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A Developmental Study of Transportable Nuclear Heat Cylinder

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Abstract

A concept of the transportable nuclear heat source has been developed. The overall shape and key design parameters have been presented. The component models are integrated for the numerical analysis. The natural circulation heat transfer is presumed to be the sole heat removal mechanism from the core. Based upon the result of the numerical simulations, many different sizes of the reactor and power ratings are possible. Depending upon the geometry of the reactor system, available mass flow (induced by the buoyancy force in the core) has been found to be uniquely determined when the core inlet temperature of the liquid metal coolant and the core power are fixed. The total mass of the reactor system has been minimized for a given value of the power rating. It has been found that there are optimum height ratio (i.e., the core to the riser heights) and diameter ratio (i.e., the core to the vessel diameters) for the least of the total reactor system mass. This study shows that the convectional heat transfer on the interior surface of the vessel wall could be the most challenging in developing the transportable nuclear heat source.

I. Introduction

During several decades of utilizing controlled nuclear fission energy, much experience has been built up in the field of nuclear reactor design, manufacturing, operation and maintenance. Meanwhile, the dominating nuclear energy utilization turned out to be the electricity generation from water-cooled reactors. One may find that the nuclear island has been substituted for the fuel burner of the fossile power plant system. If one recall that the refueling frequency of the nuclear reactor is significantly less than that of the fossile power plant, this simple idea of the substitution is somewhat absurd. Moreover, one of advantages of the nuclear reactor is converting the fertile material into the fissile material while the fuel is burning. Due to this reason, it seems possible to design a very long life core, that is, longer than about 10 years. The idea of the long life core may significantly increase the merit of nuclear power source since we may solve many problems in the areas of fuel handling and transportation, waste disposition, reactor operation, nuclear proliferation.

It is believed to get a great deal of benefit in power plant economy and standardization if the reactor can be transported in an assembled form to the site. Moreover, the reactor can be disposed with the fuel within the vessel, the disposal process would be simplified much. These features are possible if we use the liquid metal as its core cooling material, which would be frozen under the atmospheric temperature.

If the long and short term reactivity control system would be built inside the vessel and therefore, the reactor be operated autonomously, there should be no need to open the vessel during its life time.

This new idea of design should significantly help the public to accept the nuclear power as safe and environment-friendly heat source. As a result, this idea would open a new era in nuclear fission energy utilization. Therefore, it is the time to integrate all the possible design and engineering skills to produce this new nuclear heat source which meet the emerging needs as a power source, which is economic, safe, diversely applicable, environment friendly, easy decommissioning and proliferation-resistant.

In this study, new idea of nuclear heat source named Nuclear Heat Cylinder (NHC) has been presented. The nuclear heat cylinder can be manufactured and assembled in a factory and transported to the site. With simple installation effort, the NHC can be augmented with the secondary system which is designed to convert the heat into the other useful form of energy. The design analysis models have been developed for proposed generic structure of NHC. The size, power rating and the other important design parameters have been presented.

II. Nuclear Heat Cylinder

The core of the NHC can be cooled by natural circulation of the liquid metal coolant. The driving force of the coolant circulation is presumed to be fully induced by the buoyancy force generated within the reactor core. The equal amount of heat generated in the core should be removed from the reactor for a continuous operation. The idea of heat removal used in the NHC design is that heat can be transferred through the vessel wall. Based upon this idea, there should be two different aspects of heat transport; one is the heat removal from the core by the buoyancy driven flow and the other is the combination of conduction and convection heat transfers of the vessel wall. It is obvious that the heat removed from the core should be balanced with the heat transported through the vessel for steady-state operation under which condition, the core inlet temperature of the coolant remain unchanged.

Before discussing a generic NHC, it should be pointed out that the most convenient and versatile geometry of heat source container has been chosen to be a *cylinder*. From this judgement of the vessel shape, the internal components of the NHC have to be selected for the maximum natural circulation of the coolant with the vessel. This idea leads to the concept of a reactor core inside a pool of liquid. As shown in Figure 1, the generic form of the NHC can be characterized as its major components, which are the core inlet plenum, the reactor core and its barrel, the riser, and the vessel annulus.

The liquid metal should be used as the cooling fluid since the long-life core requires high fertile-to-fissile conversion ratio (i.e., a hard neutron spectrum). Moreover, the liquid metal can be solidified when the reactor is shutdown for permanent disposal without removing the spent fuel.

