Experimental Study Corrosion Parameters of Copper as an Eco-Friendly Heat Collector for Solar Water Heaters

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Data Article

ABSTRACT

The corrosion behaviour of copper as a solar collector material was adequately simulated in tests in a solar water heating system. The weight loss technique of corrosion determination was used under exposure conditions ranging from slightly acidic to alkaline. Uniform corrosion was observed and corrosion rates; calculated estimates of the life of a typical collector made of copper were evaluated and found to be below 0.0254 mmpy and the subsequent evaluation of the life of a 3mm thick pipe shows lives of over a hundred years under the varying exposure conditions. A significant fact is that uniform corrosion took place over the period of the test.

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1. INTRODUCTION

A common device in water-filled systems is the water heater. One very important issue yet to be resolved in the design of water heaters is the choice of materials for fabrication so as to ensure minimum cost and long life [1]. The materials that are in direct contact with the water, which may be acidic or alkaline, undergo gradual degradation in mechanical and physical properties. This form of degradation, which results in loss of material and causes pollution, especially if the water from such heaters is to be used domestically, is called corrosion. Corrosion is expensive, aesthetically displeasing and hazardous to health and safety [2]. Copper, with its excellent corrosion resistance in aqueous media and its good thermal properties, is the most attractive metal for collectors. However, copper is expensive and, from relaxed economic considerations, its use is unattractive. If the corrosion rate of a copper solar collector is low enough to guarantee a very large life, copper may still turn out to be the most cost effective material available [3]. The good corrosion of copper assumed above is predicated on copper corroding uniformity. The geometry of a solar collector is such as to encourage local cell effects which may lead to localized corrosion or pitting should copper be susceptible to Pitting in solar collectors, corrosion damage becomes more pronounced and estimates based on weight-loss techniques become grossly misleading [4]. Finally, since corrosion is usually a multi-variable process, it is usually not safe to extrapolate from laboratory data to actual situations [5]. Cursory survey of the literature also revealed that there is little or no corrosion data on solar collector materials. In view of the above, this study was undertaken to investigate the corrosion behaviour of copper as a solar collector.

2. MATERIALS AND METHODS
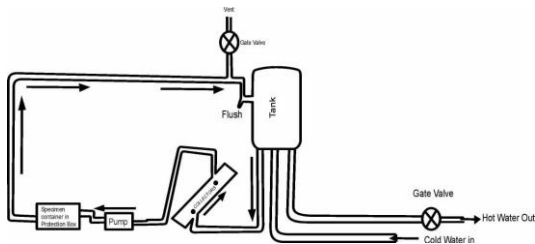
2.1 Experimental Set Up

Fig. 1. Shows the general layout of the experiment

This consists of:

(i) A flat plate solar collector comprises two (1mx1 m) parallel flat plates with 12.5 mm diameter risers spaced 8 cm apart. The corrugated collector was initially nickel plated but due to age, the plating was far from perfect and it was repainted with black gloss paint. The initial solar collector excludes the pump and the specimen container as it was thermos siphon driven between collector and tank. (ii) The pump is a KB25 KWABATA centrifugal pump with a maximum head of 100' (33 m) and a maximum capacity of 21US gallons / minute. A variac variable device to vary motor speed was added. The pump was to aid the circulation of the hot water through the specimen container.

(i) The specimen container (Fig. 2), fabricated in the chemistry department of University of Delta, Agbor was a 100 m diameter tube and the function for vertical holding of specimen was 60 mm. The glass was protected by holding it in a box stuffed with saw dust.

(ii) The specimens used were 30 mm x 30 mm x 1.5 mm cut from cold rolled copper sheet. Each specimen has a 9.5 mm diameter central solar to enable it to be held vertically as shown in Fig. 3. As in the figure, five specimens were used at a time.

2.2 Preparation of the Test Solutions

Solutions of approximate pH values of 5-10 were used. For acidic solutions, the tank was filled with tap water near to the brim and a little dilute acid was introduced into the tank. The pump was run for about 30 minutes to mix the water and the acid and the pH was measured. More acid would then be added or solution run off and water added until approximate value of pH desired was obtained. For the alkaline solution, solid sodium hydroxide was introduced through the specimen mounting glass portion to fill the system with water.

The pump was then activated to run for about 30 minutes to dissolve and mix the sodium hydroxide. The pH was measured and more sodium hydroxide or water was introduced until the approximate pH value desired was obtained.

