VAPORIZATION RATE ANALYSIS OF PRIMARY COOLING WATER FROM REACTOR PUSPATI TRIGA (RTP) TANK

Tonny Anak Lanyau[1], Mohd Fazli Zakaria, Yahya Ismail, Phongsakorn Prak Tom, Syahirah Abdul Rahman, Roslan Md Dan, Mohd Huzair Hussain, Mohammad Suhaimi Kassim, Mohd Fairus Farid

Nuclear Power Division, Malaysian Nuclear Agency,
Ministry of Science, Technology and Innovation,
Bangi, 43000 Kajang, Selangor Darul Ehsan,MALAYSIA
[1]tonny@nuclearmalaysia.gov.my

Abstract

Primary cooling system consists of pumps, heat exchangers, probes, a nitrogen-16 diffuser and associated valves is connected to the reactor TRIGA PUSPATI (RTP) tank by aluminium pipes. Both the primary cooling system and the reactor tank is filled with demineralised light water (H_2O), which serves as a coolant, moderator as well as shielding. During reactor operation, vaporization in the reactor tank will reduce the primary water and contribute to the formation of vapor in the reactor hall. The vaporization may influence the function of the water subsequently may affect the safety of the reactor operation. It is essential to know the vaporization rate of the primary water to ensure its functionality. This paper will present the vaporization rate of the primary cooling water from the reactor tank and the influence of temperature of the water in the reactor tank to the vaporization rate.

Keywords: Vapor, vaporization rate, primary cooling water, RTP

Abstrak

Sistem penyejuk primer terdiri daripada pam, penukar haba, alat pengesan, sebuah peresap nitrogen-16 serta injap-injap yang dihubungkan ke tangki reaktor TRIGA PUSPATI (RTP) oleh paip aluminium. Kedua-dua sistem penyejuk primer dan tangki reaktor ini diisi dengan air ringan dinyahgalian(H_2O) yang berfungsi sebagai penyejuk, penyederhana serta perisai. Semasa reaktor beroperasi, pengewapan di dalam tangki reaktor akan mengurangkan air primer dan menyumbang kepada pembentukan wap air di dewan reaktor. Pengewapan ini boleh menjejaskan fungsi air serta boleh menjejaskan keselamatan operasi reaktor. Adalah penting untuk mengetahui kadar pengewapan air primer bagi memastikan kefungsiannya. Penulisan ini akan menyajikan kadar pengewapan air penyejuk primer dari tangki reaktor dan pengaruh suhu air di dalam tangki reaktor terhadap kadar pengewapan.

Kata kunci: Vapor, vaporization rate, primary cooling water, RTP

I. INTRODUCTION

Reactor PUSPATI TRIGA (RTP) is an open pool type reactor. Reactor coolant system consists of a tank, water cooling system and water purification system. The water cooling system consists of primary cooling system and secondary cooling system. The primary cooling system equipped with pumps, heat exchanger, probes, a nitrogen-16 diffuser and associated valve is connected to the tank by aluminium pipes. The 6.5m high with 2m diameter aluminium tank is filled by demineralised light water (H_2O), serves as coolant, moderator as well as shielding. Figure 1 shows the cutaway view of the RTP.
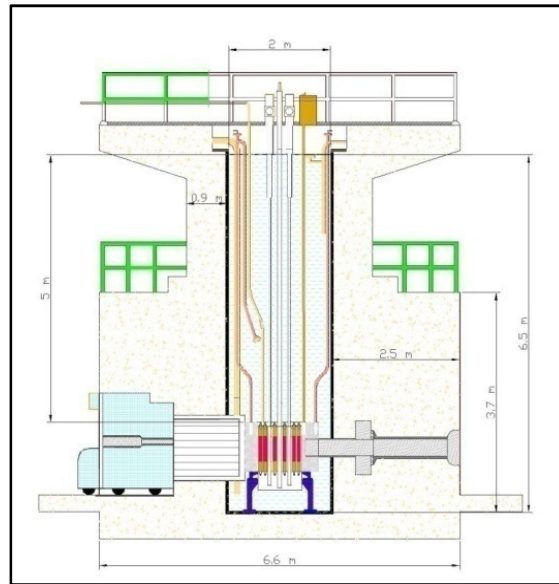

