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Conceptual Design of Passive Safety System for Lead-Bismuth Cooled Fast Reactor

A G Abdullah, A B D Nandiyanto

Department of Electrical Engineering
Faculty of Technical and Vocational Education, Universitas Pendidikan Indonesia

Corresponding author: ade_gaffar@upi.edu

Abstract. This paper presents the results of the conceptual design of passive safety systems for reactor power 225 MWth using Pb-Bi coolant. Main purpose of this research is to design of heat removal system from the reactor wall. The heat from the reactor wall is removed by RVACS system using the natural circulation from the atmosphere around the reactor at steady state. The calculation is performed numerically using Newton-Raphson method. The analysis involves the heat transfer systems in a radiation, conduction and natural convection. Heat transfer calculations is performed on the elements of the reactor vessel, outer wall of guard vessel and the separator plate. The simulation results conclude that the conceptual design is able to remove heat 1.33% to 4.67% from the thermal reactor power. It's can be hypothesized if the reactor had an accident, the system can still overcome the heat due to decay.

1. Introduction

During steady-state of reactor operation, time-independent of temperature distribution, all of the generated heat will be removed naturally (Lamars et al., 2001). Cooling concept is one of the most critical part in the reactor design. The material selection of the fuel, cooling, cladding and reactor vessel should be the main consideration for reactor design. It must be far below its melting temperature. In case of core reactor melt down, cladding will be ruptured then fission product will be released.

Most of the nuclear power plant, i.e. 2nd generation, which operate nowadays still use active safety system to eliminate the decay heat. In this type of system, pump plays an important role to maintain reactor core temperature after shutdown. Fukushima accident have shown the minor point of the system when energy supply to pump was stop. The conceptual design of next generation reactor, i.e. 3rd generation, is relaying on passive safety system, where natural circulation is done by convection in the primary coolant. The major point of the systems: the ability to cool down reactor core without energy supply to pump, high reliability, simple and economist [1].

In this study, simulation of the design system of the passive safety system, i.e. Reactor Vessel Auxiliary Cooling System (RVACS) in 300 MWth of Pb-Bi coolant fast breeder reactor, will be analyzed. Utilization of liquid Pb-Bi allows the primary system to operate at high pressure condition, and if coupled with secondary system, it will be able to counterfeit the risk of LOCA (Loss of Coolant Accident) [1].The optimization is done to obtain high heat transfer value, thus the RVACS will give good performance on removing heat. Optimization is done on two aspect of the design: the properties aspect, which includes emissivity effect of guard vessel and perforated plate, also the effect of viscosity and air conductivity.

2. Reactor Vessel Auxiliary Cooling Systems (RVACS)

RVACS is a passive safety system in the liquid metal reactor that capable of maintaining system condition during accident [2]. The heat removal mechanism is conducted by natural circulation that passes through guard vessel air window and the wall surrounding the guard vessel. Heat from the reactor is transferred to the atmosphere via multiple stacks which connected by common inflow and outflow plane.

The RVACS performance is a function of pressure difference between airflow inlet and airflow outlet, inlet air temperature, variation air density along the path and pressure drop characteristic in system. The inlet and outlet pressure difference, and inlet temperature of RVACS are also influenced by air velocity and direction [3]. Reactor design is consist of vessel, interior and exterior of reactor vessel, which are separated by liquid metal gap. Design of RVACS can be seen in figure 1 [4]:

