FEASIBILITY OF HEAT PIPE TECHNOLOGY FOR PASSIVE HEAT REMOVAL IN NUCLEAR POWER PLANTS

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Abstract

Heat pipes are efficient and reliable heat transfer devices that have been widely used in space applications. Due to their passive operation, they are attractive and suitable devices for passive heat removal for future nuclear power plants. The use of heat pipes has been proposed in few small reactor designs for passive heat removal from the reactor core. Other potential applications of heat pipes include transferring excess heat from nuclear reactor's containment building to the atmosphere by integrating low temperature heat pipes into the containment building, as well as passively cooling spent fuel bays. This paper reviews heat pipe technology and its applications for passive heat removal in nuclear power plants. Heat pipe components and the limiting factors that should be considered in a heat pipe design are discussed briefly and feasibility studies of using heat pipes for passive cooling of a spent fuel pool is discussed.

1. Introduction

A heat pipe is a closed loop heat-transfer device enclosing a working fluid that transfers heat from a hot source to a cold sink through a combination of evaporation, convection and condensation heat transfer mechanisms. Heat pipes operate passively, and are highly reliable with limited or no maintenance required. In comparison to conduction through a solid metal, heat transfer rates across a heat pipe can be greater by more than one order of magnitude [1].

After the Fukushima Daiichi nuclear disaster in 2011 March, the capability of passively removing decay heat for an indefinite period of time following station blackout is considered as an option to prevent core melt. Eliminating the need for offsite emergency response is one of the goals of new generation reactor design [2]. Heat pipe technology is an attractive alternative that can reliability remove decay heat from the nuclear power plant for an indefinite time due to their passive operation, low maintenance, and high efficiency.

In this report, factors limiting heat pipe performance are discussed. In addition, the feasibility of using heat pipes in passively removing spent fuel pool and reactor core decay heat following a station blackout is discussed.

2. Heat Pipe Technology

The idea of the heat pipe was first suggested by R.S. Gaugler of General Motors Corporation in the early 1940's. However, it was not until the independent reinvention of heat pipes by G.M. Grover in the early 1960's that a serious development of heat pipes began [1].

A heat pipe is a closed loop heat transfer device incorporating an evaporator, adiabatic section, condenser and working fluid. The working fluid absorbs energy from the heat source and changes from liquid to gas phase in the evaporator section. The produced gas passes through the adiabatic section into the condenser section, where the gas is condensed, releasing its energy to the heat sink and returned to the evaporator as a liquid. Figure 1 illustrates schematically a conventional heat pipe [3], which incorporates a wick material to produce capillary pressure to return the condensed fluid to the evaporator. Because this type of heat pipe does not rely on gravity or external forces to return the working fluid to the evaporator section, it is extensively used in space applications.

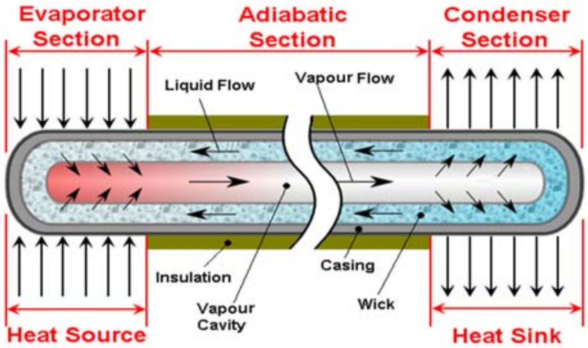


Figure 1 Schematic of a Conventional Heat Pipe [1]

Heat pipes do not contain any moving mechanical parts. As a result, they are highly reliable and they can operate over long periods of time with minimal or no maintenance if proper materials are selected [1]. Due to their properties, heat pipes have been proposed to transfer heat from the reactor core in a number of space reactors and small modular reactor concepts.