Figure 1: Cutaway view of RTP

The existing of the water vapor which produced moisture in the reactor hall may come from environment carried by the outside air to the reactor hall and vaporization of the primary water from the tank. The high moisture content in the reactor hall may influence the safety and the continuity of the reactor operation. It will increase the corrosion rate of the reactor components and instruments and then lead to disruption of reactor operation. Besides, the water vapor may affect the lifetime of the electronic components which has a high sensitivity to the water vapor. During the operation, water temperature will be increased and the evaporation will occur subsequently reduce the level of the water in the tank. The water level shall be maintained at range 6.348m to 6.297m. In condition the water level fell to 6.322m (7" from the pool top), and then the water must be topped up manually by the reactor operator through the water purification system. In order to analyse such condition, this study is conducted with aims:

i. To calculate the vaporization rate of the primary water in the reactor tank to the reactor hall.
ii. To predict the time to reach the maximum level for topping up water.

Theory

Vaporization is a phase transition from the liquid or solid phase to gas phase. There are three types of vaporization; evaporation, boiling and sublimation. Evaporation occurs only on the surface of a liquid. In steady state condition, heat transferred is an energy transmitted during the evaporation. So, the vaporization rate is a mass transfer rate between water and air. This phenomenon can be computed by Fick's Law. The Fick's Law states molecule diffusion defines as a random transfer or movement of the molecule through fluid. The diffusion equation adopted by Fick's Law is:

$$\bar{J}_{diff,A} = \frac{\dot{N}_{diff,A}}{A} = -CD_{AB}\frac{d\left(C_A/C\right)}{dx} = -CD_{AB}\frac{dy_A}{dx} \qquad ..... \qquad \left(\frac{mol}{m^2.s}\right)$$

Where, $\bar{J}_{diff,A}$ = Diffusive molar flux $\left(\frac{\text{kmol}}{\text{m}^2}.\text{s}\right)$

C = Molar concentration (molar density) of the binary mixture $\left(\frac{\text{kmol}}{\text{m}3}\right)$

D_{AB} = Binary Diffusion Coefficient or Mass Diffusivity $\left(\frac{\text{m}^2}{\text{s}}\right)$

y_A = Mass fraction of species A

x = Diffusion distance (m)

$\dot{N}_{diff,A}$ = molar flow rate of species A

A = Surface Area (m^2)

The reactor tank shown in Figure 2 is filled with demineralised water and exposed to the circulated air at constant pressure and temperature by the ventilation system in the reactor hall .The evaporation of the water in the reactor tank occurred because of mass transfer process of the water vapor from the reactor tank to the air in the reactor hall when there is unsaturated air on the surface of water in the tank undergoing the heat transfer due to the temperature difference between the air and the surface of the water.
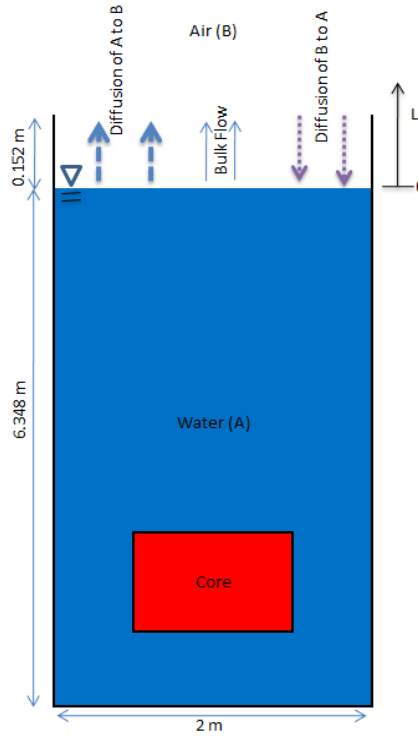
Figure 2: Vaporization phenomena in RTP tank

