Chapter 6: Experimental study with a Hybrid Nano-Oil for Assessing the Generalized Nusselt Number Correlation

The literature review revealed the need for heat transfer experiments with hybrid nano-oil. Therefore, experiments are performed with Therminol VP1 (TVP1) and 1% (V/V) Al_2O_3-CuO-TVP1 hybrid nano-oil subjected to uniform heat flux conditions. The objective is to assess the developed generalized Nusselt number correlation for an oil-based hybrid nanofluid. The chapter presents the preparation and stability of the oil-based hybrid nanofluid, the developed experimental setup, the estimated friction factor, the heat transfer coefficient, and Nusselt number. To the best of the authors' knowledge, no such detailed experiments with hybrid nano-oil are reported thus far. The details of the experiment setup, the adopted procedure, and the findings are presented subsequently.

6.1 Experimental Setup and Procedure

The schematic of the forced convection experimental setup is shown in figure 6.1. It comprises a heat transfer fluid tank (HTF tank), pump, bypass valve, flow meter, test section (heated and unheated section), U-tube manometer, power supply, and chiller. HTF tank stores sufficient fluid, which is supplied as soon as the pump is turned on. Initially, the HTF is heated by an immersion heater placed inside the HTF tank up to the desired inlet fluid temperature (T_{in}) and a chiller is used to maintain the steady operating condition. A one-horsepower pump is used to circulate the HTF through the test section, including the chiller. A bypass valve is installed to control the flow of HTF and to attain the desired flow rate during the experiment. A turbine-type flow meter is installed to record the flow rate in liters per minute (LPM). The test section comprises a 4 m long, straight, horizontal copper tube depicting a PTC absorber with an external heating element. The test section (copper tube) is divided into two parts, viz. unheated and heated length of 2 m, the outer diameter of the tube is 0.025 m, and the inner diameter of the tube is 0.023 m. Thus, a sufficient length-to-diameter ratio of ~86 is provided to attain the hydraulically fully developed inflow condition for the heated copper tube. A detailed assessment of the same is provided in Chapter 5.

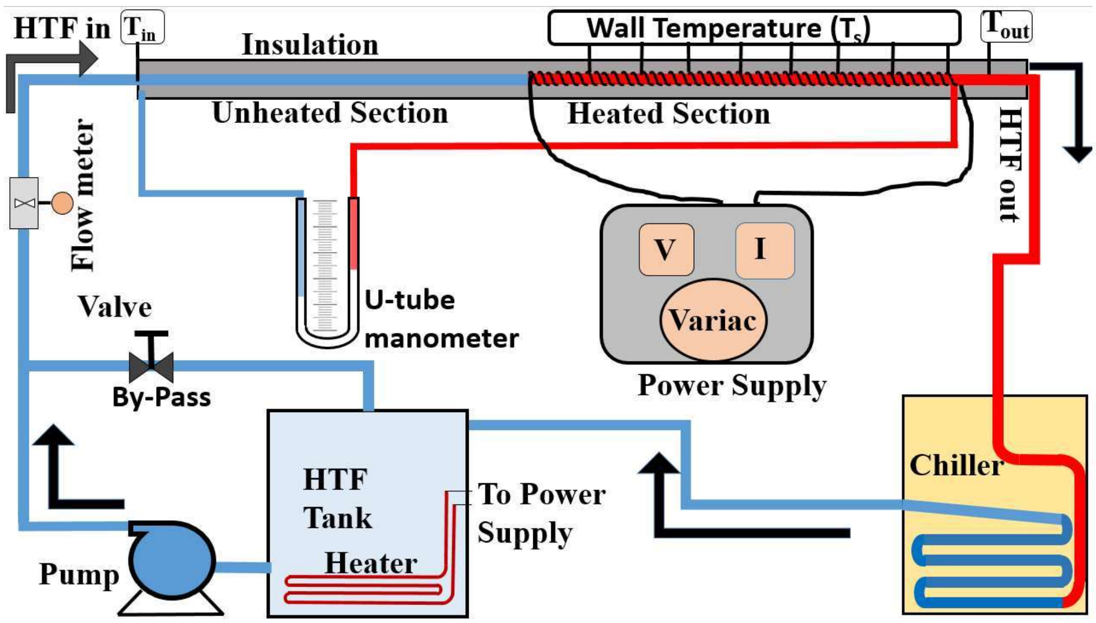


Figure 6.1 Schematic of the installed experiment setup for the heat transfer with therminol and hybrid nano-oil

