Numerical simulation of spent fuel pool using shell and tube heat exchanger

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***Abstract*— The CO2 emissions are considered responsible of the climate changes for the Earth. As these emissions are produced also by burning the fossil fuels to produce electrical energy, many countries in the world are transforming their national electrical production systems, decreasing the electrical production deriving from fossil fuels and increases that one deriving from nuclear power plant.**

A problem particular to power generation by nuclear reactors is that of decay heat. In fossil fuel facilities, once the combustion process is halted, there is no further heat generation, and only a relatively small amount of thermal energy is stored in the high temperature of plant components.
Decay heat is the heat released as a result of radioactive decay. This heat is produced as an effect of radiation on materials: the energy of the alpha, beta or gamma radiation is converted into the thermal movement of atoms.

In nuclear reactor engineering, decay heat plays an important role in reactor heat generation during the relatively short time after the reactor has been shut down, and nuclear chain reactions have been suspended. The decay of the short-lived radioisotopes created in fission continues at high power, for a time after shut down. The major source of heat production in a newly shut down reactor is due to the beta decay of new radioactive elements recently produced from fission fragments in the fission process. but many accident occurred such as fukushima recently so This research focuses on the spent fuel cooling system and temperature distributions in different positions which was presented a computer model and simulation results by the Matlab based.

***Index Terms*—About four key words or phrases in alphabetical order, separated by commas.**

I. INTRODUCTION

A problem particular to power generation by nuclear reactors is that of decay heat. In fossil fuel facilities, once the combustion process is halted, there is no further heat generation, and only a relatively small amount of thermal energy is stored in the high temperature of plant components. Decay heat is the heat released as a result of radioactive decay. This heat is produced as an effect of radiation on materials: the energy of the alpha, beta or gamma radiation is converted into the thermal movement of atoms [1]. In nuclear reactor engineering, decay heat plays an important role in reactor heat generation during the relatively short time after the reactor has been shutdown, and nuclear chain reactions have been suspended. The decay of the short-lived radioisotopes created in fission continues at high power, for a time after shutdown. The major source of heat production in a newly shutdown reactor is due to the beta decay of new radioactive elements recently produced from fission fragments in the fission process [2].

When a nuclear reactor has been shutdown, and nuclear fission is not occurring at a large scale, the major source of heat production will be due to the delayed beta decay of these fission products (which originated as fission fragments). For this reason, at the moment of reactor shutdown, decay heat will be about 6.5% of the previous core power if the reactor has had a long and steady power history. About 1 hour after shutdown, the decay heat will be about 1.5% of the previous core power. After a day, the decay heat falls to 0.4%, and after a week it will be only 0.2%. The decay heat production rate will continue to slowly decrease over time; the decay curve depends upon the proportions of the various fission products in the core and upon their respective half-lives [7]. An approximation for the decay heat curve valid from 10 seconds to 100 days after shutdown is given by [8]

$$\frac{P}{P_0} = 0.066\left((\tau - \tau_S)^{-0.2} - \tau^{-0.2}\right)$$

The removal of the decay heat is a significant reactor safety concern, especially shortly after normal shutdown or following a loss-of-coolant accident. Failure to remove decay heat may cause the reactor core temperature to rise to the point that fuel melting and core damage will occur. The inability to remove decay heat has caused nuclear accidents, including the nuclear accidents at Three Mile Island and Fukushima I [9]. The failure of ESWS circulating pumps was one of the factors that endangered safety during the 1999 Blayais Nuclear Power Plant flood [9].

The heat removal is usually achieved through several redundant and diverse systems, from which heat is removed via heat exchangers. Water is passed through the secondary side of the heat exchanger via the essential service water system [9], which dissipates the heat into the 'ultimate heat sink', often a sea, river or large lake. In locations without a suitable body of water, the heat is dissipated into the air by recirculating the water via a cooling tower.

Various factors affect the removal of decay heat in a system consisting of fuel pool, primary pumps, associated piping system and shell and tube type heat exchangers. These include type of heat exchanger which used, inlet temperature of the auxiliary coolant, the pool volume, primary coolant volume flow rate, auxiliary coolant volumetric flow rate, length of pipes in the heat exchanger, reactor power before shutdown, reactor operation time and number of pipes in the heat exchanger.

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II. LITERATURE REVIEW

A. Fuel pool cooling system

Storage pools are used for spent fuel from nuclear reactors. They are typically 12 meter deep, with the bottom 4.3 meter equipped with storage racks designed to hold fuel assemblies removed from the reactor. A reactor's pool is especially designed for the reactor in which the fuel was used and situated at the reactor site. An away-from-reactor, independent spent fuel storage installation (ISFSI) is also sometimes used. In many countries, the fuel assemblies, after being in the reactor for 3 to 6 years, are stored underwater for 10 to 20 years before being sent for reprocessing or dry cask storage. The water cools the fuel and provides shielding from radiation. While only about 2.4 meter of water is needed to keep radiation levels below acceptable levels, the extra depth provides a safety margin and allows fuel assemblies to be manipulated without special shielding to protect the operators. The Nuclear Regulatory Commission estimates that many of the nuclear power plants in the United States will be out of room in their spent fuel pools by 2015, most likely requiring the use of temporary storage of some kind [10].

About a quarter to a third of the total fuel load of a reactor is removed from the core every 12 to 18 months and is replaced by fresh fuel. Spent fuel rods generate intense heat and dangerous radiation that must be contained. Fuel is moved from the reactor and manipulated in the pool generally by automated handling systems, although some manual systems are still in use. The fuel bundles fresh from the core are normally segregated for several months for initial cooling before being sorted into other parts of the pool to wait for final disposal. Metal racks keep the fuel in controlled positions for physical protection and for ease of tracking and rearrangement. High-density racks also incorporate boron-10 or other neutron-absorbing material to ensure subcriticality. Water quality is tightly controlled to prevent the fuel or its cladding from degrading. Current regulations in the United States permit re-arranging of the spent rods so that maximum efficiency of storage can be achieved [11].

