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Thermalhydraulic design of non-instrumented capsule for irradiation experiments in HANARO

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Abstract

It has been possible that various kinds of irradiation experiments are proceeded through the construction of HANARO. The non-instrumented capsule was designed for life time evaluation of nuclear material. The thermalhydraulic design of non-instrumented capsule was divided into two parts. Firstly, pressure drop experiments was performed to satisfy allowable limits on pressure drop and coolant flow rate for experimental hole IR-1 inside HANARO core. The tube diameter and lower part design of non-instrumented capsule was decided from the experiment. Secondly, thermal design to control the maximum specimen temperature was conducted by GENGTC one dimensional program.

1. Introduction

The nuclear irradiation behavior of reactor material is of prime importance in the development of nuclear material. Especially irradiation experiments for high flux zone require experimental capsule with structural stability at high neutron flux.

Various capsules with special purposes have been developed in the many countries during the last 40 years[1]. Also, for the purposes such as new alloy development, nuclear fuel development and life time estimation of material, various types of capsules having high performance are under development in JMTR. In Korea, instrumented capsules to control the temperature are under development in KAERI [2]. Through the construction of HANARO, it has been possible that the material irradiation test and nuclear fuel test are proceeded in KAERI. Thus the design and the fabrication of irradiation test capsule installed in reactor core of HANARO is important thing for the utilization of it. There are various type of capsules used in irradiation purpose.

The thermalhydraulic design process of non-instrumented capsule is divided into two parts such as pressure drop experiment to satisfy hydraulic design interface in HANARO core, thermal design to control the maximum specimen temperature. In case of installing the capsule in irradiation hole, the coolant flow rate and the pressure drop in the hole is changed, which will affect the coolant flow rate of the fuel region. So, in order to obtain required pressure drop, the pressure drop experiments was proceeded. Thermal design should consider the distribution of specimen and spacer to maintain the maximum temperature of test specimen about 320 °C. GENGTC program was used for the calculation of these analyses. The results of the analyses were reflected for the design of non-instrumented capsule.

2. Irradiation condition and capsule configuration

There are many experimental holes inside reactor core of HANARO. Their sizes and locations are optimized to maintain required reactor quality and level without significant disturbance due to reactor operating conditions and other near-by experiments. The schematic diagram for core configuration of HANARO is as shown in Fig. 1. The developed capsule was inserted in the IR-1 hole located in high flux core region. The irradiation condition and size of IR-1 hole are as following.

Inner diameter(Cm) : 8.01
Fast Neutron Fluxes(nv): 1.3 x 10^{14}
Thermal Neutron Fluxes(nV): 4.8 x 10^{14}
Operating Temperature(^{o} C): 35

Capsule geometry was designed in 50.8 mm in diameter due to the results of thermal design and 960 mm in height due to geometric compatibility of handling tool. The schematic diagram of capsule is as shown in Fig. 2. The capsule is composed of outer tube, upper grapple head, lower end cap, specimen and spacers, flow control parts. The outer tube, 3.5 mm in thickness, was made of the material of Aluminum 6061 and filled with helium gas for anulus space inside tube. The upper grapple head was designed to have the same configuration as the upper part of HANARO fuel. So, capsule can be controlled by HANARO fuel handling tool. The flow control parts were composed of nine subassemblies. The role of these subassemblies are to control flow rate of IR hole in less than allowable limits and to fix the capsule for receptacle of reactor core. Entire configuration and dimension of capsule was decided on the basis of structure of HANARO core and the results of pressure drop experiment to satisfy the allowable limits which are hydraulic design requirement of HANARO core. Detail structure of capsule inside was designed in reference with user requirement and irradiation purpose of specimen.

