COMPARISON OF SOLAR DISH DRIVEN RECOMPRESSION SUPERCRITICAL CO_2 BRAYTON CYCLES WITH REHEAT AND WITHOUT REHEAT

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ABSTRACT

The present work compares the two types of indirect heated closed loop Brayton cycles using supercritical CO_2 as a working fluid; (a) recompression with reheat Brayton cycle and (b) recompression without reheat Brayton cycle. These cycles are integrated with parabolic dish solar collector. The operating parameters are varied to assess their effects on the performance of the integrated systems. Results Show that the thermal efficiency of recompression with reheat cycle is almost 47.7 % while that of without reheat cycle is 45.02 % approximately. However, when the parabolic solar dish collector (PDSC) is integrated to the Brayton cycles, the overall energy efficiency for the reheat system is 30.37%, while the latter system has 27.5%, approximately. When compressor pressure ratio is increased, overall efficiencies of the reheat integrated system rise linearly but for the other system efficiencies increase up to the critical value and then gradually reduced.

1. INTRODUCTION

The use of conventional energy resources causes different types of environmental hazards including acid rain, ozone layer depletion and global warming etc. Renewable energy resources such as solar, geothermal, wind and biomass can be good alternatives to the traditional energy resources. These are environmentally friendly, pollution free, available in abundant quantities almost throughout the whole world. Among the renewable resources, solar energy has the greatest advantage as it is clean, pollution free and can be converted directly or indirectly for power generation requirements. Recently two main solar technologies are being used for power generation, photovoltaic and solar thermal power. The use of photovoltaic system is challenged by the solar thermal power plants by Schwarzbozl et al. [1]. Different types of sustainable power production systems were assessed on cost basis and discussed by IRENA [2]. Concentrated solar power technologies consist of various types of solar to thermal conversion techniques including parabolic trough system (PTS), parabolic dish system (PDS), linear Fresnal and solar power tower or central tower system [3]. They convert the solar radiation into thermal heat that can be further utilized for power generation [4] by integrating them into different steam and gas cycles. Parabolic dish collectors are one of the emerging technologies that are used to produce heat by focusing the solar rays onto a receiver. This system has an advantage as compared to the other solar collectors as cosine losses are not considered in dish system [5]. For solar thermal power generation applications, Abid et al. [6] showed that parabolic dish system has an advantage over parabolic trough system. The overall exergy as well as outlet temperature of PD collectors are higher as compared to PT solar collectors.

Closed gas turbine cycles having simplicity, compactness and low cost with shorter construction duration are preferred to the steam cycles. Feher [7] suggested that supercritical closed loop cycles were the most favourable power generation systems that can gain higher efficiencies compared to the steam cycles. Supercritical Carbon dioxide (S-CO_2)

Brayton cycles are prominent effective technologies having cycle thermal efficiencies of almost 50%. When these gas cycles are integrated with solar systems, they can exhibit better performance and higher thermal efficiencies due to the greater concentration ratio, was depicted by Ho and Iverson [8]. Furthermore, CO_2 was suggested as a working fluid with supercritical cycles integrated with solar power thermal systems by Song et al. [9] as well as Organic Rankine Cycle in waste heat applications [10]. Its initial cost is lower than other power cycles with better performance at higher temperatures [11]. Moreover, S-CO_2 Brayton cycles have simplicity, safety and better economy as compared with the steam and helium based power cycles [12].

It can be observed from the literature that many researchers explored work about S-CO_2 Brayton cycles integrated with central receiver system and limited amount of research has been carried out on parabolic trough solar collectors incorporated with S-CO_2 cycles. However, PDSC system is not examined for its integration with S-CO_2 Brayton cycles by any researcher. The present study which is from author's master thesis [21] focuses on the relation between rate of heat generation by the parabolic dish and the net power generated from both of the above mentioned S-CO_2 Brayton cycles.

2. SYSTEMS DESCRIPTION

The power cycles integrated with parabolic dish system is shown in Fig. 1 and Fig. 2, whereas T-s diagram is given by Fig. 3. Due to the limited space, parabolic dish integrated without reheat Brayton cycle is explained here. The efficiency of S-CO_2 system is better in the recompression version as heat rejected from the cycle is reduced by introducing another compressor (recompressing compressor).

