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Study the Effects of System and Operating Parameters on the Parabolic Collector

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Abstract: ***The authors investigate the effect of system and operating parameters on the performance of parabolic collector. The effects of system and operating parameters were investigated using the developed mathematical expressions for collector efficiency, heat removal factor, fluid outlet temperature and power etc. The results were simulated and then simulated results were plotted for investigation like effect of thermal loss parameter and radiative loss parameters on the collector efficiency, heat removal factor, fluid outlet temperature, rise of temperature and effect of mass flow rate on the fluid outlet temperature. In connection with the power generation, plots were drawn for the effect of (T_M–T_{AMB}) on the variation of concentration efficiency, concentrator irradiance on P_M/P_{MN}, evaporation temperature on thermal to electric power efficiency (Conversion efficiency) of the plant and overall efficiency of solar power plant.***

Keywords: Parabolic Collector, Radiative and thermal loss parameters, Collector efficiency, Heat removal factor, Fluid outlet and inlet temperatures, rise of temperature, mass flow rate, conversion efficiency, concentrator irradiance

1. Introduction

The system consists of a solar collector and a storage device that supply thermal energy to a load, which is input to the heat engine for solar driven power generation. The facts that we are dealing with the parabolic trough collector used for solar thermal electric power system at high temperature, it is necessary to consider the radiative terms into account. Subsequently, two process are consider simultaneously: (a) the energy transfer between the thermal fluid, circulating along the absorber of the collector field, and water or water-vapor, and (b) the thermodynamic cycle of the water-vapor fluid. The process of converting thermal into mechanical power, Rankine cycle, is represented by means of a reversible thermodynamic cycle.

Milton, M. R. et al [1], studied the modeling behavior of a solar power plant with parabolic linear collector is most important as a design and optimization tool that can approach a variety of situation. A variety of procedures to calculate the property of operational behavior of solar power plant with parabolic linear collectors can be found in the technical literature.

Yebra, L. J. et al. [2] developed the design of advanced control systems to optimize the overall performance of parabolic trough collectors solar plants with direct steam generation is today a high-priority line of research.

The effect of the changes of absorber tube temperature on absorber emissivity in the LUZ systems was reported by Lippke [3]. The increase of emissivity with temperature has a major effect on collector thermal loss and collector efficiency.

A direct steam generation collector (DSG) has also been proposed as a future generation of the LUZ type trough collector by Cohen and Kearney [4]. This configuration has the advantage of eliminating the costly synthetic oil, intermediate heat transport piping loop and oil to stream heat exchanger.

Odeh, S. D. et al. [5] studied the performance of parabolic trough solar collectors solar thermal electric generation system is evaluated for Australian climate conditions. The largest Solar Electric Generation System (SEGS) currently in operation uses a parabolic trough solar collector and synthetic oil in the collector loop.

The receiver of the SEGS system consists of a steer heat absorption type coated initially with black chrome and later with a cermet selective surface of low thermal emittance by Cohen [6], Cohen and Kearney [7]. Heinzed, et al. [8] developed an optical model of a parabolic trough collector for various uses in thermal power generation systems and Lippke, F. [9] investigated that the behavior of Solar Energy Generation System Plant for part-load.of a plant of capacity 30 MW in the LUZ systems.

Rolim, M. M. et al. [10] was developed an analytical model for a solar thermal electric generating system with parabolic trough collectors. The energy conversion of solar radiation into thermal power along the absorber tube of the parabolic collector was studies, taking into consideration the non-linearity of heat losses and its dependence on the local temperature. The overall maximum cycle efficiency is found for evaporation temperature around 320^0C.

Cooper and Dunkle [11] derived a differential equation to take into account the variation of the heat loss coefficient. The drawback was expressed in terms of fluid, rather than absorber, temperature. Although mathematically convenient, this bypass some of the key physics of the problem, restricting the validity of the results.

Dudly et al. [12] proposed a semi-empirical equation for the thermal efficiency curve of the collector based on the experimental data, expressed as a second degree polynomial that relates thermal efficiency and temperature, considering a quadratic temperature dependence of thermal losses, Fraidenraich, N. et al. [13] developed a closed form solution that enables to calculate the profiles of the absorber temperature, fluid temperature and power delivered along a parabolic linear focus collector.