2.1 Heat Pipe Components

Heat pipe components are selected based on operation conditions, and normally operate within an internal absolute pressure range of 10 kPa to 2 MPa. The first consideration in selecting a working fluid is the temperature range over which the fluid will operate and the working fluid boiling point. For instance, nitrogen usually used as a working fluid for operating temperature in a range of -203°C to -160°C due to its low boiling point and water is suggested for operating temperatures in a range of 30°C to 200°C [1][3]. In addition to boiling point of the working fluid, its compatibility with wick and container material, latent heat, thermal conductivity and viscosity are important factors in selecting a suitable working fluid.

The container transfers the heat between the working fluid and outside environment; therefore, its thermal conductivity is an important factor in selecting container material. In addition, the container should be able to withstand the pressure differential across the heat pipe at all operating conditions. The container should also be leak-tight, corrosion resistant to the working fluid, and prevent diffusion of gas into the heat pipe. Some of the important factors in selecting container material are compatibility with the working fluid, wick material and the environment, thermal conductivity, strength to weight ratio, wettability and ease of fabrication [1][3].

2.2 Heat Transfer Limitation

There are factors that limit the amount of power that can be transferred by a heat pipe. Figure 3 shows the heat transfer limitation in a capillary or thermo-siphon heat pipe.

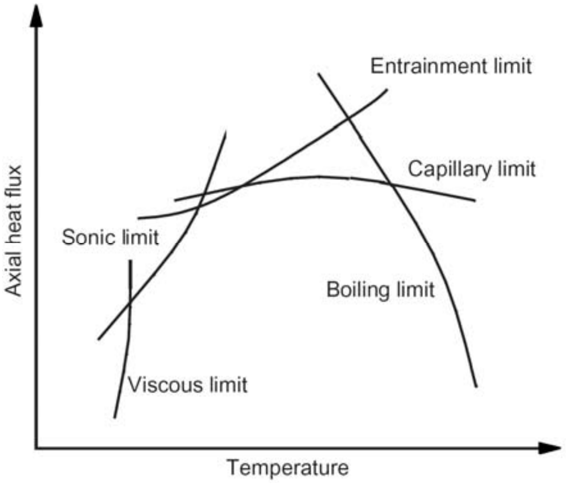


Figure 2 Limitation to Heat Transfer in a Capillary or Thermo-Siphon Heat Pipe

Maximum heat transport capability, in most cases, is restricted either by entrainment of liquid by the vapour flow or by critical heat flux of the evaporator surface in thermo-siphon heat pipes [1][3]. Shear force at the interface of the vapour and liquid affects the mass flow rate of the condensed liquid to the evaporator. High vapour velocities may cause a sufficient shear force at the liquid vapour interface to tear the returning liquid from the surface and entrain it into the vapour flow stream. This is often a concern for a heat pipe that operates at high temperatures [1][3]. In the absence of gravity, where a wick structure is used, the capillary pressure is the limiting factor in a heat pipe. As is shown in Figure 3, viscous and sonic phenomena limit heat pipe performance at low operating temperatures.

2.3 Types of Heat Pipe

Heat pipes can be classified based on the method in which the condensed gas is returned to the evaporator, such as gravity (thermo-siphon), capillary, centrifugal, electro-kinetic, magnetic, etc. Of these, the gravity-assisted and capillary-driven heat pipes are of interest for this report.

Heat pipes can also be designed in a loop shape, where the vapour and returning liquid have separate flow paths. Although not as compact as the standard heat pipes, these can work at higher power rates. Where the heat source is placed at the same elevation as the heat sink, a wick material may be used in the loop heat pipe to increase the flow rate of the working fluid and to spread the liquid evenly in the evaporator.

Figure 2 shows schematically a gravity-assisted loop heat pipe. Because the heat source is located at a lower elevation relative to the heat sink, a gravity driven flow is established, eliminating the need for a wick structure. As a result, the pressure drop in the wick structure (i.e. the capillary limit) is eliminated. In addition, loop heat pipe has separate steam and liquid path, therefore, the entrainment limit is eliminated as well. The gravity-assisted loop heat pipe can transfer large heat loads over long distances efficiently, making these an attractive device for passively and efficiently removing decay heat in nuclear power plants. Their performance is mainly limited by the boiling limit in the evaporator. This type of heat pipe has been employed in advanced nuclear power plants [4].

