Solar steam in an aqueous carbon black nanofluid

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Abstract

A limited number of experimental studies report intensive steam generation in direct adsorption solar collectors with nanofluids. Most nanofluids used for these applications are produced with expensive gold nanoparticles. This contribution proposes a low-cost alternative solution made of water and carbon black nanoparticles. Our nanofluid-generated yet nanoparticle-free steam is produced in a parabolic collector with 73% efficiency and 25°C superheat under the solar conditions in the Nordic region.

Keywords: nanofluid, solar steam, boiling, solar collector, carbon black

1. Introduction

The first successful attempt of sun-enabled, *in-situ* steam generation of nanofluids (NF) was reported by Neumann et al. (Rice University) [1] less than decade ago. Using low-concentration aqueous suspension of golden nanoparticles (NP), they demonstrated evaporation efficiency of around 80% and relatively high steam temperature (120-130°C) [2]. The developed "nano-steam" technology was utilized in a pilot experimental rig for effective off-grid disinfection. Another important contribution comes from prof. Wen's group [3] (Beihang University), where the solar steam was produced at natural irradiation of 220 sun (Fresnel lens) from an electrolyte containing up to 13 ppm of 20-nm Au particles. Even though the obtained efficiencies of the process were similar to [1], the nanofluid temperature did not rise to the same superheat values. The practical applicability of the considered NFs could be strongly criticized because of the high cost of gold NPs and lack of information on potential toxicity of the solar steam that may contain NPs. An alternative solution [4] was proposed by Ni et al. (MIT) based on carbon black (CB) NPs, studying different CBNFs under artificial radiation. The degree of light concentration and volume fraction of the particles were insufficient to obtain notable superheat while still providing reasonable evaporation efficiency up to 60%. Another interesting contribution from the Hubei University considers a mixture of graphene oxide-Au NPs in water under the lens-concentrated natural heating

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(0.85 sun). The maximum process efficiency was 59.2%, even though the temperature never exceeded 80°C, i.e. surface evaporation was probably the dominant mechanism of steam generation.

These experiment were conducted out in regions with excessive solar resources or under the artificial solar irradiation. This raises questions about the possibility of utilizing the technology in a moderate climate. In the present study, we investigate a low-cost solar steam application based on CBNF with different composition that improves thermal properties of the steam.

2. Experiments

Our nanofluid was produced mixing CBNPs (ENSACO 350G) and water from the Bergen communal network (pH 8.2, chemical composition presented in S.0, the supplementary materials). ImageJ processing of TEM-scans (JEOL 2100) of dry CBNPs (Fig. 1A) returns 51±17 nm mean particle size (particle size distribution in Fig. S.1). NF samples (pH 9.5) were homogenized using Branson 3510 ultrasonic bath (320 W).

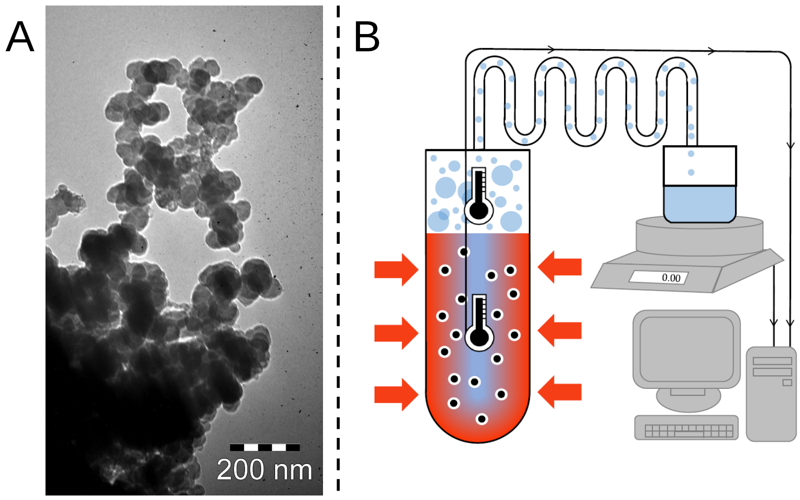

Figure 1: A: TEM of CBNPs. B: Experimental set-up

CBNF optimum composition was selected in a series of lab-scale experiments on photothermal evaporation of the fluid. The laboratory set-up (Fig. 1B) consisted of a transparent glass tube (ID 14 mm, height 148 mm), connected via PVC-pipe to a condensate collector. A 5-ml sample of CBNF was heated in the light of two halogen lamps OSRAM (400 W), delivering 5.5 kW/m^2 each. The radiative heat flux is plotted against distance from the lamp in Fig. S.2. The 300-nm shift to the red region relative to the solar spectrum was detected for the lamp. The measurement system included two thermocouples Omega(T) (±0.3°) and the scale Sartorius CPA 324S (±0.1 mg). The thermocouples were placed in the bulk of CBNF and the steam, respectively. Once the optimum composition was found, a 1-l batch of CBNF was produced for the solar collector test.

