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Research Article

Experimental Determination of Convective Heat Transfer Coefficients of Synthetic Oil Using Wilson Plot Technique

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ABSTRACT

This paper describes the experiments to determine the convective heat transfer coefficients on a synthetic heat transfer fluid flowing in a Shell-and-Tube heat exchanger. The analysis of results is carried out by application of the Wilson plot Technique, on the basis of which, the convective heat transfer coefficients were experimentally obtained for the fluid flowing inside the tube. The convective heat transfer coefficient of oil derived through Wilson plot is then compared with the convective heat transfer coefficients obtained using the classical thermal resistance equation. An empirical correlation between the convective heat transfer coefficient of oil with respect to its mean velocity of flow in the tube and the bulk oil temperature has been proposed. A correction factor of 2.3 and exploration of the exponent value of 0.2 pertaining to the velocity of oil was obtained. The values of convective heat transfer coefficients obtained after applying the correction factor are consistent with the values reported in the literature for oil-water heat transfers. The variation of the heat transfer coefficients at different temperatures is attributed to factors like vapor blanketing effect, surface temperature measurement difficulty as well as dependence of convection phenomenon on surface geometry and physical conditions of the fluids. Experimental results obtained for a temperature range of 50-200°C are extrapolated upto 400°C, the actual upper operational fluid temperatures used in concentrated solar parabolic trough power plant. The test method proposed in this paper can be useful for the development of oil as heat transfer fluids, where already established or commercialized oil is compared with the oil under development, in the same test setup and under similar test conditions.

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Introduction

Solar energy applications encompass a very wide variety of technologies such as solar photovoltaic, solar thermal for heat augmentation as well as concentrated solar power utilizing the thermal heat of the sun to produce electricity. In the solar thermal energy applications, heat transfer fluids are used to capture the Sun's heat in them and transfer it to some other usable form [1]. In order to develop such heat transfer fluids, their thermal characterization and evaluation is necessary so as to understand their heat transfer behavior in actual use [2]. A common methodology is to determine the thermal conductivity of the heat transfer fluids which however, suffers from several drawbacks especially when the fluid in question is to be used at high temperatures [3]. In particular cases when the fluid is required to be used at high temperatures of about 400°C, convective heat transfer phenomenon dominates in practical situation [4].

Nomenclature

A	Surface area
Ai	Internal heat transfer surface area of the heat exchanger tubes
A_{i-cs}	Effective cross section area of tubes
Ao	External heat transfer surface area of the heat exchanger tubes
C_1 and C_2	Constants determined by the bulk properties of the fluid flowing inside the tube
CoV	Coefficient of variation
$dT1$	Temperature differential of inlet hot fluid and inlet cold water
$dT2$	Temperature differential of outlet hot fluid and outlet cold water
d_i	Internal tube diameter
d_o	External tube diameter
f	Darcy's friction coefficient
$GR\&R$	Gage repeatability and reproducibility
h	Mean convective heat transfer coefficient
h_i	Convective heat transfer coefficient on the internal surface area of a tube obtained using Wilson Plot Technique
h_i'	Convective heat transfer coefficient on the internal surface area of a tube obtained by Graphical Superimposition
h_i''	Convective heat transfer coefficient on the internal surface area of a tube obtained by proposed Empirical Relationship
h_o	Convective heat transfer coefficient on the external surface area of a tube
H_i	Convective heat transfer coefficient on the internal surface area of a tube obtained by Classical Heat Resistance Method
Kw	Thermal conductivity of wall material
$LMTD$	Log mean temperature difference
Lw	Heat transfer contact length
Nu	Nusselt Number
mh	Mass flow rate of hot oil inside the tube in kg-s-1
Pr	Prandtl Number
q	Heat transfer rate
Re	Reynolds Number
R_i	Internal heat transfer resistance
R_o	External heat transfer resistances
RT	Total heat transfer resistance
R_w	Heat transfer resistance due to tube wall
t_f	temperatures of the fluid
t_s	temperatures of the surface
$T_{m,o}$	Mean or bulk temperature of oil, used as a reference point for evaluating properties related to convective heat transfer
Vr	Reduced velocity of oil
V_o	Velocity of hot oil across the cross sectional area in the tube
U	Overall heat transfer coefficient
ρ_h	Density of oil in kg.m-3
μ_h	Dynamic viscosity of oil in Pa-s

Heat transfer phenomenon of convection occurs when two streams of fluids, separated by a surface, are at two different temperatures and are moving with respect to the surface. While, convective heat transfer can be studied experimentally, it is generally expressed as a function of the fluid properties, heat exchanger design at a particular temperature and the velocity. Though, convective heat transfer situations are often complex, making it difficult to provide simple analytical solutions, for convenience, most researchers and literatures assume that this heat transfer follows Newton Law expressed below:

$$q = A(t_s - t_f)h \tag{1}$$

Thus, for a given fluid flow inside a heat exchanger, the convective heat transfer coefficient may be calculated if the physical properties of the fluid, the area and surface characteristic as well as fluid temperature can be measured. However, in most engineering situations, while it is possible to measure the fluid temperature by some means and known instrumentation techniques, it is often very difficult to measure the surface temperatures, especially when the fluid moves inside a confined geometry of a heat exchanger. Even when it is possible to measure the surface temperature, it often varies from one point to another and is affected by the presence of the temperature sensors. Thus, instead of measuring the surface temperatures, researchers often resort to techniques that enable them to utilize the measured fluid inlet and outlet temperatures [5].

Researchers have been trying to research fluids that can operate at increasing temperatures and at the same time improve the heat transfer ability, relative to existing fluids. While the operating temperature of the fluid can be easily measured in the lab, its heat transfer ability is generally measured either in terms of thermal conductivity or, more realistically, based on its convective heat transfer coefficient. The Wilson plot technique, which has been used by large number of researchers, is a very effective method for evaluating the convection ability of heat transfer fluids, especially when used in Shell-and-Tube type heat exchangers. The Wilson plot Method assumes that if the mass flow of one of the fluid exchanging heat is varied, then the change in total thermal resistance is a result of the change in the convective heat transfer coefficient of that fluid while the change in the thermal resistance of the other fluid as well as the thermal resistance of the tube wall can be taken as constant [6].

