Experimental Investigation of the Hot Water Layer Effect on Upward Flow Open Pool Reactor Operability

Talal Abou Elmaaty

Reactors Department, Nuclear Research Center, Atomic Energy Authority, Cairo, Egypt.

Received: 6/3/2014 Accepted: 1/4/2014

ABSTRACT

The open pool reactor offers a high degree of reliability in the handling and manoeuvring, the replacement of reactor internal components and the swing of vertical irradiation channels. The protection of both the operators and the reactor hall environment against radiation hazards is considered a matter of interest. So, a hot water layer implemented above many of the research reactors main pool, especially those whose flow direction is upward flow. An experimental work was carried out to ensure the operability of the upward flow open pool research reactor with / without the hot water layer. The performed experiment showed that, the hot water layer produced an inverse buoyant force making the water to diffuse downward against the ordinary natural circulation from the reactor core. An upward flow - open pool research reactor (with a power greater than 20 Mw) could not work without a hot water layer. The high temperature of the hot water layer surface could release a considerable amount of water vapour into the reactor hall, so a heat and mass transfer model is built based on the measured hot water layer surface temperature to calculate the amount of released water vapour during the reactor operating period. The effects of many parameters like the ambient air temperature, the reactor hall relative humidity and the speed of the pushed air layer above the top pool end on the evaporation rate is studied. The current study showed that, the hot water layer system is considered an efficient shielding system against gamma radiation for open pool upward flow reactor and that system should be operated before the reactor start up by a suitable period of time. While, the heat and mass transfer model results showed that, the amount of the released water vapour is increased as a result of both the increase in hot water layer surface temperature and the increase in air layer speed. As the increase in hot water layer surface temperature could produce a good operability conditions from reactor safety point of view, it could also harm the reactor hall walls paint and some components due to the condensation of water vapour.

1- INTRODUCTION

The goal of reactor thermal hydraulic design is to ensure that adequate cooling of the core is provided and the core integrity is maintained during normal operations, abnormal operational transients, and accidents. In general, pool type research reactors use a forced convection cooling mode as well as a natural convection cooling mode for core cooling(1). In the natural convection cooling mode, the core flow is an upward flow because of the difference of the fluid density between the core (source) and the pool (sink). It is important to know the cooling capacity of reactors under natural convective cooling for reactor safety. Research reactors normally operating much above 10 MW are predicted to experience nucleate boiling in the event of a flow inversion(2). Therefore, research reactors of power more than 20 MW are most likely cooled by forced convection in the upward flow direction to avoid coolant flow inversion in the reactor core. The activated and fission products existing in cooling water represents the main radiological components of exposure over the Pool surface. The upward forced convection cooling helps these activated components to reach the free surface of the
reactor pool. So, a hot water layer system should be implemented to reduce the dose rate hazards over the pool surface.

2- Hot Water Layer System Description:

The hot water layer system has been designed as a protection against radiation emitted by some of the isotopes present in the pool water. This purpose is achieved by the formation of a non active stable water layer over the pool water. The hot layer is continuously purified and overheated. The temperature difference between the layer and the pool reduces mixing and accordingly the potential contamination of the layer with material which may be dissolved in the pool water. The thickness of the layer is approximately 1.5 m, with a temperature difference of over 5°C with respect to the mean temperature of the reactor pool water. Water is sucked from one end of the Pool at its upper part, and it is re-circulated through the hot water layer water treatment system in order to maintain it at its specified purity level (< 1 µS/cm), as well as through an electric heater which provides the necessary power to maintain it at the required temperature, as shown in Fig (1). Then, water is returned to the opposite side of the reactor pool at its upper part. The speed of water entering the pool should be regulated to prevent the perturbation. The electrical Heater is designed to provide a rated capacity of 100 Kw. A 7.5 m³/h nominal water flow is circulated through the hot water layer system by using a centrifugal pump.

![Fig. (1): hot water layer system diagram](image1)

3- Experimental Instrumentations:

The reactor power is measured through a power channel during the experiment. The power channel measures the evolution of neutron flux during reactor power operation. This channel is calibrated according to the reactor thermal balance. The adopted power channel detector is compensated ionization chamber (CIC) detector. The temperature measurement devices used during the experiments are Alumina isolated thermo resistances (RTD), the temperature sensors are calibrated in the ETRR-2 labs. The hot water layer system flow is measured and controlled by the annubar detector; this detector is calibrated according to the manufactures data curve. The flow measured value is used for protecting the hot water layer system electrical heater, when the flow rate is reduced below a certain value the heater is turned off. The dose rate is measured by YM-17 detector. It is an intelligent area monitoring system SIMA-2 made by INVAP. It consists of a set of detector modules, each of them containing a Geiger detector, the function of this monitor is to control that the personnel
of the plant will not be exposed to a dose higher than the annual occupational admissible dose. The system will produce alarms when abnormal situations appear. Detector heads are located at ETRR2 open pool end\(^3\).

