JJMIE

Volume 4, Number 6, December 2010
ISSN 1995-6665
Pages 685 - 692

Jordan Journal of Mechanical and Industrial Engineering www.jjmie.hu.edu.jo

Experiments on Aluminum-Copper Alloys Properties as Solar Absorbers

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Abstract

In this paper, selecting absorber materials for solar collectors is experimentally investigated. Copper and aluminum alloys were cast at four different percentages of each, then their grain structure was examined and comprehensive solar tests were conducted to measure the heat capacity of each alloy and compare that with the available solar irradiance available at the test site at the Hashemite University in Zarqa, Jordan.

Keywords: Aluminum-copper alloys, grain structure, thermal solar absorbance of alloys, effectiveness of alloys.

1. Introduction

For flat-plate solar thermal collectors, copper could be the material of choice to construct the absorber section.But its high cost and weight makes finding an alternative a very viable research area. The importance of using solar collectors have increased many folds in recent years with the constant depletion of fossil fuels and the inevitable need to find alternative methods to rely on renewable sources, such as harnessing the thermal power from the sun. The Hashmite Kingdom of Jordan has more than 300 sunny days a year, making the adaptation of solar energy on a wide scale an economical and environmental advantage.

In literature, there are many different setups for solar collectors, where measuring the efficiency of heat transfer between the solar irradiance and the solar collector as the main concern. One notable effort to combine all literature on selecting the materials used listed in[i], but otherwise, the focus on experimenting with different alloys as absorber materials is limited, or the main focus would be on experimenting with special coating materials [ii,iii]. Hence, the aim of this paper is to research the viability of alloying copper with aluminum, and then select the best percentage to use in the actual absorber.

2. Theoretical background

For the experimental work intended for this research, it is necessary to calculate the heat capacity of the alloys composed of various percentages of aluminum and copper.

The governing equation will include the specific heat for each constituent and multiplied by its mass fraction within the total mass of the alloy. The heat capacity equation is a function of the temperature rise as follows:

$$Q = \left[m_{Cu} c_{p_{Cu}} + m_{Al} c_{p_{Al}}\right] \Delta T \quad (1)$$

where,

Q is the heat capacity of the total alloy [J]

Cp_{Cu} is the specific heat of copper, 395 KJ/Kg.k,

$Cp_{Al}$is the specific heat of aluminum, 920 KJ/Kg.k, and

ΔT is the temperature rise in the alloy, in either k or °C

The above equation will be used later to compare the heat gained through each alloy due to its exposure to solar radiation with the available heat irradiation values obtained from the Hashemite University solar station in Zarqa, Jordan. It is worth noting that the values obtained will be divided by the time in seconds required for the temperature rise to obtain the values in Watts and make the units of both the measured values and the readings compatible.

3. Experimental setup

In this section, the preparation of test specimens and the equipment used for their testing will be presented.

3.1. Specimen Preparation

The specimens needed for the experimental tests are alloys cast of four compositions of copper and aluminum formed into two basic geometries; cylindrical specimens for both Scanning Electron Microscope (SEM) testsand the composition test, and also flat plate specimens for the solar tests.

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3.1.1. Master alloy preparation

To produce the test specimens with the desired composition, four sets of master alloys were cast with copper composition of 20%, 40%, 60% and 80% by weight of the Cu-Al alloy. The master alloys were prepared in specially fabricated graphite crucible (Figure 1).

