# Abstract

The mini/microchannel can be found in the wide area of engineering applications due to its high heat removal density from small space and volume and hence the fluid flow and heat transfer in mini/microchannels have emerged as an important research area. The performance of the mini channel heat sink (MCHS) can be enhanced by using hybrid nanofluid due to its better thermophysical properties. To quantify the enhanced performance characteristics and to fulfill the research gaps, numerical and experimental investigations have been done on MCHS using various hybrid nanofluids and ribbed channels. Various types of nanoparticles have been used in this research, such as oxides ($Al_2O_3$, MgO, CuO, $TiO_2$), carbide (SiC), nitrite (AlN), carbon allotropes (MWCNT and Graphene), metals (Cu), nanocomposite (rGO-ZnO) and phase change material (capric acid). The hybrid nanofluids have been prepared with different combinations and compositions. Stability and homogeneity have been checked and required thermophysical have been measured.

An experimental facility of MCHS has been developed based on the requirement of research work. Different operating conditions as volume flow rate (0.1-0.5lpm), Reynolds number (50-600), inlet temperature (20-40$^{o}$C), volume concentration (0.01 and 0.1%), Mixing ratio (5:0 to 0:5), Heat flux (30 - 70W/cm$^2$) and channel aspect ratio (2.5 to 5) have been considered. Effects on the heat transfer characteristics (convective heat transfer coefficient, Nusselt number and thermal effectiveness) and pressure drop characteristics (pressure drop and friction factor) and the relative effect of heat transfer coefficient and pressure drop (i.e., comparison factor) are examined. Effects on the figure of merit, performance evaluation criteria, coefficient of performance and entropy generation rate are also discussed. Heat transfer coefficient and Nusselt number continuously increase with flow rate, nanoparticle dispersion in base fluid and fluid

inlet temperature. Allotropes of carbon (MWCNT and graphene) dispersed hybrid nanofluids are found better in term of heat transfer coefficient but also with a penalty of maximum pressure drop. The maximum heat transfer coefficient of 5324.82 $W/m^2.K$ is yielded by using $Al_2O_3$+graphene/DI water hybrid nanofluid. An increment of about 32.89% is observed in pressure drop for $Al_2O_3$+graphene dispersed hybrid nanofluid as compared to base fluid (DI water). Oxide-nitrite dispersed hybrid nanofluid is found best due to better combined hydrothermal parameters (comparison factor, COP, FOM and PEC). Comparison factor is found about 1.4 at 0.1 lpm for oxide-nitrite mixture dispersed hybrid nanofluid. Dissimilar particle combination (spherical-cylindrical) yields an optimum particle ratio of 3:2 for best hydrothermal performance; however, no optimum ratio is found for a similar particle combination. With the rise in volume concentration, heat transfer coefficient and pressure drop both increase, but no significant effect on their relative parameter is observed. As the particle concentration increases from 0.01 to 0.1 vol%, the cost of nanoparticles increases 10 times and the maximum enhancement in the heat transfer coefficient is only 11.1% (1.1 times). The comparison factor (ratio of heat transfer coefficient and pressure drop) increases significantly with fluid inlet temperature. Pressure drop for $Al_2O_3$+MWCNT hybrid nanofluid decreases by 10.15% as compared to water when temperature increases from 20$^oC$ to 40$^oC$. The effect on FOM and PEC is, however, insignificant. Heat transfer coefficient and pressure drop both increase for lower aspect ratio but negligible effect on PEC and FOM. The use of PCM is found favorable if its melting occurs during the process. Composite (rGO-ZnO) dispersed hybrid nanofluid yields maximum thermal performance improvement. Maximum Nusselt number enhancement of 16.7% is observed with composite hybrid nanofluid as compared to DI water.

CFD study has been carried out to predict velocity and temperature profiles using both single-phase and multi-phase models. Nusselt number and friction factor for both models have been compared with the experimental results and observed that the mixture-multiphase model is in good agreement due to better capture of the heat transfer and flow mechanisms (relative motion between base fluid and nanoparticles). So, the mixture-multiphase model has been used for further study. Hybrid nanofluids, having nanoparticles of higher thermal conductivity, yield a higher heat transfer coefficient; however, they do not show any difference in pressure drop due to the same size nanoparticles. Also, velocity profiles for different hybrid nanofluids are identical. Hybrid nanofluids yield higher temperature as compared to DI water at channel outlet due to more heat transfer. The combined effect of the interrupted channel (due to different types of ribs) and hybrid nanofluids have been finally investigated. The maximum heat transfer coefficient (4789.1 $W/m^2K$) and Nusselt number (about 11.17) are observed by the semi-circular rib with $Al_2O_3$+Cu hybrid nanofluid. The maximum and minimum pressure drop and friction factor are observed for rectangular ribbed channel and semi-circular ribbed channel, respectively. A maximum pressure drop is about 198.79 $N/m^2$ is found for the combination of rectangular ribbed channel and $Al_2O_3$+Cu hybrid nanofluid. The thermal performance factor is observed to be rise with an increase in flow rate for the semi-circular ribbed channel.