II.1. Inlet Plenum

In the region of the inlet plenum, the reactivity control device and the core supporting plate are possible to exist. The inlet plenum normally serves for mixing the coolant thereby the preferential velocity components in the coolant can be removed before entering the reactor core.

II.2. Reactor Core

The shape of the reactor core is known to be heavily dependent on the reactor physics design of the reactor core. A non-uniform radial flow distribution in the core may be necessary since the power generation is not uniform in the core. A small amount of the core bypass flow is normally allowed due to the space between the core and the core barrel. The coolant temperature rise through the core depends upon the linear power rating of the fuel that can be determined from the reactor physics design of the reactor core. In view of the flow dynamics, the fuel rod supporting device (e.g., the grid) is assumed to exist and additional pressure drop in the core is expected on top of the friction and gravitation losses.

II.3. Riser

The riser is an adiabatic flow passage which is extended upward from the exit of the core. The riser is normally provided in the pool type reactor where the natural circulation is important. Since the riser normally stabilizes the natural circulation flow system, an optimum height of riser may need to be determined. It should be noted that the area changing riser is not considered in the generic design of NHC.

II.4. Vessel

Since the vessel wall supposedly functions as the major heat sink in the NHC, the surface area, the length and the flow area of the vessel annulus are important. The internal surface area of the vessel can be increased without increasing the vessel volume by introducing the fin or the equivalent on the vessel wall. Two important thermal-hydraulic concerns in modifying the internal surface of the vessel wall would be the flow resistance and the wettability of the coolant to the wall.

The flow area and the length of the vessel annulus virtually determine the overall size of the vessel. The uppermost part of the vessel is required to buffer the coolant volume expansion.

III. Design Constraints

In view of the thermal-hydraulic system design, *the linear power rating* of the fuel element is important. A large value of linear power rating may lead to high coolant temperature rise in the core when the height of the core is given. Even though large coolant density difference through the core is desirable for developing large buoyancy driven core flow, there are two concerns. One may be the hydrodynamic instability of the buoyancy driven coolant circulation feature of the NHC. The hydrodynamic instability, however, could be avoided by adjusting the size of the riser and/or placing a flow restricting device at the inlet of the lower plenum. The other concern is the structural integrity of the fuel element since larger linear power rating results in larger axial temperature difference within a fuel element. Therefore, there should be a limiting value for the linear power rating.

The amount of the fuel material within the core can be determined by the *pitch to diameter ratio* of the fuel array and the core size. Moreover, since the coolant flow area in the reactor core is determined by the pitch to diameter ratio, the velocity of the coolant in the core depends upon the pitch to diameter ratio for a given coolant mass flow rate. It should be noted that the pitch to diameter ratio is also important for the neutron physics design of the reactor core.

The *core inlet temperature* of the coolant controls the overall temperature of the reactor system. The average temperature of the NHC is important for the design of the secondary system which is considered in this study as a system boundary. The coolant temperature is lowest at the core inlet, which should be marginally higher than the melting temperature of the coolant.

There must be more design constraints which are not believed to be very important at this stage of design.

IV. System Models

The purpose of modeling the generic NHC is to find out maximum heat removal capability of a given NHC geometry and the core heat generation. The NHC is feasible if the maximum heat removal (i.e., the natural circulation heat removal) exceeds the core heat generation with a reasonable temperature gradient in the vessel wall. The exterior surface of the vessel is the modeling boundary in this work.

IV.1 Pressure Drop Models

The pressure drop can be obtained from the momentum equation as:

$$-\frac{\partial p}{\partial x}=\frac{\partial G}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{G^2 A}{\rho}\right)+\frac{\tau_w P_f}{A}+g\rho\sin\theta \tag{1}$$

We are now interested in pressure drop of each reactor component under steady state. Integrating in Eq.(1) over a given component of length, L, we obtain,

$$\Delta p=\Delta p_{acc}+\Delta p_{fric}+\Delta p_{grav} \tag{2}$$

where

$$\Delta p_{acc}=\int_L \frac{1}{A(x)}\frac{\partial}{\partial x}\left(\frac{G^2 A(x)}{\rho}\right)dx$$

$$\Delta p_{fric}=\int_L \frac{\tau_w(x)P_f(x)}{A(x)}dx=f\frac{L}{D}\rho v^2$$

$$\Delta p_{grav}=\int_L g\rho(x)\sin\theta dx$$

The idea of the naturally cooling core (i.e., no coolant circulation pump in the system) is to utilize the pressure gain induced by the coolant density reduction due to the heating in the reactor core, which is closely related with the third term in Eq.(2). In the naturally cooling core, the frictional pressure drop is minimal for the turbulent flow condition comparing the other pressure drop components.