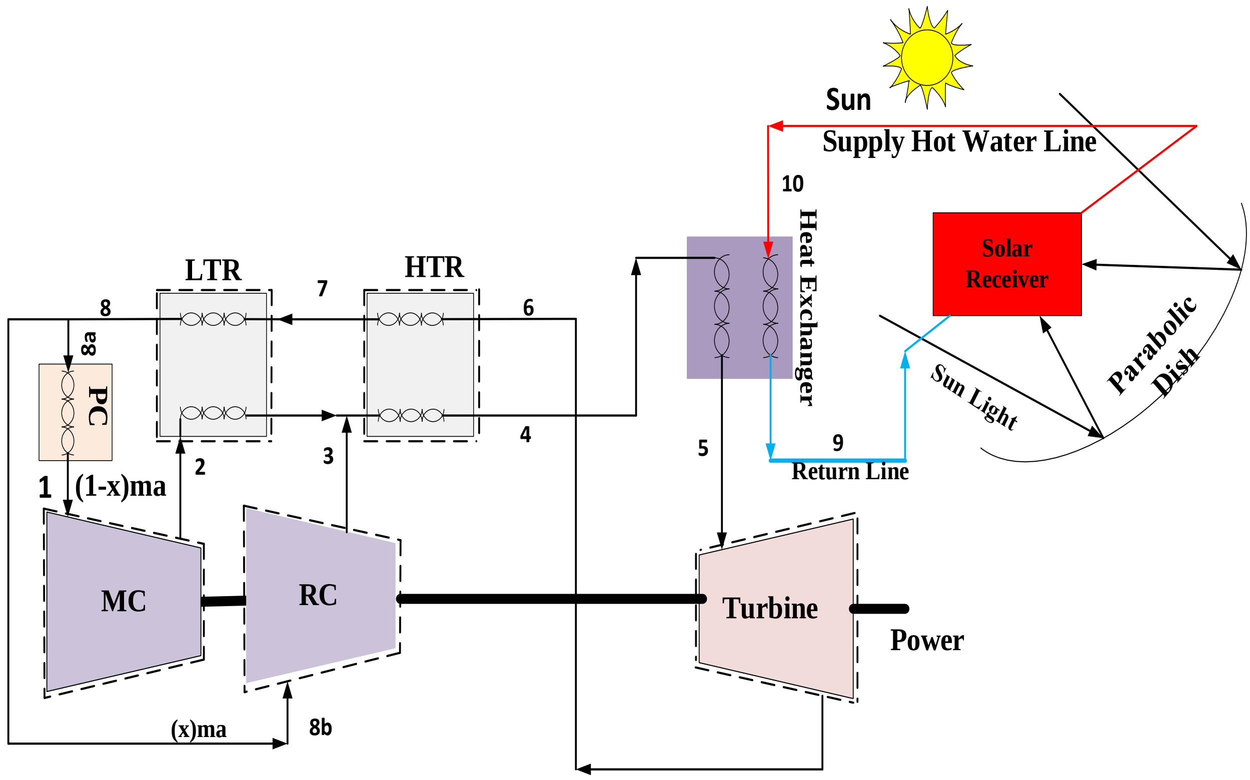

Fig. 1. Schematic of the suggested solar S-CO_2 recompression without reheat Brayton cycle

