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Effects of Density Variation on the Cooling of the Nigeria Research Reactor-1 (NIRR-1)

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ABSTRACT

A major safety concern in operating a nuclear reactor is to prevent the fuel temperatures from reaching levels where they can lead to the release of fission products into the reactor vessel. This can be achieved by proper core cooling. The Nigeria Research Reactor-1 (NIRR-1) which is a tank-in-pool Miniature Neutron Source Reactor (MNSR) uses de-ionized water as coolant and moderator. The cooling process is by natural convection and hence the effect of temperature on its density needs to be ascertained to ensure effective circulation of the coolant. In this work, the density variation with coolant temperature of the NIRR-1 was measured. The results show that there is a variation in density of about 38 g/l between the NIRR-1 coolant temperatures of 0 to 100 ^oC. The equation relating the density variation with temperature has been established. There was strong correlation between the density variations of ordinary water with NIRR-1 (De-ionized water) water against temperature.

Key words: De-ionized water, Density, Temperature, MNSR.

INTRODUCTION

Years ago, high purity water was used only in limited applications. Today, deionized (DI) water has become an essential ingredient in hundreds of applications including: medical, laboratory, pharmaceutical, nuclear reactors, cosmetics, electronics manufacturing, food processing, plating, countless industrial processes, and even the final rinse at the local car wash.

A major safety concern in operating a nuclear reactor is to prevent the fuel temperatures from reaching levels where they can lead to the release of fission products into the reactor vessel. The Nigeria Research Reactor-1 (NIRR-1) is a tank-in-pool Miniature Neutron Source Reactor (MNSR) which uses deionized water as moderator and coolant [5]. Detailed description of the reactor and its operating parameters were presented by [1]. The core region of NIRR-1 is located close to the bottom of the reactor vessel under 4.7 m of water. The 1.5 m^3 of water contained in the reactor vessel acts as a moderator, radiation shield and primary cooling medium. The reactor core cooling is achieved when water is drawn into the core through the core inlet orifice, by natural convection. The water molecules move through the channels within the fuel elements to the top of the reactor core, and finally exit through the core outlet orifice. The water heated by the fuel elements finds its way to the top of the reactor vessel, while the reactor core draws in colder water from the vessel through its inlet orifice. The heat generated by the fuel elements gives rise to the increase in reactor water temperature. This heat is extracted through the walls of the reactor vessel, into the 30m^3 volume of water contained in the reactor pool [3].

The feed-water makeup system is designed to produce quality water from the 'raw water' for the reactor vessel water and for the pool water.

i) The output water quality of the system is shown in Table 1, and the system yield is 0.50.7 m^3/hr

ii) Flow direction of the feed-water makeup system is as shown below:

Source Water (tap/raw water) $\rightarrow$ Filter $\rightarrow$ Booster Pump $\rightarrow$ Flow-meter $\rightarrow$ Cation Column $\rightarrow$ Anion Column $\rightarrow$ Mixed-Bed Column $\rightarrow$ Output (feed-water storage tank)

iii) Working principle of the system:

The source water (tap/raw water) passes through the stainless steel mechanical filter, removing the solids/particles, suspensions, colloids and bacteria. The filtered water passes through the cation resin column where the cations in the water are absorbed by the resins. The exchangeable H^+ ions in cations is substituted into water and combined with anions to form the corresponding acid. The reaction formula is as follows

$$R \cdots H^+ + \left\{ \begin{matrix} K^+ & \frac{1}{2}SO_4{}^{2-} \\ Na^+ & Cl^- \\ Ca^{2+} & HCO_3{}^- \\ Mg^{2+} & HSiO_3{}^- \\ \ldots & NO_3{}^- \end{matrix} \right\} \rightarrow R^- \left\{ \begin{matrix} K^+ \\ Na^+ \\ Ca^{2+} \\ Mg^{2+} \\ \ldots \end{matrix} \right\} + H^+ \left\{ \begin{matrix} \frac{1}{2}SO_4{}^{2-} \\ Cl^- \\ HCO_3{}^- \\ HSiO_3{}^- \\ NO_3{}^- \end{matrix} \right\}$$

When the water containing mineral acid passes through the anion column, the anions in the water are absorbed by strong acid resin. But the exchangeable ions OH^- are substituted into the water and combined with H^+ ions in the water to form water.

