An Emergency Core Cooling System (ECCS) for Nuclear Power Reactor Using Passive Loop Heat Pipe

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ループ式ヒートパイプによる原子炉緊急冷却装置

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1. Introduction

Nuclear energy share in global electricity production is growing fast due to its high energy density, advanced reactor technology, low greenhouse gas emissions and ease of installation and plant expansion. Nuclear energy provides a promising way to meet the power needs of the growing population. In nuclear power plants, kinetic energy produced by the nuclear fission of the radioactive material, which is uranium 235 (U-235) or plutonium 239 (Pu-239) in general, is converted to heat, thereby to useful electrical power. Nuclear fission provides very high energy density, for example 1 kg of U-235 can produce 3 million times the energy generated by an equivalent mass of coal. Japan has total of 55 nuclear power reactors with total electric power capacity of 49 GW (30% of the country’s demand). Figure 1 shows the locations of the nuclear power plants in Japan.

The two most commonly used electricity generating nuclear reactors are the pressurized water reactor (PWR) and the boiling water reactor (BWR). A PWR involves pumping high pressure coolant (water) to the reactor core vessel to extract heat release as a result of the nuclear fission reaction. The water heated to high temperature after acquiring energy from core fuel is then passed through a steam generator to heat up the secondary coolant to produce steam. The resulting steam in the secondary loop is passed through turbine to generate mechanical power that is converted to electricity by the generator. Unlike a PWR, in a BWR the steam (~282°C) is generated in the nuclear core and is used to drive the turbine directly. In case of an accident, a BWR is more susceptible to radiation leaks than a PWR is, due to direct utilization of the contaminated steam outside the primary containment. The BWR containment consists of a drywell that houses the reactor with a related cooling system and wet well or a suppression pool. The suppression pool contains water for core cooling during an emergency reactor shutdown.

Figure 2 presents the schematic of a boiling water reactor (BWR)-based nuclear power plant, showing the reactor vessel with the fuel and control rod assemblies, turbine and generator arrangement, seawater-cooled condenser, suppression pool, and, most importantly, the electrically driven emergency core cooling system (ECCS) with pumps. The nuclear
power plants normally use seawater for the cooling purpose. The BWR plant shown in Fig. 2 is similar to the one used in the Fukushima Daichi reactor No. 1 that suffered from the nuclear accident in March 2011, due to the cooling system failure. The No. 1 reactor had thermal and electric power outputs of 1,380 and 460 MW respectively. The ECCS, which is activated after the reactor shutdown, typically uses the diesel generators to power a number of pumps for spraying high-pressure water on the hot core. The existing ECCS systems are not reliable and can fail as consequences of natural disasters.

One of the worst nuclear accidents at Fukushima nuclear power plant was resulted from the failure of the electric generators for the ECCS. This failure was caused by the M9 earthquake and the tsunami triggered by it. When an earthquake hits, the nuclear reactors are automatically shut down by using a control rod mechanism. After shutdown, the emergency core cooling system is required to transfer and dissipate the residual heat from the core and maintain the reactor below the fuel meltdown temperature (~1,800°C). If the active water cooling system stops due to loss of electrical power, then the reactor internal temperature and pressure will rise due to steam formation which will cause a meltdown and explosion. To make nuclear power plants safer against such accidents, a heat pipe based system for removing decay heat from the reactor core is proposed and analyzed in this paper.

The decay heat output by the reactor after shutdown \( P(t) \) can be expressed by the Eq. (1); \( P(t) \) depends on the normal thermal power before shutdown \( P_o \), time for which the reactor was in operation before shutdown \( t_s \), and the time since the reactor shutdown \( t \).

\[
\frac{P(t)}{P_o} = 0.066[t^{-0.2} - (t_s + t)^{-0.2}]
\]  

The decay heat variation for a nuclear reactor, which has 1,350 MW of thermal power and has been operated for the last 5 years before shutdown, is presented in Fig. 3. It is observed that immediately after the reactor shutdown, the decay heat is around 6.4% of total thermal power under the normal operating condition, and falls to 0.5% after a day and continue to decrease exponentially with respect to time.

2. Heat Pipe Based ECCS Design

Figure 4 shows the proposed loop-type heat-pipe based emergency core cooling system that utilizes the initial water charge system and the loop type heat pipe for core cooling after shutdown. The concept uses an emergency cooling water tank installed at a certain height for initial water charge into the core, which is fed by gravity in a specific time (~10 min), followed by passive core cooling using the loop type heat pipe. The purpose of the initial water charge is to avoid the Leidenfrost effect; in this, a liquid comes in contact with a surface, which is significantly hotter than the liquid’s boiling point, produces an insulating vapour layer that keeps the liquid from rapid boiling, thereby the heat transfer from the hot surface to the vapor is limited. Here, the gravity-assisted initial flooding of water onto nuclear fuel helps to limit the occurrence of this phenomenon.

The loop heat pipe system is designed for cooling a 27 MW heat load, which is the extent of the decay heat output after the initial water charge of 32 kg/s for 10 min. The evaporator consists of 75 tubes, 0.15 m in outer diameter and 7 m long, placed around the circumference of the fuel core. All the evaporator pipes are connected via top and bottom
ring-shaped headers. The natural convection cooled condenser consists of 1,260 tubes, each 0.15 m outer diameter and 5 m long, with the aluminium fins. All of these tubes are connected by top and bottom rectangular headers. The heat pipe material is stainless steel SUS-316L with an internal Ti coating to make the system compatible with water as the working fluid. Figure 5 presents a three-dimensional view of the emergency core cooling system using the loop-type heat-pipe system.

