

Chapter 2: Literature Review

In continuation with the introduction, this chapter presents an in-depth literature review for heat transfer fluids and heat transfer in PTC absorbers, Nusselt number correlations for turbulent flow of pure and nanofluids for PTC absorber, and heating conditions for parabolic trough absorbers. These are presented subsequently.

2.1 PTC Absorber: Heat Transfer and Heat Transfer Fluids

Different HTFs are used for the removal and transportation of heat from a PTC absorber [4][14][16][17]. The HTFs include water, molten salt, thermal oil, and nanofluids for their enhanced thermophysical properties [17][18][19][20][21][22]. Recent investigations have revealed the improved stability of nanofluids [20] and their positive environmental impact through the enhanced thermal efficiency of the PTC receiver [23]. A detailed investigation of the thermophysical properties of nanofluids, hybrid nanofluids, and Nusselt number correlation for nanofluids was recently reported by [19][21][24][25].

Numerous investigations are performed for heat transfer in PTC absorbers with water, water-based nano-fluids/hybrid nanofluids, oil, and oil-based nanofluids/hybrid nanofluids, etc. [1][14][24][26]. Experiments with water-based nanofluids in the parabolic trough receiver reported a thermal-efficiency enhancement of about 7-24% for Al_2O_3 [26][27][28], 8.66% for TiO_2 [29], 11-13% for Fe_2O_3 [28] as compared to water. However, Coccia et al. [30] found marginal improvements using Fe_2O_3 , SiO_2 , TiO_2 , ZnO , Al_2O_3 , and Au as nanoparticles with water as the base fluid. Kasaeian et al. [31] experimentally found that using 0.2 – 0.3 % V/V of MWCNT nanoparticles in mineral oil enhances up to 7% thermal efficiency for a PTC absorber. Experiments and numerical simulations for heat transfer via natural convection are performed with spherical-shaped (Al_2O_3), tubular-shaped (multi-walled CNT), and flake-shaped (Graphene) nanoparticles [32][33]. They

reported that the nanofluid with MWCNT outperforms Al_2O_3 and multi-wall CNT in terms of heat transfer enhancement at several volume fractions. Computational studies with TherminolVPI based nanofluids showed a thermal-efficiency enhancement of 12.5% for Cu [34], 13.9% for Ag, 7.2% for Al_2O_3 [32], and 4.4% for Single-wall Carbon Nanotube (SWCNT) [33] as nanoparticles. Computational studies with Al_2O_3 Therminol66 nanofluid showed a thermal-efficiency enhancement of 0.5% [35]. These findings are generally attributed to the higher thermal conductivity of nanofluids than that of pure fluids [22][36][37].

Computational fluid dynamics (CFD) analysis for the turbulent flow of Al_2O_3 -water and CuO-water inside a PTC absorber, with $2.5 \times 10^4 \leq Re \leq 2.5 \times 10^5$ and particle volume fraction of 0.5%, 1.5% and 3%, are performed by Ghasemi et al. [38][39]. They reported (a) heat transfer enhancement by 28% for Al_2O_3 -water and 35% for CuO-water and (b) a positive correlation between the Nusselt number and the particle volume fraction. CFD investigations are reported with Cu-TVP1 for 1 to 6 % V/V of nanoparticles [34] and an efficiency enhancement of up to 12.5% for the PTC absorber. Also, an enhancement in heat transfer coefficient by 8%, 18%, and 32% is reported for 2%, 4%, and 6% V/V of nanoparticles for $Re \leq 2.5 \times 10^6$, respectively. Mwesigye et al. [32] simulated the heat transfer in a PTC absorber for $Re \leq 1.8 \times 10^6$, using non-uniform flux distributions, and reported an enhancement in the convective heat transfer coefficient by about 7.9 %, 3.9%, and 6.4% for Ag-TVP1, Al_2O_3 -TVP1, and Cu-TVP1 with 6% V/V of nanoparticles, respectively. Saha et al. [40] numerically investigated the turbulent flow through a horizontal pipe for a uniform heat flux of 50 kW/m^2 , 40 nm diameter of Al_2O_3 and TiO_2 nanoparticles with 4-6 % V/V in water, and $1 \times 10^4 \leq Re \leq 1 \times 10^5$. They reported an augmentation in Nusselt number by about 9.45%-20.63% for Al_2O_3 -water and 8.9%-19.78% for TiO_2 -water. They reported further enhancement in Nusselt number by