The reaction formula is as follows:

$$R \cdots OH^- + H^+ \left\{ \begin{matrix} SO_4{}^{2-} \\ Cl^- \\ HCO^-{}_3 \\ Mg^{2+} \\ NO_3{}^- \\ \cdots \end{matrix} \right\} \rightarrow R \cdots \left\{ \begin{matrix} SO_4{}^{2-} \\ Cl^- \\ HCO^-{}_3 \\ Mg^{2+} \\ NO_3{}^- \\ \cdots \end{matrix} \right\} + H_2O$$

The exchange principle of the mixed bed column is that it acts as an action of innumerable multiplex beds. The load ratio of cation to anion resin is determined by the quality of output pure water. If the output (purified) water is acidic, the load on anion resin is increased in order to raise the pH value. If the output (purified) water is basic, the load on anion resin is decreased to reduce the pH value. For more information, see document: Deionized water supply system [3].

Density is a physical property of matter which describes the relative “heaviness” of an object at a given volume. Density can be expressed as mass per unit volume or density is the mass of an object or substance divided by it’s volume. Since NIRR-1 water circulation is by natural convection, the role of density variation with temperature is very significant to the coolant flow through the core.

MATERIALS AND METHODS

The density of water is approximately one gram per cubic centimeter. More precisely, it is dependent on its temperature, but the relation is not linear and is not even monotonic (see Table 2). When cooled from room temperature liquid water becomes increasingly dense, just like other substances. But at approximately 4 °C, pure water reaches its maximum density. As it is cooled further, it expands to become less dense. This unusual negative thermal expansion is attributed to strong, orientation-dependent, intermolecular interactions and is also observed in molten silica [4]. During NIRR-1 operation, the reactor water temperature shall remains well below 100 ^{o}C as demonstrated during the on-site zero-power experiment. This is to ensure that boiling does not occur as well as avoid speeding up corrosion of the NIRR-1 fuel elements which are in the form of $U\text{-}Al_4$ alloy clad in alumina. It is known that elevated temperatures may accelerate the process of corrosion in Aluminium alloys [3].

In this work, the density and viscosity of the NIRR-1 water was measured using the following apparatus:

- Heating Mantle (Model: SB-162, by Stwart, Germany)
- Rotational Viscometer (Model: DVE-210, by Brookfield, USA)
- Magnetic Stirrer (by Alnico, India)
- Thermometer (Mercury-in-glass ≤ 200°C, by Pyrex, England)
- Density Bottle (50ml capacity, by Pyrex, England)
- Balance (Model: PW-184 ADAM, by Paw Series, England)
- Beakers (200ml capacity, by Pyrex, England)

The following steps were taken:

i. The mass of the density bottle was measured and zeroed using the digital balance.
ii. 50 ml of the reactor water was poured into the density bottle and its temperature was read using the thermometer and the mass was measured and recorded in Table 3.
iii. About 100 ml of the reactor water was poured in to the beaker and heated using the heating mantle and magnetic stirrer. The heated water was then poured into the 50 ml density bottle where the mass and the temperature were measured and recorded in Table 3, respectively.
iv. Step (iii) above was repeated by raising the temperature of the water up to about 100 °C.
v. Steps (i to iv) were then repeated two more times and the average values were recorded in Table 3.
vi. The density of the water at each temperature was calculated as the ration of the mass to the volume of the water and recorded in Table 4.
vii. About 150 ml of the reactor water was poured into the viscometer and its temperature was read and the viscosity was measured and recorded in Table 5.
viii. The water was then poured in to the beaker and heated using the heating mantle and magnetic stirrer. The heated water was then poured into the viscometer and the temperature and the viscosity were measured and recorded in Table 5.
ix. Step (iii) above was repeated by raising the temperature of the water up to about 100 °C.
x. Steps (i to iv) were then repeated two more times and the separate values were recorded in Table 5.

The line of best fit was drawn in either case and its equation was determined using Microsoft Excel programme. The equations of the lines of best fit were used to extrapolate the densities and the dynamic viscosities at any given temperature as shown in Table 6.