4- Experimental Procedures:

The reactor is operated according to start up procedures. The reactor power, the dose rate, the mean pool temperature and the hot water layer temperature are recorded with time. First, the hot water layer electrical heater is in off mode. After certain time from operation (delayed period), the hot water layer electrical heater is switched on. The pre mentioned parameters are continuously recorded with time.

5- Heat and Mass Transfer Modelling:

The increase in the hot water layer temperature above the main pool temperature is resulted in water evaporation from the hot water layer surface. In the current study, the rate at which water evaporates from the surface of the pool is estimated. A more accurate function for the diffusion coefficient\((D_{a,w})\) of water vapor in air is obtained using a regression curve fit to the data from Bolz and Tuve (1976)\(^4\):

\[
D_{a,w} = -2.775 \times 10^{-6} + 4.479 \times 10^{-8}T + 1.656 \times 10^{-10}T^2
\]  

(1)

A heat transfer analogy for flow over an isothermal flat plate will be employed to estimate the rate of evaporation from the pool. The Reynolds number and Schmidt number will be determined and used in the Nusselt number correlation for flow over a flat plate, in order to compute the Sherwood number. The film temperature \((T_{\text{film}})\) is computed:

\[
T_{\text{film}} = \frac{T_s + T_\infty}{2}
\]  

(2)

Where; \(T_s\) is the hot water layer surface temperature, \(T_\infty\) the flowing air blanket temperature.

The film temperature is used to determine the required air properties (\(\mu, \rho\), and \(\nu\)).

The Schmidt number is computed according to:

\[
S_C = \frac{\nu}{D_{a,w}}
\]  

(3)

And the Reynolds number is computed according to:

\[
Re = \frac{\rho D U_\infty}{\mu}
\]  

(4)

Where, the characteristic length of the pool is assumed to be its diameter (D). The convection correlation for flow over an isothermal plate is used, in that correlation Prandtl number is replaced with the Schmidt number and the output is assigned to the average Sherwood number \((Sh)\) rather than the average Nusselt number, as indicated\(^5\).

\[
Sh = 0.664 (Re)^{0.5} (Sc)^{1/3}
\]  

(5)

The average Sherwood number is used to compute the average mass transfer coefficient:

\[
h_D = \frac{Sh D_{a,w}}{D}
\]  

(6)
The mass transfer rate is driven by the difference between the concentration of water vapor at the pool surface and in the free stream. The partial pressure of the water vapor at the pool surface \( (p_{w,sat}) \) is the saturation pressure of water at \( T_s \). The concentration of water vapor at the pool surface \( (c_{w,sat}) \) is the density of water vapor evaluated at the partial pressure and temperature. The mass fraction of water vapor at the pool surface is:

\[
mf_{w,sat} = \frac{C_{w,sat}}{\rho}
\]  

(7)

The partial pressure of water in the free stream \( (p_{w,\infty}) \) is the product of the relative humidity and the saturation pressure of water evaluated at \( T_\infty \) \( (p_{w,sat,\infty}) \).

\[
P_{w,sat} = RH \cdot P_{sat,w,\infty}
\]  

(8)

The concentration of water vapor in the free stream \( (c_{w,\infty}) \) is the density of water evaluated at the partial pressure and temperature. The mass fraction of water in the free stream is:

\[
mf_{w,\infty} = \frac{C_{w,\infty}}{\rho}
\]  

(9)

The blowing factor is calculated using

\[
BF = \frac{\ln(1 + B)}{B}
\]  

(10)

where;

\[
B = \frac{mf_{w,\infty} - mf_{w,sat}}{mf_{w,sat} - 1}
\]

The mass fraction of water in air is small and therefore the correction in mass transfer associated with the induced velocity at the surface of the pool is;

\[
\bar{h}_{D,e} = \bar{h}_D \cdot BF
\]  

(11)

The mass flow rate of water due to evaporation is calculated according to the corrected mass transfer coefficient:

\[
m_w = \bar{h}_{D,e} \frac{\pi D^2}{4} (C_{w,sat} - C_{w,\infty})
\]  

(12)

6- RESULTS AND DISCUSSION

Fig. (2) shows the development of both the measured reactor power and the measured dose rate with time. An exponential increase in power trend is recorded from the power channel (CIC1) . The reactor reached the predetermined power level value \( (5.8 \times 10^8 \text{ n/cm}^2\cdot\text{s}) \) after 0.75 hr from the reactor start up. The automatic reactor power control system, which controls the reactor power, is connected to maintain that level of power. The first action for the connected automatic power system is a step down, so a spontaneous drop of the power is recorded as shown in Fig. (2).
During the rest of reactor operation period, the reactor power is approximately stationary by means of the automatic control system. At the end of the operation period kept reactor is shutdown by the compensating control rods, so spontaneous reduction in reactor power from the operating power level to the zero power level is recorded. During the reactor start up period the measured dose rate was a back ground level due to low reactor power, when the reactor power is raised a pronounced increase in dose rate was recorded. The maximum recorded dose rate level was 66.75 μsv/hr after 1.67hr from reactor start up. The dose rate level is stabilized at that value for a period of time; hence the dose rate starts to decrease under the effect of the hot water layer. From the reactor operation experience, the dose rate level is usually proportional to the reactor power level, so the test is performed at a moderate power level not to produce any undesirable exposures. That means, in the absence of the hot water layer system, for reactor power level greater than $5.8 \times 10^8$ n/cm².s the dose rate will be certainly higher than, $66.75$ μSv/hr, the matter that could trip the reactor due to the high recorded dose rate.