decreasing the size of nanoparticles from 40 nm to 10 nm. Bianco et al. [41] numerically investigated the turbulent forced convection with Al₂O₃-water and reported 4%, 20%, and 33% enhancement in the average heat transfer coefficient for 1%, 4%, and 6% V/V of the nanoparticles. Sokhansefat et al. [42] reported heat transfer enhancement for the PTC absorber using Al₂O₃-synthetic oil. Investigations using the hybrid nanofluids revealed a greater Nusselt number enhancement than the mono-dispersed nanofluids [9][43]. Rostami et al. [44] proposed using a pipe with an elliptical cross-section for forced convection of MWCNT–water nanofluid and reported efficiency enhancement for 0.1% V/V of the nanoparticles. The energy, exergy, and economic investigation by Vahedi et al. [45] for heat transfer in PTC absorber using nanofluids revealed an optimal value of $Re = 20000$ considering friction-based losses. Fahim et al. [46] reported heat transfer enhancement in PTC absorbers using nanofluids, and in particular, the highest value for Nusselt number is obtained for a Cu-based nanofluid compared to Al₂O₃ and TiO₂. Numerical investigations are performed for the heat transfer in PTC absorber with Cu, CuO, Ag, and Al₂O₃ nanoparticles for a volume fraction (ϕ) up to 5%, and Syltherm 800 oil as the base fluid by Basbous et al. [47]. In these simulations, the water-based Nusselt number correlations for nanofluids are used. The authors reported a 36% improvement in the convective heat transfer coefficient and a 21% reduction in the overall thermal loss coefficient for Ag-Syltherm 800 nano-oil.

Hybrid nanofluids are synthesized by dispersing a combination of suitable nanoparticles in a base fluid. Thus, hybrid nanofluids may be treated as a special type of nanofluids. Its characterization, stability, and heat transfer analysis are summarised in various literature [48][49][50][51][52][53][54]. They reported an increase in Nusselt number, compared to base fluid, by about 12 (a) 35% for Nanodiamond Nickel-water hybrid-nanofluid [55], (b) 121.7% for Al₂O₃-TiO₂ syltherm oil hybrid-nanofluid, [9](c)

11.6 % for Al_2O_3 embedded Hitec salt, however only for 30 minutes[56]. Numerical simulations are performed by Bellos et al. [9] for heat transfer in the LS-2 PTC absorber with 3% Al_2O_3 -Syltherm 800 nano-oil, 3% TiO_2 -Syltherm 800, and 1.5% Al_2O_3 -1.5% TiO_2 -Syltherm800 nano-oils. They used the water-based Nusselt number correlation as in Minea et al. [57]. They reported enhancement in Nusselt number is 121% for hybrid nano-oil, 23.8% for TiO_2 nanofluid, and 23.4 % for Al_2O_3 nanofluid. Numerical simulations are performed for heat transfer in the LS-2 PTC absorber with Al_2O_3 - CeO_2 - Syltherm800 and Al_2O_3 - CuO - Syltherm800 hybrid nano-oils by Al-Oran et al. [43]. They also preferred the water-based Nusselt number correlation by Minea et al. [57]. They reported the Nusselt number enhancement by 167% for 4 V/V% of Al_2O_3 - CeO_2 and Al_2O_3 - CuO in hybrid nano-oils, compared to pure oil.

A general observation remains that the use of nanofluids enhances heat transfer performance. However, uniform dispersion and stability of nanofluids, agglomeration, cost, and pumping power requirements remained challenging [20][58]. To conclude, nanofluids are indeed a prospect for CST system design, with a note of caution that challenges and issues are to be well addressed [48][54][58]. Most of the reported investigations deal with water-based nanofluids or hybrid nanofluids. However, computational studies are performed for TherminolVP1 or Therminol66-based nanofluids. Therefore, the reported Nusselt number correlations for water-based nanofluids are valid up to a temperature of 373 K. *These investigations allow concluding (a) the hybrid nanofluids are very promising for the heat transfer in a PTC absorber and (b) water-based Nusselt number correlations for nanofluids are used.* It is worth noting that selecting an HTF is essential for a PTC absorber. Currently, parameters like Mouromtseff number, Bonilla number, and Lenert number are being proposed [59][60][61][62]. However, detailed analyses presented in chapter 3 revealed an inconsistent behavior of these dimensional numbers while evaluating

the suitability of different pure and nanofluids for heat transfer. *This leads to a query: is this possible to develop a consistent, non-dimensional parameter for selecting an HTF?*

