NUMERICAL ANALYSIS OF SHELL AND TUBE HEAT EXCHANGER WITH CONTINUOUS HELICAL BAFFLES BY USING MOLTEN SALTS AND THERMAL OILS

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ABSTRACT: Three variants of shell and tube heat exchangers with zero, six and eight helical baffles are investigated in the present study for the heat transfer performance with hot molten salt flowing in the tube at inlet temperatures 838K and 563K and cold thermal oil flowing in the shell. Three types of thermal oils namely Exceltherm SST, LV1 and MK1 were analysed for relative performance. It was observed that the temperature increases rapidly with increase in the number of helical baffles and higher temperatures are realised for all three oils for Solar Salt at 838K compared to Solar Salt at 563K. The possible reason could be due to restricted passages created between the baffles (with higher number of baffles) causing the cold fluid flowing in the shell having better contact with the hot fluid flowing in the tubes. The restricted passages result in higher velocities in between baffles and causes better heat transfer. Solar Salt and oil Exceltherm SST combination has the highest Nusselt Number and overall heat transfer coefficient (OHTC) among the three oils investigated and further the difference in OHTC for the three oils is marginal and also no significant changes in the value is noticed for Solar Salt at 563K and 838K. In view of oil Exceltherm SST having highest Nusselt number and OHTC, using oil Exceltherm SST would be better option for heat exchangers designed for maximum heat transfer coefficient. However, when higher outlet temperatures are desirable, oil Exceltherm MK1 would be a better option though it has lower OHTC and Nusselt number.

***Keywords* –Continuous helical baffles, Shell and tube heat exchangers, Molten Salts, Thermal Oils, Concentrated Solar power Technologies.**

1. INTRODUCTION

The Shell-and-tube heat exchangers (STHXs) are widely used in many industrial areas, such as refining, power generation, chemical industry, food processing, etc. The conventional design of shell and tube heat exchangers with segmental baffles apart from having low heat transfer coefficient on the shell side has other major disadvantages namely large back mixing due to the zigzag flow pattern, fouling occurring in dead zones on each side of a baffle up against the shell and high shell side pressure drop. Various shell-side intensification technologies with improved baffle layouts to overcome the listed shortcomings have been developed to increase the heat transfer coefficient on the shell side and reduce the shell side pressure drop and the helical baffles was one of the improved structures. The helical baffles was firstly proposed by Lutcha and Nemcansky (1990) and their findings revealed that the flow pattern with properly arranged helical baffles on the shell side could approach a plug flow resulting in high transfer coefficient associated with lower shell side pressure drop. In recent years, helical baffle heat exchangers have been gradually popularized in industrial applications because of reduced fouling, lowered maintenance and operating costs, had increased service life. Research on helical baffle heat exchangers has mainly focused on baffle configurations, including various inclination angles, baffle shapes, and connection patterns [1-5]. Many Researchers investigated heat transfer in conventional Shell-and-tube heat exchangers for concentrated solar power (CSP) using molten salts and thermal oils [6]. Molten salts become continuously more attractive as thermal energy storage (TES) and heat transfer fluid (HTF) materials due to their expected thermal stability at high temperatures (> 600°C) and low costs. The key advantages of using molten salts as HTF and TES are their reasonably low-costs, scalable energy storage capacity, low vapor pressure (unpressurized storage) and low viscosity (pumpability) [7-9]. Thermal oil are widely used in CSP and it can be used for more than 30 years and another advantage of this thermal oil is its low vapor pressure (1.06 MPa at 398°C), which reduces the pressure required in the solar field piping to keep the oil in a liquid phase when it is at its maximum working temperature. The thermal limit of 398°C is another constraint of this thermal oil, because the overall CSTP plant efficiency depends on the temperature of the super-heated steam delivered to the power block, and such temperature is limited by the temperature of the oil used to generate it [10-12].

2. METHODOLGY

A continuous helical baffle shell and tube heat exchanger (CHB-STHE) of overall specifications as given in table-1 is modelled in Solid Works modelling software and imported into geometry module of Ansys CFX CFD software. The model of the CHB-STHE front and side views are show in fig:1. The isometric view of continuous helical baffle (0,6,8) shell and tube heat exchangers are shown in fig:2 and the isometric views of CHB-STHE after completion of meshing is shown in fig:3.