Analytical modeling of a solar power plant with parabolic linear collector was used as a basic for the development of a code implemented by Jones et al. [14] in the TRNSYS thermal simulation software. Quaschninget at. [15]used a model based on previous works

1.1 Useful Thermal Energy

The useful solar energy collected by a solar collector $Q_u(t)$ is influenced by three major factors:

- The ability of the absorbing element to absorb the available insolation that is incident on the element after being reflected from or transmitted through other collector components.
- The magnitude of the thermal losses due to convection to the ambient air and
- The magnitude of thermal losses due to radiative exchange with the surroundings.

The useful solar energy can be expressed mathematically as

$$Q_u(t)=q_u(t)\,A_c=(\tau\alpha)_e q_s(t)\,A_c - \breve{U}\,A_e\,(\breve{T}_e - T_a) - \varepsilon_e\sigma\,A_e\,(T_e^4 - T_a^4) \qquad (3.1)$$

(Usable Energy Collected= Energy Absorbed – Convective Losses– Radiative Losses)

A measure of the collector performance is the ratio of the useful collected energy $Q_u(t)$ to the available incident energy $q_s(t)\,A_c$. This ratio is called the collector efficiency (η). Eqn. (2.31) can be rearranged to obtain the collector efficiency as

$$\eta=\frac{Q_u(t)}{q_s(t)A_C}=(\tau\alpha)_e-\frac{1}{q_s(t)A_C}\{\breve{U}\,A_e(\breve{T}_e-T_a)-\varepsilon_e\,\sigma\,A_e(\breve{T}^4_e-T^4_a)\} \qquad (3.2)$$

In dimensional form or:

$$\eta=\frac{Q_u(t)}{q_s(t)A_C}=(\tau\alpha)_e-\frac{1}{\psi(t)}[b(\theta_e-\theta_a)+a\,(\theta^4_e-\theta^4_a)] \qquad (3.3)$$

In dimensionless form:

Where,

$$a=\frac{\varepsilon_e\sigma A_e T^4{}_a}{q_{s,ref}\,.A_C} \qquad (3.4)$$

$$b=\frac{UA_eT_e}{q_{s,ref}\,A_C} \qquad (3.5)$$

$$\theta e=\breve{T}e\,/\,\breve{T}_a \qquad (3.6)$$

$$\theta_a=T_a\,/\,\breve{T}_a \qquad (3.7)$$

$$\Psi(t)=q_s(t)/q_{s,ref} \qquad (3.8)$$

If the relationship of the form

$$\frac{F_R}{\psi(t)}[(\tau\alpha)_e-\{b(\theta_{fi}-\theta_a)+a\,(\theta^4_{fi}-\theta^4_a)\}]=$$

$$(\tau\alpha)_e-\frac{1}{\psi(t)}[b(\theta_e-\theta_a)+a(\theta^4_e-\theta^4_a)] \qquad (3.9)$$

As assumed, then equation (3.3) becomes in dimensional form:

$$\eta=F_R[(\tau\alpha)_e-\frac{1}{q_s(t)A_C}\{\breve{U}\,A_e(\breve{T}_{fi}-T_a)-\varepsilon_e\,\sigma\,A_e(\breve{T}^4_{fi}-T^4_a)\}] \qquad (3.10)$$

In dimensionless form:

$$\eta=F_R[(\tau\alpha)_e-\frac{1}{\psi(t)}\{b(\theta_{fi}-\theta_a)+a\,(\theta^4_{fi}-\theta^4_a)\}] \qquad (3.11)$$

The net enthalpy gain $Q_u(t)$ of the fluid flowing through the collector is given by

$$Q_u(t)=\delta_c\,m_cC_p\,(T_{fo}-T_{fi}) \qquad (3.12)$$

The value of $Q_u(t)$ is related to the insolation $q_s(t)$ through the definition of collector efficiency by

$$Q_u(t)=\eta\,q_s(t)\,A_c \qquad (3.13)$$

Substitution of Eqns. (3.11) and (3.12) in Eqn. (3.13), we obtain

$$\text{Or, } T_{fo}=T_{fi}(1-\frac{bF_R}{\gamma})+\frac{TF_R}{\gamma}[\Psi(t)(\tau\alpha)_e+b\theta_a]-(\frac{aT_aF_R}{\gamma})(\theta^4_{fi}-\theta^4_a) \qquad (3.14)$$

And,

$$\gamma=\delta_c\,m_cC_p\breve{T}_a\,/q_{s,ref}\,A_c \qquad (3.15)$$

The parameter γ is a measure of the ratio of the ability of the working fluid to remove energy from the collector to the reference solar energy.