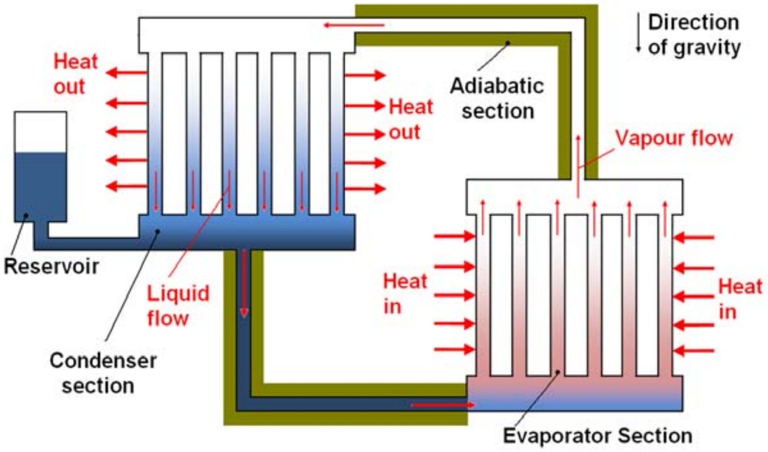


Figure 3 Gravity-Assisted Loop Heat Pipe [5]

3. Applications of Heat Pipe for Passive Decay Heat Removal

Passive safety systems are considered for advanced reactor designs to remove decay heat during station blackout conditions. Total loss of grid and Diesel powers that lead to the Fukushima Daiichi nuclear disaster in 2011 March underlined the significance of passive decay heat removal. Typically, these systems consist of a heat exchanger submerged in a water pool located above the reactor, with piping connecting the reactor's inlet and outlet. Using the reactor coolant as the working fluid, decay heat generated in the core vaporizes the coolant, which is then condensed in the heat exchanger. In this fashion, the decay heat is deposited in the pool water, preventing core melt and fission product release.

In addition, the need for long term passive cooling of the spent fuel pool has been highlighted after the Fukushima Daiichi nuclear disaster. Loop heat pipes are considered a good candidate for passive heat removing from the spent fuel pool, with these two applications discussed in greater detail.

3.1 Passive Long Term Core Decay Heat Removal

At the moment of reactor shutdown following a long period of power history, the heat generated due to the decay of short-lived radioisotopes is approximately 6.5% of the full power level and falls to approximately 0.5% after a day. The heat generated steadily decreases over a period of years, but the total heat generated over that period can be considerable. When dealing with irradiated fuel, consideration must be given in the selection of the ultimate heat sink (UHS).

In the case of the advanced reactor designs, the UHS water pool temperature increases until boiling occurs. The pool continues to act as a heat sink as the water inventory is boiled off, typically within 24 to 72 hours, depending on the reactor plant design. Intervention is then required, usually in the form of refilling the pool from mobile equipment or from a nearby water reservoir using diesel powered pumps.

A loop heat pipe can be used to transfer the heat from UHS water pool to the environment to delay the point of intervention. Such a system is suggested for some advanced reactors such as the Canadian Supercritical Water-Cooled Reactor (SCWR) [6][7]. In this reactor concept, isolation condenser heat exchangers passively transfer the core decay heat from the reactor vessel to a UHS water pool [6]. A separate loop heat pipe can be used to transfer the heat from UHS water pool to the environment to prevent the UHS water pool from drying out. Figure 4 shows the cross section of the Canadian SCWR. This figure shows the UHS water pool and the atmospheric air heat exchanger of the loop heat pipe that is located outside the containment building.