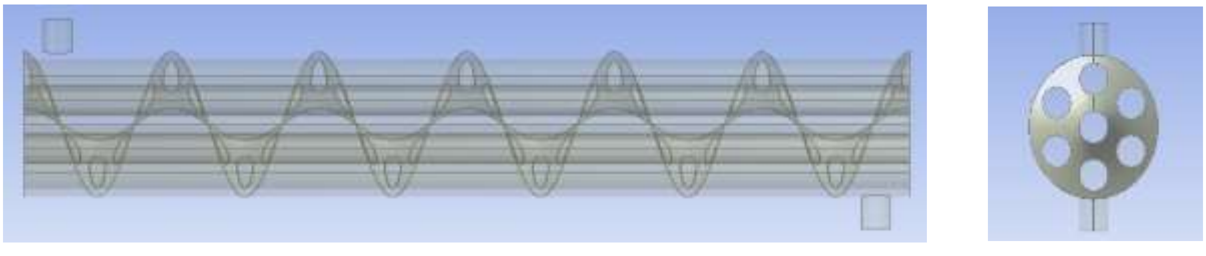
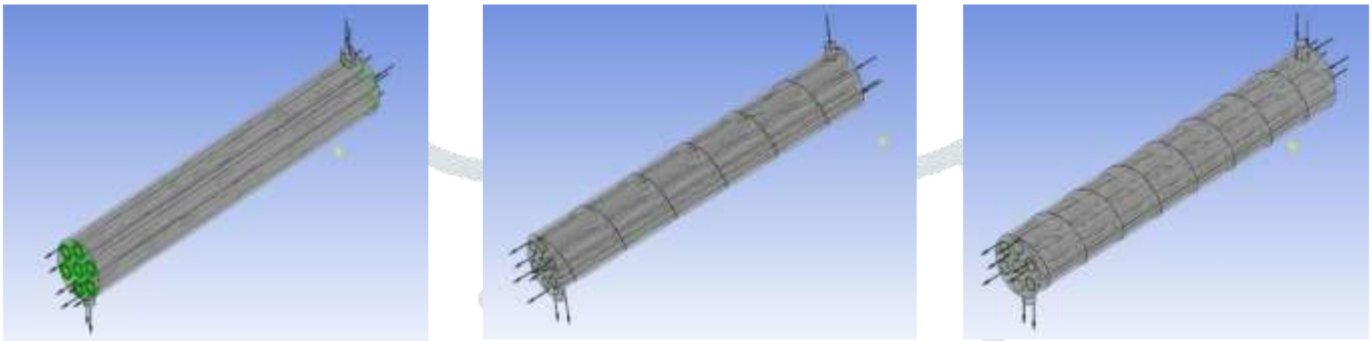


Fig: 1 Model of the CHB-STHE front and side views

Table:1 Specifications of Continuous helical baffle shell and tube heat exchanger

S. No	Parameters	value
1	Baffle spacing (B)	0m/3m/2.25m
2	Baffle angle (θ^0)	$0^0/59.04^0/46.03^0$
3	Tube pitch (T_P)	0.8m
4	Inside diameter of shell (D_I)	2.7m
5	Inside diameter of tube (T_I)	0.6m
6	Outer diameter of tube (T_O)	0.612m
7	Effective length of tube (L)	18m
8	Number of tubes (N_T)	7



a) 0 Baffles **b) 6 Baffles** **c) 8 Baffles**

Fig: 2 Isometric views of a) 0 baffles b) 6 baffles c) 8 baffles continuous helical baffle heat exchangers

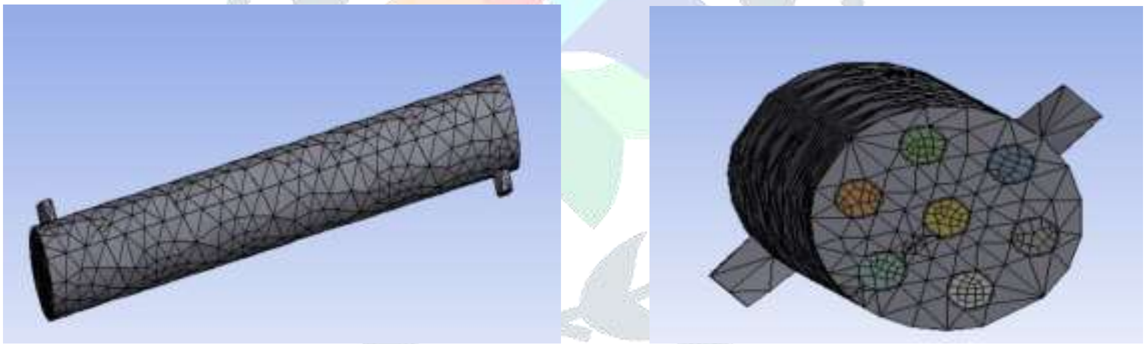


Fig:3 Isometric views of CHB – STHE after completion of meshing

Physical and Thermo dynamic properties of various thermal oils and molten salt used in the present study. Here table-2 shows the molten salt thermophysical properties and table-3 shows the thermal oil thermophysical properties.

Table: 2 Molten salt thermophysical properties

Temp (K)	Density [Kg/m3]	Heat capacity (J/Kg K)	Thermal conductivity (W/m K)	Dynamic Viscosity (Pa-s)
290	1899	1495	0.5	3.25
565	1740	1538	0.55	1.16

Table 3.3 Thermal oils thermophysical properties

Temp (K)	Density [Kg/m3]	Heat capacity (J/Kg K)	Thermal conductivity (W/m K)	Dynamic Viscosity (Pa-s)
XCELTHERM LV1	1048.7	1623	0.1341	3.422
XCELTHERM MK1	1049.3	1599	0.1347	2.629
XCELTHERM SST	936.2	1968	0.1125	11.141

3. DATA REDUTION

3.1 Determining the heat transfer rate:

Heat transfer rate of shell side fluid:

$Q_C = M_C * C_{PC} * (T_{CO} - T_{CI})$

Heat transfer rate of tube side fluid is:

$Q_H = M_H * C_{PH} * (T_{HI} - T_{HO})$

Average heat transfer rate is defined as:

$Q_{AVG} = (Q_H + Q_C)/2$

Heat balance deviation in percentage is:

$EPS = ((Q_H - Q_C)/Q_{AVG}) * 100$

3.4 Temperature difference, LMTD:

$LMTDN = (T_{HI} - T_{HO}) - (T_{CO} - T_{CI})$

$LMTDD = \log((T_{HI} - T_{HO})/(T_{CO} - T_{CI}))$

$LMTD = LMTDN/LMTDD$

3.5 Over-all heat transfer coefficient:

The overall heat transfer coefficient, U, is defined by

$A_O = N_T * (pi) * T_O * L$

$U = Q_{AVG}/(A_O * LMTD)$

3.6 Heat transfer coefficient of tube side:

$F_T = (1.82 * \log(Re_h) - 1.64)^{-2}$

(if $Re_h < 2300$)

$$H_T = \left(\frac{K_H}{T_I}\right)\left(3.657 + \frac{0.0677 * Re_h * Pr_h * \left(\left(\frac{T_I}{L}\right)^{1.33}\right)^{0.33}}{1 + 0.1 * Pr_h * \left(Re_h\left(\frac{T_I}{L}\right)\right)^{0.3}}\right)$$

(else if $Re_h > 2300$ and $Re_h < 10000$)

$$H_T = \left(\frac{K_H}{T_I}\right)\frac{\left(\left(\frac{F_T}{8}\right) * (Re_h - 1000) Pr_h\right)}{\left(1 + 12.7\left({}^{F_T}/_{8}\right)^{0.5} * \left(Pr_h{}^{0.667} - 1\right)\right)}\left(1 + \frac{T_I}{L}\right)^{0.67}$$

(else if $Re_h > 10000$)

$$H_T = 0.027 * \frac{K_H}{T_O} * Re_h{}^{0.8} * Pr_h{}^{0.667} * \left(\frac{Mu_h}{Mu_{wh}}\right)^{0.14}$$

Nusselt number of tube side:

$$Nu_T = \frac{H_T * T_I}{K_H}$$

3.7 Heat transfer coefficient of shell side:

$$D_E = 4 * \frac{T_P^2 - (\Pi * 0.25 * T_O^2)}{\Pi * T_O}$$

Where, Thermal conductivity of tube (K_T)=385

$$H_S = \frac{1}{\frac{1}{U} - \frac{T_O}{T_I * H_T} - \frac{T_O}{2K_T} * \log\frac{T_O}{T_I}}$$

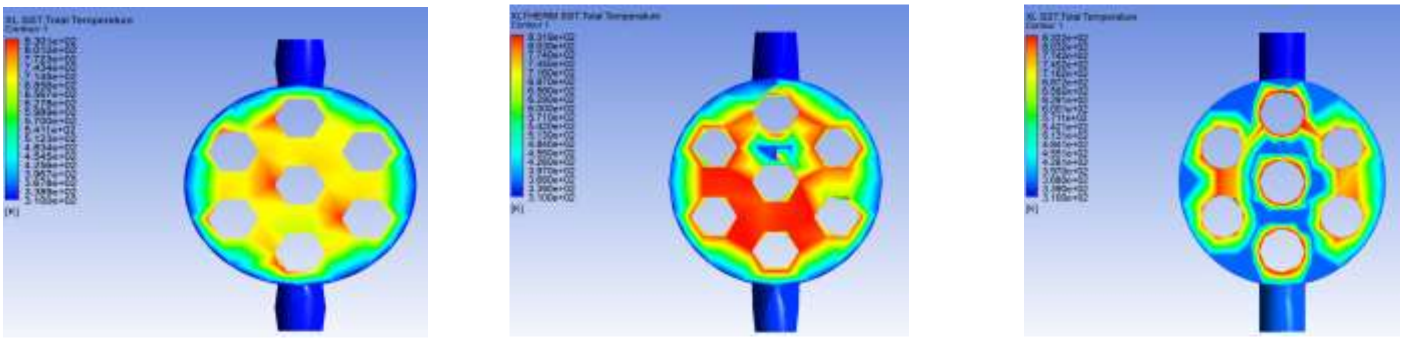
Nusselt number of shell side:

$$Nu_S = \frac{H_S * D_E}{K_C}$$

4. RESULTS AND DISCUSSIONS

4.1 Temperature contours:

Temperature contours for 0 baffles, 6 baffles, 8 baffles in continuous helical baffle heat exchangers side views are shown in fig:4. Here 8 baffles heat exchanger having the highest shell side temperature distribution compared to 0 baffles and 6 baffles.