The loss factors has been used for a sudden enlargement of the flow area as[1]:

$$K_e = 1 - \frac{2}{\alpha_2}\frac{A2}{A3} + \left(\frac{A_2}{A_3}\right)^2\left(\frac{2}{\alpha_3} - 1\right) \qquad (3)$$

where the subscripts 2 and 3 represent the upstream and the downstream, respectively. For a contraction,

$$K_c = \frac{1 - (A_1/A_0)^2(C_c^2/\beta_0) - 2C_c + 2(C_c^2/\beta_1)}{C_c^2} - 1 + \left(\frac{A1}{A_0}\right)^2 \qquad (4)$$

where

$$C_c = 0.62 + 0.01e^{A_1/A_0},$$

where the subscripts 0 and 1 represent the upstream and the downstream, respectively, and α_i and β_i have been set to be 1.0.

The frictional pressure drop has been estimated by the following form:

$$f = a + b\,Re^c \qquad (5)$$

where different sets of constants were used depending upon the value of Reynolds number. The path of coolant circulation within the vessel has been modeled as a loop in which the sum of pressure drop vanishes.

IV.2 Heat Transport

In modeling power rating of the generic NHC, the heat removal capability is directly related with the coolant flow induced by its buoyancy force. The heat generated within the core can be expressed under steady state condition as:

$$Q^{CORE} = \dot{m}c_p\,\Delta T^{CORE} \qquad (6)$$

If the core temperature rise, ΔT^{CORE}, is given, the flow rate can be determined by solving Eq.(2) for a given geometry (i.e., the flow loop) of the NHC. Since the coolant flow rate should also satisfy Eq.(6) for a given power rating, we have to solve Eqs. (2) and (6) for the mass flow rate simultaneously.

On the other hand, the amount of heat transported through the vessel wall can be determined by

$$Q^{TR} = (\overline{T}_{vi} - \overline{T}_{wo})/R_T \qquad (7)$$

where $\overline{T}_{vi}$ is the average bulk coolant temperature near the vessel wall, $\overline{T}_{wo}$ is the average exterior surface temperature of the vessel, and the total heat transfer resistance can be given by

$$R_T = \frac{1}{h_{vi}A_{vi}} + \frac{\ln(D_{vo}/D_{vi})}{2\pi k_v H_v} \qquad (8)$$

If we solve Eq.(7) for the temperature difference, we obtain

$$\overline{T}_{vi} - \overline{T}_{wo} = Q^{TR}R_T = Q^{CORE}R_T \qquad (9)$$

where the steady-state is assumed, that is, we need the balance between the heat transported from the core (Q^{CORE}) and the heat removed through the vessel wall (Q^{TR}) for a continuous operation. The temperature difference given by Eq.(9) is that required to remove the amount of the heat generated by the core (i.e., Q^{CORE}). Two different heat transfer correlations[1,2] have been used for the convection inside the vessel wall since available correlations show large deviations:

IV.3 Core Flow

The reactor core of the generic NHC has been assumed as a triangular array of fuel rods. Therefore, the pitch to diameter ratio (i.e., rpd) should be able to represent the core flow area fraction, such as:

$$f_{\text{flow}}^{\text{CORE}} = 1 - \frac{\pi}{2\sqrt{3}} / \text{rpd}^{2} \tag{4}$$

In general, since there should be a fuel supporting system, we need geometrical information of this system for the core pressure drop estimation. In the generic NHC, however, the shape of the fuel supporting system has not been assumed. Instead, the form loss factor of the fuel supporting system has been assumed to be ten times as that of the friction loss in the core.

It should be also noted that the bypass flow in the reactor core which is normally very small fraction of the total core flow, has not been separately considered in this study.

IV.4. Riser and Vessel

The riser has been assumed as an adiabatic flow passage, that is, the thermophysical properties of the coolant are not supposed to be changed through the riser. It should be noted that the height of the riser is very important for developing core flow and the stability of the flow system.

The flow flowing out of the riser may reach the upper part of the vessel and then cooled down in the vessel annulus region. The upper part of the vessel was assumed as an open region where the coolant flowing from the riser can be freely dispersed so that no much pressure loss is expected. The vessel annulus region has been assumed to have a plain smooth surface in this study.