Wilson Plot Method and Its Modifications

In applying the Wilson plot method, the following factors are generally assumed:

- The thermal resistance of one of the heat exchanging fluids remains constant
- The mass flow and thus the velocity of the other fluid is varied, keeping the flow in the turbulent regime
- The heat transfer surface is smooth on both sides
- For the sake of calculations, the thermal resistance due to fluid fouling is neglected
- The value of the exponent of the velocity of the fluid, whose mass flow rate is varied, is based on a Nusselt number correlation such as Equation 2.

A number of researchers have proposed variations and modifications of the Wilson Plot method, extending its use to various additional applications [7,8]. Some of these modifications were made to address certain unavoidable issues which are manifested during particular convective heat transfer processes, such as those in a forced laminar flow region, phase change of the fluid during the process, etc [9]. Wilson in his original work assumed the velocity exponent value to be 0.8. Modifying Wilson's original method, several researchers proposed using the exponent of the Reynolds Number in the well-known correlation of convective heat transfer in a flow inside tubes:

$$N_u = C(Re)^n (Pr)^m \tag{2}$$

For the particular case of Shell-and-Tube type heat exchangers, the original Wilson Plot method [10] has been utilized by researchers in determining the convective heat transfer coefficient of heat transfer fluids. Neglecting the fluid fouling effect for the sake of analysis, the Wilson plot method involves categorizing the total thermal resistance across the heat exchanger into internal thermal resistance, external thermal resistance and all other thermal resistances taking part in the heat transfer process as shown below:

$$R_T = R_i + R_w + R_o \tag{3}$$

Equation 3 is often expressed as,

$$R_T = \frac{1}{A_{i/o}U} = \frac{1}{A_i h_i} + \frac{\log\left(\frac{d_o}{d_i}\right)}{2\pi k_w L_w} + \frac{1}{A_o h_o} \tag{4}$$

During experimentation, heat transfer problems are addressed by stabilizing the temperatures at which the heat exchange takes place, i.e. when steady state is achieved [11]. Once the steady state is achieved, it is assumed as well as observed, that the heat given by the warmer fluid is taken by the colder fluid, thus satisfying the following Equation 5:

$$q = m_h C_{ph} dT_h = m_c C_{pc} dT_c = U_{i/o} A_{i/o} LMTD = \frac{LMTD}{R_T} \tag{5}$$

$$R_T = \frac{1}{U_{i/o} A_{i/o}} = \frac{LMTD}{m_c C_{pc} dT_c} \tag{6}$$

Where;

$$LMTD = \frac{dT_1 - dT_2}{\log\left(\frac{dT_1}{dT_2}\right)} \tag{7}$$

Thus, for the case of Shell-and-Tube type heat exchanger, the Wilson plot Method assumes that if the mass flow of one of the fluid exchanging heat is varied, then the change in total thermal resistance is a result of the change in the convective heat transfer coefficient of that fluid. On the other hand, the thermal resistance of the other fluid, as well as the thermal resistance of the tube wall, are assumed to remain unchanged [12]. Thus, in light of this method, Equation3can be rewritten as,

$$R_T = R_i + C_2 \tag{8}$$

Where, $C_2 = \text{Constant} = R_w + R_o$.

Wilson's method also assumes that for a fully developed turbulent flow inside a circular tube, the convection coefficient is proportional to the power of the reduced velocity of the fluid flowing inside the tube, thus taking care of the gross property variation of the fluid with temperatures [13]. Thus, variation of the convective heat transfer inside the tube with reducing velocity can be expressed as:

$$h_i \propto V_r^{\,n} = C_1 . V_r^{\,n} \tag{9}$$

and,

$$R_T = \frac{1}{C_1 . A_i} + C_2 \tag{10}$$

where C_2 is constant defined in Equation8 and C_1 is constant which is determined by the bulk properties of the fluid flowing inside the tube.Equation10 represents a straight line having the constant C_2 as the intercept and $1/(C_1.Ai)$ as the slope.

Now, R_T can be obtained by measuring the inlet and outlet bulk fluid temperatures and the mass flow rates of the two heat exchanging fluids flowing inside and outside of the tubes of the heat exchanger. The inlet and outlet temperatures of the two fluids can be used to calculate the log mean temperature difference. RT can then be calculated by substituting the LMTD calculated using Equation 7 in Equation 6.

During experimentation, the mass flow rate of the hot oil inside the tube is varied from 1500 kg/hr to 1800 kg/hr. A Wilson Plot is obtained by calculating R_T from the mass flow rate and temperature measurements, using Equation 6, while varying the flow velocity inside the tube. Assuming a value of the exponent "n" in Equation 9 – based on previous studies, analysis or experiments – R_T can be plotted as a function of $1/V^n_r$. The plotted experimental data should fall near a straight line, whose slope and intercept can be obtained using regression analysis, as shown in Figure 1. The values of the two constants "C_1" and "C_2" can now be obtained from the plot, and the internal and external heat transfer coefficients can be calculated.

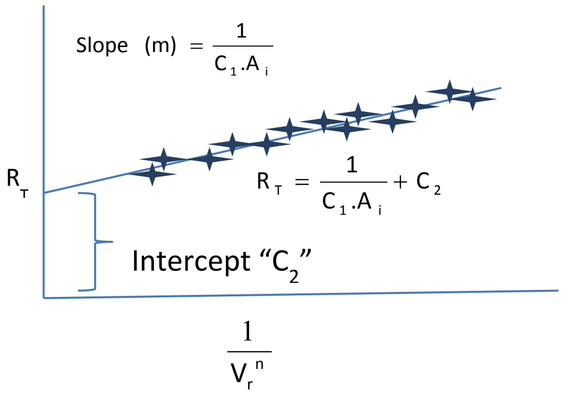

Figure1. Original Wilson plot.

