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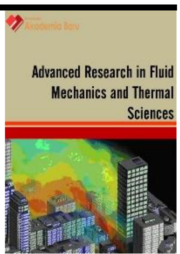

New Aqueous solution for Direct Solar Absorption Refrigeration Systems

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ABSTRACT

Solar-driven absorption refrigeration technology has the potential to reduce the peak electricity demand and global warming. Optimization of this technology can change the future energy economy of the world. Herein, the straightforward and inexpensive preparation of new stable aqueous solution for direct solar absorption refrigeration systems is reported. Standard copper solution can be added to the aqueous lithium bromide solution used in absorption refrigeration systems in a simple one-step process under ambient conditions. The resulting solution is multifunctional as it improves the steam absorption in the absorber, absorbs the solar energy and converts it directly to heat, enhancing the efficiency of steam generation in the generator. Experiments to measure the viscosity, thermal conductivity, transmittance, photo-thermal conversion and steam absorption are demonstrated. The results show an enhancement of ~32.5% in the direct photo-thermal conversion and ~10.5% in the steam absorption rate, and negligible change in the viscosity and thermal conductivity of the new aqueous solution comparing to the conventional one. Thus, this stable new solution might be considered as an alternative of nano solutions and it has the potential to improve the solar absorption refrigeration technology, reducing the size and cost and saving Earth.

Keywords:
Aqueous solution; absorption refrigeration; photo-thermal conversion; solar cooling

1. Introduction

The production of cold plays an important role in the modern life. It is crucial for many engineering applications such as air conditioning, food processing, pharmaceutical products conserving, etc. Due to some attractive features of vapour compression refrigeration systems (VCRSs), like the higher performance per unit cost; lower volume per unit cooling capacity; and favourable operational and maintenance characteristics [1–3], they have become the dominant technology to produce cold in the world. However, these systems (VCRSs) contribute significantly

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against the sustainability. This drawback is because VCRSs are usually driven by electricity, increasing the electrical power demand around the world continuously, especially in the four major emerging economies: Brazil; Russia; India; and China (BRIC), and in the wealthy oil countries of the Gulf Cooperation (GCC) [4,5]. According to the International Institute of Refrigeration in Paris (IIF/ IIR), approximately 15% of the world's production of electricity and 45% of the whole consumption of residential and commercial buildings is consumed by refrigeration and air conditioning processes [6]. Generally, the percentage of electricity consumption for cold production differs among countries. More than 50% of the produced electricity is consumed to drive air conditioning systems in countries suffering extreme hot and moist climate such as in the Middle East [6–8]. Consequently, electrical VCRSs are one of the main contributors to the global warming phenomenon in two ways. One way is that these systems participate in increasing the CO_2 and other pollutants emission as combustion-the most common and cheap technology to generate electricity-accounts ~71% of electricity generation around the world [9]. The other way is the leakage (5% - 15% of the unit content) of non-natural refrigerants such as CFCs, HCFCs, and HFCs, which have effects on the ozone layer and/or the global warming phenomenon [10,11].

The awareness of the world community regarding the pollution and global warming phenomenon has increased and many international agreements have been signed after Montreal and Kyoto protocols to reduce the emissions of greenhouse gases (GHGs). Thus, research has been intensified to improve and develop technologies that can reduce energy consumption, peak electrical demand and cost [6,12]. One of these technologies is the vapour absorption refrigeration systems (VARSs), which are driven thermally. Low-grade heat sources like hot gases flue, exhaust gases and solar energy can run these systems. However, the large volume, high cost and low performance are intrinsic issues within this technology. Recently, efforts have been done to increase the prospects of solar cooling systems as eco-friendly systems by developing H_2O-LiBr based VARSs. This is due to advancements in the nanotechnology and solar thermal collectors [1–3,12,13].

