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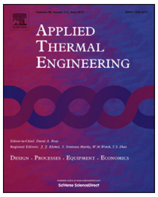

Effects of titania nanoparticles on heat transfer performance of spray cooling with full cone nozzle

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ABSTRACT

Spray cooling using aqueous titania nanofluids was studied. The temperatures of a testing plate under various spraying conditions were first measured; an inverse heat conduction technique was then applied to convert these measured temperatures into heat transfer coefficients (HTCs). It was found that the HTC increased logarithmically with the volume flux, but was decreased with the increase of the nanoparticle fraction. A correlation analysis was performed to quantify the HTC reduction caused by the increase of nanoparticles, and reconfirmed that the major cause for the HTC reduction was the difference in the impact (or impingement) behavior between solid nanoparticles and fluid droplets. A comparison study of the present findings with the previous published results was also performed and indicated that all results compared were consistent to each other based on the similar spray cooling conditions with different nanofluids or nozzles. The effects by using aquatic titania nanofluids instead of aquatic alumina nanofluids and by using full-cone nozzle instead of solid jet nozzle were specifically assessed and the associated rationales for the differences in these effects were given.

1. Introduction

Spray cooling has been used to remove heat from hot surfaces for many applications, from cooling space systems [1] to nuclear reactor cooling [2], from coal gasification cooling [3] to fire suppression [4], from metal quenching [5] to cooling electronic systems [6,7], and from continuous casting cooling [8,9] to steel roll-strip cooling [10,11]. This type of cooling can be very effective and simple, because the momentum of the liquid coolant under high spray pressure can allow the liquid to get much closer to the hot surface than it would be in pool boiling, in which the heated surface is immersed in the water, creating a thinner vapor film that greatly reduces the heat transfer rates.

Recently, the technology of spray cooling has been further developed by using aquatic based nanofluids instead of pure liquid. Nanofluids are fluids containing particles with the size less than 100 nm. As compared with the base fluid, these nanoparticles, such as metal or oxide, possess much higher conductivities and are expected to enhance the thermal properties, including higher thermal conductivity and heat transfer coefficient (HTC), of the nanofluids. A tremendous number of publications on nanofluids have been published. Among then, a substantial number of experimental studies indeed indicate that, by adding high-conductivity nanoparticles, the HTCs can be enhanced as compared with that using only the base fluid in a wide range of heat transfer problems [12,13]. On the other hand, a moderate number of studies report that the suspended nanoparticles can deteriorate the heat transfer performance of the nanofluids. Pak and Cho [14] studied heat convection of water based TiO_2 nanofluids moving in a circular pipe and found that the HTC of the nanofluid with a particle concentration of 3 vol% was 12% smaller than that of pure water. In studying the natural convection of aqueous nanofluids between two horizontal aluminum disks, Wen and Ding [15] found that the HTC could decrease more than 50% as the wt% of TiO_2 nanoparticles increased from 0 to 2.5%. By numerically evaluating the effect of water-based nanofluids on a square microchannel heat exchanger, Mohammed et al. [16] found that, with an increase in the fraction of titania nanoparticles, the overall heat transfer rate decreased. In addition to titania–water nanofluids, the degradation in HTCs could also be found in nanofluids with suspensions of Al_2O_3, CuO, and diamond nanoparticles [12,17].

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This inconsistency or anomaly in the heat transfer performance by nanofluids can also be found in the problems of spray cooling. Bansal and Pyrtle [18] experimentally studied the effects of the alumina nanoparticles on the heat fluxes for spray cooling of metal blocks and observed that the heat transfer enhancement using water/alumina nanofluid could reverse from positive to negative dependent on the target surface temperatures. They also reported that no noticeable difference of the heat transfer performance of the nanofluids by varying the nanoparticle fraction from 0.25 to 0.50 wt%. Duursma et al. [19] applied a needle type of nozzles to experimentally investigate the spray cooling of a hot metal surface using ethanol and DMSO (dimethyl sulfoxide) based Al nanofluids and found that the heat fluxes of nanofluid spraying were deteriorated for ethanol-based solutions but somewhat enhanced for DMSO nanofluids as comparing with their respective base-fluid counterparts. Recently, Bellerová et al. [20,21] studied spray cooling using aquatic-alumina nanofluids and found that the HTC of the nanofluid cooling decreased as the nanoparticle volume fraction (φ_v) increased. Dependent on the type of nozzles used for spray cooling, they observed a 20%–40% reduction of HTC by increasing φ_v from 0 to 16.45% [20,21].