2.3 Instrumentation

The temperature was measured with a mercury-in-glass thermometer introduced through the spout to allow it attain temperature of the water that was being pumped. A Griffin pH meter was used to measure the pH.

Specimen solutions were taken from the spout. Each specimen was weighed on analytical balance to an accuracy of 0.001 gram.

2.4 Test Run

A minimum of 120 hours were used for each test. This consisted of at least 40 hours of pump-running during the day. Tests were performed on polished and unpolished specimens.

3. RESULTS AND DISCUSSION

Tests were carried out to determine effects of initial pH, effects of surface condition and effect of temperature variation.

The above table shows that the smaller the initial pH, the bigger is the pH change. Thus, while sample 1 with pH of 7.2 changed by 2.1. The same trend of wider difference between initial and final pH values was noticed with alkaline solutions. The fact that the final pH values were within the alkaline region may be attributed to the availability of oxygen reduction, an important

Catholic reaction and hence the consequent tendency of the solution to be more alkaline and settle at a constant pH. As the test continued, the alkaline corrosion products formed buffer the solution once formed within a zone of pH values.

It would appear there is a reasonable correspondence between corrosion and the changed calculation of corrosion rates shown on the table. Assumes that all weight loss has been due to general (uniform) corrosion and not to localized corrosion such as pitting and intergranular corrosion. The corrosion rate in millimetres penetration per year (mmpy) was calculated from the equation 1 below [6].

$$CR(mmpy) = \frac{87.6 \times W}{DAT} \qquad (1)$$

Where W= weight loss in milligrams
D = metal density in g/cm^3
A = area of the sample in cm^3
and T = time of exposure of the metal sample in hours.

Corrosion rate is more affected by the change in some environmental factors such as air temperature and precipitation which lead to a time of wetness and provides a wet environment on the substrate surface for electrochemical corrosion [7].
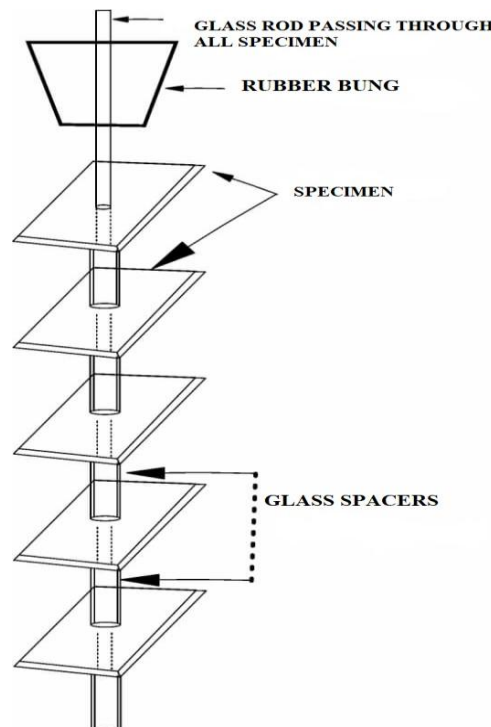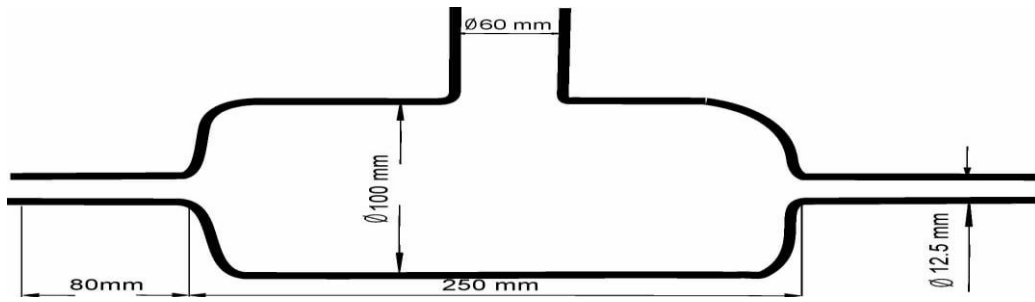