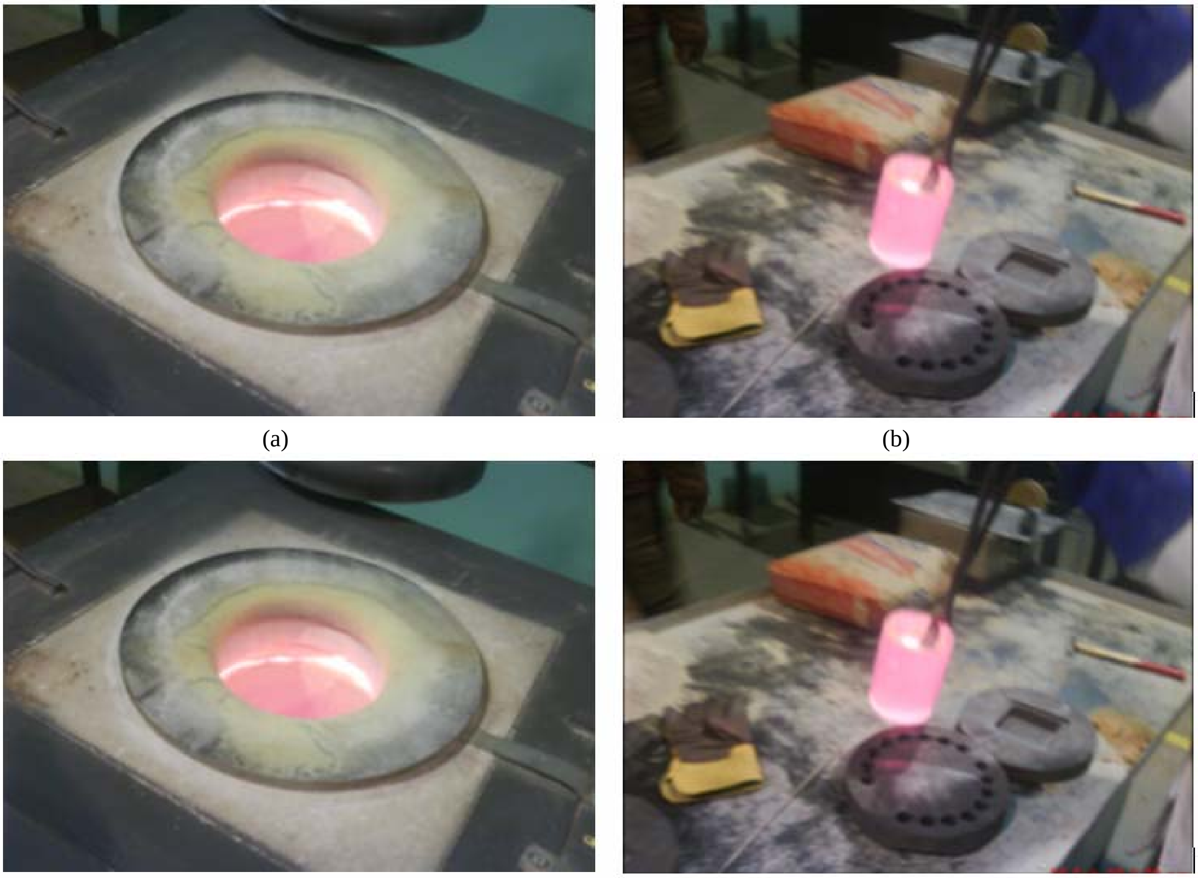
Graphite was also used as a casting die for cylindrical and flat plate test specimens, as seen in Figure 2, since graphite can be easily machined into the desired shape and dimensions with no or very minimum contamination of cast specimens and high durability at high temperatures. The molten master alloy is poured from the crucible into the appropriate die to produce the desired geometry, which is either a cylindrical specimen (ϕ=20mm, h=35mm), or a flat-plate geometry (150x150x10mm).

Figure 1 Graphite Crucible

Figure 2 Graphite dies (a) cylindrical specimens and (b) flat plate specimens

3.1.2. Specimen casting

Casting of master alloys was conducted at the casting workshop at the Hashemite University. Pure aluminum in the form of power transmission lines was acquired from the Jordanian Electric Power Company (has a purity percentage of 96%). As for copper, brass nuggets were bought due to budget limitations. The master alloy components were weighed using an electric scale as fractions of the estimated weight (specimen volume times the density of the components plus 10% error margin). Each composition was then placed in the crucible and placed in the induction oven at the casting workshops and stirred with a special ceramic stirrer to homogenize the metal mix, and then poured in the appropriate dies, as seen in Figure 3.