The useful thermal power, integrated along absorber length, can be written in terms of thermal fluid temperature at the collector entrance (T_{fi}) and at the collector exit (T_{fo}) as

$$Q_u(t)=Q_u=m_fc_p(T_{fo}-T_{fi}) \qquad (3.16)$$

1.2 Energy Transfer between Thermal Fluid And Water-Vapor

Let us assume $T_4=T_{fo}$ and $T_1=T_{fi}$. (17)

Let the thermal fluid enters into the set of heat exchangers always at the same temperature (T_4) and exits at temperature (T_1). The temperature variations of the thermal fluid and the water-vapor fluid along the heat exchangers are shown in Fig. 3.2

The transfer of energy within the heat exchangers can be summarized with two equations:

$$m_fc_p\,(T_4-T_1)=m_v\,(\Delta h_w+\Delta h_{ev}+\Delta h_v) \qquad (3.18)$$

$$m_fc_p\,(T_4-T_2)=m_v\,(\Delta h_{ev}+\Delta h_v) \qquad (3.19)$$

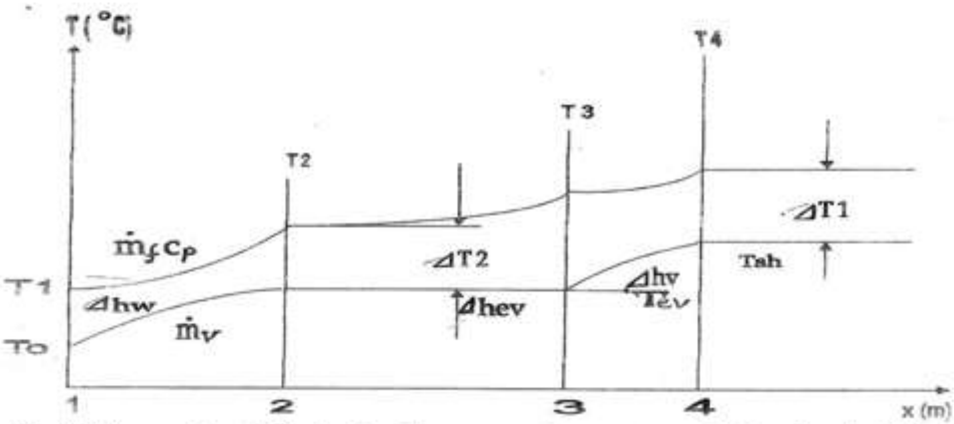

Fig. 3.2 Temperature in the heat exchangers and temperature pinch points (ΔT1) and (ΔT2)

2. Mechanical and Electric Power

The elementary mechanical work per unit mass of working fluid, for preheating (T_{ev}-T_0), evaporation (T_{ev}) and steam superheating regions (T_{sh}-T_{ev}), can be expressed as Δ

$$\delta w_w = dh_w \quad (3.20)$$

$$\delta w_w = dh_{ev} \quad (3.21)$$

$$\delta w_v = dh_v \quad (3.22)$$

Where (Δh_w), (Δh_{ev}) and (Δh_v) are the change in enthalpy transferred from the thermal fluid to the preheating water, evaporating water and superheating steam. Integrating above equations (3.20), (3.21) and (3.22) yield the work during the preheating, evaporating and superheating the steam as follows:

$$w_{w1\text{-}2} = h_2 - h_1 \quad (3.23)$$

$$w_{ev2\text{-}3} = h_{hfg} \quad (3.24)$$

$$w_{v3\text{-}4} = h_4 - h_3 \quad (3.25)$$

The total mechanical power is, then given by:

$$W = m_v (w_{w1\text{-}2} + w_{ev2\text{-}3} + w_{v3\text{-}4}) \quad (3.26)$$

Finally, the electric power can be estimated using a constant value for the conversion efficiency of mechanical to electrical power. For convenience, the maximum electric power can be expressed as

$$P_{el,max.} = \eta_{el} W \quad (3.27)$$

3. Results and Discussions

3.1 Effect of Thermal Loss Parameter on Collector Efficiency

Fig. 4.16 shows the efficiency of parabolic trough collector as a function of dimensionless insolation for a fixed value of radiative loss parameter of 0.003459 and various values of thermal loss parameter, b. It has been observed that the maximum and minimum values of efficiencies have been found to 78.63 % and 53.16 %, 77.51 % and 47.54 %, 76.38 % and 41.91 %, 75.26 % and 36.29 %, and 74.13 % and 30.66 % for thermal loss parameters 0.01125, 0.0225, 0.03375, 0.045 and 0.056, respectively.

