NUMERICAL INVESTIGATION FOR HEAT TRANSFER FROM LIQUID METAL TO AIR AND NITROGEN IN SERPENTINE COIL HEAT EXCHANGER

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ABSTRACT: State-of-the-art solar thermal power plants use thermal oils, water/steam, air or molten salts as heat transfer fluids (HTF). Oils can typically not operate at temperatures that would allow for high efficiency in the thermal-to-electric power conversion process. Solar salt melts at 220 °C. Under strong solar irradiation, it can be operated up to an outlet bulk temperature of 565 °C, but not higher in order to avoid film temperatures above 600 °C where it chemically decomposes. Advanced heat transfer fluids should have a low melting and a high boiling temperature resulting then in an increased operating temperature range. Pure liquid metals and their alloys have high thermal conductivities and thus show high potential for large heat transfer rates. Earlier authors carried out detailed study on screening of liquid metal candidates as advanced heat transfer fluids in solar power systems and concluded that the candidates with the highest potential are sodium, lead-bismuth eutectic alloy (LBE) and tin. In the present study a parallel flow serpentine coil heat exchanger is investigated numerically using Ansys CFX CFD Software for heat transfer between hot liquid metals, sodium and sodium potassium eutectic at 900 K and 600K and cold fluid air or nitrogen at inlet temperature of 310K.Cold fluid mass flow rate is varied from 0.5 to 2.5 Kg/Sec while hot fluid mass flow is kept constant at 5 Kg/Sec. Heat balance check is carried out for each CFD simulation and is found to be below allowable deviation of 5% . Overall heat transfer coefficient and cold fluid heat transfer coefficient increased linearly as the cold fluid mass flow rate increased for both liquid metals (sodium and sodium potassium eutectic), Sodium potassium eutectic shows slightly higher values compared to sodium liquid metal, nitrogen performed better when compared to air with both liquid metals (at 900 K and 600K). The outlet temperatures of cold fluids are high at 0.5 Kg/s, and are less at higher cold fluid mass flow rates of 2.5 Kg/s. Air outlet temperatures are high compared to nitrogen for both liquid metals at 600 K and 900 K. Nusselt number of both hot fluid and cold fluid increased when the cold fluid mass flow rate is increased. Nitrogen is having higher Nusselt numbers compared to air at both 600 K and 900 K. whereas sodium potassium is having higher Nusselt numbers compared to sodium at both 600 K and 900 K.

***Keywords*–liquid metals, shell and serpentine coil heat exchanger, Sodium, Sodium potassium eutectic, Concentrated Solar power Technologies.**

1.INTRODUCTION

Liquid metals have excellent properties as heat transport fluids due to the high thermal conductivity and their wide applicable temperature range. The latter opens the gate utilizing more efficient power conversion options beyond the limitations of current thermal solar energy systems. By utilizing them as thermal storage medium, an improved coupling of state-of-the art power conversion systems (PCS) to solar plants seems promising. Sodium is being used as the heat transfer fluid in 19th century and the low melting point and high boiling points and better thermo physical properties made sodium as better HTF. The eutectic mixture consists of 78% potassium and 22% sodium is also being used as HTF in solar thermal energy systems (Dawid Taler, 2016). Liquid metals as advanced heat transfer fluids that can give required advantages like higher working temparature and lager heat flux densities in concentrated solar power systems for increased efficiency and reduced cost. These heat transfer fluids have higher thermal conductivities, the operating temperature are 1173 K for sodium and 1873 K for lead bismuth eutectic. Five candidates with better thermo physical properties among alkali heavy and fusible liquid metals were studied where sodium (Na) and sodium potassium eutectic (NaK) are already having applications in solar and nuclear systems where other have no real time operational applications in the respective fields (J. Pacio, Th. Wetzel,2013). (Nikola Lorenzin, Alberto Ab_anades,2016.). This study is reviewed is major issues like safety compatibility with structural material. (Jung-Yang San, Gean-Sheng Lin, Kai-Li Pai,2009) The effectiveness weakly depends on NTU and no of tubes, the effectiveness of the serpentine coil is same as the straight through heat exchanger. Based on the previous experiments two liquid metals sodium (Na) and sodium potassium eutectic (NaK) are considered for this study and air and nitrogen are used as the cold fluids for receiving the heat from the hot fluid (Nikola Lorenzin, Alberto Ab_anades,2016.).

2. METHODOLOGY

A parallel flow serpentine coil heat exchanger is of the specifications given in table 1 is modeled in solid works and it is imported geometry ANSYS software. The detailed views are shown in figure 2.1.

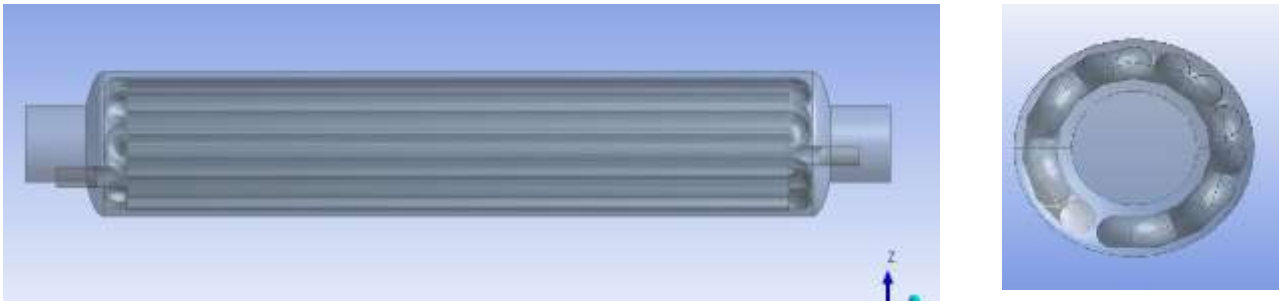


Fig 2.1: serpentine coil heat exchanger model front and side views

Table 2.1 Specifications of the serpentine coil heat exchanger

S. No	parameter	value
1	Material	Copper
2	Length of the shell	1.83 m
3	Outer Diameter of the shell	0.304 m
4	Outer Diameter of the tube	0.042 m
5	Inner Diameter of the tube	0.04 m