Equilibrium exists between the liquid and vapor phase at the water interface (x= 0), and thus the vapor pressure at the interface must equal to the saturation pressure of the water at specified temperature. If the surrounding gas at the top of the reactor tank (x= L) is not saturated, the vapor pressure in the interface will be greater than the vapor pressure at the top of the tank. Thus, this pressure (or concentration) difference will drive the vapor upward from the air-water interface into the stagnant gas. The upward flow will be sustained by the evaporation of water at the interface. In steady state conditions, the molar (or mass) flow rate of the vapor through the stagnant gas column remains constant. So,

$$\bar{J}_A = \frac{\dot{N}_A}{A} = Constant$$

Also, under steady state conditions, there must be an upward bulk fluid motion with an average velocity, V that is just large enough to balance the diffusion of air downward so that the net molar (or mass) flow rate of the gas at any point is zero.

$$\bar{J}_B = \frac{\dot{N}_B}{A} = 0$$

The bulk motion of the gas will results in additional mass flow of vapor upward. Therefore, the molar flux of the vapor can be expressed as,

$$\bar{J}_A = \frac{\dot{N}_A}{A} = \bar{J}_{A,conv} + \bar{J}_{A,diff} = y_A (\bar{J}_A + \bar{J}_B) - CD_{AB}\frac{dy_A}{dx}$$

Noting that $\bar{J}_B = 0$, solving the $\bar{J}_A$ gives,

$$\bar{J}_A = -\frac{CD_{AB}}{1 - y_A}\frac{dy_A}{dx} \Rightarrow -\frac{1}{1 - y_A}\frac{dy_A}{dx} = \frac{\bar{J}_A}{CD_{AB}} = constant$$

Since $\bar{J}_A$ = constant, C = constant, and D_{AB} =constant. Separating the variables and integrating from x = 0, where $y_A(0) = y_{A,0}$, x =L, where $y_A(L) = y_{A,L}$ gives

$$-\int_{y_{A,0}}^{y_{A,L}} \frac{dy_A}{1 - y_A} = \int_0^L \frac{\bar{J}_A}{CD_{AB}} dx$$

Performing the integrations,

$$\ln\frac{1 - y_{A,L}}{1 - y_{A,0}} = \frac{\bar{J}_A}{CD_{AB}}L$$

Then the molar flux of A, which is the *Vaporization Rate of species A per unit interface area*, becomes

$$\bar{J}_A = \frac{\dot{N}_A}{A} = -\frac{CD_{AB}}{L}\ln\frac{1 - y_{A,L}}{1 - y_{A,0}}$$

Where L is the length of the diffusion, $y_{A,L}$ is a mass fraction at x=L and $y_{A,0}$ is a mass fraction at x=0.

Some assumptions have been made in this study including:

   i.   The velocity of circulated air in the reactor room is neglected (stagnant); assume the vaporization only affected by reactor operation.

  ii.   The effect of the temperature in the reactor hall is neglected.

 iii.   The effect of negative pressure in the reactor hall is neglected.

 iv.   The air or gas in the reactor hall is assumed to be insoluble in the water.

  v.   Vapor is assumed to behave as ideal gases.

II.   EXPERIMENTAL PROCEDURE

Before the reactor operates, the experimental devices including water temperature probe, portable temperature meter and portable electronic camera were set up as shown in Figure 3, 4 and 5. Two temperature probes are attached at the pool and the ends of the probe are submerged 0.2 m under the surface of the pool water to measure

the temperature of the water surface. The electronic camera is connected to the screen monitor in the control room to ease the data recording.

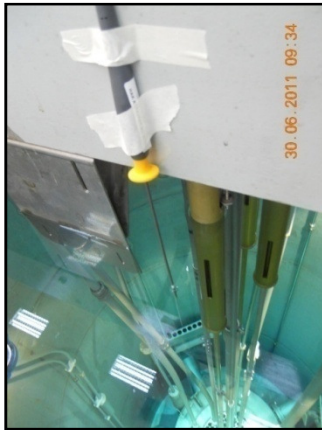Figure 3: Portable temperature meter
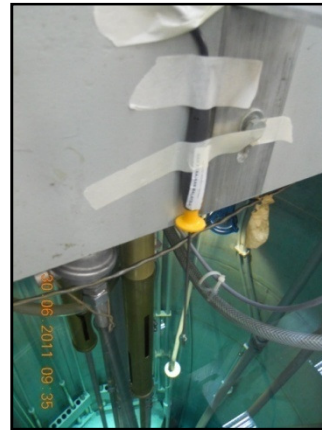