(a) (b) (c) (d)

Figure 3 Casting steps: (a) crucible at induction furnace, (b) & (c) pouring, and (d) cast specimens after cooling

The specimens were all allowed to cool at room temperature after casting, and then the cylindrical specimens were cut using the metallurgical saw available at the metallurgy lab at the Hashemite University, with coolant present to remove excess material.

3.2. Composition test

This test was conducted to ensure that the test specimens contain the desired amounts of each component of the alloy. The technique used is X-Ray fluorescence on a computer-controlled Phillips X-Ray spectrometer located at the NDT lab at the Hashemite University. A cylindrical specimen of each composition was used for the test as the machine can accommodate specimens 27-40mm in diameter and up to 40mm height.

3.3. Scanning Electron Microscope (SEM) test

This test was planned to attempt to correlate the grain size, segregation and distribution of the master alloys with their behavior during solar testing. Each of the four compositions were represented by a specimen and all of them were cut at the Metallurgy lab at the Hashemite University, mounted in Backlite, then ground by successively finer sand paper (starting from 600 up to 1200 grit silicon carbide). Then, all specimens were polished using 6-micron diamond paste on an alcohol film on a rotary bed with hand pressure. Care was taken to gently rotate the specimen while grinding it opposite to the rotary bed direction. Finally, the specimen were etched using a solution prepared from 2.5ml Nitric Acid, 1.5ml HCl, 1ml Hf and 95ml water, and the specimens were examined under the microscope at magnifications of 100x and 200x.

3.4. Solar Test

The purpose of this test is to quantify the effect of altering the Cu-Al composition within the alloy as the chosen material for a solar absorber. The test was scheduled for 21^{st} and 22^{nd} of April 2009 since only one operational thermocouple and data acquisition instrument was available due to budget limitations, and thus the tests were conducted for two specimens, the first was installed one hour before the solar noon (11:45 am, Jordan Standard Time) for those days and a second was installed one hour after, since the solar irradiation of the sun is symmetrical in intensity and incidence angles [i] around the solar noon and for one hour on each side. This means that tests were started before 11:00 am and lasted till around 11:40 am for one specimen, and another specimen is fitted from 11:40 am and left till around 12:30 pm. Tests were conducted at the Hashemite University in Zarqa, Jordan (32N latitude and 36.14 E Longitude). The recorded data will be compared with available solar irradiation readings from the Hashemite University solar station and dedicated to recording solar radiation all year round.

The test assembly shown in **Figure 4** consists of a special high-emissivity glass enclosure that permits the maximum amount of solar radiation due to the low content of iron. The enclosure isolates the test specimens from the convective effects of the wind as the class box was sealed from the bottom with a commercial sealant.

Figure 4 Solar test setup

The setup was placed in direct sunlight and the azimuth angle (the location of the sun measured away or towards the south) was adjusted manually by rotating the device around its yaw axis 15° per hour as the sun moved across the sky. The device was also inclined at 19° in winter (43.3° in summer) according to the zenith angle for the experimentation location at 32.1 N, 36.1 E, according to [4]. This provision ensures that incident solar rays are perpendicular to the projected area of the surface at all times.A thermocouple was fixed at the bottom of each test specimen and connected to a digital data acquisition device to measure the temperature rise in the specimens. Since the test specimens are cast, each one was accurately weighed and the weight recorded. Actual readings were also taken from the solar station at the Hashemite University that includes a Pyranometer that measures the global radiation on horizontal surfaces. It is mounted on the roof of the Engineering College, and contains carefully calibrated thermoelectric elements fitted under a glass cover, with data recorded every 5 min and then averaged on hourly, daily, and monthly basis. The sensor is a photodiode detector having a spectral response from 0.4 to 1.1 microns, with a sensitivity of 100 mV per1000 W/m^2, and an accuracy of ±5%. The effectiveness of each alloy will be calculated as the thermal capacity of each composition according to the following relation:

$$Eff(\%) = \frac{(Cp_{cu} * m_{cu} + Cp_{Al} * m_{Al})\Delta T}{I_o A_p} \qquad (2)$$

were Cp_{cu}, Cp_{Al} are the specific heats of copper and aluminum, respectively as given previously in [KJ/Kg.K], m_{cu}, m_{Al} are the mass fraction of copper and aluminum, respectively, in each alloy in [Kg], ΔT is the temperature rise of each alloy as recorded by the thermocouples [K], and while I_o is the solar radiation intensity (W/m^2) and A_p is the alloy projected area in m^2.