Both liquid metals have superior thermo physical properties compared to other conventional heat transfer fluids and their properties given in these following tables (table 2.2 and2.3).

Table 2.2: Thermophysical properties of sodium liquid metal

Sodium (Na)				
Temp (K)	Density (Kg/m^3)	Heat Capacity (J/Kg K)	Thermal conductivity (W/m K)	Dynamic Viscosity (Pa-s)
600	874	1301	73.7	3.21e-4
900	805	1252	58.34	2.01e-4

Table

2.3: Thermophysical properties of sodium potassium eutectic liquid metal

Sodium Potassium eutectic (NaK)				
Temp (K)	Density (Kg/m^3)	Heat Capacity (J/Kg K)	Thermal conductivity (W/m K)	Dynamic Viscosity (Pa-s)
600	809.4	900	25.6	2.856e-4
900	737	879	26	1.693e-4

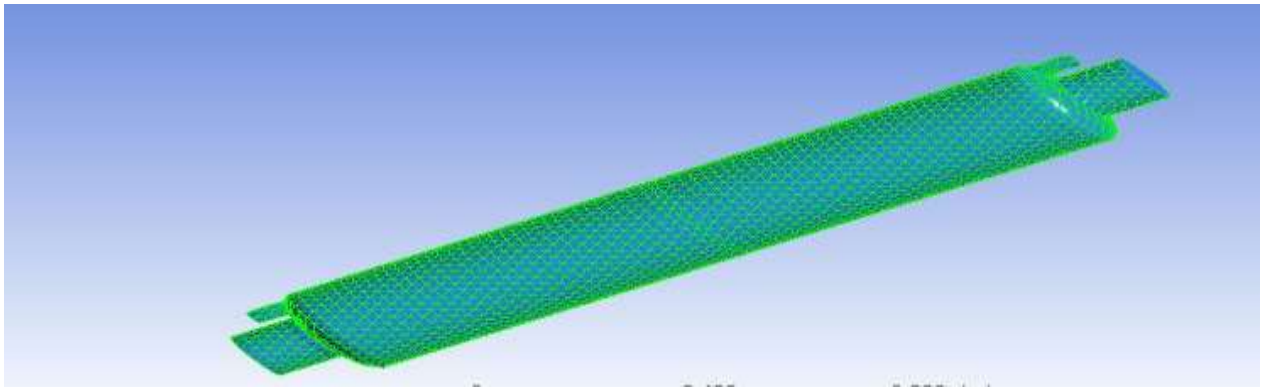


Fig 2.3: Meshing of the serpentine coil heat exchanger

3. DATA REDUCTION:

The model calculations for the sodium at 900 K with air at 2.5 Kg/s is given below

Heat transfer rate of the shell side fluid:

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

= 153.738 Kw

Heat transfer rate of tube side fluid:

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

= 158.039 Kw

Average heat transfer rate defined:

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

= 155.889 Kw

Heat balance deviation in percentage:

$$EPS = \left(\frac{Q_H - Q_C}{Q_{AVG}}\right) * 100$$

= 2.820

Logarithmic mean temparature difference:

$$LMTD1 = \frac{(T_{HI} - T_{CI}) - (T_{HO} - T_{CO})}{\ln(\frac{(T_{HI} - T_{CI})}{T_{HO} - T_{CO}})}$$

$$P = \frac{(T_{CO} - T_{CI})}{(T_{HI} - T_{CI})}$$

$$R = \frac{(T_{HO} - T_{HI})}{(T_{CI} - T_{CO})}$$

$$F = \frac{(\frac{\sqrt{R^2 + 1}}{R - 1}) * \log(\frac{1 - P}{1 - RP})}{\log(\frac{\frac{2}{P} - 1 - R + \sqrt{R^2 + 1}}{\frac{2}{P} - 1 - R - \sqrt{R^2 + 1}})}$$

$$LMTD = F * LMTD1$$

= 542.780

Overall heat transfer co-efficient:

$$U = Q_{AVG} * A_O * LMTD$$

= 92.369 W/M^2

Effective diameter of shell:

$$D_E = 4 * (\frac{P}{A})$$

= 0.144 M

Nusselt number of shell side:

$$NU_C = 0.02155 * {Re_C}^{0.8018} * {Pr_C}^{0.7095}$$

= 971.738

Shell side heat transfer co-efficient:

$$HT_C = \frac{NU_C * K_C}{D_E}$$

= 176.006 W/M^{2}K

Tube side heat transfer co-efficient:

$$H_T = \left(\frac{1}{\frac{1}{U} - \frac{1}{H_C} - \frac{D_O}{K_T} * \log\left(\frac{D_O}{D_I}\right)}\right) * \frac{D_I}{D_O}$$