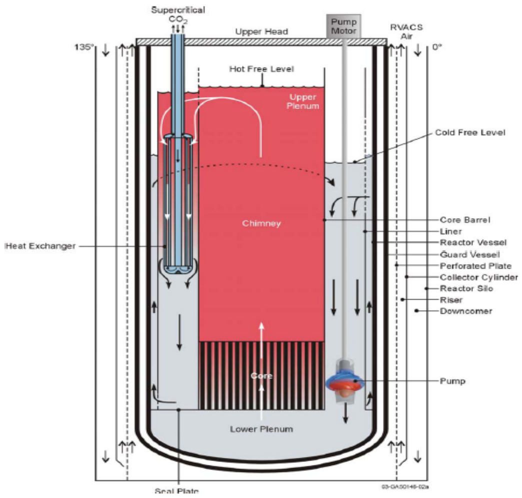

Figure 1. Pool type reactor

Heat is removed by air flow from the down comer to upper part which is passing through air riser and flow to the atmosphere via chimney. This mechanism is preceded by buoyancy force due to air density change. Heat is moved by air convection on two surfaces: outer wall of guard vessel and separator. Heat is transferred to separator from guard vessel wall by thermal radiation. And then, the heat is transferred by conduction via vessel and guard vessel.

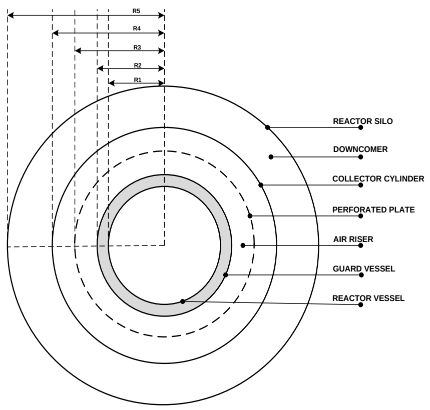

Figure 2. Cross section of RVACS

Figure 3 shows the RVACS geometry. In RVACS design, separator element is added on the surface of guard vessel (do not directly contacted). The purpose of the separator addition is to decrease heat on convection process. However, in some calculation the addition separator element is sometimes neglected.

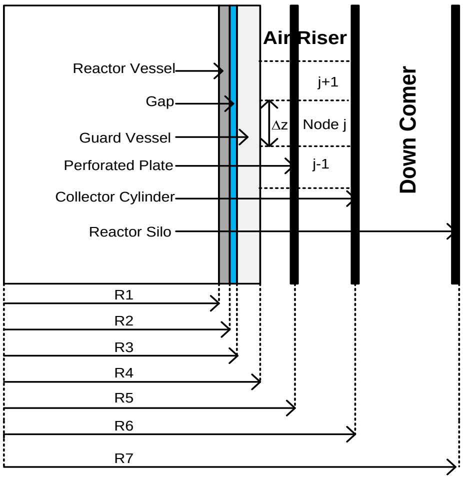

Figure 3. RVACS Geometry

3. Computation Methods

The RVACS design uses several assumptions: Analysis is conducted under steady state; Vessel and guard vessel temperatures are assumed to be constant, azimuthally; Separator is perfectly isolated; Heat convection coefficient (h) in riser is azimuthally constant; All of the inlet and outlet pipes are perfectly isolated; The heat convection between coolant and reactor wall are constant; Coolant temperature is linearly varies on axial direction; Heat that transfer via liquid metal gap is modeled in conduction model; Axial conduction and radiation is neglected.

According to fig. 3, calculation of heat transfer from guard vessel to separator is the radiation calculation:

$$\dot{Q}_{in,S} = C_G A_G (T_G^4 - T_S^4) \tag{1}$$

A_G is the area of guard vessel surface, T_G and T_S are guard vessel temperature and separator temperature, respectively, while C_G is define as follows:

$$C_G = \sigma \left[\frac{1}{\varepsilon_G} + \frac{A_G}{A_S}\left(\frac{1}{\varepsilon_S} - 1\right) \right]^{-1} \tag{2}$$

Where σ d is boltzman constant, ε_G and ε_S are the emissivity of guard vessel and separator, respectively. The heat transfer from separator to air was modeled by the pure convection process:

$$\dot{Q}_{out,S} = h_j A_S \left(T_S - T_{bulk}\right)_j \tag{3}$$

Heat convection coefficient, h_j, is calculated based on [5]:

$$h_j = 0{,}0229\, Re^{0{,}8}\, Pr^{0{,}4}\, \frac{k_{air}}{D_h} \left(\frac{T_{Gr}}{T_{air}}\right)^{-0{,}4} \left[1 + \left(\frac{z_j}{D_h}\right)^{-0{,}3}\right] \tag{4}$$