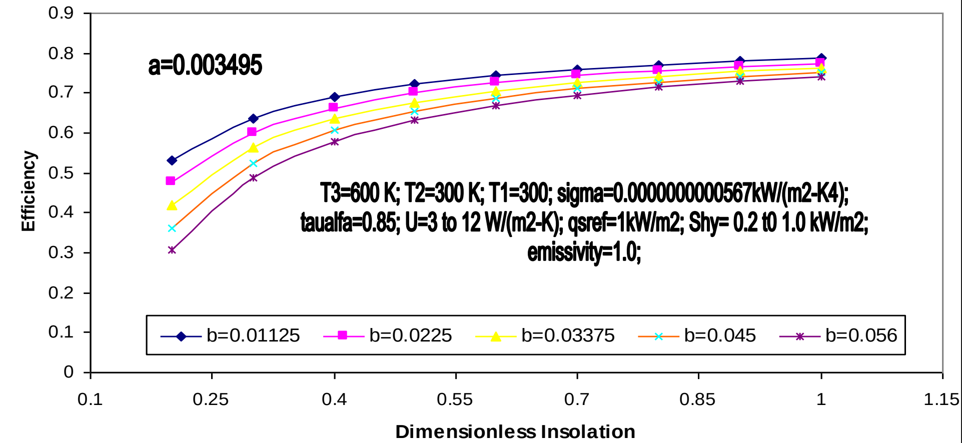

Fig. 4.16 Efficiency as a function of dimensionless insolation

3.2 Effect of Radiative Loss Parameter on Collector Efficiency

Fig. 4.17 shows the efficiency of parabolic trough collector as a function of dimensionless insolation for a fixed value of thermal loss parameter of 0.03375 and various values of radiative loss parameter, a. It has been observed that the efficiency monotonically increases with increase in dimensionless insolation at all values of radiative loss parameter, apparently because of an increase in solar radiation. The collector with lowest value of radiative loss parameter of 0.001165 maintains the highest efficiency value throughout the range of dimensionless insolation investigated. Furthermore, a slight fall is observed in the rate of increase of efficiency as dimensionless insolation increases apparently due to increase in solar radiation. The maximum and minimum values of efficiencies have been found to 79.88 % and 59.39 %, 78.16 % and 50.81 %, 76.45 % and 42.23 %, 74.73 % and 33.65 %, and 73.25 % and 25.72 % for radiative loss parameters of 0.001165, 0.00231, 0.00345, 0.00459 and 0.00574, respectively.

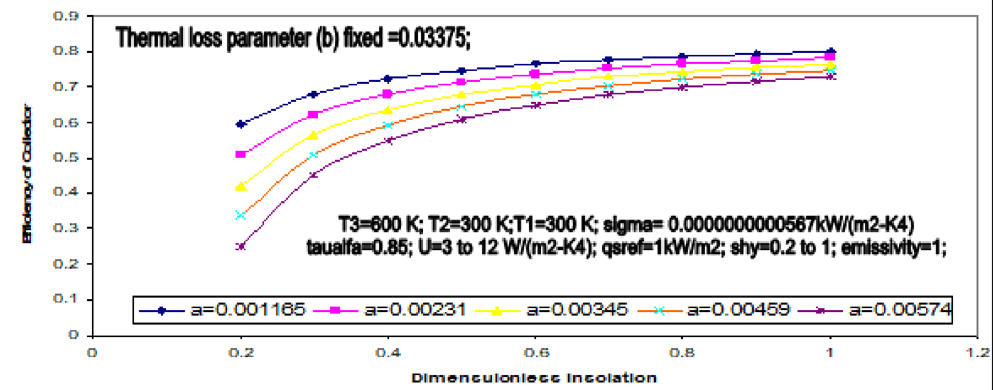

Fig. 4.17 Effect of relative loss parameter on collector efficiency

3.3 The Effect of Thermal Loss Parameter on Heat Removal Factor

Fig. 4.18 shows the heat removal factor as a function of dimensionless insolation for a fixed value of radiative loss parameter of 0.001165 and various values of thermal loss parameter, b. It has been observed that the minimum and maximum values of heat removal factor have been found to be 0.125 to 0.925, 0.112 to 0.912, 0.09 to 0.875, 0.889 to 0.0855 to 0.886 and 0.0722 to 0.873 for 0.01125, 0.0225, 0.03375, 0.045 and 0.0562, respectively.