4. Experimental results

This section presents the results obtained during the experimental stages of this research.

4.1. Composition test

The following tables list the main elements found by running the X-Ray florescence test:

1) AL 100%

Elem	Percent
Al	96.0%
Cl	0.4%
Ca	0.25%
Mn	0.27%
Fe	0.91%
Cu	0.15%
Zn	0.16%
Pd	1.8%
Re	0.06%

2) 20% Cu +80%Al

Elem	Percent
Al	69%
Ca	0.1%
Mn	0.84%
Fe	1.99%
Ni	0.16%
Cu	8.3%
Zn	16.5%
Ru	2.4%
Sb	0.4%

3) 40% Cu +60%Al

Elem	Percent
Al	56%
Cl	0.81%
Mn	0.61%
Fe	1.1%
Cu	29.5%
Zn	9.37%
Nb	0.2%
Os	0.2%
Pb	0.64%

4) 60% Cu +40%Al

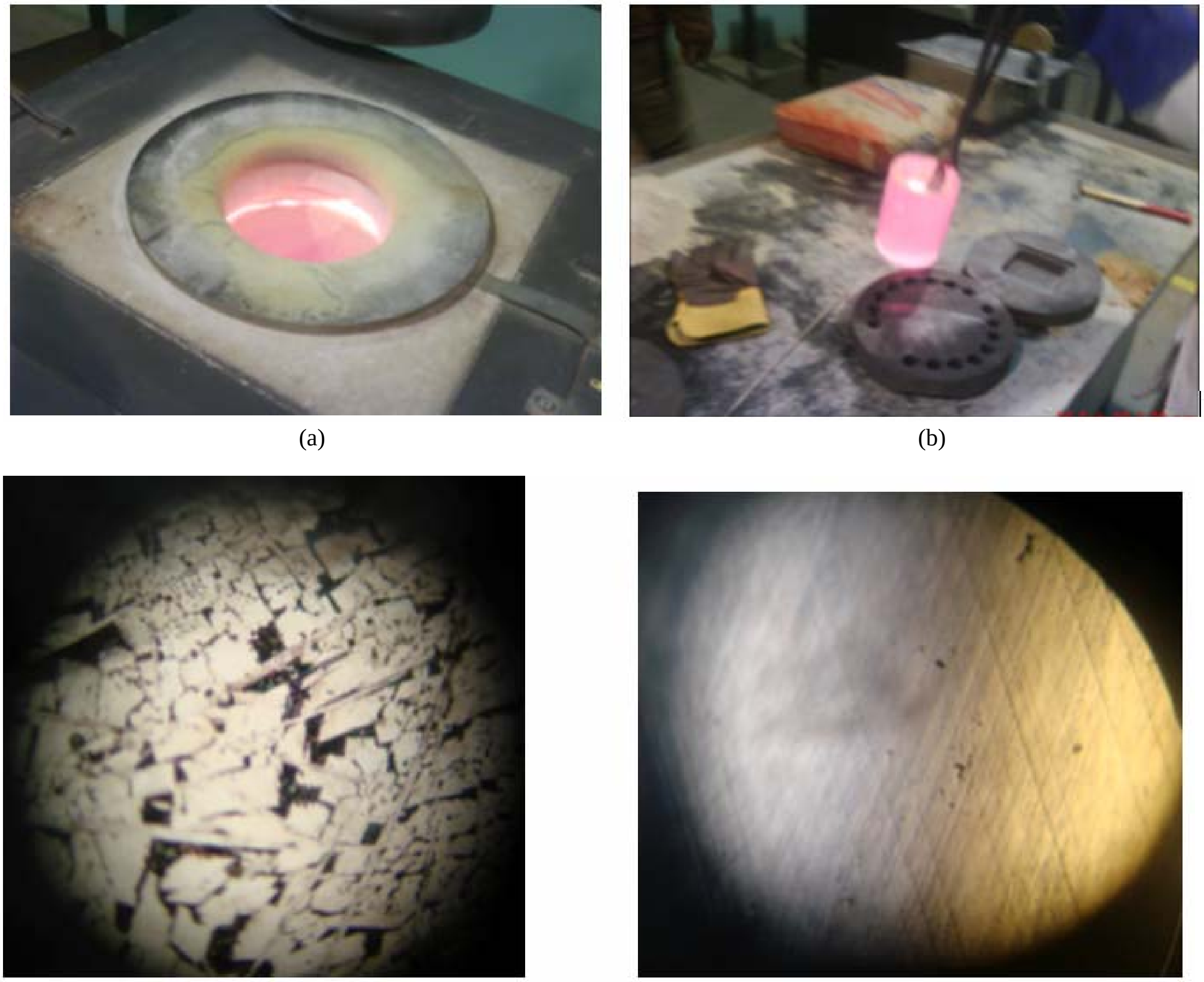
Elem	Percent
Al	33%
Mn	0.73%
Fe	1.6%
Cu	46.4%
Zn	15.1%
Nb	0.3%
Pd	2.0%
Os	0.1%
Pb	0.35%