Fig. 2. Specimen container

Fig. 3. Specimen

Table 1. Initial pH

Specimen S/N	Initial pH of test solution	Initial weight of specimen w_1 (mg)	Final weight after exposure w_2 (mg)	Weight loss $w_1 - w_2$ (mg)	Test solution after run	Calculated pH Corrosion rate in (mmpy)	Temperature range
1	5.20	35773.00	35743.00	30.00	9.50	0.022	32.50
2	6.10	35541.00	35514.00	27.00	9.20	0.020	29.50
3	7.20	35254.00	35237.00	17.00	9.30	0.012	39.00
4	8.00	35528.00	34498.00	30.00	9.90	0.022	39.00
5	9.10	35265.00	34238.00	27.00	9.60	0.022	35.50
6	9.80	35546.00	36517.00	29.00	9.90	0.018	35.50

Table 2. Temperature

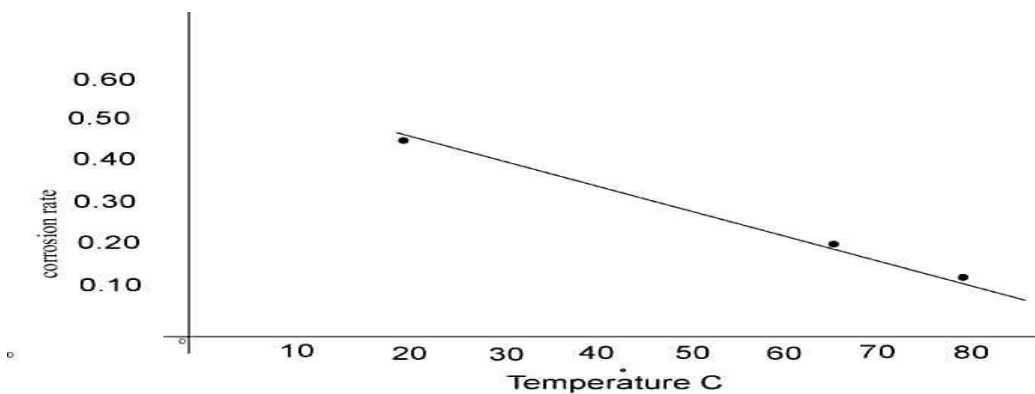| Sample	1	2	3	4	5	6
Temperature mean °C	44.90	45.60	48.40	44.00	42.10	44.70
Temperature range °C	32.50	29.50	39.00	39.00	35.50	35.50
Corrosion	0.022	0.020	0.022	0.023	0.018	

Fig. 4. Relationship between corrosion and temperature

Two–hourly temperature readings were taken through the test-run for particular samples from where Table 2 was generated.

From Table 1, it appears that the higher the mean temperature, the smaller was the corrosion rate. This result agrees with [7], that as oxygen is removed, copper corrosion is stifled. Fig. 4 shows that there is a drop in corrosion rate as temperature increases. The works of [8,9,10] shows that oxygen solubility in water decreases very rapidly as the temperature rises.

The confirmation through the present experiments that there exists a relationship between corrosion and oxygen solubility is provided by Fig. 5, where there is a direct correlation. This implies that corrosion in copper solar collectors is more serious at lower temperatures. At the higher temperatures likely to be encountered, copper corrosion becomes insignificant.

Above Table 3, shows corrosion rates obtained for polished and unpolished specimens. The polishing of the surface was done using grit 320 emery paper. The test results shown in the table were obtained using samples exposed to motion less water of different initial pH. This table shows that:

i. Corrosion rates for polished surfaces are lower than for unpolished surfaces in alkaline solution and vice-versa in the acidic solution. This may be explained by a possible delay in the formation by sodium hydroxide of an inhibitive film on an unpolished surface due to obstructive influence of surface dirt. It should be noted that the corrosion rates obtained in the solar heater were much higher than in motion-less water. This is expected as the water motion and possible scurring of the surface by particles which are characteristic of solar heaters favors corrosion.

ii. Corrosion rates are higher in acidic water solutions and lower for neutral and alkaline solutions.