Fig. (3) shows the recorded dose rate variation with the measured hot water layer temperature. The electrical heater is turned on after 0.75 hr from reactor start up (the time of maximum power). The mean pool water temperature is increased due to the released heat from the reactor core, that temperature is approximately stabilized after two hours from power rising. The hot water layer temperature increased as a result of both the reactor core released heat and the gained heat from the hot water layer electrical heater. For the operation period in which the mean pool water temperature is higher than the hot water layer temperature, the recorded dose rate is in its higher level due to both the buoyancy and the core upward flow effects. When the hot water layer temperature exceeded the mean pool water temperature, both the buoyancy and the core upward flow effects on the recorded dose rate are gradually reduced. After 3.85hr from the reactor start up, the recorded dose rate was decreased to $31$ μSv/hr. At that time, the temperature difference between the hot water layer and the mean pool water is recorded 4°C as shown in Fig. (3).
Fig. (3): Dose rate variation with hot water layer temperature

Fig. (4) shows the variation of the released water vapour flow rate with time at different reactor hall environmental conditions. The hot water layer surface temperature is considered one of the important controlling parameters for the released of water vapour. As the hot water layer surface temperature increased the evaporation rate is increased. Many parameters are contributed in affecting the water vapour releases from the hot water layer surface, like; the hall temperature, the relative humidity and the velocity of air blanket existed on pool surface. For constant hot water layer surface temperature and the ambient temperature is increased from 18°C to 21°C, the temperature gradient between the hot water layer surface temperature and the reactor hall is decreased, hence a reduction in the released evaporation rate is noticed. A more pronounced decrease in the evaporation rate was noticed as a result of increasing the relative humidity from 50% to 60%. The velocity of air blanket existing on pool surface has a strong effect on increasing the evaporation rate. Although the relative humidity is increased to 60% and the environmental temperature is increased to 21°C, the increase in air blanket velocity from 1m/s to 1.5 m/s produced a higher increase in evaporation rate.

Fig. (5) shows the accumulative released water with time. The accumulated water is increased with reactor operating time. For the reference modelling condition 50% RH, 18°C and 1m/s the accumulated water was 6.047 Kg, some of this water is trapped in the hot water layer tank though a dehumidification process while the remainder is released in the reactor hall. The escaped water vapour to the reactor hall causes many defects for the reactor hall ceiling and walls paint. The increase in both the relative humidity and the ambient temperature reduces the produced accumulative water. At 60% RH and T∞ =21°C could produced 5.216 kg water by the end of the operation period.
7- CONCLUSION

The hot water layer system proved that it is an efficient shielding system against gamma radiation for open pool upward flow reactor. A suitable range of temperature difference between the upper water layer and the mean pool water should be adopted to minimize the dose rate on pool surface to protect both the operators and the reactor hall environment. The presence of hot water layer enables the operator from using the irradiation vertical channels during the reactor operation at different powers. The operability of a research reactor of type open pool, upward flow and power
higher than 20 MW is decreased a lot due to the radiation hazards on pool surface. The heat and mass transfer model results showed that, the released water vapour is proportional with the hot water layer surface temperature. As the increase in hot water layer surface temperature could produce a good operability conditions from reactor safety point of view, it harms the paints of the reactor hall building walls. The high velocity of the air blanket above the reactor pool top end increases the water evaporation rate, while the humid and hot conditions for the reactor hall reduces the released vapour.

Nomenclature

- \( C \): Water vapour concentration \( \text{Kg/m}^3 \)
- \( D \): Hydraulic Diameter \( \text{m} \)
- \( D_{a,w} \): diffusion coefficient \( \text{m}^2/\text{s} \)
- \( \dot{h}_D \): Average mass transfer coefficient \( \text{m/s} \)
- \( \dot{h}_{D,c} \): Corrected average mass transfer coefficient \( \text{m/s} \)
- \( m \): Mass flow rate \( \text{Kg/s} \)
- \( m_f \): mass fraction of water vapor
- \( P \): Partial pressure of water \( \text{Pa} \)
- \( Re \): Reynolds number
- \( Sc \): Schmidt number
- \( Sh \): Sherwood number
- \( U \): velocity \( \text{m/s} \)
- \( \rho \): Density \( \text{Kg/m}^3 \)
- \( \mu \): Viscosity \( \text{Pa.s} \)
- \( \nu \): Kinematic viscosity \( \text{m}^2/\text{s} \)

Subscript
- \( a \): air
- \( s \): surface
- \( \infty \): infinity
- \( w \): water
- \( \text{sat} \): saturation
- \( c \): Corrected

REFERENCES