Based on the work carried out by past researchers, it has been observed that the exponents of the Reynolds Number and Prandtl Number in Equation 2 varies as a function of the Prandtl Number. If the Prandtl Number is smaller than 1, the values of the exponents of the Reynolds Number and Prandtl Number are relatively close to each other. As the Prandtl Number increases, its exponent isreduced, while the value of the exponent of the Reynolds Number increases [14]. To accommodate for these variations and increase the prediction's accuracy in the transition region, Gnielinski modified the Petukhov correlation [15, 16] in the following form:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re-1000)\,Pr}{1+12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}}-1\right)} \qquad (11)$$

Applicable for: "$2300 \le Re \le 10^6$and $0.5 \le Pr \le 200$"

f = Darcy's Friction Coefficient obtained from the Blasius Correlation applicable for turbulent flow in smooth pipes

$$f = \frac{0.3164}{(Re)^{0.25}}$$

Taking Gnielinski's equation as the most appropriate correlation for Tube-and-Shell type heat exchangers, the relevant general form of the Nusselt number correlation can be written as [14]:

$$Nu = C(Re)^n(Pr)^m\left[1+\left(\frac{d_i}{L_w}\right)^{\frac{2}{3}}\right] \qquad (12)$$

Where d_i is tube inner diameter and L_w is length of the tube

Evaluation of Convective Heat Transfer Coefficient of a Solar Thermal Fluid

A test apparatus was prepared for the evaluation of convective heat transfer characteristics of heat transfer fluids at the high operating temperatures normally encountered in solar thermal plants. It included the following components:

- Tube-and-Shell heat exchanger with a counter-flow.
- Closed-loop piping system.
- Temperature measurement sensors and instrumentation.
- High precision, reliable and low maintenance mass flow meter, for flow at temperatures of up to + 0.75% of readings in liquids and + 1% for gases/steam(Model Optima's 6400F, made by Krohne).
- Data acquisition system.
- SCADA operating software

Figure 2 and Figure 3 respectively depict the photograph and schematic of the test setup used for evaluation of thermic fluids for their intended application in solar thermal systems.

Figure 2. Photograph of the test setup for evaluation of heat transfer fluid

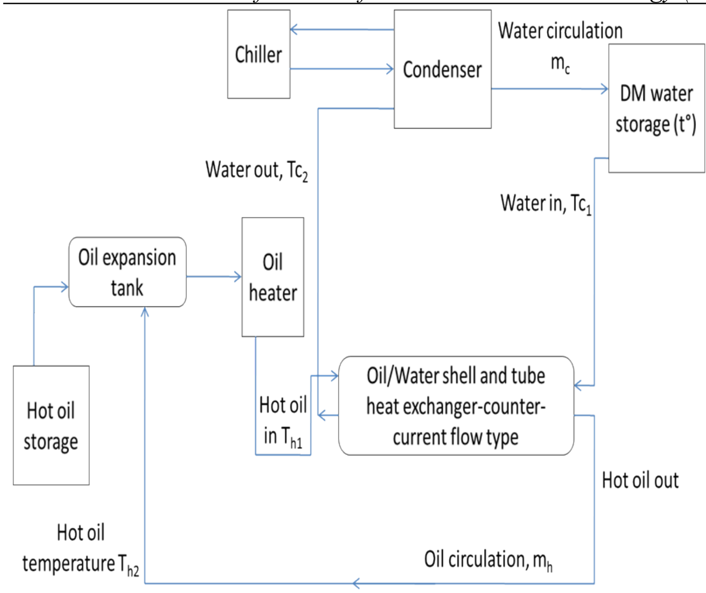

Figure3. Schematic of test setup for evaluation of heat transfer fluid

During the experiments, electrical heaters were used for heating of the heat transfer fluids, emulating the thermal charging process performed by a solar collector. Heat transfer was obtained by passing the hot thermic fluid through the counter-flow Shell-and-Tube heat exchanger. De-mineralized (DM) water was used as the fluid between the tubes and the shell. The inlet and outlet temperatures of water were recorded during experimentation (water temperature measurements were accurate within ± 0.75% of readings in liquids and ± 1% for steam).Tests were performed with a fully synthetic grade heat transfer fluid, of biphenyl oxide-biphenyl chemistry, as working fluid, having kinematic viscosity of 2.48 c Stat 40°C, flash point of 124°C and pour point of 12°C [16]. The following experimental procedure was performed in the test setup:

- The test loop was filled with DM water in the shell side and a pressure of about 10 bar was applied using nitrogen
- The oil was filled in the tube side, then an initial pressure of about 6-7 bar was applied using nitrogen, and the oil was heated in a separate chamber, using electrical heaters
- Both of the fluids, water and oil, were circulated during heating in their respective sides, until the set temperature of the oil was achieved.
- Then, steady-state heat transfer is achieved in the heat exchanger, at a predefined flow rate of the water and oil (as indicated by reaching minimal temperature variations in both, oil and water)
- The flow rates and temperatures of the oil and water were then measured at their respective inlet and outlet, into and from, the heat exchanger.
- For application of the Wilson plot technique, the flow rate of the water was fixed at 1200 kg per hour and the flow rate of the oil, at a particular temperature, was then varied from a maximum of about 1800 to as low as 1500 kg per hour.
- The inlet and outlet temperatures of the oil and water stream are then recorded at each flow rate under steady state condition.
- In line with the Wilson Technique, it is assumed that the thermal resistances in the water side and in the tube walls are constant [18-21].

Analysis

The following steps are conducted to obtain the overall resistance, RT:

(a) The LMTD, defined in Equation 7, is calculated using the inlet and outlet temperatures of the hot & cold fluids.

(b) The mass flow rate of the water is noted from the flow meter

(c) The specific heat of water at given temperature is taken from standard data books [22].

(d) The temperature differential of the water stream is calculated by subtracting the value of outlet temperature of water from its inlet temperature.

Using the data obtained in the above steps, at specific operating conditions, the value of RT can be calculated at these conditions using Equation 6.

