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Technical Note

# Enhancement of nucleate boiling heat transfer using carbon nanotubes

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**Abstract**

The effect of carbon nanotubes (CNTs) on nucleate boiling heat transfer in R22 and water is investigated with the addition of 1.0 vol% of CNTs. Test results showed that CNTs increase boiling heat transfer coefficients of these fluids. Especially, large enhancement up to 28.7% was observed at low heat fluxes of less than 30 $kW/m^2$. With increasing heat flux, however, the enhancement was suppressed due to vigorous bubble generation. Fouling on the surface was not observed during this study. Optimum quantity and type of CNTs and their dispersion should be examined for their commercialization in power plants and refrigeration equipment.


*Keywords:* Nucleate pool boiling heat transfer; Heat transfer enhancement; Nanofluids; Carbon nanotubes (CNTs)

## 1. Introduction

Recently, environmental protection and energy conservation have become important issues due to greenhouse warming caused mainly by the use of fossil fuels. One of the fundamental ways of reducing greenhouse warming is to increase the efficiency of energy conversion devices. In order to accomplish this goal, heat exchanger performance needs to be improved in power plants and refrigeration and air-conditioning equipment.

Boiling heat transfer has been employed in many thermal energy dissipation systems due to its high heat removal capacity. For the past few decades, many studies were carried out to further increase the boiling heat transfer coefficients (HTCs) and some successful passive type enhanced surfaces such as low fin tube, Thermo-Excel-E tube, Turbo-B tube, Turbo-C tube have been applied to many heat exchangers [1]. Development of this kind of passive technique relying upon the surface geometry, however, is almost at the point of saturation and at this time active heat transfer enhancement technique needs to be developed to overcome the present environmental problem.

One of the active ways of enhancing heat transfer is to use so called 'nanoparticles' which have been developed for the past 10 years [2,3]. For this purpose, various nanofluids based on mainly copper and aluminum nanoparticles were developed. Theoretically, these particles with high thermal conductivity should improve the heat transfer near the laminar sublayer. Even though many nanoparticles were applied to the single phase heat transfer of water, actual heat transfer improvement was not yet reported. Furthermore, when these particles were applied to the boiling heat transfer, they even caused an accumulation of undesirable deposits, usually called fouling, on heat transfer surface and consequently HTCs were decreased [4–6].

In this study, carbon nanotubes (CNTs) were applied instead of conventional nanoparticles to the boiling of R22 and water to examine their effect for power generation and refrigeration and air-conditioning applications. Over the past decade, CNTs with a honeycomb carbon structure have attracted much attention due to their remarkable mechanical and electrical properties [7,8]. In fact, they are known to have very high thermal conductivity [7,8] and hence it is expected that liquids containing CNTs would increase the heat transfer near the laminar sublayer. In turn, this will result in overall heat transfer improvement. The objective of this study is to examine the effect

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of CNTs on overall heat transfer performance in nucleate boiling that occurs at the boilers and evaporators of power plants and refrigeration and air-conditioning equipment. In nucleate boiling, vapor is generated by nucleation of bubbles at the surface.

## 2. Experiments

### 2.1. Experimental apparatus

In this work, nucleate boiling HTCs of R22 and water were measured on a 152.0 mm long plain tube of outside diameter of 19.0 mm using the same experimental apparatus with the same tube specimen described in Ref. [9]. Fig. 1 shows a schematic diagram of the experimental apparatus for nucleate boiling heat transfer. The apparatus was composed of a test vessel and a refrigerant circulating loop. The test vessel was made of a stainless steel pipe of 102.0 mm inside diameter and 230.0 mm length. In order to observe the boiling phenomenon, a sight glass was installed in the front section of the vessel. The vapor boiled off from the heat transfer tube went into the condenser and was condensed there and the liquid was fed to the bottom of the test tube by gravity. An external chiller with an accurate temperature controller was used to condense the vapor and at the same time to maintain the pool temperature to set a temperature. The entire vessel was insulated thoroughly with polyurethane insulation to prevent possible heat transfer from the surroundings.