RESULTS AND DISCUSSION

Table 1 shows the NIRR-1 water quality parameters. Table 2 shows the variation of Water - Density with temperature [2]. We can see that the water density reached its maximum of 999.97 kg/m^3 at 4 °C. Figure 1 shows the graphical view of the variation of the water density with temperature [2]. The density dropped as the temperature rises above or falls from 4 °C in parabolic nature. Table 3 shows how the mass of NIRR-1 water varies with temperature at a fixed volume for three different experiments. The average of the masses was computed at the temperature where all the measurements were possible. Table 4 which has been extracted from Table 3 shows the average of the masses and their corresponding calculated densities variation with temperature. Similar to the pattern of [2] results, the density decreases with increase in temperature for the liquid NIRR-1 coolant. Figure 2 shows the graphical variation of the average density with. The curve was also parabolic within the limit of the measurement. In order to predict the density of the NIRR-1 water at any given temperature, the equation of line of best fit of the curve was drawn.

Table 1: NIRR-1 Water Quality (SAR, 2005)

Item	Requirement
Specific resistance	0.5 – 1.0 MΩ cm
pH values:	6.00 ± 0.5
Cl^- content	< 0.05 ppm
Cu^{++} content Pb^{++} content	<0.1 ppm <0.1 ppm
Total solid residues (TSR)	<2 ppm

The equation was

$$Y = 0.00002X^3 – 0.0006X^2 + 0.0233X + 999.97$$

Where Y = Density (g/l); X = Temperature (^oC)

Table 5 and figure 3 show the extrapolated density variation with temperature of the NIRR-1 water.

Table 2: Variation of Water - Density with temperature (Lide, 1990)

Temp (°C)	Density (kg/m^3)
100	958.40
80	971.80
60	983.20
40	992.20
30	995.65
25	997.05
22	997.77
20	998.21
15	999.10
10	999.70
4	999.97
0	999.84
−10	998.12
−20	993.55
−30	983.85

Table 3: Masses of 50 ml of NIRR-1 water at different temperatures

S/No	Temperature (^oC)	Mass (g)			
		Exp. 1	Exp. 2	Exp. 3	Average
1	21	49.8155	49.9819	49.9024	49.8999
2	23	49.8466	-	49.9116	-
3	24	-	-	49.8884	-
4	26	49.8018	49.8900	49.8389	49.8436
5	27	49.8021	-	49.8400	-
6	30	-	49.8024	-	-
7	36	-	49.7080	49.6092	-
8	40	49.6257	49.6619	49.5997	49.6291
9	43	49.5523	-	49.5608	-
10	46	49.5127	49.5112	49.5200	49.5146
11	49	49.4383	49.4800	-	-
12	54	-	-	49.3570	-
13	59	49.1827	49.2783	49.2239	49.2283
14	67	-	49.1292	49.0010	-
15	69	48.9744	-	-	-
16	73	-	48.8921	48.8636	-
17	74	48.8407	48.8499	48.8508	48.8471
18	77	48.7921	48.8007	-	-
19	78	48.7666	48.7296	48.7200	48.7387
20	80	-	48.6898	-	-
21	83	-	-	48.5999	-
22	85	48.5344	48.5373	48.5608	48.5442
23	87	48.5340	48.4290	-	-
24	91	48.3715	48.3698	48.3801	48.3738
25	93	-	48.3215	48.3097	-
26	96	48.2181	48.2406	48.2321	48.2303
27	97	48.2056	48.1988	48.2000	48.2015
28	98	48.1271	48.1893	-	-

Table 4: Average Mass and corresponding Density Vs temperature of NIRR-1 water

S/No	Temperature (°C)	Average Mass (g)	Average Density (g/l)
1	21	49.8999	998.00
2	26	49.8436	996.87
3	40	49.6291	992.58
4	46	49.5146	990.29
5	59	49.2283	984.57
6	74	48.8471	976.94
7	78	48.7387	974.77
8	85	48.5442	970.88
9	91	48.3738	967.48
10	96	48.2303	964.61
11	97	48.2015	964.03

Table 5: Extrapolated density variation with temperature of NIRR-1 water

S/No	Temperature (°C)	Extrapolated Density (g/l)
1	0	999.97
2	5	999.94
3	10	999.62
4	20	998.20
5	30	995.81
6	40	992.58
7	50	988.64
8	60	984.09
9	70	979.06
10	80	973.67
11	90	968.05
12	100	962.30