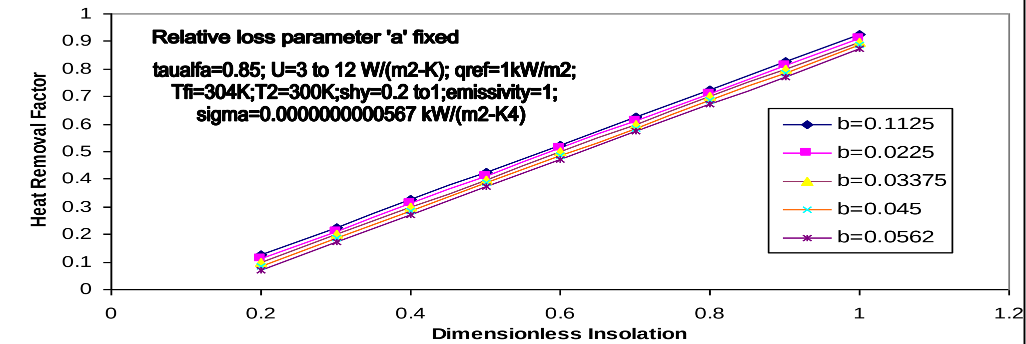

Fig.4.18 Effect of thermal loss parameter on heat remaval factor as a function of dimensionless insolation for a=0.001165

3.4 Effect of Radiative Loss Parameter on Heat Removal Factor

Fig. 4.19 shows the heat removal factor as a function of dimensionless insolation for a fixed value of thermal loss parameter of 0.03375 and various values of radiative loss parameter, a. It has been observed that the minimum and maximum values of heat removal factors have been found to be 0.139 to 0.925, 0.119 to 0.919, 0.0987 to 0.899, 0.078 to 0.879 and 0.058 to 0.858 for relative loss parameters of 0.001165, 0.00231, 0.00345, 0.00459 and 0.00574, respectively.

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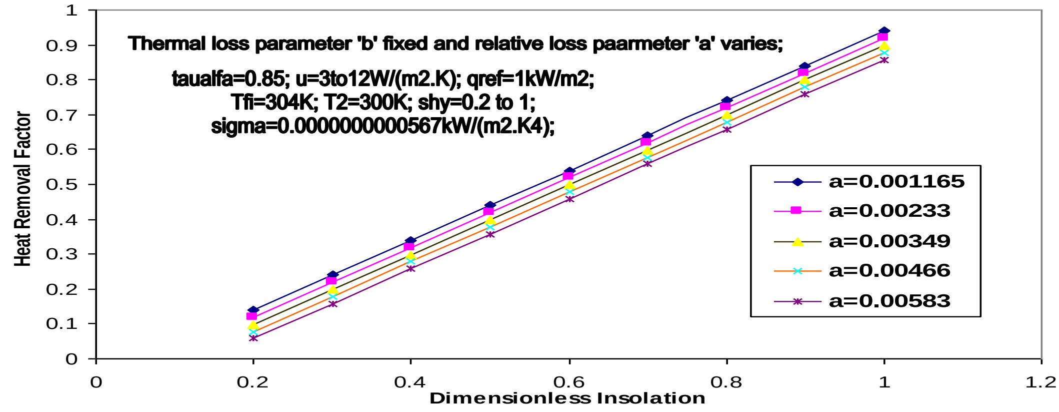

Fig. 4.19 Effect of relative loss parameter on the heat removal factor as a function of dimensionless insolation for b=0.03375

3.5 Effect of Relative Loss Parameter on Fluid Outlet Temp

Fig. 4.20 shows the plot of fluid outlet temperature of parabolic collector as a function of dimensionless insolation for different values of relative loss parameter and fixed value of thermal loss parameter, b=0.03375.The fluid outlet temperature linearly increases from 350.15^0 C to 365.57^{0}C at a=0.001165 and fixed value of b=0.03375 and then these values of minimum and maximum temperature are 353.09^0 C to 368.42^0 C at a=0.00229, 356.76^0 C to 373.80^0 C at a=0.00342, 360.81^0 C to 385.73^0 C at a=0.00454 and 363.54^0 C to 401.11^0 C at a=0.00567, respectively. It is also found that the rate of rise of outlet fluid temperature for b=0.056225 is higher as compared to other values of thermal loss parameters.

