Water evaporation rate of RSG-GAS spent fuel storage pool

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Abstract. Water in spent fuel storage pool that serves as a water cooling of decay heat and radiation shielding must be kept steady from evaporation. Knowledge of the evaporation rate of spent fuel storage pool is needed so that the amount of make up water can be well known for nuclear safety purposes. This study aims to calculate the rate of water evaporation in RSG-GAS spent fuel storage pool. The Shah and Carrier correlations were used to calculate the rate of evaporation based on operational data obtained in the spent fuel storage pool, i.e, pond water temperature, room temperature, relative humidity, and airflow velocity in the SFSP building. The evaporation rate calculation was performed in two conditions: during ventilation and air conditioning are operated and not operated. The calculation result shows that the rate of water evaporation rises from 0.0138 kg/m².h to 0.0747 kg/m².h when using Shah correlation, and from 0.0153 kg/m².h to 0.0831 kg/m².h when using Carrier correlation. From the calculation found that the needs of make-up water per day to replace the water loss by evaporation is 42.28 - 43.84 kg/day. The rate of evaporation of pond water during operational of ventilation air conditioning is greater than when ventilation air conditioning is not operated. The result shows that the increase of water evaporation rate of spent fuel storage pool is strongly influenced by the increase of vapor pressure difference and the length of operation time of VAC.

Keywords: water evaporation rate; make up water; Nuclear spent fuel storage pool; RSG-GAS
Nomenclatures

| Symbol | Definition |
|--------|------------|
| $E$    | Evaporation rate (kg/m$^2$.h) |
| $h_{lg}$ | Latent heat of vaporization of water (kJ/kg) |
| $p_{w}$ | Partial pressure of water vapor in air saturated at water surface temperature (Pa) |
| $p_r$ | Partial pressure of water vapor in air at room temperature and humidity (Pa) |
| $P_{at}$ | Air pressure at room (Pa) |
| $p_{w,r}$ | Partial pressure of water vapor in air (Pa) |
| $w_w$ | Specific humidity of air (kg of moisture/kg of air) |
| $w_r$ | Specific humidity of air (kg of moisture/kg of air) |
| $T_w$ | Temperature at water surface ($^\circ$C) |
| $T_r$ | Temperature at room ($^\circ$C) |
| $V$ | Air velocity (m/s) |
| $\varphi$ | Relative humidity (%) |
| $E_{VAC}$ | Total water evaporated during operational of VAC in one day (kg/day) |
| $E_{VAC-OFF}$ | Total water evaporated during non-operational of VAC in one day (kg/day) |

Acronyms

| Acronym | Definition |
|---------|------------|
| SFSP    | Spent Fuel Storage Pool |
| RSG-GAS | Reaktor Serba Guna GA. Siwabessy |
| VAC     | Ventilation and Air Conditioning |

1. **Introduction**

The pool water in the spent fuel storage pool (SFSP) serves as a spent nuclear fuel cooling for the continuously generated decay heat and as a radiation shielding for workers and the environment. In the spent fuel storage pool of Multipurpose Reactor G. A. Siwabessy (RSG-GAS), the pool water level has been maintained 3.6 m from the peak of the fuel to allow radiation exposure in the work area not to exceed 5 μSv / hr. In normal operation, the pool water is lost due to suspected evaporation. In order to maintain the safety of SFSP operation, the calculation of SFSP water evaporation rate is needed to make it easier in determining the volume of additional make up water required.

Study of water evaporation rate calculation in pools has been widely practiced in various fields, both nuclear and non-nuclear. Generally, the evaporation rate studies have been conducted in indoor and outdoor swimming pools (disturbed or undisturbed), tanks, water storage vessels, and in cases of water spills. In the nuclear field, the rate of evaporation of pond water has been studied primarily in spent fuel storage pools.