= 219.169 W/M^{2}K

Nusselt number of hot side fluid:

$$NU_T = \frac{H_T * D_O}{K_H}$$

= 0.1503

Effectiveness:

$$C_R = \frac{C_{MIN}}{C_{MAX}}$$

$$NTU = \frac{U * A_O}{C_{MIN}}$$

$$\varepsilon = \frac{1 - \exp(-NTU(1 + C_R))}{(1 + C_R)}$$

= 0.1057

Table 2.4 output values for sodium 900 K with air at 2.5 Kg/s

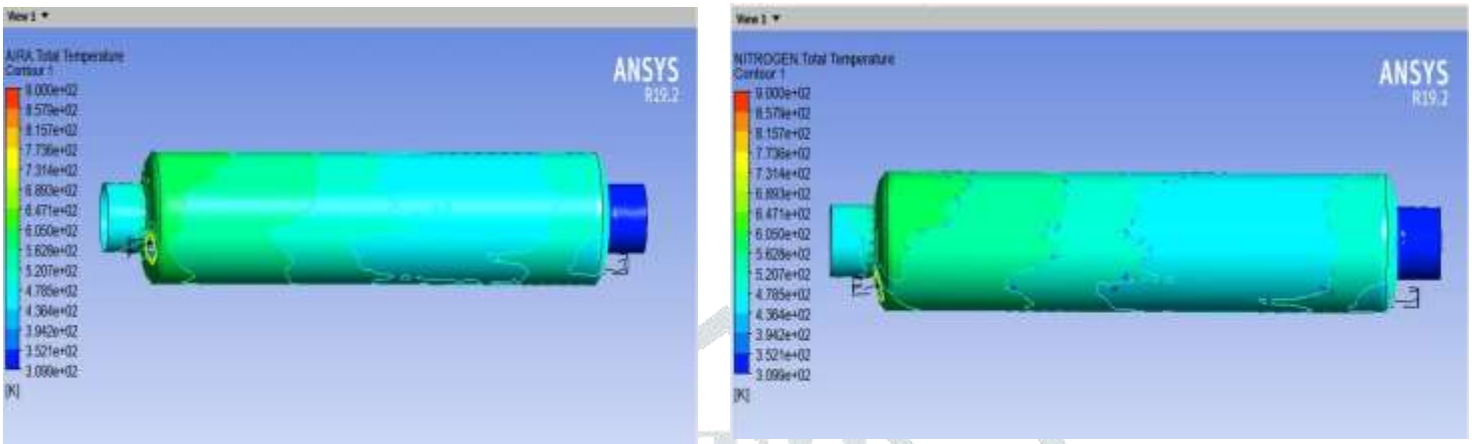
Sodium - 900K - Air								
Cold Fluid Mass Flow Rate (Kg/S)]	**LMTD**	**Qavg [KW]**	**Nu_h**	**Nu_c**	**H_T [W/m^{2}K]**	**H_C [W/m^{2}K]**	**U [W/m^2]**	**ε**
0.5	545.721	40.519	0.0356	253.524	52.199	45.963	23.879	0.1366
1	546.990	72.730	0.0691	451.672	100.810	81.888	42.763	0.1227
1.5	546.390	102.11	0.0974	663.496	142.090	114.852	60.105	0.1150
2	544.913	129.70	0.1243	805.656	181.356	146.065	76.553	0.1097
2.5	542.780	155.89	0.1503	971.738	219.168	176.0668	92.369	0.1057

4. RESULTS AND DISCUSSIONS

4.1 TEMPARATURE CONTOURS:

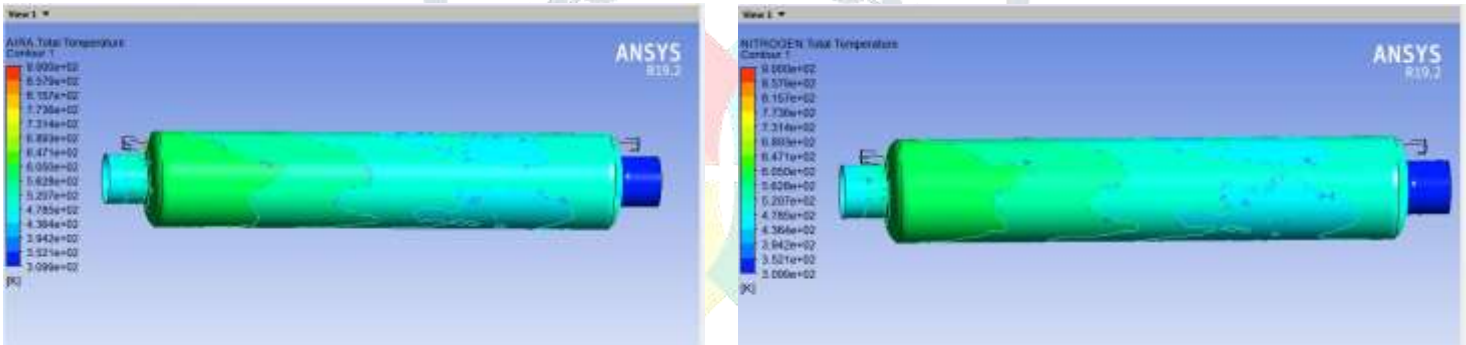
The temparature contours of shell side is show in following figures (4.1 and 4.2) when each liquid metal is being used with air and nitrogen when hot fluid mass flow rate of 5 Kg/s at 900 K and the cold fluid mass flow rate of 0.5 Kg/s at 310 K.