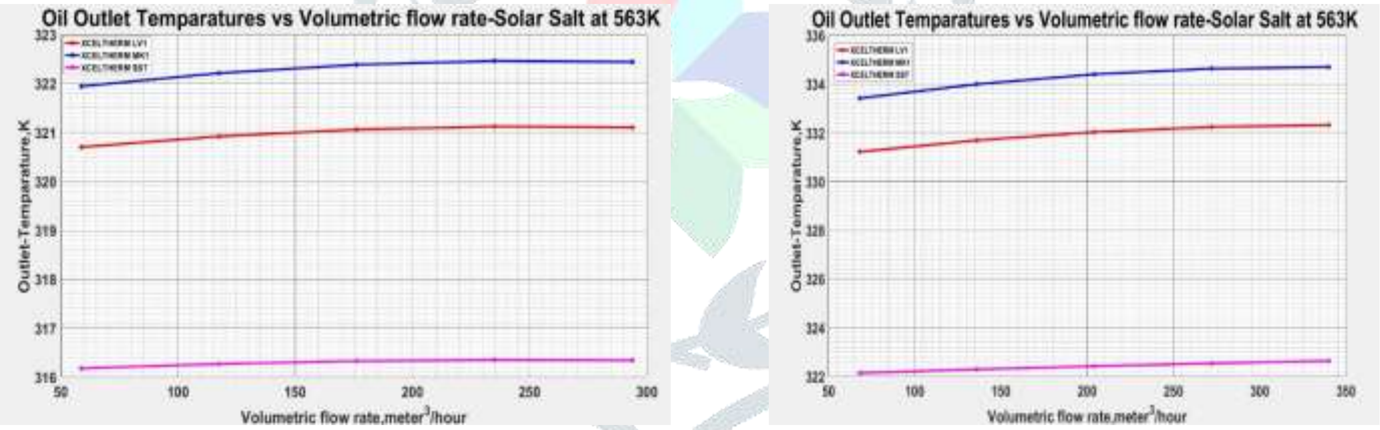


a) 0 Baffles b) 6 Baffles c) 8 Baffles

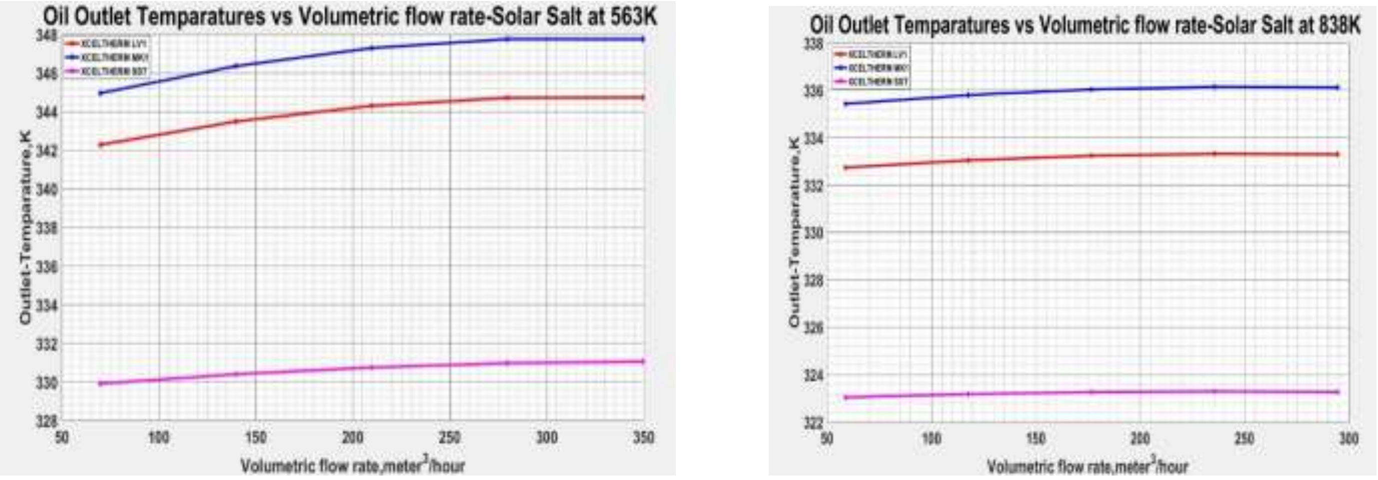
Fig: 4 Contour of total temperature distribution on a) 0 Baffles b) 6 baffles c) 8 baffles cross section (side views) outlet side

4.2 Graphs:

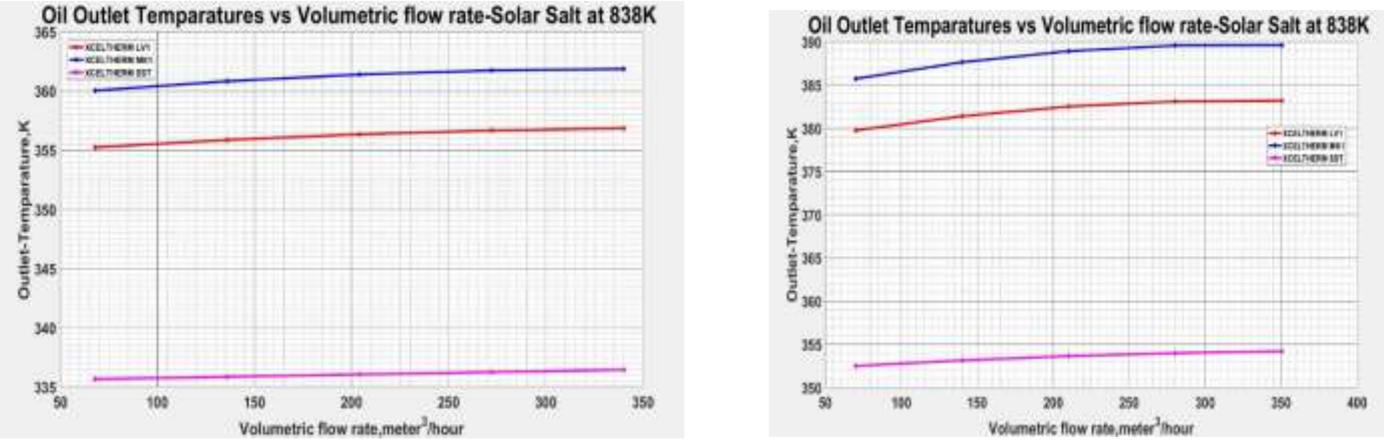
Figure 5 a to f represents variation of outlet temperatures of 3 types of thermal oils investigated namely SST, LV1 and MK1 in the heat exchanger 0 baffles, with 6 and 8 continuous helical baffles. In case of SST oil, the temperature more or less remains same with variation in volumetric flow ratio of Solar Salt at 563k and 838k, indicating that no change of temperature with increase in Reynolds number of hot fluids, that is Solar Salt. The same trend is seen for other two oils also for all the three heat exchangers studied. However, the temperature increases rapidly with increase of continuous helical baffles and higher temperatures are realised for all three oils for Solar Salt at 838k compared to Solar Salt at 563k. The temperature for SST rises from 316k for without baffles to 322k and 330k for 6 and 8 baffles respectively. The possible reasons for the rise of temperature with increasing baffles could be due to restricted passages created between the baffles causing the cold fluid flowing in the shell having better contact with the hot fluid flowing in the tubes. The restricted passages result in higher velocities in between baffles and causes better heat transfer. It is above seen that among the three oils integrated oil MK1 showed highest outlet temperature of 346k followed by 343k and 330k for 8 baffles while lower of temperatures are noticed for heat changes is without baffles. For Solar Salt at 838k, the same trend is observed indicating 385k for MK1 followed by 380k and 352k for LV1 and SST respectively.