Carrier [1,2] studied the rate of pond water evaporation to design an indoor pool in case of heating, with ventilation, and air conditioning equipment. His study resulted a correlation of evaporation rate dependent on water velocity, vapor pressure difference, and latent heat of evaporation.

The ASHRAE Handbook [2,3] added a multiplier factor (i.e activity factor) to correct the Carrier correlation at the swimming pool evaporation rate. Human activity factor was added to predict the rate of evaporation. A new correlation, obtained from the results, corrected the Carrier correlation.

Boelter et al [1,3] conducted an experiment in undisturbed water pool in calm air with temperature variation up to 94°C. A correlation obtained from the results, states that the rate of evaporation was influenced by the difference in the concentration of water vapor on the surface of the pond water with the concentration of water vapor in the room air.

Shah [4] studied the prediction of evaporation rate in indoor swimming pool at temperatures of 26-32 °C and relative humidity 32-72%. In his investigation, the influence of various factors such as vapor pressure difference, humidity ratio, and specific density were taken into account. The results showed that the vapor pressure difference has a very significant effect on the rate of water evaporation.
In another study, Shah [5] investigated the water evaporation rate of pool that had human activity and without human activity. The results show that swimming pools with human activity have a higher rate of evaporation than without human activity. Evaporation increases proportional by the increase in pool surface because of the increased contact area of water with air and the rise of water temperature.

Asdrubali [6] conducted an experiment to investigate the rate of evaporation in indoor pool water with ventilation system. He compared his experimental data with calculations based on Shah, Hannsen and Mathisen, and Smith. The results showed that his prediction model of evaporation rate has a good agreement with the literature compared.

L. Lecoq et al [7] examined the factors that have the greatest effect for the water evaporation rate. Experiments were performed using droplet from stainless plate in wind tunnel with variation of temperature, relative humidity, and air velocity. The results showed that relative humidity is a factor that has the greatest effect to the water evaporation rate.

J.L.F Blázquez [8] investigated water evaporation rate in indoor swimming pool using CFD model and validated with experimental data. The boundary conditions in the CFD model are set at the water-air interface. The model was validated with 4 experimental studies under different conditions with a combination of temperature, humidity, and airflow velocity. The results showed that the simulation of water evaporation rate in VAC system obtained a good result with a relative average error of 3.3%.

Shah [9] developed an evaporation calculation method in a calm water pool (undisturbed) by correcting his previous correlations. The method was done by extending the scope not only on the positive density difference, but also on the negative density difference. The calculations performed were validated by 11 test data. He determined a constant value to calculate the rate of water evaporation in the air movement generated by the ventilation system in the room. His result was a new correlation that can be used for swimming pools and other indoor pools with calm water surface such as SFSP.

Shah [10] in newer studies developed calculations of the water evaporation rate in swimming pools, water storage tanks, water spills, and spent fuel pools on nuclear power plants. A combination of experiments and theoretical studies was conducted to develop a method of calculating the water evaporation rate. Shah also compared his calculations with Smith et al. and Meyer, Boelter data and Hugo data (2013) in the case of evaporation rate in SFSP water. The results showed a good agreement of evaporation rate values obtained from Shah's correlation with other data.

M. Quinn Brewster [11] investigated the experiment of water evaporation rate of SFSP in the case of emergency conditions (e.g. station blackout). His results then compared with experimental data obtained by Boelter. The results showed a good agreement with Boelter experiment, and on SFSP there was a high mass transfer rate during the pool water has a temperature up to 99 °C.

Hugo et al [3] examined experimentally the rate of water evaporation in the SFSP. In their study, they compared the calculations using the existing correlation with the diffusion model using forced air flow. The results showed that the diffusion model prediction has approximately equal with predictions using Shah correlation. The Shah correlation model was the best use for the SFSP evaporation in case of low water temperatures. At high water temperatures, experimental data Boelter et al. used to validate their correlation. The results showed that there was linearity in experimental results of Boelter et al. and produced a new diffusion correlations.

