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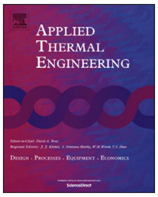

Research paper

Ultrafast cooling of a hot moving steel plate by using alumina nanofluid based air atomized spray impingement

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HIGHLIGHTS

- Enhancement of spray cooling heat transfer rate by alumina nanofluid is studied.
- Cooling experiments are conducted from a high initial plate temperature of >900 °C.
- Effect of surfactants on cooling capacity of alumina nanofluid is also investigated.
- A cooling rate of 230 °C/s is achieved for application in ROT of a hot strip mill.

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ABSTRACT

The objective of the present work is to examine the heat transfer aspect of alumina nanofluid based air atomized spray impingement on a hot moving steel plate with an initial temperature well above the Leidenfrost point. The influence of surfactants in increasing the effectiveness of nanofluid as a heat transfer media has also been investigated. The experimental study has been conducted with four different types of coolants namely water, water-alumina, water-alumina-SDS and water-alumina-tween20. The thermo-physical properties (viscosity and thermal conductivity) of the coolants have been measured as they affect the heat transfer rate. The heat transfer result indicates that enhanced cooling rates are obtained using nanofluids as compared to that of water.

1. Introduction

Research on the enhancement of heat transfer with the use of additives in water is finding wide interest in the recent years. Extensive work has been carried out by many researchers to produce high cooling efficiency by using additives like, surfactants [1–4], oil [5] and nanofluids [6–8]. The mechanisms of enhancing the heat transfer for different additives are different. The surfactant reduces the surface tension and as a result droplet spreads more on the cooled surface [3]. Due to this, the water evaporation rate increases and as a result the cooling rate enhances. The droplets of the nano-fluids evaporate and leave the nano-particle on the surface of the plate which are helpful in breaking the thin vapour layer thereby increasing the heat transfer rate [6].

The conventional additives in the coolant have a limited capability to extract heat from the hot surface because of their thermal and physical properties. Therefore, it is required to develop a new type of coolant which is having higher thermal efficiency. The nanofluids are one of those coolants which have high thermal conductivity due to the presence of metal particle. Trisaksri and Wongwises [9], Wang and Mujumdar [10] have reported that the thermal conductivity of the nanofluid is higher than that of the base fluid (water). Murshed et al. [11] experimentally investigated the change in thermal conductivity of water due to the dispersing TiO_2 nanoparticles in it and the findings reveal that the TiO_2 nanoparticle suspension enhances the thermal conductivity; also it depends on the particle size and shape. Wang et al. [12] studied the change in thermal conductivity of a fluid due to the addition of nanoparticles. In their study two types of nanoparticles (Al_2O_3 and CuO) and four types of base fluids (water, vacuum pump fluid, engine oil, and ethylene glycol) were used. They reported that the thermal conductivity of the base fluid is much lower than that of nanoparticle-fluid mixture.

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The mechanism for enhancing the heat transfer rate from a static hot surface, by using nano-fluids, has been reported by a few researchers. Mitra et al. [6] studied the heat transfer characteristics by using two types of nano-fluids, namely water-TiO_2 and water-multi walled carbon nano-tubes. The cooling experiments were conducted by laminar water jets and a definite enhancement in the cooling rate was observed with nanofluids as compared with pure water. It is also observed that, a quick shift from film boiling to transition boiling takes place due to the vapour film instability in presence of the nanoparticle in the working fluids. Liu and Qiu [7] studied the heat transfer characteristics of a cooling surface with the CuO nanoparticle suspension in the water jet and investigated the effects on nucleate boiling heat transfer and the critical heat flux due to nanoparticles. The finding summarised by Liu and Qiu is that the nucleate boiling heat transfer is reduced by means of nanofluid as compared to the base fluid and enhances the critical heat flux (CHF) due to the development of a very lean nanoparticle sorption film on the hot surface. Maiga et al. [8] studied the laminar forced convection heat transfer with two types of nanofluids, namely water–γAl_2O_3 and Ethylene Glycol–γAl_2O_3 mixtures, and found that on increasing the particle concentration the heat transfer coefficient (HTC) increases. Palm et al. [13] numerically investigated the usefulness of the metallic nanoparticle suspension in the coolant for heat transfer study. They found that, with the comparison of pure water, the nanofluid enhances the average heat transfer coefficients sufficiently. An experimental study has been made by Zeitoun and Ali [14] to investigate the heat transfer of a circular hot disk with alumina/water nanofluid jet. They used different concentrations of nanoparticle and observed that the Nusselt number increased with the increase in the nanoparticle concentration in the coolant. Huang and Jang [15] numerically investigated the heat transfer performance with alumina nanoparticle suspension in water by jet impingement. They found that on increasing the nanoparticle concentration the Nusselt number increases.