Figure 4: Temperature Probe #1

Figure 5: Temperature Probe #2

Figure 6: Water level monitor in Control Room

Figure 7: Water level monitor at the Pool Top

The experiment is conducted at 1MWth power level. The temperature readings are recorded from portable temperature meter. In the mean time, the bulk water temperature also being recorded from the console panel in the

control room. The temperature readings were recorded every 100kWth interval from zero power to 1 MWth. When the power level is reached 1 MWth, then the temperatures were recorded for every 30 minutes interval until reactor shutdown. After reactor shutdown, it was cooled down until the bulk water temperature reaches 30^0C. At this point, water level reading has been recorded.

III. RESULT AND DISCUSSION
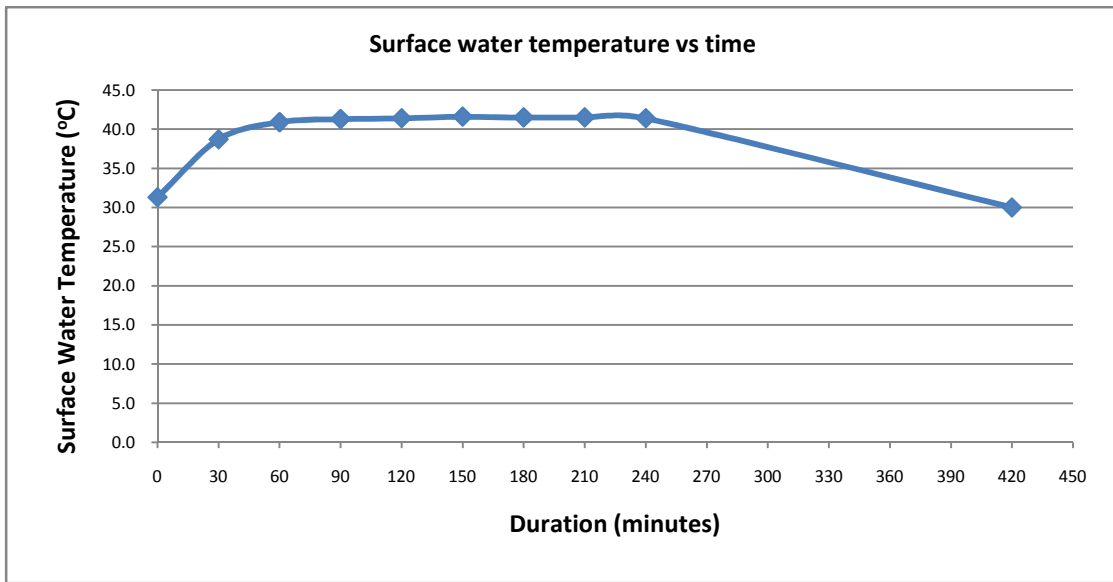
The recorded data is presented in the Figure 8.

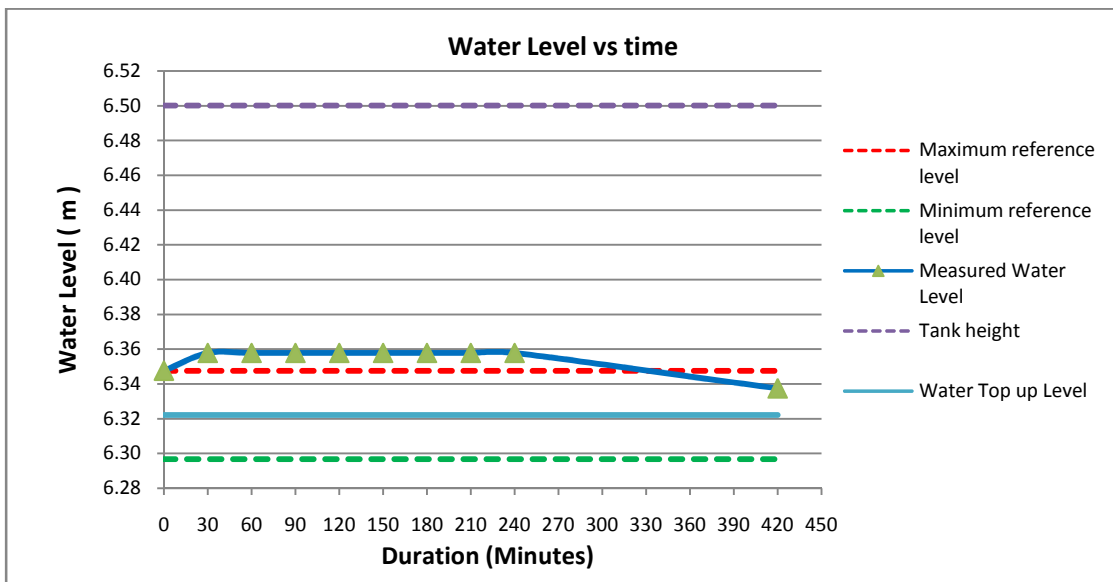Figure 8: Surface water temperature versus time

