# Modeling of Proposed Passive Heat Pipe Loops Cooling System

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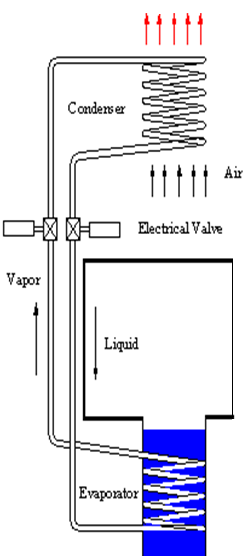
**Abstract**

Heat-pipes are passive heat transfer devices, which have very long lives when properly designed and fabricated. Spent fuel pool heat should be removed to keep fuel temperature within safe limit. Usually SMRs have also spent fuel storage tanks to compromise heat that need to be removed. Gravity assisted two-phase closed heat-pipe loop (GTPCHL) covered by removal of decay heat (or heat after shutdown) with evaporator and condenser lengths each 100m helical coil shape with 100m condenser and evaporator length and 3 mm thickness as a passive cooling system for a nuclear spent fuel storage pool. This study proposes a completely passive cooling system using thermosyphon loop for cooling and dissipation of the residual heat of wet spent fuel storage by running as main or alternative cooling system. The design focuses on heat removal from the spent fuel storage tank of a SMRs. The model considers natural convection by air for the condenser part of the heat-pipe loop to confine the residual heat. A numerical simulation, using special design of (GTPCHLs), was used to investigate the thermal performance of the (GTPCHL). The effects of heat loads were analyzed. Demineralized water was used as the (GTPCHL) working fluid. The atmospheric air was circulated around the condenser as a cooling system. The thermal performance of the (GTPCHL) is evaluated at heat input ranging from (100, 200, 300, 400 and 500 kW) with filling ratio of the working fluid of 100%. From this model the heat-pipe’s wall and fluid temperatures, heat transfer coefficients, time constants, and other thermal characteristics have been estimated. The transient response of (GTPCHL) was found to depend mainly on the average evaporator thermal resistance. The results show that a good thermal performance is obtained at high evaporator heat load obtained from nuclear spent fuel storage tank and lower ambient temperature.

## INTRODUCTION

Safety features in nuclear reactors are the most important parameters that determine the possibility of public acceptance of these reactors. The term “nuclear” is usually perceived by the public as being associated with destruction or radioactive hazards on human health [1]. Nuclear safety regulations have been remarkably developed in the last decades. The risk of accidents in nuclear power plants is now becoming low and declining [6]. In over 16,000 cumulative reactor-years of commercial operation in 32 countries, there have been only three major accidents in nuclear power plants. These include Three Mile Island (USA 1979) where the reactor was severely damaged, but radiation was contained and there were no adverse health or environmental consequences, Chernobyl (Ukraine 1986) where the destruction of the reactor by steam explosion and fire killed 31 people and had significant health and environmental consequences [2]. The death toll has since then increased to about 56. In the Fukushima accident (Japan 2011) where three old reactors (together with a fourth one) were written off and the effects of loss of cooling due to a huge tsunami were inadequately contained. Only the Chernobyl and Fukushima accidents resulted in radiation doses to the public greater than those resulting from the exposure to natural sources [3]. Nuclear power plants are designed to be safe in their operation and in the event of any malfunction or accident, no industrial activity can be represented as entirely risk-free. Incidents and accidents may happen, and as in other industries, will lead to progressive improvement in safety [7]. Current nuclear power reactors mainly use a combination of inherent safety characteristics, and engineered safety systems, whose function may be active or passive [8]. The criticality accident at the Tokyo Electric Power Company’s Fukushima Daiichi nuclear power plant in 2011, suggested reducing reliance on active systems so as to reduce human errors. However, the term passive safety is not a synonym for inherent safety, because the reactor remains subject to other kinds of failure such as structure or mechanical failure or human interference [4]. This paper develops a model to evaluate the thermal performance of the (GTPCHL) for application in nuclear reactors. Passive systems must fulfil some conditions. These conditions include reliability and availability in short and long terms under adverse conditions, longevity (shelf life) against corrosion or deformation, testability, and simplicity as well as other considerations for effective human-machine interaction [9]. Grade (A) passive systems require no signal input, external power source, moving mechanical parts, nor moving working fluids. For example, nuclear fuel cladding, pressure boundary systems, hardened building structure against seismic and/or other external events are Grade (A) passive systems. For grade (B) passive systems, no signal input, no external power source, no moving mechanical parts, and moving working fluids are required. Examples of Grade (B) passive systems include natural air circulation around contaminant walls, reactor shutdown emergency cooling systems, and heat Pipe. For passive systems Grade (C), no signal input, or external power source are required, but moving mechanical parts, and moving or not working fluids are required. Examples of Grade (C) passive systems include cooling system based on fluid release through relief valves (accumulators). Grade (D) passive systems are called intermediate zone between active and passive processes, it needs external signal to trigger the passive process. It could be noticed that the more self-contained are the devices, the higher the degree of passivity is [11]. GTPHL consists of passive two-phase heat transfer devices that make use of the highly efficient thermal transport process of evaporator and condensation to maximize the thermal conductance between a heat source and a heat sink. The amount of heat that can be transferred by these devices is normally several orders of magnitude greater than pure conduction through a solid metal (exceeds that of copper 200- 500 times), [16]. GTPHL may be vertically oriented or inclined wickless heat pipe, with a liquid pool at the bottom. At operation, the GTPHL receives heat through the evaporator from an external source to the liquid pool. Consequently, a part of the working fluid evaporates. The vapour, driven by pressure differential between the evaporator and condenser flows through the adiabatic section towards the condenser section. In the condenser section, vapor is condensed into liquid imparting its latent heat of evaporation to the heat sink in the condenser section. The liquid returns internally from the condenser to the evaporator due to gravitational forces. Thus, the thermal-hydraulic cycle of the working fluid is completed.

