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Thermal Power Calibration and Error Minimization of 3MW TRIGA Mark-II Research Reactor

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Abstract— The thermal power calibration of the reactor is very important to get the accurate power and neutron flux. In the present experiment thermal power calibration is performed at 100 kW reactor power by calorimetric method (rate of temperature rise). Reactor tank constant of the BAEC TRIGA Research Reactor (BTRR) is also determined. In this study, a series of experiments were conducted using two types of stirrer for calibration of the BTRR thermal power. One stirrer (which is denoted as old stirrer) has four sets of propellers setting with the shaft at equal distance. Another stirrer (new) has one set of propeller setting at the bottom end of the shaft. New stirrer and associated systems were designed for proper mixing of the pool water to maintain the uniform temperature in the reactor pool water. Power calibration was performed at different speed of the new stirrer and optimum speed of the stirrer was determined to minimize calibration error. The experiment with new stirrer reduces thermal power error from 15% to 0.1% compared with old stirrer. The calculated and measured heat capacity constant (K) value for BTRR was found to be 26.35 kWh/^{o}C and 26.67 kWh/^{o}C respectively. The measured result is in good agreement with the design value. This paper describes thermal power calibration, determination of heat capacity constant, stirrer effect, optimum speed of the stirrer motor for uniform pool water temperature and calculation of heat losses from the reactor pool.

Index Terms—TRIGA research reactor, thermal power calibration, calorimetric method, stirrer effect, heat capacity constant, error minimization, neutron detector.

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1 INTRODUCTION

BANGLADESH Atomic Energy Commission (BAEC) has been operating a 3 MW TRIGA Mark-II research reactor since 14 September 1986. The reactor has been used for manpower training, radioisotope production and various R&D activities in the field of neutron activation analysis, neutron radiography and neutron scattering. The digital Instrumentation and Control (I&C) system has been installed in the BAEC research reactor on June 2012 by replacing the old analog I&C system. The reactor fuel is a solid, homogeneous mixture of U-ZrH alloy containing about 20% by weight of uranium enriched to about 19.7% U-235 and about 0.47% by weight of erbium. Accurate reactor thermal power calibration is important for safe monitoring and evaluation of reactor operation [1]. Since the first TRIGA reactor was built, different calibration methods have been developed for the reactor thermal power. BAEC TRIGA Research Reactor (BTRR) has four nuclear channels for monitoring the reactor thermal power. These are multi range linear power channel (NMP-1000), wide range log power channel (NLW-1000), safety channel % power 1 (NP-1000) and safety channel % power 2 (NPP-1000). Among these two channels are used to ensure operational safety of the reactor. Power monitoring of nuclear reactors is performed by neutron detectors, which are calibrated by thermal methods [2, 3]. The nuclear channels receive signals from fission chambers and ion chambers which are positioned around the reflector of the reactor core (Figure-1).

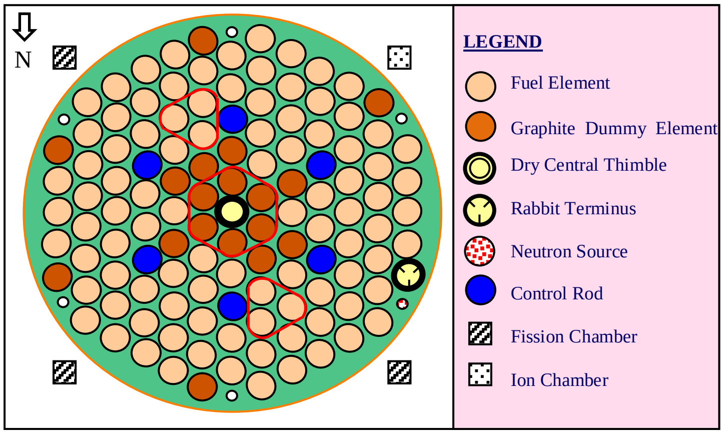

Fig.1: Reactor core configuration and location of neutron detectors [4]

Thermal power calibration is very much important, because reactor thermal power is directly proportional to neutron flux in the core. The calorimetric procedure is essentially the same whether it involves the calorimetric determination of heat

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equivalence of electrical energy or the rate of heat generation by a research reactor core. In each case, the calorimeter contains a relatively large volume of pool water and is constructed with insulated walls to reduce the flow of energy through the calorimeter walls. Thermal power calibration of the reactor is conducted at 100 kW reactor power level. In the present experiment the power calibration is performed by calorimetric method (rate of temperature rise). Heat constant of the BTRR tank is also determined. A new stirrer was designed for proper mixing the pool water to minimize the calibration error. Conduction, convection and evaporation heat loss was also determined to get the accurate thermal power of the reactor.

