Chapter 7: Conclusions and Future Work

A detailed literature review has revealed that despite many industrial and domestic applications, medium-temperature (373-573 K) concentrated solar thermal (CST) systems are less explored than low or high-temperature systems. For instance, oil-based parabolic trough collector-based systems offer a viable green option for process heat applications in this temperature range. Moreover, several recent investigations demonstrated the distinct advantages of using nanofluids for heat transfer systems. Therefore, this thesis presents an assessment of nano-oils as an alternate heat transfer fluids (HTF) for solar thermal systems like a parabolic trough collector (PTC). The literature review also revealed several research gaps, like the need for a consistent HTF selection criterion, unavailability of Nusselt number correlations for nano-oils or hybrid nano-oils, limitation of the widely-employed computational fluid dynamics (CFD) approaches for PTC absorber, and the dearth of experimental data for heat transfer with nano-oil and hybrid nano-oil. The overarching results and recommendations for the future are covered in this chapter. The following key findings were arrived at after meticulous computational and experimental analyses.

- A non-dimensional figure of merit (FoM = Nu/Cp) is proposed to analyze the heat transfer with a fluid relative to the pressure drop. An HTF offering a higher value of *FoM* will be preferred for a heat transfer system like a PTC absorber. Finally, realizing the limitations of dimensional parameters, *FoM*-based qualitative and Mollier-type quantitative look-up diagrams are created to enable the comparative assessment and selection of HTF, including oils, solar salts, and nanofluids.
- Nusselt number correlations are available for water-based, nanoparticle-specific, nanofluids, and hybrid nanofluids that are described in the literature review. Thus, the need for generalized Nusselt number correlation, applicable to a wide range of fluids and nanoparticles, is realized. A novel separation approach is developed to

address the same. Based on the separation approach, the following generalized Nusselt number correlations are proposed for nanofluid (Nu_{NF}) and hybrid nanofluid (Nu_{HNF}) is as follows:

$$\underbrace{Nu_{NF}}_{\textbf{experimental}} = \underbrace{0.93\ \alpha_r^{-0.059}\phi^{-0.026}n^{0.357}}_{\textbf{correction factor }(\eta)} \underbrace{\left\{\frac{\frac{f}{8}(Re-1000)Pr}{1+12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}}-1\right)}\right\}}_{\textbf{\textit{Gnielinski correlation}},\ Nu_{BF}}$$

$$\underbrace{Nu_{HNF}}_{\textbf{experimental}} = \underbrace{1.01\ \alpha_r^{0.08879}\phi^{0.0542}n^{-0.1482}}_{\textbf{correction factor }(\eta)} \underbrace{\left\{\frac{\frac{f}{8}(Re-1000)Pr}{1+12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}}-1\right)}\right\}}_{\textbf{\textit{Gnielinski correlation}},\ Nu_{BF}}$$

- A comparative assessment revealed that the proposed generalized correlations predict the experimental and computation-based average Nusselt number well within an uncertainty of about ±10-20% for the turbulent flow of water-based and oil-based nanofluids and for a wide range of nanoparticles.
- Motivated by a PTC absorber, CFD-based heat transfer analysis is performed for the turbulent flow of HTF through a long, straight, horizontal copper tube with discrete heating conditions. Here, the top and bottom (external) surfaces of the copper tube are exposed to a low (1 kW/m^2) and high heat flux (up to 50 kW/m^2). The findings reveal that (a) the effect of gravity leads to asymmetry for a low Reynolds number, and its influence decreases on increasing the Reynolds number, (b) the coefficients in the standard logarithmic law may be corrected with the Richardson number (*Ri*), (c) discrete heating causes asymmetric temperature distribution, and thus, Nusselt number also varies for the top and bottom surfaces exposed to different heat flux levels. Finally, the following correlations are deduced for the top and the bottom surface-area-averaged Nusselt numbers:

$$Nu_{corr(t)} = 1.192 {Nu_{gen}}^{0.981} {q_r}^{-0.786}$$

$$Nu_{corr(b)} = 3.757 {Nu_{gen}}^{0.743} {q_r}^{0.115}$$

- Heat transfer experiments are performed for turbulent flow pure Therminol VP1 (TVP1) and Al_2O_3-CuO-TVP1 hybrid nano-oil through a 4 m long, straight, horizontal, copper tube, which is subject to uniform heat flux condition and for Reynolds number range 8000-20000. The stability of the prepared hybrid nano-oil was inspected by the visual inspection method and also by the pH value method.
- The experiment revealed a 15% increase in surface-area averaged Nusselt number for hybrid nano-oil compared to pure oil. The pressure drop is found to be 12 % higher for hybrid nano-oil in comparison to pure oil. However, the FoM for hybrid nano-oil is found to be 5-6 % higher than that of pure oil. Thus, the use of hybrid nano-oil is recommended for a parabolic trough absorber. Also, the generalized Nusselt number correlation is found to predict the experiment-based values for hybrid nano-oil well within ±15%. Therefore, the use of generalized Nusselt number correlation for hybrid nano-oil is recommended for heat transfer analysis in a PTC absorber.

Future Work

The proposed generalized correlations can be improved by (a) using the effects of different nanoparticle shapes (like diamond, brick, and lotus etc.) and nanoparticles diameter, (b) generating an experiment-based dataset with different oils and nano-oils, and (c) performing radiation-based experiments to replicate the discrete or prevalent non-uniform heat condition for solar thermal. The need for extensive research in the future to ascertain the long-term stability of oil-based nanofluids and hybrid nanofluids is required. Last but not least, the well-adopted CFD methodologies need a careful assessment and improvement or adaptation for special heating conditions that are prevalent in solar thermal systems.