A cartridge heater was used to generate uniform heat flux on the tube. Data were taken in the order of decreasing heat flux from 80 kW/m$^2$ to 10 kW/m$^2$ with an interval of 10 kW/m$^2$ in the pool temperature at 7 °C and 100 °C for R22 and water, respectively. Since Ref. [9] contains all the details of the test apparatus, tube specimen and its manufacture, measurements, experimental procedure, data reduction scheme, fouling effect, repeatability of data, data verification, etc. they will not be presented again here. An interested reader is referred to Ref. [9] for the details. In this work, only the measurement error will be reported, which was estimated by the method suggested by Kline and McClintock [10]. In general, the measurement error was less than 8% at all heat fluxes. The repeatability of the experiment was always within 5% which was within the measurement error.

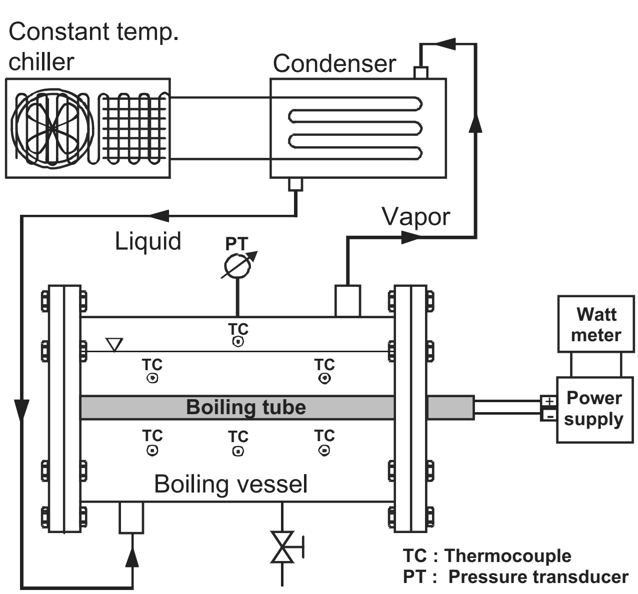


Fig. 1. Schematic diagram of the test facility.

### 2.2. Application of CNTs

In this study, multiwalled CNTs were mixed with two working fluids. The average diameter and length were 20 nm and 1μm respectively. There has been no report on the boiling heat transfer with CNTs and hence optimum amount of CNTs was not known apriori. Therefore, 1.0 vol% of CNTs was added to the working fluids as a first trial. Good dispersion of CNTs in the working fluids would be important. In this study, however, no special dispersion method was applied and CNTs were merely added to see their macroscopic effect on nucleate boiling heat transfer.

## 3. Results and discussion

### 3.1. Confirmation of test result with well-known correlations

Fig. 2 shows the comparison of the measured data of R22 with Stephan and Abdelsalam [11], Cooper [12] and Jung et al.'s [9] nucleate boiling heat transfer coefficient prediction correlations. One can easily see that R22 data agree with the well-known correlations showing a deviation of less than 20%. Recently, Jung et al. [9] measured nucleate boiling heat transfer data of 8 halocarbon refrigerants and made a specific correlation for halocarbon refrigerants based upon those data. As seen in Fig. 2, their correlation

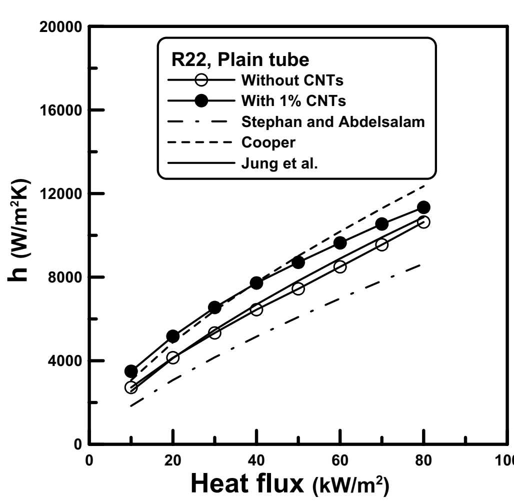


Fig. 2. Nucleate boiling heat transfer coefficients with 1.0 vol% CNTs for R22.