## Theoretical Model

****A model has been performed to describes the thermal and phase flow of closed two-phase thermosyphon (GTPCTLs) as shown in table 1. A computer mathematical model was developed to calculate the temperature of the GTPHL as well as the time needed to reach steady state conditions. The equations are solved by Engineering Equation Solver program (EES) [15]. This model presents a theoretical investigation of thermosyphon behaviour in the transient regime. The transient model was adopted to simulate the response of thermosyphon with pure water. The transient thermal behaviour of (GTPCTL) has been utilized to obtain a mathematical expression of the system response. A model describing both thermal and phase flows of the GTPHL has been performed by M. Abdelaziz, et al [12] as shown in Figure (1), which is basically divided axially into three basic regions: evaporator (heating), adiabatic (thermally insulated) and condenser (cooling) sections. The thermosyphon main tube made of aluminium alloy 6061 (nuclear grade) with each region is mathematically and thermally treated due to variation of the heat transfer processes as in table 1. In addition, the evaporator region is filled of a liquid (pure water). When the power is on generated from nuclear fuel, the heat generated in the evaporator is rising its temperature with time. The heat transferred to the wall causing its temperature to rise and with time transfer the heat to the liquid. On reaching the saturation temperature, any heat added causes the saturated fluid to evaporator. Then the heat rate is carried by the vapour flows from evaporator to condenser, which is rejected to the heat sink through atmospheric temperature [5]. The model is analyzed in one-dimension, where the axial coordinate x is mainly measured from the evaporator bottom with assumptions:- One-dimensional flow model, (GTPCTL) is in the vertical orientation, The vapour superheat is very small; the vapor is taken at the saturated conditions, constant wall material (Al6061) properties, such as density, specific heat and thermal conductivity, the kinetic and potential energy components are neglected in the energy balance equations when compared with heat transfer rate, the density, thermal conductivity, enthalpy and other properties of saturated liquid are temperature depended, tthe condenser are calculated at mean value for both, the heat-pipe starts up from initial condition when the power is suddenly on and the heat-pipe steady-state carried out enough time.

*Fig. (1) Schematic of Proposed Passive Safety Heat Pipe Loops Cooling System*

TABLE 1. RANGES OF EXPERIMENTAL TESTS

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Material | Studied Parameter | Nuclear Heat Load Q. Range (KW) | Ambient Temp. oC | Filing ratio % | Condenser Length Lc. (m.) | Heat-pipe diameter. (cm.) |
| Al6061 | Heat Load | 25-50-75-100-125-150 | 30 oC | 100% | 100 | 15 |
| Al6061 | Ambient Temp. oC | 500 | 30-32.5-35 | 100% | 100 | 14 |

### Equations of the Model

This more basic model was developed to show the heat-pipe reaction time as a function of the different factors and to give numerical formulas for variations in system variables. A model of this kind can also be used to assist heat-pipe design. The evaporator wall is represented by the first body. It can be thought of as a temperature-indicating, thermally thin body. The entire working fluid, which interchanged with the evaporator wall and the working fluid, was connected to the second body. The temperature (Tf) of the working fluid indicates that it was deemed saturated. The behaviour of a wickless heat pipe, sometimes referred to as a gravity-assisted two-phase closed heat-pipe loop heat-pipe, is examined in this model in the transient domain. A two-phase closed heat pipe loop with assistance from gravity was simulated using the transient model. A mathematical model of the system response was developed by utilizing the transient thermal behaviour of the heat-pipe. Based on the method, computer simulation software was developed to calculate the heat-pipe's temperature and the amount of time needed to reach steady state conditions. This application can be viewed as a basic tool for modelling and developing the passive system loops in the transient regime. The equations of heat balance for each body (fluid and wall) are:

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |

Using equation (1 and 2) by the finite difference at a specific time step Δt, we may calculate Tw and Tf.

|  |  |
| --- | --- |
| (3) |  |

|  |  |
| --- | --- |
|  | (4) |

Where: Tw: wall temperature, Tf: fluid temperature, Se: evaporator area = π\*D\*Levap, Sc: condenser area = π\*D\*Lcond., Cf: fluid thermal capacitance, Cw: wall thermal capacitance, and the evaporator’ heat transfer coefficient.

|  |  |  |  |
| --- | --- | --- | --- |
| The radial and axial heat fluxes are:  qr = Qnet / (π \* di \* Le) | | (5) | |
| qax = Qnet/ (π \* di2 / 4) | | (6) | |
|  | (7) | |

τh is the time constant and X is the variable of the heat-up phase.

Where: Xss: steady state variable value.From Zuber-Forester’s equation:



(8)

Average condenser heat transfer coefficient could obtain:

|  |  |
| --- | --- |
|  | (9) |
|  |  |

Based on this approach, computer simulation software was created to calculate the thermosyphon loop's temperature and the time it takes to attain steady state conditions. The Engineering Equation Solver program (EES) is used to solve the equations.

3. Discussion of the Analytical Modelling Results

**3.1 Transient start-up operation**

Transient test operation is performed at start-up and steady-state for passive closed two-phase thermosyphon loop for nuclear wet fuel storage tank using water as working fluid. These measurements involve the change of wall and fluid temperatures during the startup transient operation. In these model, prior to startup the thermosyphon is initially (t = 0 s) at the ambient temperature, then the power input to the evaporator is sudden started. The program is ran for each interval of time Δt, till the thermosyphon temperature reach the steady state values. The thermosyphon using water as working fluid, the time required to reach the steady state operation is about 1800 seconds. Fig. (2 and 3) indicate the increment of evaporator, condenser and fluid temperatures with time. The figure is divided into two regions. In the first region, the vapour density is too low to support continuum flow. Heat added to the thermosyphon evaporator is absorbed solely as sensible heating, resulting in temperature rise. As a result, the temperature gradient of evaporator section is considered relatively high in the first interval of heating (t = 0-1200 sec.). While the rest of the heat energy forms some vapour which flows from of the evaporator and condenses on the adiabatic section causing its surface temperature to rise. In this period of time the response of condenser sections are lower than the evaporator section. At the time range (t >1200 sec.) most of the heat energy is absorbed as latent heat in working fluid thus, increasing the generated vapour. The vapour temperature is high enough to sustain continuum flow. Finally, as the steady state is approached, the rate of temperature increase slows down. This is due to the decrease in temperature difference between vapour and working fluid.

**3-2 Average evaporator wall, fluid and condenser wall temperatures also the output power from condenser section**

At certain value of thermal load, figs. (2) and (3) illustrates the theoretical mean temperatures predicted by the mathematical model for average evaporator wall, fluid and condenser wall temperatures. Also the output power from condenser section respectively versus time. The thermosyphon is initially at ambient temperature, then the electric power input to the evaporator is increased suddenly from zero to the full power, it is shown from the figures that, the temperatures of each section and the output power increase rapidly at the beginning of operation due to the increase of heat flow from object to another, with time. But as a result of reduction of the temperature driving forces, the rate of change temperature with time decreases until steady state condition is reached. At steady-state, both the wall and vapour temperatures and the output-power remain constant.

**3-3 Heat transfer coefficients**

The process of heat transfer in the liquid pool of the evaporator section is generally assumed to be common nucleate boiling whose heat transfer coefficient may be calculated from Forester–Zuber equation [13]. Natural convection heat transfer on a surface depends on the geometry of the surface and on its orientation. It also depends on the variation of temperature on the surface and the thermo-physical properties of the fluid involved [14]. The intensity of heat transfers within the (GTPCTL) is analyzed through the determination of the average heat transfer coefficients (he) and (hc) in evaporator and condenser. The average heat transfer coefficients he is estimated for the start-up, steady-state by means of the mathematical model and it is calculated for different thermophysical properties of working fluid. Including three subsequent processes, heat-up transient and steady-state transient as shown in figs. (2-C and D) also fig. (3-B). the estimation is carried out in the case of high values of filling ratio, means that the evaporator is fully filled with liquid. At the condenser section, a global heat transfer coefficient (hc) has been considered which combines conduction through the wall and convection (external side of the wall) show that there little change at the overall condenser heat transfer coefficient during all processes of the operation for the heat-up transient and steady-state.