1.



(a) (b)

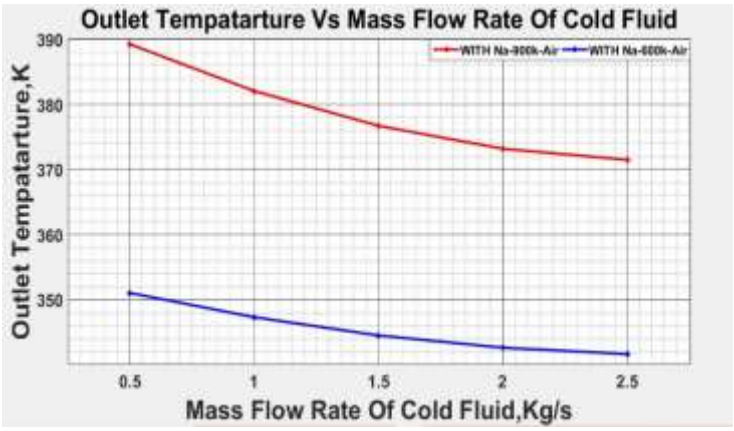
Fig 4.1: Temparature contour of shell (a) sodium with air (b) sodium with nitrogen

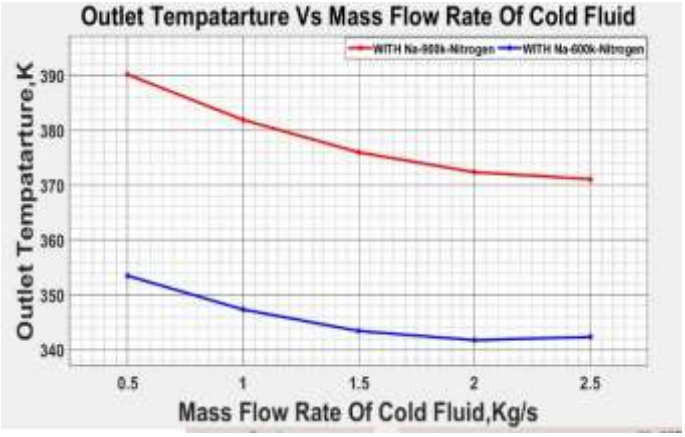


(a) (b)

Fig 4.2 Temparature contour of (a) NaK with air (b) NaK with nitrogen

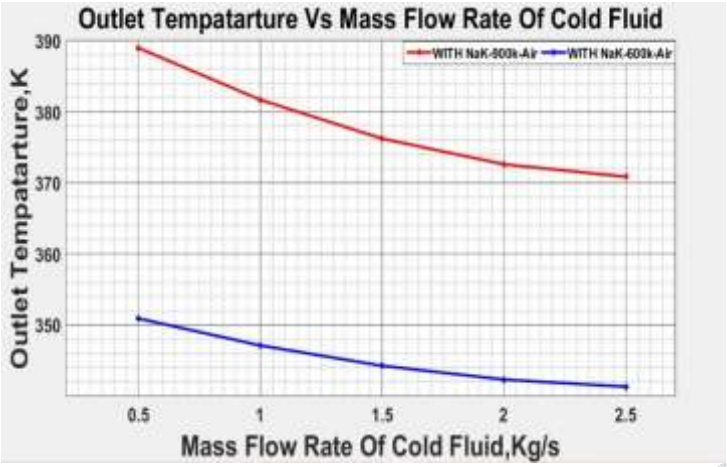
4.2 GRAPHS

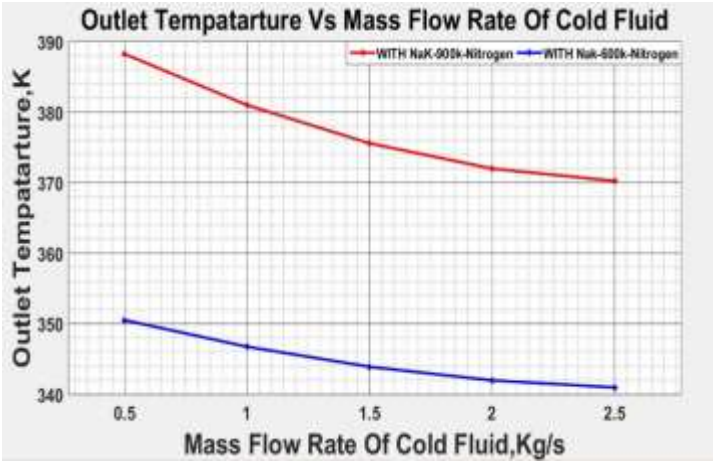




(a) (b)

Fig 4.4: Outlet temparature Vs mass flow rate of cold fluid (a) NaK and air (b) NaK and nitrogen