The lower region of the vessel was also assumed as an open area where the coolant may lose its kinetic energy. In this region, no much gravitational and frictional pressure drops are expected. An orifice or the equivalent has been placed at the entrance of the lower plenum for a design reservation to model possible reactivity control structures.

V. Results and Discussion

It is possible to design the NHC of wide variety of the vessel size and the power rating using the generic NHC model. In this study, the followings are used as the criteria for the design:

1. The core temperature rise per unit height of the core is fixed to be 100°C/m on the average. Therefore, the core height determines the core coolant temperature rise in this design.
2. The pitch to diameter ratio (rpd) of the fuel array in the core was fixed to be 1.2614. This value controls the flow area in the core, and therefore, is closely related with the coolant velocity in the core. The pressure drop induced by the fuel array supporting device (e.g., the grid) has been assumed to be 10 times as that of the frictional pressure drop in the core.
3. The reactor core inlet temperature was fixed to be 300°C.

As a coolant material, the Pb-Bi is used to take advantage of its low melting temperature than Pb. It should be noted that simulation capability of the generic NHC model is not limited to any specific coolant material.

The total mass of the coolant in the system has been considered to be an important parameter. As will be shown, the total mass can be limited because of the transportability of the NHC.

As can be seen in Figure 2, the NHC system has been divided into 10 volumes. Each volume can be characterized as its flow area and the length.

The result of the NHC design has been summarized for different power ratings and geometry of the NHC. The thermophysical properties, the pressure drop and the dimension of each component are shown in Tables 1 and 2. Based upon this flow loop calculation, the mass flow solution has been converged to 2079 kg/s. As can be seen in Figure 3, the mass flow rate solution is unique and no flow instability is expected in NHC-REF. The important design parameters of the NHC-REF are shown in Table 3.

Based upon the presented model, the developed coolant flow rate is reduced if we increase the form loss or the friction loss. It is also found that the mass flow vanishes when the riser length is too short or the vessel wall flow area is too small. This result implies that the buoyancy driven pressure gain within the core cannot overcome the friction and form losses through the loop unless the geometric parameters be carefully determined.

The mass flow solution is not very sensitive to the friction factor within the range of the value used in the NHC-REF (i.e., ~2000 Kg/s). In fact, if the riser is not too short ($H^{RISER}>\sim 0.5H^{CORE}$), the solution is always possible except for very small vessel annulus flow area.

The calculated values shown in Table 3 are insensitive to the core inlet temperature of the coolant. It has been found that the presented results do not change much as far as the coolant is single phase liquid.

The power rating per unit mass of the NHC system has been considered. It is obvious that the major part of the total system mass is from the mass of the liquid metal coolant in the NHC system. Since the power rating (or the maximum amount of heat that can be removed by a specific geometry of the NHC) is determined by the buoyancy induced mass flow rate of the coolant, the size of the vessel and the riser for a given core size can be optimized. From extensive numerical simulations, it is found that the optimum riser length has been found to be approximately equal to the size of the core height. This trend is valid for different values of the core barrel to equivalent vessel flow diameter ratio. It should be noted that the equivalent vessel flow diameter can be found by projecting the cross section of the vessel annulus to a round tube. In other words, for a fixed height of the lower plenum, the ratio of the riser to the core height is close to unity when the power rating per unit mass of the NHC system has the maximum value. This result has been plotted in Figure 4.

The diameter ratio of the core barrel (or, the riser) to the equivalent vessel annulus area has also been studied to find the optimum value. As can be seen in Figure 5, an optimum value of ~1.2 has been found.

When the sizes of the riser and the vessel are optimized as above, the aspect ratio of the vessel (i.e., the diameter to the height ratio) is found to control the power rating per unit mass of the NHC system. It is found that the power rating per unit system mass monotonically increases with the value of the aspect ratio as shown in Figure 6. This result implies that the longer vessel is more efficient, which is due to the natural circulation heat transfer. It should be noted, however, that as can be seen in Figure 6, the aspect ratio may not need to be too large.

It is possible to obtain the same power rating with different geometry of the NHC. In general, as mentioned previously, longer vessel has larger value of the power rating per unit system mass. Five different designs of the NHC have been presented in Table 4. For these NHC designs, the optimum dimension discussed in the previous section has been applied.

Finally, it is found that the generated heat of the presented nuclear heat cylinder cannot be fully transported through the vessel wall. The bottle neck of the heat transport has been found to be the convectional heat transfer on the interior surface of the vessel when a plain (i.e., smooth) surface is used. Therefore, this result shows necessity of a vessel internal surface modification to enhance the convectional heat transfer.

