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# Experimental investigation on nanofluid flow boiling heat transfer in a vertical tube under different pressure conditions

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ABSTRACT

In this study, the saturated flow boiling heat transfer of $\gamma$-$Al_2O_3/H_2O$ nanofluids with 20 nm diameter and 0.1%, 0.5% volume concentration in a vertical tube is experimentally carried out. An ultrasonic oscillation was used to prepare nanofluid. The influences of such important parameters as surface heat flux (50–300 kW m$^{-2}$), pressure (0.2–0.8 MPa) and mass flux (350–1100 kg m$^{-2}$ s$^{-1}$) on boiling characteristics are taken into consideration. It is confirmed that the most enhancement is about 86% for $\gamma$-$Al_2O_3/H_2O$ nanofluids saturated flow boiling heat transfer compared with deionized water, and the average value of Nusselt number was enhanced 23% and 45% respectively for 0.1 vol.% and 0.5 vol.% in this study. And the Nusselt number of nanofluid flow boiling increases with increasing the surface heat flux, the volume concentration of nanoparticle and pressure. It is confirmed that nanoparticles deposited on the heating surface by SEM observation and nanoparticles do not change obviously after boiling by TEM observations, they are attribute to the continuous operation of ultrasonic oscillation. In addition, the influence of mass flux on the enhancement rate of nanofluid saturated flow boiling heat transfer is negligible. Furthermore, a dimensionless parameter was proposed for nanofluid saturated flow boiling heat transfer data processing.



## 1. Introduction

The researches of nanofluid preparation, physical properties and stability [1–5] and its wide application prospects as nuclear power system, solar collector and spray cooling [6–9] flourishes since nanofluid was proposed in 1995 by Choi, due to the nanofluid's excellent heat transfer capacity. Thus, the convective and pool boiling heat transfers of nanofluid were developed rapidly [10–16].

However, different scholars have different opinions on whether nanofluid boiling heat transfer is enhanced or not. Bang and Chang [17] had been convinced that nanoparticle deposited on the heating surface and the number of nuclear boiling site was decreased, thus, the heat transfer capacity of nanofluid boiling was decreased. On the contrary, Taylor and Phelan [18] proposed the boiling incipience of nanofluid is 2–3 K smaller than pure water. In addition, the enhancement of nanofluid heat transfer is about 25–40%. In the application, flow boiling is more familiar, and the relevant research has been increased in the past few years. Kim et al. [19] experimentally investigated the flow boiling heat transfer of $Al_2O_3/H_2O$ nanofluid (0.01 vol.%), and the results shows the CHF (Critical Heat Flux) of nanofluid is increased about 30%. After that, they presented the coefficient of flow boiling heat transfer for nanofluid increased with the heat flux and mass flow rate under atmospheric pressure [20]. Thereafter, more and more nanofluid flow boiling characteristics had been experimentally or numerically investigated. Coursey and Kim [21] studied $Al_2O_3$/ethanol heat transfer of nanofluid flow boiling, and they confirmed that nanoparticle degrades or has no effect on flow boiling. Peng et al. [22] experimentally investigated the flow boiling heat transfer of Cu/R113 nanofluid in a horizontal tube of 8.12 mm inner diameter under the pressure of 78.25 kPa. The results presented that the nanofluid flow boiling heat transfer is improved mostly 29.7% with 0.00–0.05 wt.% nanoparticle concentration. Akhavan-Behabadi et al. [23] experimentally investigated CuO/R-600a-Polyester nanofluid flow boiling heat transfer inside a horizontal smooth tube with mass flow rate of 50–400 kg s$^{-1}$, heat flux of 3–8 kW m$^{-2}$ and nanoparticle concentration of 0–1.5 wt.%. The results showed that the maximum heat transfer enhancement is about 63% compared with based fluid. Sarafraz and Hormozi [24] studied $CuO/H_2O$ forced convective and subcooled flow boiling heat transfer using experimental method with mass flux of 35–1059 kg m$^{-2}$ s$^{-1}$. The results showed that heat transfer

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**Nomenclature**

| | |
|---|---|
| $Bo$ | boiling number |
| $c_p$ | specific heat at constant pressure (kJ kg$^{-1}$ K$^{-1}$) |
| $d$ | diameter of nanoparticle (m) |
| $D$ | diameter of test section (m) |
| $h$ | heat transfer coefficient (W m$^{-1}$ K$^{-1}$) |
| $h_{fg}$ | latent heat (J kg$^{-1}$) |
| $k$ | thermal conductivity (W m$^{-1}$ k$^{-1}$) |
| $k_B$ | Boltzmann constant |
| $l$ | length of test section |
| $M$ | relative molecular weight |
| $N$ | Avogadro constant |
| $Pr$ | Prandtl number |
| $q$ | heat flux (W m$^{-2}$) |
| $Q$ | heat (W) |
| $r$ | radius of test section (m) |
| $R$ | deviation |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density (kg m$^{-3}$) |
| $\mu$ | dynamic viscosity (kg m$^{-1}$ s$^{-1}$) |
| $\Phi$ | heat of unit volume of test section (W m$^{-3}$) |
| $\eta$ | thermal efficiency |
| $\varphi$ | nanofluid volume concentration (%) |
| $\upsilon$ | kinematic viscosity (m$^2$ s$^{-1}$) |