a) zero baffles b) 6 baffles



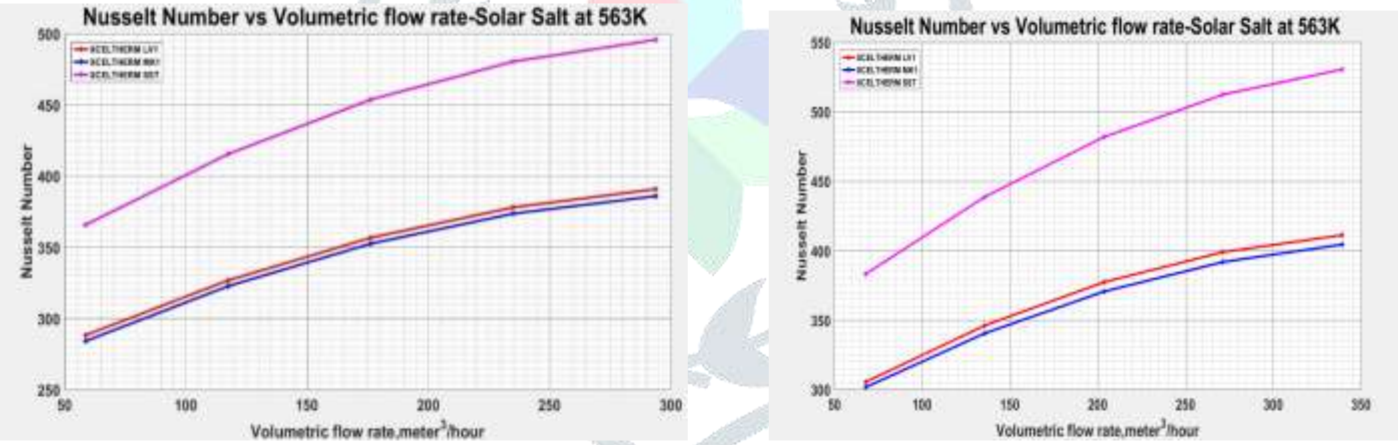
c) 8 baffles d) zero baffles



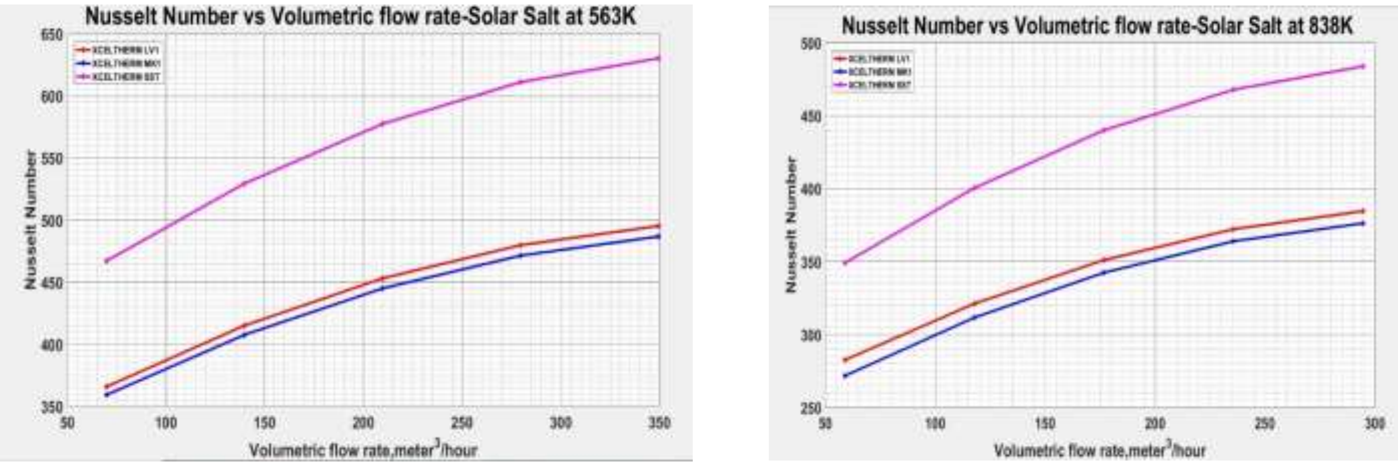
e) 6 baffles **f) 8 baffles**

Fig 5: Outlet Temperature versus Volumetric Flow Rate – Solar Salt at 563k and 838k of zero baffles, 6 baffles, 8 Baffles