2 MEASUREMENT OF REACTOR THERMAL POWER

The basic equation for the calculation of reactor thermal power is

$$q = K\frac{dT}{dt} \qquad \textbf{(1)}$$

where q is the power and K is the heat capacity constant.

The reactor pool heat capacity constant can be calculated as well. In the first approximation, it is assumed that the rector pool temperature is constant throughout the pool. The reactor pool has been approximated as an insulated "point" system. Reactor pool can be treated as insulated when water temperature is close to air and soil temperatures. So the reactor heat capacity K can be simply calculated from wet pool volume V_w. The total volume of the BTRR pool water is 22.68 m^3.

For the TRIGA system, the mass is mainly the water in the tank because of its large heat capacity. The product of the metal components mass times their individual heat capacity is too small compared to the heat content of the large volume of water.

2.1 Experimental Setup and Procedure

I. Preparation of Water System

A. The reactor pool water temperature was kept uniform and almost similar of ambient temperature to minimize the heat loss from reactor tank surface to air.

B. The experiment was conducted without operating the reactor cooling systems.

C. Reactor tank water On-line purification system was turned off to prevent heat loss from reactor pool to demineralizer plant

D. Reactor tank was isolated by closing motor operated valves MOV-1&2 of the primary cooling system and also turn off the valves of DV 1&2 of the demineralizer plant.

II. Temperature Measurement System

Two RTDs (Pt-100) were positioned inside the pool at about 15 feet elevated differences to measure the pool water temperature. The RTDs are connected separately with two digital temperature meter.

III. Mixing of pool water

Two kinds of stirrer were used for proper mixing the pool water to maintain the uniform temperature in the reactor pool.

The following steps were followed for thermal power calibration of the reactor.

i. With the reactor tank isolation and the stirrer running, the bulk water temperature was recorded until stable temperature is achieved. This temperature is the initial temperature of the pool water and is designated as (T_1).

ii. Reactor was critical at 100 kW. The bulk water temperature was recorded after every 2 minutes for an hour. Temperature (^{o}C) vs Time (min) graph was plotted with the recorded data. Then the slope i.e. rate of temperature rise was calculated from the graph. Finally, using following equation thermal power of the reactor was calculated.

Calculated Thermal Power = Slope × 60 × 100 / 3.752 kW
Where reactor tank constant is 3.752 ^{o}C/100 kWh

2.2 Effect of New Stirrer on Calibration Results

A tank constant (ΔT per hour per 100 kW power) is calculated for the applicable heat content of the system and then the reactor power is determined from the measured rate of temperature rise during the reactor operation. It is very much needed to use stirrer to homogenize the temperature of the tank water during the thermal power measurement. It is to be mentioned that the stirring produced by the motor driven impeller assures that all the water in the tank participates in the calorimetric measurements. The small rate of energy added by the pump motor is typically less than 1 kW and is negligible for power calibrations performed at 200-1000 kW [5]. The proper stirrer should be selected for proper mixing of the water. It is also important to run the stirrer at optimum speed for properly mixing the tank water to get the homogenize temperature.

Under the present experiment two types of stirrer effect were determined for thermal power calibration of BTRR. One stirrer (which is denoted as old stirrer) has four sets of propellers setting with the shaft at equal distance. The old stirrer was used for the last couples of years for the thermal power calibration. The results were analyzed and the thermal power calibration error was found to be about 15% with old stirrer. It is to be mentioned that calibration error can be ±21% if stirrer is not used for thermal power calibration by calorimetric method [6]. A new stirrer was introduced for proper mixing of the pool water to maintain the uniform temperature in the reactor pool. The new stirrer has one set of propeller setting at the bottom end of the shaft. The technical specifications of the old and present stirrer (new stirrer) are given in the Table-1. Figure-2 shows the schematic view of old and new stirrer in the reactor pool.

