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Heat transfer enhancement using air-atomized spray cooling with water–Al_2O_3 nanofluid

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ABSTRACT

The study deals with the air-atomized spray cooling using nanofluid as the cooling media for high heat flux applications. The nanofluid has been prepared by commercial Al_2O_3 particles of diameter less than 13 nm and water. Heat transfer study has been carried out on a pre-heated steel specimen of dimensions 100 mm × 100 mm × 6 mm. The initial temperature of the plate which was subjected to air-atomized spray cooling was over 900 °C. Various coolants consisting of 0.1% volumetric concentration of water–Al_2O_3 mixture, with or without a dispersing agent (surfactant) were used for the study. The dispersing agents used are sodium dodecyl sulphate (SDS) and polyoxyethylene (20) sorbitan monolaurate (Tween 20). Inverse heat conduction software INTEMP has been used for estimating the surface heat flux and temperatures taking into account the measured internal temperature histories by the thermocouples during the cooling process. The results obtained using nanofluid coolants are compared with that of the results where pure water (filtered potable water) is used as a coolant. The analyses reveal that the cooling rate, critical heat flux and heat transfer coefficients are significantly enhanced when nanofluids are used as coolants in air-atomized spray process. Also, the nanofluid coolants with dispersing agent shows a better enhancement of heat transfer over that of the nanofluid without the dispersing media. The nanofluid with dispersing agent Tween 20 is found more effective than that of its counterpart. Overall, the percentage enhancement in cooling rate of all these nanofluids compared with pure water (filtered potable water) is 10.2% for water–Al_2O_3, 18.6% for water–Al_2O_3–SDS, and upto 32.3% for water–Al_2O_3–Tween 20.

1. Introduction

Spray cooling plays crucial role in many industries including nuclear reactors, electronic chips, coal gasification, fire suppression, heat treatment of steel plates in the run-out table, etc. The ability of high momentum liquid sprays to extract high heat flux at controlled rates from the metals parts operated above 600 °C has made them invaluable in these applications. As the temperature of the metal parts is above Leidenfrost point [1], heat transfer occurs through boiling of spray droplets which can be called spray evaporative cooling [2]. On the basis of the evaporation period of the droplet on the hot surface, different boiling regimes namely film boiling, transition boiling, nucleate boiling and single-phase forced convection occur sequentially during cooling.

In recent years, steel of high strength is an essential component in many industrial applications. In steel processing industries, the steel of high strength properties are generally achieved during cooling of steel strips in the run-out table (ROT) [3]. Here, the cooling rate plays an important role in the thermo-metallurgical phase transformations which eventually govern the final mechanical properties of the steel. The major temperature ranges of cooling intensity which are important for phase transformations in steels are 900 °C–600 °C and 900 °C–200 °C [4,5]. Upon applying a faster cooling intensity, in the former temperature range, steel of dual phase microstructure (ferrite–pearlite, pearlite–martensite, martensite–austinite, etc.) can be found which exhibits high tensile strength and the later temperature range gives a fully martensite phase microstructure which provides ultra high strength in steels.

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Since the plate temperature is high above 900 °C during cooling, the heat transfer rate is affected by different boiling regimes [6]. In the conventional spray methods, the hot plate is covered by the vapour film at the initial stage of cooling and as a consequence the heat transfer rate is drastically reduced [7,8].

The literature reveals that air-atomized spray has been a very promising cooling technique for high heat flux applications and moreover, in this methodology minimum vapour film affect has been observed. In air-atomized spray, which is used for fast cooling operation, fine atomized water is sprayed on the surface to be cooled. This atomization, in evaporative cooling, should be in such a way that the individual droplet on the heated surface will be completely evaporated and does not merge in a water film, as in the case of water spray cooling [9]. The main advantage of air-atomized spray cooling is that high volumetric flow of air sweeps the partially evaporated droplets from the surface [10,11]. Therefore, the water does not accumulate on the hot plate and the vapour film is not produced due to the water accumulation [12].

Recently, enhancing heat dissipation using nanofluids gained primary importance for thermal systems operated at high temperatures. Nanofluid is a two phase mixture where particles of size less than 100 nm are suspended in the base fluid leading to increased thermal conductivity because it is the key property to increase cooling characteristics of conventional fluids. A considerable research has been found in the literature to understand the heat transfer enhancement using different water based nanofluids; however most of these studies are limited to either pool boiling or cooling of low temperature substrates [13–19]. For example, Nguyen et al. [20] investigated the heat transfer potential of water–Al_2O_3 nanofluid for an electronic liquid cooling system. It has been found that addition of nanoparticles increases the heat transfer coefficient of water by 40%. It is also discovered that nanoparticles of size 36 nm shows more efficient heat transfer performance than that of particles of 47 nm. The enhancement of heat transfer coefficient of a low temperature plate by using water–Al_2O_3 nanofluid jet impingement has been studied by Yousefi et al. [17]. It has been observed that the alumina nanoparticles of lower fractions yield enhanced heat transfer and it decreases with increasing nanoparticles concentration. Vafaei and Borca-Tasciuc [21] reviewed the role of nanoparticle deposition on heat transfer enhancement of hot surfaces. It has been discovered that the suspended nanoparticles in base fluid modifies the heated surface characteristics upon impingement, active bubble nucleation site density, surface wettability and spreadability of coolant on the surface leading to higher boiling heat transfer performance.