2.2 Nusselt Number Correlation: Pure and Nanofluids

The Nusselt number correlations are widely utilized for heat transfer estimation in a PTC absorber using 1D or system-level numerical tools. A summary of well-known correlations for the turbulent flow of pure fluid and mono-dispersed nanofluids is presented in Table 2.1. It is evident that these are developed for a specific nanoparticle and its volume fraction. A detailed assessment of these correlations, their limitations, and their capabilities are presented in chapter 3 of the thesis.

Table 2.1 Nusselt number correlations for pure and mono-dispersed nanofluids

Reference	Nusselt number correlations	Particle, (ϕ %)	Condition
Dittus-Boelter [63]	$Nu = 0.023Re^{0.8}Pr^{0.4}$	-	$Re > 10000$ $0.6 < Pr < 160; L/D > 10$
Gnielinski [63]	$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{f}{8}}(Pr^{\frac{2}{3}} - 1)}$ <p>where, $f = (1.84 \log Re - 1.64)^{-2}$.</p>	-	$3000 < Re < 5000000$ $0.5 < Pr < 2000;$ $L/D > 10$
Xuan and Li [64] (2003)	$Nu_{NF} = 0.0059(1 + 7.6286\phi^{0.6886}Pe_d^{0.001})Re_{NF}^{0.9138}Pr_{NF}^{0.4}$	Cu ($\phi < 2\%$)	$10000 < Re_{NF} < 25000$
Maiga et al. [65] (2006)	$Nu_{NF} = 0.085Re_{NF}^{0.71}Pr_{NF}^{0.35}$	γAl_2O_3 ($\phi < 10\%$)	$10000 < Re_{NF} < 50000$ 00 $0.5 < Pr_{NF} < 2000$

Duangthonguk and Wongwises [66] (2010)	$Nu_{NF} = 0.074Re_{NF}^{0.707}Pr_{NF}^{0.385}\phi^{0.074}$	TiO ₂ ($\phi < 2\%$)	$3000 < Re_{NF} < 18000$
Vajja et al. [67] (2010)	$Nu_{NF} = 0.065 (Re_{NF}^{0.65} - 60.22)(1 + 0.0169\phi^{0.15})Pr_{NF}^{0.542}$	CuO ($\phi < 0.06\%$) SiO ₂ , Al ₂ O ₃ ($\phi < 0.1\%$)	$3000 < Re_{NF} < 16000$
Sajadi and Kazemi [68] (2011)	$Nu_{NF} = 0.067Re_{NF}^{0.71}Pr_{NF}^{0.35} + 0.0005Re_{NF}$	TiO ₂ ($\phi < 0.25\%$)	$5000 < Re_{NF} < 30000$
Sunder et al. [69] (2012)	$Nu_{NF} = 0.02172Re_{NF}^{0.8}Pr_{NF}^{0.5}(1 + \phi)^{0.5181}$	Fe ₃ O ₄ ($\phi < 0.3\%$)	$3000 < Re_{NF} < 22000$ $3.7 < Pr_{NF} < 6.5$
Minea [57] (2017)	$Nu_{NF} = 0.0074Re_{NF}^{0.9}Pr_{NF}^{0.67}\phi^{0.063}$ (also for Hybrid Nanofluid)	Al ₂ O ₃ -SiO ₂ $3\% < \phi < 4\%$	$7800 < Re_{HNF} < 22000$
Esfe et al. [70] (2020)	$Nu_{NF} = 0.0129Re_{NF}^{0.9363}Pr_{NF}^{0.3167}\phi^{0.0932}$	MgO $0.5\% < \phi < 2\%$	$6000 < Re_{NF} < 32000$