3. Method of capsule design

3.1 Pressure drop experiments

Three hexagonal experimental holes such as CT, IR1, and IR2 are located in inner core of HANARO for irradiation experiment of nuclear material. When the irradiation experiment is not proceed, the 36 element dummy fuel is inserted to these holes lest coolant flow rate of reactor core should have the influence. Thus, in case of inserting non-instrumented capsule, coolant flow rate of reactor core should be maintained to allowable limits. To satisfy this design requirements, the pressure drop experiment was proceeded[3]. The schematic diagram of test loop system for experiment is shown in Fig. 3.
From the experiment, the detail configuration of flow control part was obtained, which should satisfy allowable limits on pressure drop and coolant flow rate inside IR-1 hole. This limits are 19.6 kg/s in flow rate, 209 KPa in pressure drop. To obtain required pressure drop, the experiment was performed by changing diameters of orifice rings and size of flow area in end plate and flow rate control assembly as shown in Fig. 4. The classification of test is divided into three category as following. Test matrix for pressure drop experiment is shown in table1.

. Category I: The outer diameter of orifice ring is fixed to 60 mm and flow area of end plate and flow rate control assembly are changed.
. Category II: Flow area of end plate is fully open, the flow area of flow rate control assembly and outer diameter of orifice ring are changed
. Category III: The outer diameter of orifice ring is fixed to 64 mm and flow area of end plate is fully opened, the flow area of flow rate control assembly is changed.

Fig. 5 show results of test matrix from category I to categoryIII. In these figures, category III is agreeded with allowable limits in comparison with other experimental results.
To investigate detail trend, enlarged curve is shown in Fig. 6.The value of pressure drop is respectively 207 KPa in category III-1 and 214 KPa in category III-2 to 16.9 kg/s. Namely, it is induced that flow rate of IR-1 hole is kept under 19 kg/s in case pressure drop is fixed to 209 KPa

From the overall comparison illustrated in Fig. 5 and Fig. 6, it can be concluded that category III-1 is well agreed with allowable limits. According to experimental results, when outer diameter of capsule tube is 48.6 mm in diameter, flow area of capsule is fixed as following

. Flow control assembly: 1350 mm^2
. End plate: 1961 mm^2
. Outer diameter of orifice ring: ∅ 64 mm

The above results were used to decide configuration and dimension of lower part for non-instrumented capsule.

3.2 Thermal Design

In the design of capsule it is necessary to perform a lot of heat transfer calculations. The cross section area of capsule is cylinderical annulus type surrounded by outer tube. The annulus between outer tube and inner spacer contains He gas. The heat transfer calaulation is considerably complicated by the facts that gamma heat in the solid elements, variation of thermal conductivity with temperature, radiation heat transfer, and change of dimensions due to thermal expansion must be considered. Thus, the solution becomes one of trial and error of repeated iteration. GENGTC one dimensional program is used for thermal analysis of capsule [4].

3.2.1 Governing equation

The detailed heat transfer theory for the capsule is as following. The outside temperature of capsule is calculated by following equation.

$$T_s = T_\infty + \frac{Q}{h\,A} \tag{1}$$

Where, h is heat convection coefficient and T_∞ is coolant temperature. The general conduction heat transfer equation in cylinderical coordinates with uniform internal heat generation is as follow.

$$T_i = T_o + \frac{G(r_o^2 - r_i^2)}{4k} + \left(\frac{Q\,r_i}{A_i\,k} - \frac{G\,r_i^2}{2k} \right) \log_e \frac{r_o}{r_i} \tag{2}$$

Where, T_i and T_o denote the inside temperature and outside temperature for cylinder node of capsule model.

The thermal conductivity k is calculated by the following polynomial form

$$k = C_o + C_1 \overline{T} + C_2 \overline{T}^2 + C_3 \overline{T}^3 + C_4 \overline{T}^4 \tag{3}$$

Here, $\overline{T}$ is arithmetic mean temperature of annulus.