Then, the value of d_i and L_w of the present experimental setup are introduced to Equation 12, and itis used for calculating Nu and hi for each of the operating conditions where RT had been obtained.

$$Nu = \frac{h_i d_i}{k} = C(Re)^n (Pr)^m . [\ 1 + \frac{0.01575}{1.25}^{\frac{2}{3}}\ ]$$

$$= C(Re)^n (Pr)^m \left[1.054\right]$$

$$h_i = 1.054\ V^{0.8}\ T_{m.o} \qquad (13)$$

Where, $T_{m.o}$ is the mean oil temperature expressed as a function of oil properties. Equation 13 assumes that the gross heat transport properties of the oil can be expressed as a function of the mean fluid temperature and fluid velocity and the exponent value of velocity is assumed to be0.8, based on the past literatures [14].

$1/V^n_r$ values for the Wilson plot are obtained from the experiments, where the oil's mass flow rate was varied from 1500 to 1800 kg/hr. After plotting the values of R_T vs $1/V^n_r$ and using a linear curve fitting method, the straight line expression in the form of Equation 10 is obtained for each set of temperatures of the oil flowing inside the tube, while the water flow rate and temperature in the Shell are kept constant. Table1 shows the values of intercept "C_2" and slope "$1/C_1Ai$", shown schematically in Figure 1, at each mean temperatures of the oil.

An expression for ho can be derived by combining Equation 3, Equation 4 and Equation 8, and as below:

$$R_o = (C_2 - R_w) = \frac{1}{h_o.A_o}$$

Hence,

$$h_o = \frac{1}{(C_2 - R_w).A_o} \qquad (14)$$

Table1.Experimentally determined values of intercept "C2" and slope "1/C1Ai"based on a modified Wilson method

Mean Oil Temperature	Slope "1/C1.Ai" Value	Intercept "C2" value
50	0.00108	0.0062
75	0.00086	0.0072
100	0.00102	0.01052
125	0.0008	0.0045
150	0.00092	0.00562
175	0.0046	0.0056
200	0.001325	0.007175

Taking the value of the thermal conductivity of steel k_w from the standard data book and substituting in Equation 4, Rw is calculated. Further, the value of intercept C2 obtained graphically and the value of R_w is substituted in Equation 14 to obtain the value of ho, the convective heat transfer coefficient of steam flowing in the shell side.

The overall heat transfer coefficient can be calculated from Equation 15:

$$U = \frac{1}{R_T A_o} \qquad (15)$$

The slope of the line obtained using Wilson plot is inversely proportional to the constant C1inline with Equation 16.

$$C_1 = \frac{1}{m.A_i} \qquad (16)$$

From Equation 12 and Equation 13, an expression for determination of hi can be derived so as to obtain Equation 17. The convective heat transfer coefficient of the oil flowing on the tube side can be calculated by substituting the value of "C1" into the Equation 17:

$$h_i = C_1.V^{0.8}.T_{m.o} \qquad (17)$$

An examination of Equation 13 and Equation 17 shows that C1 represents the bulk heat transport properties of the oil at the mean oil temperatures for a given geometry of the heat exchanger. Ideally C_1 should be equal to the numerical value of 1.054 times mean oil temperature as taken in Equation 13.However, during the fluid flow inside the tube, there are several other heat transport properties as well as few experimental uncertainties which can influence the value of C1. Further, the exponent of reduced velocity V_r was assumed initially to be equal to 0.8, which may or may not hold true. In order to verify the value of hi obtained from the Wilson Method it should be compared with previous references, or preferably, with the value of hi obtained using another test method. This is described below in the Results and Discussion section of this paper.

Results and Discussion

The thermal fluid commonly used in applications of concentrated solar power is a eutectic mixture of diphenyl-oxide and diphenyl, having kinematic viscosity of 2.48 c Stat 40°C, flash point of 124°C and pour point of 12°C. In the present study, starting from a temperature of 50°C, up to 200°C, in steps of 25°C, the test runs using the oil are repeated for three times so as to arrive at analyze the repeatability of the tests. The coefficients of convective heat transfer obtained using Equations 14, Equation15 andEquation17, are tabulated in Table2 and shown in Figure 4.An error analysis of the measurements of hi, the convective heat transfer coefficient of the oil flow inside the tubes, is presented in Appendix I.

Table2. Experimentally determined values of heat transfer coefficients for synthetic oil based on modified Wilson Plot Technique

Mean Oil Temperatu re	Convectiv e Heat Transfer Coefficien t on Water Side ho	Convectiv e Heat Transfer Coefficien t on Oil Side hi	Overall Heat Transfer Coefficien t U
50	181	192	99
75	116	259	86
100	80	201	63
125	182	245	115
150	138	250	106
175	155	410	115
200	116	149	80

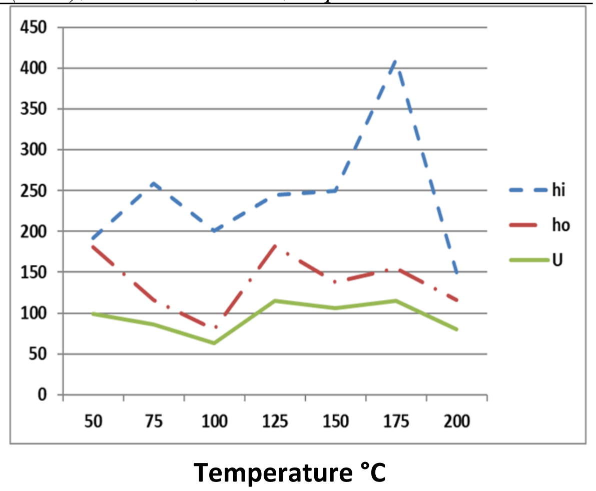

Figure4. Heat transfer coefficients at various experimental temperatures

The behavior of the individual heat transfer coefficients, ho, U and hi, shown in Figure 4are discussed below:

1. As can be seen in Figure 4, and consistent with Equation 4, the overall heat transfer coefficient, U, is smaller than hi and ho, and varies less than them. As expected, it is affected more by the lower of these two coefficients (ho). U decreases by about 30% as the temperature increases from 50°C to 100°C, because of the relatively large decrease (~50%) of ho in this temperature range. As T increases from 100°C to 125°C, U increases because the water in the shell side starts to transfer more heat. Between 125°C to 175°C, the variations in U are relatively small following the heat transfer coefficient on the water side. Beyond 175°C, there is a steep decrease owing to the vapor blanket effect on both water and oil side. As can be observed from Equation 4, mathematically also, U shall almost always be less than the individual values of ho and hi and the same is being observed in Figure 4. Furthermore, the value of U is within the range of values reported in the literature for oil-water systems [23]