The maximum temperature of the spent fuel bundles decreases significantly between 2 and 4 years, and less from 4 to 6 years. The fuel pool water is continuously cooled to remove the heat produced by the spent fuel assemblies. Pumps circulate water from the spent fuel pool to heat exchangers, then back to the spent fuel pool. The water temperature in normal operating conditions is held below 50°C [10]. Radiolysis, the dissociation of molecules by radiation, is of particular concern in wet storage, as water may be split by residual radiation and hydrogen gas may accumulate increasing the risk of explosions. For this reason the air in the room of the pools, as well as the water, must be continually monitored and treated [11].

B. Design requirements

The SFP cooling system is designed to meet the following requirements [11, 12,13]:

i. Provide sufficient cooling to the fuel element due to heat generated by decay of the fission product.
ii. Remove heat produced during any activity in the spent fuel pool.
iii. Provide appropriate radiation shielding from irradiated fuel elements.
iv. Circulate water from the spent fuel pool in order to maintain the purity of the demineralized water within the specified limit.
v. Provide sufficient coolant inventory for SFP during LOCA.

C. Overview of Previous research on spent fuel storage

Bandini and et al. [15] validated the CATHARE V2.5 Thermal-Hydraulic code against full-scale PERSEO tests for decay heat removal in LWRs. Improvement in the modeling of the large water reserve pool was suggested to reduce the discrepancies observed between code results and test measurements. They proposed DHR system is able to keep the primary coolant temperature within a safety range for a sufficient time, avoiding the lead freezing or over-heating.

H. Qian, Z. Li and L. Ren [16], studied the passive decay heat removal system (DHRS) installed in the Chinese Experimental Fast Reactor (CEFR), They used OASIS code. The model included the main thermal transfer system and DHRS circuit. The transient analysis of loss of off-site power (LOSP) accident with various initial steady states was performed. The calculation results showed that the initial steady state does not essentially affect the peak cladding temperature in the core.

Damiani and Pini Prato [17], studied the issue of bayonet-tube steam generators proposing the EBBSG (External Boiling Bayonet Steam Generator) system, in which the reaction heat is extracted from the lead by means of coolant under vapor phase. This is possible owing to an external feed-water boiling, based on the known Loeffler scheme, coupled to the bayonet tube concept. They proposed a decay heat removal (DHR) system to match the EBBSG scheme. The DHR system is fully passive, exploiting natural circulation phenomena. The performance of the proposed DHR system was investigated through a Matlab-Simulink model.

EckhardKrepper and Beyer [18], did experimental and numerical investigations of temperature stratification phenomena in passive safety systems for decay heat removal and found modern concepts of nuclear power reactor systems are equipped with passive systems for decay heat removal. The investigated the capability of actual computational fluid dynamics (CFD) codes to describe temperature stratification phenomena.

Williams, Hejzlar and Saha [19], Analyzed a convection loop for Gas Cooled Fast Reactor (GFR) post-LOCA decay heat removal using a computer code (LOCA-COLA) for steady state analysis of convective heat transfer loops that natural circulation cooling of the GFR is feasible under certain circumstances. Both helium and CO_2 cooled system components were found to operate in the mixed convection regime, the effects of which are noticeable as heat transfer enhancement or degradation. They found that CO_2 outperforms helium under identical natural circulation conditions. Decay heat removal had a quadratic dependence on pressure in the laminar flow regime and linear dependence in the turbulent flow regime.

Gerasimovand et al. [20] studied decay heat power of uranium, plutonium, and thorium spent fuel at long-term storage. Decay heat power of actinides from plutonium spent fuel corresponding to the end of the period of accumulation of 100 years is 2.5 times higher than that of uranium spent fuel. Maximal decay heat power of actinides from uranium spent fuel is 1.2 times higher than that of thorium spent fuel.

Merzari and Gohar [21] simulated completely passive spent fuel pool of the KIPT accelerator driven subcritical assembly system of Ukraine, All simulations provided consistent predictions and helped confirm that the temperature within the pool is below boiling point.

Ye and et al. [22] proposed a novel completely passive spent fuel pool cooling system using the high-efficiency heat pipe cooling technology that is available in an emergency condition such as a station blackout. They used computational coolant dynamics (CFD) simulation. The simulation results reveal that the passive cooling system effectively removes the decay heat from the SFP with the storage of 15-year-old spent fuel assemblies with emergency reactor core unloading and prevents the burnout of the fuel rods.

Wang, Guo and Chen [23] studied the performance of AP1000 passive containment cooling system (PCS). The results indicated that: at the time of 72 hours after break accident, there is no water in passive containment cooling water storage tank (PCCWST), PCS cannot completely remove reactor core decay heat to environment just with the effect of natural convection and thermal radiation.

Gulshani and Huynh [24] found a simple mathematical model to examine the heat transfer phenomena in a single-phase counter-current subcooled water flow that is relevant to CANDU in a shutdown, maintenance state where the main heat-transport-circuit pumps are shutoff and the shutdown-cooling pumps are or become unavailable.

Wang and Zhang [25] developed a 1-D transient thermal hydraulic code named LR which is based on DHRS of CEFR. LR code can be used for coupling calculations of heat exchange and flow in the primary side of DHX (decay heat exchanger), middle loop of DHRS and air side of AHX (air heat exchanger). The result of this research is particular to that of Russian CBTO and fits the conclusions of theoretical analysis.

Wright and et al. [26] examined the passive residual heat removal heat exchanger (PRHR HX) that provides decay heat removal for postulated LOCA and non-LOCA events in AP1000.Component testing was performed for the AP600 PRHR HX to determine the heat transfer characteristics and to develop correlations to be used for the AP1000 safety analysis codes. The results of these simulations show that the heat removal capacity of the PRHR HX was conservatively represented in the AP1000 safety analyses.

It is noted that the each previous study focused on a specific types of reactors and thus cannot be used for other reactor types. The current study is a comprehensive study of a generic open system that can be applied.

D. Aim of the work

This research focuses on the spent fuel cooling system and temperature distributions.

A model of the cooling system was made, and a Matlab computer program, based on the model, was used to investigate the effect of different parameters on it.