Figure 9: Water Level versus Time

Figure 8 shows the relationship of surface water temperature and duration from the time power level reach 1MW. From start up to target power at 1MWth, surface water temperature shows no increase and water level as well indicate no changes. The temperature started to increase when the power level 1 MWth has been achieved. The temperature increased rapidly in 60 minutes from 31.3°C to 41.5°C.After an hour of operation at 1MWth, the temperature shows no significant changes until the reactor shutdown about 4 hours later. Water level indicates some increase about 0.01m from the reference level after 30 minutes of reaching the target power. The increasing of water level is due to the expansion of water molecule when the temperature increased. The water level remains at 6.358 m during the operation until the reactor shutdown. Even though after shutdown, the water level remains constant because the temperature remains high. Continuous cooling is needed to cool the reactor to below 30°C. After the reactor has cooled down about 3 hours, then the water level indicates decreasing of 0.010m from the reference level.

From the Figure 8, the temperature was recording the stabile value at 41.5°C. Therefore, this value is used to calculate the vaporization rate at 1 MWth power level. By neglecting the effect of negative pressure in the reactor hall, the pressure in the reactor hall was assumed as atmospheric pressure. The air at the water surface will be saturated. Therefore, the partial pressure of water vapor in the air at the water surface of the reactor tank will simply be the saturation pressure of water at 41.5°C.

Calculation

$$y_{vapor,0} = y_{A,0} = \frac{P_{vapor,0}}{P} = \frac{P_{sat\ @\ 41.5\ ℃}}{P_{atm}} = \frac{8.1745\ kPa}{101.325\ kPa} = 0.0806 \qquad \text{... (1)}$$

$$C = \frac{P_{atm}}{R_u\ T} = \frac{101.325\ kPa}{(8.314\ kPa.m^3/kmol.K)(314.5\ K)} = 0.03875\ kmol/m^3 \qquad \text{... (2)}$$

$$A = \pi r^2 = \pi(1)^2 = 3.1416\ m^2 \qquad \text{... (3)}$$

$$D_{AB@41.5℃} = 2.7985 \times 10^{-5} m^2/s \qquad \text{... (4)}$$

$$L = 0.010\ m \qquad \text{... (5)}$$

$$y_{A,L} = 0 \qquad \text{... (6)}$$

By substituting (1), (2), (3), (4), (5) and (6) into the *Vaporization Rate Equation*, we get:

$$\bar{J}_A = \frac{\dot{N}_A}{A} = -\frac{CD_{AB}}{L} \ln\frac{1 - y_{A,L}}{1 - y_{A,0}}$$

$$\bar{J}_A = \frac{\dot{N}_A}{A} = -\frac{\left(0.03875\frac{kmol}{m^3}\right)(2.7985 \times 10^{-5}\frac{m^2}{s})}{0.010\ m} \ln\frac{1 - 0}{1 - 0.0806}$$

$$\bar{J}_A = \frac{\dot{N}_A}{A} = -9.1128 \times 10^{-6}\ kmol/m^2.s$$

So,

$$Molar\ Flow\ Rate\ of\ vapour\ ,\ \dot{N}_A = A \times 9.1128 \times 10^{-6}\frac{kmol}{m^2 s}$$

