FLATT-A COMPUTER PROGRAMME FOR CALCULATING FLOW AND TEMPERATURE TRANSIENTS IN NUCLEAR FUELS

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Abstract

FLATT is a computer code written in Fortran Language for BESM-6 computer. The code calculates the flow transients in the coolant circuit of a Nuclear Reactor, caused by pump failure, and the consequent temperature transients in the fuel, clad, and the coolant. In addition any desired flow transient can be fed into the programme and the resulting temperature transients can be calculated. A case study is also presented.

NOMENCLATURE

A - area
b - thickness of cladding
E - kinetic energy
K - thermal conductivity
L' - Extrapolated length of fuel
P - rate of energy loss
P_{PHO} - Steady state hydraulic losses of pump-motor
Q - volumetric heat generation
T - Temperature
t - Time
W - Total power developed by the fuel
Δt - Time interval
x - Distance from fuel channel inlet

a - radius of fuel pin
C - specific heat
h - heat transfer coefficient
L - length of fuel
l - Reflector thickness
P_{MCHO} - Steady state mechanical losses of pump-motor
R - Ratio of flow at time t (after beginning of transient) to steady state
V - volume
w - coolant mass flow rate
ρ - density

Subscripts

c - coolant

FO - refers to fluid at steady state

m - maximum

o - steady state or centre

PO - refers to pump-motor at steady state

Clad - cladding

f - fuel

mo - maximum at steady state

t - at time t

x - refers to values at distance x

I. INTRODUCTION

As soon as the power to the primary coolant circulating pump of a nuclear reactor fails the reactor should be shut down. However, there will be a time delay between the pump failure and the reactor shutdown. Further, the reactor power will not come down to zero immediately after shut down. Initially the power falls down exponentially and then gradually over a period of time. This is due to the production of energy by decay of fission products and is called decay heat. The circulating flow also does not reduce to zero as soon as the power to pump fails. Because of the hydraulic and mechanical energy present in the system at the time of failure of the pump, the flow reduces gradually after the pump failure. A computer code FLATT (Flow And Temperature Transients) has been written to calculate the coolant, clad and fuel temperatures during the flow and power transients. The basic features of the code, the equations used and the method of calculation are all described in following pages. A case study is also presented.

II. FLOW COASTDOWN MODEL

When the power to the pump is lost both the pump impeller and the coolant in the loop begin to slow down. The coolant flow decay in a loop is dependent upon the driving head developed by the pump impeller, the dynamic interaction of the coolant and impeller, the frictional resistance to the coolant in circulation and the inertia of both the impeller and the coolant. The mechanical losses in the pump, like disc friction, bearing losses etc. are also important parameters which affect flow decay characteristics during latter part of the flow coast down.

An analytical solution for flow decay is obtained by T. Yokomura(1). Reference (1) gives the detailed analysis. This flow coastdown model is based on the following assumptions:

1) The fluid has constant density
2) pressure drop through the passages is proportional to the square of the flow rate.
3) energy loss due to mechanical friction in pump system is proportional to the angular velocity of the impeller.
4) hydraulic energy loss in pump system is proportional to the cube of the flow rate.
5) pump flow rate is proportional to angular velocity of the pump.

Using these assumptions and taking an energy balance of the system Yokomura obtains the following equation.

$$\frac{dR}{dt} = -(AR^2 + BR + C) \qquad (1)$$

where constants

$$A = \frac{(P_{PHO} + P_{FC})}{2(E_{FO} + E_{PO})}, \quad B = 0, \quad C = \frac{P_{MCHO}}{2(E_{FO} + E_{PO})} \qquad (2)$$

$$\text{let} \quad D = B^2 - 4AC \qquad (3)$$

The initial condition is $R = 1$ at $t = 0$

The solution of equation (1) for $D < 0$, which is the condition of interest to us is given below.

$$R = \frac{\sqrt{|D|}}{2A} \tan\left(\tan^{-1}\frac{B+2A}{\sqrt{|D|}} - \frac{t \times \sqrt{|D|}}{2}\right) \qquad (4)$$

This equation is used for calculating the flow coast down curve. It should be noted here that if mechanical losses in the pump system are taken to be zero (i.e. $C=0$), the solution obtained for flow coastdown, though simple, predicts the time required for flow to become zero as infinite. This does not give a true picture of flow coast down in latter stages. Since we are interested in finding the temperatures at latter stages of flow coastdown so as to decide how soon the emergency coolant pumps should start functioning, it is necessary to take into account the mechanical losses also.

The code is written in such a way that one has the option not to use equation (4) for calculating the flow transient. In such a case one can feed any desired flow transient as input and the programme will calculate the temperature transients due to the input flow transient.