I. MODELING OF THE POOL SYSTEM

4.1 Description of system and components

The closed loop system used in this work consists of fuel pool, primary pumps, associated piping system and shell and tube type heat exchanger whose main function is to provide the sufficient cooling for fuel in the pool, as shown in Figure (4.1).

In this study, the temperature of the main and auxiliary cooling fluids were calculated for different conditions to investigate the effect of different parameters on those temperatures by using numerical methods.

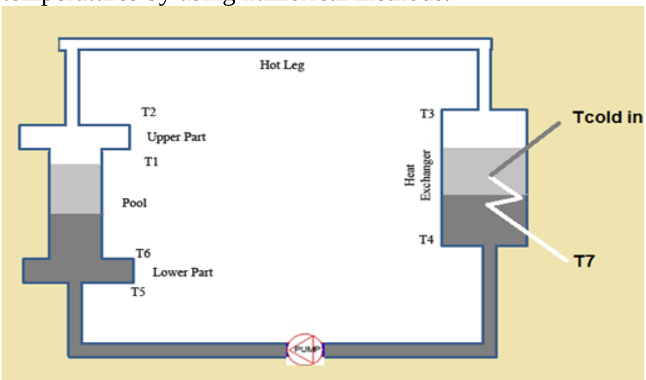

Figure 4. 1 Temperature distribution on system

The temperature was calculated at the following locations in the systems (figure 4.1):

- T_1 : Temperature of the coolant exiting the pool (℃)
- T_2 : Temperature of the coolant exiting the volume after pool (℃)
- T_3 : Temperature of the coolant at the end of hot pipe (℃)
- T_4 : Temperature of the coolant exiting the heat exchanger (℃)
- T_5 : Temperature of the coolant at the end of cold pipe (℃)
- T_6 : Temperature of the coolant entering the pool (℃)
- T_{ci} : Temperature of the coolant entering the heat exchanger (℃)
- T_7 : Temperature of the secondary coolant exiting the heat exchanger (℃)

A. Heat Exchanger calculations

The heat exchanger is a piece of equipment built for efficient heat transfer from one medium to another. The media may be separated by a solid wall to prevent mixing or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment [27]. The classic example of a heat exchanger is the steam generator found in a nuclear power plant in which a circulating coolant known as primary coolant, carrying the energy from the nuclear reactor flows through tubes in the steam generator while secondary coolant flows around it to cool it. The heated secondary coolant is then used to move the turbine shaft.

Factors which affect the rate of heat transfer in heat exchangers include:-

1. The thickness of the material of the tubes.

2. The temperature difference between the two fluids.
3. The thermal conductivity of the materials of construction.
4 .The physical size of the exchanger and the surface area of the tubes.
5. The number of tube side passes (channel head baffles), and shell side passes (transverse baffles), through the exchanger.
6. The type and direction of flow

The general equation for heat transfer across a surface is:

$$q = UA\Delta T \quad (4.1)$$

Where

q = heat transferred per unit time, W,

U = the overall heat transfer coefficient, W/m^2℃

A = heat-transfer area, m^2.

ΔT = the mean temperature difference, the temperature driving force, ℃.

The prime objective in the design of an exchanger is to determine the surface area required for the specified duty (rate of heat transfer) using the temperature differences available.

The overall coefficient is the reciprocal of the overall resistance to heat transfer, which is the sum of several individual resistances. For heat exchange across a typical heat exchanger tube the relationship between the overall coefficient and the individual coefficients, which are the reciprocals of the individual resistances, is given by [27]:

$$\frac{1}{U_O} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{2k_w} + \frac{d_o}{d_i} X \frac{1}{h_{id}} + \frac{d_o}{d_i} X \frac{1}{h_i} \quad (4.2)$$

Where

U_o = the overall heat transfer coefficient based on the outside area of the tube, W/m^2℃

h_o = outside coolant film coefficient, W/m^2℃

h_i = inside coolant film coefficient, W/m^2℃

h_{od} = outside dirt coefficient (fouling factor), W/m^2℃

h_{id} = inside dirt coefficient, W/m^2℃

k_w = thermal conductivity of the tube wall material, W/m^2℃

d_i = tube inside diameter, m.

d_o = tube outside diameter, m.

The flow rate inside the tube ($m^{\cdot}$) is a function of the density of the coolant (ρ_t), the velocity of the coolant (u_t), cross-sectional flow area of the tube (A_c), and the number of tubes (N_t) [27].

$$m^{\cdot} = \rho_t u_t A_c N_t \quad (4.3)$$

$$N_t = \frac{4m^{\cdot}}{\rho_t u_t \pi d_i^2} \quad (4.4)$$

The criterion of distinguishing between laminar and turbulent flow is the observed mixing action. Experiments have shown that inside tubes, laminar flow exists when the Reynolds number (Re) is less than 2000[27]. Re is defined as:

$$Re_t = \frac{\rho_t u_t d_i}{\mu_t} \quad (4.5)$$

where μ_t is the viscosity of the tube-side coolant, u_t is coolant velocity inside the tubes, and ρ_t is the density of coolant in the tubes.

Nusselt number is a function of Reynolds number and Prandtl number. There are equations developed according to the type of flow. For turbulent flow, the following equation developed by Petukhov-Kirillov can be used [27].

$$Nu_t = \frac{(\frac{f}{2}) Re_t Pr_t}{1.07 + 12.7 (\frac{f}{2})^{\frac{1}{2}} (Pr_t^{\frac{2}{3}} - 1)} \quad (4.6)$$

Where f is the friction factor which can be calculated from

$$f = (1.58 ln Re_t - 3.28)^{-2} \quad (4.7)$$

The heat transfer coefficient for the tube-side is expressed as follows:

$$h_t = Nu_t \frac{k_t}{d_i} \quad (4.8)$$

Where Nu_t is the Nusselt number for the tube-side coolant, k_t is the thermal conductivity of the tube-side coolant, and d_i is the tube inside diameter.

