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Comparative Evaluation of Combined Power Systems having SOFC-HAT and SOFC-HAT-CO_2 Power Cycle

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ABSTRACT

Comparative evaluation of solid oxide fuel cell-humid air turbine based combined power system and the solid oxide fuel cell-humid air turbine-supercritical carbon dioxide based power system is presented in this paper. The study focuses on the effective utilization of the available waste heat in solid oxide fuel cell by integrating it with other power generation options. The integration of solid oxide fuel cell and humid air turbine offers the opportunity for effective energy utilization leading to the performance improvement of the combined system as compared to only solid oxide fuel cell. Another possibility to increase the utilization of the available exhaust heat is by combining the solid oxide fuel cell-humid air turbine and supercritical carbon dioxide based cycle for the performance enhancement. This work relates to the thermodynamic modeling for energy analysis of the distinctive power generation options. The parametric investigation has been carried out for the varying cycle pressure ratio, turbine inlet temperature, fuel utilization factor and humidity ratio on the output parameters namely work output and efficiency. Results show that the work output increases by 4.54 % when the SOFC-HAT cycle is integrated with sCO_2 cycle. Paper presents the implication of independent parameters on the dependant parameters in graphical form.

Nomenclature

A	Area in m^2
h	Enthalpy
n	No. of cell
V	Voltage in volts
I	Density of current in A/m^2
W	Work
Q	Heat produced
T	Temperature in Kelvin
C	Cooler
P	Pressure
M	Mixer
PR	Preheater
S	Separator
U	Utilization factor
ε	Heat exchanger effectiveness
η	Efficiency
y	Index of adiabatic process
c	Specific heat
CPR	Cycle pressure ratio
TIT	Turbine inlet temperature in Kelvin
FUF	Fuel Utilization factor
LHV	Lower heating value, kJ/kg
HR	Humidification ratio
GT	Gas turbine
ST	Steam turbine
ORC	Organic Rankine cycle

1. Introduction

The natural resources are being extensively exploited to meet the increasing energy requirements. As a result, the natural resources are depleting fast. Also, the emissions from the fossil fuel based energy conversion create adversities for the environment. Therefore, the non-conventional energy conversion options have been tried. Among the available options, the SOFC is the direct energy conversion option offering higher efficiency while operating at high temperature. SOFC provides the opportunity for hybrid power systems depending upon the methodology of utilizing the exhaust heat. The integration of SOFC- HAT cycle offers the potential of maximizing the fuel utilization with respect to the output from both the SOFC as well as HAT. Here the high-temperature exhaust of SOFC is used in HAT for augmenting the combined power output but the exhaust leaving the combined system still holds the potential for its further utilization. Therefore, sCO_2 cycles can be further integrated with SOFC-HAT combined cycle. In the SOFC-HAT-sCO_2 hybrid system, energy leaving SOFC-HAT integrated system is used by a waste heat boiler to capture waste heat to run the sCO_2 cycle.

The present paper deals with the thermodynamic modeling of a new combined cycle arrangement comprising of SOFC, HAT and sCO_2 cycle for comparing it with the combination of SOFC & HAT cycle. The comparison of performance of the two combined power systems namely SOFC-HAT-sCO_2 cycle and SOFC-HAT cycle arrangements is studied

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in light of the utilization of waste heat available at the exhaust. Novelty of the work lies in the conceptualization of the two different combinations of SOFC, HAT and sCO_2 cycle for understanding the extent of useful energy conversion in respective combined systems. The outcome of comparative study is useful for those working towards maximizing the energy utilization in SOFC based power systems.