On the other hand, there has been no research on the water evaporation rate of RSG-GAS SFSP. This study is important due to safety factor of SFSP. Therefore, in this research, the evaporation rate of pool water in RSG-GAS SFSP was done. In the method, the calculation used was Shah and Carrier correlation based on operation data of RSG-GAS SFSP, which consist of temperature data of pool water, room temperature, relative humidity, and airflow velocity in SFSP room during operational of ventilation and air conditioning (VAC) and non operational of VAC. The results will be used as knowledge to determine the amount of make-up water required when evaporation occurs in SFSP water.
2. Methodology

In this research, the water evaporation rate in RSG-GAS SFSP is calculated using Shah and Carrier correlation. Operation data of SFSP such as pool water temperature data, room temperature, relative humidity, and airflow velocity in the SFSP room were input to the correlation. In this calculation, RSG-GAS SFSP operating data is in VAC condition turned on and turned off. The calculation of each correlation used will be compared to the result.

The Shah correlations used is[10]:

\[ E = 0.00005 \left( P_w - P_r \right) \]  

The Carrier correlations used is[3]:

\[ E = \frac{(0.089 + 0.0782 \nu)(P_w - P_r)}{h_{fg}} \]  

The formula to calculate \( p_w \) is[12]:

\[ p_w = \frac{w_r P_{at}}{w_w + 0.62198} \]  

\( w_w \) as a function of temperature the following expression is used[12]:

\[ w_w = 0.00080264 + 0.000024525 T_w + 2.542e - 06 T_w^2 - 2.5855e - 08 T_w^3 + 4.038e - 10 T_w^4 \]  

The formula to calculate \( p_r \) is[12]:

\[ p_r = p_{wrr} \varphi \]  

\( p_{wrr} \) is calculated using [12]:

\[ p_{wrr} = \frac{w_r P_{at}}{w_r + 0.62198} \]  

\( w_r \) as a function of temperature the following expression is used[12]:

\[ w_r = 0.00080264 + 0.000024525 T_r + 2.542e - 06 T_r^2 - 2.5855e - 08 T_r^3 + 4.038e - 10 T_r^4 \]  

Airflow velocity are obtained from direct measurements on the air above the pool water surface. From the measurement results obtained airflow velocity is 0.6 m/s while VAC is operated, and 0 m/s while VAC is unoperated. Where \( h_{fg} \) obtained based on Table 1.

| Temperature [°C] | Heat of vaporization, \( h_{fg} \) |
|------------------|----------------------------------|
|                  | [J/mol] | [kJ/kg] | [kWh/kg] | [BTU(lb)/lbm] |
| 0.01             | 45054   | 2500.9  | 694.69   | 1075.2        |
| 2                | 44970   | 2496.2  | 693.39   | 1073.2        |
| 4                | 44883   | 2491.4  | 692.06   | 1071.1        |
| 10               | 44627   | 2477.2  | 688.11   | 1065.0        |
| 14               | 44456   | 2467.7  | 685.47   | 1060.9        |
| 18               | 44287   | 2458.3  | 682.86   | 1056.9        |
| 20               | 44200   | 2453.5  | 681.53   | 1054.8        |
| 25               | 43988   | 2441.7  | 678.25   | 1049.7        |
| 30               | 43774   | 2429.8  | 674.94   | 1044.6        |
| 34               | 43602   | 2420.3  | 672.31   | 1040.5        |
| 40               | 43345   | 2406.0  | 668.33   | 1034.4        |
| 44               | 43172   | 2396.4  | 665.67   | 1030.3        |
| 50               | 42911   | 2381.9  | 661.64   | 1024.0        |
| 54               | 42738   | 2372.3  | 658.97   | 1019.9        |
| 60               | 42475   | 2357.7  | 654.92   | 1013.6        |
| 70               | 42030   | 2333.0  | 648.06   | 1003.0        |
| 80               | 41579   | 2308.0  | 641.11   | 992.26        |
3. Results and Discussion
The evaporation rate calculations performed when the SFSP operation under VAC conditions is turned on and turned off described as follows:

3.1 Water evaporation rate during VAC turned on
The calculations performed are based on the measurement data of air and water parameters in the pool chamber to determine the effect of VAC to the evaporation rate. Temperature data, relative humidity, pressure, and air velocity are taken after the ventilation system is turned on.