The number of tubes is calculated by taking the shell circle and dividing it by the projected area of the tube layout,

$$N_t = (CTP) \frac{\pi D_s^2}{4 A_1} \quad (4.9)$$

A_1 is the projected area of the tube layout expressed as area corresponding to one tube, D_s is the shell inside diameter, and CTP is the tube count calculation constant that accounts for the incomplete coverage of the shell diameter by the tubes, due to necessary clearances between the shell and the outer tube circle and tube omissions due to tube pass lanes for multitude pass design. The CTP values for different tube passes are [27]:

one-tube pass → CTP=0.93

two-tube pass → CTP=0.90

three-tube pass → CTP=0.85

A_1 is expressed as

$$A_1 = (CL) P_T^2 \quad (4.10)$$

Where P_T is the tube pitch and CL is the tube layout constant

for 90º and 45º → CL=1

for 30º and 60º → CL=0.87

The shell inside diameter is calculated from

$$D_s = 0.637 \sqrt{\frac{CL}{CTP}} [\frac{A_O (PR)^2 d_O}{L}]^{1/2} \quad (4.11)$$

$$PR = \frac{P_T}{d_O} \quad (4.12)$$

$$A_O = \pi d_O N_t L \quad (4.13)$$

Substituting in eq. (4.9), the Nusselt equation becomes,

$$N_t = \frac{\pi (CTP) D_s^2}{4 (CL) (PR)^2 d_O^2} \quad (4.14)$$

The equivalent diameter is calculated along (instead of across) the long axes of the shell and therefore is taken as four times the net flow area as layout on the tube sheet (for any pitch layout) divided by the wetted perimeter [27].

Square and triangular pitch-tube layouts are the most famous in heat exchanger as shown in figure (4.2)

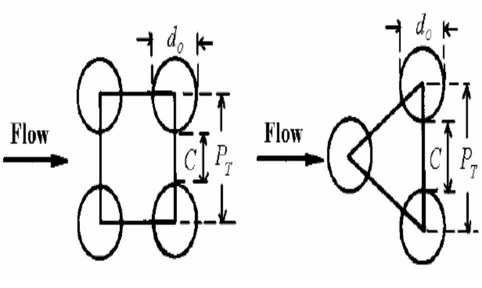

Figure 4. 2 Square and triangular pitch-tube layouts

for a square pitch

$$D_e = \frac{4(P_T^2 - \frac{\pi d_O^2}{4})}{\pi d_O} \quad (4.15)$$

for the triangular pitch:

$$D_e = \frac{4(\frac{P_T^2 \sqrt{3}}{4} - \frac{\pi d_O^2}{8})}{\pi d_O / 2} \quad (4.16)$$

Reynolds number for the shell-side is based on the tube diameter and the velocity on the cross flow area at the diameter of the shell:

$Re_s = (\frac{m_s}{A_s})\frac{D_e}{\mu_s}$ (4.17)

Note that all the parameters in eq. (4.17) are for the shell side. The heat transfer coefficient for the shell-side in the Kern Method can be estimated from

$h_o = \frac{0.36 k_s}{D_e} Re_s^{0.55} Pr_s^{1/3}$ (4.18)

B. Mathematical Model

The flow passes through the pump inside the piping to the volume before pool and then to the pool. In the pool the coolant absorbs the heat and its temperature rises. It then flows to the volume after pool and then through the piping to the heat exchanger. The heat exchanger absorbs the heat from the coolant, which flows with low temperature to the pump to repeat the cycle.

To follow the temperature change, the system was divided into six parts.

- Spent fuel pool

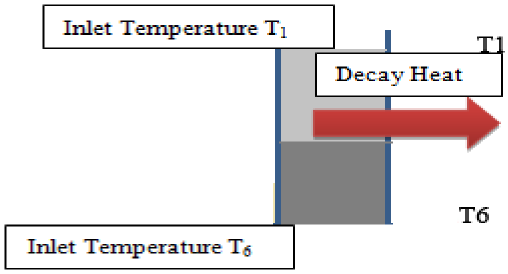

Figure 4. 3 The spent fuel pool

The pool is divided into three parts:

1. Upper part where this water barrier serves as a radiation shield, limiting the gamma dose rate at the surface of the pool and also in case of accident supply the coolant to the system .
2. Main part where the fuel was put inside this part.
3. Lower part where accumulate the water to maintain the main velocity inside the pool without turbulent

The spent fuel pool (SFP) is shown in figure 4.3. The governing equation is:

$$\frac{dT_1}{dt} = \frac{1}{(m*C_p)}[((m_c * C_p)(T_1 - T_6)) + Q] \quad (4.19)$$

Where:

T_1 : Temperature of the coolant exiting the pool,℃
T_6 : Temperature of the coolant entering the pool,℃
m : mass of coolant in the pool, kg
m_c : Main coolant mass flow rate, m^3/sec
C_p : specific heat at constant pressure, kJ/kg.K
Q : Decay Heat, kW

- upper part of the pool

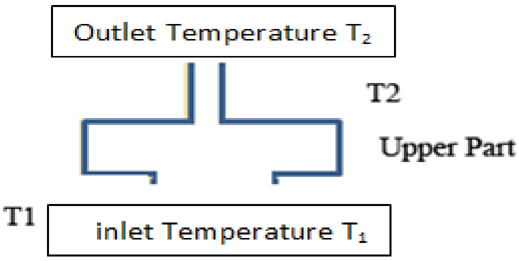

Figure 4. 4 upper part of the pool

The volume after the pool is shown in figure 4.4. The governing equation is:

$$\frac{dT_2}{dt} = \frac{1}{t_1}T_1 - \frac{1}{t_1}T_2 \quad (4.20)$$

Where:

T_2 : Temperature of coolant exiting the upper part of the pool,℃
t_1 : The time required to fill the upper part of the pool, sec

- Hot leg

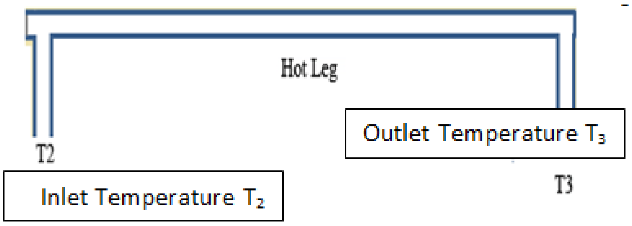

Figure 4. 5 pipe from the pool to the heat exchanger

The hot leg (pipe in which the coolant flows from the pool to the heat exchanger) is shown in figure 4.5. The governing equation is:

$$\frac{dT_3}{dt} = \frac{1}{t_2}T_2 - \frac{1}{t_2}T_3 \quad (4.21)$$

Where:

T_3 :Temperature of the coolant at the end of the hot pipe,℃
t_2 : the time required to fill hot pipe,sec

- Heat exchanger

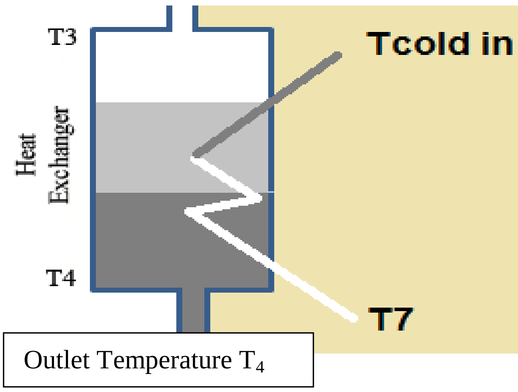

Figure 4. 6 Heat exchanger

Figure 4.6 shows the heat exchanger, which has two types of coolants, a primary coolant (or the coolant), which is used to cool the spent fuel, and a secondary coolant, which is used to cool the primary coolant. For the hot pass, which has the primary coolant, the governing equation is:

$$\frac{dT_4}{dt} = \left(\frac{1}{m_{sh} * C_p}\right)\left[\left((m_c * C_p)(T_3 - T_4)\right) - q\right] (4.22)$$

Where :

T_4: Temperature of the coolant exiting the heat exchanger,℃
m_c: Coolant mass flow rate, m^3/sec
q : Removable heat from hot coolant, kW
m_{sh} : mass of coolant in the shell, kg

For the cold pass, which has the secondary coolant:

$$\frac{dT_7}{dt} = \frac{1}{(m_{st} * C_p)}\left[\left((m_s * C_p)(T_{ci} - T_7)\right) + q\right] (4.23)$$

Where:

T_{ci} : Temperature of the secondary coolant entering the heat exchanger,℃
T_7 : Temperature of the secondary coolant exiting the heat exchanger,℃
m_s : Secondary coolant mass flow rate, m^3/sec
m_{st} : Mass of secondary coolant in the tubes, kg

- Cold leg

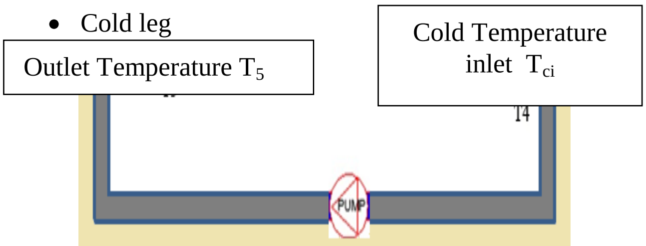

Figure 4. 7 pipe from the heat exchanger to the pool

The cold leg (pipe in which the coolant flows from the heat exchanger back to the pool) is shown in figure 4.7. The governing equation is:

$$\frac{dT_5}{dt} = \frac{1}{t_3} T_4 - \frac{1}{t_3} T_5 \quad (4.24)$$

Where:

T_5 : Temperature of the coolant at the end of the cold pipe,℃
t_3 : time required to fill the cold pipe, sec.

- lower part of the pool

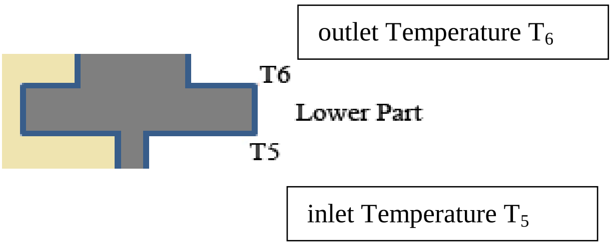

Figure 4. 8 lower part of the pool

The volume after the pool is shown in figure 4.4. The governing equation is:

$$\frac{dT_6}{dt} = \frac{1}{t_4} T_5 - \frac{1}{t_4} T_6 \quad (4.25)$$

Where:

T_6 : Temperature of the coolant entering the pool,℃
t_4 : time required to fill the cold volume, sec.

II. RESULTS AND DISCUSSION

A. The effect of different parameters

- Parallel heat exchanger:

In this case, the heat exchanger used to cool the primary coolant was a parallel flow heat exchanger. Figure 5.1 shows the coolant temperature change with time. The figure shows the temperatures of the primary coolant (a) after leaving the passing over the spent fuel (T_2) and (b) exiting the heat exchanger after losing the energy gained from the spent fuel (T_4), and, (c) the auxiliary coolant exiting the heat exchanger after gaining energy from the primary coolant (T_7).
The temperature rose from an initial value (due to the addition of spent fuel energy) until a maximum value. After that, it started to decrease gradually due to the decrease in decay heat with time (figure 5.1). As expected, the maximum temperature of the system was found to be T_2. However, at normal operation, T_2 was within the safe limits.

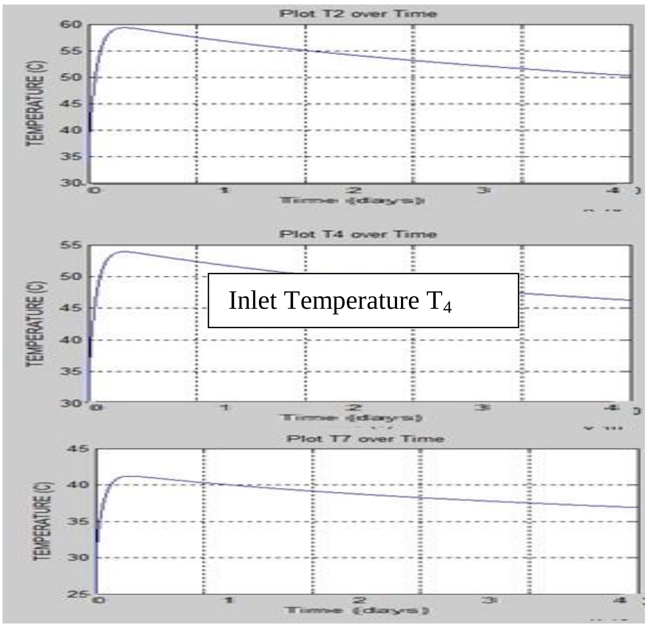

Figure 5. 1 Change of T2, T4, T7 with time when a parallel flow heat exchanger was used

- Counter heat exchanger:

In this case the heat exchanger was counter flow. As seen in Figure 5.2, the temperature sharply increased from the initial value to the maximum due to start of operation and decay heat. After that it gradually decreased due to decreasing in decay heat value with time.
Comparing figures 5.2 and 5.3 shows that using a counter flow heat exchanger decreased maximum value of T_2 (which is the highest temperature of the system) by about 3%, which is not a significant change.