3. Reactor Thermal Analysis

The reactor vessel was analysed on the basis of energy balance under the different core cooling conditions as follows:

3.1 ECCS failure: No cooling

If the cooling function of the ECCS fails, the temperature of the reactor vessel will increase continuously due to the decay heat released by the nuclear fuel inside the core. Figure 6 presents a thermodynamic model of the system under a no-cooling condition. The heat removal can be mathematically expressed by Eq. (3).

\[ MC_{pw} (T_{ri} - T_{rf}) = P(t) \Delta t \]

Where, \( M \) is the water mass inside the reactor, \( C_{pw} \) is the specific heat capacity of water, \( T_{ri} \) is the reactor initial temperature and \( T_{rf} \) is the reactor final temperature after \( \Delta t \) time. \( P(t) \) is the rate of decay heat output by reactor, with 1,350 MW nominal output, as mentioned in Eq. (1). Figure 7 presents the transient temperature response of 200 tons of water inside the reactor; the temperature is initially at 282°C and reaches nuclear meltdown temperature (>1,800°C) within 2 days.

3.2 Loop heat pipe based ECCS

Heat pipe is turned out feasible to provide a reliable and powerless two-phase heat-transfer system for the removal of the decay heat without any failure consequences. The required thermal resistance for a heat pipe system, which is based on 27 MW of initial decay heat, 50°C ambient, and 282°C initial reactor water temperature, is \( 8.6 \times 10^{-6} \) K/W. Based on the proposed loop-type heat-pipe design, the heat pipe thermal resistance, \( R_{hp} \), is estimated to be \( 5.78 \times 10^{-6} \) K/W which is lower than the required value thereby qualifying the heat pipe design for the present reactor core cooling capacity. Figure 8 presents a thermal model with heat pipe; the heat removal can be mathematically expressed by Eq. (3).

\[ MC_{hp} (T_{ri} - T_{rf}) = (P(t) - Q_{hp}) \Delta t \]
Where, $Q_{hp}$ is the heat pipe heat removal rate given as:

$$Q_{hp} = \frac{(T_a - T_r)}{R_o}$$

(4)

Where, $T_a$ is the ambient temperature ~50°C.

Figure 9 shows the transient response of the reactor vessel temperature, $T_{rf}$, with heat pipe heat removal system as calculated from Eq. (3). $R_o$ is the overall thermal resistance of the heat pipe heat removal system that includes heat pipe thermal resistance, reactor water to evaporator external surface thermal resistance and condenser external surface to air thermal resistance. It is observed that with the given configuration of the heat pipe, and natural cooling of condenser, the reactor water temperature will be cooled down below 100°C within 12 h of the reactor shutdown.

### 3.3 Loop type heat pipe ECCS with initial water charge

The proposed heat pipe based ECCS system with initial water charge represents a more advanced and developed version of a simple loop heat pipe system by providing reliable cooling of the ECCS system using heat pipe and by addressing high temperature heat transfer limiting issues (Leidenfrost effect) using a gravity fed initial water charge for 10 min. Figure 10 represents the thermal model of the proposed system and Eq. (5) shows the energy balance for the overall system.

$$MC_{pw}(T_{tf} - T_{ri}) = [(P(t) - Q_{hp}) + m_w C_{pw}(T_a - T_{rf})] \Delta t$$

(5)

Where, $m_w$ is the gravity fed water mass flow rate.

Figure 11 presents the estimated reactor water temperature, $T_{rf}$, with a 10 min initial water charge (32 kg/s) and heat pipe based emergency core cooling system, as calculated from Eq. (5). Based on the simulation model, it is estimated that the proposed cooling system can reduce the core temperature to lower than 100°C within 5 to 6 h. For comparison, if the initial water charge is not used then the reactor temperature is reduced lower than 100°C in approximately 12 h, as discussed in the last section. Therefore, the initial water charge helps to reduce the cooling time by more than half as well as helping to address limiting heat transfer issues during system startup.

### 4. Experimental Approach

In order to validate the concept of cooling nuclear reactor core using loop-type heat pipe with initial gravity water charging, a lab prototype with 1:10,000 scale will be fabricated and tested. The proof of concept prototype will be expected to transfer heat load up to 3 kW and will be down-scale on the basis of 1) evaporator length to diameter ratio,
2) evaporator active heat flux, and 3) evaporator axial heat flux criteria, to simulate experimental conditions close to real scale model. Heat pipe container material and working fluid will be similar to the proposed configuration. Figure 12 shows the preliminary prototype design. The oil tank represents the nuclear reactor vessel. The loop heat pipe evaporator consists of 8 pipes, 25 mm in diameter and 0.5 m long. All the pipes connect via top and bottom header. The condenser will be cooled by natural air convection. It consists of 5 pipes of diameter 25 mm in diameter and 0.6 m long. Each of condenser pipes has 60 aluminium fins 120 mm in diameter with a fin thickness of 0.5 mm and a fin gap of 10 mm.

5. Conclusions

Based on the present investigation, it can be concluded that loop type heat pipe emergency core cooling system can be successfully utilized to cool a nuclear reactor core. The proposed heat pipe emergency core cooling system was designed to dissipate 27 MW (2% of full thermal power) of decay heat from a reactor vessel at an initial temperature of 282°C to ambient air at 50°C. It is recommended to use initial water charge for 10 min with 32 kg/s flow rate to accelerate the cooling time of the core and provide a safer cooling system. With combined initial gravity feed water charge and heat pipe cooling, the designed system can reduce nuclear core temperature to less than 100°C in less than 6 h. It is suggested to install 4 to 5 separated type heat pipe system to make a more reliable design. The proposed system can be operated completely passive which will provide a safer operational environment for nuclear power plants.

References

1) World Nuclear Organisation, Available:
2) Energy Business Daily, Available:
   http://energybusinessdaily.com/power/nuclear-power-2/

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