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Spent nuclear fuel with a hybrid heat pipe for electricity generation and thermal management

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ABSTRACT

The global warming resulting from the emission of the greenhouse gases has led to tightened restrictions on the use of fossil. Therefore, renewable energy for new energy sources is being widely investigated. However, renewable energy has limitations such as location, environmental conditions, and the potential construction of a new electricity grid. Spent nuclear fuel (SNF) is one of the potential new energy candidates that does not emit the greenhouse gases or suffer from limitations of other renewable energy sources. In this research, generating electricity by using SNF is suggested with a hybrid heat pipe system. Thermal energy from SNF worldwide is ~750 MWth; however, this energy is not used as an energy source but just removed by chilling in water or in air in storage facilities. To achieve electricity generation from SNF, a dry storage cask with heat pipes and a Stirling engine (UCAN, UNIST CANister) are designed. Using a 1/10-scale test facility, the experimental test of heat transfer and electricity generation as the module of the storage system is conducted. The results yield good agreement with those predicted by the thermal resistance network model, and the electricity generation of the Stirling engine is in the range from 2.3% to 3.2% of the total heat load. The calculated temperature distributions are a good agreement, deviating within 12.2%, and the cooling efficiencies range from 17.51% to 26.33%. The results show the advantages of the use of SNF and its effects, focusing on thermal management and energy generation. The amount of SNF will gradually increase because of the continued operation of nuclear power plants. The usable heat from the SNF is generated due to the decay of fission products during at least several hundred years, which enables to use the SNF as one of the energy sources.

1. Introduction

The rate of increase of the global average surface temperature has doubled during the past 50 years [1]. Global warming is caused by the increase in greenhouse gases, especially those emitted from fossil fuels. Therefore, current EPA regulations for fossil-fuel CO_2 emission have gradually become stricter [2]. The International Panel on Climate Change predicts that global temperatures will rise about 1.4–5.8 °C until 2100 as a result of fossil fuel emissions [3]. Recently, the restriction on the use of fossil fuel is carried out to mitigate the global warming caused by greenhouse gases. Then, the need of alternative energy sources arises to meet the energy demand without emissions of the greenhouse gases. Renewable energies such as wind power, hydropower, tidal power, wave power, solar power, and biomass have been widely developed and used as a possible alternative energy source [4–6]. However, these sources have a critical weakness in that the efficiency of extraction and performance of generating facilities are limited according to the environment, operation temperature, and location. Therefore, great electrical grid distances between the power generation region and the cities are required and the unstable electric generation from renewable energy cannot be considered as a source of fixed power to meet electricity needs. Most renewable energy plays the role of backup power in the energy market and its price is high in comparison with that of fossil fuel.

Spent nuclear fuel (SNF) is a potential new energy candidate with a stable energy supply that can be exploited with the current electrical grid. Current SNF is not used for electric generation; rather, the fuel rods are just cooled by chilling in water or in air in spent fuel storage facilities. In general, the spent fuels of pressurized water reactors are placed into intermediate storage pools for 3–5 years owing to their high decay heat and radiation [7]. After that, air cooling in dry storage casks is employed for ~40–60 years. Decay heat is continuously released in each dry storage cask; however, it cannot be considered as an energy source. In 2014, the amount of global SNF in storage was > 371,000 metric tons, and the growth of this amount is > 12,000 metric tons per year [8]. Five years after shutdown of a nuclear power plant,

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Nomenclature

A	area [m^2]
$\dot{C}$	cost rate [\$/h]
C_p	specific heat [J/kg K]
g	gravitational constant [m/s^2]
h	heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat [kj/kg]
k	thermal conductivity [W/mK]
L	characteristic length [m]
$\dot{m}$	mass flow rate [kg/s]
n	number of heat pipes [–]
t	thickness [m]
T	temperature [K]
$\overline{T}$	average temperature [K]
P	pressure [Pa]
Pr	Prandtl number [–]
q	heat input [W]
Q	heat load [W]
$\dot{Q}$	heat transfer rate [W]
R	resistance [K/W]
W	work [W]
$\dot{Z}$	capital cost rate [\$/h]