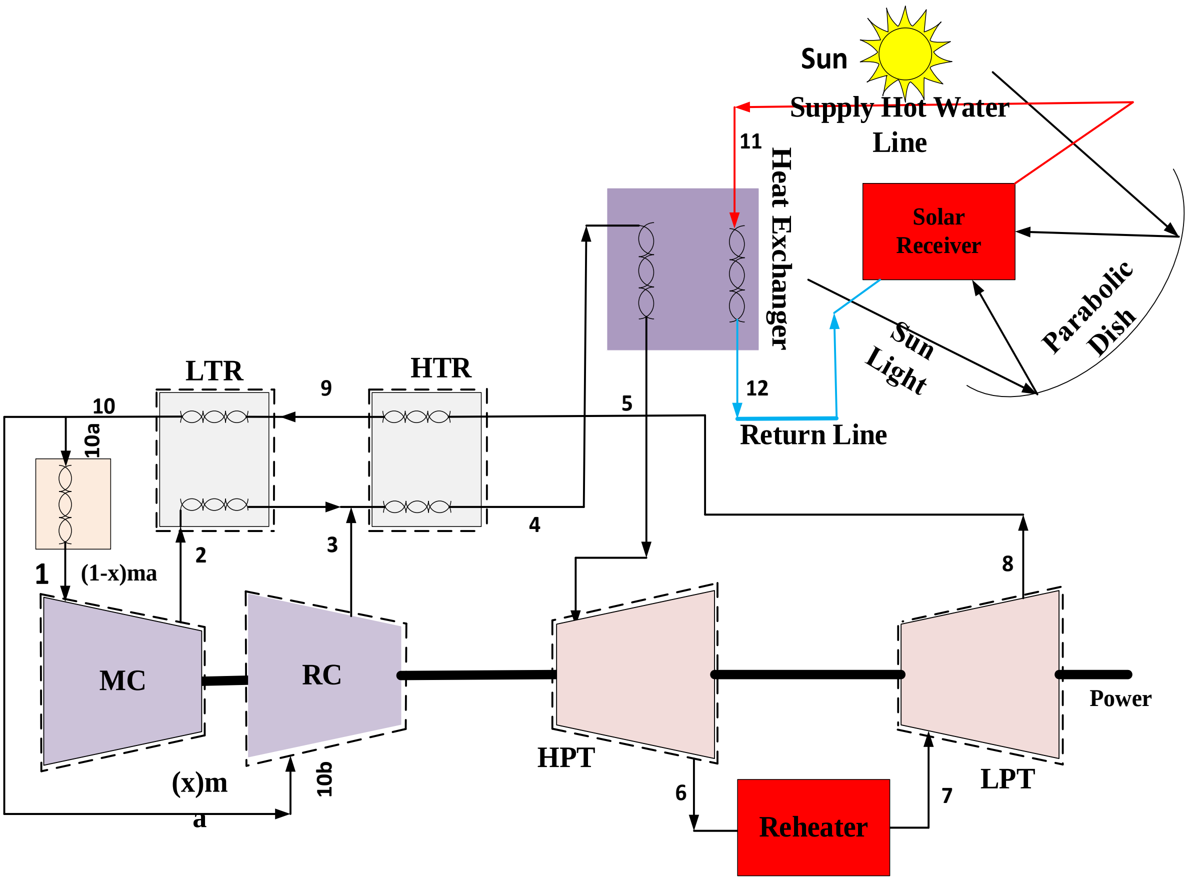

Fig. 2. Schematic of the proposed solar S-CO_2 Recompression with Reheat Brayton cycle

The low pressure flow passes from low temperature regenerator (recuperator, LTR) and divided into two streams at LTR exit (point 8). Main stream (1-x) ma becomes cool as it proceeds to pre-cooler through point (8a-1) and then through main compressor (1-2), its pressure increases and eventually enters into the LTR. The remaining low fraction stream with mass flow rate (x) ma passes through recompression compressor (8b) and mixes with the stream exiting LTR at state 3. Due to this split flow, cold fluid capacitance decreases so pinch point problems will be avoided. Before getting thermal heat from solar receiver, the main stream is heated through HTR and after the solar receiver it passes through the turbine at state 5. It is important to concentrate that stream (8b) has non-zero flow and due to this, there is different mass flow rate for streams in LTR. Stream 7 has higher mass flow rate than that of stream 2. Furthermore, pressure of stream 7 is less than that of stream 2. Parabolic dish collector system (solar receiver) provides thermal heat to the Brayton cycles through heater and reheater (when reheat system is used). Hot water leaving the receiver enters into the heat exchanger at point 10 and after exchanging heat with the S-CO_2 cycle it comes back to the receiver collector via point 9. The outlet temperature of the fluid circulating in the collector loop is high enough to energize the S-CO_2 in the Brayton cycle. This heat energy further drives the turbine to do its job properly.

Table 1. Input Operating and Design Parameters for S-CO_2 Brayton Cycles and parabolic dish system.

Parameters	Values	Remarks
Temperature at the main compressor inlet [14]	305 K	S-CO_2 Brayton cycles
Turbine inlet temperature [14]	823 K	----------
Pressure at the main compressor inlet [14]	7.6 MPa	-----------
Pressure at the compressor exit	20 MPa	------------
Mass flow rate [15]	19.6 kg/sec	--------
Aperture area [6]	10.46 m^2	Parabolic dish system
Receiver area	0.0316 m^2	----------
DNI	1000 W/m^2	---------
$\dot{m}_{receiver}$	0.1 kg/sec	--------

3. METHODOLOGY

The configuration of both types of Brayton cycles are modelled by considering the energy, exergy and mass analysis using Engineering Equation Solver (EES) [13].

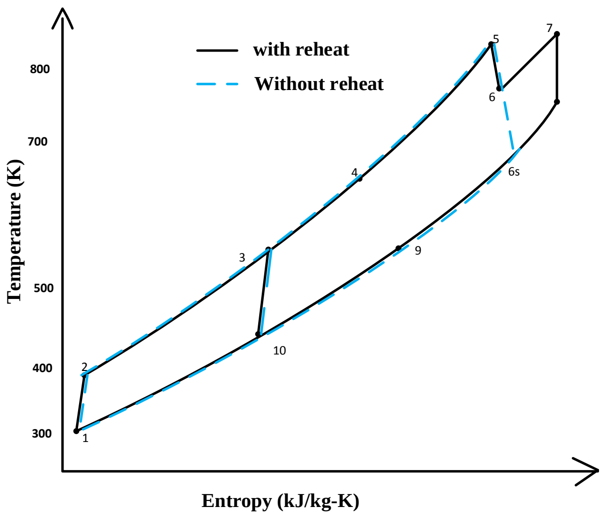

Fig. 3. T-s diagram of recompression with and without reheat S-CO_2 Brayton cycle

3.1. Analysis of S-CO_2 Brayton cycles

In this section S-CO_2 recompression cycle with reheat is considered. A similar analysis can be made for the cycle without reheat; only this time the reheat component is omitted. Effectiveness of HTR can be calculated as:

$$\varepsilon_{HTR} = (T_8 - T_9)/(T_8 - T_3) \quad (1)$$

Effectiveness of LTR is:

$$\varepsilon_{LTR} = (T_3 - T_2)/(T_9 - T_2) \quad (2)$$

Thermal heat available

$$\dot{Q}_u = \dot{m}(h_5 - h_4) + \dot{m}(h_7 - h_6) \quad (3)$$

$$\dot{Q}_u = \dot{m}(h_5 - h_4) \quad (4)$$

Net power output from the cycle is:

$$\dot{W}_{net} = \dot{W}_{tur} - \left(\dot{W}_{mc} + \dot{W}_{recomp}\right) \quad (5)$$

Thermal efficiency for both the Brayton cycles can be expressed as:

$$\eta_{th} = \dot{W}_{net}/\dot{Q}_u \quad (6)$$

Specific exergy at all points is calculated by $e_x = h - h_o - T_o.(s - s_o)$ [16] considering that both enthalpy and entropy are zero at dead state.