In order to consider radiation effects of annulus, radiation shape factor is evaluated as follows.

$$F_{i/o} = \frac{1}{1/e_i + (r_i / r_o)[(1/e_o) - 1]} \tag{4}$$

Also, the conductive heat transfer rate is as follow.

$$Q_k = \frac{k\, A_i\, (T_i - T_o)}{r_i \log_e (r_o / r_i)} \qquad (5)$$

The radioactive heat transfer rate, Q_r is as follow.

$$Q_r = 0.174\, F_{i/o}\, A_i \left[(T_i / 100)^4 - (T_o / 100)^4 \right] \qquad (6)$$

The calculation proceeds from the outside surface inward until all node temperatures are evaluated. After the node temperatures are calculated using the input radii, these radii are corrected for thermal expansion, then the temperature recalculated. The thermal expansion coefficient of each material is calculated from

$$\boldsymbol{a} = \boldsymbol{b}_1 + \boldsymbol{b}_2\, T_m \qquad (7)$$

Where, $\boldsymbol{a}$ is the average expansion coefficient from 70 °F to T_m. T_m is arithmatic mean temperature and $\boldsymbol{b}_1$, $\boldsymbol{b}_2$ are constants arranged for each material. The new radii for the solid node, r_i are the calculated from

$$r' = r + \frac{1}{3}\left\{ r_{70} \left[1 + \boldsymbol{a}\, (T_m - 70) \right] - r \right\} \qquad (8)$$

where, r_{70} is node radii at 70 °F and r is node radius used in input data.
Flow chart of the program used for repeated calculation is shown in Fig. 7.

3.2.2 Modeling

Experimental irradiation holes of HANARO have various neutron flux according to their positions in reactor core. In temperature calculation for non-instrumented capsule, r-heat rate due to neutron flux is very important to calculate the thermal distribution inside capsule. The r-heat rate in experimental holes is usually cosine distribution in axial direction of reactor core . So, the distribution values of r-heat rate can be obtained to multiply average value by distribution rate. Heat transfer coefficient for outer surface of capsule in coolant boundary is 1.88 W/cm^2 °C[5]. Capsule modeling by GENGTC program is based on the assumption to change the cross section area as a circles. So, inside area of non-instrumented capsule is transferred to the circular cross section area as shown in Fig. 8. The method of transformation is composed of two steps. First step is that make real circumferential length of capsule equal that of model.

Second step is to equal the density per unit area between real capsule and model. As a results,the density of model is newly modified in circular area . In this modeling, spacer and specimen were just assumed as circles and the areas of those parts were changed. The non-instrumented capsule was divided into six section in axial direction for thermal calculation. To calcaulate the temperature distribution of six sections, one dimensional analysis by GENGTC code was conducted to the nodes of each section. In case of temperature calculation of the nodes, it is very important to maintain and control the gas gap between the nodes because gap causes the large temperature gradient[6].

Fig. 9 shows the temperature evaluation for sections in axial direction of capsule based on assumption of full power before irradiation. In this figure, six symbolized points designate calculated maximum temperature of specimen for each section. To control the temperature of every section around 320 °C, the repeated calculation of various input data were proceeded for the change of capsule inside condition such as selection of material, control of gas gap, and variation for spacer size and the number of specimen.

4. Conclusion

The non-instrumented capsule was designed for life time evaluation of nuclear material. The pressure drop experiment and thermal design were proceeded to satisfy design interface of HANARO and user requirement. Flow control parts to control flow rate and pressure drop for experimental hole was designed and tested in cold test loop II. From the experiment by capsule test matrix, flow rate of IR-1 hole was controlled to be close to 19.6 kg/s in case of pressure drop of 209 KPa. Thermal calculation was conducted by GENGTC one dimensional program. The maximum specimen temperature by various input data was evaluated according to user requirement. Maximum temperature distribution for six section in axial direction of capsule was controlled around 320 °C by repeated calaulation. The design method of capsule can be applied to various type of non-instrumented capsule for nuclear material test in HANARO.