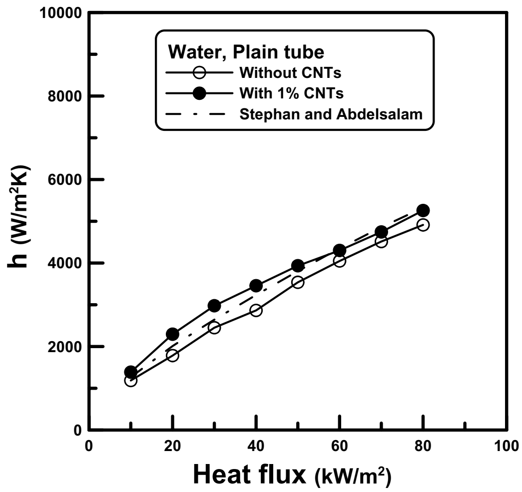


Fig. 3. Nucleate boiling heat transfer coefficients with 1.0 vol% CNTs for water.

agreed best with R22. Fig. 3 shows that measured data for water agree well with Stephan and Abdelsalam's correlation [11] showing 9% deviation. This comparison indirectly confirms the validity of the test data.

### 3.2. Effect of CNTs on horizontal plain tube

Figs. 2 and 3 show the HTCs of R22 and water with and without CNTs and Table 1 lists the heat transfer enhancement with CNTs at heat fluxes of 20 and 60 kW/m$^2$. Test results show that nucleate boiling HTCs of these two fluids were increased with the addition of CNTs. Especially, nucleate boiling heat transfer was enhanced up to 28.7% at low heat flux. As the heat flux increased, however, the heat transfer enhancement with CNTs decreased. Especially, this reduction in heat transfer enhancement was noticeable with water. At 80 kW/m$^2$, the heat transfer enhancement of water was only 6.3%.

From this observation, it may be tentatively concluded that CNTs enhance boiling heat transfer greatly at low heat fluxes. For this situation, the bubble generation is not vigorous at the surface and CNTs with high thermal conductivity can penetrate into the bubble zone near the surface and touch the surface (or thermal boundary layer) to instantly generate more bubbles. As the heat flux increases, however, more bubbles are generated and the chance of penetration and touching the thermal boundary layer by CNTs becomes low. This was seen visually in an open glass flask containing low vapor pressure refrigerant of R123 which was heated at the bottom by an alcohol burner. At low heat flux, addition of CNTs induces explosion of bubbles on the glass surface. As the heat flux increased, the explosion of bubbles by adding CNTs was reduced significantly. Based on this observation, it is expected that large boiling heat transfer enhancement is expected with the addition of CNTs in the boilers (or evaporators) of refrigeration system in which normal heat flux range is 10–30 kW/m$^2$. For power plants, however, adding CNTs may not result in a large improvement because the normal heat flux encountered in steam generators is very high. For R22, the average heat transfer enhancement at all heat fluxes was 20% while for water that was 15%.

In 2003, You and Kim [13] showed that water with $Al_2O_3$ nanoparticles can increase the critical heat flux by 200%. Measurements could not be taken at or near critical heat flux with the present experimental apparatus and hence their finding could not be verified in this study. But present nucleate boiling heat transfer data indicate that CNTs would act as good agitators at or near critical heat flux where bubble generation is suppressed. This characteristic may be useful for the safety enhancement in nucleate power plants.

Unlike conventional nanoparticles, CNTs did not cause fouling on the heat transfer surface. Same measurements were carried out a few times to see the fouling effect over a period of 3 weeks and the results varied little and little contamination was seen on the surface. Conventional nanoparticles have the affinity to the metal surface but CNTs did not show this kind of behavior. For further confirmation, however, a long term study needs to be carried out.

Finally, it is expected that there are optimum type and amount of CNTs for various working fluids. In the present study, 0.5 vol% of CNTs was also added for these working fluids and no change in the results was observed. In the long run, more studies are needed to obtain optimum type and amount of CNTs for boiling heat transfer enhancement of various fluids. Furthermore, dispersion of CNTs in working fluids needs to be studied in conjunction with boiling heat transfer. Finally, the effect of CNTs on enhanced heat transfer tubes needs to be examined since most of the commercial heat exchangers employ many enhanced tubes of various surface geometries.