Exergy balance for each component of the S-CO_2 Brayton cycle is:

$$\frac{dX_{cv}}{dt} = \sum_j \dot{X}_{qj} - \dot{W}_{cv} + \sum_i \dot{m}_i X_i - \sum_o \dot{m}_o X_o - \dot{X}_d - \dot{X}_{loss} \quad (7)$$

With:

$$\dot{X}_{qj} = \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j \quad (8)$$

The second law efficiency of the Brayton cycle is:

$$\eta_X = \dot{W}_{net}/\dot{X}_{qj} \quad (9)$$

3.2. Analysis of PDSC

The dish model used in current study is taken from the system proposed by Lloyd C. Ngo [17]. The collector energy efficiency can be defined by the relation:

$$\eta_{en,PDSC} = \frac{\dot{Q}_u}{\dot{Q}_{sun}} \quad (10)$$

$$\dot{Q}_{sun} = G_b A_a \quad (11)$$

The heat gain is calculated by taking the fluid temperature difference.

$$\dot{Q}_u = \dot{m}\, C_P(\, T_{out} - T_{in}\,) \quad (12)$$

The actual useful heat gain of concentrating solar system can also be calculated by applying famous Hottel-Whillier equation [17]:

$$\dot{Q}_u = A_a F_R \left(S - \frac{A_r}{A_a} U_L (T_{in} - T_0)\right) \quad (13)$$

where S denotes the absorbed radiation ($S = \eta_0 G_b$) and η_0 is the optical efficiency or thermal performance of the parabolic dish receiver ($\eta_0 = 0.85$) as taken from [18].

Heat removal factor F_R can be expressed as [3]:

$$F_R = \frac{\dot{m} C_P}{A_r U_L}\left[1 - \exp\left(\frac{-A_r U_L F_1}{\dot{m}\, C_P}\right)\right] \quad (14)$$

Overall energy efficiency of integrated system can be determined as:

$$\eta_{en,ov} = \dot{W}_{net}/\dot{Q}_{solar} \quad (15)$$

$$\dot{Q}_{solar} = \frac{F_R A_a S}{1000} \quad (16)$$

To calculate the total exergy of the dish receiver, it is necessary to find out exergy in and exergy out from the receiver.

$$\dot{X}_{in} = \dot{m}.C_p(T_{in} - T_0 - T_0.\ln(T_{in} - T_0)) \quad (17)$$

$$\dot{X}_{out} = \dot{m}.C_p(T_{out} - T_0 - T_0.\ln(T_{out} - T_0)) \quad (18)$$

$$\dot{X}_{tot} = \dot{X}_{out} - \dot{X}_{in} \quad (19)$$

The total exergy content of solar is estimated by using Patella's approach [36] and is given as:

$$\dot{X}_{solar} = G_b.A_a.\eta_{pet} \quad (20)$$

where η_{pet} is the Patella's efficiency.

$$\eta_{pet} = 1 - \frac{4T_0}{3T_{sun}} + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4 \quad (21)$$

Finally, exergy efficiency of the PD solar collector and integrated system can be analysed as, respectively.

$$\eta_{X,PDSC} = \frac{\dot{X}_{tot}}{\dot{X}_{solar}} \quad (22)$$

$$\eta_{X,ov} = \frac{\dot{W}_{net}}{\dot{X}_{solar}} \quad (23)$$

4. RESULTS and DISCUSSION

The two different types of recompression S-CO_2 Brayton cycles are integrated with parabolic dish system to analyse the effect of various operating parameters on the integrated systems performance parameters. The inlet temperature of fluid in the receiver, pressure ratio, minimum cycle temperature, compressor outlet pressure and turbine inlet temperature are varied and their effect on the rate of heat produced, net power output and energetic as well as exergetic efficiencies of the integrated systems has been observed.

