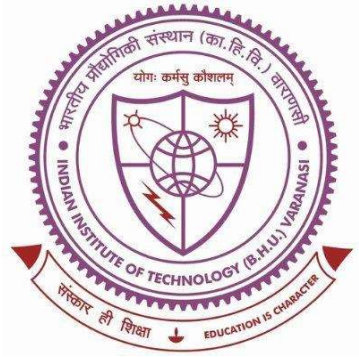
# On the Assessment of Nano-oils for Medium-temperature Solar Thermal Systems




A thesis submitted in partial fulfillment for the

Award of Degree

**Doctor of Philosophy**

By

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It is further certified that the student has satisfactorily fulfilled all the requirements of the Comprehensive Examination, Candidacy, SOTA, and Pre-submission seminar for the award of the Ph.D. degree.

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I, **"Satish Upadhyay,"** certify that the work embodied in this thesis is my bonafide work and was carried out by me under the supervision of **Dr. Laltu Chandra** and **Prof. Jahar Sarkar** from "2018" to "2023", at the **Department of Mechanical Engineering, Indian Institute of Technology (BHU), Varanasi**. The matter embodied in this thesis has not been submitted for the award of any other degree. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my work.

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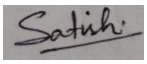

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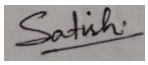

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| | | | |
|---|---|---|---|
| $A$ | model constants | P | pressure ($N/m^2$) |
| Bo | Bonilla number | q” | heat flux ($W/m^2$) |
| $C$ | constants | $q_r$ | heat flux ratio |
| $c_p$ | specific heat capacity (J/kg K) | r | radial location (m) |
| D | tube diameter (m) | Re | Reynolds number |
| E | the sum of the square of the error | S | modulus of the mean rate of the strain tensor ($s^{-1}$) |
| f | friction factor | T | temperature (K) |
| $G_K$ | generation of turbulent kinetic energy ($kg/m/s^3$) | U or V | the velocity of the fluid (m/s) |
| I | turbulent intensity | $u_\tau$ | friction velocity (m/s) |
| K | Turbulent kinetic energy($m^2/s^2$) | $y^+$ | dimensionless wall coordinate |
| L | tube length (m) | | **Greek symbols** |
| Le | Lenert number | θ | Angle (in degree) |
| M | sample size | $\alpha$ | thermal diffusivity ($m^2/s$) |
| Mo | Mouromtseff number | $\varepsilon$ | dissipation rate of K ($m^2/s^3$) |
| n | Shape factor, constant | ψ | Sphericity |
| Nu | Nusselt Number | $k$ | thermal conductivity (W/mK) |

| | | | |
|---|---|---|---|
| $k_s$ | Thermal conductivity of solid (W/mK) | RANS | Reynolds-Averaged Navier-Stokes |
| $\rho$ | density (kg/m$^3$) | RKE | Realizable k- ε |
| $\sigma_K$ | turbulent Prandtl number for K | SB | Soybean oil |
| $\sigma_\varepsilon$ | turbulent Prandtl number *for* $\varepsilon$ | SKE | standard k- ε |
| | **Abbreviations** | SS | Solar salt |
| $Al_2O_3$ | Aluminium oxide | TVP1 | Therminol VP1 oil |
| $Al_2O_3$-$TiO_2$ | Alumina-Titanium oxide | T55 | Therminol 55 oil |
| CA | Canola oil | T66 | Therminol 66 oil |
| CFD | Computational fluid dynamics | | **Subscripts** |
| CP | Coefficient of Pressure | bf | base fluid or pure fluid |
| CST | Concentrated Solar Thermal | b | bottom |
| Cu-$Al_2O_3$ | Copper-Alumina oxide | corr | correlation |
| FOM | Figure of Merit | gen | generalized |
| GNP-Ag | Graphene nanoplatelets-Silver | hnf | hybrid nanofluid |
| H | Hitec | i | inner |
| HXL | Hitec XL | in | Inlet |
| HTF | heat transfer fluid | nf | nanofluid |
| MWCNT-$Fe_3O_4$ | Multi-Walled Carbon Nanotube | ns | nanostructure (nanolayer) |
| ND-Ni | Nano Diamond –Nickel | o | overall |

| | | | |
|---|---|---|---|
| out | outer | w | wall |
| p | nanoparticle | z | axial location (m) |
| r | ratio | , | the fluctuation from a mean value |
| s | salt | - | time averaging |
| t | top | | |