5) 80% Cu +20%Al

Elem	Percent
Al	7.4%
Mn	1.00%
Fe	2.64%
Ni	0.21%
Cu	69.1%
Zn	16.9%
Nb	0.4%
Ru	1.8%
Pb	0.58%

4.2. SEM test

The following figures are the result of the SEM test for all four percentages:



(a) (b)

(c) (d)

Figure 5 . SEM photos for (a) 20%Cu, (b) 40%Cu, (c) 60%Cu and (d) 80%Cu

4.3. Solar test

This section presents the results of the thermal solar test for the four percentages of copper. The temperature rise for each specimen is a direct indication of its thermal capacity through the duration of the test.

This will be taken as a fraction of the available irradiation values from the Hashemite University solar station (being the maximum amount available) and plotted against time to arrive at instantaneous values for the effectiveness of the heat capacity of the alloy as calculated using equation (2).

4.3.1. Results for 20%Cu-80%Al

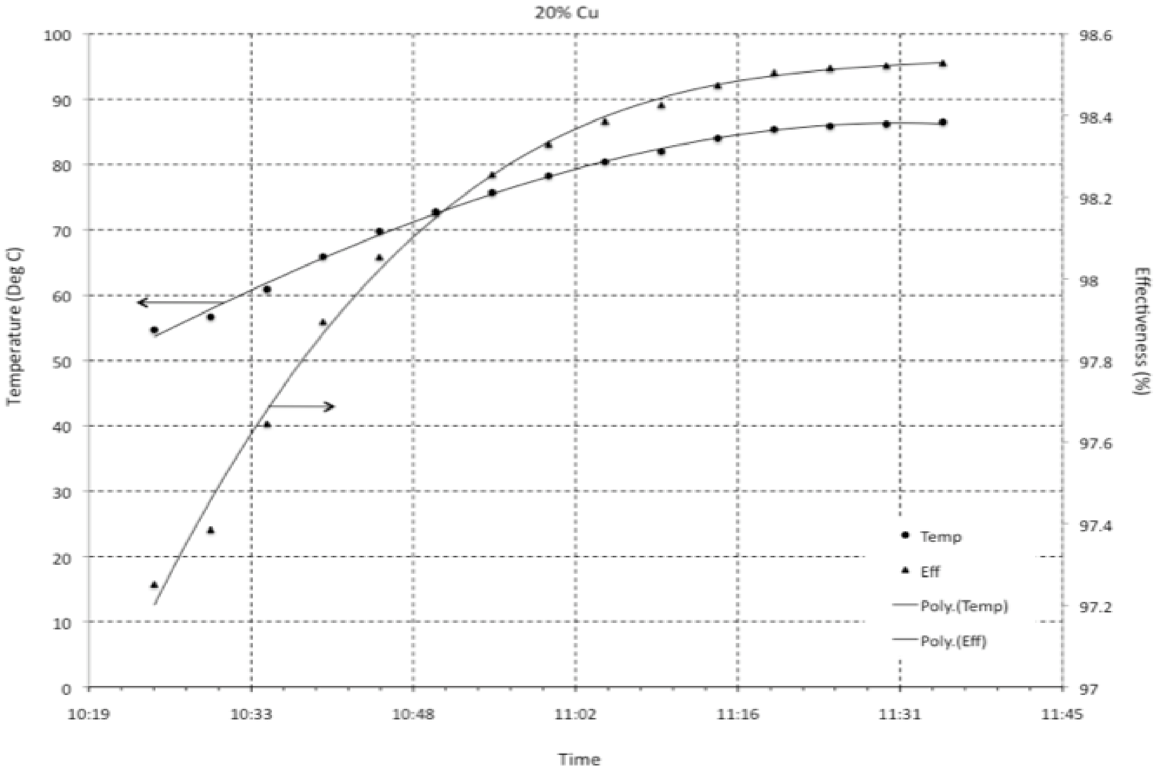


Figure 6 Temperature rise and effectiveness for 20% Cu content

4.3.2. Results for 40%Cu-60%Al

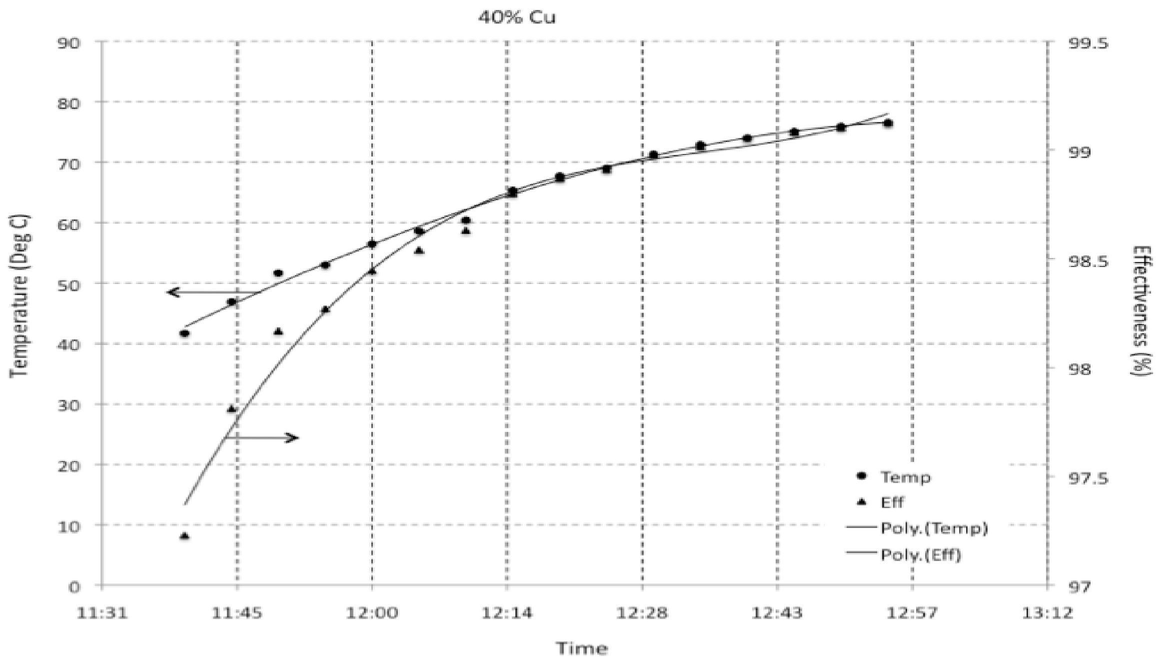


Figure 7 Temperature rise and effectiveness for 40% Cu content

4.3.3. Results for 60%Cu-40%Al

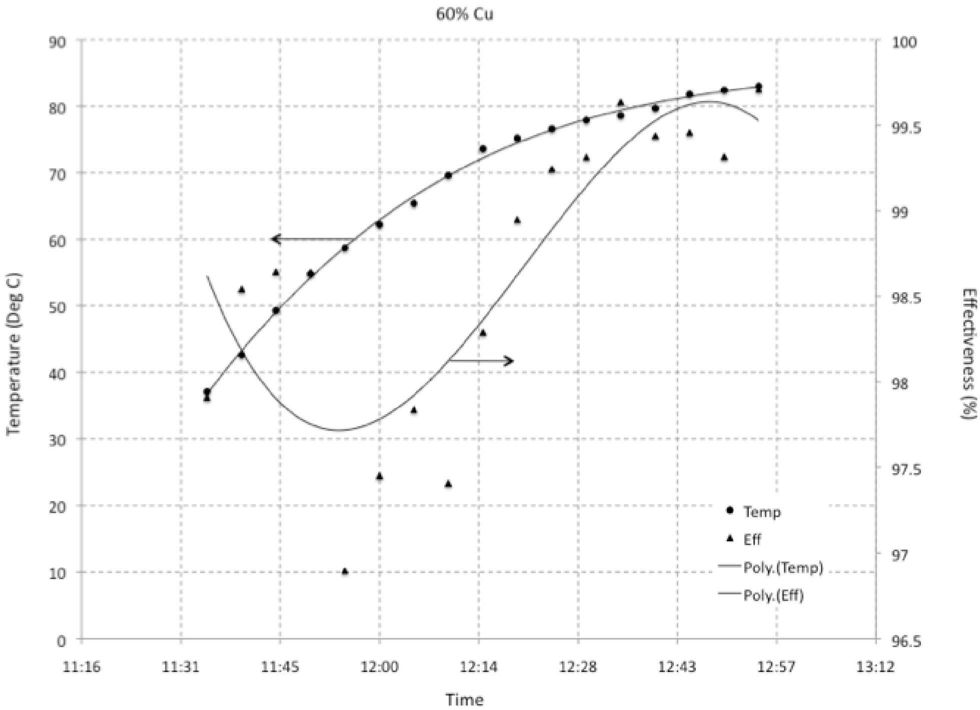


Figure 8 Temperature rise and effectiveness for 60% Cu content

4.3.4. Results for 80%Cu-20%Al

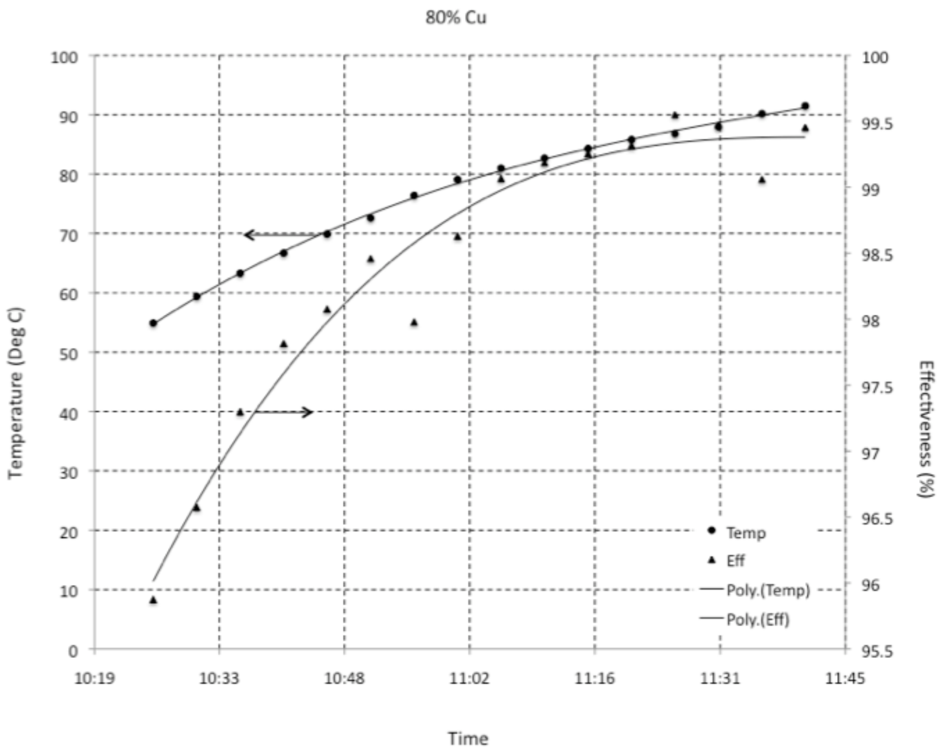


Figure 9 Temperature rise and effectiveness for 60% Cu content

5. Experimental discussion