2. The convective heat transfer coefficient “ho” for the water side decreases initially as the temperature increases from50 to 100°C owing to the latent heat effect. Between 100°C and 125°C, there is a sharp increase in the value of ho, due to the fact that the thermal conductivity of water increases with its temperature up to about 130°C and then starts decreasing [24]. Around the same temperature, vapor blanketing also reduces the heat transfer on the water side [25]. Consequently, ho decreases by about 20% as the temperature increases from 125°Cto 150°C. Further increase of the temperature causes the vapor blanket to collapse and there is a gradual increase of heat transfer as the temperature rises from 150°Cto 175°C.
3. The coefficient of convective heat transfer coefficient of oil hi experiences maximum variation in its values during the experiments because the oil is receiving energy from two sources i.e. the electrical heating and the pump. Both of these sources contribute a lot on the flow pattern, heat transfer ability and hence in the variations of the heat transfer coefficients of oil. Since, oil is in turbulence at the entrance of heat exchanger, the initial heat flow is high. From 50°C to 100°C, the oil tends to lose its momentum of flow and hence the value of hi decreases. As the temperature rises from 100°C to 125°C, hi increases because the thermal conductivity of water also increases and there is a consistent heat flow between oil and water. Between 125°C and 150°C, hi is nearly constant. Then it rises sharply, by about 60%, as T increases from 150°C to 175°C, Followed by an even larger decline as T increases from 175°C to 200°C.”
4. Beyond 150°C, vapor blanket collapses under the combined effect of velocity, time and temperature and the heat transfer increases drastically and then starts to normalize.
5. Chemical nature of oil and water causing varying degree of wetting ability of the heat transfer surfaces also effects heat transfer variations
6. Experimentation procedure such as variation in surface temperature during heat transfer, high surface temperatures of the oil heaters causing momentary vapor formation in the oil and the continuous testing of oil in the test setup wherein the inlet temperature of water is not constant at all temperatures of oil also causes variation. Ideally, a suitable chiller should have been designed along with the test set up so that the inlet temperature of water could be maintained uniform for all temperatures of heat transfer with respect to inlet temperatures of hot oil.

Like most other test methods used for evaluating the performance of oils, the present test method should be used primarily for a comparison between new oil, under consideration as a heat transferring fluid, and commercially used oil, in the same test setup and similar test conditions. Owing to limitation of experimental setup, the heat transfer between oil and water could only be measured up to a temperature of about200°C.Beyond this temperature the oil’s vapor pressure exceeded the maximum allowable pressure of the test apparatus.

Note that the value of h_i given in Table 2 and Figure 4 are calculated using the empirically simplified Equation17, where the slope1/ (C_1A_i),is obtained from Wilson plot. The Wilson plot itself is drawn using the reduced velocity function of the hot fluid flowing inside the tube based on certain assumptions as listed below:

- the thermal resistance of one of the heat exchanging fluids remains constant,
- the mass flow and thus the velocity of the other fluid is varied, keeping the flow in the turbulent regime,
- the heat transfer surface is smooth on both sides,
- the thermal resistance due to fluid fouling is neglected

- the value of the exponent of the velocity of the fluid, whose mass flow rate is varied, is assumed.

In line with earlier reported results by the authors [5], another way of obtaining h_i, the local convective heat transfer coefficient of the oil in the tube is proposed here, for comparison with the present values. It utilizes the values of R_T and ho obtained from the Wilson Plot and by substituting them in the classical thermal resistance Equation 4. For the sake of clarity, let this local convective heat transfer coefficient of oil obtained through Equation 4 be denoted by "Hi":

$$R_T = \frac{1}{A_i H_i} + \frac{\log\left(\frac{d_o}{d_i}\right)}{2\pi k_w L_w} + \frac{1}{A_o h_o} \quad (4a)$$

The two values of local convective heat transfer coefficient of oil – h_i, derived based on Equation 17 using the slope of Wilson Plot, and H_i, derived using Equation 4a – can then be compared. Thus, the validity of Equation13 can be assessed and a correction factor can be obtained so that a generalized form of the local convective heat transfer coefficient in terms of the mean fluid velocity and the mean temperature is derived. Let this corrected convective heat transfer coefficient be denoted by hi'.

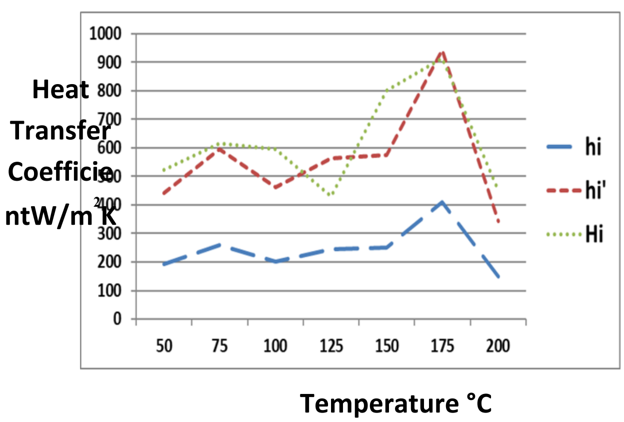

Figure5. Superimposition of the heat transfer coefficient curve obtained through Wilson plot onto that obtained from calculation using classical thermal resistance equation

The values of the three convective heat transfer coefficients, hi as derived from Equation17, Hi as obtained from Equation 4a and the corrected value hi' obtained by superimposing the curves of hi over that of Hi are graphically shown in Figure5.