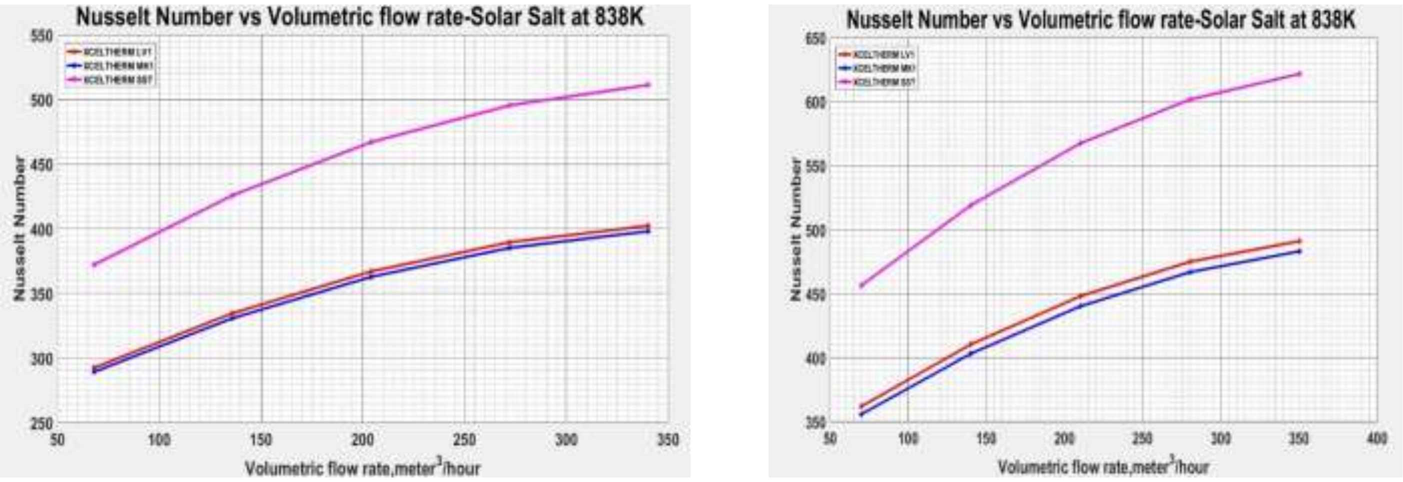
Nusselt number variation with volumetric flow rate of Solar Salt at 563k and 838k for the three thermal oils investigates for the heat exchanger without baffles, with 6 baffles and with 8 baffles is presented in figure 6 a to f. It is seen that thermal oil SST has highest Nusselt number for all the three types of heat exchangers. Also, the Nusselt number rapidly rises with increasing volumetric flow rate of Solar Salt. The Nusselt number for oil SST increases from 364 to 497 for Solar Salt 563k while for Solar Salt 838k, it rises from 347 to 485 for the heat exchanger without baffles. However, with 6 and 8 baffles, rapid rise in heat transfer with increasing number of baffles causes Nusselt number to rise from 364 to 380 for 6 baffles followed by 465 for 8 baffles for Solar Salt at 563k. The possible reason for rise in Nusselt number with increasing number of baffles (from 0 to 8 baffles) could be due to fluid flowing with higher velocity in between the baffles resulting in better interaction of cold fluid that is thermal oil with the hot solar salt flowing inside the tubes. Since Nusselt number is inversely proportional to thermal conductivity, oil SST with lowest value of thermal conductivity of 0.1125 as against 0.1347 for MK1 and 0.1341 for oil LV1. For this reason, oil SST recorded highest Nusselt through the outlet temperature of the oil SST has lowest value of 316k, 322k, 328k compared to higher temperature for 345k, 360k and 385k for oil MK1 for the three heat exchangers investigated (For Solar Salt 563k and volume flow rate 60 m/hr). Similar trend of Nusselt number increase for Solar Salt 838k is observed for rapid increase of Nusselt number with increase in volumetric flow and also rise of outlet temperatures of all the three oils.