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Table1. Capsule Test Matrix

Category	Test No.	Flow Rate Control Assembly		Size of Orifice Ring (mm)	End Plate		Remark
		Flow Area (mm^2)	Area rate		Flow Area (mm^2)	Area rate	
I	I-1	2353	80.1	60	1961	66.7	Fix: Orifice Ring (60)
	I-2	1846	62.8	60	1961	66.7	
	I-3	1846	62.8	60	1773	60.3	
	I-4	1846	62.8	60	1585	53.9	
II	II-1	1846	62.8	72	1961	66.7	Fix: End Plate(Fully open)
	II-2	1846	62.8	67	1961	66.7	
	II-3	1846	62.8	64	1961	66.7	
III	III-1	1624	55.3	64	1961	66.7	Fix: Orifice Ring (64)
	III-2	1350	45.9	64	1961	66.7	

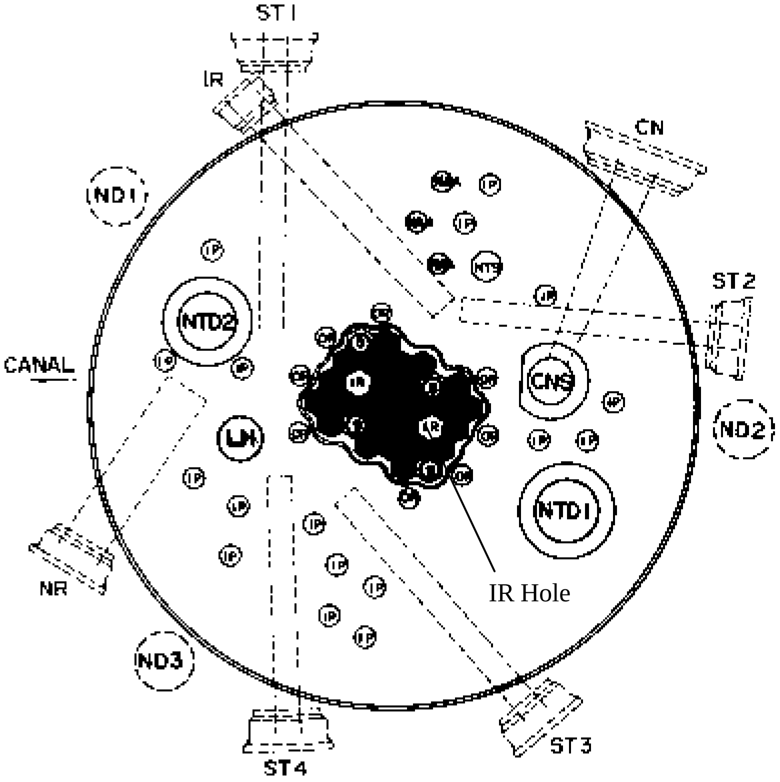


Fig. 1 Top view of irradiation holes in HANARO