K-type thermocouples and a data acquisition (DAQ) system are installed to record the inlet, outlet, and wall temperatures. A U-tube manometer is installed to measure the pressure drop across the straight tube using the height of the mercury column. The test section is externally insulated, with sufficient thickness, to mitigate heat losses. It is worth mentioning that the inlet and outlet of the test section are provided with a wire mesh to promote mixing and redistribution of HTF temperature. Therefore, the measured temperatures are interpreted as the bulk mean as far as possible. The measured parameters, the corresponding instruments, their range, and accuracy details are provided in Table 6.1.

Table 6.1 The measured parameters, instruments, and their operating range/accuracy

Parameters	**Instruments**	**Range**	**Accuracy**
Flow rate	Turbine-type flowmeter	10 to 50 LPM	±0.1 LPM
Temperature	K-type thermocouple	20 to 300 ºC	±0.1 ºC
Wattmeter	Wattmeter, Specification: 250 V, 50 Hz, Maximum 10 A	Less than 2.2 KW	±0.25%

A photograph of the installed experimental facility is shown in figure 6.2a. The externally-insulated, long, straight test section (copper tube), including thermocouples, is wrapped with nichrome wire as a heating element (see figure 6.2b). Silicon rubber is provided between the unheated and heated part of the test section to mitigate the heat transfer, as far as possible, during the experiment. K-type thermocouples are installed on the outer wall of the copper tube using a groove of 0.5 and a high-temperature epoxy. Due care is taken to isolate the thermocouple sensor from the heating element by utilizing insulation around the same. The thermocouples are uniformly spaced (25 cm) along the axial direction on the heated section, and some probes are placed along the circumferential direction to record azimuthal variation, if any, for the applied boundary conditions. Several efforts were made to perform the experiments both for uniform and non-uniform heat flux distributions along the azimuthal direction. However, achieving a non-uniform heat flux distribution depicting discrete heating conditions, as in Chapter 5, was not possible using the installed nichrome wire-wrapped copper tube. The authors finally concluded that the same can be attained, possibly by using an external radiation source, and is of future interest. However, the current experiment provided helpful data for the assessment of the generalized Nusselt number correlation for hybrid nano-oil. The installed, multiple, K-type thermocouples at the inlet and outlet near the wire mesh are shown in figure 6.2c.