Thus, total of heat transfer that pass through guard vessel is:

$$\dot{Q}_{out,G} = h_j A_G \left(T_G - T_{bulk}\right) + \dot{Q}_{rad,G} \quad (5)$$

The heat transfer to surface of outer guard vessel from primary cooling system was modeled by conduction process. The calculation was done by serial resistance between cooling temperature and guard vessel outer wall temperature.

$$R_{TOT} = R_C + R_{RV} + R_{GAP} + R_G \quad (6)$$

Where:

$$R_C = \left(h_C \pi D_1 \Delta z\right)^{-1}$$
$$R_{cylinder} = \frac{\ln\left(D_{out}/D_{in}\right)}{\pi k \Delta x} \quad (7)$$

k is thermal conductivity of the material that fill the gap between reactor vessel and guard vessel. D_{in} and D_{in} outer diameter and inner diameter of the cylinder, respectively. Thus, the heat transfer that enter the guard vessel is:

$$\dot{Q}_{in,G} = R_{TOT}^{-1}\left(T_C - T_G\right) \quad (8)$$

4. Result and Discussion

The referred design that was used in simulation is shown in table 1. Analysis was covered most of the coolant temperature. If the result of coolant shows temperature below maximum of cladding temperature, then the design is assumed to be done successfully. This because power level decay that passes through cladding is very small and there will be a few thermal resistances between cladding and primary coolant.

Tabel 1. Main parameters of RVACS design

Reactor power	225 MWth
Coolant	Pb-Bi
Fuel	UO_2-PUO_2
High of RVACS	40 m
Downcomer gap	5,86 m
Radius of reactor vessel	4,62 m
The Thickness of reactor vessel	0,4 m
The Thickness of guard vessel	0,1 m

The simulation was started by calculating total of heat transfer on referred design. It was found that RVACS is capable of eliminating heat of about 4.39 MWth or about 1.95% of total thermal power of reactor. Heat is eliminated in RVACS system by natural circulation from the static atmosphere around reactor vessel. The result of the simulation is shown in figure 4.

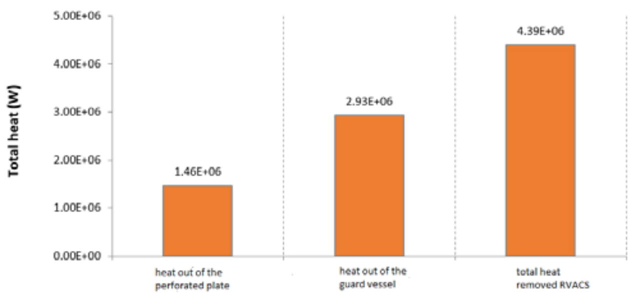

Figure 4. Total heat removal of RVACS reference design

Figure. 5 and 6 show change of the RVACS performance due to optimization of guard vessel emissivity, perforated plate, viscosity and air conductivity. Performance of RVACS increased when guard vessel emissivity and perforated plate values were close unity. On the other hand, optimizations of viscosity and air conductivity indicated insignificant contribution to the power of RVACS heat transfer.

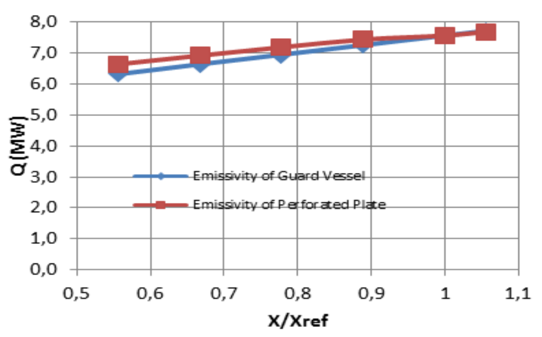

Figure 5. The effect of changes in emissivity value of guard vessel and the perforated plate

