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Nanofluids spray heat transfer enhancement

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ABSTRACT

Spray cooling experiments were carried out to study the effect of seven (7) different types of nanofluids on heat transfer enhancement. Three different concentrations of 0.04%, 0.07%, and 0.1% by volume of Ag, Al, Al_2O_3, Fe_3O_4, SiO_2, TiO_2 and multi-walled carbon nanotubes (MWCNTs) dispersed with deionized (DI) water were tested, and transient as well as steady spray boiling experiments were conducted over a copper flat plate heater 4 cm^2 in size with a 1 cm thickness. The spray was issued by a 270 μm full-cone nozzle with a spray height of 30 mm and a spray mass flux of 1.5×10^{-3} kg/cm^2 s. Both a transient cooling curve and steady boiling curve were obtained. The results revealed that the average heat transfer coefficient (HTC), as well as the associated critical heat flux (CHF), are significantly enhanced, and the enhancement ratio can be up to 1.7 (HTC) and 1.84 (CHF), respectively, corresponding to the DI water as the nanofluids' volume fraction increased from 0.04% to 0.1%.

1. Introduction

Spray cooling, either non-boiling or boiling, is a very powerful and effective means to remove heat from hot surfaces with a low surface superheat and low mass flux [1–4]. This occurs when liquid is forced through a small orifice/or nozzle into dispersed fine droplets on the surface [5]. The enhancement for a large heat removal comes from the higher convective heat transfer coefficient (HTC). It allows for phase changes in high temperatures and high heat flux applications, such as the cooling of electronic devices, nuclear power generation, cryogenics and steel making processes. A quite detailed review of spray cooling heat transfer was reported by Kim [2]. The HTC during spray cooling is governed not only by the temperature difference between the spray and the wall but by the characteristics of the spray itself, which include droplet size, liquid type, spray velocity, spray angle, spray height, and the target surface temperature/wettability. If the thermal property of the liquid changes, it results in a heat transfer enhancement (e.g. with nanoparticle additions).

Over the past few decades, nanofluids, which are most likely liquids containing suspensions of nanoparticles ($\leqslant$100 nm), have been reported and proven to have the potential to enhance heat transfer either in conduction due to their resultant higher thermal conductivity or in convection due to the inclination to break the hydrodynamic/thermal boundary layer especially for laminar convection, which makes them very attractive as the most effective heat transfer fluids in many applications. However, reported documents and open citations show that the possible mechanism and the thermal conductivity increase, leading to heat transfer enhancement with volume/mass fraction increase/or decrease of the nanofluids, are still controversial [6] and need further work/examination in detail.

There are many ways to enhance the heat transfer with nanofluids. Nanofluid liquid spray is one of them that has been studied for the effects that the mass concentration/or volume fraction of the nanoparticles have on the heat transfer coefficients (HTC) of the base fluids, DI water in most cases. In fact, the application of nanofluids in spray cooling for electronic devices is an emerging area of research [7]. Nanofluid spray cooling with boiling can cause a buildup of a thin porous layer of nanoparticles on the heater's surface, which may significantly improve the surface wettability and, consequently, result in a CHF increase; however, the layer may be responsible for a decrease in the boiling heat transfer coefficient as the nanoparticle volume/mass fraction increases due to the nanoparticle deposit on the heater's surface. Obviously, the related heat transfer mechanisms are not yet completely understood [8]. Further systematic experimental studies need to be conducted. Water has been the most commonly used working fluid with nanoparticles so far, due to its ease of use and great capability to suspend the most nanoparticles.

Phase change heat transfer during single drop impacts on a hot solid surface was explored using distilled water and TiO_2–water nanofluid. The Weber number (We) was in the range of 25–239, and it was found that TiO_2 nanofluids improved the boiling heat transfer at a low wall superheat as reported by Okawa et al. [9].

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Nomenclature

C_p	specific heat, kJ/kg K
CHF	critical heat flux, W/cm^2
d_j	spray nozzle diameter, μm
d_{32}	Sauter mean diameter, $\Sigma\, d_i^3/\Sigma\, d_i^2$, μm
H	spray height, mm
h	heat transfer coefficient, W/m^{2}K
$\bar{h}$	average heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
k_{cu}	thermal conductivity of the copper plate, W/m K
m	mass flux, kg/cm^{2}s
q''	heat flux, W/cm^2
Re	Reynolds number
x, y, z	coordinates, m
T	temperature, °C
T_j	spray exit temperature, °C
u_j	spray exit velocity, m/s
u_o	impact velocity, m/s
We	Weber number

Greek symbols

ρ	density of liquid, kg/m^3
σ	surface tension, N/m
μ	viscosity of liquid, N s/m^2
ϕ	volume fraction of nanoparticle
ΔP	pressure drop across the nozzle, Pa