III. FUEL GEOMETRY AND POWER SOURCE DISTRIBUTION

1. Fuel Geometry: The programme has been written for calculating temperature distribution in cylindrical fuel geometry. The fuel is divided into fifty axial nodes and eleven radial nodes. The cladding forms the twelfth radial node.

2. Power Source Distribution: The radial power generation is assumed to be uniform in the pin. The axial power generation is assumed to be sinusoidal and the corresponding equations are built into the programme. However, if the axial power distribution is non-sinusoidal it can be given as input quantity and the programme will calculate the temperature distribution accordingly.
For sinusoidal power distribution(2) .

$$Q_x = Q_m \sin\left(\pi(x + l)/L'\right) \tag{5}$$

$$Q_m = W\pi / 2L' \cos(\pi\ell/L')\, A_f \tag{6}$$

The transient power generation rate can be either input or calculated from equations.

IV. STEADY STATE TEMPERATURE DISTRIBUTION CALCULATIONS:

The steady state temperature distribution of fuel, clad and coolant serves as the starting point for the transient temperature calculations. Hence these are calculated first.

For sinusoidal axial power distribution the coolant temperature at x is given by

$$T_c(x) = T_{c,\,in} + \frac{Q_{mo} \quad A_f \quad L'}{\pi \; w \; C_c}\left(\cos\frac{\pi\ell}{L'} - \cos\frac{\pi(x+\ell)}{L'}\right) \tag{7}$$

The corresponding clad temperature at mean clad radius is given by

$$T_{clad}(x) = T_c(x) + \frac{Q_{xo} A_f}{h_o A_h} + \frac{Q_{xo} A_f}{2\pi K_{clad}} \ln\left(\frac{a+b}{a+(b/2)}\right) \qquad (8)$$

At any point x the radial temperature distribution in the fuel is given by

$$T_f(r,x) = T_{clad}(x) + \frac{Q_{xo}(a^2-r^2)}{4 K_f} + \frac{Q_{xo} A_f}{2\pi K_{clad}} \ln\left\{\frac{a+(b/2)}{a}\right\} \qquad (9)$$

V. TRANSIENT TEMPERATURE CALCULATIONS:

1. Location of Radial Nodes: The location of radial nodes is shown in fig. 1. The fuel cross-section is divided into a central circle of diameter Δr and ten annular rings of thickness Δr. The 0^{th} node is located at the centre of the fuel cross-section. Node numbers 1 to 10 are located at the mean radii of annular rings and node number 11 is the mean radius of clad.

2. Equations for Node Temperature Change: Assuming symmetry about the axis the unsteady state heat conduction equation for an infinite cylinder can be written as

$$\frac{K}{\rho C}\left[\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr}\right] + \frac{Q_x}{\rho_f C_f} = \frac{dT}{dt} \qquad (10)$$

In finite difference form this reduces to[4]

$$\Delta T_n = \frac{K_f \Delta t}{\rho_f C_f (\Delta r)^2}\left\{\left(1-\frac{1}{2n}\right)(T_{n-1}-T_n) + \left(1+\frac{1}{2n}\right)\right.$$

$$\left.(T_{n+1}-T_n)\right\} + \frac{Q_x \Delta t}{\rho_f C_f} \qquad (11)$$

where ΔT_n is the change in temperature of the n^{th} node over a time interval of Δt and T_n is the temperature of the n^{th} node at the beginning of the time interval. Equation (11) holds good for nodes 1 to 9 and is used for calculating the transient temperatures of these nodes. However equation (11) is not valid for 0^{th} node (i.e. centre of fuel). For this node we have

$$\Delta T_o = \frac{4 K_f \Delta t}{\rho_f C_f (\Delta r)^2}(T_1 - T_o) + \frac{Q_x \Delta t}{\rho_f C_f} \qquad (12)$$

In between the tenth and eleventh nodes we have the outer half of the fuel annulus and the inner half of clad. Based on the area at interface, an equivalent conductance between nodes 10 and 11 is defined as follows

$$C_{e_{eq}} = (C_{e1} \cdot C_{e2})/(C_{e1} + C_{e2}) \qquad (13)$$

where C_{e_1} is the conductance of outer half of fuel annulus and C_{e_2} is the conductance of inner half of the clad.