In the open literature, the heat transfer mechanisms by conventional cooling techniques (water jet and water spray) have been described by many researchers. In the authors' earlier work, the cooling of a hot static steel plate has been investigated by using air atomized spray impingement [16]. Despite these attempts, cooling of a hot moving steel plate constitutes quite a demanding task. Therefore, the present work deals with experimental studies on the cooling rate enhancement of a hot moving steel plate with an air atomized spray with different additives in water. The additives used for the preparation of different coolants are given in Table 1. The different types of coolants are water (W), mixtures of water/Al_2O_3 (WA), mixtures of water/Al_2O_3/SDS surfactant (WAS) and mixtures of water/Al_2O_3/Tween-20 surfactant (WAT). The nanofluid coolants have been prepared by adding two different types of dispersing agents namely ionic surfactant sodium dodecyl sufate (SDS) and non-ionic surfactant Tween-20. The surfactant reduces the surface tension; as a result spreadability of the droplet increases on the solid surface [17]. Since, in the present investigation, cooling experiment deals with air atomized spray impingement, therefore the coolant (primarily water) temperature never goes beyond the boiling point of water. As a result the surfactant molecules do not undergo thermal degradation and remain stable.

Table 1
Different additives used in the coolants.

Additives	IUPAC name	Molecular formula	Molar mass (g/mol)	Melting point (°C)
Alumina nanoparticle	Aluminium oxide	Al_2O_3	101.96	2072
SDS	Sodium lauryl sulphate	$NaC_{12}H_{25}SO_4$	288.37	206
Tween-20	Polyoxyethylene (20)	$C_{58}H_{114}O_{26}$	1227.54	

2. Experiment setup and nanofluid

2.1. Spray cooling apparatus

All the cooling experiments with nanofluids were carried out in a closed chamber as shown in Fig. 1. A laboratory scale experimental setup has been designed and fabricated for research and development. The moving bed setup is based on the crank and slider mechanism, where the movement of slider is reciprocating in nature. The slider contains the ceramic brick on which the hot steel plate has been kept for cooling purpose. The steel plate is moving with slider at a constant speed of 0.4 m/s. The movement of the slider is restricted to 0.1 m on either sides. The slider movement is controlled by a 3 HP motor.

Fig. 1 shows the schematic diagram of the experimental setup. For the experiments the atomized spray nozzle has been kept facing the top surface of steel plate and a fixed distance is maintained between the nozzle tip and the plate surface (60 mm). The rotameters are used to measure the water and air flow rate. For intrinsic supply of water and air, solenoid valves have been used which are placed behind the nozzle. A centrifugal pump of maximum capacity 1.39×10^{-3} m^3/s has been used for water supply, and for air supply a compressor has been used. A video camera (Sony, DCR-SX63) has been installed to record the cooling experiment and the subsurface transient temperature data has been recorded by data logger.

2.2. Preparation of nanofluids

The alumina nanoparticles have been slowly added to the water for preparing the nanofluids and stirred vigorously for 2 h to avoid the formation of agglomerates. After the preparation of final solution, a small volume of the solution has been taken to find the particle size distribution of the dispersed nanoparticle in the solution. The dynamic light scattering (Malvern Instruments Ltd., Zetasizer Nano, UK) has been used to analyze the nanofluid solution. Fig. 2 shows the particle size distribution of the alumina nanoparticles in the solution. It can be seen from the figure that the size of nanoparticles present in the solution lies between the range of 5–50 nm and a maximum percentage is found to be distributed around 10 nm.

For the cooling experiments three different kinds of coolants other than water have been prepared. The first kind of coolant is the mixture of pure water and alumina nanoparticle, in which the nanoparticles are uniformly dispersed in the water which is called alumina nanofluid. The second and third types of coolants are prepared by mixing two different kinds of surfactants (SDS and Tween-20) in the alumina nanofluids. The surfactants are mainly used for decreasing the surface tension of the fluids, such that the nozzle can produce smaller droplet and it is easy to evaporate. In the authors' earlier study of cooling experiments on the stationary steel plate, it can be seen that the surfactant added water gives the better cooling performance [3].

2.3. Properties of nanofluids

Four types of coolants have been used in the present investigation namely water (W), mixtures of water/Al_2O_3 (WA), water/Al_2O_3/SDS surfactant (WAS) and water/Al_2O_3/Tween20 surfactant (WAT). The concentration of alumina nanoparticles in all types of nanofluid is 100 ppm. The WAS mixture is prepared by the addition of SDS surfactant (concentration 600 ppm) in the alumina