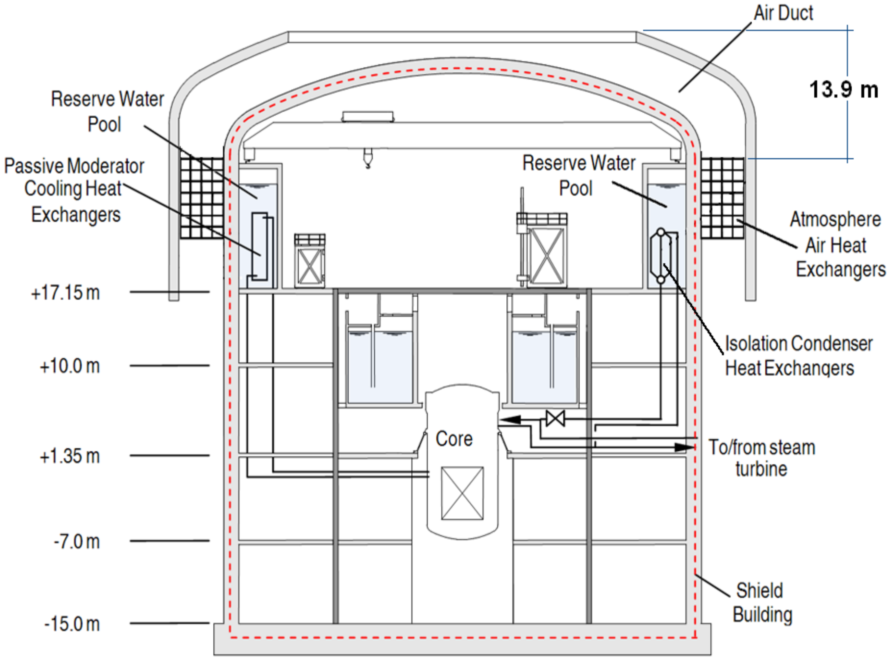
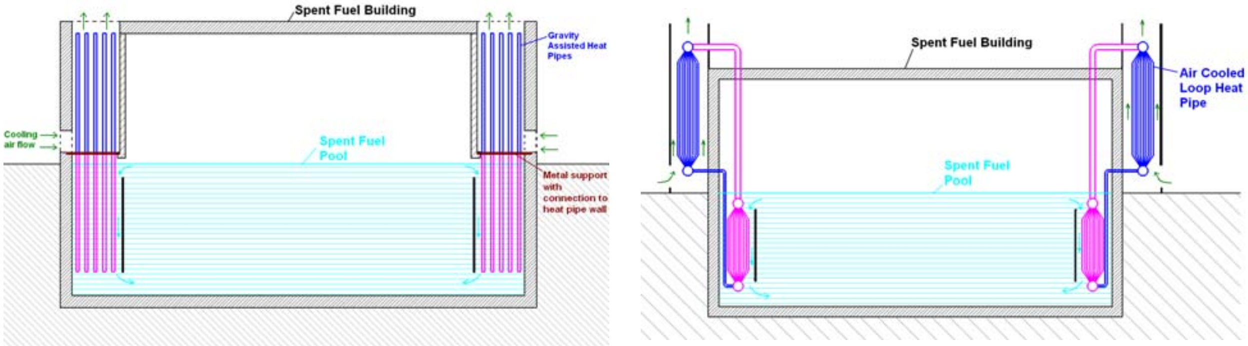


Figure 4 Canadian SCWR Shield Building Cross-Section

3.2 Passive Cooling of Spent Fuel Pool

Fuel assemblies are typically stored in a spent fuel pool after irradiation in the reactor core until their decay heat is sufficiently reduced for dry storage. The pool water temperature is maintained by pumping the water through heat exchangers. Under station blackout conditions, this active system must be powered by a backup source of power such as stand-by diesel generators. After the Fukushima Daiichi accident in which all back-up power was lost, the necessity of spent fuel pool long term passive cooling system was identified. In such conditions, as with the UHS water pool, the spent fuel pool temperature will increase until boiling occurs. The pool continues to act as a heat sink as water inventory above spent fuel boils off, with this period typically lasting from several days to weeks, depending on the pool design. Intervention is then required, usually in the form of refilling the pool from mobile equipment or diesel powered pumps.