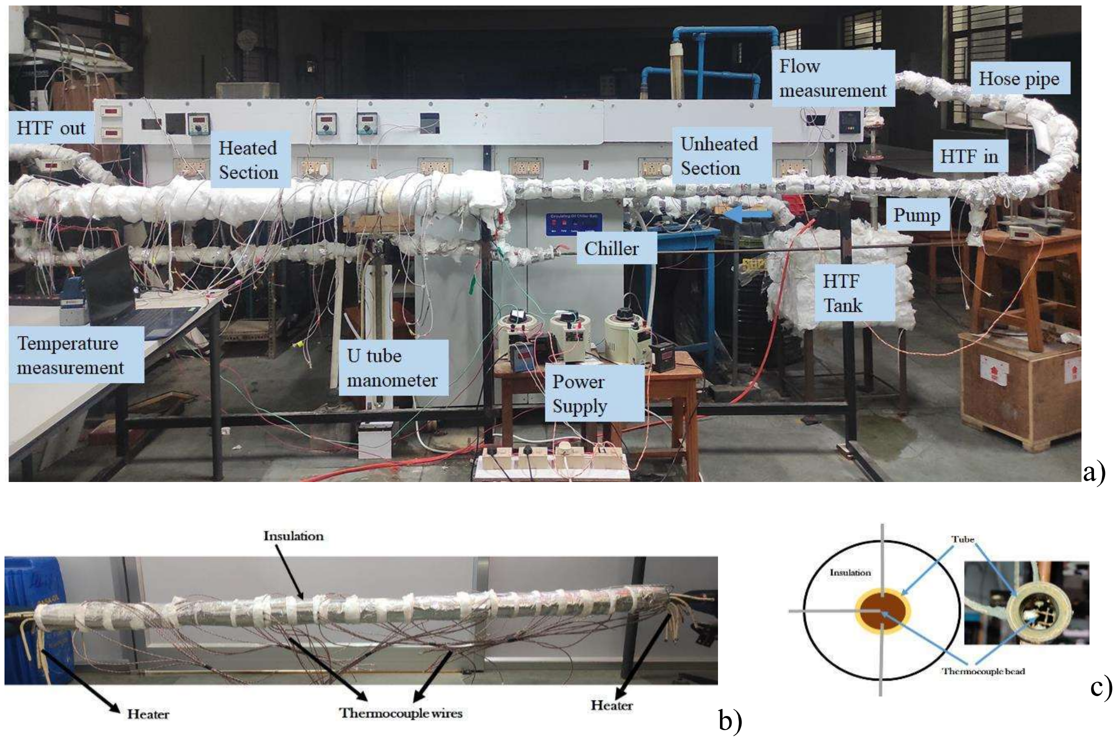


Figure 6.2 Photograph of a) the installed experimental setup for heat transfer with oil and hybrid nano-oil, b) the installed, externally insulated heating section with thermocouples, and c) the installed thermocouples at the inlet and outlet to measure fluid temperature.

The following step-wise approach is adopted for performing the experiments:

Step 1: The HTF is heated to the desired inlet temperature, and the flow rate is steadily increased to attain the desired flow rate or the corresponding Reynolds number in the range of 8000 - 20000. Subsequently, the flow is allowed to stabilize for some time.

Step 2: The power supply is turned on, and the same is regulated using a variac. The same is measured using a wattmeter and verified using the attached voltmeter and ammeter. This allows external heating of the 2 m long test section.

Step 3: The system is allowed to operate and stabilize. Once the steady state is attained, the flow rate, inlet, outlet, and wall temperatures are recorded.

Following the adopted procedure, the HTF is heated to attain the inlet temperature of 353 K. The flow rate of HTF is maintained at a value between 10 – 26 Lpm with an increment of 2 Lpm. The first set of experiments is performed with TVP1 oil, and the second set of experiments is performed for 1% (V/V) Al_2O_3-CuO TVP1 hybrid nano-oil. The input power to the 2 m long, straight copper tube is maintained at 3.2 kW for all the experiments. Achieving a higher power was challenging because of safety-related issues in the laboratory. Several parameters are noted for the experiment after attaining a steady state. This was inferred from the measured fluid and solid temperatures in the test section. The thermophysical properties of pure oil are adopted from EES [97] and that of hybrid nano-oil, as in Table 5.2. Thus, after calculating the thermophysical properties and using the appropriate equations presented later in the data deduction, the Nusselt number and friction factor are calculated and compared with the standard correlation discussed in section 6.2.4.

6.1.1 Hybrid Nano-Oil Preparation: Al_2O_3-Cuo TVP1

Hybrid nano-oil is prepared by mixing an appropriate fraction of Al_2O_3 and CuO nanoparticles in TVP1. In general, 1g of hybrid nanoparticles comprises 0.8g of Al_2O_3 and 0.2 g of CuO nanoparticles. Thus, to prepare 1% (V/V) of hybrid nanofluid, 395.4 g of Al_2O_3 and 98.84 g of CuO nanoparticles are dispersed in 11L of TVP1 oil. The high-precision electronic weighing machine (model: SWIL 220, India) is used to measure the weight of nanoparticles and surfactants with a resolution of 0.1 mg. The measured quantity of nanoparticles is mixed in TVP1 with a magnetic stirrer (Tarsons Digital Spinot) for more than 2 hours. Subsequently, for proper dispersion of the hybrid nanoparticles, Sodium Dodecyl Sulfate (SDS) is used [132]. After stirring, the solution is sonicated in the ultrasonicator (Labman Scientific Instruments, India) for more than 2 hours. The steps for hybrid nano-oil preparation are shown in figure 6.3. The stability of the prepared hybrid nano-oil is inspected by two methods, viz. a) visual inspection and b) pH Value. The concept of isoelectric point (IEP) is used to test the stability of a hybrid nanofluid by its pH value. The stability of a hybrid nanofluid can be ensured if its pH value is far from the isoelectric point of nanoparticles [133]. This is attributed to a large repulsive force between the suspended nanoparticles in the base fluid. For example, the isoelectric point of Alumina nanoparticles is 9.1 [134], and that of copper oxide nanoparticles is 10 [135]. The pH value is measured by a pH meter (model: CL 54+Toshcon Industries, India). The pH meter is calibrated before measurement, and the measurement is repeated three times. The stability of the hybrid nano-oil is discussed in section 6.2.1.