To the best of the authors' knowledge, all the Nu_{hnf} correlations for the turbulent flow of water-based hybrid nanofluids are listed in Table 2.2. Minea et al. [57] numerically reported Nu_{hnf} correlation, for Al₂O₃-TiO₂ water and Al₂O₃- SiO₂ water, $3\% \leq \phi \leq 4\%$ and $7800 \leq Re_{hnf} \leq 22000$. Sundar et al. deduced experimentally Nu_{hnf} for ND-Ni (spherical-spherical)-water [55] and MWCNT-Fe₃O₄ (cylindrical-spherical)-water [71]. They found an enhancement of 34.43% for 0.3 % volume concentration of ND-Ni and 31.1% for 0.3 % volume concentration of MWCNT-Fe₃O₄ at $Re_{hnf} = 22000$ compared to water. Yarmand et al. [72] experimentally reported Nu_{hnf} for GNP-Ag (platelet-

spherical)-water at $Re_{hnf} = 5000$ and 17500 . They reported enhancement in Nu_{hnf} up to 32.7% for $\phi = 0.1\%$ in comparison to water. Suresh et al. [73] experimentally reported enhancement in Nu_{hnf} up to 8.0%, for Al_2O_3 -Cu (spherical spherical)-water for $\phi = 0.1\%$ and $2300 \leq Re \leq 13000$.

Table 2.2 Nusselt number correlations for hybrid nanofluids.

References	Nusselt number correlations for hybrid nanofluids (Nu_{hnf})	The volume concentration of Nanoparticle, (ϕ)	Condition
Suresh et al. [73] (2014)	$Nu_{hnf} = 0.000264Re_{hnf}^{1.166}Pr_{hnf}^{1.166}(1 + \phi)^{77.56}$	$Al_2O_3 - Cu$ $\phi = 0.1\%$	$2300 < Re_{hnf} < 13000$ $Pr_{hnf} = 6.2$
Madhesh et al. [74] [21] (2014)	$Nu_{hnf} = 0.0012Re_{hnf}^{1.148}Pr_{hnf}^{0.333}(\phi)^{0.064}$	$Cu-TiO_2$ $0.1\% < \phi < 2\%$	$4000 < Re_{hnf} < 14000$ $6 < T < 80\text{ }^\circ C$
Sundar et al. [71] (2014)	$Nu_{hnf} = 0.0215Re_{hnf}^{0.8}Pr_{hnf}^{0.5}(1 + \phi)^{0.78}$	$MWCT-Fe_3O_4$ $0 < \phi < 0.3\%$	$3000 < Re_{hnf} < 22000$ $4.5 < Pr_{hnf} < 6.13$ $20 < T < 60\text{ }^\circ C$
Yarmand et al. [72] (2015)	$Nu_{hnf} = 0.0017066Re_{hnf}^{0.9253}Pr_{hnf}^{1.29001}$	$GNP-Ag$ $0 < \phi < 0.1\%$	$5000 < Re_{hnf} < 17500$ $20 < T < 40\text{ }^\circ C$
Minea et al. [57] (2017)	$Nu_{hnf} = 0.0074Re_{hnf}^{0.9}Pr_{hnf}^{0.67}(\phi)^{0.063}$	$TiO_2- Al_2O_3$ $SiO- Al_2O_3$ $3\% < \phi < 4\%$	$7800 < Re_{hnf} < 22000$

Sundar et al. [55] (2018)	$Nu_{hnf} = 0.022Re_{hnf}^{0.8}Pr_{hnf}^{0.5}(1 + \phi)^{0.86}$	ND-Ni $0 < \phi < 0.3\%$	$3000 < Re_{hnf} < 22000$ $4.39 < Pr_{hnf} < 5.71$ $30 < T < 60 \text{ }^\circ\text{C}$
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2.3 PTC Absorber: Discrete Heating