*Superscripts*

| | |
|---|---|
| 0 | temperature of 293.15 K |
| $Bi$ | bubble interior |
| $dau$ | data acquisition uncertainty |
| $f$ | fluid |
| $f0$ | standard state of atmospheric pressure and 273.15 K in temperature |
| $fr$ | freezing point |
| $g$ | gas phase |
| $i$ | thermocouple number for |
| $in$ | inner |
| $l$ | liquid phase |
| $max$ | maximum value |
| $min$ | minimum value |
| $muu$ | measuring unit uncertainty |
| $nf$ | nanofluid |
| $out$ | outer |
| $p$ | particle |
| $s$ | stainless steel |
| $w$ | wall |

*Abbreviations*

| | |
|---|---|
| CHF | critical heat flux |
| SEM | scanning electron microscope |
| TEM | transmission electron microscope |

coefficient was increased with increasing heat flux and mass flux, and it was decreased with increasing nanoparticle concentration. In 2010, Boudouh et al. [25] researched the flow boiling heat transfer of $Cu/H_2O$ nanofluid (0.00056–0.0056 vol.% and 35 nm nanoparticle diameter) in a narrow vertical channel with 0.8 mm diameter. The results showed the local heat transfer coefficient in increased with increasing the concentration. Xu and Xu [26] studied $Al_2O_3/H_2O$ (0.2 wt.% concentration, 40 nm nanoparticle diameter) nanofluid flow boiling in a micro-channel (0.1 mm $\times$ 0.25 mm). The heat transfer was improved and they provided the bubble departure frequency is greater and the bubble contact angle is smaller in nanofluid. Recently, Sun and Yang [27] investigated the flow boiling of nano-refrigerants (Cu/R141b, Al/R141b, $Al_2O_3$/R141b, and CuO/R141b) in a horizontal channel with 10 mm inner diameter. They presented that the heat transfer of nano-refrigerants are increased with increasing mass fraction, quality and velocity.

Unfortunately, it is also deficient for the research of nanofluid on flow boiling heat transfer and application [28]. For nanofluid flow boiling, the pressure is an important impact factor. More works about nanofluid flow boiling should been done, especially the influence of pressures.

In present study, the flow boiling of $\Gamma$-$Al_2O_3/H_2O$ nanofluid in a vertical tube is experimentally studied under different pressure conditions, and such influence factors as heat flux, mass flux and nanoparticle volume concentration are considered. Furthermore, SEM (Scanning Electron Microscope) is used to observe nanoparticle deposition on the heating surface, and TEM (Transmission Electron Microscope) is used to observe nanoparticle shapes and sizes. It is confirmed that no obvious changing of nanoparticles has been found in the flow boiling process. A new dimensionless parameter is proposed for the flow boiling heat transfer of nanofluid, and this work lays a foundation for the correlation of nanofluid flow boiling heat transfer.

## 2. Experiment set up

### 2.1. Experimental system

So as to investigate nanofluid saturated flow boiling in a vertical tube, Fig. 1 shows the experimental system which has been designed and constructed. It is consisted of a vertical test section, a stainless steel shield pump, a nanofluid/water tank, heat regenerator, preheating section, condenser, and data acquisition system to measure and record the pressure, temperature, mass flow rate. Moreover, the system also includes an ultrasonic vibration unit which is used to prevent the nanoparticles from depositing in the tank, and a gas (nitrogen) loop which is used to stabilize and control the system pressure. The test section is a vertical stainless steel tube with the inner diameter of 6 mm, the outer diameter of 8 mm and the length of 1100 mm. A programmable DC power with 0.05% power uncertainty is used to electrically heat the test section in order to obtain the constant wall heat flux. Moreover, the preheating section is also electrically heated by a programmable DC power so that the inlet fluid temperature is controlled through adjusting its power. On the outer surface of test section, ten calibrated T-type thermocouples are arranged with a 10 mm interval between each other. The inlet and outlet fluid temperatures are measure by two K-type thermocouples. Thermal insulation materials are surrounded on the test section to minimize the heat loss and the thermal efficiency can reach over 98% in the convective heat transfer process near saturated flow boiling in this study. The pressure drop is measured by a differential pressure transducer with the working range of 0–200 kPa and the uncertainty of 0.25%. In the experimental process, the fluid temperature and wall temperature, are all automatically recorded by acquisition system per 10 min. When the changing rates of all the parameters mentioned above are less than 0.2%, the system can be confirmed to reach the steady state. The parameters of the test section and system are shown in Table 1.