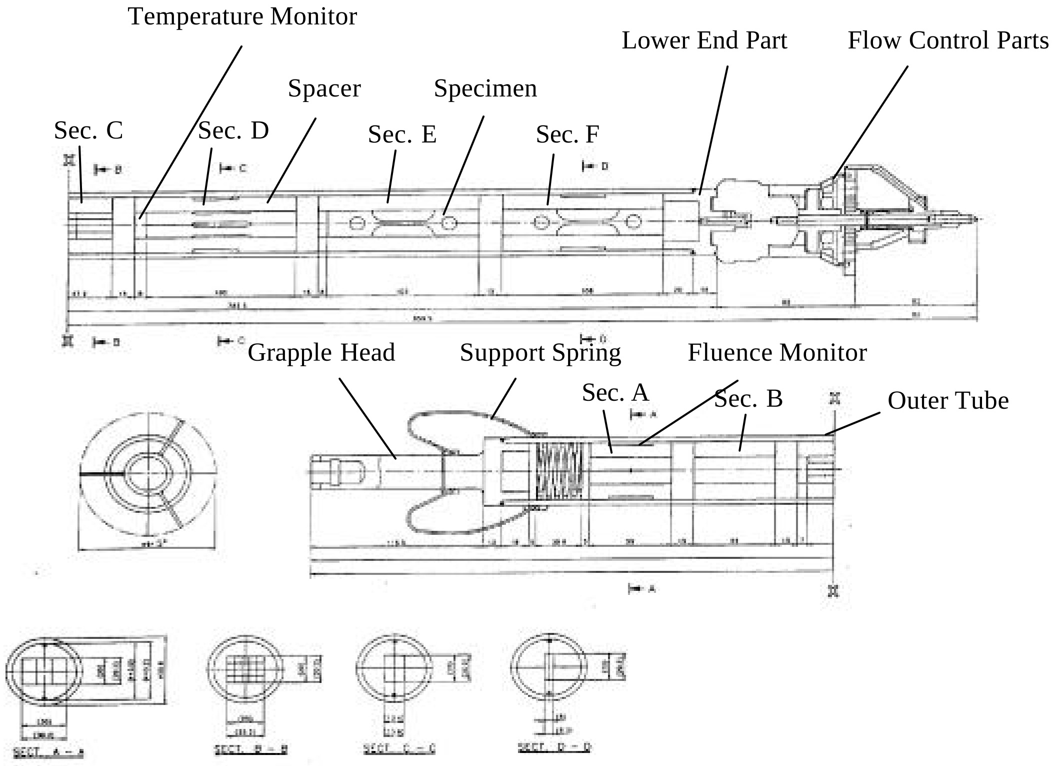


Fig. 2 Schematic diagram of non-instrumented capsule

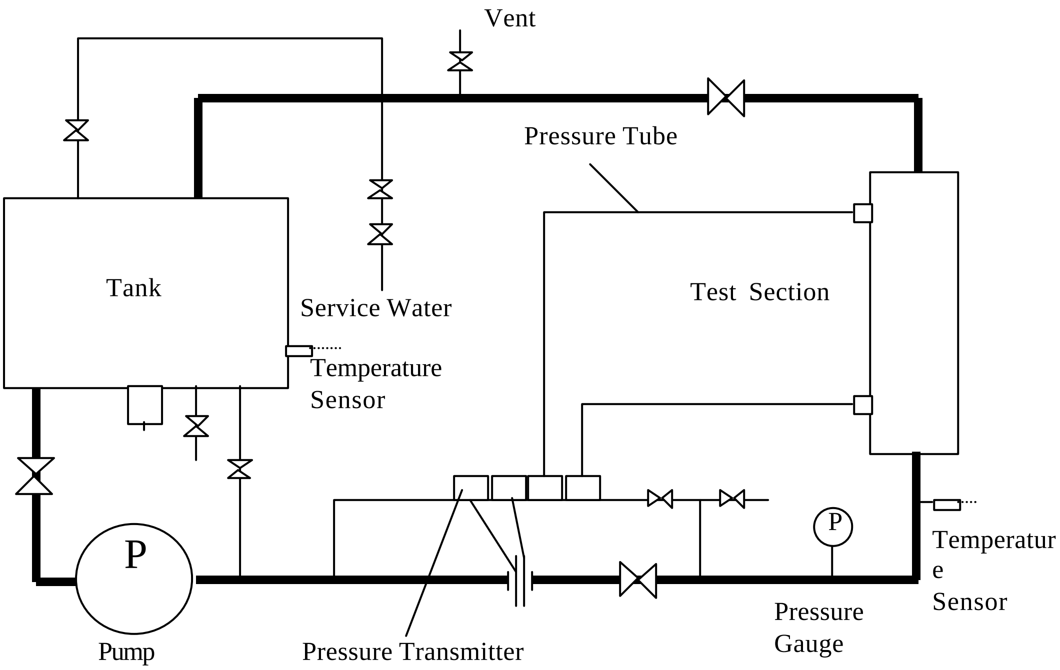


Fig. 3 Schematic diagram of cold test loop II

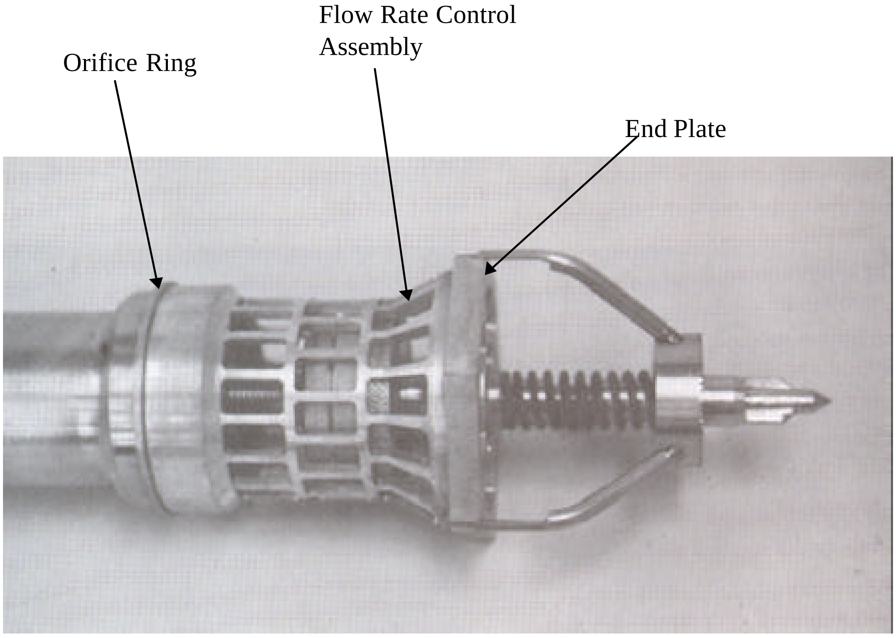
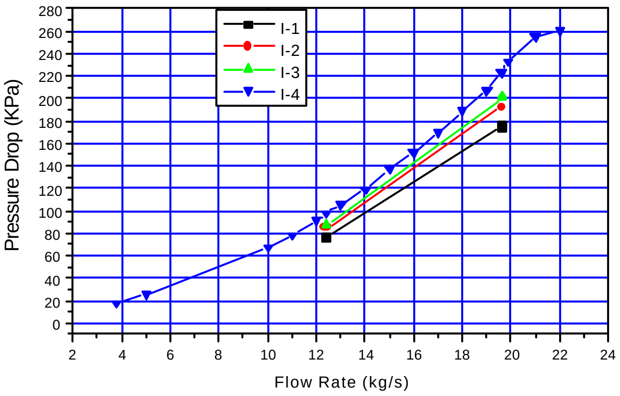
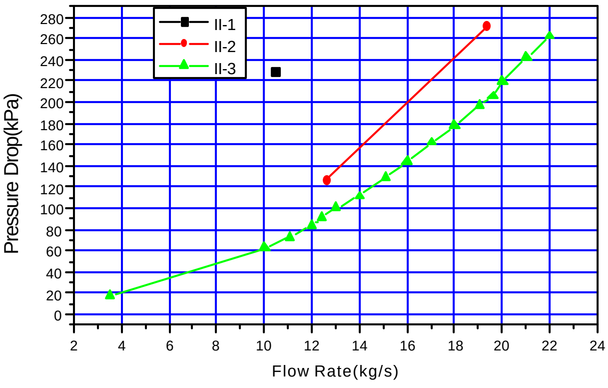