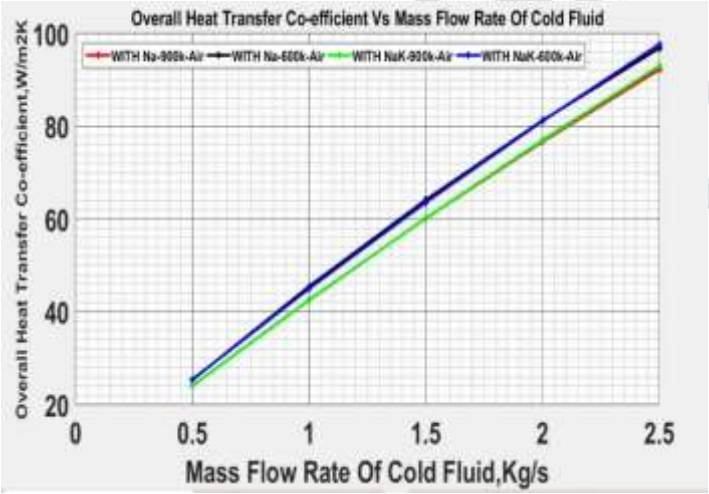


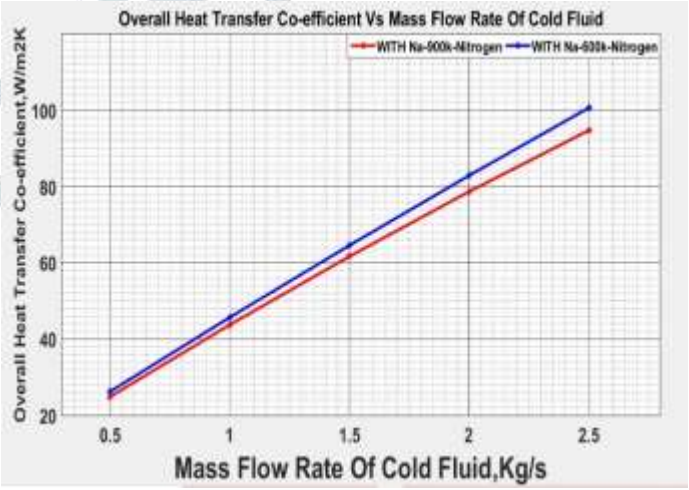


(a) (b)

Fig 4.4: Outlet temparature Vs mass flow rate of cold fluid (a) NaK and air (b) NaK and nitrogen

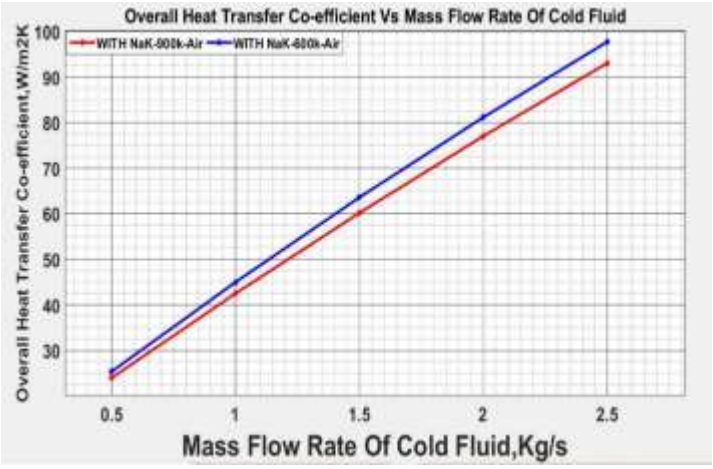
Figures 4.3 and 4.4 represent variation of outlet temperatures of air and nitrogen (cold fluids) when mass flow rate is varied from 0.5 to 2.5 kg/s (mass flow rate of hot fluid i.e., Na and NaK at 900 K and 600 K is kept constant at 5 kg/s). It is seen that at both hot fluid temperatures, the variation in outlet temperatures of air as well as nitrogen is almost identical for Na and NaK. Maximum variation for Na is 20 K for both cold fluids at 900 K and 10 to 12 K at 600 K. The possible reason could be due to lower Reynolds number of hot fluids at 600 K. (the heat transfer coefficient depends on Nusselt number and Nusselt number in turn depends on Reynolds number and Prandtl number). As the Reynolds number depends on the thermo physical properties viz density and viscosity, the density to viscosity ratio would be lower at 600 K compared to the ratio at 900 K (2.72e+06 for sodium liquid metal at 600 K and for sodium liquid metal 4.004e+06 at 900 K). Since outlet temperatures of both cold fluids are identical and mass flow rates are also same, the quantity of heat transfer from hot fluid would be strongly dependent on relative specific heats of the cold fluids. The quantity of heat transferred to nitrogen is 42 Kw and 159 Kw at mass flow rates of 0.5 and 2.5 Kg/s respectively, whereas the quantity of heat transferred to air is 40 Kw and 155 Kw at 0.5 and 2.5 Kg/s respectively.

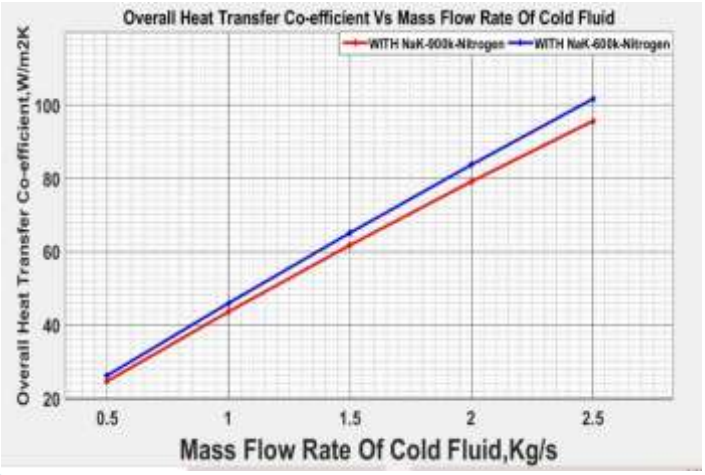




(a) (b)

Fig 4.6: Overall heat transfer coefficient Vs mass flow rate of cold fluid (a) sodium with air (b) sodium with nitrogen