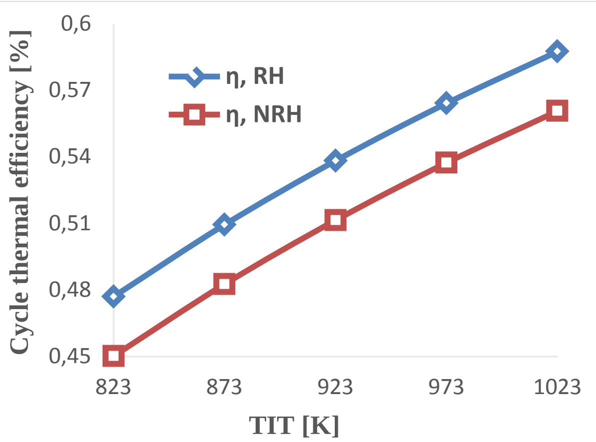

Fig. 4. Turbine inlet temperature effect on thermal efficiency of the cycles

The thermal efficiency of reheat recompression and without reheat recompression S-CO_2 Brayton cycles have been assessed at different inlet temperatures of the turbine as depicted in Fig. 4. However, the efficiencies of both systems are validated at turbine inlet temperature=823 K and at this temperature the reheat cycle has higher first law efficiency (47.70%), whereas, the without reheat cycle gets efficiency approximately (45.02 %) showing a good agreement with the results obtained by [14, 16, 19]. This is the indication that the recompression, regeneration and reheating, introducing to S-CO_2 Brayton cycle is able to gain thermal efficiencies more than the ultra-supercritical (USC) plant [20], supporting its integration with solar system applications.

The PDSC model is analysed for different values of inlet temperatures by conducting the parametric study and its effect on energy and exergy efficiency of the PDSC is examined. The energy efficiency shows a decreasing trend by increasing the inlet temperature of the receiver because energy efficiency of receiver is ratio between rate of heat produced to energy available from solar and heat generation rate decreases when inlet temperature of receiver will enhance, whereas, solar energy remains constant. Finally, energy efficiency of collector is reduced. The collector’s exergy efficiency is given in eq. 22 and exergy of solar is independent of the inlet temperature of the receiver, however the total exergy increases with rise in the inlet temperature of the receiver (exergy input is decreased and total exergy will increase (see eq. 17 & 19)). Finally, exergy efficiency increases and is given in Fig. 5.

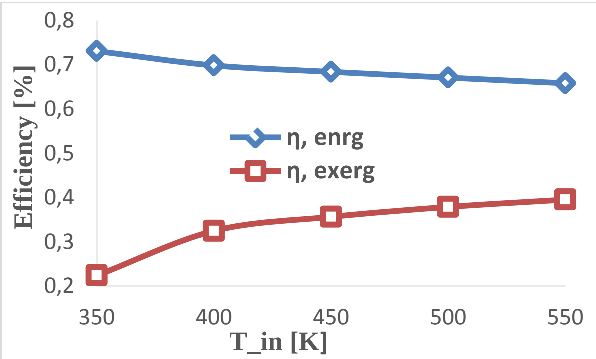

Fig. 5. Effect of Inlet Temperature on Efficiency of PD Solar Collector

Fig. 6 shows the effect of compressor outlet pressure on the overall energetic and exergetic efficiencies of both systems. Efficiency values of the both integrated systems increase by enhancing the maximum cycle pressure as all compressors and turbines work also rise but increase in turbine work is significantly more as compared to the main compressor work.

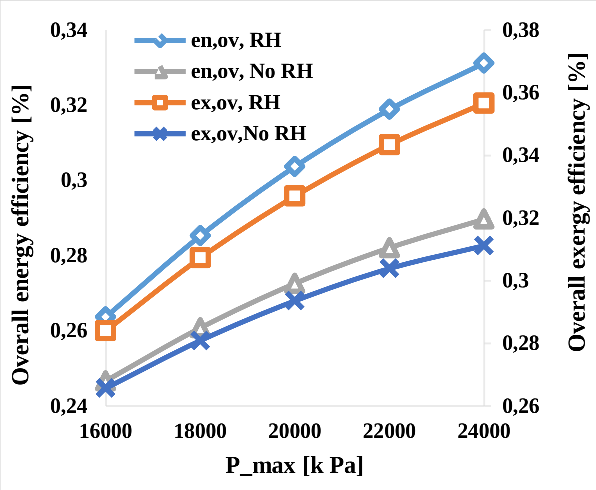

Fig. 6. Compressor outlet pressure effect on overall Efficiencies of integrated systems

Therefore, net work out put increases which gives more efficiency. But for the values of greater pressure, the improvement in overall energy efficiency values is not significant due to the diversion of the system from critical point. Finally, systems efficiencies increase in the beginning but very less increment has been found due to the recompressed fraction of mass attains its highest value.

The overall energy efficiency of the integrated solarized S-CO_2 recompressed without reheat Brayton system decrease when minimum cycle temperature will increase but for recompression reheat system, it will slightly increase as given in Fig. 7. As inlet temperature of the without reheat system increases, main compressor work will also increase but turbine work and recompressing recompressor work almost remain constant as they are away from the critical point. So the power produced by the turbine will be decreased that leads to reduction in net work output. Hence the overall energy efficiency for without reheat system will be reduced from almost 27.26% to 26.62%$_{@T\_max=823\ K}$. However, in the reheat integrated system the second turbine plays a significant role to maintain the efficiency of the system (as it increases the power) by compensating the increase in main compressor work. Thus the overall energy efficiency of reheat system slightly improves from 30.36 % to 30.95% by increasing the turbine inlet temperature.

