Applied Thermal Engineering 96 (2016) 277–285

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Hybrid heat pipe based passive cooling device for spent nuclear fuel dry storage cask

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HIGHLIGHTS

- Hybrid heat pipe was presented as a passive cooling device for dry storage cask of SNF.
- A method to utilize waste heat from spent fuel was suggested using hybrid heat pipe.
- CFD analysis was performed to evaluate the thermal performance of hybrid heat pipe.
- Hybrid heat pipe can increase safety margin and storage capacity of the dry storage cask.

ARTICLE INFO

Article history:
Received 2 October 2015
Accepted 25 November 2015
Available online 9 December 2015

Keywords:
Heat pipe
Passive cooling
Spent nuclear fuel
Dry storage
CFD

ABSTRACT

Conventional dry storage facilities for spent nuclear fuel (SNF) were designed to remove decay heat through the natural convection of air, but this method has limited cooling capacity and a possible re-criticality accident in case of flooding. To enhance the safety and capacity of dry storage cask of SNF, hybrid heat pipe-based passive cooling device was suggested. Heat pipe is an excellent passive heat transfer device using the principles of both conduction and phase change of the working fluid. The heat pipe containing neutron absorber material, the so-called hybrid heat pipe, is expected to prevent the re-criticality accidents of SNF and to increase the safety margin during interim and long term storage period. Moreover, a hybrid heat pipe with thermoelectric module, a Stirling engine and a phase change material tank can be used for utilization of the waste heat as heat-transfer medium. Located at the guide tube or instrumentation tube, hybrid heat pipe can remove decay heat from inside the sealed metal cask to outside, decreasing fuel rod temperature. In this paper, a 2-step analysis was performed using computational fluid dynamics code to evaluate the heat and fluid flow inside a cask, which consisted of a single spent fuel assembly simulation and a full-scope dry cask simulation. For a normal dry storage cask, the maximum fuel temperature is 290.0 °C. With hybrid heat pipe cooling, the temperature decreased to 261.6 °C with application of one hybrid heat pipe per assembly, and to 195.1 °C with the application of five hybrid heat pipes per assembly. Therefore, a dry storage cask with hybrid heat pipes produces relatively low temperature inside a cask and reduces the possibility of structural failure due to thermal degradation.

1. Introduction

Spent nuclear fuel (SNF) is the nuclear fuel generated after the fission process in nuclear reactor and includes fissile materials such as uranium and plutonium. According to the International Atomic Energy Agency, over 10,000 metric tons of SNF are generated by nuclear reactors worldwide every year, and about 80% of SNF are kept in the designated storage facilities [1]. Since SNF contains highly radioactive material and releases decay heat from nuclear materials, it has to be kept in special facilities immediately after utilization. After burning out in the reactor, spent fuel assemblies are unloaded immediately into a water pool adjacent to the reactor, which is called a SNF pool. Inside the water pool, decay heat and radiation of the SNF assemblies decreases for a few years to decades. After reaching a certain level of heat and radiation after being cooled in the pool, they are transferred to air-cooled dry casks for storage onsite.

After the Fukushima nuclear power plant accident, it was revealed that the technology of spent fuel pools was not perfect in accident such as station blackout without emergency power, for the case that coolant pump stops due to a power loss [2]. In addition, fuel discharge burnup continues to increase. Spent fuel pool is not enough to satisfy the demands for storing high burnup fuels and large amounts of SNF. Therefore, introduction of additional facilities for interim and long term storage of SNF is inevitable. Recently,

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http://dx.doi.org/10.1016/j.applthermaleng.2015.11.086
1359-4311/

dry storage methods have been preferred owing to their good expandability of storage capacity and their easy long-term maintenance [3]. Dry storage uses a gas or air as coolant with passive cooling, and a neutron shielding material instead of the water used in wet storage systems. It is relatively safe, independent of the external power for operation and does not require high-cost facility management.

Considering dry interim storage facilities, metal or concrete casks are the most utilized system worldwide and have been actively developed in many countries. Of these, metal casks have been considered for the pressurized water reactor spent fuel storage in Korea. The Korea Radioactive Waste Agency has been developing a dual-purpose metal cask (DPC) for dry interim storage and long-distance transportation [4]. However, the metal cask has issues that must be overcome: high manufacturing costs, high temperatures of nuclear fuel rods, inaccessibility for monitoring the spent fuel during the storage period, and potential re-criticality problems during accident situations. Re-criticality accident can occur in dry cask when external events such as flooding increase the neutron reaction rate due to surrounding water, which has a high capacity to moderate neutron. If dry cask becomes re-criticality state, uncontrollable reaction can be a factor to release radioactive material to the environment as well as harm the integrity of both spent fuel and cask. In other words, high temperature of nuclear fuel rods and potential re-criticality problems are considered to be the most important for evaluating the long-term integrity and safety of the dry storage facilities.

