$

$$A_2 = \frac{Q}{V_c} + \frac{S}{V_c}[(1-\alpha)\rho_\ell h_\ell + \alpha\rho_v h_v](u_1 - u_2)$$

$$B_1 = \rho_\ell - \rho_v$$

$$B_2 = \rho_v h_v - \rho_\ell h_\ell$$

$$C_1 = (1-\alpha)\frac{d\rho_e}{dT_c} + \alpha\frac{d\rho_v}{dT_c}$$

$$C_2 = (1-\alpha)\frac{d(\rho_\ell h_\ell)}{dT_c} + \alpha\frac{d(\rho_v h_v)}{dT_c}$$

The first derivatives of average void ratio and coolant temperature can be obtained from Eqs.(A.11) and (A.12).

$$\frac{d\alpha}{dt} = \frac{A_1C_1 + A_2C_1}{B_1C_2 + B_2C_1} \tag{A.13}$$

$$\frac{dT_c}{dt} = \frac{B_1A_2 - B_2A_1}{B_1C_2 + B_2C_1} \tag{A.14}$$

The coolant pressure is given as a saturation pressure at temperature T_c.

$$P_c = P_{sat}(T_c) \tag{A.15}$$

The thermo-hydrodynamic state of the interaction region and the movement of coolant column velocity at time $t + \Delta t$ are defined by Eqs.(32), (33), (A.13), (A.14) and (A.15) based on the state at time t.