TABLE 1

TECHNICAL SPECIFICATION OF OLD AND NEW STIRRER

Parameters	Old Stirrer	New Stirrer
Propeller Diameter	0.165 m	0.24 m
Pitch	0.0012 m	0.05 m
Number of Blade	3 (Three)	3 (Three)
Number of propeller	4(Four)	1(One)
Propeller to propeller distance	0.30 m	NA
Propeller shaft diameter	0.02 m	0.04 m

Parameters	Old Stirrer	New Stirrer
Propeller shaft length	2.75 m	0.91 m
Pool depth from propeller to core	3.65 m	5.50 m
Propeller material	304 SS	6061 Aluminum
Motor drive	1.5 kW, 350 rpm, 50 Hz (Fixed rpm)	1.5 kW, 350 rpm, 50 Hz (Variable rpm by frequency controller)

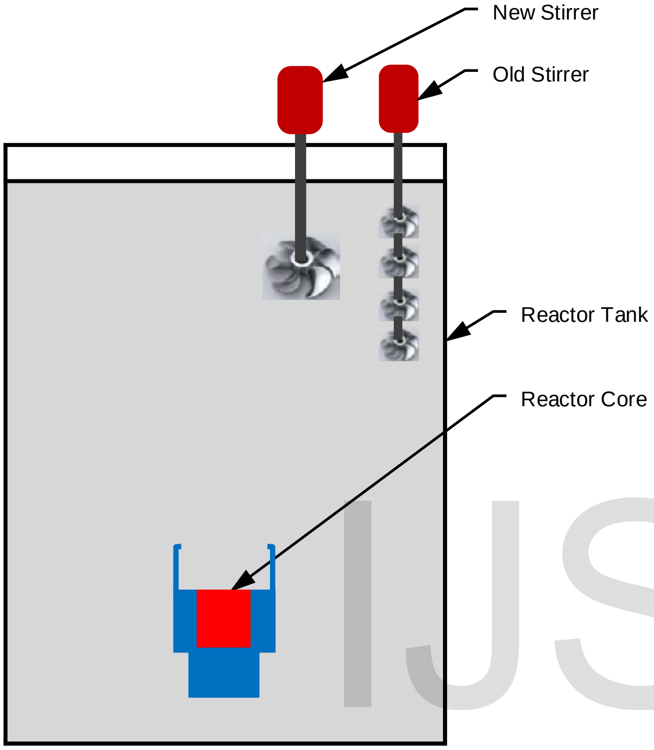

Fig. 2: The old and new stirrer in the reactor pool.

2.3 Determination of Optimum Motor Speed for Effective Stirring

The power calibration was performed at different frequency (10 Hz, 20 Hz, 30 Hz and 40 Hz) of the stirrer motor speed controller.

It is observed at motor speed controller frequency 10 Hz that after 1 hour reactor operation at 100 kW indicated power, the tank water temperature is raised about 4.55 °C which is higher than the reactor tank constant value (3.752 °C/100 kWh) given by TRIGA reactor designer General Atomics (GA), USA. Excess temperature rise at motor speed controller frequency of 10 Hz is due to the improper mixing of the tank water. At motor speed controller frequency 20 Hz and 30 Hz, tank water temperatures were also found to be 3.94 °C and 3.78 °C respectively. The calculated thermal power was found to be 119.9 kW, 104.3 kW and 100.7 kW for motor speed controller frequency 10 Hz, 20 Hz and 30 Hz respectively. So from the analysis of the result, it can be concluded that due to the improper mixing of the tank water, calculated thermal power was found to be higher.

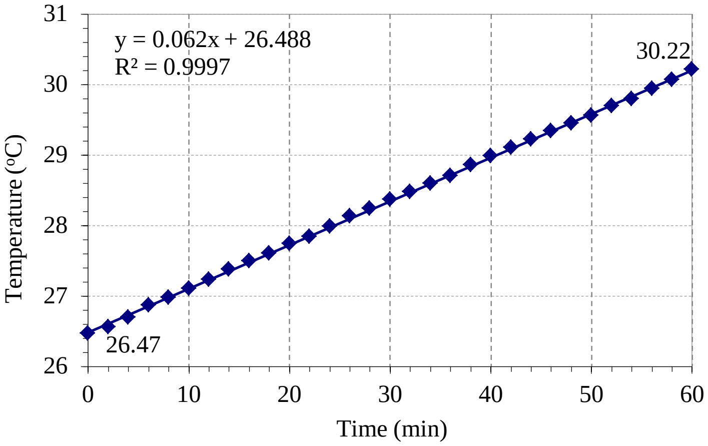

Fig. 3: Temperature rise rates during power calibration at motor frequency 40 Hz.