a) zero baffles **b) 6 baffles**



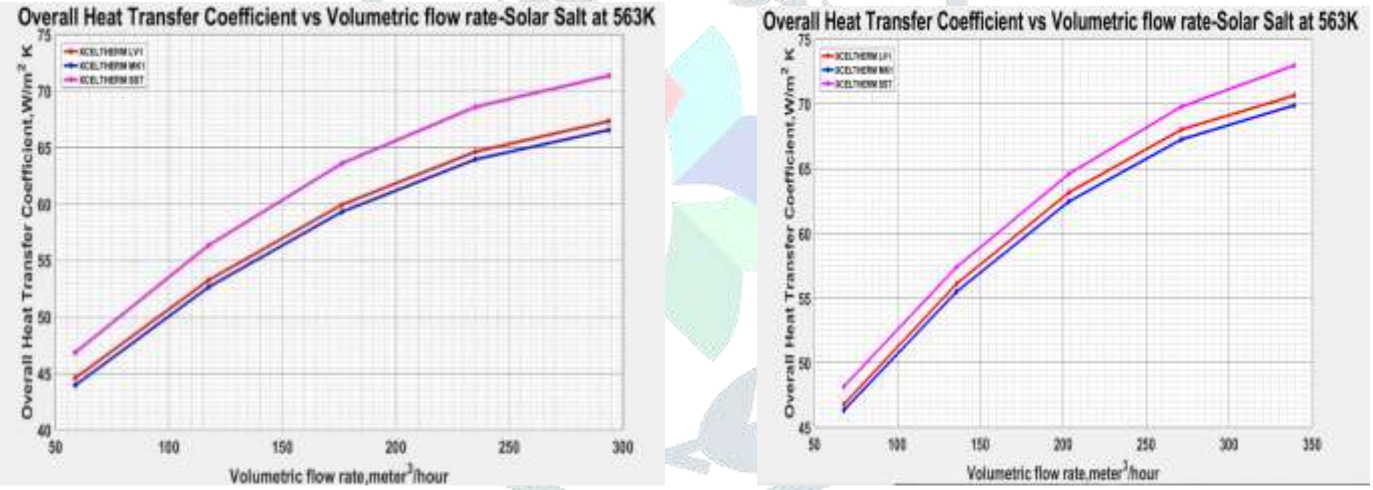
c) 8 baffles **d) zero baffles**



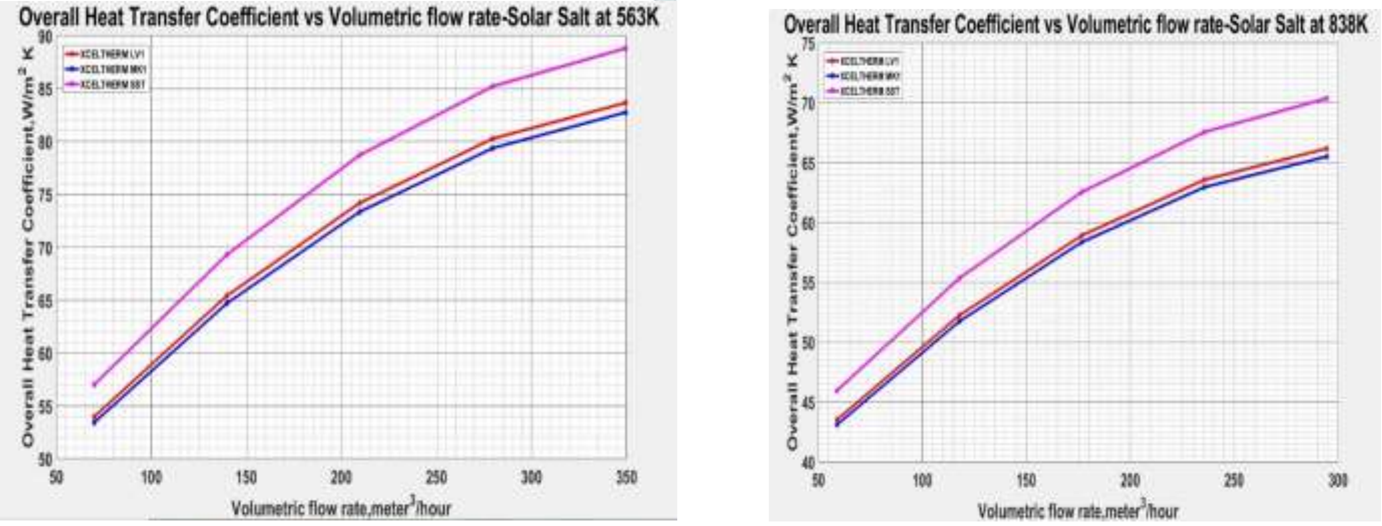
e) 6 baffles **f) 8 baffles**

Fig 6: Nusselt Number versus Volumetric Flow Rate – Solar Salt at 563k and 838k of zero baffles, 6 baffles and 8 baffles