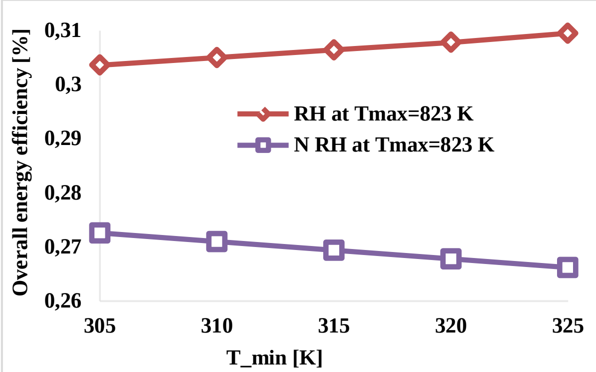

Fig.7. Effect of minimum cycle temperature on overall energy efficiency of both systems

Effect of pressure ratio on the overall efficiencies of with reheat and without reheat solarized S-CO_2 Brayton systems are presented in Fig. 8. As pressure ratio increases, efficiency of the both systems will increase. But after the critical point (2.6), the efficiency of the recompression without reheat system is decreased slightly because of the increment in main compressor work that leads to lessen the cycle net work output. But in the case of reheat system, again the second turbine helps to maintain the system efficiency after the increase in main compressor work. That's why reheat system has an overall energy efficiency in an improved mode.

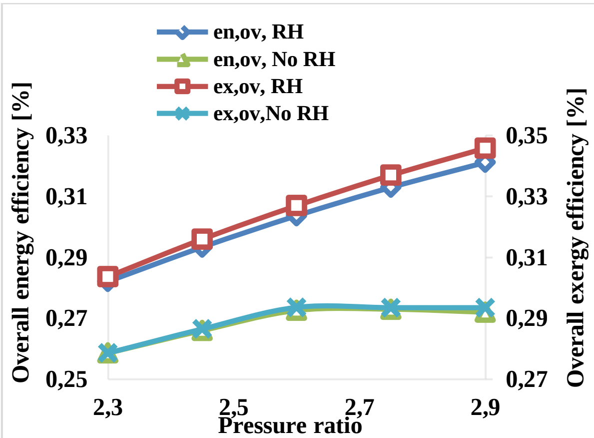

Fig. 8. Effect on overall energy and exergy efficiencies due to the variation in pressure ratio

Fig. 9 represents that by enhancing the TIT, both systems exhibit positive behaviour. For reheat system integrated energy and exergy efficiency increases linearly from 30.37% to 47.31% and 32.70% to 50.95%, accordingly.

The recompression without reheat system has showed the similar nature with low values than the reheat system. The exergy values are higher than the energy efficiency values because exergy represents the maximum available potential of any system (see eq. 23).

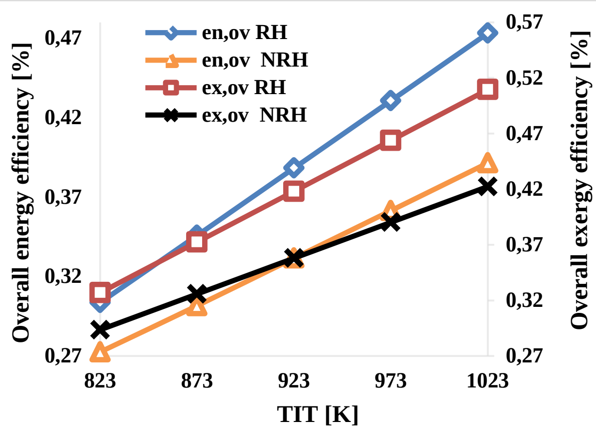

Fig.9. Turbine inlet temperature effect on overall efficiencies of the integrated systems

Inlet temperature of the heat transfer fluid is another key parameter that changes the performance of the solar collectors as well as the whole integrated system. Fig. 10 shows the relation between the heat production rate and increase in receiver inlet temperature at different solar irradiations.

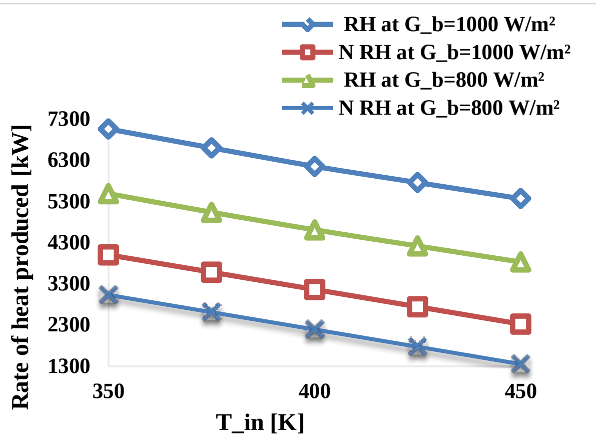

Fig. 10. Effect of inlet temperature of receiver on rate of heat produced

By increasing the inlet temperature, the above said performance parameter will decrease for reheat and for without reheat integrated systems approximately from 7.059 MW @ T_in=350 K to 5.366 MW @ T_in=450 K for DNI of 1000 W/m^2 and from 4.001 MW @ T_in=350 K to 2.320 MW @ T_in=450 K, respectively. This is due to the surface temperature of the absorber tube will become greater when fluid inlet temperature will rise. Due to this reason, heat loss to the surrounding also enhances that will lower the rate of heat production, network output and efficiency as well.