Then thermal power calibration was performed again at 100 kW indicated power level with stirrer motor speed controller frequency 40 Hz. Temperature rise rate for this experiment is shown in Figure-3. It is seen from Figure-3 that after 1 hour reactor operation at 100 kW indicated power, the tank water temperature is raised 3.75 °C which is very close to the tank constant value (3.752 °C/100 kWh). It indicates that the pool water is mixed properly at stirrer motor speed controller frequency 40 Hz.

Figure-4 shows the calculated thermal power versus stirrer motor speed controller frequency. Figure-5 shows percent deviation (% error) of calculated power at different stirrer motor speed controller frequency. It is to be mentioned that during this experiment, actual reactor power was 99 kW and the indicated power was adjusted to 100 kW considering 1 kW heat loss from reactor tank to the environment.

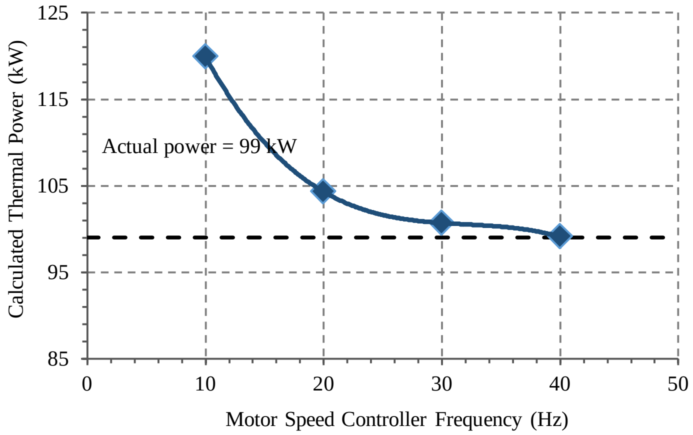

Fig. 4: Calculated thermal power versus motor speed controller frequency for 100 kW power.

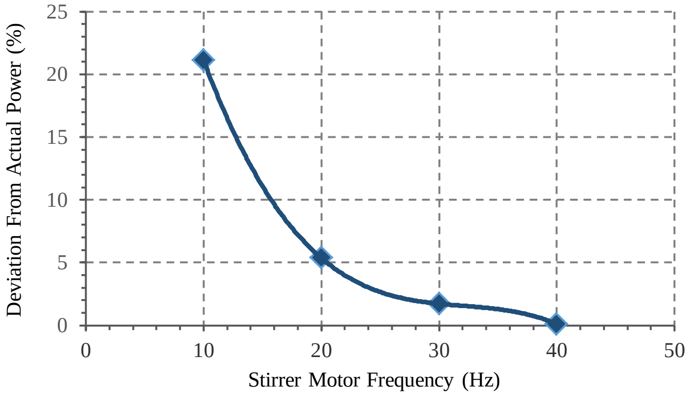

Fig. 5: Percent deviation (% error) from actual thermal power versus stirrer motor controller frequency

From Figure-5 it is observed that deviation of calculated power (% error) from actual power decreases with the increasing of stirrer motor controller frequency. At stirrer motor controller frequency 10 Hz, error is about 21.1% and at stirrer motor controller frequency 40 Hz, error is about 0.1%. From the results it can be concluded that during reactor thermal power calibration, stirrer motor speed controller frequency to be fixed at 40 Hz to homologize temperature distribution in the reactor tank water.

The results of the error estimation in thermal power calibration process at different conditions (without stirrer, old stirrer and new stirrer) are given in Table-2.

TABLE 2

ERROR ESTIMATION IN THERMAL POWER CALIBRATION PROCESS AT DIFFERENT CONDITIONS

Stirrer type	% Error	Remarks
Without stirrer	± 21%	[6]
Old stirrer	15%	Due to improper mixing of pool water
New stirrer at motor speed controller frequency 40 Hz	0.1%	Due to proper mixing of pool water

3 MEASUREMENT OF REACTOR POOL HEAT CAPACITY CONSTANT

Reactor pool heat capacity constant can be calculated as well. In the first approximation, it can be assumed that the reactor pool temperature is constant throughout the pool and neglect all heat losses from the pool. The reactor pool can be approximated as insulated "point" system. Reactor pool can be treated as insulated when water temperature is equal to air and concrete temperatures. So the reactor heat capacity K can be simply calculated from wet pool volume V_w:

$$K = \rho \cdot V_w \cdot c_p \qquad (2)$$

where ρ is the water density and c_p is the water specific heat capacity.