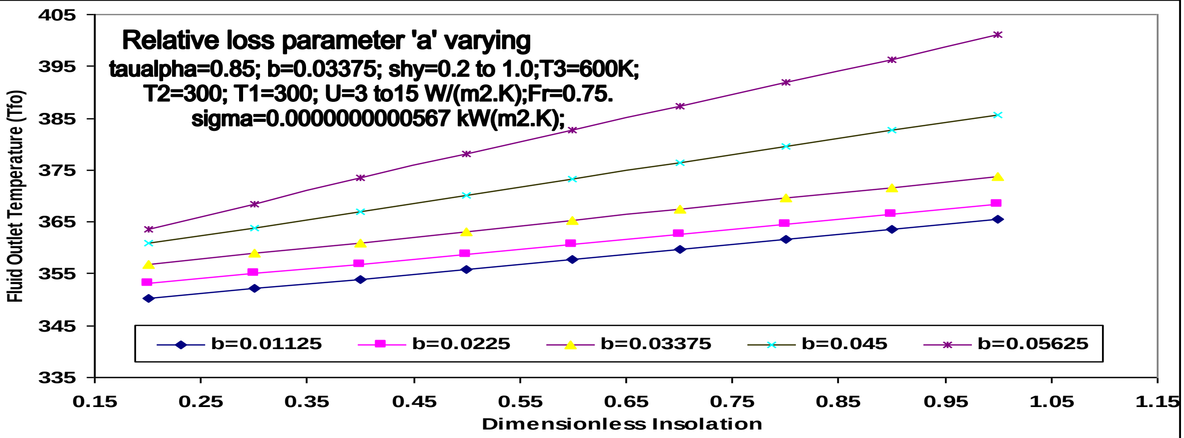

Fig. 4.20 Effect of relative loss parameter on the fluid outlet temperature as a function of dimensionless insolation for b=0.03375

3.6 Effect of Thermal Loss Parameter on Fluid Outlet Temp

Plots shown in Fig. 4.21 show that the effect of thermal loss parameter on outlet fluid temperature for a fixed value of radiative loss parameter. It has been found that the outlet fluid temperature rises from 345.52^0 C to 387.71^0 C, 350.58^0 C to 392.77^0 C, 355.63^0 C to 397.83^0 C,360.69^0 C to 401^0 C and 365.75^0 C to 407.94^0 C for thermal loss parameters of 0.01125, 0.0225, 0.0375, 0.045 and 0.056, respectively.

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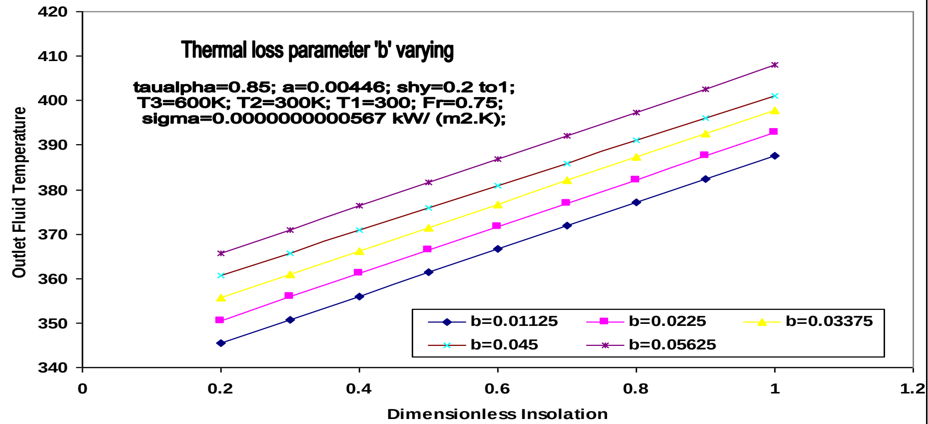

Fig. 4.21 Effect of thermal loss parameter on outlet fluid temperature as a function of dimensionless insolation for a=0.00448

3.7 Effect of Mass Flow Rate on Outlet Fluid Temp

The plot shown in Fig. 4.22 shows the outlet fluid temperature as a function of mass flow rate for various values of dimensionless insolation and fixed value of radiative loss parameter and thermal loss parameter. It is found that the maximum and minimum value of outlet fluid temperature as mass flow rate increases from 0.2 to 1.0 kg/s is found to be 360.11^0 C and 341.69^0 C for dimensionless insolation of 0.2, a=0.00464 and b=0.0375 and then these value increase with respect to increase in mass flow rate at higher values dimensionless insolation. The maximum and minimum values are found to be 370.36^0 C and 348.57^0 C, 377.15^0 C and 353.15^0 C, 388.51^0 C and 360.76^0 C, and 399.99^{0}Cand 367.15^0 C for dimensionless insolation of 0.4, 0.6, 0.8 and 1.0, respectively.