5.1. Composition test

From the tables presented at section 4.1, it can be clearly detected that there is a high percentage of zinc present in the alloy, and the percentage of copper is lower than the percentage expected (around 13% less copper than expected). This was noted for future experiments, and copper nuggets with higher purity will have to be purchased. But for the purpose of this investigation, the amount of copper in each alloy will be a good indication on the solar capabilities of the material as well as its manufacturability.

5.2. SEM test

All the specimens were allowed to cool down to room temperature without quenching. And since the phase diagram of Al-Cu alloy shows no significant metallurgical changes for alloys with less than 80% Cu composition [i], it is interesting to note the difference in the grain structure for each alloy type depending on the amount of copper and trace materials available in the alloy. For example, with the alloy denoted 20%Cu, the addition of Cu and other elements caused the aluminum grains to exhibit a grain refinement effect [ii], where the aluminum grains are smaller and have almost equal size, as seen in Figure 5 (a). This effect is to be contrasted with the grain structure at the 40%Cu alloy in Figure 5 (b), where aluminum have solidified in the form of dendrites, which would be expected since aluminum is still more dominant than copper (or any other trace materials present), which lead to the formation of Al_2Cu during cooling, which also has a strong grain refinement effect [ii], as can be seen clearly around the dentritic arms in the figure. The more significant result from the SEM graphs was the one for 60%Cu alloy, where the copper grains are seen to be surrounding the aluminum grains in Figure 5 (c), where this diffusion happens around temperatures between 300-400°C when the amount of copper in the master alloy melt allows this diffusion [ii]. This arrangement will be shown to have a significant influence of subsequent solar thermal testing of this alloy as explained in the next section.

5.3. Solar test

By examining the solar test figures (Figure 6 thru Figure 9) a direct relation is seen between the temperature rise within the specimen and its effective increase in heat capacity of each alloy. The figures show small variations in the general trends among each other, except for Figure 8 that displays the variation for the 60% Cu content, where the scatter of the data points is noticeable, but the more interesting observations is that it scored the best effectiveness value (highest values for both minimum and maximum values of effectiveness on the curve).

One possible explanation can be inferred from examiningFigure 5(c), that shows the SEM results for the 60%Cu alloy, and shows the grains of copper surrounding the grains of aluminum and being more significant in size and opacity than in the case of 20%Cu content. This made the 60%Cu alloy more attractive to use as an absorber material than any other alloy, especially when taking another observation into account, that although all the alloys have the same Zn content, the 80%Cu alloy showed high brittleness characteristics which made it extremely difficult to manufacture and handle, and made it more susceptible to damage during installation and operation.

6. Conclusion

This research focused on testing different compositions of copper-aluminum alloys experimentally to determine their effectiveness as solar absorbers. The alloys were prepared by casting, examined under the SEM and solar experiments were conducted on the produced compositions (namely 20%, 40%, 60% and 80% copper content). It was concluded that there is a correlation between the grain structure and the thermal effectiveness of each alloy, especially the 60% Cu one, where the darker copper grains surrounded their aluminum counterparts. This result is primarily attractive when considering alternatives for pure absorber materials, since pure copper has superior heat transfer properties but is heavy and expensive, while with the economic availability of aluminum and its low density, it fails to be an effective replacement to copper alone.

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