Greek symbols

α	thermal diffusivity [m^2/s]
β	thermal expansion [K^{-1}]
ε	emissivity [–]
σ	Stefan-Boltzmann constant [$W/m^2 K^4$]
ρ	density [kg/m^3]
ν	kinematic viscosity [m^2/s]
μ	dynamic viscosity [Pa·s]
τ	working hour [h]
Ω	maintenance cost [\$]

Subscripts

amb	ambient
assem	assembly
axial	axial
ba	basket
c	condenser of the heat pipe
conv, can	convection of the canister
conv, top	convection of the top lid
e	evaporator of the heat pipe
eff	effective
elec	electricity
g	gas inside canister
h	heater
HP	Heat pipe
in	input
l	liquid
o	overall
out	output
rad	radiation
radial	radial
s	surface
sat	saturation
St	Stirling
tot	total
v	vapor
w	wall

commercial uranium SNF is down to 2–3 kWth/(tons of Uranium fuel) (approximately double that of the fuel assembly) [9,10]. Worldwide, the energy from SNF is > 750 MWth. This energy source emits no greenhouse gases from the fuels and no additional electrical grid is needed because of the existing infrastructure of nuclear power plants.

There are several ideas and patents for use of SNF, including photovoltaic-cell-based generation, thermal electric modules, and Stirling engine concepts [11–14]. A power generation system from a spent fuel cask was suggested by the Westinghouse Electric Company. This concept considers the various heat engines (Rankine cycle engine, Stirling engine, and thermal electric device) for electric generation and application of both dry and wet storage systems for the additional cooling system [11]. However, this system's performance, efficiency, possible design, and experimental verification cannot be confirmed. A hydrogen generation system inside a spent fuel pool was also suggested because of the well-developed nuclear power plant grid [12]. It seems that this system can also not be validated and applied owing to the issue of a potential hydrogen explosion inside the reactor containment building. To generate electricity from spent fuel, a scintillator–photovoltaic-cell-based radiation energy conversion method was suggested [13,14]. In this research, computational modeling and its validation were conducted for confirming the amount of electric energy generated.

As described previously, several research studies have been conducted based on SNF to use the decay heat energy and radiation energy and as an additional application of the storage facility. In these studies, the conceptual design and theoretical analysis were suggested for generating electricity by using SNF. However, most of the concepts cannot be confirmed based on the experimental results and the theoretical results cannot be validated. To achieve enhanced cooling performance and recycling of waste heat, an advanced dry storage cask concept (UCAN, UNIST CANister) was proposed at the Ulsan National Institute of Science and Technology (UNIST) [15,16]. This concept consists of a hybrid heat pipe combined with a heat pipe heat removal device, Stirling engine, and a DC generator for contributing to roles of both cooling and recycling the spent fuel. The hybrid heat pipe has a metal cladding, a working fluid, and a neutron absorber (B_4C), and the evaporator and condenser are located at the center of each fuel assembly and at the top of the dry storage cask, respectively. Due to the high capability of generating low heat with high efficiencies, the Stirling engines for the waste heat are widely studied in recent decades [17–21]. The heat from the spent fuel is transported from the spent fuel assembly to the top of the cask by the phase change of the water. The Stirling engine can operate by using the temperature difference between the upper dry cask and air and cool the dry storage cask.

In this paper, combined thermal management and electric generation using an integrated cooling and power generation system were analyzed based on the results from a 1/10-scale test facility. To confirm the effect of the electricity generation system of the dry storage cask, the heat transfer performance of the dry storage cask for electric generation and its thermal efficiency were investigated. The experimental results gave the temperature distribution of the wall inside the dry cask, the heat transfer performance of the integrated cooling and power generation system, and the generation efficiency under operational conditions. These results demonstrate that the UCAN concept can possibly be used to enhance the dry storage cask and generate electricity without enormous design change.

2. Description of the storage cask with a hybrid heat pipe

In this section, the dry storage cask with a hybrid heat pipe concept, the UNIST canister (UCAN), is described. The initial concept of the UCAN was suggested for application to a metal cask-type dry storage