A loop heat pipe can be used to transfer the heat from a spent fuel pool to the environment to delay the point of intervention. Since the conditions and temperatures are virtually identical to those found in the UHS water pool, appropriately sized heat pipes, similar to those proposed for the reactor core decay heat removing, can be used to passively transfer the decay heat generated by the spent fuel to the environment. Figure 5 (A) and (B) illustrate standard wick-type and loop type heat pipe concepts for passive decay heat removal of a spent fuel pool. While it remains possible to accomplish this with standard heat pipes as shown in Figure 5 (A), loop type heat pipes, Figure 5 (B), are preferred due to their greater power transferring capability.



(A) (B)

Figure 5 Passive Decay Heat Removal from Spent Fuel Pool Using (A) Gravity-Assisted Heat Pipe and (B) Gravity-Assisted Loop Heat Pipe

3.3 Preliminary CATHENA Simulations

Canadian Algorithm for THErmalhydraulic Network Analysis (CATHENA) code, which is a one-dimensional, two-phase, non-equilibrium system thermalhydraulics code, was used to understand the loop heat pipe behavior in greater detail.

Figure 6 shows a schematic view of a suggested loop heat pipe that can be used to transfer heat from an atmospheric-pressure water pool to the atmosphere. The evaporator and condenser heat exchange surface area relates to the convection heat transfer coefficients of the heat exchanger in their respective environment and the temperature differential between pool water and heat sink. The heat transfer coefficients for the evaporator (heat exchanger in UHS water pool, h_{pool}) and condenser (air heat exchanger, h_{air}) are estimated to be 291 W/(m$^{2\cdot}$K) and 4.0 W/(m$^{2\cdot}$K) respectively [8]. The UHS water pool temperature is conservatively assumed to be 90°C (T_{pool}), indicating a 10°C subcooling for the atmospheric pressure of the reactor building. The environment air temperature is conservatively assumed to be 40°C (T_{air}), giving a 50°C temperature difference between UHS water pool and environment.

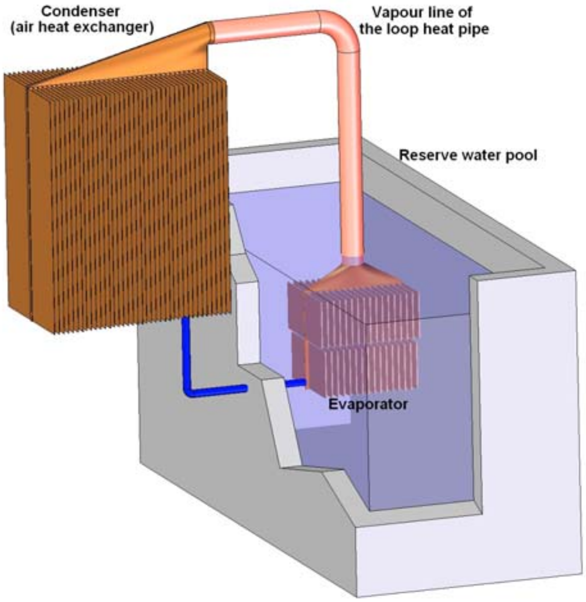


Figure 6 Schematic View of the Loop Heat Pipe of the UHS Water Pool Cooling System

Figure 7 shows the loop heat pipe model in the CATHENA simulation. This figure shows the loop heat pipe that consist of an evaporator (EVP), hot leg (HLEGV, HLEGH), cold leg (CLEGV, CLEGH), and a condenser (HEX). The evaporator and the condenser are modeled by pipe components in CATHENA and each component has ten nodes. The hot leg pipe and cold leg pipe are modeled by a vertical pipe and a horizontal pipe, respectively, in which each one has ten nodes as well.