Net power generation by both the integrated systems are found to be reduce from nearly 3.177 MW to 2.415 MW for reheat system and 1.800 MW to 1.044 MW for without reheat system, respectively as inlet temperature increases between 350 K to 450 K at solar intensity of 1000 W/m^2. Fig. 11 also shows the variation in power output for other value of DNI.

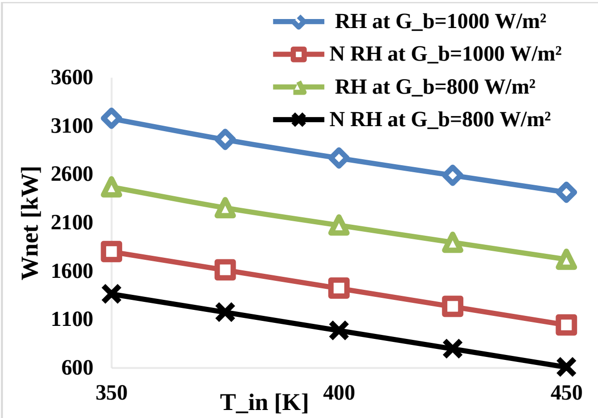

Fig.11. Effect of inlet temperature of receiver on net power output

The integrated energy efficiency of reheat system is reduced from 30.37% to 23.08%, while 27.26% to 15.80% degradation in energy efficiency is observed for without reheat system by varying the inlet temperature between 350 K to 450 K (@ DNI=1000 W/m^2) given by Fig.12. Furthermore, overall energy efficiency values for both the systems at DNI=800 W/m^2 have been decreased in a similar pattern.

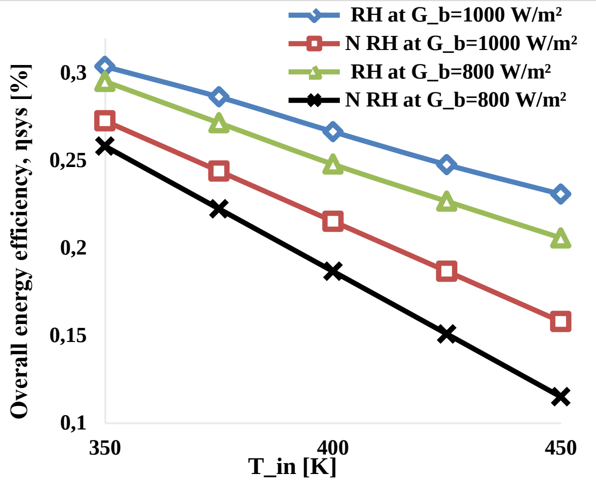

Fig. 12. Effect of inlet temperature of receiver on overall energy efficiency of the systems

The warm ambient surrounding plays an essential role to increase the performance of solar collectors and it is the foremost input parameter which affects the efficiency of solar thermal power plants. When the ambient temperature is high, solar collector receives more energy resulting in higher outlet temperature. Higher outlet temperature gives the higher rate of heat production and ultimately more network output. Finally performance of the system improves.

As ambient temperature varies from 285 K to 325 K, the network output also increases. Recompression with reheat Brayton system generates substantial more work as compared to the recompression without reheat system. When inlet temperature is 350 K, reheat integrated system will generate almost 3.070 MW to 3.353 MW, whereas, the other system gives 1.686 MW to 1.990 MW network. By increasing the inlet temperature up to 400 K, the values of network output lies in the range of 2.663 MW to 2.942 MW for reheat system and 1.308 MW to 1.612 MW for without reheat system, approximately and is given by Fig. 13.

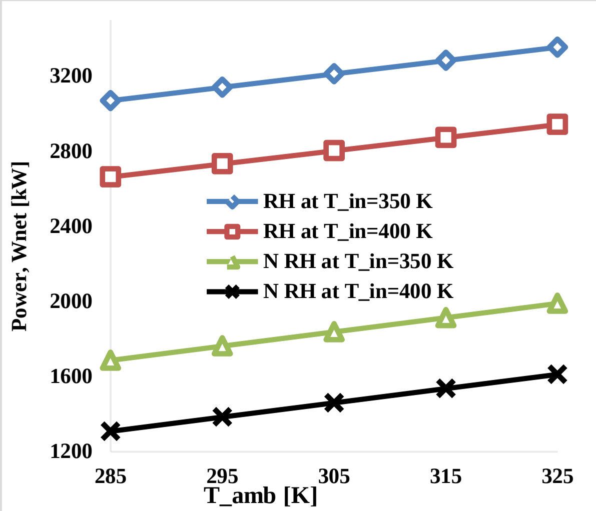

Fig. 13. Effect of ambient temperature on power output at different inlet temperatures