$$\dot{N}_A = 3.1416\ m^2 \times 9.1128 \times 10^{-6}\frac{kmol}{m^2 s}$$

$$\dot{N}_A = 2.8628 \times 10^{-5}\frac{kmol}{s}$$

In a mass basis, $\dot{m}_A = 2.8628 \times 10^{-5} \frac{kmol}{s} \times M_{water}$

$$\dot{m}_A = 2.8628 \times 10^{-5} \frac{kmol}{s} \times 18 \frac{kg}{kmol}$$

$$\boldsymbol{\dot{m}_A = 5.1530 \times 10^{-4} \frac{kg}{s} \Rightarrow 1.8551 \frac{kg}{h}}$$

From the calculation, when the reactor operates at 1 MWth ,the vaporization rate is $2.8628 \times 10^{-5} \frac{kmol}{s}$ (or $5.1530 \times 10^{-4} \frac{kg}{s}$) and the water level will decrease 0.010m. From this value, the time of the water reach the 6.322m, which is at this time the operator should be topping up the water manually through the demineralizer can be predicted. Also, the time to reach minimum reference level of the water can be calculated.

Maximum reference level = 6.348 m

Water Top Up level = 6.322 m

Minimum reference level = 6.297 m

$Volume\ of\ water\ decreased\ at\ 6.322\ m = A \times L$

$$= (3.1416m^2)(6.348m - 6.322m) \Rightarrow 0.0816\ m^3$$

$Mass\ of\ water\ volume\ at\ 6.322m = 0.0816m^3 \times 1000\ kg/m^3 \Rightarrow 81.6kg$

$Time\ of\ reaching\ 6.322m\ at\ 6hours\ operation\ per\ day = 81.6kg \div 1.8551 \frac{kg}{h} \Rightarrow \frac{43.98h}{\frac{6h}{day}} \Rightarrow \boldsymbol{7.33\ days}$

Also,

$Volume\ of\ water\ decreased\ at\ 6.297\ m = A \times L$

$$= (3.1416m^2)(6.348m - 6.297m) \Rightarrow 0.1602\ m^3$$

$Mass\ of\ water\ volume\ at\ 6.297m = 0.1602m^3 \times 1000\ kg/m^3 \Rightarrow 160.2kg$

$Time\ of\ reaching\ 6.297m\ at\ 6\ hours\ operation\ per\ day = 160.2kg \div 1.8551 \frac{kg}{h} \Rightarrow \frac{86.35h}{\frac{6h}{day}} \Rightarrow \boldsymbol{14.39\ days}$

IV.   CONCLUSION

The vaporization rate of the water in the reactor tank is $2.8628 \times 10^{-5} \frac{kmol}{s}$ (or $5.1530 \times 10^{-4} \frac{kg}{s}$) when the reactor is operated at 1 MWth and the temperature of the water surface is 41.5°C. The operation at 1 MWth power level for 4 hours a day will decrease the water level at 0.010m. In 6 hours operation per day, the water level will decreased to 6.322 m (7 inches from pool top) after 7.33 days operations and 6.297m (8 inches from pool top) after 14.39 days operations.

V.   RECOMMENDATION

In the real situation, vaporization occurs not just during the operation, but even after the reactor shutdown or no operation the water still vaporise by the driven force of the air flow from the ventilation system. Therefore, the effects of the air flow to the vaporization should be considered. The vaporization rate may be different at different power level. So, it is essential to analyze the vaporization rate at different power levels and duration of operation.

REFERENCES

[1]   Heat Transfer 2nd Edition, Yunus A. Çengel,The MacGraw-Hill Companies, 2002.

[2]   A Heat Transfer Textbook, Third Edition, John H.Lienhard IV/John H.Lienhard V,2002.

[3]   Analisa laju Penguapan Air Pendingin Primer dari tangki reaktor TRIGA 200 Bandung, Reinaldy Nazar,2008.

[4]   PUSPATI   TRIGA   reactor   Safety   Analysis   Report,   Nuclear   Power   Division, NUKLEARMALAYSIA/L/2008/34(S)