As explained, a PTC absorber is exposed to a peripherally non-uniform heat flux (see figure 1.2). In particular, the lower half periphery of the absorber is subject to a high flux concentration, and its upper half is subject to global irradiance. Therefore, the heat transfer analysis for the turbulent flow of heat transfer fluid (HTF) inside a parabolic trough absorber subjected to non-uniform heat flux distribution has gained research interest [38][41][75][76][77]. Monte Carlo ray tracing (MCRT) analyzes non-uniform flux distribution on the absorber surface and is coupled with CFD for detailed heat transfer analyses [78][79]. Numerical heat transfer analysis by Xu et al. [80] using supercritical CO₂, including the effect of non-uniform flux and buoyancy in the PTC absorber, revealed that the maximum heat transfer coefficient at the bottom is attributed to the presence of secondary flow. For discrete heating, the upper half of the PTC absorber tube is subject to constant heat flux, viz., the global irradiance, and its lower half is exposed to the concentrated solar irradiance. The heat flux ratio between the bottom and top surfaces is defined as the heat flux ratio (q_r). Ghasemi et al. [38][39] numerically simulated the heat transfer in a PTC absorber for $q_r = 30$. Several studies focussing on the secondary reflector and its merits for improving q_r and enhancing efficiency, are performed [81][82]. Balaji et al. [82] analyzed a linear Fresnel reflector system with parabolic and involute secondary reflectors and reported a high optical efficiency of 62.3% and 83.3 %. Gong et al. [83] and Tang et al. [10] designed a secondary reflector to obtain a uniform flux distribution for (a)

mitigating the thermal stresses and (b) enhancing the thermal efficiency of a PTC absorber. They used the maximum heat flux of around 50 kW/m^2 . Shajan et al. [84] investigate the need for a secondary reflector to homogenize the flux distribution on the PTC absorber surface, leading to performance enhancement. Studies are performed with a PTC absorber for a concentrated heat flux of up to 60 kW/m^2 on the bottom surface [10][85][86][87]. Several CFD investigations for heat transfer in the PTC absorber ignored the effect of buoyancy or gravity; see, e.g., [40][86][88]. Whereas a few investigations, including the effect of gravity, reported gravity-induced anisotropy for the temperature and velocity field [89][90]. Anisotropy may lead to the deviation of the statistical axial velocity from the standard logarithmic law. Balin et al. [91] performed a direct numerical simulation for turbulent flow over a bump and found that the velocity profile deviates from the standard logarithmic law. Also, deviation from standard logarithmic law is reported for open channel flow with Langmuir circulation [92][93]. Wang et al. [94] numerically analyzed the effect of gravity and non-uniform heat flux on the convective heat transfer with supercritical CO_2 . They reported (a) anisotropy in the computed velocity and temperature field and (b) heat transfer enhancement at the bottom surface and reduction at the top surface.

Chang et al. [95] showed using flow through a circular tube for $1.3 \times 10^4 \leq Re \leq 3.3 \times 10^4$ (a) non-uniform heat flux leads to circumferential and axial variations in fluid and wall -temperature, and (b) Dittus-Boelter correlation is suitable for estimating the overall Nusselt number. Remley et al. [96] experimentally investigated the turbulent flow through a vertical channel with the trapezoidal-shaped cross-section subjected to non-uniform heat flux. They reported an under-prediction for Nusselt number, by about 11-28 % for $1.0 \times 10^4 \leq Re \leq 2.0 \times 10^4$, from Dittus-Boelter, Gnielinski, and Sieder-Tate correlations. Generally, it is observed that the overall Nusselt number differs substantially from the corresponding values at the top and bottom surface for non-uniform heat flux.

Thus, the need for a thorough assessment of the top, bottom, and overall Nusselt numbers is realized. Furthermore, the previous investigations did not address the effect of using hybrid nano-oils on the local Nusselt number considering gravity, and the suitability of the velocity logarithmic law for turbulent flow of nano-oils with discrete heating.

2.4 Research Gaps

- A wide range of heat transfer fluids is available for the medium-temperature range. The literature review revealed the need for criteria to select a heat transfer fluid for the PTC absorber.
- Nusselt number correlations are available only for water-based nanofluids and hybrid nanofluids. Therefore, the need for a generalized correlation for water-based and oil-based nanofluids/hybrid nanofluids is realized.
- Nusselt number correlations for turbulent flow in a tube generally apply to uniform heat flux boundary conditions. Therefore, the need for adopting the generalized correlations to discrete heating is realized for the PTC absorber.
- The literature review revealed a dearth of experimental data on heat transfer with hybrid nano-oil for the medium-temperature range, which is essential for the PTC absorber.