The generator and absorber are two main intrinsic components of a VARS. They together eliminate the need for a compressor, which demands high electrical power. Therefore, a pump can be used to circulate weak H_2O-LiBr solution from the absorber – where the refrigerant (steam) is absorbed by a strong H_2O-LiBr solution – to the generator – where the refrigerant (steam) is released thermally from a weak H_2O-LiBr solution. These two components are responsible for the bulky, costly and low-performance features of VARSs comparing to the VCRSs, and their optimisation is essential in developing the VARSs technology and crucial to change the future energy economy of the world [1,2,12]. Seeding nanoparticles within the H_2O-LiBr solutions (nanosolutions) is one of the recent proposals to optimise the performance of both the generator and absorber. This proposal has two aims: firstly, to absorb the solar energy directly by a nanosolution [14–16] and secondly, to enhance the heat and mass transfer in the generator and absorber [17–19].

Intensive research work has been conducted to investigate the effects of nanoparticles in photo-voltaic [20–27] and in photo-thermal [28–34] applications. Brownian motion of the nanoparticles and subsequent micro-convection has stimulated researchers to utilise nanoparticles in mass transfer enhancement. Although some studies reported enhancements in the mass transfer [35–38], other studies argued that enhancement is due to reactions, such as adsorption, between the solute and the nanoparticles (grazing effect of nanoparticles) [38–43]. However, the stability of the nanoparticles in strong ionic solutions such as these used in the absorption refrigeration systems is a problematic issue and measures are required to enhance stability and avoid aggregation and agglomeration problems [18,44–50]. Furthermore, it is well known that seeding nanoparticles in a fluid can increase the effective viscosity, increasing the pumping power consumption [51,52]. Moreover, a bench mark study has shown that no anomalous increase in the effective thermal conductivity of nanofluids, and the classical theory introduced by Maxwell in 1881 and generalised by Nan *et al.,* can well predict the effective thermal conductivity [53]. Therefore, due to these issues, the need for an alternative refrigeration solution has emerged.

To the best of our knowledge, no effort has been done to prepar a solution that can be an alternative to the nanosolutions, i.e., a solution that can absorb the solar energy directly without the need for absorbing surface and enhance the steam absorption rate. Thus, herein, we report a very stable new alternative aqueous solution, which has the potential to be used in the direct solar VARSs. The viscosity, thermal conductivity, transmittance, photo-thermal conversion and steam absorption of the new aqueous solution were measured carefully and precisely.

2. Experimental

2.1 New Aqueous Solution Preparation and Characterization

Lithium bromide (LiBr) powder (99^+% purity, 86.845 g/mol molecular weight, 3.464 g/cm^3 density, Li^+— Br^-, anhydrous white powder) was supplied by ACROS ORGANICS. Standard copper solution (Cu $(NO_3)_2$. $3H_2O$ in 0.5 M nitric acid, 999 ±2 mg/l) was supplied by MERK. An analytical scale (KERN ABT 220-5DM, 0.1 mg resolution), standard cylinders and precise micropipettes were used in preparation of the samples. Using a magnetic stirrer, a 50 wt.% mass concentration of aqueous lithium bromide solution (LiBr-H_2O) was firstly prepared by dissolving LiBr salt in de-ionised (DI) water by the ratio 1:1. Nitric acid (0.5 M) was used to dilute the stock standard copper solution to different concentrations of copper (i.e., 125, 250, 500, and 1000 mg/l). By using a precise pipette, 8 ml of each copper solutions were added to 32 ml of the 50 wt.% LiBr-H_2O. The colour of the resultant solutions directly changed from transparent to dark, as shown in Figure 1. The final concentrations are 0, 25, 50, 100, and 200 mg/l of copper in 40 wt.% LiBr-H_2O. The complete reaction equation can be written as follow