As per Equation 13, the value of C_1 ideally should be equal to 1.054 times mean oil temperature as taken in Equation 13. However, during the fluid flow inside the tube, there are several other heat transport properties as well as few experimental uncertainties which influence the value of C_1. In order to find the best possible value of C_1, the curves in Figure5wereobtained by suitably multiplying the values of hi as obtained from the Wilson plot using Equation13 such that the curve moves upward and gets super imposed onto the values of Hi obtained thru the classical thermal resistance Equation 4a. The most suitable multiplication factor so obtained can then be introduced into Equation 13, to more accurately calculate the convective heat transfer coefficient, designated as h_i", expressed in terms of the velocity and mean temperature of the hot oil flowing inside the tube; as expressed in Equation18:

$$h_i'' = 2.3.V^{0.2}.T_{m.o} \quad (18)$$

The 2.3multiplication factor obtained on the basis of above discussions is able to accommodate the oil's Prandtl number and Reynolds number, experimentally taking into consideration the gross properties of oil and their variations with mean oil temperature. Further, so as to obtained an accurate fit, the exponent of velocity needed to be reduced to 0.2 from the initially assumed value of 0.8, during the process of superimposing the curve of hi" onto Hi. The exponent value of 0.8 was assumed on the basis of Wilson's original work whereas the value of 0.2 is derived based on the experiments and the chemical nature of the solar grade heat transfer oil. Equation 18 takes into consideration bulk heat transport properties of the fluid at various temperatures as well as experimental uncertainties. The corrected values of convective heat transfer coefficient hi" are compared with the original hi obtained using Wilson Plot, the H_i

obtained using classical heat resistance method and also with the graphically obtained hi values and are tabulated in Table3.

Table3. Comparison of heat transfer coefficients of oil obtained using different manners of calculations and derivations

Mean Oil Temperature °C	h_i	H_i	h_i’	h_i”
	Obtained from Wilson plot method	Obtained from classical thermal resistance equation	Obtained by graphical comparison	Based on proposed empirical relationship
50	192	524	442	499
75	259	614	596	540
100	201	595	462	581
125	245	432	564	622
150	250	802	575	664
175	410	914	943	705
200	150	450	344	745

A plot of the values of convective heat transfer coefficient h_i” obtained using the proposed empirical relationship in comparison to convective heat transfer coefficient obtained through the classical heat resistance method H_i up to the actually measured experimental temperatures of 200°C is shown in Figure 6.

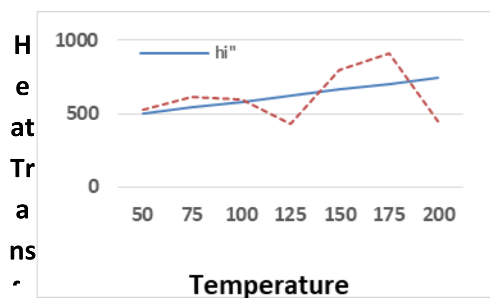

Figure 6. Comparison of Convective heat transfer coefficients hi” and Hi up to experimentally measured temperatures of 200°C.

The present test set-up enabled measurements of the heat transport properties of the oil, especially, the convective heat transfer coefficients, at elevated temperatures. Thus, it was able to overcome the gap area identified by the authors in the beginning of this study to a great extent. However, the test setup as designed suffered from a deficiency that it could not sustain the oil vapor pressure at T > 200°C. Hence, the measurements described above could not be performed beyond that limit on a regular basis. During the initial commissioning tests, taking enough safety measures, the test set-up was operated till a temperature of 350°C, on a one-time basis. The values of density and viscosity were measured up to 350°C during this trial run. It is worthwhile to mention here that the test set-up was designed taking the oil properties as published in its product data sheet [16] wherein a pressure of ~ 12 bar was specified at a temperature of 400°C.

Thus, using the experimentally determined values of density and dynamic viscosity, the Reynolds number up to a temperature of 350°C was also obtained.SeeFigure7 and Figure 8respectively, along with their regression equation and regression coefficients.

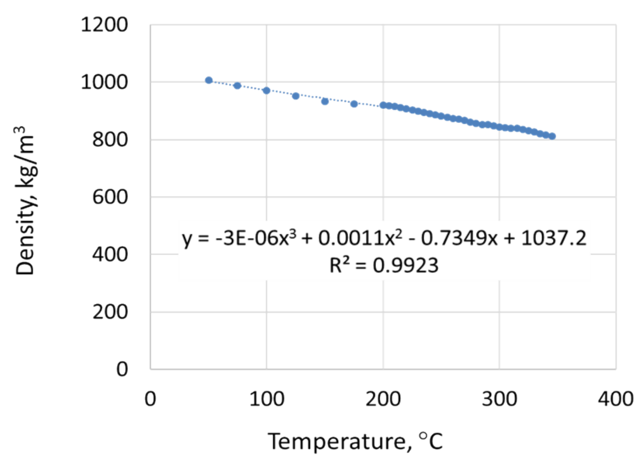

Figure7. Curve fitting for experimentally measured values of density of oil versus temperatures

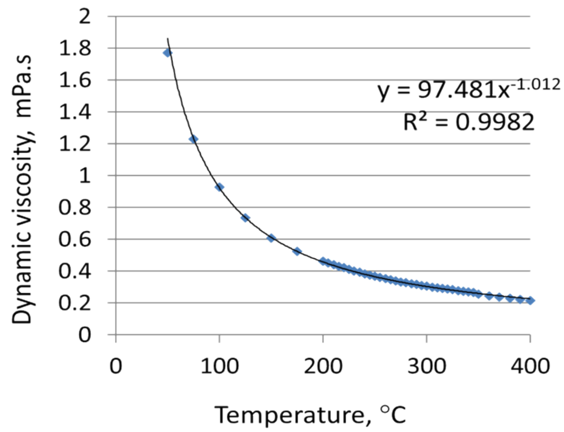

Figure 8. Curve fitting for experimentally measured values of dynamic viscosity of oil versus temperatures

From Figure 7and Figure 8, it is seen that the regression coefficients of both, the density and dynamic viscosity of the oil are very high (> 0.99), signifying that the respective curve-fitting expressions provide a good representation of the measurements. The values of density and dynamic viscosity, experimentally obtained up to a temperature of 350°C, were extra plated to 400°C using the regression equations. The oil's velocity and Reynolds number were calculated from the density and dynamic viscosity, as shown in Equation 19:

The velocity in tubes,

$$V_o = \frac{m_h}{\rho_o . A_{i-cs}} \qquad (19)$$

Where,

$A_{i-cs} = 18 \text{ x } (\pi/4)\, d_i^2 = 0.00351 \text{ m}^2$ ($d_i = 0.01575$ m)

Thus, the velocity of the oil, $V_o = \dfrac{m_h}{0.00351.\rho_o}$

$$\text{Reynolds Number, Re} = \frac{\rho_o V_o d_i}{\mu} \qquad (20)$$

The Reynolds number for the oil flow was calculated using Equation 20 at various temperatures and is shown in Figure 9.