3. Results and discussion

3.1. Artificial illumination

Figure 2 illustrates the dynamics of photo-thermal boiling of 3wt% CBNF during lab-scale experiments. In this test we detected no signs of early sub-cooled boiling as reported by Neumann et.al. [1]: the fluid gradually reaches saturation after about 7 min. The system most possibly follows the heating scenario proposed by Ni et.al. [4], where trapping of thermal boundary layers for individual nanoparticles was proposed as the driving force of the process. Following our visual observations (video 1), CBNF starts boiling at the saturation temperature. Evaporation of CBNF down to 58% of initial sample volume compacts the solution. The inter-particle separation distance reduces so the steam bubbles gain superheat slightly over 11 K, i.e. almost twice larger the superheat for 5.5 kW/m^2 from the conventional water boiling curve. In Ni et.al. [4] the equivalent superheating was not demonstrated at 5-10 sun. Following our CFD-estimates (STAR-CCM+), the system gauge pressure never exceeded 2 kPa, so that this temperature cannot be explained by pressurization of the steam. The optical microscopy (Keyence DM VHX 2000) of CBNF sample prior to boiling experiments confirmed formation of NP agglomerates in water up to the maximum size $\approx$7 μm (Fig. S.3). The sample was kinetically stable due to the Brownian motion and due to the fact that the velocity of thermal convection $v = \sqrt{Gr}\nu/H$ $\approx$0.07 m/s [1] overcame the NP settling velocity 3.3$\cdot 10^{-5}$ m/s ($St \ll$1). An interesting observation made here is that the superheat required to stabilize a steam bubble around the agglomerate of this size was $\Delta T = 4T_s\sigma/\rho_v r_{lg} d_p$ = 11.4K [3] [2], which could potentially support the theory of vapour shell formation, proposed by Neumann et al. [1].

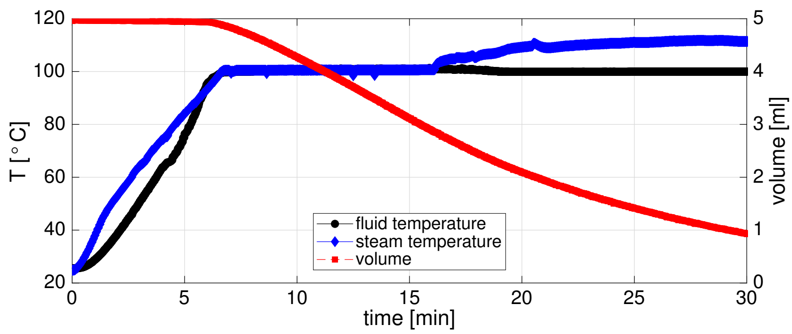

Figure 2: Lab-scale experiment log

The condensate samples, studied with FRITSCH ANALYSETTE 22, contained no traces of nanoparticles; the particles from CBNF condensate were of the sizes equivalent to the dimensions of natural contaminants in pure tap water (see Figs. S.4.1-S.4.2 showing the particle size distributions). The condensate from a reference sample of Fe_3O_4 nanofluid with

[1] Gr - Grashof number, ν - kinematic viscosity, H-height of CBNF column

[2] T_s-saturation temperature, σ - surface tension, r_{lg}-latent heat of vaporization, ρ_v - steam density, d_p - particle size

the same volume fraction of heavier NPs (184±55 nm) was contaminated with nanoparticles (Fig. S.4.3). We attribute this observation to different wettabilities of the compared NPs.

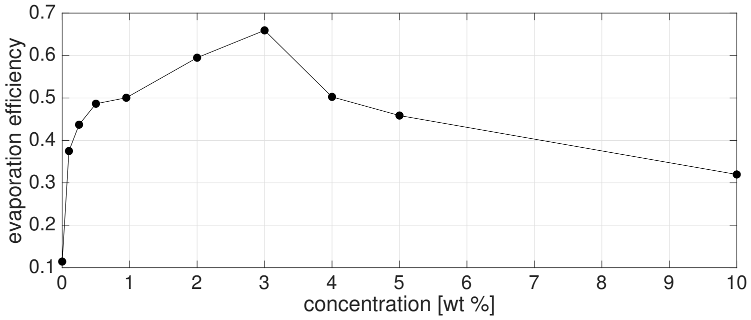

Figure 3: Evaporation efficiency

The evaporation efficiency of the process is presented against initial CBNP concentration in Fig. 3. Following [4], this parameter is defined as the ratio of the amount of heat, utilized for CBNF evaporation and superheating of produced steam, to in-coming heat. Screening the composition, we observed maximum at 3 wt%, below which the addition of new particles increased heating and the number of nucleation sites. The optical depth does reduce with concentration and, passing the optimum, CPNPs limit photo-thermal exposure of the bulk.