The review of literature shows that the researches are being carried out for arriving at efficient SOFC based power systems. Brief details of some works done in this area are detailed herein. Kim et al. [1] modeled the HAT cycle for thermodynamic study of the effect of ambient temperature and comparing the performance of HAT integrated with simple GT cycle. Rao et al. [2] presented the economic analysis along with analysis based on Ist and IInd law of thermodynamic for the SOFC-HAT cycle. Kuchonthara et al. [3] compared different power cycle combining options like SOFC-STIG (Steam injected gas turbine), SOFC-GT, SOFC-ST, and SOFC-HAT. This study found that the increasing TIT offers improvement in thermal efficiency in SOFC-HAT & SOFC-STIG with a preheated compressed air system in recuperator. Jonsson et al. [4] reviewed HGT (Humid gas turbine) cycles used with water/steam injected gas turbine/humidified air turbine and found efficiency of humidified turbine to be more than that of gas turbine. Nyberg et al. [5] presented the thermodynamic evaluation of different HAT cycle layouts and studied the contribution of different components individually to efficiency and power. Yan et al.[6] analysed the integrated SOFC-GT-organic Rankine cycle and compared it with SOFC-GT-Kalina cycle. Gogoi et al. [7] simulated SOFC-GT-ST combined power system based on Ist and IInd law of thermodynamics and compared the effect of different parameters on system performance. Zhao et al. [8] studied the SOFC-HAT combination and suitable working conditions for getting maximum efficiency. Ahn Yoonhan et al. [9] compared various sCO_2 cycle layouts for cycle performance and concluded that these sCO_2 cycle can achieve relatively high efficiency within (450-600^oC) as compared with other power systems. Meng et al. [10] did investigations upon SOFC, GT and trans critical carbon dioxide cycle. Singh and Singh [11] compared the implications of using different fluids in the ORC of SOFC-GT-ORC combination. Kumar and Singh [12] investigated the SOFC-GT cycle with inter cooling and reheating which yielded an efficiency of 60.32 %. Zhao et al. [13] compared the methanol-reforming SOFC-GT-CCHP (Combined cooling & heating power cycle) and methanol-reforming SOFC-HAT-CCHP and showed that the later cycle has higher efficiency at suitable working conditions. Lieu et al. [14] studied the SOFC-GT-CO_2-TCO_2 (Trans critical carbon dioxide) cycle having ORC from an exergy point of view. Arora and Singh [15] investigated GT-ST combined cycle driven by solar energy as an option that offers carbon emission free and environmental friendly power plant. Shukla et al. [16] identified the performance of SOFC-GT system with different operating parameters in SOFC current density, fuel circulation ratio and fuel utilization factor. Prakash and Singh [17] have conducted study of thermo economic study of GT-ST combined power plant with carbon capture and conversion of captured carbon dioxide into methane. Roy et al. [18] analysed the thermodynamic, economic, and environmental performance of integrated system of MCFC (Molten carbonate fuel cells), GT, sCO_2 cycle using biomass-fuelled distributed energy system and found the highest thermodynamic efficiency of 40.88 % and cost of electricity as 0.1057 $/kWh. The study showed its environmental benefits in comparison to a fossil fuel-based plant of similar capacity. Kumar and Singh [19] presented thermodynamic and economic evaluation of SOFC-GT-VARS (Vapour absorption refrigeration system)-ORC combined system and also analysed the implications of variation in input parameters on overall system performance. Singh and Singh [20] have done thermodynamic modeling of SOFC-GT-CCHP combined cycle for effective utilization of energy in the system. Ghorbani et al. [21] simulated thermodynamic and economic analysis for power and liquid CO_2 generation using parabolic solar collectors, SOFC and post combustion CO_2 separation unit. Seo et al. [22] presented design and performance analysis of sCO_2 heat exchangers. Based on the study, the tubular type with staggered tube bundle was selected as sCO_2 heat exchanger for analysis with LPG and air as heat source.