$$2LiBr + Cu(NO_3)_2 \leftrightarrow CuBr_2 + 2LiNO_3 \tag{1}$$

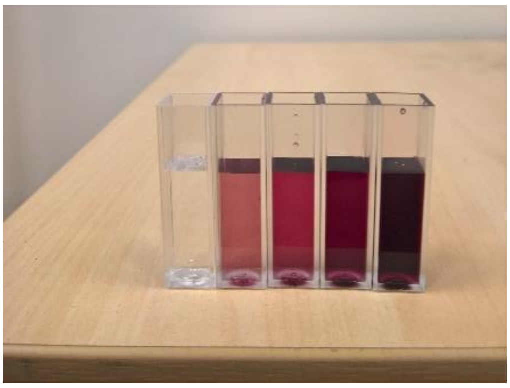


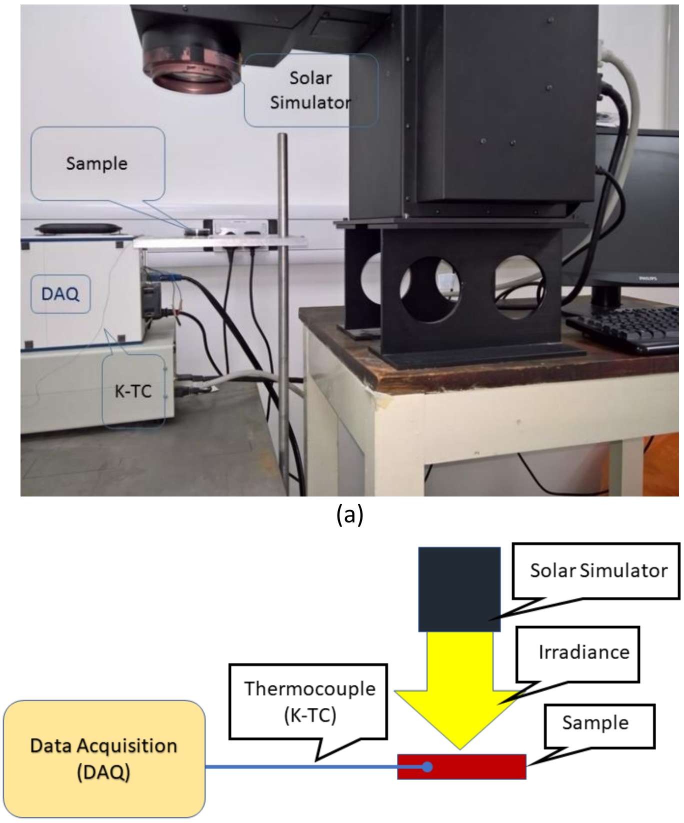
Fig. 1. Picture of the samples with different copper concentrations in 40 wt.% LiBr-H_2O

As shown in Eq. (1), all the compounds are soluable in water; therefore, the new aqueous solution prepared in this way is very stable. The stability was tested for more than 2 years and no changes were detected, i.e., neither sedimentation nor colour change was detected.

An ultraviolet-visible-near infrared (UV-Vis-NIR) Spectrophotometer (UV-1800, Shimadzu Corporation, Japan) was used to measure the transmittance of the prepared solutions. A KD2 Pro from Decagon Devices, Inc. was used to measure the thermal conductivity (k). The 6 cm single-needle sensor (accuracy~5% for $0.02 \le k \le 2$ W/m.K) was inserted vertically in 3.5 cm diameter sample. The whole setup was placed on a heavy optical table in an isolated room to minimise the vibration effect on the readings. Each test was repeated three times for each sample and the r^2 was greater than 0.9999 for all runs. For the dynamic viscosity measurements, a Discovery HR-2 from TA instruments was used. Four runs were performed for each sample at room temperature (25 ^{o}C).

2.2 Photo-Thermal Conversion Experimental Setup

The experimental setup of the photo-thermal conversion experiments is shown in Figure 2. A sun simulator (ORIEL® Sol3A^{TM}, Xenon Arc Lamp) was used as a light source to minimise the uncertainties accompanied with the outdoor sunlight. This sun simulator provides a radiation spectrum matches the solar spectrum, and the intensity can be varied by using suitable filters. This device is certified to International Electrotechnical Commission (IEC 60904-9 2007 edition), Japanese Industrial Standards (JIS C 8912) and American Society for Testing and Materials (ASTM E 927-05) standards.