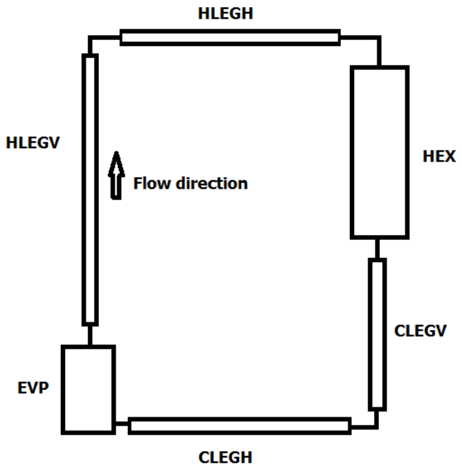


Figure 7 Gravity-Assisted Loop Heat Pipe Model

The boundary conditions are specified as follows:

- The UHS water pool and air temperatures are assumed to be 90°C and 40°C respectively,
- Convective heat transfer coefficient of the evaporator (heat exchanger in UHS water pool) is estimated to be 291 $W/(m^2K)$,
- About 40 kg of water inventory is assumed in the loop heat pipe, based on the evaporator volume and estimated void fraction of the working fluid at power, and
- Convective heat transfer coefficient of the condenser (air heat exchanger) are estimated to be 4.0 $W/(m^2K)$.
- The initial conditions for each component are given as 85°C and 57.8 kPa.

The analysis showed that the ratio of evaporator-to-condenser surface areas and the amount of water present in the loop heat pipe have significant effects on the heat transfer efficiency of the system. For the analyzed loop heat pipe, the optimum evaporator to condenser surface area ratio for 40 kg of water as working fluid and operating temperature of the loop heat pipe are estimated based on these conditions to evaluate the feasibility of using loop heat pipes to remove the decay heat.

In order to optimize the heat transfer relative to the combined surface area of the evaporator and condenser, a series of CATHENA simulations were performed by changing the heat transfer surface area of the condenser, with the evaporator heat transfer area is fixed at about 120 m^2. An individual loop heat pipe module with an evaporator surface area of about 120 m^2 is thus assumed. This surface area is estimated based on a plate type heat exchanger with 30 plates of 2 m by 1 m and 2 cm thick. A gap 10 cm is assumed between neighboring plates.

Heat transfer per combined surface area varies with the condenser to evaporator surface area ratio as shown in Figure 8 for 40 kg of water inventory in the loop heat pipe. It shows that the total heat rejected from the system increases as the condenser/evaporator surface area ratio increases, and plateaus at approximately 10:1 ratio. Meantime, the heat rejected per combined surface area reached its optimum value of ~0.154 kW/m^2 at the surface area ratio of about 3:1, indicating optimized modules offer volumetric and perhaps economic advantages.

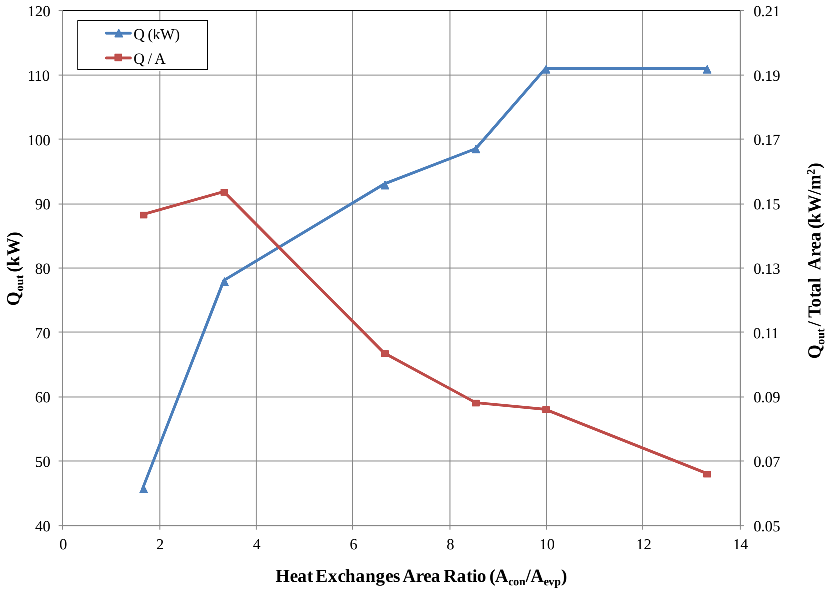


Figure 8 Total Heat Transfer and the Heat Transfer per Combined Surface Area as a Function of Surface Area Ratio for ~40 kg of Water as Working Fluid