**3-4 Thermosyphon resistance and cooling water temperature difference**

The model is design to simulate the full transient operation of thermosyphon and all the thermosyphon feature including thermosyphon resistance which means, temperature difference between the average outer wall temperature of the evaporator and that of the condenser (Tw - Tcond) resulting from a numerical model. From figures (2-F and 4-B) the thermosyphon resistance fluctuates at the end of steady-state mode. This fluctuates may be attributed to the sudden changing of the power applied on the evaporator section (heat Load). These fluctuations are created due to the irregular formation of vapour in evaporator. This process of evaporation is believed to be irregular.

**4. Conclusion**

A numerical simulation using special design of AL6061 gravity assisted two-phase closed heat-pipe loops were used to evaluate the (GTPCTL’s) thermal performance. The effect of the evaporator and condenser configuration, atmospheric air temperature, and heat load were analyzed. Demineralized water was used as the (GTPCTL’s) working fluid. The atmospheric air was circulated around the condenser as a cooling system. The results show that the best thermal performance was obtained at high evaporator heat load. The simulation model showed a pattern and trend line that can be used to predict the heat transfer phenomena of the (GTPCTL’s) with varying inputs. A theoretical network model has been proposed to predict the transient response of a gravity-assisted two-phase heat pipe working with pure water at different heat loads of (100, 200, 300, 400 and 500 kW). The wall and fluid temperatures, heat transfer coefficients, time constants, and other thermal characteristics have been estimated and the following conclusions can be drawn:

1. The transient response of a gravity-assisted heat pipe is found to depend mainly on the evaporator heat load and ambient temperature. Increasing the heat loads as well as decreasing the ambient temperature causes a reduction in the time constants, which leads to a better performance of the heat pipe.
2. The evaporator and condenser heat transfer coefficients are found to increase with power increase and ambient temperature decreases, though the corresponding values of the later are much less than those obtained for the evaporator.
3. The model prove that the loops are applicable, cheap, reliable and one of the passive system to remove heat load to keep fuel elements in safe conditions.

5. FIGURES

A **B**

C D

E F

*Fig. 2. The effect of different heat pipe parameters at different heat loads. (a) Wall Temperature and Time constant of heat-pipe at different heat loads, (b) Fluid Temperature and Time constant of heat-pipe at different heat loads, (c) average evaporator heat transfer coefficient of heat-pipe at different heat loads, (d) average condenser heat transfer coefficient of heat-pipe at different heat loads, (e) Output power of heat-pipe at different heat loads, (f) Temperature difference between wall and fluid temperature at different heat loads.*

 (A) (B)

*Fig. 3. The effect of different heat pipe parameters at different heat loads. (a) Wall and fluid temperature and Time constant of heat-pipe at different ambient temperature, (b) average evaporator and condenser heat transfer coefficient of heat-pipe at different ambient temperature,*



(A) (B)

*Fig. 4 The effect of different heat pipe parameters at different heat loads. (a) Output power of heat-pipe at different ambient temperature, (b) Temperature difference between wall and fluid temperature at different ambient temperature,*

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## NOMENCLATURE

A: area (m2), Ac: cross section area (m2),

Cp: specific heat (J/kg. K), d: diameter (m),

dh: hydraulic diameter (m), F: liquid filling ratio,

g: gravity (9.81 m/s2), h: heat transfer coefficient (W/m2 .K),

hfg: latent heat of vaporization (J/kg .K), K: thermal conductivity (W/m.K),

Keff: effect, thermal conductivity (W/m .K), p: pressure (N/m2),

Q: Heat flux (W/m2), S: area (m2)

T: time (s) T: temperature (oC),

U: overall heat transfer coefficient (W/m2 .K), nc: natural convection,

Re: Reynolds number factor ∆Ps saturated pressure difference (psi),

Cpl: specific heat of liquid (kJ/kg.K), m: mean,

µ: Dynamic viscosity (N.s/m2), ρ density (kg/m3),

ν: kinematics viscosity (m2 /s), τ time constant (s) Abbreviations

HTC: Heat transfer coefficient GTPCHL gravity two-phase closed thermosyphon loop, ETC: effective thermal conductivity. a: axial

A: adiabatic, am: ambient,

ax: axial, c: condenser,

e: evaporator, eq: equivalent,

l: liquid,