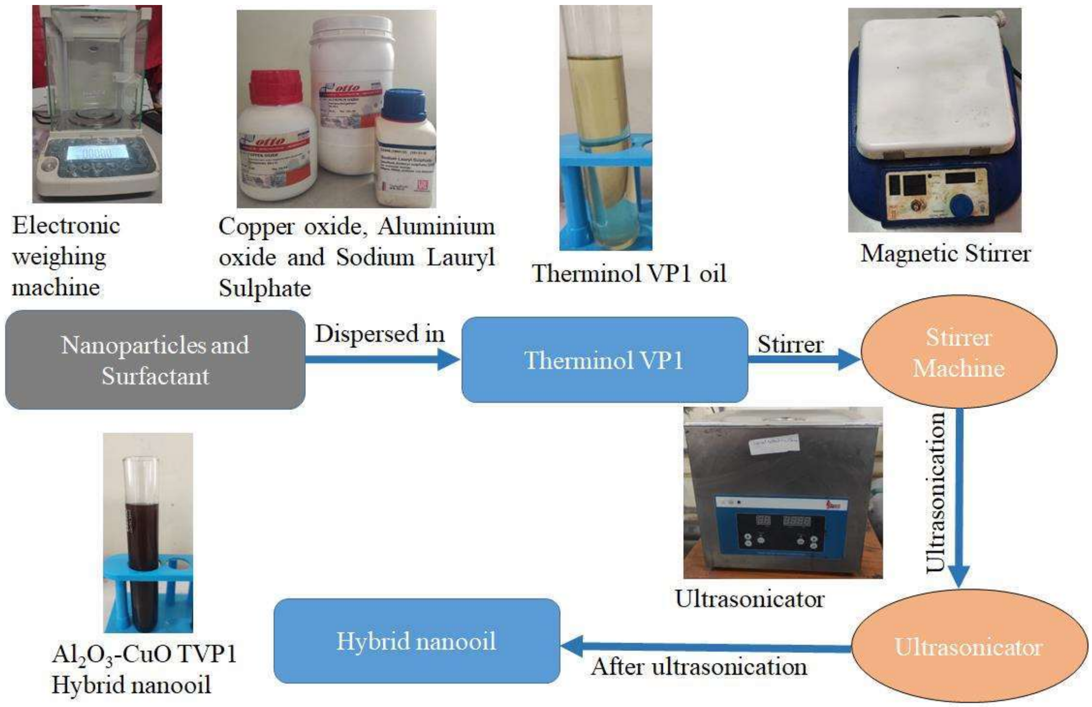


Figure 6.3 Equipment used and steps for the preparation of hybrid nano-oil.

6.1.2 Data Deduction

To calculate Nusselt number and friction factor, the following equations are used:

Rate of electrical heat input: $\dot{Q}_{electrical} = VI$ (6.1)

Rate of heat removal by HTF: $\dot{Q}_{absorbed} = \dot{m}c_p(T_{out} - T_{in})$ (6.2)

The recorded heat loss rate $(\dot{Q}_{electrical} - \dot{Q}_{absorbed})$ is less than 3% of the rate of electrical power input. The surface-area averaged convective heat transfer coefficient is obtained by Newton's law of cooling as follows:

$$\bar{h} = \frac{\dot{Q}_{absorbed}}{A(T_s - T_b)} \quad (6.3)$$

where $T_s = \frac{\sum_{i=1}^{8} T_{si}}{8}$ K, $T_b = 0.5(T_{in} + T_{out}), A = \pi(D_{in}L),$ T_{in} is the inlet temperature of the fluid, T_{out} is the outlet fluid temperature of the fluid, T_s is the average wall temperature,

T_b is the mean bulk fluid temperature, A is the inner surface area of the tube, L is the heated length of the tube, and D_{in} is the inner diameter of the tube.