It is worth noting that only few researches are available in the literature on enhancement of heat transfer rate of high temperature substrates using nanofluid as a coolant media. Chakraborty et al. [22] studied the surfactant water–TiO_2 nanofluid jet impingement cooling of a steel plate of temperature 900 °C. It is concluded that the cooling rate of steel plate increased significantly using nanofluid compared with that of water due to improved thermophysical properties of coolant. Moreover, the presence of surfactant along with nanofluid decreases the surface tension leading to higher surface wettability which affects the activation nucleation sites for higher heat transfer rates. Mitra et al. [23] reported that the cooling rate of steel plate of temperature above 900 °C is enhanced by application of water–TiO_2 and water–MWCNT nanofluid jets. It is found that the deposition of nanoparticles on the heated surface during cooling causes vapour layer instability which leads to quick shift from film boiling to transition boiling heat transfer regime. Barret et al. [24] applied the low concentration water-based alumina nanofluid coolants for improved thermal performance in nuclear fusion reactor. Recently, Tseng et al. [15] found the enhancement of spray cooling heat transfer of heated metal plate of temperature 200 °C using water–TiO_2 nanofluid coolants. It is observed that heat transfer rate of hot surface decreased with increase in nanoparticle concentration. Apart from the cooling enhancement by nanofluids, few studies report that the suspended nanoparticles reduce the cooling performance as compared to that of base fluid [25–27]. It is concluded that the deterioration of heat transfer rate is also due to existence of nanoparticle deposition layer on the heated surface. The deposited nanoparticles decrease the surface roughness of the heated plate if the size of the deposited nanoparticles is smaller than that of the size of cavities of the heated surface. Bellerova et al. [28,29] studied the spray cooling of 200 °C temperature substrate by solid jets using water–Al_2O_3 nanofluids and found that the nanofluids have poor heat transfer rate compared to that of water.

In summary, there are many discrepancies in the literature regarding the heat transfer potential of nanofluids as compared to that of the base fluid, water. However, most of these studies are limited to cooling of low temperature substrates. Considerable information on nanofluid jet impingement cooling of high temperature substrates is available, but efforts to understand the air-atomized nanofluid spray cooling process have been scarce. No study is available in the open literature on cooling of high temperature substrates (above 900 °C) using water–Al_2O_3 nanofluids. Therefore, the current study is aimed to understand the heat transfer performances of water–Al_2O_3 nanofluids with/without surfactant in air-atomized spray cooling of a stainless steel plate of initial temperature 900 °C.

2. Experimental facility

2.1. Materials used

The experimental conditions for air-atomized spray cooling are shown in Table 1. The nanoparticles employed are commercial grade Al_2O_3, procured from Sigma–Aldrich (India) having <13 nm primary particle size with 99.8% purity. The surface-active agents used are an anionic surfactant i.e., Sodium dodecyl sulphate (SDS) and a non-ionic surfactant i.e., Polyoxyethylene (20) sorbitan monolaurate (Tween 20), which are purchased from Merck (India). All these surfactants have >98% purity. The surfactant concentrations considered in the present study are also presented in Table 1. The reason behind the selection of a surfactant of specified concentration is that this has been optimized by the authors in their earlier work for enhanced heat transfer rates [30]. A 0.1 vol% of nanofluid, with or without the presence of surfactant has been used as the coolant. In preparation method, the commercial grade Al_2O_3 nanoparticles are dispersed in the base fluid (water) with a high shear mixer to produce a stable nanofluid. After 20 min of continuous stirring, the solution is being subjected to ultrasonication

Table 1
Experimental conditions.

Parameter/test substances	Value of parameters
Initial plate temperature	>900 °C
Spray cone angle	32°
Flow rate of air	30 m^3/h
Flow rate of liquid	16.67×10^{-5} m^3/s
Test liquid	Water/Al_2O_3
Volume fraction of Al_2O_3 nanoparticles (vol%)	0.1
Dispersing agents	
SDS	600 ppm
Tween 20	56 ppm
Coolant temperature	30 °C