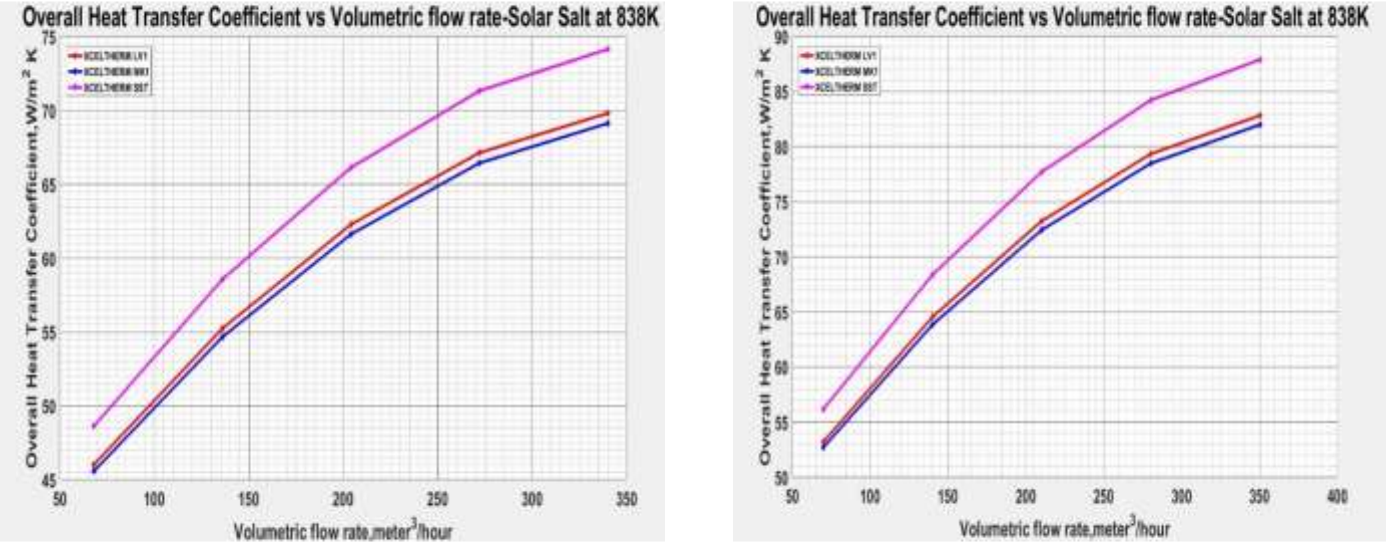
The Overall heat transfer coefficient (OHTC) for all the three heat exchangers investigated for Solar Salt at 563k and 838k is presented in figure7 a to f. The heat exchanger with Solar Salt and oil SST has the highest OHTC among the three oils. The rapid increase of OHTC with volumetric flow shows the similar trend for the Nusselt number increase unlike the large difference is Nusselt number for three oils, the difference in OHTC for the three oils is marginal and also no significant changes in the value is noticed for Solar Salt 563k and 838k. In case of SST oil, OHTC value raises from 46.53 to 71 for Solar Salt 563k while it is 45.64 to 70.64 for Solar Salt 838k (for the case without baffles). For 8 baffles the raise of OHTC for the same oil is from 56.58 to 89.18 for Solar Salt 563k and from 55.78 to 88.25 for Solar Salt 838k (for 8 baffles). As observed earlier for Nusselt number increase with increasing number of baffles. In case of OHTC also the value has significantly increased with increasing number of baffles that is from 46.53 for zero baffles to 56.58 for 8 baffles for Solar Salt 563k and from 45.64 to 55.78, for Solar Salt 838k.



a) zero baffles **b) 6 baffles**



c) 8 baffles **d) zero baffles**



e) 6 baffles **f) 8 baffles**

Fig 7: Overall Heat Transfer Coefficient versus Volumetric Flow Rate -Solar Salt at 563k and 838k of zero Baffles, 6 baffles and 8 baffles

In view of oil SST having highest Nusselt number and OHTC, using oil SST would be better option for heat exchangers designed for maximum heat transfer coefficient. However, 18 higher outlet temperatures one desirable oil MK1 would be a better option though it has lower OHTC and Nusselt numbers.

5. CONCLUSION

For the purpose of the solution to the restriction of continuous helical baffle heat exchangers (CHB-STHXs) in heat transfer, three variations of baffle angles and pitch lengths with different thermal oil combinations were investigated by numerical simulation. It is proved that the performance of heat exchangers is significantly influenced by varying angles and pitch lengths and also which oil is better option for heat exchangers designed for maximum heat transfer coefficient. The main conclusions are as follows:

(1) The inclination angle and helical pitch both play pivotal roles that effecting the performance of the continuous helical baffle heat exchanger. Variation of outlet temperatures of 3 types of thermal oils investigated namely SST, LV1 and MK1 with Solar Salt (at 563k and 838k) in the heat exchanger without baffles pitch (B) is 0 and angle (θ) is 0^{0}, with 6 baffles (B-3m, θ - 59.03^{0}) and 8 (B-2.25m, θ – 46.03^{0}) continuous helical baffles.
(2) The temperature increases rapidly with increase the number of helical baffles and higher temperatures are realised for all three oils for Solar Salt at 838k compared to Solar Salt at 563k due to restricted passages created between the baffles causing the cold fluid flowing in the shell having better contact with the hot fluid flowing in the tubes. The restricted passages result in higher velocities in between baffles and causes better heat transfer.
(3) Thermal oil SST has highest Nusselt number for all the three types of heat exchangers and also it is rapidly rising with increasing volumetric flow rate of Solar Salt. Among the three oils integrated oil MK1 showed highest outlet temperature with lowest Nusselt number compared to oil SST (Since Nusselt number is inversely proportional to thermal conductivity).
(4) The heat exchanger with Solar Salt and oil SST has the highest overall heat transfer coefficient (OHTC) among the three oils. The difference in OHTC for the three oils is marginal and also no significant changes in the value is noticed for Solar Salt 563k and 838k.
(5) In view of oil SST having highest Nusselt number and OHTC, using oil SST would be better option for heat exchangers designed for maximum heat transfer coefficient. However, 18 higher outlet temperatures one desirable oil MK1 would be a better option though it has lower OHTC and Nusselt numbers.

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