Experiment-based average Nusselt number and friction factor are calculated as follows:

$$\overline{Nu} = \frac{\bar{h} D_{in}}{k} \tag{6.4}$$

$$f = \frac{\Delta P}{\frac{L}{D_{in}}\left(\frac{\rho V^2}{2}\right)} \tag{6.5}$$

6.1.3 Uncertainty Analysis

The various parameters like dimension, flow rate, temperature, and power input are measured by vernier caliper, turbine flowmeter, k-type thermocouple, and wattmeter, respectively. The uncertainty calculation for the dependent parameters such as Reynolds number, Prandtl number, heat transfer rate, convective heat transfer coefficient, Nusselt number, friction factor, coefficient of pressure, and Figure of Merit are calculated using the following equation 6.6 [136]:

$$U_z = \left[\left(\frac{\partial Z}{\partial X_1} i_1\right)^2 + \left(\frac{\partial Z}{\partial X_2} i_2\right)^2 + \left(\frac{\partial Z}{\partial X_3} i_3\right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial Z}{\partial X_n} i_n\right)^2\right]^{\frac{1}{2}} \tag{6.6}$$

Where, $i_1, i_2, i_3, \ldots\ldots\ldots, i_n$ are the uncertainties of the independent variables, and Z is a function of the independent variables X_1, X_2, X_3,…, X_n.

Table 6.2 Uncertainty estimation for different experiment-based parameters

Parameters	**Uncertainty (%)**
Heat transfer rate	±2.833

Reynolds number	±2.831
Prandtl number	±3.464
Convective heat transfer coefficient	±2.840
Nusselt number	±3.475
Pressure drop	±2.236
Friction factor (*f*)	±3.102
Coefficient of pressure (C_P)	±3.098
Figure of merit (FOM)	±4.655

6.1.4 Validation

The experiment-based average Nusselt number and friction factor for pure TVP1 are compared with the Gnielinski correlation (see figure 6.4a) and Petukhov correlation (see figure 6.4b). The measured values are found well within ±10%. The turbulent intensity increases with the increasing Reynolds number from 8000 to 20000. Consequently, as expected, the Nusselt number increases with the increasing Reynolds number, and the friction factor decreases.

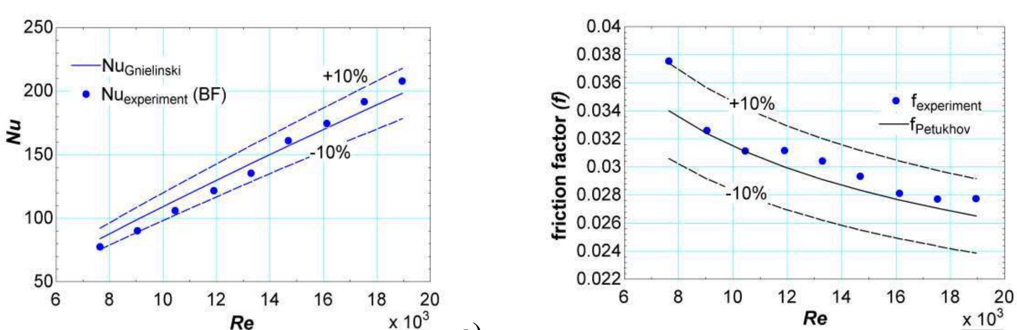


Figure 6.4 Comparison of the experiment-based Nusselt number and Friction factor with a) Gnielinski correlation and b) Pethukov correlation for Therminol VP1.

6.2 Results and Discussion

6.2.1 Hybrid Nanofluid: Stability

Figure 6.5 shows the samples of pure TVP1 and Al_2O_3-CuO-TVP1 hybrid nano-oil. The stability of the hybrid nanofluid is inferred from visual inspection. Figure 6.5b-f shows the photograph of hybrid nano-oil that is captured after zero, one, two, three, and four days of preparation. In particular, until day 2 (Figure 6.5d), there is no practical visual evidence of nanoparticle sedimentation. After day 2, some minor sedimentation is evident (see figure 6.5d). The stability of the prepared hybrid nano-oil is also inspected by the concept of an isoelectric point (IEP). The isoelectric point of Al_2O_3 is 9.1, and CuO is 10, which is far away from the measured pH value of 5.1 for the hybrid nano-oil. Moreover, experiments are performed continuously; thus, the sedimentation process, say beyond day 2, is unlikely to affect the experimental outcome.

a) b) c) d) e) f)

Figure 6.5 Photograph of a) TVP1, (b)-(f) 1% (V/V) Al_2O_3-CuO-TVP1 hybrid nano-oil starting from day 0 to day 4.