Since monitoring from the interior of the cask is impossible owing to helium gas seal, many research groups have estimated the aspects of a dry cask in normal or abnormal conditions by computational fluid dynamics (CFD) simulation. In et al. conducted numerical analysis to predict the three dimensional distribution of fuel temperature in a dry cask containing 21 fuel assemblies [5]. Results of the CFD approach for 10-year cooled spent fuel indicated that the helium flow and temperature in a dry cask agreed well with experimental data, and maximum fuel temperature was estimated to be 330 °C. Herranz et al. performed a CFD analysis for a HI-STORM 100S cask with FLUENT 14.0 to investigate the thermo-fluid dynamics within a dry storage cask considering the fuel rod temperature [6]. Application of a 3-D model to dry cask under normal conditions showed that the fuel maximum temperature is 348.34 °C, well below the regulation limit of 400 °C. Kim et al. performed the preliminary safety analysis of criticality for the DPC developed in Korea [7]. In normal condition, maximum effective multiplication factor, k_{eff}, was estimated to be 0.36884. The maximum k_{eff} value was evaluated to be 0.94658 in case of a flood, which is also below the regulation requirement of 0.95, but near the criticality value.

These analysis results showed that dry cask satisfied the regulation criteria such that cladding temperature of the spent fuel should be kept less than 400 °C during the storage period and maximum effective multiplication factor value below critical value of 1. However, high temperature condition inside the cask can accelerate the thermal degradation of the structural materials comprising the metal cask and fuel assembly, as well as limit the storage capacity of the metal cask. In addition, although k_{eff} value from simulation was below the criticality level in both normal and abnormal cases, it is not certain that all possibility of re-criticality issues for the cask can be neglected during natural disasters such as flooding.

In this paper, heat pipe-based cooling device, which is called hybrid heat pipe, for a dry storage cask was suggested to enhance the safety and storage capacity of the metal cask as well as prevent re-criticality accident. To evaluate the concept of the cooling device, a two-step CFD analysis, which consists of single fuel assembly model and full scope dry cask model, was conducted for the cooling performance of hybrid heat pipes. In the single fuel assembly model, the subchannels of the spent fuel assembly and the hybrid heat pipes were analyzed to determine the heat transfer capacity of hybrid heat pipe. In the full-scope dry cask model, the concept of effective thermal conductivity, based on the result of the single fuel assembly model, was used to perform an economic CFD calculation to evaluate the thermal performance of the heat pipe-based cooling device for a dry storage cask.

2. Hybrid heat pipe based passive cooling device and its applications

2.1. Concept of hybrid heat pipe

Heat pipe is an excellent passive heat transfer device that uses the principles of both conduction and phase change [8]. It consists of a sealed metal pipe, working fluid, and wick structure. Liquid returns to the evaporator section through the wick structure by capillary force. Using capillary force and density difference due to the temperature difference, an external power source for operation of the heat pipe is unnecessary. With this passive operation characteristic, heat pipe has been considered to be a heat sink and a passive cooling system for nuclear applications [9]. Fig. 1 shows a schematic of the operating principle of a general heat pipe.

Hybrid heat pipe, which is a heat pipe containing neutron absorber materials, was suggested for passive cooling in nuclear applications by UNIST thermal-hydraulics and reactor safety laboratory in Korea [10]. With the heat transfer characteristics of a heat pipe, a hybrid heat pipe has the capability of both removing the decay heat and controlling reactivity with neutron absorber materials. Hybrid heat pipe can be used in nuclear applications such as a passive in-core cooling system substituting control rod for an advanced nuclear power plant, wet storage pool and dry storage cask for SNF. In this study, hybrid heat pipe was applied to a metal cask-type dry storage facility. Fig. 2 shows the hybrid heat pipe-equipped DPC for dry storage of spent fuel.

Geometry, working fluid selection, and wick structure should be properly selected in the heat pipe design for each specific application

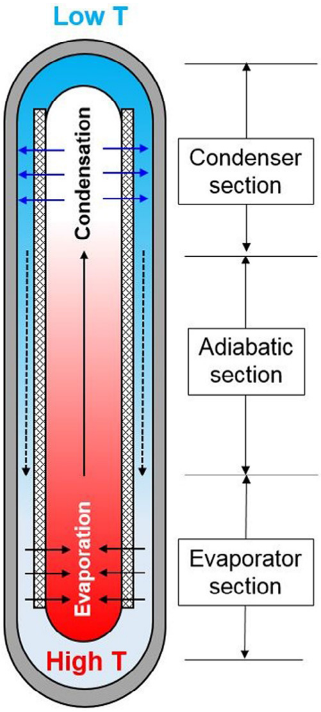

Fig. 1. Operation of heat pipes.