Using this equivalent conductance, the temperature change in 10th node over a time Δt is given by

$$\Delta T_{10} = \frac{K_f \Delta t}{\rho_f C_f (\Delta r)^2} \left\{ \frac{19}{20} (T_9 - T_{10}) + \frac{C_{e_{eq}} \Delta r}{K_f} \; \frac{21}{20} (T_{11} - T_{10}) \right\} + \frac{Q_r \Delta t}{\rho_f C_f} \qquad (14)$$

Proceeding along similar lines, the equations for temperature change of node 11 and coolant can be written as follows.

$$\Delta T_{11} = \frac{\Delta t \left\{ 21 \Delta r \, C_{e_{eq}} (T_{10} - T_{11}) + 2(a + b) \, h_{eff} \, (T_c - T_{11}) \right\}}{2 \, \rho_{clad} \, C_{clad} \, \left\{ a + (b/2) \right\} \cdot b} \qquad (15)$$

$$\Delta T_c = 2\pi (a+b) \, h_{eff} \, \Delta t \, (T_{11} - T_c)/(V_c \, C_c) \qquad (16)$$

$$\text{where } h_{eff} = C_{e_3} \cdot h_t/(C_{e_3} + h_t) \qquad (17)$$

where C_{e_3} is the conductance of the outer half of clad.

3. Flow at any Node: For the transient temperature calculations it is assumed that the coolant remains stationary at the axial node during the time taken by it to travel a distance equal to the (5) axial node length. In calculating this time the variation of velocity due to the flow transient is also taken into account. As soon as this time is completed the coolant mass is assumed to move instantaneously to the next axial node and the temperature of the coolant at the axial node is made equal to that in the preceding axial node. The coolant temperature at the channel inlet is assumed to be constant.

VI. CASE STUDY

The programme FLATT has been commissioned and its flow chart is given in Fig. 2. It has been used for calculating temperature transient in fuel pin of a research reactor (to be built at Trombay) during flow coastdown. The data used in the analysis is given in Appendix I. The fuel for this reactor will be seven pin cluster, each pin consisting of a rod of uranium metal clad in aluminium. The average power generated in one fuel pin and corresponding average flow associated with the pin have been used in the analysis. Time step has to be chosen to satisfy convergence criterion. This is given by (3)

$$\frac{K_f \Delta t}{\rho_f C_f \ (\Delta r)^2} \leq 1/2 \qquad (18)$$

On the basis of this equation the time step for transient analysis should be less than about 15 milliseconds. However in order to study the influence of time step on the predicted temperatures, part of the analysis was carried out with different time steps of 1 m sec, 2 m sec, 5 m sec and 10 m sec. The predicted temperatures were found to agree very closely. To save computer time a time interval of 10 milliseconds was chosen for detailed calculations. With Δt = 10 milliseconds, the time required to carry out transient analysis for 80 secs. was found to be 10 minutes on the BESM-6 computer. For time interval of 10 milliseconds the power transient and the predicted flow and temperature transients are plotted in fig. 3.

REFERENCES

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APPENDIX I

DATA FOR FLOW AND TRANSIENT TEMPERATURES

Kinetic energy of pump-motor rotor : 10.446 x 10^5 kg.m.

Kinetic energy of coolant in loop : 1.14 x 10^4 kg. m.

Initial rate of hydraulic losses : 1.51 x 10^5 kg.m./sec.

Mechanical losses in pump-motor : 5.34 x 10^3 kg.m./sec.

Steady state thermal power to coolant : 1104 KW

Coolant velocity : 8.24 m/sec.

Coolant inlet temperature : 50°C

Fuel (Uranium) diameter : 12.7 mm.

Clad (aluminium) outer diameter : 14.7 mm.

Fuel length : 3050 mm.

Reflector thickness : 305 mm.