2. Layouts of SOFC-HAT and SOFC-HAT-sCO_2 combined power system

SOFC -HAT combined power system layout is given in figure 1a with air getting compressed from state 1 to state 4. Then it enters into preheater 1 after taking heat from exhaust gases and enters into SOFC cathode inlet. Simultaneously, the fuel (natural gas) enters into fuel compressor at state 2 for being compressed to state 5. Then it enters into preheater 2 and after taking heat from exhaust gases it enters into SOFC anode inlet. The water enters the pump at state 3 and is pumped to state 6 where water is separated in the separator and supplied in preheater 3 and preheater 4 for heat interaction. Hotter fuel and preheated water are mixed for the reforming reactions inside the mixer (M) before entering the SOFC. Air and fuel at states 5 and 13 respectively are sent to the SOFC where DC electricity is generated and converted to AC electricity in the inverter. A good amount of heat is released in the electrochemical reactions inside SOFC and the same is used for steam reforming, heating the anode, and cathode. The unused amount of fuel from SOFC is sent to the afterburner for creating the working fluid for expansion in the humid air turbine. High temperature air coming from the SOFC cathode enters the cooler where water coming from the mixer is heated from the air. The air leaving the cooler enters into the humidifier to become humidified air using the water coming from state 18. Subsequently, the humidified air goes to the afterburner in which supplementary fuel is added for being burnt to achieve the desired turbine inlet temperature. Gases coming out at the state 21 are utilized for producing work in the humid air turbine upto state 22. The energy carried by the exhaust from the humid air turbine is utilized in the four preheaters and the exhaust at state 26 is finally discharged out to the atmosphere. Figure 1b shows the SOFC-HAT-sCO_2 combined cycle arrangement in which the heat available with exhaust gas at state 26 is utilized in waste heat boiler for heating the supercritical carbon dioxide. The sCO_2 gas at state 'b' enters the waste heat boiler to extract heat from the exhaust gas from state 26 to 27 for leaving as high energy stream at state 'c' to enter the sCO_2 turbine and produce turbine work. The expanded sCO_2 gas is then cooled in the heat exchanger from state 'd' to state 'a' before getting compressed from the state 'a' to state 'b'. The ûue gases leave out at state 27 from the waste heat boiler.

3. Thermodynamic modeling [6,19 and 20]

Thermodynamic modelling of the SOFC-HAT-sCO_2 and SOFC-HAT combination relies upon the following assumption [12,13 and 14].

I. Thermodynamic system is operating in the steady state.
II. Fuel cell anode and cathode have identical temperatures at the inlet and outlet respectively.
III. Polytropic efficiency of compressor and turbine take care of deviations from ideal performance.
IV. Pressure loss across the system is neglected.
V. Water enters the humidifier at saturation temperature.

The potential of the combined system is investigated with the aim of best utilization of waste heat for achieving the high cycle efficiency. Independent parameters as TIT, CPR, FUF, and HR are chosen for estimating the dependent parameters namely cycle efficiency and power output.

Specific heat, in kJ/kg K is taken as the function of temperature as detailed ahead in equations (1),(2),(3).

Specific heat of air is,

$$c_{P\,air}(T) = (28.5462 - 1.541409\times10^{-3}\times T + 9.790716\times10^{-6}\times T^2 - 3.877293\times10^{-9}\times T^3)/28.85 \quad (1)$$

Methane is the fuel in SOFC with specific heat as,

$$c_{P\,f}(T) = (19.2494 + 52.1135\times10^{-3}\times T + 11.973\times10^{-6}\times T^2 - 11.3173\times10^{-9}\times T^3)/16 \quad (2)$$

Combustion product's specific heat,

$$c_{Pgas}(T) = 0.991615 + 6.99703\times10^{-5}\times T + 2.7129\times10^{-7}\times T^2 - 1.22244\times10^{-10}\times T^3 \quad (3)$$

3.1 Air Compressor

Compression is governed by: $\frac{T_4}{T_1} = \left(\frac{P_4}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma\times\eta_{P,Comp}}\right)}$ (4)

Air compressor work, $w_{comp,air} = \int_{T1}^{T4} c_{p,air}\,dT$ (5)