4. DEDUCTIONS

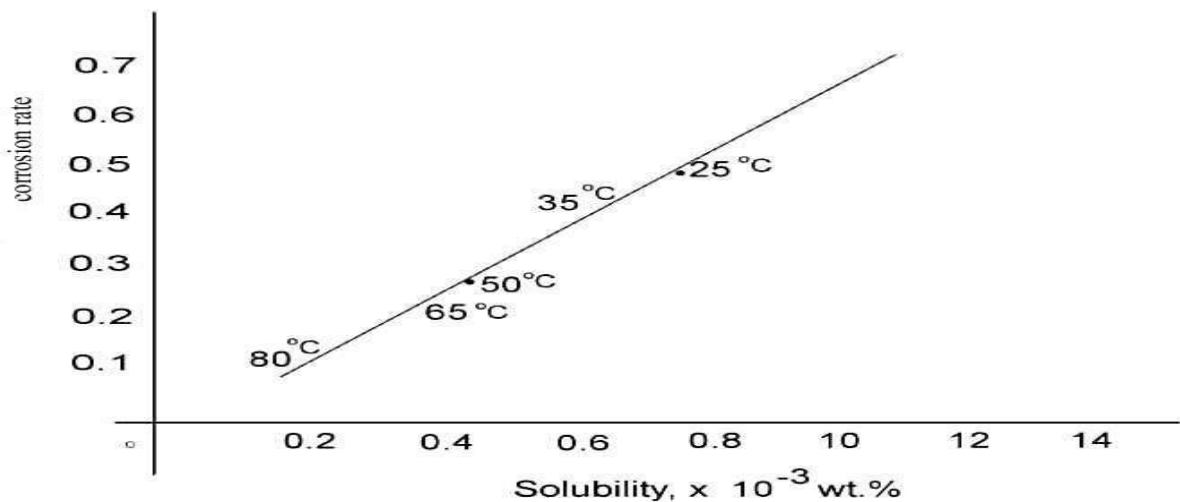The estimated life of a 3 mm thick copper pipe under varying exposures.

Fig. 5. Relationship between corrosion and oxygen solubility

Table 3. Surface condition

Sample	Polished			Unpolished		
	Initial pH	Final pH	Corrosion rate (mmpy)	Initial pH	Final pH	Corrosion rate (mmpy)
1	5.20	7.10	0.018	5.20	6.90	o.o166
2	6.10	7.20	0.0173	6.10	7.00	0.0137
3	7.00	7.20	0.0117	7.10	7.20	0.0137
4	7.90	8.00	0.0060	8.00	7.10	0.0089
5	9.10	9.10	0.0055	9.10	7.10	0.0083
6	9.90	9.40	0.0164	10.00	7.30	0.0165

Table 4. Life estimate of a 3mm thick copper pipe

Sample		Corrosion Rates (mmpy)			Estimated Life (1 year)		
	Pipe size	Actual	Polished	Unpolished	Actual	Polished	Unpolished
1	3mm	0.022	0.0180	0.0166	144.50	176.3	191.7
2	3mm	0.020	0.0172	157.0	183.50	183.50	184.60
3	3mm	0.012	0.0117	0.0137	255.60	270.60	231.50
4	3mm	0.022	0.0060	0.0089	145.00	512.30	355.10
5	3mm	0.023	0.0055	0.0083	139.20	578.70	384.60
6	3mm	0.018	0.0164	0.0165	180.10	192.90	192.60

From Table 4, in all cases under test, the life expectancy is more than one hundred years where a zinc or iron pipe exposed to similar conditions may last forty years [8-11]. However, the estimated life on this table is very conservative as this failure is due to corrosion. According to [12,13,14], even with corrosion, its effect may be uniform as pitting corrosion may occur. It may also happen that the neater handles corrosion promoting solutions, in which case the life expectancy will be much shorter. Whatever case we consider, it would appear that a copper solar heater will be cheaper in the long run, although the initial cost of copper is high. This economy comes from the need for less frequent replacements.

5. CONCLUSIONS

Though in this work, copper has been found to be very suitable for use in a solar collector. All the corrosion rates calculated were below 0.0254 mmpy and the subsequent evaluation of the life of a 3 mm thick pipe shows lives of over a hundred years under the varying exposure conditions. A significant fact is that uniform corrosion took place over the period of the test. The low values of corrosion rates calculated will be unsuitable for life predictions if localized attack [15], e.g. pitting took place on the copper sample; failure will invariably occur faster than predicted in this work. Hand-polishing had a generally insignificant effect in acidic solutions but the effect may be important when exposed to alkaline solutions. In all the solutions, temperature was found to have a profound effect on the corrosion of copper. This decreased as the temperature increased due to the reduced solubility of oxygen in water with increasing temperature. What this has brought out is that in the usage of solar energy for water heating, trouble with the collectors should be more serious at the low temperature zones. A level of protection may be expected for collectors capable of generating higher temperatures.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/99708