# Abstract

Enhancement of heat removal from a hot surface is an important criterion in many industrial applications. The major applications include extraction of large heat fluxes from metal parts such as hot fuel bundle post-loss-of-coolant accident in nuclear fusion reactors, heat treatment of steel plates on the run-out table and high power electronic systems. In steel processing industries, in order to meet the severe requirements of market and reduce production costs of high quality steels, ultrafast cooling has gained primary importance. The wide range of multi-phase microstructures and advanced mechanical properties that can be obtained while cooling between 900 and 600 $^{o}$C temperature range emphasise the significance of ultrafast cooling technique. Ultrafast cooling is a newly developing heat treatment technique, in which the product of cooling rate ($^{o}$C/s) and plate thickness (mm) is preferably of the order greater than 800. Therefore, achieving a maximum cooling rate of greater than 134 $^{o}$C/s on a 6 mm thick plate has been categorized as ultrafast cooling and it is difficult to attain in a conventional cooling system due to the Leidenfrost effect at high initial surface temperatures. Nowadays, use of additives in base coolant is a technique applied to enhance the boiling heat transfer performance in pool, jet and spray cooling systems. The main idea of using additives is to enhance the spreading and the evaporation rate of impinged coolant on the solid surface by altering its thermo-physical properties. However, much of the state of art on this subject has been limited to either pool boiling or cooling of low temperature substrates.

Therefore, the basic objective of the current research is to contribute to the enhancement of cooling rates using different additive based cooling processes. The base coolant used for the study is pure water, in which, additive (surfactants, polymers, alcohols, and nanoparticles) has been mixed to prepare the coolant. To achieve the objective, transient cooling experiments have been conducted using two different cooling systems such as jet and air-atomized spray. The specimen used to perform the cooling experiments is an AISI 304 grade stainless steel plate of initial temperature greater than 900 $^{o}$C. In order to measure the transient temperature during cooling, K-type thermocouples have been inserted within holes that are precisely drilled at different locations parallel to the quench surface. A data acquisition system has been used to measure the thermocouple input signals with a rate of 10 samples/s during cooling. In order to estimate the heat flux and temperatures on the quench side of the plate, a commercial inverse heat conduction software “INTEMP” is used on the basis of the measured internal temperature data by the thermocouples. Before performing the cooling experiments, the physical properties of coolants have been measured to understand the heat transfer enhancement mechanism.

The first cooling process used in the current study is the different surfactant added water jet. The results depict that increase in cooling rate has been observed with increasing concentration of surfactants. Use of surfactant added water minimizes the surface tension and promotes wettability and spreadability characteristics of coolant at high surface temperatures and as a consequence high cooling rate (176 $^{o}$C/s) has been observed. Air-atomized spray cooling with different surfactant additives has been studied as second cooling process. Addition of surfactant decreases the surface tension resulting in minimization of splattered coolant from the surface. Also, the lowered surface tension causes in reduction of solid-liquid contact angle which leads to the improvement of surface wettability as well as spreading by expanding the impinged spray droplet width. The higher width of the droplet covers more area of contact which, in turn increases the rate of evaporation of droplets. Moreover, decrease in surface tension is certainly the dominant factor to intensify the boiling process as a consequence of vapour film wave length of instability. Therefore, the resulting heat transfer rate from the surface becomes faster and as a result maximum cooling rate of 214 $^{o}$C/s has been achieved. Further, for achieving better ultrafast cooling rate, air-atomized spray cooling study has been performed with ethanol (with or without presence of surfactant), mixed-surfactant systems, polymer, and Cu-water nanofluid additives. The presence of ethanol, with or without presence of a surfactant, decreases the surface tension and it also alters the bubble coalescence and droplet burst process. As a consequence a maximum cooling rate of 235 $^{o}$C/s has been obtained. The mixed-surfactant systems show the synergetic physical properties which leads to a maximum cooling rate of 240 $^{o}$C/s. Upon using polymer additive, a very low surface tension has been achieved, as a result a maximum cooling rate of 253 $^{o}$C/s has been attained. In the case of Cu-water nanofluid spray cooling, a cooling rate of 267 $^{o}$C/s has been obtained due to the deposition of nanoparticles leading to increase in surface roughness and number density of bubble nucleation sites. Overall, the cooling rates obtained in the current research for all the additive based cooling processes are found to be in the higher range of an ultrafast cooling process of an AISI 304 steel plate of 6 mm thickness. Furthermore, the study also covers the role of ultrafast cooling for creation of martensite phase microstructure and improved mechanical properties of different carbon steels. The tensile strength and the hardness of the final product after the ultrafast cooling process confirm the advanced high strength grade with martensite phase composition of 65 to 95 %.

Keywords: Air-atomized spray cooling; Boiling heat transfer; Ethanol; Heat transfer enhancement; Jet impingement cooling; Mixed-surfactant; Nanofluid; Polymer; Surfactant; Ultrafast cooling