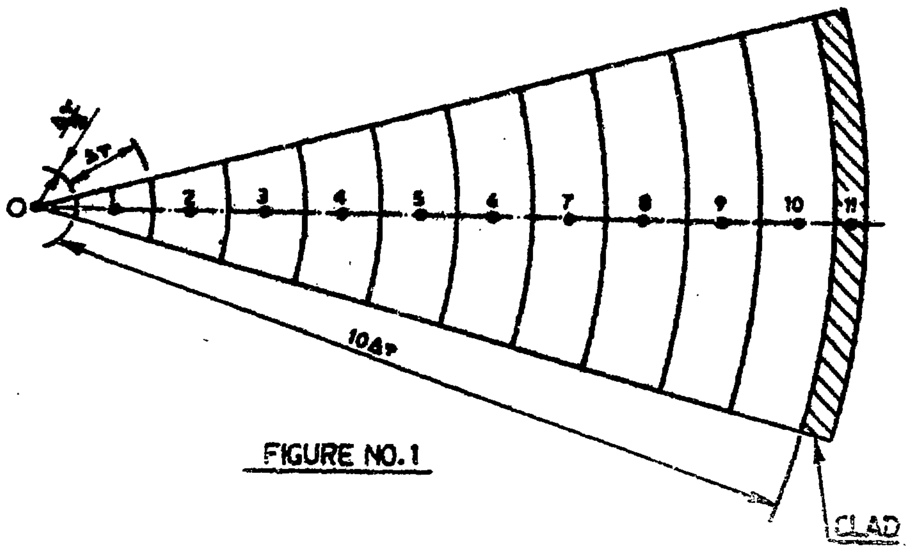

FIGURE NO.1

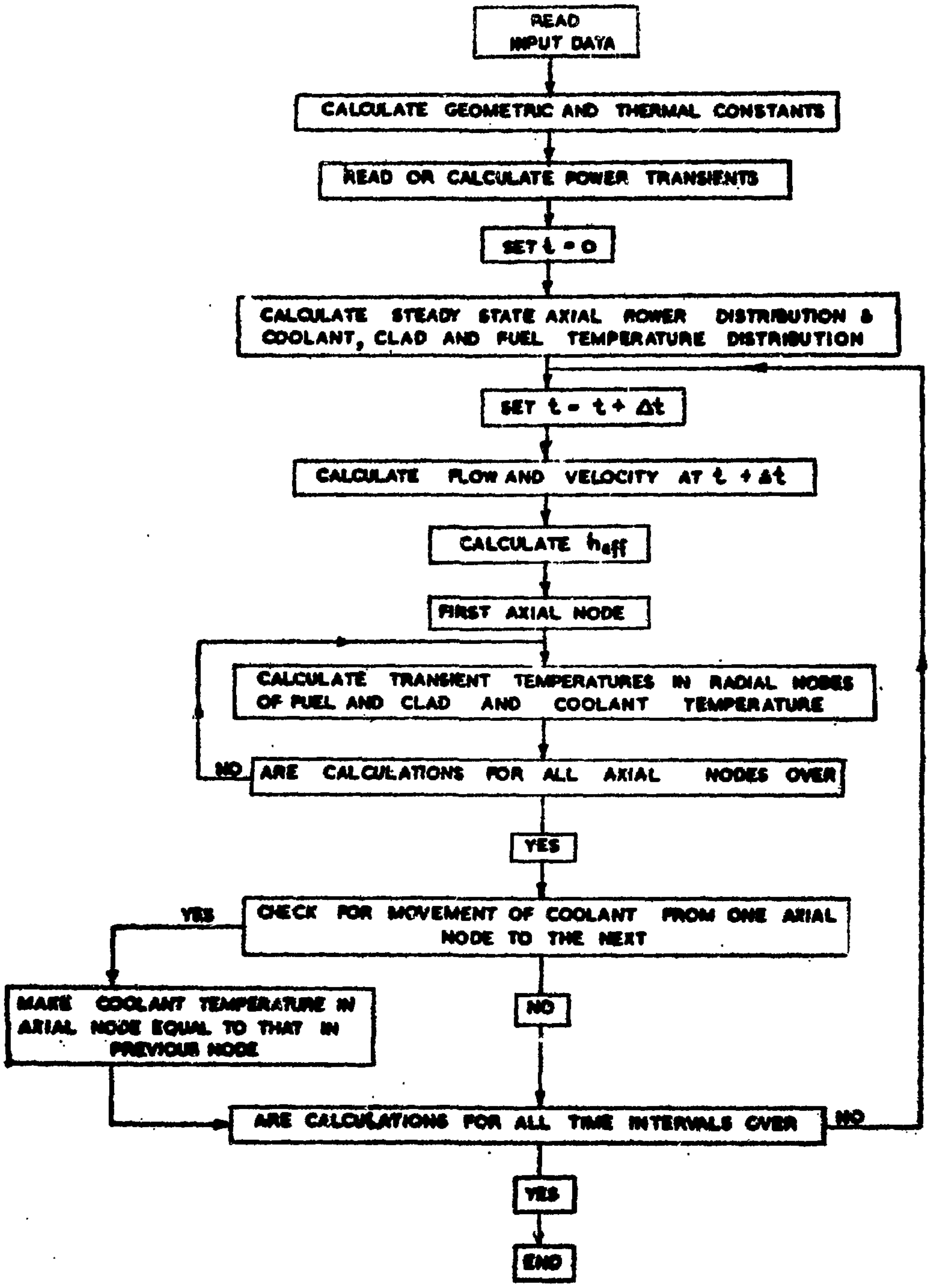
READ INPUT DATA
CALCULATE GEOMETRIC AND THERMAL CONSTANTS
READ OR CALCULATE POWER TRANSIENTS
SET t = 0
CALCULATE STEADY STATE AXIAL POWER DISTRIBUTION & COOLANT, CLAD AND FUEL TEMPERATURE DISTRIBUTION
SET t = t + Δt
CALCULATE FLOW AND VELOCITY AT t + Δt
CALCULATE h_eff
FIRST AXIAL NODE
CALCULATE TRANSIENT TEMPERATURES IN RADIAL NODES OF FUEL AND CLAD AND COOLANT TEMPERATURE
NO
ARE CALCULATIONS FOR ALL AXIAL NODES OVER
YES
CHECK FOR MOVEMENT OF COOLANT FROM ONE AXIAL NODE TO THE NEXT
YES
MAKE COOLANT TEMPERATURE IN AXIAL NODE EQUAL TO THAT IN PREVIOUS NODE
NO
ARE CALCULATIONS FOR ALL TIME INTERVALS OVER
NO
YES
END