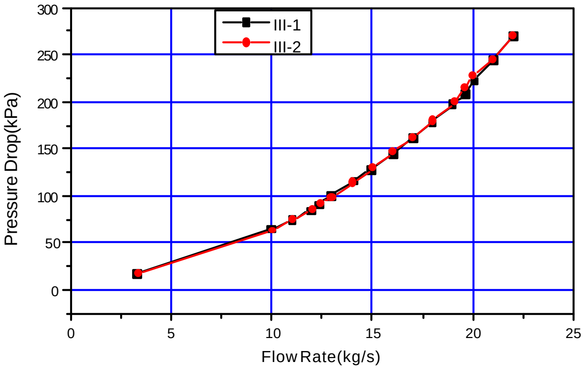
Fig. 4 Flow control parts for pressure drop experiments in cold test loop



(a) Category I experiments(OD of orifice ring: 60mm)



(b)Category II experiments(Flow area of end plate: fully opened)



(c) Category III expexperiments(OD of orifice ring: 64mm)

Fig. 5 Comparison of pressure drop vs flow rate for capsule test matrix

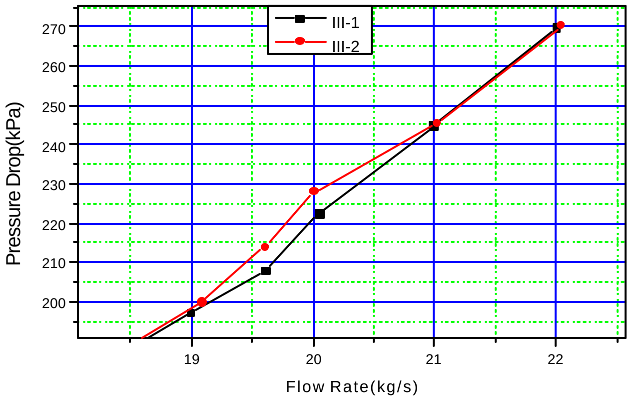


Fig. 6 Detailed comparison of pressure drop vs flow rate for category III experiments