6.2.2 Convective Heat Transfer Coefficient and Nusselt Number: Oil and Hybrid Nano-oil.

The experiments are performed using the prepared 1% (V/V) Al2O3-CuO-TVP1 hybrid nano-oil for the flow rate 10 – 26 Lpm with an increment of 2 Lpm. Figure 6.5a compares the experiment-based surface-are averaged heat transfer coefficient for pure oil and Al2O3-CuO-TVP1 hybrid nano-oil. Similar comparisons are made for the calculated Nusselt number (see figure 6.5b). These show improvement for both surface-area averaged heat transfer coefficient and Nusselt number with hybrid nano-oil. In general, the Nusselt number for hybrid nano-oil is increased by around 15% as compared to pure oil. Therefore, it may be argued that the use of hybrid nano-oil will reduce the surface area for a PTC absorber by about 15% for a given temperature difference and input power compared to pure oil. Thus, the use of hybrid nano-oil seems favorable for concentrated solar thermal systems. However, one question remains: Is the pressure drop also favorable for the turbulent flow of hybrid nano-oil? This is discussed subsequently.

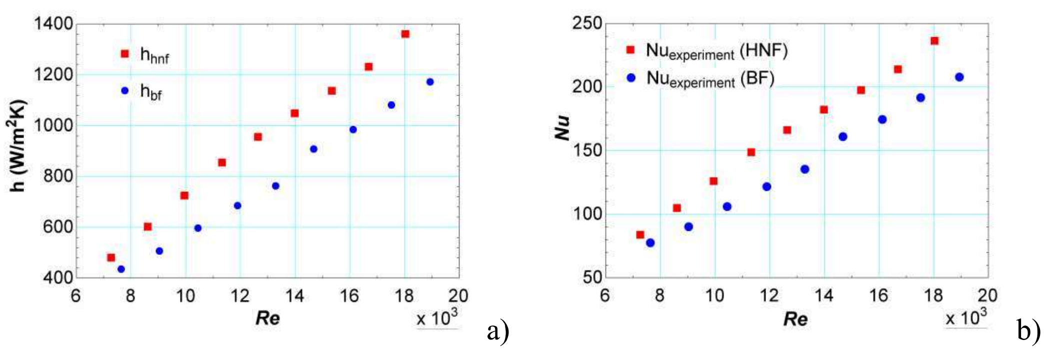


Figure 6.6 a) Convective heat transfer coefficient and b) Nusselt number for TVP1 and Al_2O_3-CuO-TVP1 hybrid nano-oil.

6.2.3 Pressure drop and Friction Factor: Oil and Hybrid Nano-oil

The measured pressure drop for pure oil and hybrid nano-oil are compared in figure 6.7a. It is evident that (a) pressure drop increases with the volume flow rate of pure oil and Al_2O_3-CuO TVP, and (b) the turbulent flow of Al_2O_3-CuO-TVP1 hybrid nano-oil experiences, in general, about 12% higher pressure drop compared to TVP1 over the considered volume flow rates. Also, the estimated friction factor using equation 6.5 is higher for Al_2O_3-CuO-TVP1 compared to TVP1 for a range of Reynolds number (see figure 6.7b). Therefore, the use of hybrid nano-oil in the PTC absorber will require a higher pumping power than the pure TVP1. This is certainly a disadvantage of using hybrid nano-oil. However, one final question remains: is there any relative benefit for heat transfer relative to the pressure drop with hybrid nano-oil? To answer this question, finally, a comparison between the proposed figure of merit (FoM = $\overline{Nu}/Cp$) for pure oil and hybrid nano-oil is reported at the end.