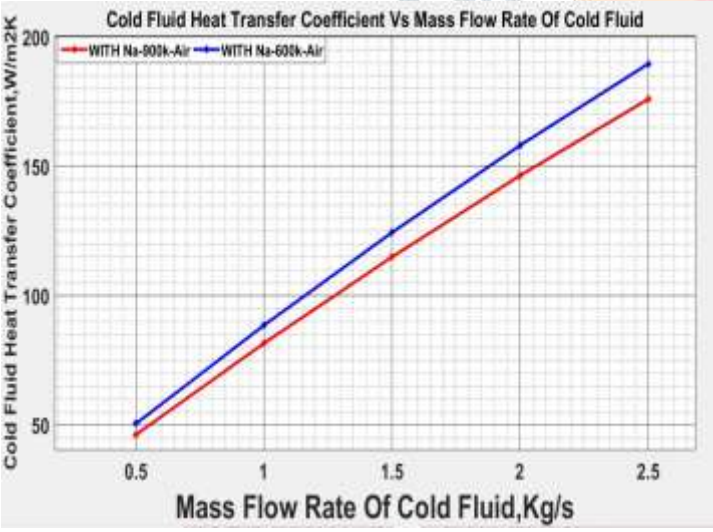


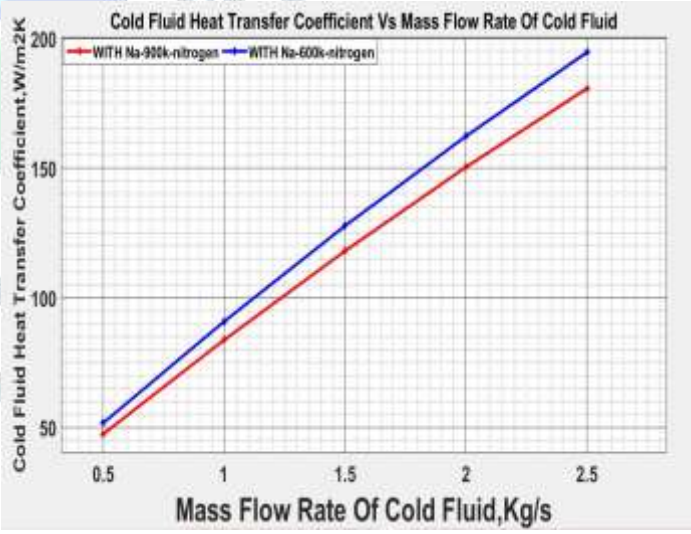


(a) (b)

Fig 4.7: overall heat transfer coefficient Vs mass flow rate of cold fluid (a) NaK with air (b) NaK with nitrogen

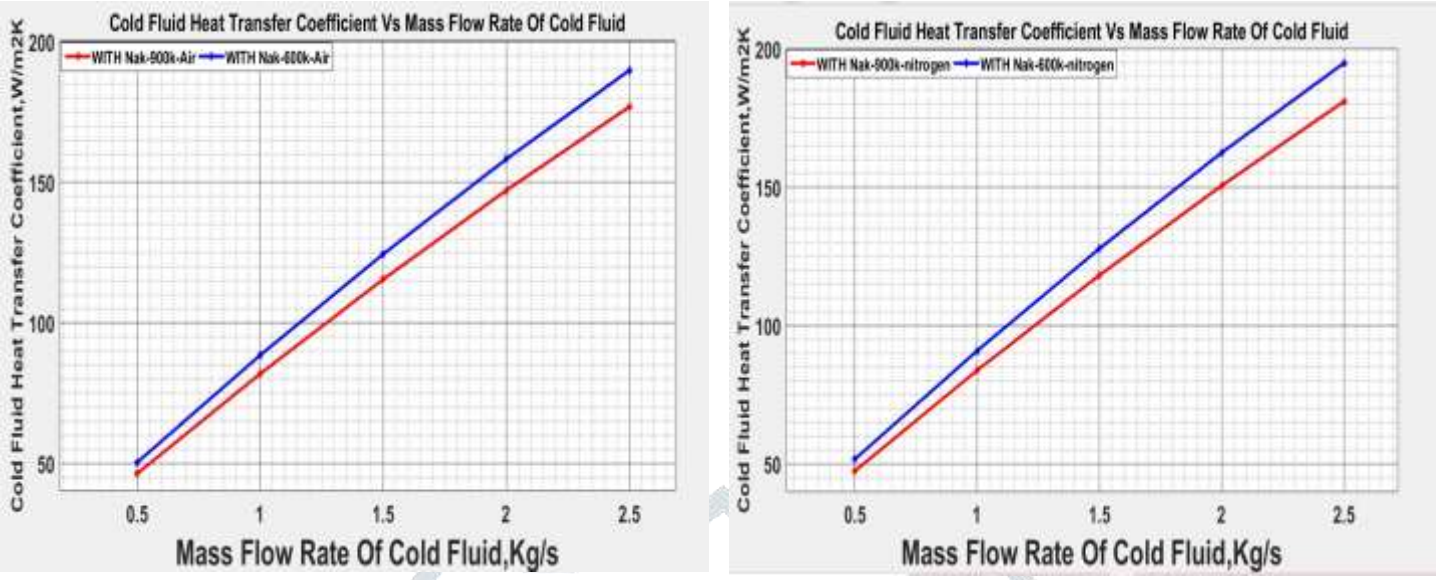
Referring to figures 4.6and 4.7 each cold fluid shows similar trend at 900 K and 600 K with regard to variation of overall heat transfer coefficient when mass flow rate is varied from 0.5 to 2.5 Kg/s. The variation is totally linear i.e., uniform increase of overall heat transfer coefficient with increase in mass flow rate of cold fluid. Among air and nitrogen, the overall heat transfer coefficient for nitrogen at 600 K and 900 K shows slight increase over the value for air (deference in overall heat transfer coefficient at 2.5 Kg/s is 2 W/m^2K and 3.5 W/m^2K at 900 K and 600 K respectively, the deference is 0 at 0.5 Kg/s). For sodium potassium eutectic liquid metal, the trend is similar. (deference is at flow rate of 2.5 Kg/s is 2.5 W/m^2K and 3.6 W/m^2K at 900 K and 600 K respectively, the deference is 0 at 0.5 Kg/s).