(a)

(b)

Fig. 2. Photo-thermal conversion experimental setup: (a) A photograph picture and (b) a schematic diagram

The performance parameters of the solar simulator are; non-uniformity < 2% and temporal instability < 0.5%. By using a precise micro-pipette, a 6.5 ml sample was put in a Petri dish (33 mm diameter) and covered to minimise the losses from the sample. A well-calibrated K-type thermocouple (Omega 5TC-TT-K-36-36, a precision of ±0.5 ^{o}C and a diameter of 0.13 mm) was used to measure the temperature. The bulk temperature data was recorded to a PC via data acquisition hardware under the LabVIEW environment three times for each sample and the standard deviation was $\leq$ 0.5 K.

2.3 Steam Absorption Experimental Setup

A constant thickness and surface area samples were used in the steam absorption measurements to avoid the uncertainties accompanied by the falling film experiments. Figure 3 shows the experimental setup for the steam absorption measurements. To ensure sensibile detecting for the steam absorption, A 114 mm Petri dish was placed on an analytical scale (KERN ABT 220-5DM, 0.1 mg resolution), which was connected to a PC through LabVIEW environment. The analytical scale was placed on a heavy optical table in an isolated room to minimise the effect of vibration on the readings. A precise pipette was used to put 35 ml of each sample in the Petri dish, and its mass change due to the absorption of the steam was recorded for 600 s three times and the standard deviation was ≤ 0.1 mg. The room temperature and relative humidity were control within 1°C and 1% respectively.

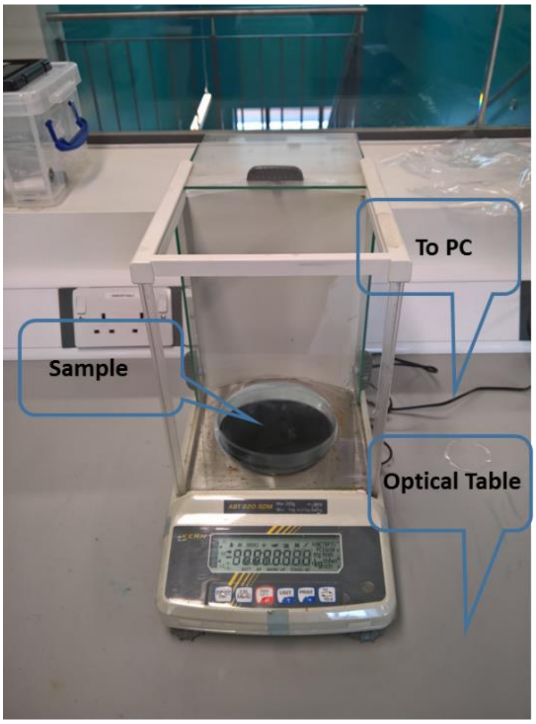


Fig. 1. Steam Absorption Experimental Setup

3. Results and Discussion

Figure 4 shows the dynamic viscosity of the aqueous lithium bromide solution 40 wt.% with different copper concentrations. The results reveal shear thickening behaviour and more importantly, negligible change in viscosity as the copper concentration increases, which means no more pumping power is required to pump this new aqueous solution.