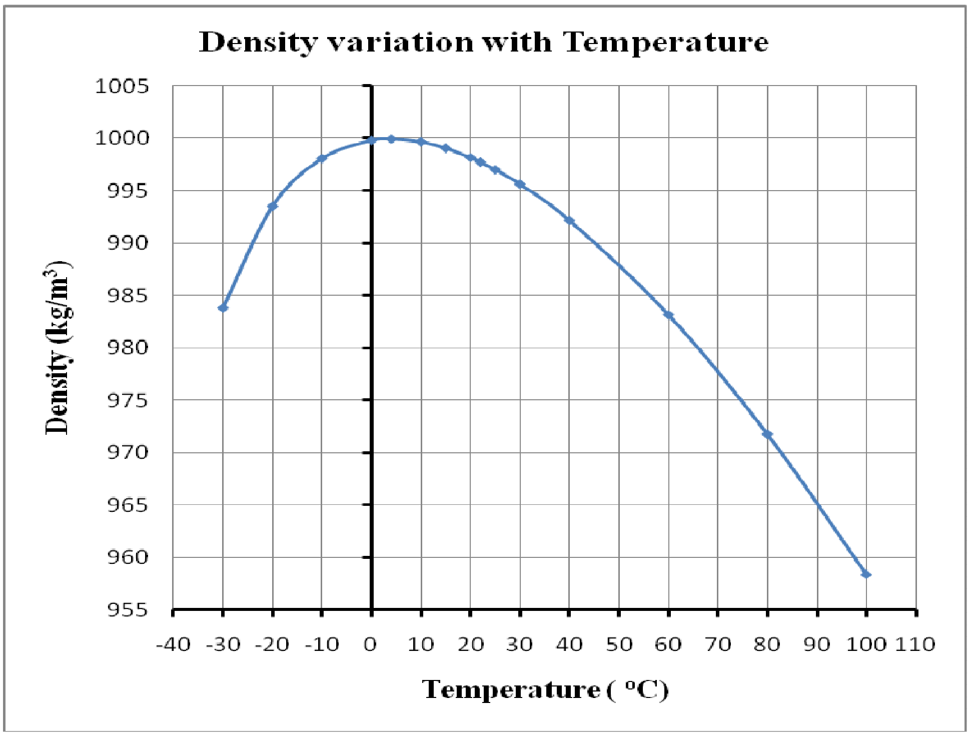

Figure 1: Variation of Water - Density with Temperature (Lide, 1990)