The simulation showed that a loop heat pipe module with evaporator and condenser surface areas of 120 m^2 and 390 m^2 respectively can reject about 78 kW from a water pool. Figure 9 shows the average temperatures, pressure and void at different locations along the loop for this case. The simulation reached a steady state although there were oscillations at some locations along the loop due to two-phase flow.

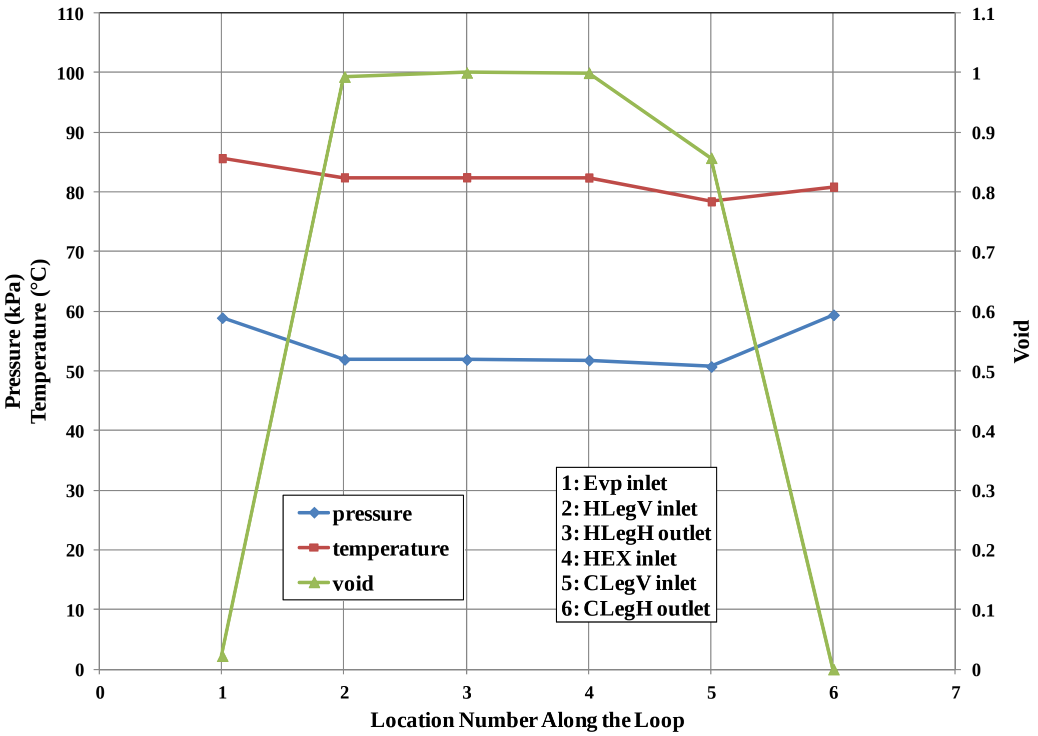


Figure 9 Average Temperatures, Pressure and Void at Different Locations along the Loop for Condenser to Evaporator Surface Area Ratio 3:1 and 40 kg Water

Simulations with different mass of water showed that the loop heat pipe performance can be affected by the initial mass of water in the system. This effect was identified and studied by a few researches as well [1][9]. The effect of changing the total mass in the system on the rejected heat was examined by changing the total mass from ~10 kg to ~130 kg. Figure 10 shows the mass flow rate and the rejected heat as a function of the total mass for the condenser to evaporator surface area ratio of 3:1. Both the mass flow rate and the rejected heat reached their optimum values at a total water mass of ~30 kg. This simulation shows that a loop heat pipe module filled with ~30 kg water and evaporator and condenser surface area of about 120 m^2 and 390 m^2 respectively, can remove about 80 kW of decay heat.