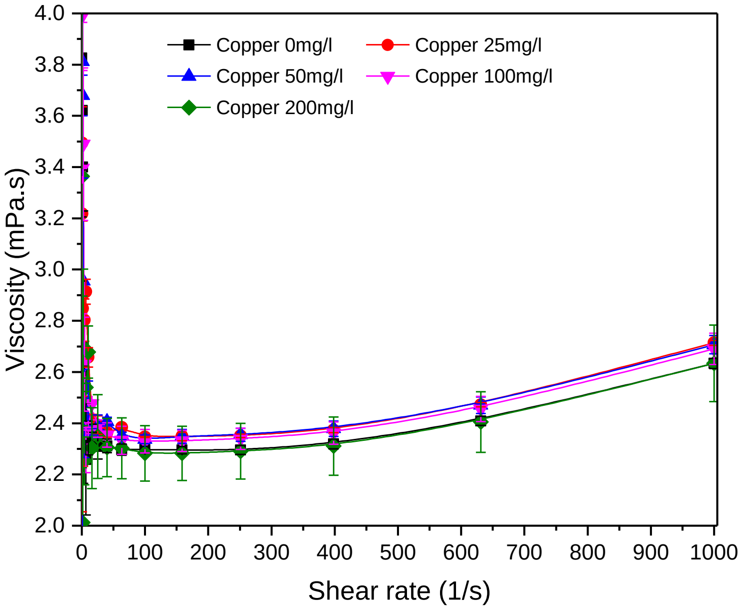


Fig. 4. Viscosity of different concentration of copper in 40 wt.% LiBr-H2O

The effective thermal conductivity (k) and the ratio between the effective and the base thermal conductivities (k/k_0) of the solutions are presented in Figure 5. It is clear that the concentration of copper has a negligible effect on the effective thermal conductivity as all the data are fall in the range of the measuring device error (±5%). This is understandable since the maximum concentration of copper is 200 mg/l (200 ppm).

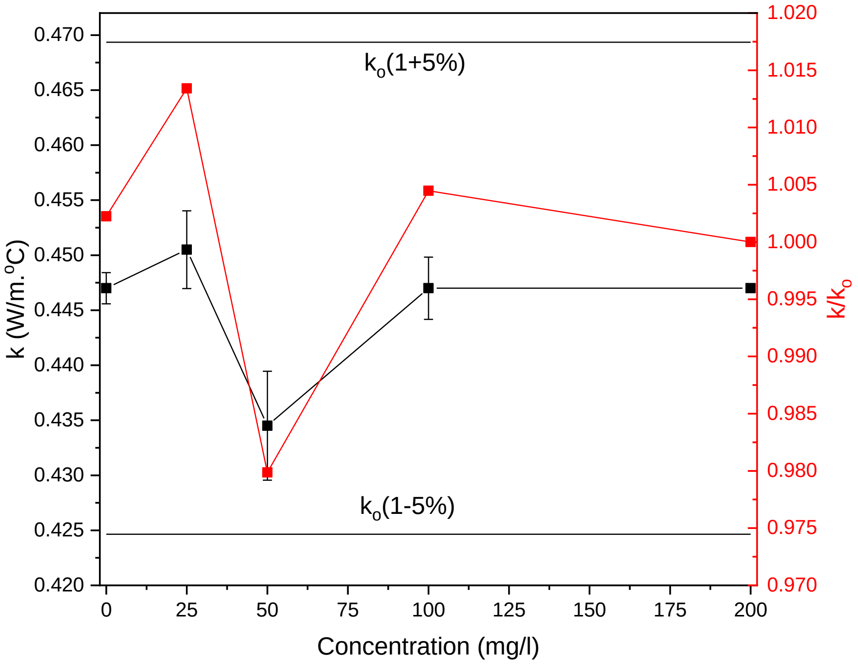


Fig. 5. Thermal conductivity of different concentration of copper in 40 wt.% LiBr-H2O

Figure 6 shows the spectral transmittance (T %) of different concentrations of copper in 40 wt.% LiBr-H_2O. It is obvious that the conventional aqueous lithium bromide solution is almost transparent (see Figure 1), while adding copper solution to LiBr-H_2O changes the transparency significantly.

Copper concentration increases, transmittance decreases. When the copper concentration is 200 mg/l, the transmittance is almost zero over the wavelength range of 200nm≤**λ**≤600nm. However, transparency increases when 600nm≤**λ**≤750nm. After that, it decreases again when **λ**≥750nm. The result reveals that the new aqueous solution has the potential for the direct absorption of the solar energy since ~42% and ~78% of the solar energy is in the wavelength range 300nm≤**λ**≤700nm (visible light) and 300nm≤**λ**≤1100nm respectively. Also, water molecules (in the solution) can absorb the NIR (near-infrared radiation 1100nm≤**λ**≤2500nm) efficiently.