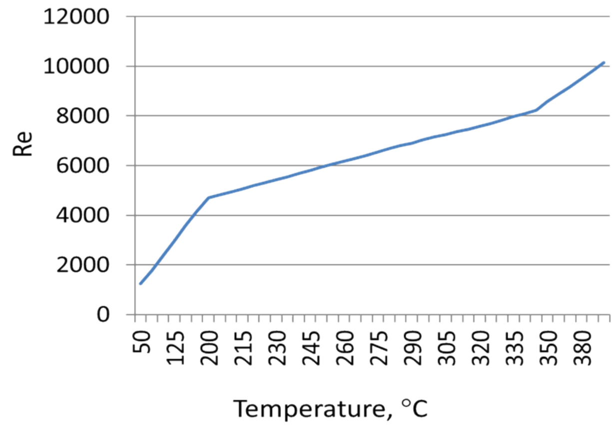

Figure 9. Calculated Reynolds number of the oil flow at elevated temperatures

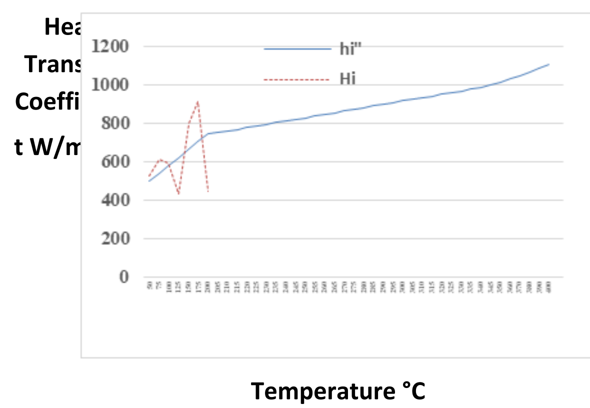

Figure 10. The empirical and calculated convective heat transfer coefficients, Hi and hi", shown from 50°C up to 200°C and 400°C, respectively

Equation 19 is used to calculate the velocity of the oil based on measured values of the density and viscosity up to 350°C and extrapolation from 350°C to 400°C. Then, the convective heat transfer coefficient, hi" is calculated using Equation 18 over the full operational range (50° – 400°C). From Figure 10, it can be noticed that there is a change of slope at 200°C because of the fact that up to the temperature of 200°C, the hi" values are calculated at a temperature interval of 25°C while beyond 200°C, the hi" values are calculated at a temperature interval of 5°C. Similarly, beyond 350°C, the hi" values are calculated at an interval of 10°C and hence the change of slope of the curve. Figure 11 has been plotted for the full temperature range of 50-400°C by considering the uniform temperature intervals of 25°C from where it can be observed that the curve for hi" is much smooth and uniform. The values of convective heat transfer coefficient with uniform temperature differences up to 400C is given in Appendix II.

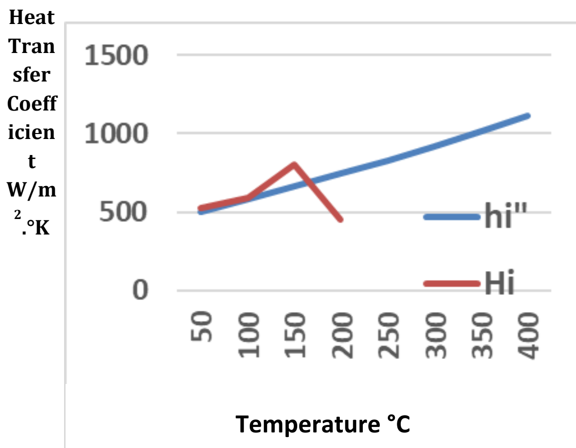

Figure 11. Convective heat transfer coefficients plotted at uniform temperature intervals of 25°C for entire operational mperature range of solar grade synthetic oil

Conclusions

(1) Experimental work on a commonly used synthetic heat transfer fluid was carried out in a test setup centered on Shell-and-Tube heat exchanger. Efforts were made to maintain the flow of the fluid in the turbulent or near turbulent regime.

(2) In line with the Wilson Method, the flow of the cooling fluid in the shell outside of the tubes was kept steady and constant and the velocity of fluid flowing inside the tubes was reduced gradually in the experimentation.

(3) On the basis of the Wilson Technique, the convective heat transfer coefficients were experimentally obtained for the fluid flowing inside as well as outside the tube and then the overall heat transfer coefficient was also calculated.

(4) There was a wide variation in the values of the heat transfer coefficients at different temperatures of oil, especially in the value of the convective heat transfer coefficient for the oil (hi), obtained using the Wilson Technique. Following a~35% increase-decrease-increase trend, as T was raised from 50° to 125°C, hi increased from ~250 to ~410 W/(m2-K)(>60%),as T increases from 150° to 175°C, then dropped to 150 W/(m2-K) (65%)as T increases from 170° to 200°C.

(5) If the measurement is carried out in a narrow temperatures range, say within 50-60°C, the variation of the heat transfer coefficients would be quite less. Because the heat transfer coefficients evaluated in this work are over a relatively wide temperature range, between 50°C and 400°C, several peaks and valleys appear in the data graphs.

(6) A superimposition of the convective heat transfer coefficient of oil derived using the slope of the Wilson Plot and that derived using the classical thermal resistance lead to a correction factor of 2.3 which can be utilized to express the local convective heat transfer coefficient in terms of mean fluid velocity and mean temperature. The 2.3 multiplication factor is able to accommodate the gross properties of oil and their variations with mean oil temperature.