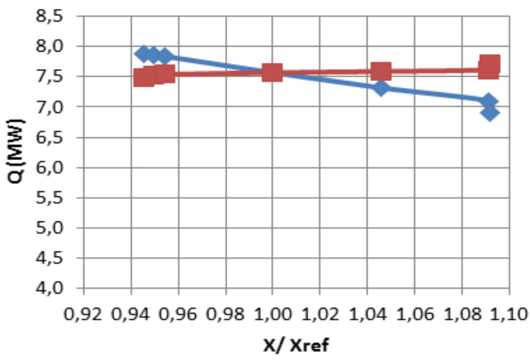

Figure 6. The effect of changes in viscosity and air conductivity

Figures 7, 8 and 9 show optimization results on RVACS geometry. Performance of RVACS was highly affected by optimization of RVACS height. While diameter optimization or gap channel gave less influence, this means that power of heat transfer is similar with simulation result on reference design.

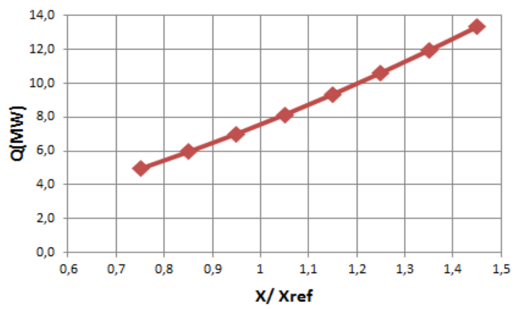

Figure 7. The change height effects of RVACS

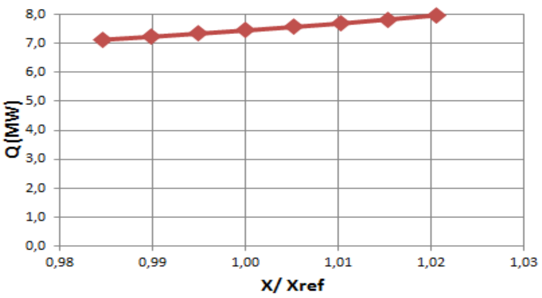

Figure 8. The change diameter effect of RVACS

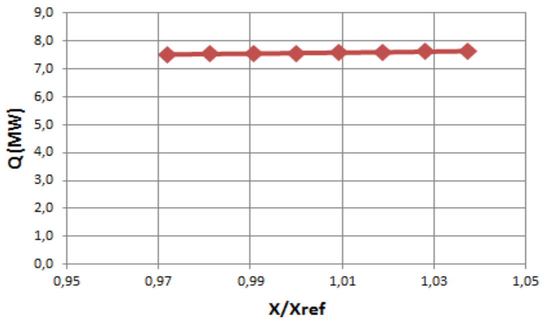

Figure 9. The change channel gap effect

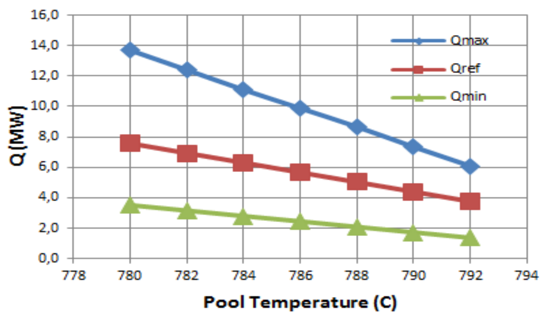

Figure 10. Heat removal capabilities of RVACS

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Figure 10 shows combination of result of all optimization, i.e. minimum design, reference design and maximum design. Simulation result concludes that this theoretical design was able to eliminate heat from 1.33% to 4.67% of power thermal reactor.

5. CONCLUSSION

The conceptual design generates heat transfer value that met the requirement of natural circulation reactor design by the environment. The passive safety system of RVACS will be activated to remove decay heat under accident condition. The calculation results show that the level of heat removal is good enough to prevent temperature to reach very high value, when the RVACS has good and efficient heat removal system.

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