The heat capacity constant (K) was calculated for BTRR by using the equation (2). All the thermo physical properties of water in this calculation were evaluated for 20°C. Under the present experiment reactor pool heat capacity constant (Tank constant) was measured by calorimetric method.

The calculated and measured heat capacity for BTRR were found to be 26.46 kWh/°C and 26.67 kWh/°C respectively. The comparison of calculated and measured heat capacity constants for two similar TRIGA reactors is presented in Table-3.

TABLE 3

MEASURED AND CALCULATED REACTOR HEAT CAPACITY FOR BTRR, LJUBLJANA AND VIENNA TRIGA REACTOR

Reactor Facility	Vw [m3]	K calculated [kWh/°C]	K from GA [kWh/°C]	K measured [kWh/°C]
TRIGA (Bangladesh)	22.68	26.46	26.65	26.67
TRIGA (Vienna)	16.5	19.1	18.48	19.2
TRIGA (Ljublijana)	17.6	20.4	19.05	-

From Table-3 it can be seen that reactor heat capacity K for BTRR result is very close to the value obtained by GA, USA methodology (error in order of some percent). The measured value of K was found to be closer to GA values than the calculated value. The BTRR tank constant is 3.752°C/100 kWh (GA-value for BTRR). The present experimental measured value is 26.67 kWh/°C which is equal to 3.749 °C/100 kWh. The measured result is in good agreement with the value of reactor designer GA.

It is obvious, that the heat capacity of the water in the reactor tank is a dominant factor in the whole reactor heat capacity. This was also experimentally verified for the Vienna TRIGA reactor [7], where the experimentally measured reactor heat capacity was found almost unchanged after significant changes in reactor (new fuel elements and removed rotary irradiation facility and graphite from thermal column).

Nomenclature

A = area of the upper surface of the reactor pool, m2
Cp = specific heat capacity, J/kg, ˚C
C = vapor concentration, kg/kg of dry air, dimensionless
d = thickness of each wall layer, m
g = acceleration due to gravity, m/s2
Gr = Grashof number, dimensionless
h = depth of the reactor pool, m
h_c = convective heat transfer coefficient, W/(m2k)
h_D = mass-transfer coefficient, m3/(m2-s)
k = thermal conductivity, W/(m.k)
L = characteristic length of the heat transfer surface, m
l = height of the water in the pool
m = mass flow rate transfer from the pool to the air, kg/s
Nu = Nusselt number, dimensionless
P = thermal power, W
Pr = air Prandtl number, dimensionless
Q_1 = heat losses through the lateral walls, W
Q_2 = heat losses through the bottom, W
q_c = heat losses due to the convection, W
q_{ev}= heat losses due to the evaporation, W
q_m = flow rate, kg/s
R = thermal resistance, K/W
r = radius, m
S =uncertainty, W

Sc = Schmidt number, dimensionless
T= temperature, K

Greek Symbols

β = volumetric thermal expansion coefficient of the air, K-1
ΔT = difference between the temperatures at the inlet and the outlet of the primary loop, ˚C
λ = difference between the specific enthalpy of saturated water and the specific enthalpy of saturated steam at the wet-bulb temperature of the air in the reactor room, J/kg
ν = kinematic viscosity of the air, m2/s
π = mathematical constant 3.14159, dimensionless
ρ_{air} = air density, kg/m3

Subscripts

air	relative to air
al	relative to aluminum layer
c	relative to convective
ce	relative to of the external concrete layer
ci	relative to internal concrete layer
cool	relative to cooling
D	relative to the diameter
e	relative to external radius of wall layer
ext	relative to external wall of the pool
i	relative to internal radius of wall layer
int	relative to internal wall of the pool
p	relative to constant pressure, specific heat of the coolant
sat	relative to saturation conditions for the air at the reactor room temperature
sur	relative to water pool surface relative to air at the reactor room
1	relative to the lateral walls of the pool
2	relative to the bottom of the pool

4 HEAT LOSS CALCULATION

In this experiment, we consider thermal conduction and convection to estimate heat loss from the reactor pool.