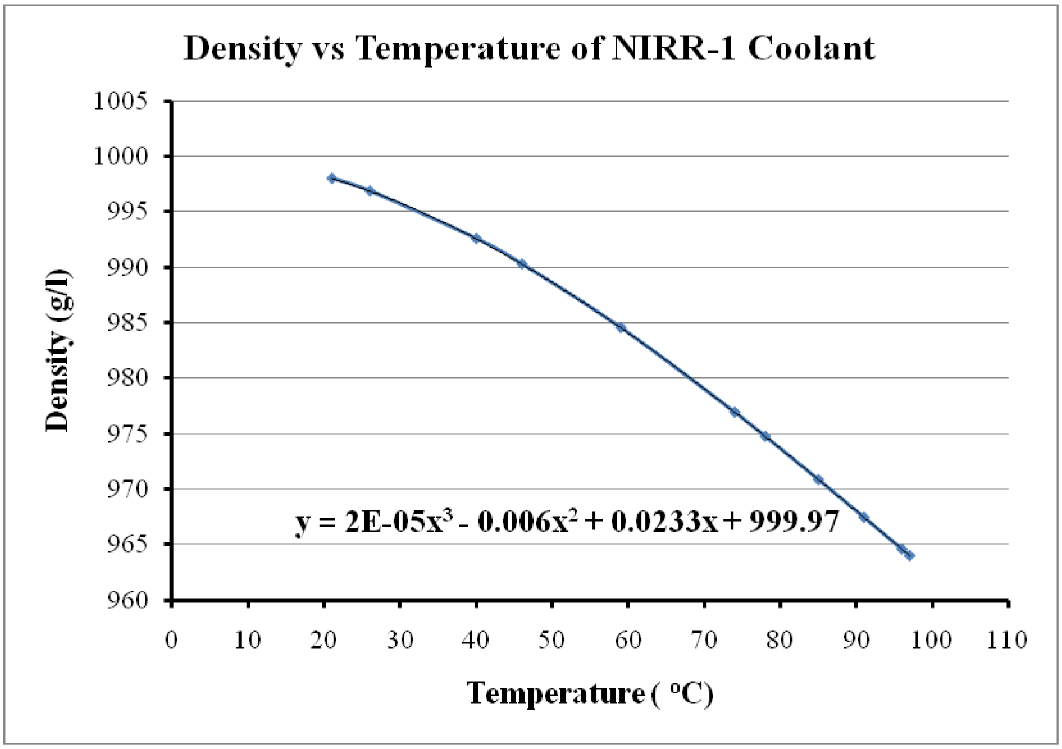

Figure 2: Variation of Average Density with Temperature of NIRR-1 water

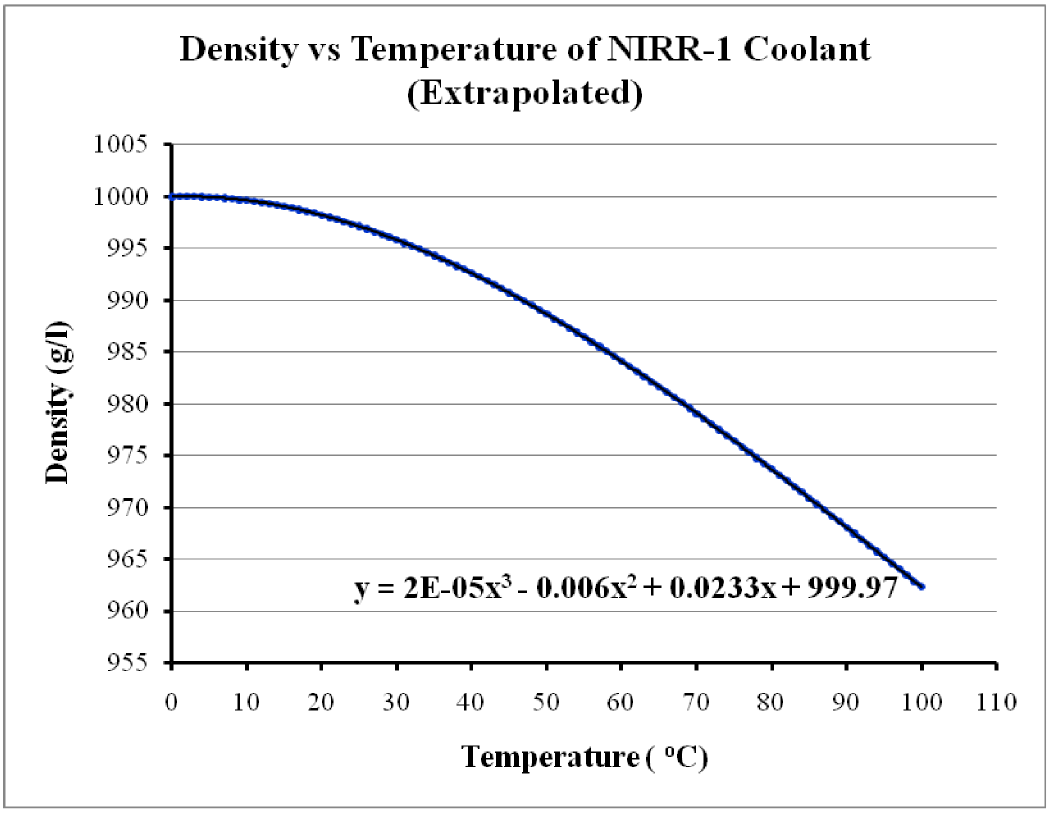

Figure 2: Extrapolated variation of Density with Temperature of NIRR-1 water with equation of line of best fit.

CONCLUSION

The density variation with coolant temperature of the Nigeria Research Reactor-1 was measured. The results showed a polynomial variation of NIRR-1 coolant density with temperature. The equation relating the density variation with temperature has been established. There was strong correlation between the density variations of ordinary water with NIRR-1 (De-ionized water) water against temperature.

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