Air and water pool temperature in SFSP building during VAC is turned on is shown in figure 1.

**Figure 1.** Air and water temperature in SFSP during VAC is turned on

Figure 1 shows that the air temperature has decreased due to VAC is turned on. The air temperature decreased from 29.00 °C to 25.31 °C during 185 minutes of VAC being operated, while the surface water temperature is stable at 25.80 °C. The air temperature in the SFSP room decreases to the desired temperature. Spent nuclear fuel stored in SFSP is suspected to have less heat generation, seen from pool water temperatures that did not decrease significantly during VAC being operated (the cooling system was turned off). Figure 1 also shows that the room temperature contributed to keep the water temperature from increasing.

While relative humidity in SFSP room during VAC is turned on is shown in figure 2.

**Figure 2.** Relative humidity of SFSP room during VAC is turned on
From figure 2 it can be seen that the relative humidity in the SFSP building has decreased because VAC is turned on. Relative humidity decreased significantly after the VAC was turned on until the 55th minute since the air temperature will cause more water vapor to condense. The condensed water vapor can be drained off by the VAC system so that the water vapor in the air decreases. After 55 minutes the relative humidity value does not have great fluctuations because the temperature of the air has reached the desired temperature. In general the relative air humidity is initially 0.76 (76%) to 0.56 (56%) during the 185 minute of VAC being operated.

The objective of VAC system is also to obtain negative pressure inside the installation against the ambient air to avoid release of radioactive material to the environment. Transient SFSP room air pressure during VAC being operated is shown in figure 3.

From figure 3 it can be seen that the air pressure of the SFSP room is decreasing as VAC is turned on. Air pressure in the room decreased significantly until the 10th minute because the air pressure that initially had a high air pressure value was suddenly inhaled by the VAC system being turned on. From figure 3 it could also be seen that the pressure in the room becomes relatively stable after the 10th minute VAC is turned on. The air pressure was initially 100.526 Pascal to 100.119 Pascal during the 185 minute of VAC being operated.

The data in figure 1 - 3 are used to calculate the value of \( p_r \) and \( p_w \). Transient value of partial pressure of water vapor in air at room temperature and humidity, \( p_r \), and partial pressure of water vapor in water saturated at water surface temperature, \( p_w \), is shown in figure 4.
From figure 4 it can be seen that the partial pressure of water vapor in air at room temperature and humidity (p_r) has decreased significantly. The p_r value is initially 3034.20 Pascal fall to 1803.24 Pascal for 185 minutes of VAC being operated. While the p_w value only slightly decreased, the initial 3309.73 Pascal become 3296.33 Pascal during 185 minutes of VAC being operated. Since p_r is the partial pressure of water vapor in the air at the temperature and relative humidity of the room, then the factor affecting the p_r value is the humidity ratio as a function of air temperature, pressure, and relative humidity of air. Humidity ratio is the ratio of moist by dry air. While p_w, the partial pressure of water vapor at the water surface, is the factor that affect the water temperature and air pressure above the water surface. At the same water temperature, the p_w value decreases by decreasing the air pressure above the water surface due to VAC operation. The value of p_r is decreasing significantly due to relative humidity which decreased significantly due to VAC operation shown in figure 5.