Similar analysis should be performed for different condenser to evaporator surface area ratios varying the water mass in the loop heat pipe to identify the optimum surface area ratio and water inventory when considering a particular heat pipe configuration.

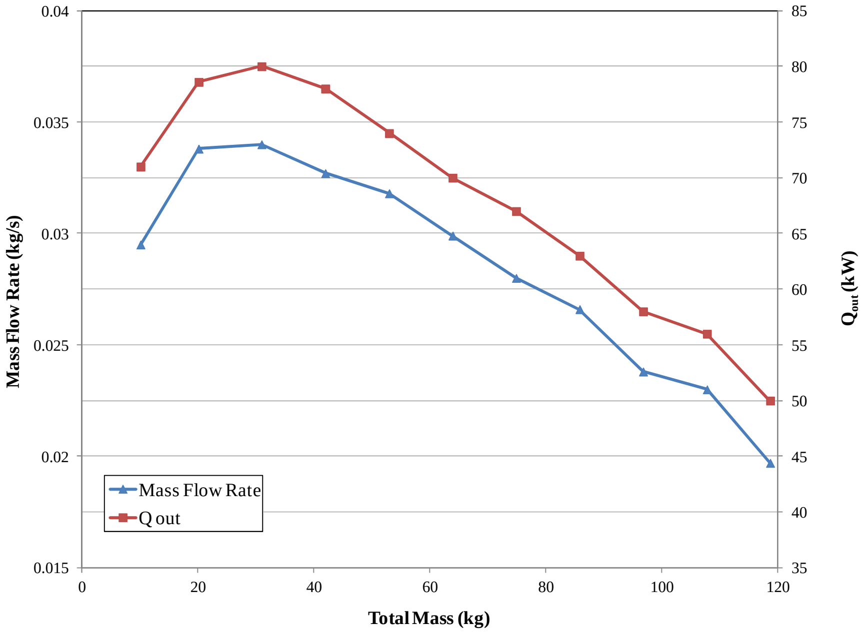


Figure 10 Mass Flow Rate and Rejected Heat as a Function of Total Mass for 3:1 Condenser to Evaporator Surface Area Ratio

4. Conclusion

Fukushima Daiichi accident highlighted the significance of long term passive cooling of nuclear reactors. In most advanced reactor designs, a large water inventory in the form of a UHS water pool is used to provide cooling to the reactor core for a limited time period following a station black out. This paper studies the feasibility of utilizing loop heat pipes to delay or prevent core melt by transferring decay heat from the fuel in the reactor core to the environment. Similar loop heat pipes can be used in spent fuel pools to remove the decay heat of spent fuel.

The feasibility study using the CATHENA computer code showed that a loop heat pipe module that loop heat pipe module filled with ~30 kg water with a condenser and evaporator surface areas of ~390 m^2 and ~120 m^2 respectively can remove about 80 kW decay heat from a water pool. Therefore, 125 loop heat pipe modules are required to remove about 10 MW decay power from spent fuel pool or UHS pool. However, detail analytical analysis and experimental studies are required to determine the loop heat pipe performance for passive cooling a water pool for an extended period of time.

Two types of simulations were performed to study individual effects of condenser to evaporator surface area ratio and water mass in the loop heat pipe on the heat transfer per combined surface area. The first type of simulation was performed with water inventory of about 40 kg and varying the condenser to evaporator surface area ratio. The simulation results showed that at the optimum condition the surface area ratio of the condenser to evaporator is about 3:1 (see Figure 8). The second type of simulation with surface area ratio of about 3:1 and varying the water inventory showed maximum heat of ~80 kW can be transferred at the water inventory of about 30 kg (see Figure 10). Note that the 3:1 surface area ratio is the optimum condition for ~40 kg of water inventory in the loop heat pipe geometry modeled in this study. A complete surface area ratio versus water inventory efficiency map would need to be developed in order to determine the highest power transfer density possible for the given geometry.

5. References

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