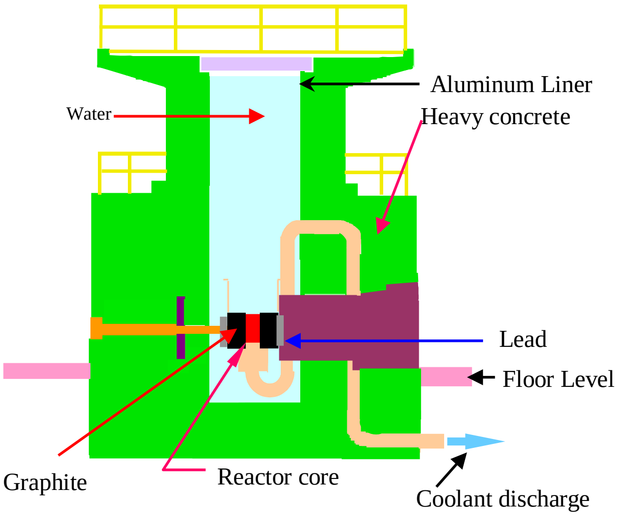

Fig. 6: Reactor tank with concrete shield structure

The core of the BTRR nuclear reactor is placed above the room floor, in the bottom of a cylindrical pool (reactor tank) 8.23 m deep and 1.98 m in diameter as shown in Figure-6. The reactor pool transfers heat to the environment by conduction to the concrete, through the lateral walls and through the bottom of the pool, and by convection and evaporation to the air at the reactor hall, through the upper surface. The reactor tank is made of a special alloy of aluminum (6061-T6). Surrounding it there is a 2.29 m thick layer of concrete in the side wall and 0.91 m thick concrete in the bottom side.

There are three ways to loss of heat from reactor pool to the environment;

1. Heat loss from pool water to aluminum tank and concrete shield structure
2. Evaporation loss from pool surface
3. Convective heat transfer from pool surface

4.1 Heat Losses from the Pool Water to the Aluminum Tank and Concrete

The heat losses through the lateral walls are given by the equation below [8]:

$$Q_1 = \frac{T_{int} - T_{ext}}{R_{al1} - R_{C1}} \tag{3}$$

Where T_{int} is the average temperature of the internal wall of the pool (aluminum tank), Text is the average temperature of the concrete around the reactor, R_{al1} is the thermal resistance of the aluminum layer, R_{C1} is the thermal resistance of the concrete layer.

The thermal resistance for cylindrical walls was obtained from the following equation [8]:

$$R = \frac{\ell}{2\pi hk} ln\left(\frac{r_e}{r_i}\right) \tag{4}$$

Where ℓ is the height of the water in the reactor pool, k is the thermal conductivity of each material, r_i and r_e are the internal and external radii of each wall layer. The heat transfer through the bottom of the pool is obtained from:

$$Q_2 = \frac{T_{int} - T_{ext}}{R_{al2} + R_{ci2}} \tag{5}$$

The values of the thermal resistance for flat surface section are obtained from the following equation [8]:

$$R = \frac{d}{Ak} \tag{6}$$

Where d is the thickness of each wall layer and A is the area of the reactor tank bottom surface.

Heat loss from pool water to aluminum tank and concrete shield structure was calculated by using the above equations. The total heat loss (Q_1+Q_2) was found to be 943 W. The result of the heat loss calculation was found from the 100 kW thermal power calibrations.

4.2 Heat Losses from the Pool to the Air in the Reactor Hall

The heat losses due to the evaporation in the upper surface of the reactor pool were calculated by the following equation [9]:

$$q_{ev} = m\lambda \tag{7}$$

where λ is the difference between the specific enthalpy of saturated water and the specific enthalpy of saturated steam at the wet-bulb temperature of the air in the reactor room, and m is the rate of mass transfer from the pool to the air, given by the equation:

$$m = h_D A \rho_{air} (C_{sat} - C_\infty) \qquad (8)$$

where A is the upper surface of the reactor pool, ρair is the air density, C_{sat} is the vapor concentration at saturation conditions for the air at the reactor hall temperature, C_∞ is the vapor concentration in the air in the reactor hall and h_D is the mass-transfer coefficient given by the following equation:

$$h_D = \frac{h_c}{\rho_{air} \cdot c_{p_{air}}} \left(\frac{Pr}{Sc}\right)^{2/3} \qquad (9)$$