To investigate the photo-thermal conversion capability of the new aqueous solution, 6.5 ml of each sample was put in a Petri dish (33 mm diameter) and subjected to 1000 W/m^2 radiation from the solar simulator for 30 min. The temperature and the rate change of the temperature are presented in Figure 7. It is clear that the new aqueous solution enhances the temperature rise significantly. For instance, the temperature of 0 mg/l copper in 40 wt.% LiBr-H_2O is ~40.5 °C after 30 min of illumination. While the temperature is ~53°C for 200 mg/l copper. These results are in agreement with the results presented in Figure 6. In other words, transmittance decreases, absorbance increases and consequently photo-thermal conversion increases. Also, it is obvious that all samples almost reach the steady state after 30 min as the rate of change of temperature rise reaches ~0. However, during the initial stage, a big difference can be seen among the rate of change of the temperature rise of the different samples. An enhancement of 32.5% in the solar energy absorption was achieved by 200 mg/l copper in 40 wt.% LiBr-H_2O during 30 min.

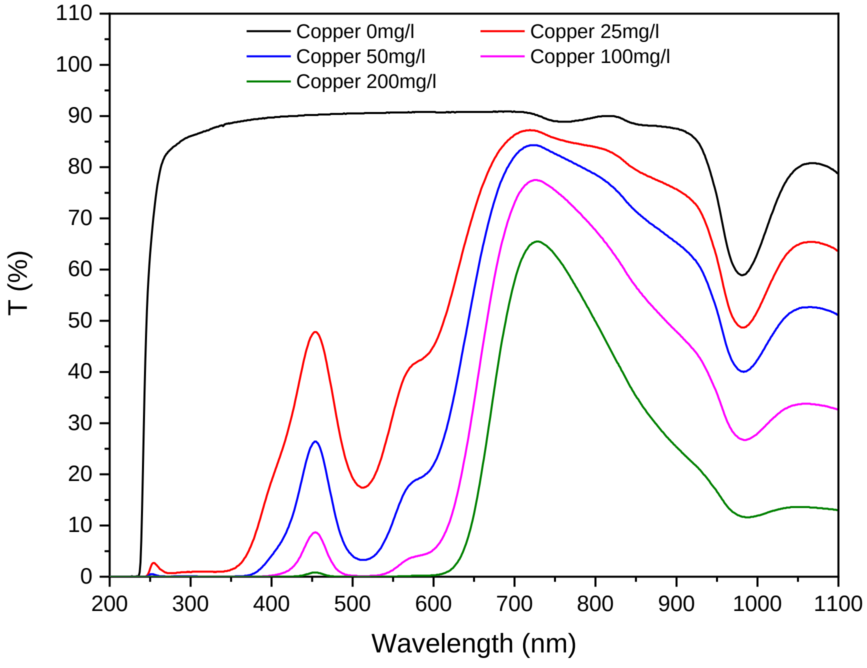


Fig. 6. A comparison of spectral transmittance of aqueous lithium bromide solutions 40 wt.% with different copper concentrations