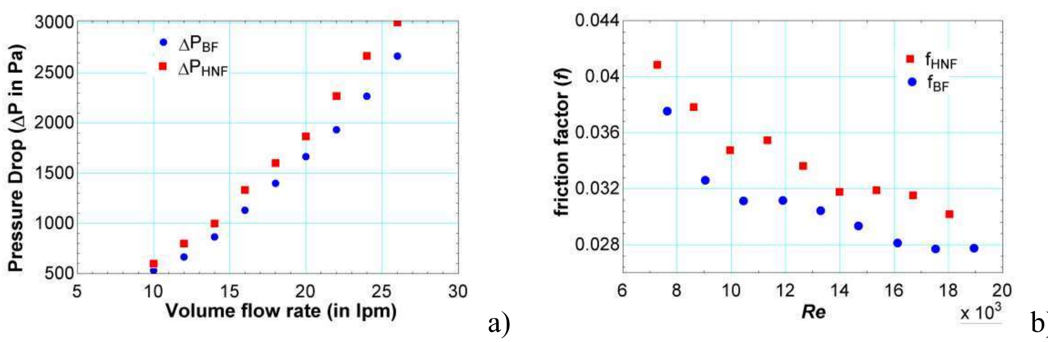


Figure 6.7 a) Pressure drop versus volume flow rate, and b) Friction factor versus *Re* for TVP1 and Al_2O_3-CuO-TVP1 hybrid nano-oil.

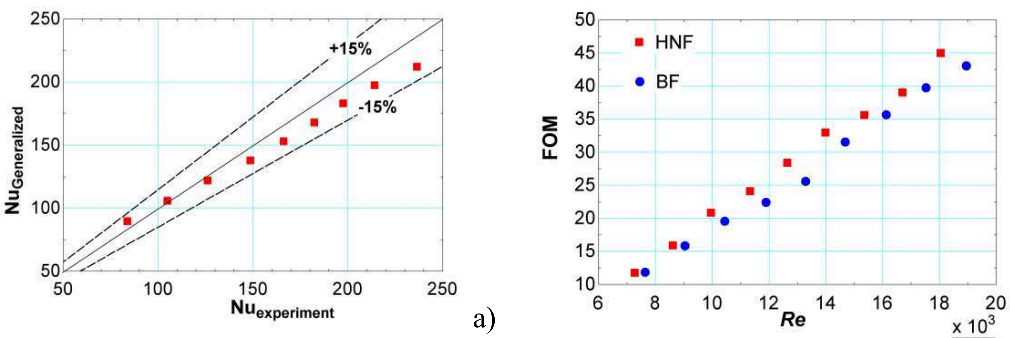
6.2.4 Nusselt Number and Figure of Merit: Oil and Hybrid Nano-oil

A comparison between the experiment-based Nusselt number and the generalized Nusselt number correlation, as in chapter 4, is presented. Figure 6.8a shows that the generalized

Nusselt number correlations predict the experiment-based values well within ±15% for the selected Reynolds range. Figure 6.8b reveals that the experiment-based FoM is 5-6% higher for the hybrid nano-oil than pure oil. Therefore, the following can be safely stated based on the experimental investigation:

a) The generalized Nusselt number correlation is suitable for the turbulent flow of hybrid nano-oil.

b) Hybrid nano-oil is recommended for PTC-absorber in comparison to pure oil.



a) b)

Figure 6.8 Comparison between a) experiment-based and generalized Nusselt number for hybrid nano-oil and b) figure of merit for TVP1 and 1% (v/v) of Al_2O_3-CuO-TVP1.

6.3 Summary

Convective heat transfer experiments are performed with pure TVP1 and 1% (V/V) Al_2O_3-CuO-TVP1 hybrid nano-oil for the volume flow rates between 10 and 26 Lpm. For this purpose, an experimental setup is developed, including a long, straight copper tube subject to uniform heat flux conditions. The key observations are as follows:

a) The visual inspection and pH value method ensured the stability of the prepared hybrid nano-oil for up to 2 days. The experiments were performed continuously, and therefore, the results are practically unaffected by the sedimentation process.

b) Surface area-averaged convective heat transfer coefficient and Nusselt number ($\overline{Nu}$) for hybrid nano-oil improves by about 15% compared to TVP1. However, the pressure drop for hybrid nano-oil is 12% higher than that of TVP1.

c) The figure of merit (FoM = $\overline{Nu}/Cp$) for hybrid nano-oil is 5-6 % higher than that of pure TVP1. This means hybrid nano-oil will offer an advantage over pure oil for heat transfer relative to pressure drop. Thus, the use of hybrid nano-oil is recommended for parabolic trough absorbers.

d) The generalized Nusselt number correlation predicts the experiment-based $\overline{Nu}$ well within ±15%. Thus, the use of generalized correlation can be recommended for hybrid nano-oil.