(a) (b)

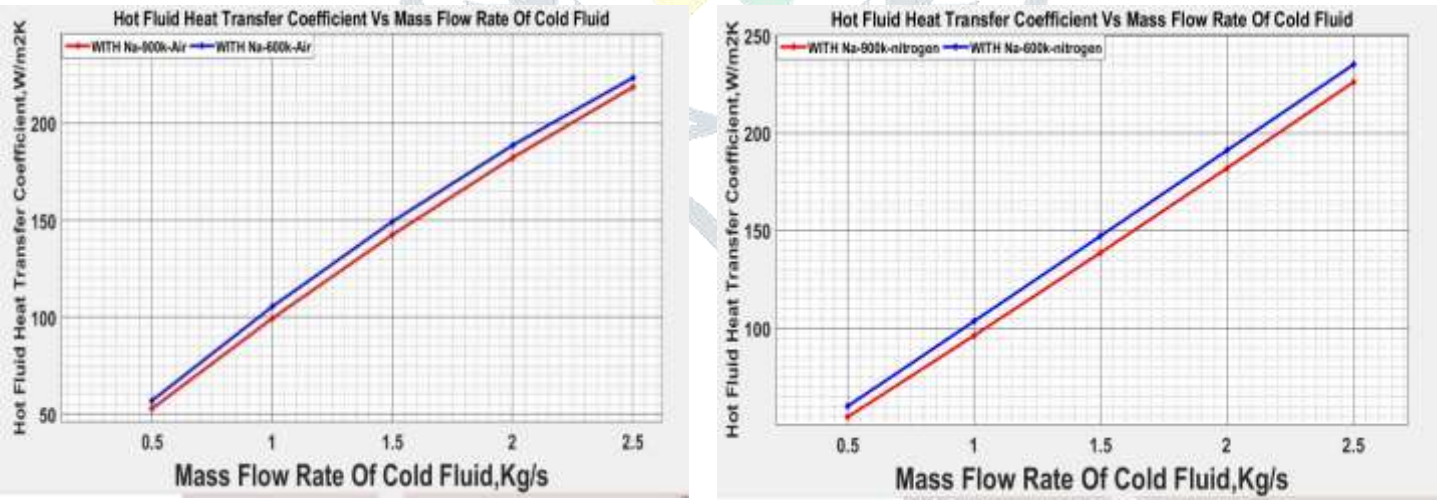
Fig 4.8: Cold fluid heat transfer coefficient Vs Mass flow rate of cold fluid (a) sodium with air (b) sodium with nitrogen



(a) (b)

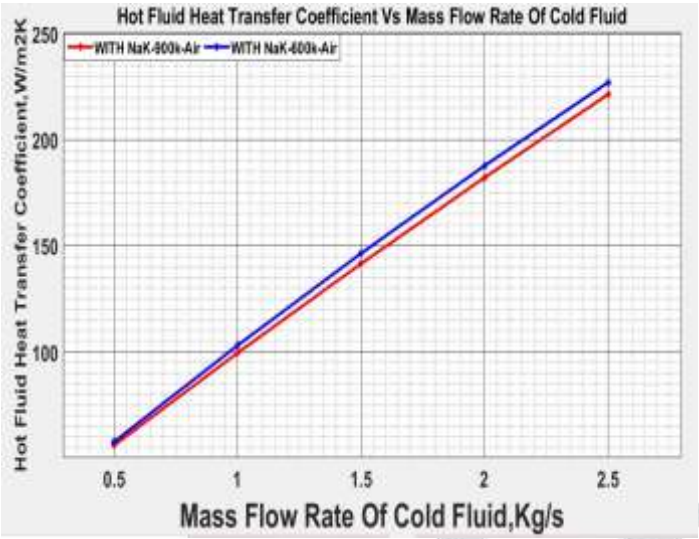
Fig 4.9: Cold fluid heat transfer coefficient Vs Mass flow rate of cold fluid (a) NaK with air (b) NaK with nitrogen