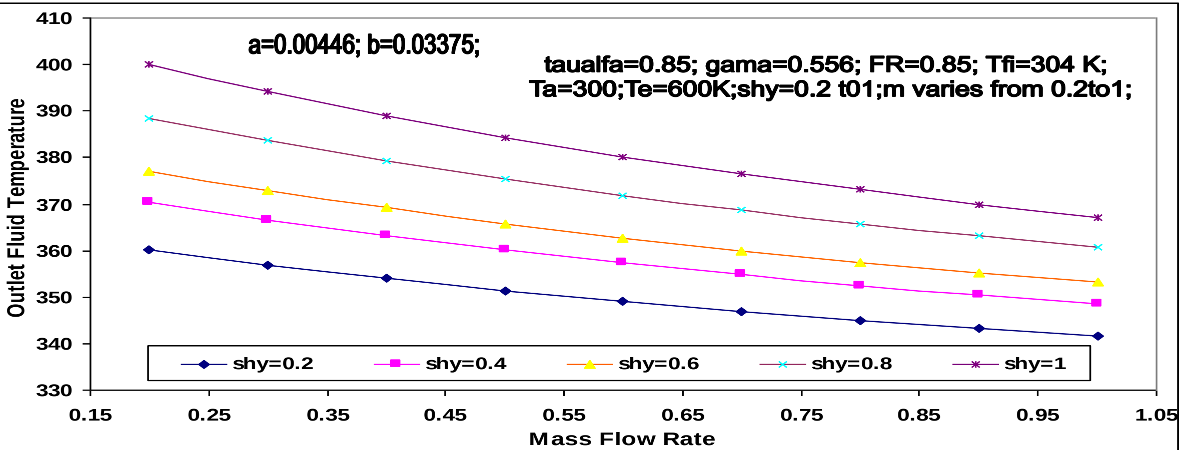

Fig. 4.22 Effect of dimensionless insolation on temperature of outlet fluid temperatutre as a function of mass flow rate

3.8 Effect of Thermal Loss Parameter on Rise of Temperature

Fig. 4.23 shows that the temperature rise (Δt) as a function of dimensionless insolation for various values of thermal loss parameter and fixed value of radiative loss parameter. It has been found that the maximum and minimum values is found to be 376.94^0 C and 334.75^0 C at b=0.056 and then these maximum and minimum temperature rise are 370.14^0 C and 329.69^0 C at b=0.045, 366.83^0 C and 324.63^0 Cat b=0.0375, 361.77^0 C and 319.58^0 C at b=0.0225, 356.71^0 C and 314.53^0 C at b=0.01125, respectively.

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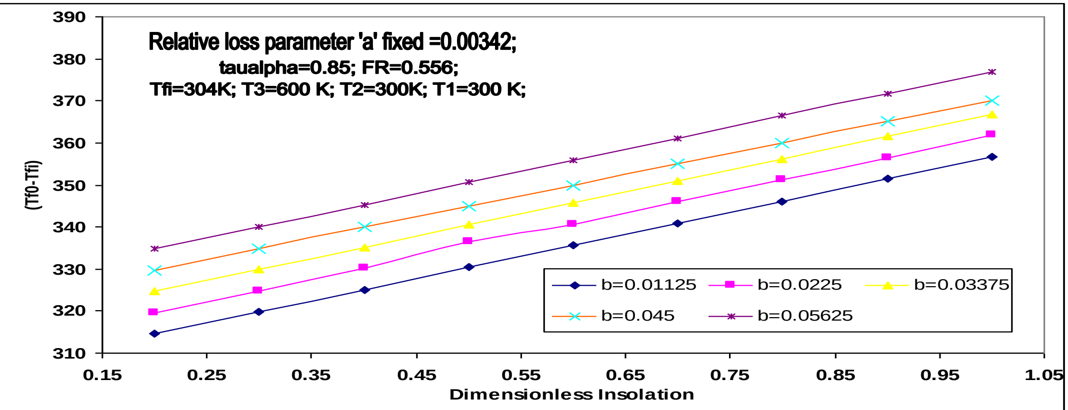

Fig. 4.23 Effect of thermal loss parameter on rise of temperature as a function of dimensionless insolation

3.9 Effect of Radiative Loss Parameter on Rise of Temperature

Plot shown in Fig. 4.24 shows the temperature rise (Δt) as a function of dimensionless insolation for various values of relative loss parameter. For a=0.001165, b=0.03375, the rise in temperature is linear from 319.15^0 C to 334.57^0 C and then these minimum and maximum rise in temperatures are 322.09^0 C and 337.42^0 C at a=0.00279, 325.76^0 C and 3422.80^0 C at a=0.00342, 329.81^0 C and 354.73^0 C at a=0.00454, 332.54^0 C and 370.11^0 C at a=0.00567, respectively. From the above plots it has also been observed the higher values of radiative loss parameter parameter ‘a’ showing more steeper rise as compared to lower value of relative loss parameter.