The data in figure 1 - 5 is used to calculate the water evaporation rate of the SFSP water. The results of the calculation of the water evaporation rate of pool water are shown in Figure 6.
From figure 6 it can be seen that the water evaporation rate increases with the length of VAC operation. The water evaporation rate rises from 0.0138 kg/m$^2$h to 0.0747 kg/m$^2$h when using Shah correlation, and from 0.0153 kg/m$^2$h to 0.0831 kg/m$^2$h when using Carrier correlation. The increasing of the water evaporation rate is caused by the increasing of vapor pressure difference which is the partial pressure difference of water vapor in the water surface ($p_w$) and water vapor in the room air ($p_r$). Thus the relationship between vapor pressure difference and the water evaporation rate is shown in figure 7.

From figure 7 it can be seen that the relationship between the rate of evaporation and the vapor pressure difference ($p_w$-$p_r$) is linear. Shah [8] also conducted experiments on air movement over the water surface due to VAC system operation. When compared with the Shah's experiments, it shows the appropriate results.

3.2 Water evaporation rate during VAC is turned off
Temperature data of water and room air in SFSP during VAC is turned off is shown in figure 8.
From figure 8 it can be seen that the air temperature in the SFSP room increased due to VAC is turned off. Air temperature which was originally 25.51 °C rose to 27.09 °C in 51 minutes of VAC is turned off. While the water temperature of the pool is stable at 25.8 °C. Transient relative humidity of the SFSP room during VAC is turned on is shown in figure 9.

Figure 9 shows that the relative humidity of air in the SFSP room fluctuates but tends to rise because the VAC is turned off. Relative air humidity which initially 0.6151 had risen to 0.6290 at 40 minutes and became 0.6181 at 51 minutes after the VAC was switched off. The transient air pressure of the SFSP room during the VAC is turned off shown in figure 10.
From figure 10 it can be seen that the air pressure in SFSP room has increased. The air pressure that was initially 99,761 Pascal rose to 99,799 Pascal after 51 minutes of VAC is turned off.

Transient partial water vapor pressure at room air (p_r) and partial pressure of water vapor on the surface of pool water (p_w) is shown in figure 11.

Figure 11 shows that the p_r value has increased significantly due to VAC is turned off, while the p_w value only slightly increases. The p_r value that was initially 1989.20 Pascal rose to 2192.59 Pascal after 51 minutes of VAC is turned off, while the p_w rose slightly from 3284.54 Pascal to 3285.80 Pascal after 51 minutes VAC is turned off.

From the data in figures 8 to 11 it can calculate the rate of water evaporation of the SFSP water during the VAC is turned off that shown in figure 12.
Figure 12 shows that the evaporation rate of the SFSP water has decreased due to the VAC being turned off. The rate of evaporation is initially 0.0648 kg/m² h to 0.0547 kg/m² h when calculated using Shah correlation. When calculated using Carrier correlation, the rate of water evaporation decreased from 0.0472 kg/m² h to 0.0398 kg/m² h. The linearity between the vapor pressure difference values the rate of evaporation of the pool water during the VAC being turned off is shown in figure 13.

Figure 13. Linerity between vapor pressure difference and water evaporation rate

### 3.3 Calculation of the make up water per day

Evaporation rate data obtained from calculations in section 3.1 and 3.2 based on the Shah and Carrier correlations used to calculate the amount of make up water per day. In normal operating conditions of SFSP, VAC is turned on during working hours for 8 hours and turned off during non working hours for 16 hours every working day. So to get the amount of make-up water needed for 1 day, by calculating the amount of water that evaporates, VAC is turned on for 8 hours and turned off for 16 hours. Since the experimental data were not carried out throughout the day, the line equations can be used to predict the rate of evaporation as long as there were no experimental data. From the data of mass evaporation rate per unit area per hour obtained from the calculation in section 3.1 and 3.2, the rate of mass water evaporation per day can be calculated for SFSP surface area is given 70 m².
(14mx5m). Experiment and prediction rate of daily evaporation rate for data based on Shah correlation is shown in figure 14 during 8 hours of VAC operation, and figure 15 during VAC is turned off.