Where Pr is the Prandtl number, Sc is the Schmidt number, Cp_{air} is the heat capacity of the air, h_c is the convection heat transfer coefficient, obtained from:

$$h_c = \frac{k}{L} Nu \qquad (10)$$

where k is the thermal conductivity in the air, L is the characteristic length of the heat transfer surface, equivalent to 0.9 times the diameter of the pool and Nu is the Nusselt number obtained from:

$$Nu = 0.14 (Gr \cdot Pr)^{1/3} \qquad (11)$$

Gr is the Grashof number given by:

$$Gr = \frac{g \cdot \beta \cdot (T_{sur} - T_\infty) \cdot L^3}{v^2} \qquad (12)$$

where g is the acceleration due to gravity, β is the volumetric thermal expansion coefficient of the air, T_{sur} is the water pool temperature at the surface, T_∞ is the air temperature in the reactor hall and v is the kinematic viscosity of the air.

The relative humidity of the air in the reactor hall was monitored during the tests. The convection heat transfer through the reactor pool surface was calculated with the following equation [9]:

$$q_c = h_c A (T_{sur} - T_\infty) \qquad (13)$$

4.3 Summary of Heat Loss Calculation

The heat loss calculation was performed by using the data for 100 kW thermal power calibration. The evaporative heat loss was calculated 65 W. It is to be mentioned that the ambient temperature (T_∞) is higher than the pool surface temperature (T_{sur}), in this condition the heat will gain by pool water from the air. The convective heat gain from the reactor pool surface was calculated 11 W.

During the experiment reactor hall inside air temperature (dry bulb) was 29.3 ºC and wet bulb temperature 26.4 ºC. The average pool water bulk temperature was found to be 28.32 ºC. The reactor shield structure (concrete) temperature is also depending on the reactor hall air temperature. In the present experiment the reactor hall air and shield structure concrete temperature are assumed same temperature. When the reactor hall air temperature is higher than pool bulk temperature then thermal conductions above reactor pool are stable and there is no convection. In this case the heat transfer from air to water occurs only by convection through the air, which can be neglected. But in the opposite case the heat transfer occurs from the pool to the open air by natural convection. The conductive, convective and evaporative heat loss at 100 kW reactor power are given in the Table-4.

TABLE 4

HEAT LOSS FOR 100 KW THERMAL POWER

Type of heat loss	Heat loss (kW)
Heat absorbed by Aluminum tank and concrete shield structure	0.943
Evaporation heat loss over pool surface	0.065
Convective heat loss over pool surface	-0.011
Total heat loss =	1.008 kW

The net heat loss was found to be 1.008 kW which is very small compare to the 100 kW thermal power.

5 CONCLUSION

The reactor pool heat capacity constant (K) and thermal power calibration of the reactor were performed at 100 kW power level of the reactor. In the present experiment the power calibration is performed by calorimetric method (rate of temperature rise). Reactor pool heat capacity constant K has been calculated and measured. The calculated and measured heat capacity constant for BTRR was found to be 26.35 kWh/ºC and 26.67 kWh/ºC respectively. The measured value of K was found to be closer to TRIGA reactor designer General Atomics (GA), USA value (26.65 kWh/ºC). The tank constant of BTRR is 3.752°C/100 kWh (GA-value for BTRR). The present experimental measured value is 26.67 kwh/ºC which is equal to 3.749°C/100 kWh. The measured result is in good agreement with the value of reactor designer, GA. The new stirrer with optimum motor speed reduces thermal power calibration error from 15% to 0.1% compare with the previous measurement (using old stirrer). The heat loss from the reactor pool to the environment was determined during thermal power calibration. The net heat loss was found to be 1.008 kW. It has been confirmed that the nuclear power channels were adjusted to 100kW considering 1 kW heat loss. From these results it can be concluded that during reactor thermal power calibration, present stirrer motor speed to be fixed at proper speed for ensuring uniform temperature distribution in the reactor tank water. The thermal power calibration error through this study has been minimized which will ensure precise flux level for neutron irradiation experiments and other neutron based utilization of the reactor.

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