Subscript

c	spray liquid layer
cu	copper
j	nozzle exit
w	target surface
o	impact
sat	saturation

However, at a high wall superheat, the opposite result occurs. Chun et al. [7] reported that a rapid quench cooling curve was obtained with nanofluids. Kwark et al. [10] reported that the deposition of Al_2O_3 nanoparticle film on the hot surface can increase the CHF as well as heat flux during nucleate boiling. Abu-Nada and Oztop [11] examined the heat transfer performance of Al_2O_3 nanofluids numerically and found an increase in the HTC as compared to pure DI water. Duursma et al. [12] found that the heat removal rate for an experimental study of nanofluid drops in spray cooling was not significantly different from that of its base fluid. Recently, Jackson et al. [13] have demonstrated that nanofluids produce a significantly higher HTC during instantaneous (~30 ms) droplet impingement than water and, moreover, the HTC increases as the surface wettability increases.

In the foregoing discussion, it was found that a firm conclusion regarding the effect of nanofluids on heat transfer enhancement has not yet been reached especially as to whether the increase in concentration of the nanofluid can cause an associated nucleate boiling heat transfer increase. A fundamental study to broaden our understanding of the underlying mechanism of the nanofluid heat transport phenomenon is essentially necessary. To this end, this study aims to explore and extensively study as well as to provide as useful a document as possible for seven (7) different types of nanofluids (Ag, Al, Al_2O_3, Fe_3O_4, SiO_2, TiO_2, MWCNT) on heat transfer enhancement with different volume fractions (0.04–0.1%). Both transient and steady-state cooling are experimentally investigated.

2. Preparation of nanofluid

In the study, Ag, Al, Al_2O_3, Fe_3O_4, SiO_2, TiO_2 and a multi-walled carbon nanotube, listed in Table 1, were supplied by Yong-Zhen Techno Material Co., Taiwan. Deionized (DI) water, with related property data listed in Table 2, was used as a base fluid. The nanofluids of different volume fractions were prepared by dispersing different quantities of the above-stated nanoparticles in DI water. The solution was sonicated continuously with an ultrasonic vibrator (D9NX-DC200H, DELTA NEW INSTRUMENT Co. Ltd.) for 24 h to ensure proper homogenization of nanoparticles to obtain a stable and uniform colloidal solution. Although there is a small increase in temperature while in the sonic bath during the solution preparation, we would keep it to reach the ambient temperature before it is used (i.e., 28 °C). There was no surfactant used in the experiment. Some evaporation of the nanofluid may have occurred due to the temperature rise during sonication. In order to avoid any significant loss of DI water, a glass cover was placed on the solution bath. Each of the nanofluids tested had volume fractions of 0.04%, 0.07% and 0.1%.

The properties of the nanofluids are presented in Table 3 and shown in Fig. 1(a)–(d). Generally, the properties, such as C_p, k, μ and ρ of the nanofluids under study, had a larger value than that of DI water except for the surface tension (σ), which was measured and correlated in a definite form (as shown in Fig. 2(a)) within ±20% uncertainty of the experimental data (see Fig. 2(b)). Due to instrument limitations, the nanofluids under study, except for Fe_3O_4 nanofluid (of magnetic nature), were first inspected and

Table 2
Working medium thermal properties (DI water at 28 °C and 1 atm).

Properties	Distilled water
Average molecular weight (kg/kg mole)	18.16
Critical temperature (°C)	374.2
Saturation temperature (°C)	99.9
Density of liquid (kg/m^3)	996
Heat of vaporization (kJ/kg)	2256.7
Thermal conductivity of liquid (W/m K)	0.616
Specific heat of liquid (kJ/kg K)	4.22
Thermal diffusivity of liquid (m^2/s)	1.440×10^{-7}
Surface tension of liquid (N/m)	0.07275
Viscosity (Ns/m^2)	8.9×10^{-4}

Table 1
Nanoparticles parameter (at 28 °C and 1 atm).

Nanoparticles	Ag	MCNT	TiO_2	SiO_2	Al	Al_2O_3	Fe_3O_4
Average dimension in water	10–50 (nm)	10–30 (nm) in diameter 10–15 (μm) in length	10–30 (nm)	10–25 (nm)	10–50 (nm)	5–30 (nm)	10–20 (nm)
Surface ratio (m^2/g)	80–105	200–300	55–85	230–280	40–65	108–112	160–170
Density (kg/m^3)	140	350	130	70	230	75	5080
Specific heat capacity (kJ/kg K)	0.235	0.45	0.7	0.91	0.89	0.5	3.85
Thermal conductivity (W/m K)	429	235	13	1.4	204	39	90