# ABSTRACT

Several industrial process heat applications use fossil fuel-based high-grade energy in the medium-temperature range of 373 – 573 K. There, the use of parabolic trough collector (PTC)-based concentrated solar thermal (CST) system is expected to save fossil fuel, enhance the system efficiency by the direct utilization of heat, and mitigate the emission of greenhouse gases. Such systems rely upon heat transfer fluids (HTFs), including nanofluids, which transport the generated heat from a receiver to the intended applications. However, some of the identified significant challenges for developing such a system are (a) selection of an HTF, including vegetable oils and nano-oils, which can operate in this temperature range, (b) Nusselt number (*Nu*) correlations are available for pure fluids, and water-based nanofluids for specific nanoparticles, (c) the dearth of experimental data for developing/adopting Nusselt number correlations for nano-oils, and (d) the limitations of the modeling approaches, especially, for analyzing heat transfer with nano-oils in PTC absorber subject to discrete heating. These aspects are addressed in this thesis as follows:

1. A novel *separation approach* is proposed to filter the effect of nanoparticles on the *Nu* correlation for nanofluids. This leads to a *generalized form of Nu* correlation for nanofluids, which allows the use of a well-accepted *Nu* correlation for a wide range of the base fluid. The generalized form of *Nu* correlation for nanofluids predicts the experiment-based *Nu* for CuO-water, $TiO_2$-water, Cu-water, and Carbon nanotube-water, primarily within ±20% except for the Graphene nanoplatelet. One way to adopt this approach for hybrid nanofluids is also discussed.
2. A consistent, non-dimensional, figure of merit (FoM) is proposed for pure or nanofluid as HTF in PTC-based CST systems operating in the medium-temperature range. The FoM-based *qualitative* and *quantitative look-up diagrams* are developed

to enable the selection of heat transfer fluids. A comparative assessment shows that the figure of merit for CuO-Canola/TherminolVP1 nano-oil or CuO-$Al_2O_3$-Canola/TherminolVP1 hybrid nano-oil increases by about 10-30%, in comparison to Canola or TherminolVP1 oil. Therefore, the use of Canola oil and Canola oil-based nano-oil or hybrid nano-oil will be beneficial for solar thermal systems in the medium-temperature range. Moreover, using TherminolVP1-based nano-oil or hybrid nano-oil will benefit concentrated solar thermal power generation systems. A preliminary cost-benefit analysis lends additional support to these findings.

3. Considering the recommendations, arising out of the above findings, heat transfer analyses are performed for the turbulent flow of binary hybrid nano-oils. The investigations lead to extending the proposed generalized Nusselt number correlation for turbulent heat transfer with hybrid nano-oils. Unlike the available water-based, nanoparticle-specific, correlations for the Nusselt number, the developed correlation needs only the thermophysical properties of base fluid and nanoparticles. The generalized *Nu* correlation for hybrid nanofluids is valid for Reynolds number from 10000 to 30000 and the Prandtl number from 0.5 to 2000. It is found that the proposed correlation predicts the computed and experimental *Nu* for different hybrid nanofluids, mostly, within ±10-20%. However, the need for experiments with hybrid nano-oils is reiterated.
4. It is worth noting that the PTC absorbers are subject to a special type of heating condition, viz., discrete heating. There, the outer periphery's upper half is exposed to direct normal irradiance or reflected part of the direct irradiance, and the lower half of the outer periphery is exposed to the concentrated solar irradiance. This results in a high heat flux ratio between the lower and upper half of the PTC absorber periphery. Therefore, the need for an in-depth understanding of the

turbulent heat transfer in PTC absorbers with pure and hybrid nano-oils, including the effect of buoyancy or gravity, is realized. Thus, the RANS-based turbulent heat transfer analyses in a 3D, long, straight for Reynolds number from 5000 to 20000 and discrete heating conditions with different heat flux ratios such as 1, 5, 10, 20, 40, and 50 for pure oil and hybrid nano-oils having 1, 4 and 6 % volume concentration of the nanoparticles. The major findings are, (a) gravity-induced anisotropy leads to high and low-speed fluid flows near the lower and upper walls and temperature redistribution at a plane, which is beneficial, (b) the statistical axial-velocity deviates from the standard logarithmic law at a Reynolds number of 5000, and (c) the ratio of surface-area-averaged Nusselt number between the lower half and upper half of the tube is 4-12.

5. Finally, experiments with nano-oils are reported to mitigate the dearth of experimental data for assessing the developed generalized Nusselt number correlation. The artificial, Joule-type, uniform heating condition is adopted for simplicity. The major findings are (a) Nusselt number enhances, pressure drop also enhances with the addition of nano-particles, (b) the calculated FoM allows confirming that the use of hybrid nano-oil is beneficial in comparison to pure oil, and (c) the generalized Nu correlations are applicable for hybrid nano-oils within the reported uncertainty of $\pm$ 15%.