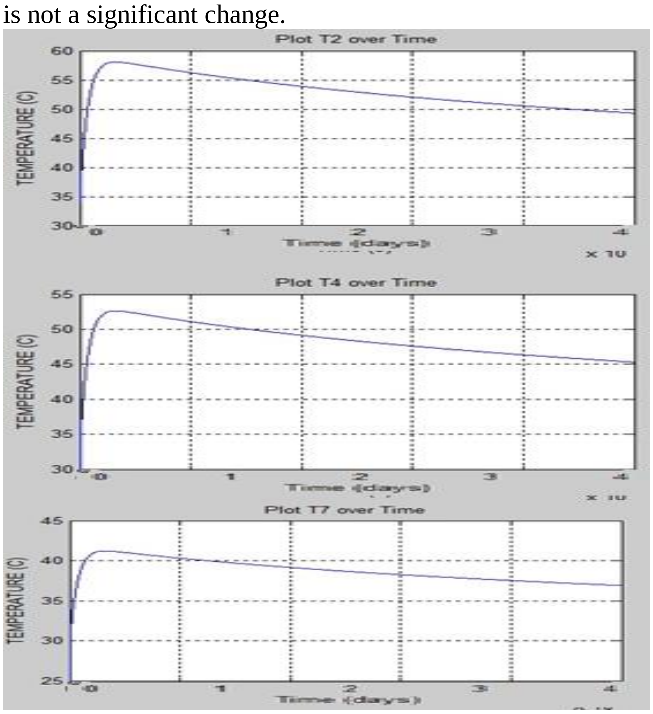

Figure 5. 2 Change of T2,T4,T7 with time when a counter flow heat exchanger was used.

- Inlet temperature of the auxiliary coolant:

Figure 5.3 shows the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different values of the inlet auxiliary coolant temperature.

It is clear from the figure that the inlet temperature of the auxiliary coolant had a significant effect on the three temperatures.

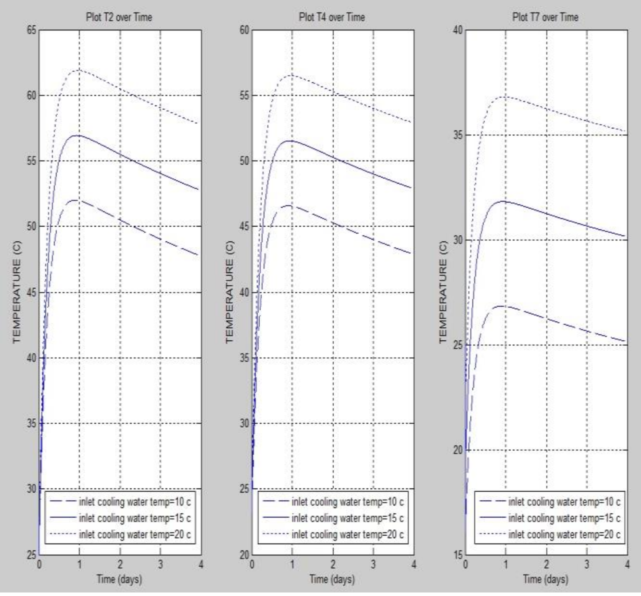

Figure 5. 3 Change of T2,T4,T7 with time for different inlet temperatures of the auxiliary coolant.

- The pool volume:

Figure 5.4 shows the change of the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different spent fuel pool volumes.

The figure shows that an increase of 500% of the pool volume produced a decrease of 5% in the maximum value of T_2 and a decrease of 2% in both T_4 and T_7.

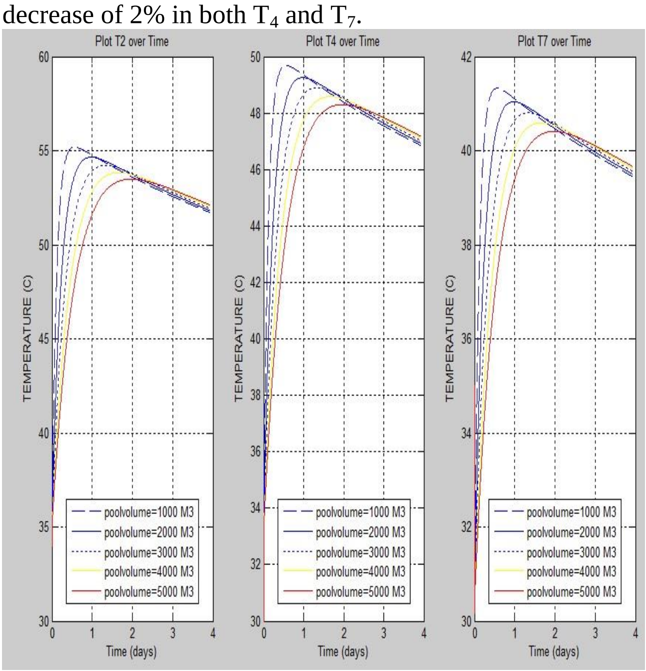

Figure 5. 4 Change of T2,T4,T7 with time for different pool volumes.

- Primary coolant volume flow rate:

Figure 5.5 shows the change of the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different values of the primary coolant flow rate.