VI. Conclusion

It has been presented in this study that the overall shape of the transportable nuclear heat source, that is, the Nuclear Heat Cylinder. The component models of the reactor system are integrated for the numerical analysis.

The natural circulation heat transfer has been used as the sole heat removal mechanism from the core in this study. Based upon the result of the numerical simulations, many different sizes of the reactor and power ratings are possible for the NHC. Depending upon the geometry of the reactor system, available mass flow (induced by the buoyancy force in the core) has been found to be uniquely determined when the core inlet temperature of the liquid metal coolant and the core power rating are fixed.

The total mass of the reactor system has been used as the objectivity to be minimized for a given value of the power rating. It has been found that there are optimum height ratio (i.e., the core to the riser heights) and the diameter ratio (i.e., the core to the vessel diameters) for the least reactor system mass. Based upon the optimum geometry found in this study, five different NHC' s have been presented.

Unfortunately, however, the core heat transported by the liquid metal in the presented reactor systems may not be fully removed through the reactor vessel wall of plain surface condition, which is the presumed to be the major and unique heat sink of the NHC system. Therefore, there should be heat transfer enhancement on the interior vessel wall. Moreover, existing heat transfer coefficient show large deviation from one to the other.

Further experimental and theoretical researches on the areas of the convective heat and momentum transfers of the low Nusselt number flow would be a help to develop the NHC of reasonable size and power rating.

References

1. Rosenow, W.M. and Choi, H., 1972, "Heat, Mass and Momentum Transfer", Prentice-Hall, Inc.

2. Notter,R.H and Sleicher, C.A., 1972, "A Solution to the Turbulent Graetz Problem-III, Fully Developed and Entry Transfer Rates", Chem. Eng. Sci., Vol27, pp2073-2093

Table 1. Pressure Drop of Each Component in the NHC-REF

Component ID*	Pressure Drop (kPa)	Height (m)	Reynolds Number	Form loss (K)	Friction loss (f L/d)
1	0.19	0.0	755863	0.17	0
2	10.4	0.1	868420	0.0	0.28E-03
3	1.39	0.0	1027005	0.25	0
4	155	1.5	1555920	0.0	0.56E-02
5	-0.65	.0	1434138	0.32	0
6	154	1.5	1212685	0.0	0.39E-02
7	-0.12	.0	1055507	0.15	0
8	0.67	.0	1135784	0.26	0
9	-320	3.1	1275398	0.0	0.99
10	-0.28	0.0	813350	0.37	0

*ID=1: LOWER PLENUM INLET, 2 LOWER PLENUM, 3 LOWER PLENUM TO CORE, 4 CORE, 5 CORE TO RISER, 6 RISER, 7 RISER EXIT, 8 VESSEL UPPER INLET, 9 VESSEL, 10 VESSEL TO BOTTOM

** LOOP PRESSURE BALANCE RESIDUAL (kPa) = -1.32620E-05

Table 2. Nodal Information of the NHC-REF Loop Calculation

Component ID	DENSITY (Kg/m3)	AREA (m2)	VELOCITY (m/s)	TEMPERATURE (°C)
1	10622.4	1.509	.130	300.00
2	10622.4	.920	.213	300.00
3	10622.4	.920	.213	300.00
4	10622.4	.396	.496	300.00
5	10442.4	.396	.504	450.00
6	10442.4	.920	.217	450.00
7	10442.4	.920	.217	450.00
8	10442.4	1.509	.132	450.00
9	10442.4	.589	.339	450.00
10	10622.4	.589	.333	300.00

Table 3. Design Result of NHC-REF

General	Power rating, Q (MWth)	50
	Linear power, Q´ (MW/m)	33.1
	Volumetric power rating, Q´´´ (MW/m^3)	35.4
	Total coolant mass, M (tonne)	50.0
	Q/M (MWth/tonne)	1.0
Thermal-Hydraulic	Coolant mass flow, m (kg/s)	2079
	Core inlet temp., T_{in}^{CORE} (°C)	300
	Core inlet velocity, V_{in}^{CORE} (m/s)	0.499
	Core temp. rise, ΔT_{in}^{CORE}(°C)	150
	Coolant velocity in riser, V^{RISER} (m/s)	0.206
	Coolant velocity in the vessel annulus, V^{VESSEL} (m/s)	0.332
Geometry	Lower plenum height/diameter, H^{LP}/D^{LP} (m)	0.1/1.1
	Core height/diameter, H^{CORE} / D^{CORE} (m)	1.5/1.1
	Riser height/diameter, H^{RISER} / D^{RISER} (m)	1.5/1.1
	Vessel height/diameter, H^{VESSEL}/D^{VESSEL} (m)	3.1/1.4
	Fuel pitch-to-diameter Ratio, rpd	1.2614