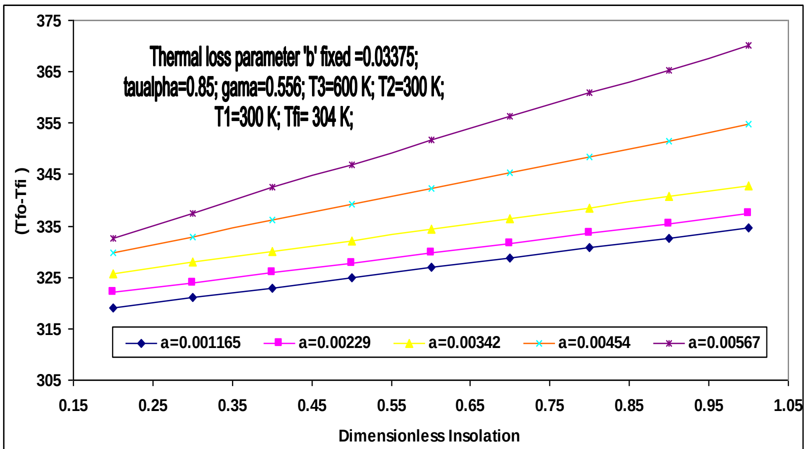

Fig.4.24 Effect of relative loss parameter on rise of temperatur as a function of dimensionless insolation

4. Conclusions

- The mathematical expression for collector efficiency, heat removal factor and outlet fluid temperature have been developed for cylindrical parabolic trough collector through which the working fluid flows.
- The plots of efficiency as a function of dimensionless insolation ψ(t) reveals that the efficiency monotonically increases with increase in ψ(t) for all values of thermal loss parameter ‘b’ and increase in the value of ‘b’, decrease the efficiencies. The thermal loss parameter, b=0.01125 maintains the highest efficiency value throughout the range of dimensionless insolation investigated. Furthermore, a slight fall is observed in the rate of increase of efficiency as ψ(t). The maximum and minimum efficiency has been found to be 78.63 percent and 53.16 percent respectively for relative loss parameter equals to 0.01125.
- It is also seen that the efficiency increases with increase in dimensionless insolation for all values of radiative loss parameter ‘a’. The radiative loss parameter, a=0.001165, maintains the highest efficiency throughout the range of ψ(t) investigated. The increase in relative loss parameter ‘a’, decrease the efficiency.
- The thermal loss parameter and radiative loss parameter also effects the values of heat removal factor of the cylindrical parabolic trough collector. It has been found that the heat removal factor linearly increases with ψ(t) for all values of thermal loss parameter. The value of heat removal factor (F_R) changes from 0.125 to 0.925 for b=0.01125 and a=0.001165 and then these values decrease with increase in the value of thermal loss parameter.
- The results show that the heat removal factor also increases from 0.139 to 0.943 with increase in ψ(t) for a=0.001165 and b=0.03375. The above values of heat removal factor then decrease with increase in relative loss parameter.
- The fluid outlet temperature (T_{fo}) as a function of dimensionless insolation plots show that the outlet fluid temperature increases linearly from 363.54^{0}C to 401.11^{0}C

for a=0.00567 and b=0.03375. The values of fluid outlet temperature are 365.74^0C and 407.93^0C respectively for a=0.00446 and b=0.05625.

- It is also seen that the outlet fluid temperature decreases with increase in mass flow rate for all values of ψ(t). The temperature fall for fixed value of ψ(t) is seen to be non-linear, the higher values of mass flow rate showing less steeper fall as compared to lower value of mass flow rate.
- The maximum and minimum value of outlet fluid temperatures as mass flow rate increases from 0.2to 1.0 kg/s is found to be 360.11^0C and 341.69^0C for ψ(t)=0.2, a=0.00446 and b=0.03375 and then these values increase with respect to increase in mass flow rate at higher values of ψ(t). The maximum and minimum values of temperatures are found to be 370.36^0C and 348.57^0C at ψ(t)=0.4, 377.15^0C and 353.13^0C at ψ(t)=0.6, 388.51^0C and 360.76^0C at ψ(t)=0.8, 399.99^0C and 367.15^0C at ψ(t)=1 respectively.

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