(7) During the process of obtaining the best fit curve of the empirical coefficient hi" onto the Hi values, the exponent of the velocity was reduced to 0.2 from the initially assumed value of 0.8. Combining this with the multiplication factor of 2.3 accounted for the variations of the fluid's bulk heat transport properties with changes of temperatures.

(8) Discrepancies in the results are caused by vapor blanketing effect, surface temperature variations and difficulties in its measurement, dependence of convection phenomenon on surface geometry, and the physical conditions of both of the fluids taking part in the heat transfer process

(9) The present study resulted into an empirical relationship of convective heat transfer coefficient with velocity of oil and mean oil temperatures, and was able to determine the

convective heat transfer coefficient of oil for its entire range of operational temperatures

(10) The present method should be especially useful for a comparison between new oil, under consideration as a heat transfer fluid, and commercially used oil, in the same set up and similar testing conditions.

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Appendix-I

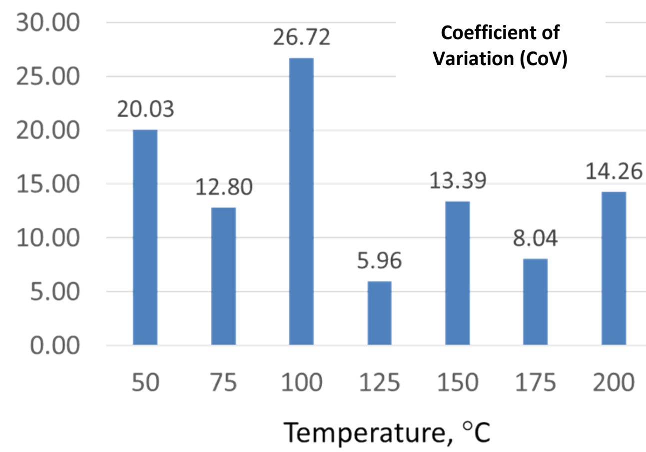
Experimental Error Analysis

I.1 Coefficient-of-Variation

CoV is a widely accepted way of comparing the test results in actual field conditions and is expressed in percentages as a ratio between the standard deviation to the mean values of the test results [26]. CoV depicts the gage repeatability and reproducibility of the test measurement system. Gage repeatability & reproducibility (GR&R) is a statistical approximation of the variation and percent of process variation for a test measurement system. It is recommended by the Automotive Industry Action Group (AIAG), Six Sigma and ISO 9000 quality plans. GR&R value between 10% and 30% suggests that the variability in the system is not negligible but may be acceptable whereas, GR&R value of up to 10% is considered as acceptable and workable [27]. The Coefficient-of-Variation (CoV) of h_i is calculated for error analysis. TableI.1 shows the CoV values depicting the GR&R of the measurement system through the Wilson test technique and the same is plotted in bar chart in FigureI.1. It can be inferred that the CoV of h_i values obtained in the experimentation is within the acceptable limits at all temperatures of the experiments.

TableI.1.GR&R of the Coefficient-of-Variation (CoV) of hi obtained while using Wilson Plot Technique

Temperature, °C	CoV
50	20.03
75	12.80
100	26.72
125	5.96
150	13.39
175	8.04
200	14.26



FigureI.1. GR&R of the Coefficient-of-Variation (CoV) of hi obtained while using Wilson Plot Technique

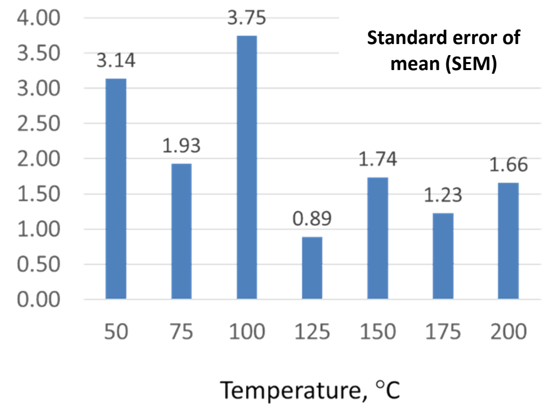
I.2 Standard Error of Mean

Standard error of means (SEM) is a statistical term that measures the accuracy with which a sample represents a population. It quantifies how much variation is expected to be present in the sample means that would be computed from each and every possible sample, of a given size, taken from the population. The units of SEM are the same as that of the original data. An analysis of the variation of the convective heat transfer coefficient of oil hi obtained in the study was done by calculating the

Standard Error of Mean (SEM) on hi with respect to temperatures. As shown in Table I.1 and Figure I.2, the standard error when using the Wilson Plot Technique and the mean value of hi can be found at various confidence levels, at different temperatures.

TableI.2. Standard Error of Mean(SEM) Values for hi obtained using the Wilson Plot Technique

Temperature, °C	SEM (W/m2.k)
50	3.14
75	1.93
100	3.75
125	0.89
150	1.74
175	1.23
200	1.66



FigureI.2.Standard Error of Mean(SEM) Values for hi obtained using the Wilson Plot Technique

Appendix-II

Values of the Convective Heat Transfer Coefficients h_i" of Oil for its full operating temperature range up to 400°C

Table II.1 Calculated Values of the Convective Heat Transfer Coefficients hi" of Oil based on empirical results at 50° – 350°C and Extrapolation from 350° – 400°C

Temperature (°C)	Convective Heat Transfer Coefficients of Oil hi" (W/m2°K)	Temperature (°C)	Convective Heat Transfer Coefficients of Oil hi" (W/m2°K)
50	500	275	875
75	540	280	883
100	581	285	892
125	623	290	901
150	664	295	909
175	705	300	918
200	745	305	927
205	753	310	935
210	762	315	943
215	770	320	952
220	779	325	961
225	787	330	970
230	796	335	980
235	804	340	989
240	813	345	998
245	822	350	1013
250	831	360	1032
255	839	370	1051
260	848	380	1071
265	857	390	1091
270	865	400	1111