Several attempts have been made to provide the theoretical bases for the thermal deterioration behaviors of nanofluids, but most of them, at the best, have been appropriate only for a special case or condition and nothing proposed so far has been generally acceptable [20–25]. For example, by using aquatic alumina nanofluids for spray cooling, Bellerová et al. [21] analytically illustrated and experimentally demonstrated that the difference in the impact (or impingement) behavior between a solid particle and a fluid droplet was the major cause for the thermal deterioration in spray cooling. Yang et al. [22] theoretically investigated the heat transfer performance of aquatic-titania nanofluids in a fully-developed channel flow subjected to constant heat-flux and found that whether the heat transfer enhancement being positive or negative was dependent on the ratio of the Brownian diffusivity to the thermophoretical diffusivity (N_{BT}). They numerically illustrated that, at zero Brownian diffusivity or $N_{BT} = 0$, the enhancement was negative and had lowest HTC and, by increasing N_{BT}, the enhancement became positive. At N_{BT} near 0.5, the positive enhancement reached its maximum. However, by studying the same channel flow with aquatic-alumina nanofluids, they found that there was no negative enhancement, even at $N_{BT} = 0$ [22]. No discussion was given by Yang et al. for the reason to have no negative enhancement by using aquatic-alumina nanofluids. Utomo et al. [25] discovered that the degree of enhancement in titania–water nanofluids was somewhat much larger or stronger than that of alumina–water nanofluids at the same mass flow rate for the similar problem considered by Yang et al. [22]. Indeed, both of these two groups [22,25] believed that the heat transfer performance could be highly dependent on the type of the nanofluid used.

Consequently, since the spray cooling experiments conducted by Bellerová et al. [20,21] are limited to aquatic alumina nanofluids, in the present study, the effect of a different type of nanofluids, i.e., TiO_2–water, used in spray cooling would be assessed and the anomaly previous found in the spray cooling performance, i.e., the cooling HTC decreases as φ_v increases, is to be re-examined. The approaches adopted are similar to those used by Bellerová et al. A comparison study is also conducted to examine the differences between the present results and those previous reported. The uniqueness in conducting the present study would be specifically discussed. A correlation between the HTCs and several spray parameters would then be developed to quantify the effects of using different nanofluids or different nozzles. Finally, recommendations for future research and development in the area of nanofluid spray cooling are provided.

Table 1
Thermofluid properties of water and titania.

Property	H_2O at 50 °C	TiO_2 at 50 °C	References
Density, ρ [kg/m^3]	992	4069	26
Conductivity, k [W/m K]	0.663	8.05	27
Specific heat, c [J/kg K]	4175	713	30,31
Viscosity, μ [Pa s]	6.58×10^{-4}	–	26

2. Experiment

An axisymmetric thermal probe developed was built to perform the experiment in the present study. The probe consisted of a test plate, a nozzle connected to a pressure-regulated flow tank, and a PC-based data acquisition system. The test plate was made of stainless steel with a cooling surface of 20-mm in diameter and a K-type thermocouple was embedded 0.37-mm underneath the cooling surface. The surface was the spray cooling area and the measured cooling curve by the probe was used as an input to an IHC (inverse heat conduction) model to inversely calculate the associated HTC of the spray cooling. The full-cone nozzle, Lechler Model 460.443CA, evaluated by Bellerova et al. [21] was selected for the present study. The nozzle had a bore diameter of 1.2 mm with a 45°-spray angle (θ_s).

2.1. *Titania/water nanofluids*

A TiO_2/water nanofluid, called Aerodisp® W 740X, produced by Evonik Industries, was selected. The Aerodisp® nanofluid contained 40 wt% TiO_2 nanoparticles and was very stable by adding a tiny amount of citric acid to neutralize the nanofluid. The mean diameter of the titania particles was 82 nm. In experiment, the 40-wt% TiO_2/water nanofluid was diluted with the base fluid, deionized water, to two lower wt%. To ensure proper homogenization of the nanoparticles and to obtain a stable and uniform colloidal solution, the nanofluids were ultrasonically mixed for 24 h.

The nanoparticle contents in the nanofluids studied were 0, 1, 10, and 40 wt%; the corresponding volume fractions, φ_v, could be calculated to be 0.0, 2.47×10^{-3}, 2.65×10^{-2}, and 1.405×10^{-1}, respectively, where the water density (ρ_f) at 20 °C used in the calculation was 998.2 kg/m^3 and TiO_2 nanoparticle density (ρ_s) at 20 °C was 4073 kg/m^3. The particle density was calculated based on the nanofluid density (ρ_{nf}) provided by the Evonik and agreed very well with data provided by a material data website [26].

By measuring the recycled nanofluid temperature after spraying, the mean temperature of the nanofluid during spray experiment was approximately 50 °C, which was used as the reference temperature for the determination of the physical properties of the nanofluids. The material properties of TiO_2 and water at 50 °C were summarized in Table 1. The k_s value adopted was based on the data reported by Maekawa et al. [27] at 50 °C, which was close to the value reported by Teja et al. [28], but approximately 30% lower than that used by Wang et al. [29]. In Table 1, the specific heat (c_s) of TiO_2 at 50 °C was reported by Mitsuhashi and Watanabe [30] and was about 0.1% higher than that of 25 °C found in a web-based reference [31].

2.2. *Testing procedures*

In testing, the test plate was heated to 200 °C by an electrical furnace and was held at that temperature for 15 min to achieve a uniform temperature distribution in the plate. The heated test plate was then loaded horizontally on the top of an airtight