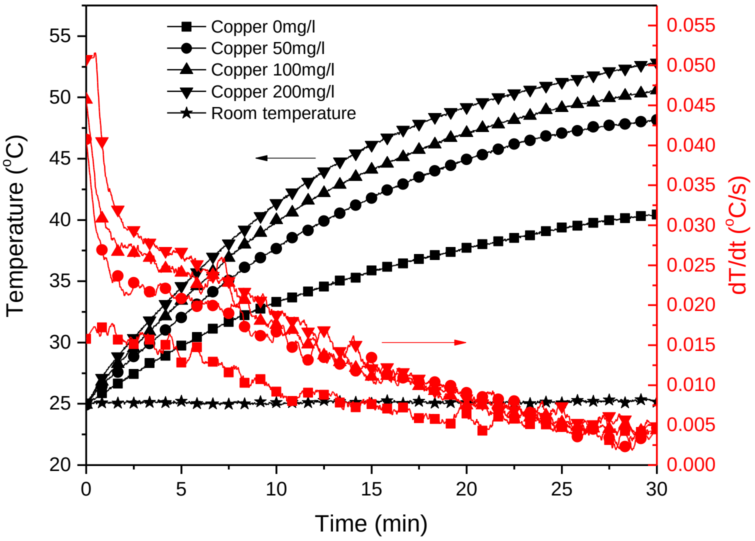
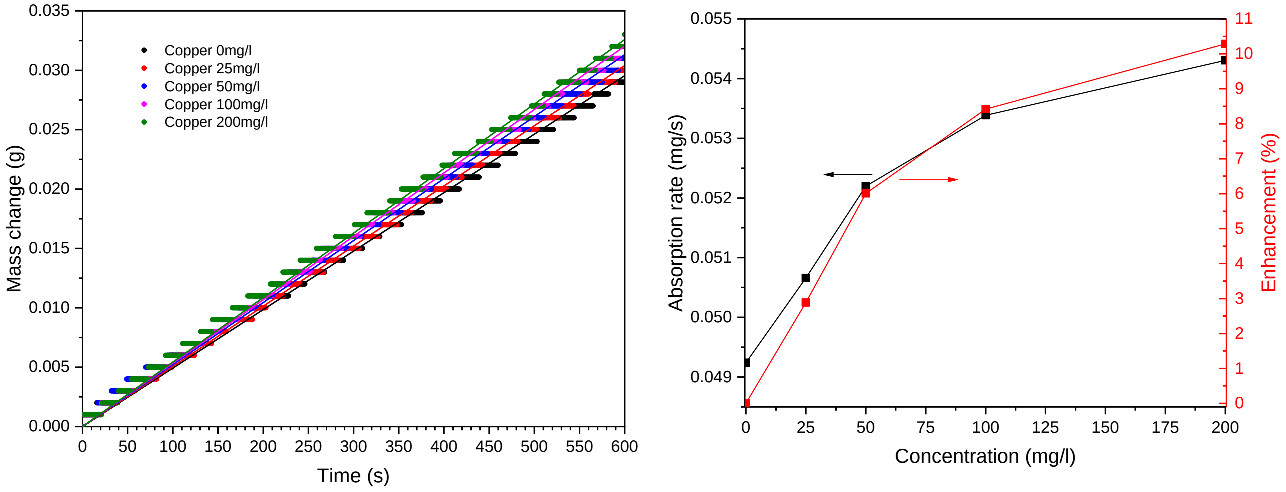


Fig. 7. Temperature rise and the rate of change of temperature of different concentration of copper in 40 wt.% LiBr-H2O

The results of the steam absorption experiments are presented in Figure 8. In Figure 8(a), the symbols are the data of the measured mass change of the samples with time. These data points construct a step figures, and this is due to the mass balance sensitivity, which is 0.1 mg. In other words, the mass balance cannot detect the mass change lower than 0.1 mg and it needs time to detect every 0.1 mg change. This time depends on the absorption rate of the solutions. The lines represent the linear fitting for the experimental data. Clearly, the mass of the absorbed steam is linearly proportional with time. However, the absorption rate is non-linearly proportion with the copper concentration in the 40 wt.% LiBr-H_2O, as shown in Figure 8(b). As a result, enhancement of ~10.5% in the absorption rate was achieved by 200 mg/l copper in 40 wt.% LiBr-H_2O. This means that the proposed new aqueous solution has a higher affinity to steam than the conventional LiBr-H_2O solution and this higher affinity is, of course, owing to existance of Cu^{+2} and NO_3^{-1} ions in the new solution.



(a) (b)

Fig. 8. Steam absorption of different copper concentrations in 40 wt.% LiBr-H2O: (A) mass change (Symbols represent the experimental data, and lines represent linear fitting); (B) absorption rate and enhancement as function of copper concentration

4. Conclusion

New aqueous solution was prepared by adding standard copper solution to the conventional aqueous lithium bromide solution via a simple one-step process under ambient conditions. Extensive experiments were performed to characterise it. The main conclusions can be listed as below. Adding standard copper solution to the conventional aqueous lithium bromide solution has

i. Negligible effect on the dynamic viscosity (i.e., no extra pumping power is required).
ii. Enhanced the direct solar energy absorption significantly, ~32.5% (i.e., less fossile fuel is consumed by the generator).
iii. Enhanced the steam absorption moderately, ~10.5% (i.e., smaller absorber is required).

This stable new solution might be considered as an alternative of nano solutions and it has the potential to improve the solar absorption refrigeration technology, reducing the size and cost and saving Earth.

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