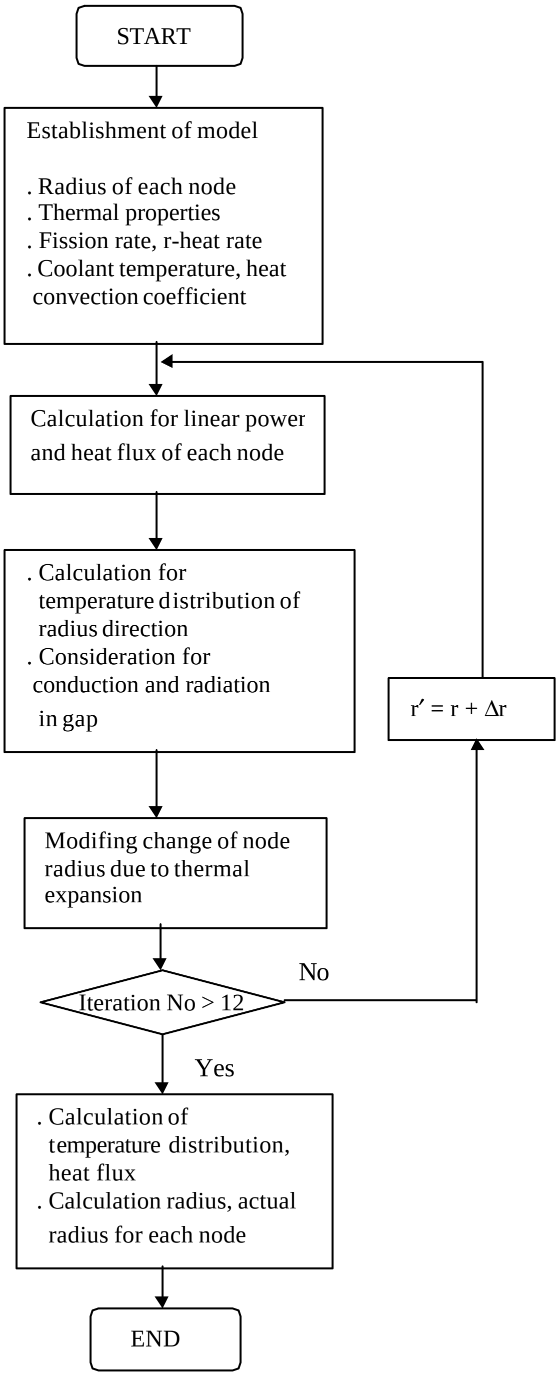


Fig. 7 Flow chart for GENGTC one dimensional program

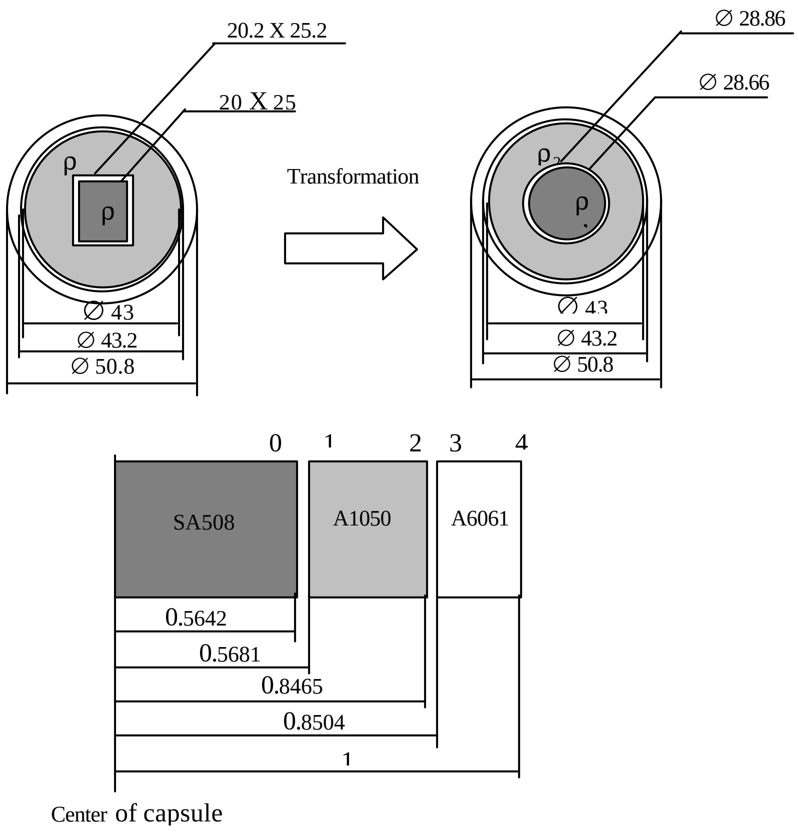


Fig. 8 Model for thermal calculation of GENGTC code (section C)

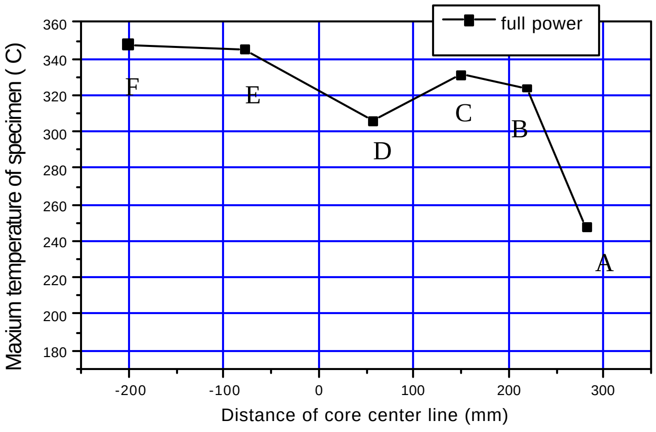


Fig. 9 Maxium temperature of specimen calculated in HANARO power