The effect of the flow rate was moderate. T_2 decreased by about 4% and T_4 decreased by 4.5% when the volumetric flow rate increased from 1000 to 1500 m^3/hr. T_2 decreased by 4% and T_4 decreased by 7% the flow rate increased from 1500 to 3000 m^3/hr. However, it did not have any effect on T_7.

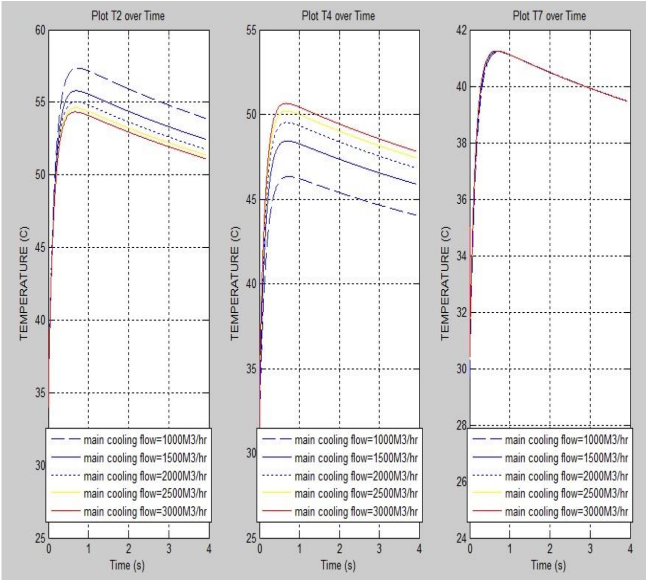

Figure 5. 5 Change of T2,T4,T7 with time for different primary coolant volumetric flow rates.

- Auxiliary coolant volumetric flow rate:

Figure 5.6 shows the change of the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different values of the auxiliary coolant flow rate.

The effect of the flow rate was significant. Both T_2 and T_4 decreased by about 14% and T_7 decreased by 21% when the volumetric flow rate increased from 340 to 510 m^3/hr (50% increase). This effect of the flow rate was less, although still significant, at higher flow rate values. T_2 decreased by 9%, T_4 decreased by 13% and T_7 decreased by 24% when the flow rate increased from 510 to 950 m^3/hr (67%).

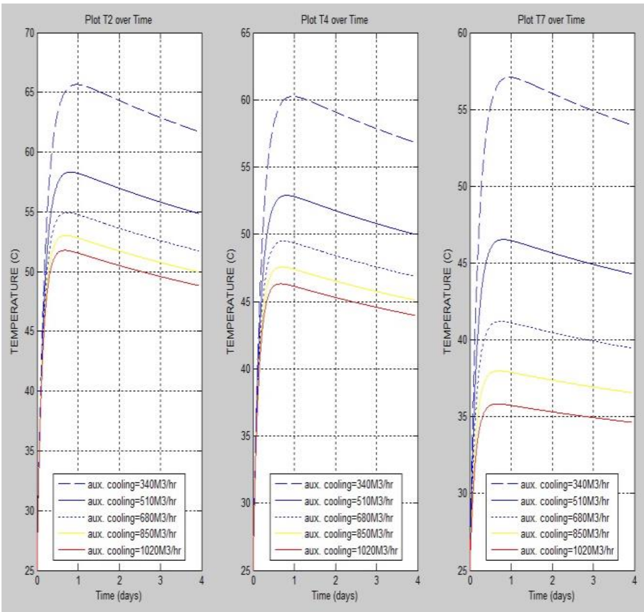

Figure 5. 6 Change of T2,T4,T7 with time for different auxiliary coolant volumetric flow rates.

- Length of pipes in the heat exchanger:

Figure 5.7 shows the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different values of heat exchanger pipe length.

The effect of the pipe length was significant on both T_2 and T_4. T_2 decreased by about 19% and T_4 decreased by and 22% when the pipe length increased from 2.6 to 3.9m (50%). The effect was less significant, but still important, for higher values of pipe length. T_2 decreased by about 12% and T_4 decreased by and 14% when the pipe length increased from 5.2 to 7.8m (again 50%).

Changing the pipe length did not affect the exiting temperature of the auxiliary coolant (T_7).

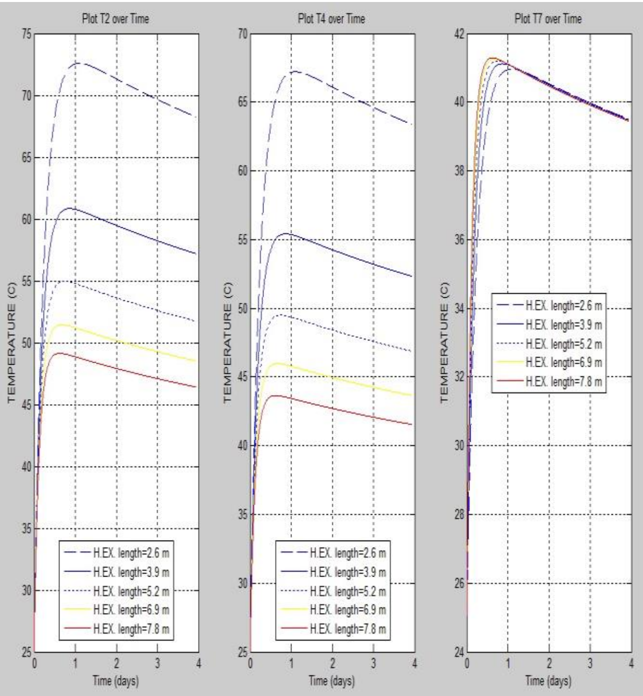

Figure 5. 7 Change of T2,T4,T7 with time for different lengths of the heat exchanger pipes.

- Reactor power before shutdown

Since the reactor power is directly proportional to the amount of fission products that are the major contributor to the decay heat, the reactor power before shutdown was changed between 2500 and 7500MW to study its effect on the temperatures inside the spent fuel system (figure 5.8)

The effect of the pipe length was significant for all values of reactor power. T_2 decreased by about 16%, T_4 decreased by 10% and T_7 decreased by 8% when the reactor power increased from 2500 to 3750MW (50%). The effect was more pronounced at higher power. T_2 decreased by about 22%, T_4 decreased by 19% and T_7 decreased by 26% when the reactor power increased from 5000 to 7500MW (again 50%).