Solar intensity or solar beam radiation is the most important inlet parameter which influences the performance of the solar collectors as well as the efficiency of whole system. Areas in the world, where solar radiations are very high, are suitable and economical for the investment of solar thermal power plants. It is basically the amount of energy transferred of the heat transfer fluid that is circulating in the collector loop. By increasing the solar radiation, the outlet temperature of the receiver will be enhanced linearly that increases the power output as well as overall system performance.

Solar intensity has major effect on the overall energy efficiency of the integrated systems whether it is reheat or without reheat system as shown in Fig 14. The reheat integrated system has an overall energy efficiency between 28.91% $_{@\ DNI=700\ W/m^2}$ and 30.37 % $_{@\ DNI=1000\ W/m^2}$ at ambient temperature of 300 K. However, the latter system also shows a promising reflection between 24.80% $_{@DNI=700\ W/m^2}$ and 27.26 % $_{@DNI=1000\ W/m^2}$ for the same conditions, showing that the reheating improves overall energy efficiency up to 11.39 per cent, approximately. When the ambient temperature is 330 K, this performance parameter has slightly higher values between 31.83 % @ $_{DNI=700\ W/m^2}$ and 32.41 % $_{@\ DNI=1000\ W/m^2}$ for reheat system and from 29.71 % $_{@\ DNI=700\ W/m^2}$ to 30.70 % $_{@\ DNI=1000\ W/m^2}$ for without reheat system.

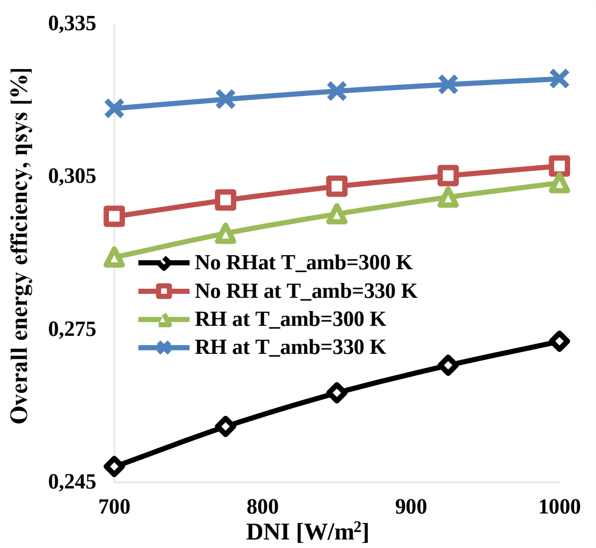

Fig. 14. Effect of solar intensity on overall energy efficiency of the integrated systems

5. CONCLUSIONS

In this study two different types of $S\text{-}CO_2$ recompression Brayton cycles are integrated with parabolic dish system. The operating parameters (Pr_{atio}, T_{min}, TIT, P_{max}, T_{amb}, T_{in} and DNI) are varied to investigate their influence on the integrated system performance. Results showed that increase in TIT and maximum cycle pressure caused the positive effect on reheat and without reheat systems, however rise in the inlet temperature from 350 K to 450 K, reduced the rate of heat produced from 7.059 MW to 5.366 MW for reheat system and 4 MW to 2.32 MW for without reheat system. Similarly, net work output and overall energetic efficiency of both the system decreased by increasing the inlet temperature.

The increase in DNI from 700 to 1000 W/m^2 resulted to rise in the overall energetic efficiency of both the systems. Moreover, the influence of rise in the ambient temperature is noticed to be increase in overall system performance due to the better ambient conditions. The effect of increase in pressure ratio and minimum cycle temperature is reliable for reheat system as the second turbine compensates the increase in main compressor work but overall efficiencies of without reheat system is observed to be reduced.

Nomenclature

A	area (m^2)
DNI	direct normal irradiation (W/m^2)
F_R	heat removal factor
G_b	solar intensity radiation (W/m^2)
h	specific enthalpy (kJ/kg)
HTR	high temperature recuperator
LTR	low temperature recuperator
$\dot{m}$	mass flow rate (kg/sec)
PDSC	parabolic dish solar collector
$\dot{Q}_u$	thermal energy (kW)
$S\text{-}CO_2$	super critical carbon dioxide
TIT	turbine inlet temperature (K)
U	overall heat loss ($W/m^2.K$)
$\dot{W}$	work output (kW)
x	recompressed mass fraction
$\dot{X}$	exergy rate (kW)
a	aperture
d	destruction
cv	control volume
e_x	specific exergy (kJ/kg)
J	source

Greek Letters

ε	Effectiveness of Heat Exchangers
η	Efficiency

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