Table 1
Enhancement in heat transfer coefficients with the use of CNTs for various fluids

| Fluids | $T_{sat}$ (°C) | $P_{sat}$ (kPa) | Heat flux (kW/m$^2$) | HTCs without CNTs (W/m$^2$ °C) | HTCs with 1% CNTs (W/m$^2$ °C) | Enhancement (%) |
|---|---|---|---|---|---|---|
| R22 | 7 | 621.5 | 20 | 4145 | 5169 | 24.7 |
| | | | 60 | 8494 | 9639 | 13.5 |
| Water | 100 | 101.3 | 20 | 1784 | 2296 | 28.7 |
| | | | 60 | 4049 | 4302 | 6.3 |

## 4. Conclusions

In this study, nucleate boiling heat transfer coefficients of R22 and water were measured with and without 1.0 vol% of carbon nanotubes. From the test results, following conclusions are drawn.

(1) For these fluids, addition of CNTs resulted in heat transfer enhancement. Especially at low heat flux the enhancement was up to 28.7%. As the heat flux

increased, however, the enhancement decreased due to vigorous bubble generation. Penetration into the thermal boundary layer by CNTs to generate more bubbles at the surface seems to be the key element in the improvement of nucleate boiling heat transfer associated with the use of CNTs.

(2) Unlike conventional nanoparticles, no fouling was observed on the surface with CNTs. For commercial use, however, a long term fouling study is needed.

(3) A further study is needed to determine optimum type and amount of CNTs for boiling heat transfer of various working fluids.

## Acknowledgement

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## References

[1] R.L. Webb, Principles of Enhanced Heat Transfer, John Wiley & Sons, New York, 1994, pp. 293–294.

[2] J.A. Eastman, U.S. Choi, S. Li, L.J. Thompson, S. Lee, Enhanced thermal conductivity through the development of nano-fluids, Proceedings of the Symposium on Nanophase and Nanocomposite Materials II, vol. 457, Materials Research Society, Boston, 1997, pp. 3–11.

[3] S. Lee, U.S. Choi, S. Li, J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, ASME J. Heat Transfer 12 (1999) 280–289.

[4] S.K. Das, N. Putra, W. Roetzel, Pool boiling characteristics of nanofluids, Int. J. Heat Mass Transfer 46 (2003) 851–862.

[5] P.V. Vassallo, R. Kumar, S. D'Amico, Pool boiling heat transfer experiments in silica-water nanofluids, Int. J. Heat Mass Transfer 47 (2004) 407–411.

[6] I.C. Bang, S.H. Chang, Boiling heat transfer performance and phenomena of $Al_2O_3$-water nanofluids from a plain surface in a pool, Int. J. Heat Mass Transfer 48 (2005) 2407–2419.

[7] P.M. Ajayan, Nanotubes from carbon, Chem. Rev. 99 (1999) 1787–1799.

[8] M.S. Dresselhaus, G. Dresselhaus, P. Avouris (Eds.), Carbon Nanotubes: Synthesis, Structure, Properties and Applications, vol. 80, Springer, New York, 2001.

[9] D. Jung, Y. Kim, Y. Ko, K. Song, Nucleate boiling heat transfer coefficients of pure halogenated refrigerants, Int. J. Refrig. 26 (2) (2003) 240–248.

[10] S.J. Kline, F.A. McClintock, Describing uncertainties in single-sample experiments, Mech. Eng. 75 (1953) 3–9.

[11] K. Stephan, M. Abdelsalam, Heat transfer correlations for natural convection boiling, Int. J. Heat Mass Transfer 23 (1980) 73–87.

[12] M.G. Cooper, Correlations for nucleate boiling formulation using reduced properties, Physicochem. Hydrodyn. 3 (2) (1982) 89–111.

[13] S.M. You, J.H. Kim, Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer, Appl. Phys. Lett. 83 (2003) 3374–3376.