3.2. Solar concentrator test

The concentrator test was run at 60°22'06.5"N and 5°21'07.9"E in the summer of 2017. The time-average environmental conditions, recorded by the meteo-station $\approx$ 2 km from the site of the experiment, were: solar heat flux 0.76±0.04 sun, pressure 1008±0.2 hPa, temperature 22.4±0.3°C and relative humidity 51.5±0.5% (Figs. S.5.1-S.5.5). During the *in-situ* experiments, CBNF was poured in a round-bottom Pyrex flask (ID 16.5 cm), that was further placed in the focus of a 1.5-m^2 parabolic collector (Marsrock) with concentration ratio 64 (40° to horizon). The scheme of the experimental system is shown in the graphical abstract. Temperature of the solar steam was controlled with a ST-9215C-300 thermistor (±0.1°C) with a digital display, protected from the solar radiation by using a layer of metal foil.

An experimental log from the solar concentrator study is shown in Fig. 4 (video 2). Here the volume of the sample was defined by processing with ImageJ digital photos taken at different stages of the process, returning average production rate of 10 ml/min. Unlike the heating in the laboratory system, CBNF was superheated up to 25°C with no detection of temporal delay at saturation conditions. The superheat was in the interval reported by Neumann et.al. [2] for a similar solar steam system with Au-Si NPs. This value again does not correspond to the conventional boiling curve, but could be explained by activation of smaller nucleation sites (cavities) at NP agglomerates for the heat flux above 48 kW/m^2. The evaporation efficiency is estimated to be 73% that corresponds to 15% of the flask area covered by the concentrated sunlight (bottom of the flask). This is well comparable with the results reported by [1].

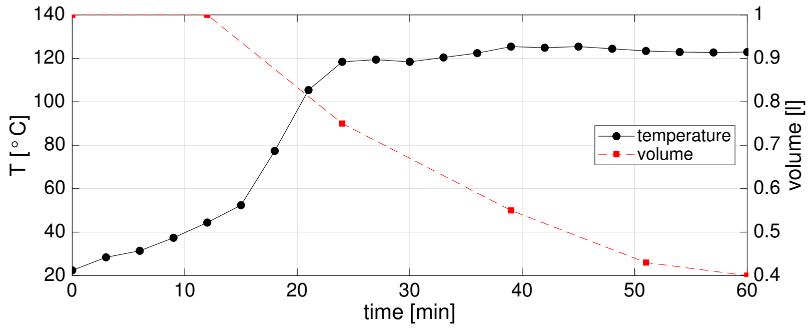

Figure 4: Concentrator experiment log

4. Conclusions

This paper describes laboratory experiments on solar steam generation in CBNF at 11 sun. Screening NF composition, we detected maximum evaporation efficiency at 3wt%. Solar steam condensate was free of nanoparticles. CBNF with optimum concentration was tested in the parabolic solar collector at 0.76 sun, the evaporation efficiency was estimated to be 73%. To our knowledge, this was the first experimental record of NP-assisted steam production in the limited solar conditions in the Nordic region. Both the laboratory system and the collector test resulted in high superheating of the steam, approaching the values from Rice University with the low-cost nanofluid and at lower sun concentration. Even though the rate of solar steam generation was not yet sufficient to establish a turbine cycle, the process is applicable for technical desalination, disinfection and direct heating.

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References

[1] O. Neumann, A. S. Urban, J. Day, S. Lal, P. Nordlander, N. J. Halas, Solar vapor generation enabled by nanoparticles, ACS Nano 7 (2013) 42–49.

[2] O. Neumann, C. Feronti, A. D. Neumann, A. Dong, K. Schell, B. Lu, E. Kim, M. Quinn, S. Thompson, N. Grady, P. Nordlander, M. Oden, N. J. Halas, Compact solar autoclave based on steam generation using broadband light-harvesting nanoparticles, PNAS 110 (2013) 11677–11681.

[3] H. Jin, G. Lin, L. Bai, A. Zeiny, D. Wen, Steam generation in a nanoparticle-based solar receiver, Nano Energy 28 (2016) 397–406.

[4] G. Ni, N. Miljkovic, H. Ghasemi, X. Huang, S. V. Boriskina, C.-T. Lin, J. Wang, Y. Xu, M. M. Rahman, T. J. Zhang, G. Chen, Volumetric solar heating of nanofluids for direct vapor generation, Nano Energy 17 (2015) 290–301.

[5] Y. Fu, T. Mei, G. Wang, A. Guo, G. Dai, S. Wang, J. Wang, J. L, X. Wang, Investigation on enhancing effects of Au nanoparticles on solar steam generation in graphene oxide nanofluids, Applied Thermal Engineering 114 (2017) 961–968.