Table 4. Different Types of NHC

		LONG	MINI	REF	TALL	SQUARE
General	Q (MWth)	5	5	50	300	300
	Q´ (MW/m)	2.52	4.17	33.1	100	151
	Q´´´ (MW/m^3)	35.2	26.6	35.4	70.9	48.0
	M-Liq. (tons)	5.06	6.76	50.0	149	222
	Q/M (MW/ton)	0.998	0.74	1.0	2.03	1.36
Thermal	T_{in}^{CORE} (°C)	300.0	300.0	300.0	300.0	300.0
	V_{in}^{CORE} (m/s)	0.497	0.375	0.499	1.0	0.677
	ΔT_{in}^{CORE}(°C)	200.0	120.0	150.0	300.0	200.0
Geometry	H^{CORE} (m)	2.0	1.2	1.5	3.0	2.0
	D^{CORE} (m)	0.37	0.45	1.1	1.34	2.0
	H^{RISER} (m)	2.0	1.2	1.5	3.0	2.0
	H^{LP} (m)	0.1	0.1	0.1	0.1	0.1
	H^{VESSEL} (m)	4.1	2.5	3.1	6.1	4.1
	D^{VESSEL} (m)	0.47	0.57	1.4	1.7	2.6

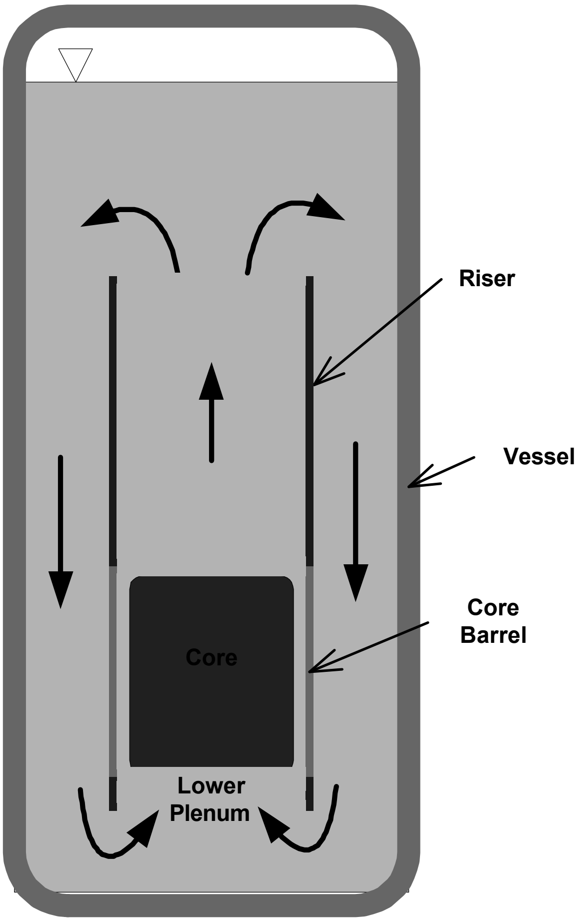

Figure 1 Schematic View of Generic Nuclear Heat Cylinder

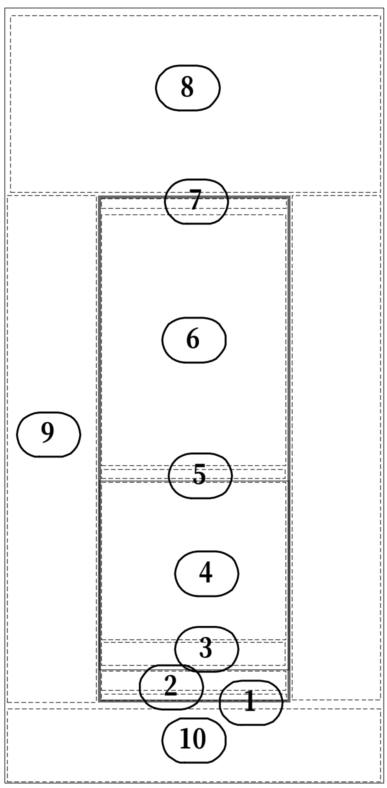

Figure 2 Nodalization for NHC Simulation

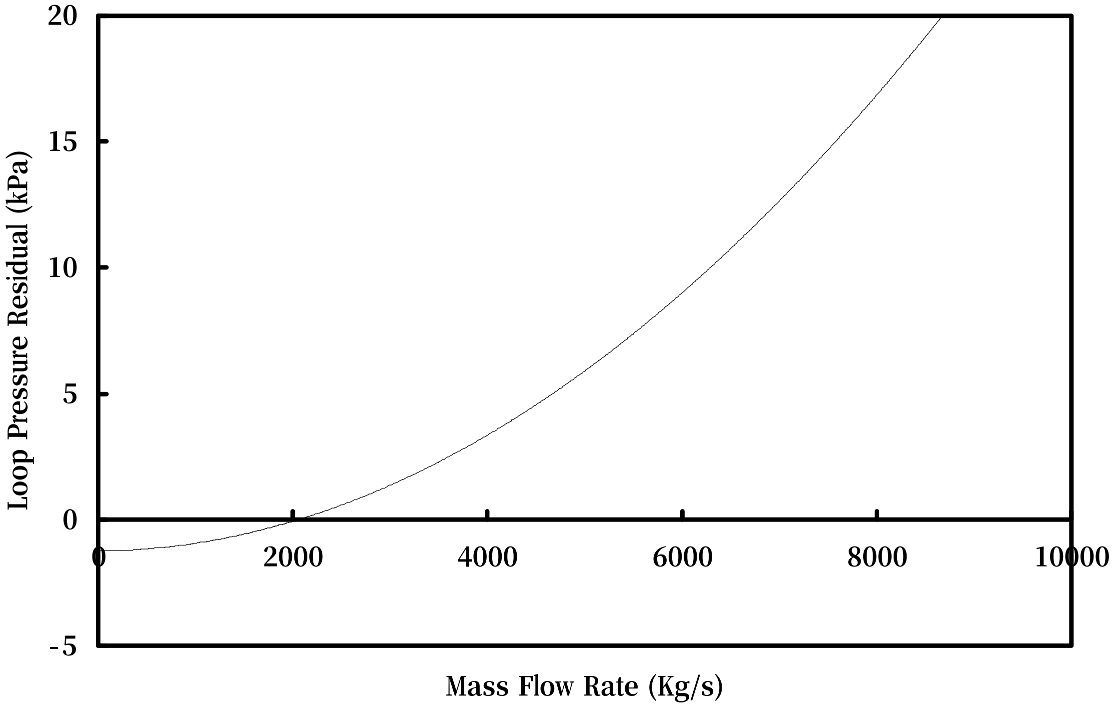

Figure 3. Loop Pressure Balance Residual versus Coolant Flow Rate Curve (NHC-REF)

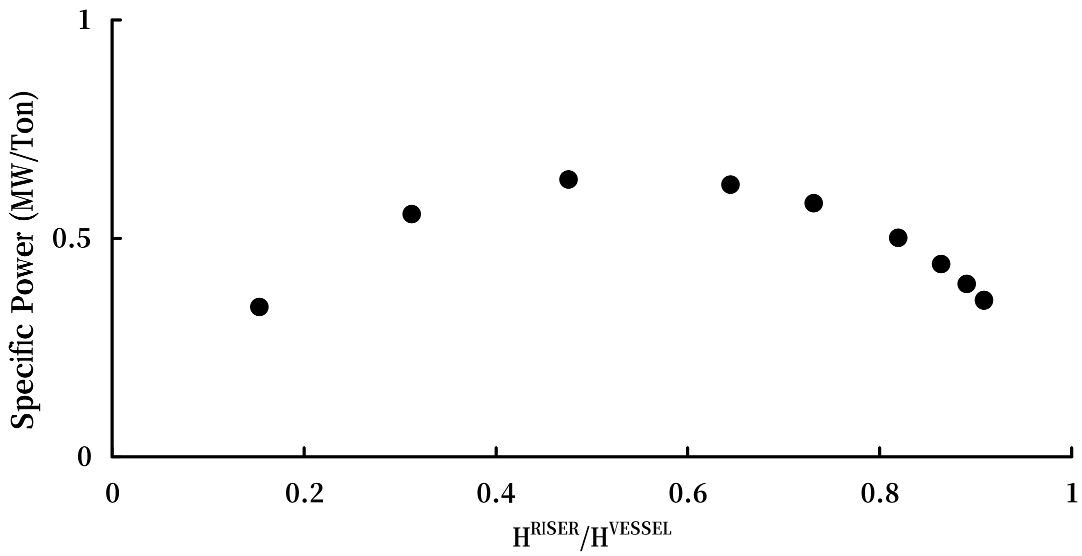

Figure 4. Optimal Vertical Dimension of the NHC ($H^{RISER}=H^{CORE}$)