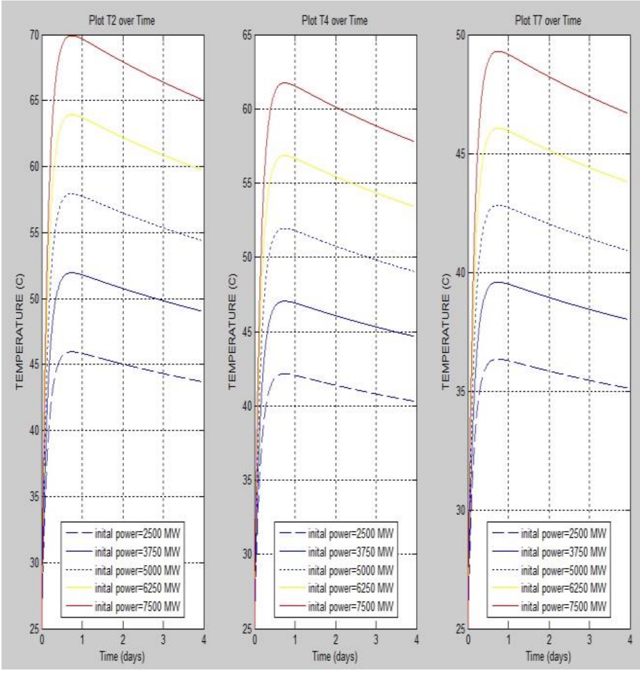

Figure 5. 8 Change of T2,T4,T7 with time for different reactor power before shutdown.

- Reactor operation time:

Figure 5.9 shows the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different values reaction operation time.

The effect of the operation time was not significant. T_2 decreased by about 4%, T_4 decreased by 3.5% and T_7 decreased by 3% when the reactor operation time increased from 350 to 525 days (50%). The effect was less significant at higher operation time.

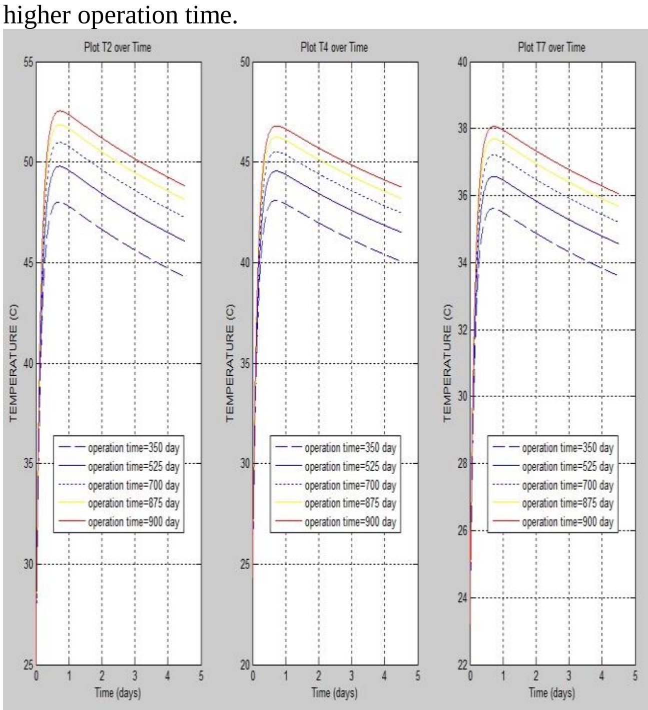

Figure 5. 9 Change of T2,T4,T7 with time for different reactor operation times.

- Number of pipes in the heat exchanger:

Figure 5.10 shows the change of the temperature of the primary coolant exiting the pool (T_2) and the heat exchanger (T_4) and the auxiliary coolant leaving the heat exchanger (T_7) for different numbers of heat exchanger pipes.

The effect of the pipe length was significant on both T_2 and T_4. Both T_2 and T_4 decreased by about 20% when the pipe length increased from 1000 to 1500 (50%). The effect was less significant, but still important, for higher values of pipe length. T_2 decreased by about 15% and T_4 decreased by and 14% when the pipe length increased from 2000 to 3000 (also 50%).

Changing the pipe length did not affect the exiting temperature of the auxiliary coolant (T_7).

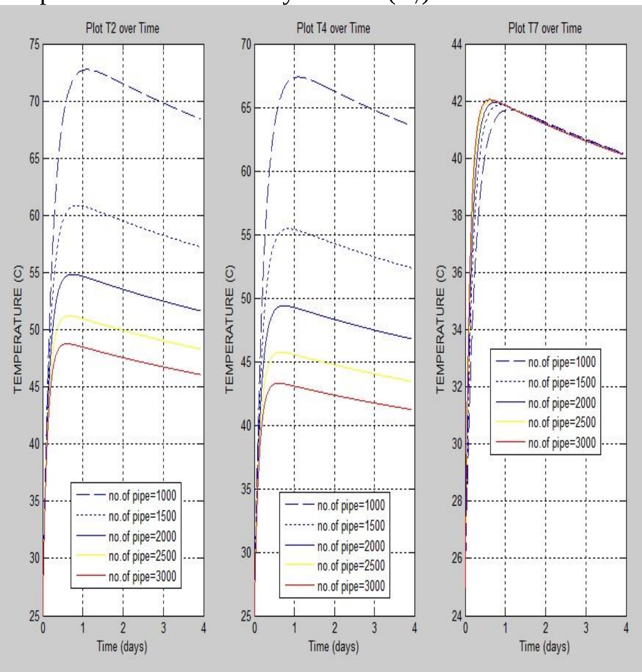

Figure 5. 10 Change of T2,T4,T7 with time for different lengths of heat exchanger pipes.

CONCLUSION

This thesis presents the calculation results of study spent fuel system performance by change different parameters that get the system more stable such as increasing the pool volume, Primary coolant volume flow rate, Auxiliary coolant volume flow rate, Length of pipes in the heat, Number of pipes in the heat exchanger and also pool volume. And also noted that Counter heat exchanger is better than Parallel heat exchanger in improve the system performance.

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