![Figure 14. Evaporation rate during 8 hours VAC is turned on using Shah correlation](image)

From figure 14 it can be seen that SFSP water evaporation rate as a function of time is defined on the equation of y1 line. By drawing a straight line at the rate of evaporation at minute 0 (VAC turned on) up to 480 minutes (VAC was first turned off), the equation of y2 line is obtained. The amount of water evaporated during the 8 hours of VAC operation can be defined as the area bounded by the y1 and y2 lines. The total evaporated water during 8 hours of operational VAC can be calculated by the integration of the curves of y1 and y2, formulated as follows:

\[
E_{VAC} = \int_{0}^{480} (y_1 - y_2) \, dx
\]

For example to calculate the amount of water evaporation for 8 hours (480 minutes) VAC operation with data from calculations using Shah correlation is calculated as follows:

\[
E_{VAC} = \int_{0}^{480} \left( -0.06991e^{-\frac{x}{22.98258}} + 0.085 \right) - 0.0161 \, dx
\]

By using integral formula above, the amount of pool water evaporated for 8 hours of VAC operation is 32.9244 kg/day.

For the condition of 16 hours (960 minutes) of VAC is turned off, the evaporation rate of SFSP water is shown in figure 15.
Figure 15 shows that the evaporation rate of SFSP water during 16 hours of VAC is turned off. The rate of evaporation of pool water as a function of time is shown by the equation of $y_1$ line. By drawing a straight line at the value of the 0th minute evaporation rate (VAC is turned off) until the 960th minute (ending VAC is turned off), we get the $y_2$ line equation. The amount of water evaporated for 16 hours during VAC is turned off can be defined as the area bounded by the $y_1$ and $y_2$ lines. The total water evaporated during 16 hours of VAC is turned off can be calculated by the integration of the curve of the $y_1$ and $y_2$ curves, formulated as follows:

$$
E_{VAC-OFF} = \int_{0}^{960} (y_1) - (y_2) \, dx 
$$

From the calculation above, water evaporated during 16 hours is 10.9181 kg/day. From the calculations in Figures 14 and 15 we can calculate the total water evaporated for 1 day (24 hours) by adding the value of water evaporated during the 8 hours of VAC operation and the water evaporated during 16 hours of VAC is turned off. So the total water evaporated for 1 day (24 hours) when using Shah correlation is 43.8425 kg/day.

If the experimental data were calculated using a Carrier correlation then in the same way calculation, the amount of evaporation of SFSP water shown in figure 16 during VAC operation, and figure 17 during VAC is turned off.
From figure 16 above, an evaporation rate as a function of time is taken to calculate the amount of water evaporation during 8 hours of VAC operation. From the calculation obtained value 31.3666 kg/day. While during 16 hours of VAC is turned off the water evaporation value as much as 10.9173 kg/day. So the total water evaporated for 1 day (24 hours) when using Carrier correlation is 42.2839 kg / day.

4. **Conclusions**
Water evaporation rate at RSG-GAS SFSP increases with the length of VAC operation. The water evaporation rate rises from 0.0138 kg/m².h to 0.0747 kg/m².h when using Shah correlation, and from 0.0153 kg / m².h to 0.0831 kg / m².h when using Carrier correlation. The increase of water evaporation rate is caused by the increase of vapor pressure difference which is the partial pressure difference of water vapor at the water surface (p_w) with room air (p_r). The relationship between vapor
pressure difference and the rate of evaporation of pool water is linear. The amount of water evaporated in a day is calculated by integration of evaporation rate of experimental results and prediction as a function of time. From the calculation, it is found that the value of 43.8425 kg/day if the data is calculated based on Shah's correlation, and 42.2839 kg/day if the data is calculated based on Carrier correlation. This value is proposed to be the amount 42.2839 - 43.8425 kg/day of make up water needed to keep the water pool level.

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