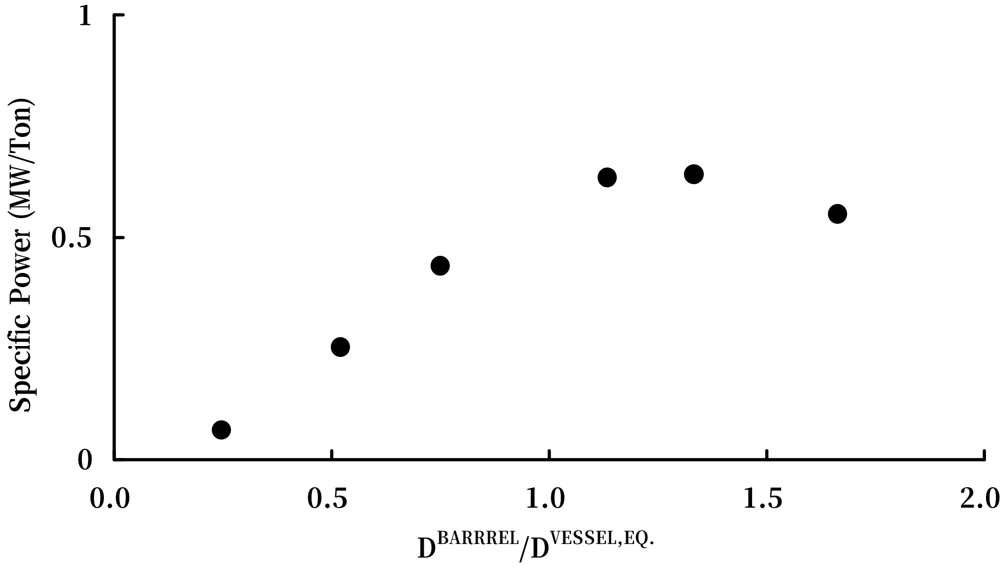

Figure 5. Optimal Radial Dimension of NHC

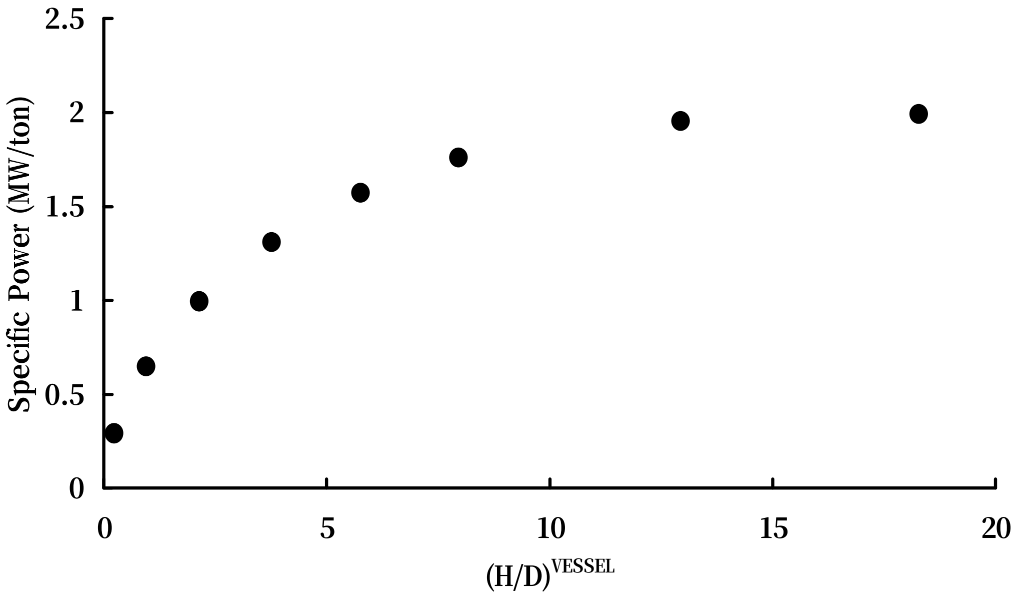

Figure 6. Dependency of the Specific Power on the Vessel Height to Diameter Ratio