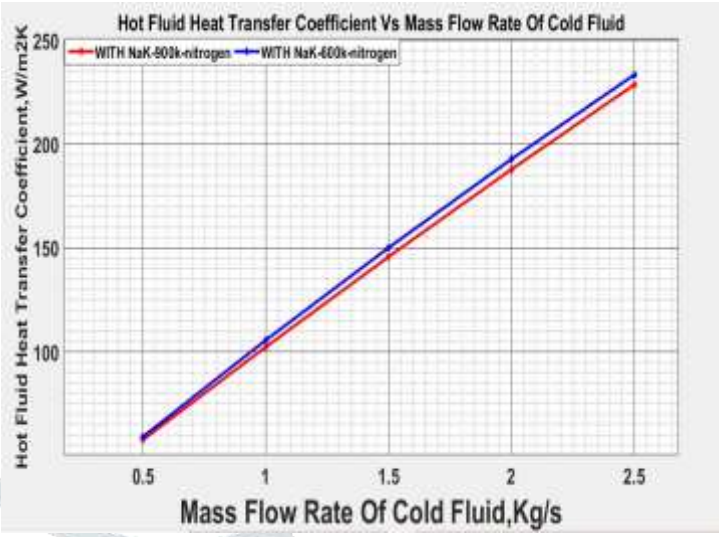
Figures 4.8 to 4.9 represents variation of heat transfer coefficient of air and nitrogen with heat transfer from hot fluids sodium and sodium potassium eutectic liquid metals at 900 K and 600 K. It is observed that for sodium liquid metal both air and nitrogen have higher heat transfer coefficient at 600 K compared to the values at 900 K at cold fluid mass flow rate of 2.5 Kg/s (194 for nitrogen,189 for air at 600k and 180 for nitrogen,176 for air at 900 K respectively). For sodium potassium eutectic similar trend is observed at 600 K and 900 K at cold fluid mass flow rate of 2.5 Kg/s (195 for nitrogen,189 for air at 600 K.181 for nitrogen,177 for air at 900 K), the difference between the cold fluid heat transfer coefficients is almost zero at cold fluid mass flow rate 0.5 Kg/s. The reason for increased heat transfer at 600 K is already explained earlier in connection with discussion on overall heat transfer coefficient. The heat transfer coefficient of air and nitrogen remained more or less the same for both liquid metals (sodium and sodium potassium eutectic).



(a) (b)

Fig 4.10 Hot fluid heat transfer coefficient Vs Mass flow rate of cold fluid (a) sodium with air (b) sodium with nitrogen





(a) (b)

Fig 4.11 Hot fluid Heat transfer coefficient Vs Mass flow rate of cold fluid (a) with NaK with air (b) with Nak with nitrogen

Figures 4.19 to 4.24 represents the variation of heat transfer coefficient of sodium and sodium potassium eutectic liquid metals at 600 K and 900 K. it is observed that when heat is transferred to cold fluid from sodium liquid metal, sodium liquid metal is having higher heat transfer coefficient at 600 K compared to the values at 900 K at cold fluid mass flow rate of 2.5 Kg/s (235.5 for nitrogen, 224 for air at 600 K compared to 224.6 for nitrogen, 219 for air at 900 K). Sodium potassium eutectic liquid metal similar trend is observed (233.6 5 for nitrogen 227.3 for air at 600 K compared 229 for nitrogen 221 for air at 900 K). The difference in heat transfer coefficients of sodium liquid metal at 600K and 900 K gradually decrease when the mass flow rate of 0.5 Kg/s, for sodium potassium liquid metal the difference in heat transfer coefficient at 600 K and 900 K is tend to become zero when the mass flow rate is 0.5 Kg/s.

5. CONCLUSIONS

A shell and serpentine tube heat exchanger is studied numerically with two different hot fluids (sodium and sodium potassium eutectic liquid metals) with two different cold fluids (air and nitrogen treated as ideal fluids). By observing the results, the following conclusions were drawn: -

- Hot fluid mass flow rates are being constant (5 Kg/s), the outlet temperatures of cold fluid are high at 0.5 Kg/s, and the outlet temparature are less when the cold fluid mass flow rates are 2.5 Kg/s. Air outlet temperatures are high compared to nitrogen for both liquid metals at 600 K and 900 K.
- Overall heat transfer coefficient increased linearly as the cold fluid mass flow rate increased for both liquid metals (sodium and sodium potassium eutectic). Sodium potassium eutectic shows slightly higher overall heat transfer coefficient (1%) compared to sodium liquid metal. Both liquid metals have slightly higher overall heat transfer coefficient when cold fluid is nitrogen compared to air (2.6%).
- Cold fluid heat transfer coefficient is increased when the cold fluid mass flow rate increased. Nitrogen is having higher heat transfer coefficient (2.5%) compared to air for both liquid metals at 600 K and 900 K. Both cold fluids showing slightly higher heat transfer coefficient (0.5%) for sodium potassium eutectic compared to sodium liquid metals at both 600 K and 900 K.
- Heat transfer coefficient of hot heat transfer coefficient increased when the cold fluid mass flow rate is increased cold fluid mass flow rate is increased from 0.5 Kg/s to 2.5 Kg/s. Sodium potassium eutectic is having higher heat transfer coefficient (2%) compared to sodium at both 600 K and 900 K. Heat transfer coefficient (2.5%) is slightly increased for both liquid metals when the cold fluid in nitrogen compared to that of air.
- Nusselt number of cold fluids is increased when the cold fluid mass flow rate is increased. nitrogen is having higher Nusselt numbers (3.4%) compared to air at both 600 K and 900 K. Nusselt number is slightly increased for both cold fluids when sodium potassium eutectic is used compared to sodium at both 600 K 900 K.
- Nusselt number of hot fluids is increased when the cold fluid mass flow rate is increased from 0.5 Kg/s to 2.5 Kg/s. sodium potassium is having higher Nusselt numbers compared to sodium at both 600 K and 900 K. Nusselt number is slightly increased (2.5%) for both hot fluids when nitrogen is used compared to air at both 600 K 900 K.

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