FIG.2

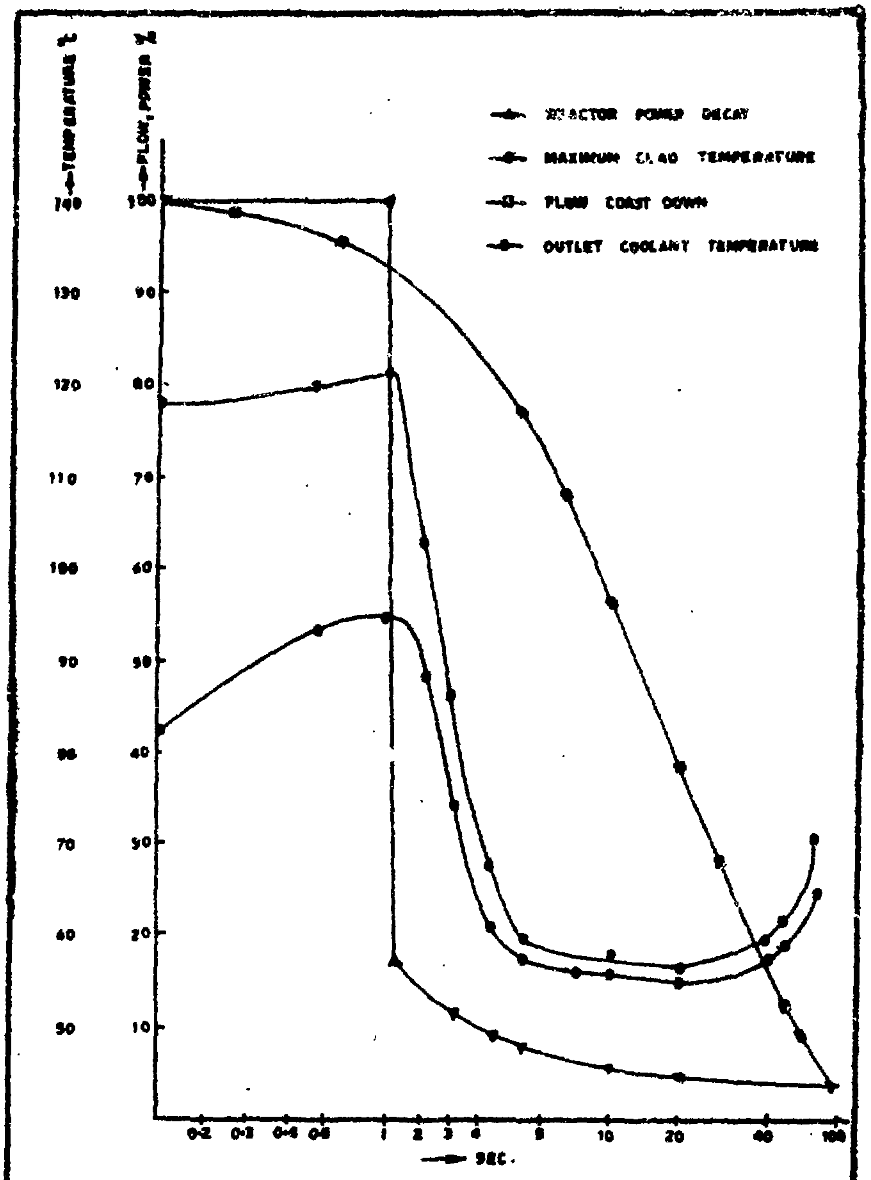

FIG. 3 — TRANSIENT FLOW AND TEMPERATURES

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