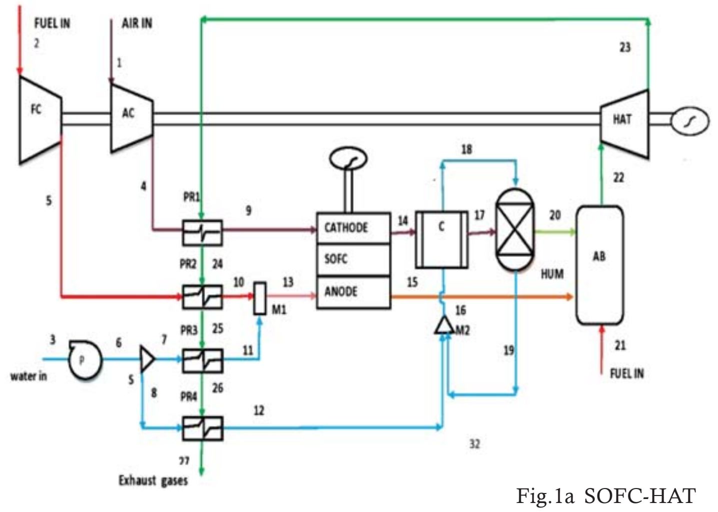
3.2 Fuel compressor

Temperature after compression is governed by: $\frac{T_5}{T_2} = \left(\frac{P_5}{P_2}\right)^{\left(\frac{\gamma-1}{\gamma\times\eta_{P,Comp}}\right)}$ (6)

Fuel compressor work, $w_{comp,f} = \int_{T2}^{T5} c_{p,f}\,dT$ (7)

3.3 Water Pump

Water pump work, $W_{pump} = m_w\,(h_6 - h_3)$ (8)



FC	FUEL COMPRESSOR
AC	AIR COMPRESSOR
PR	PREHEATER
M	MIXER
SOFC	SOLID OXIDE FUEL CELL
C	COOLER
HUM	HUMIDIFIER
HAT	HUMID AIR TURBINE
AB	AFTER BURNER
P	PUMP
S	SEPARATOR
$TsCO_2$	SUPERCRITICAL CO_2 TURBINE
$CsCO_2$	SUPERCRITICAL CO_2 COMPRESSOR
HX	HEAT EXCHANGER
WHB	WASTE HEAT BOILER

Fig.1a SOFC-HAT

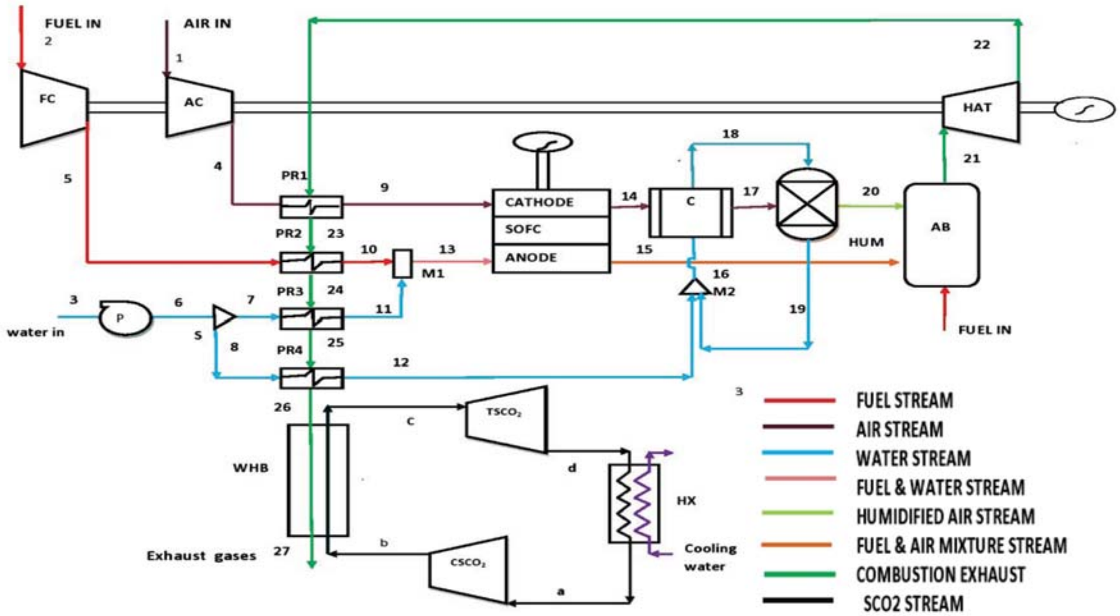


Fig.1b SOFC-HAT-sCO_2

Fig.1 Layouts of the combination of SOFC-HAT and SOFC-HAT-sCO_2

3.4 Separator

There is one separator in the cycle arrangement namely S1 with energy balance given as:

$$m_6h_6 = m_7h_7 + m_8h_8 \tag{9}$$

3.5 Preheater

Four preheaters namely PR1, PR2, PR3 and PR4 are deployed for exchanging heat between two fluids and governed by,

$$m_4(h_9 - h_4) = m_{22}(h_{22} - h_4) \quad \text{for PR1} \tag{10}$$

$$m_5(h_{10} - h_5) = m_{23}(h_{23} - h_5) \quad \text{for PR2} \tag{11}$$

$$m_7(h_{11} - h_7) = m_{24}(h_{24} - h_7) \quad \text{for PR3} \tag{12}$$

$$m_8(h_{12} - h_8) = m_{25}(h_{25} - h_8) \quad \text{for PR4} \tag{13}$$

Preheater effectiveness,

$$\varepsilon = \frac{T_9 - T_4}{T_{22} - T_4} \quad \text{for PR1} \tag{14}$$

$$\varepsilon = \frac{T_{10} - T_5}{T_{23} - T_5} \quad \text{for PR2} \tag{15}$$

$$\varepsilon = \frac{T_{11} - T_7}{T_{24} - T_7} \quad \text{for PR3} \tag{16}$$

$$\varepsilon = \frac{T_{12} - T_8}{T_{25} - T_8} \quad \text{for PR4} \tag{17}$$

3.6 Mixers

There are two mixers in cycle namely M1and M2 for realizing the mixing of different fluids entering it. The energy balance equations for the mixers are given as:

$$m_{10}h_{10} + m_{11}h_{11} = m_{13}h_{13} \quad \text{for M1} \tag{18}$$

$$m_{12}h_{12} + m_{19}h_{19} = m_{16}h_{16} \quad \text{for M2} \tag{19}$$

3.7 Solid oxide fuel cell

AC electric power, $W_{sofc,AC} = \eta_{invert} A_{cell} V_{cell} I_{cell}$ (20)

The mass balance is given as: $m_9 + m_{13} = m_{14} + m_{15}U_f + m_{15}(1 - U_f)$ (21)

Energy balance gives:

$m_9h_9 + m_{13}(U_f)LHV + m_{13}h_{13} = m_{14}h_{14} + m_{15}U_fh_{15} + m_{15}(1 - U_f)h_{15} + W_{sofc,DC}$ (22)

$W_{sofc,AC} = \eta_{invert} W_{sofc,DC}$ (23)

$\eta = \frac{W_{sofc,AC}}{m_f LCV}$ (24)

3.8 Cooler

Energy balance on cooler: $m_4(h_{18} - h_{16}) = m_{14}(h_{14} - h_{17})$ (25)

3.9 Humidifier

The humidification ratio can be expressed as:

$HR = \frac{m18-m19}{m17}$ (26)

The energy balance equation can be expressed as:
$m_{17}.h_{17} + m_{18}.h_{18} = m_{20}h_{20} + m_{19}.h_{19}$ (27)

3.10 Afterburner

The mass balance can be expressed as; $m_{15} + m_{20} + m_{f,extra} = m_{21}$ (28)

The energy balance equation can be expressed as:

$m_{15}h_{15} + m_{20}h_{20} + \eta_{comb}Q_{comb} = m_{21}h_{21}$ (29)

Where, $Q_{comb} = [m_f(1 - U_f) + m_{f,extra}].LHV$ (30)

3.11 Humid Air Turbine

Expansion in turbine is governed by, $\frac{T_{22}}{T_{21}} = \left(\frac{P_{22}}{P_{21}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)*\eta_{P,tur}}$ (31)

Humid air turbine output, $W_{HAT,tur} = m_{21}\int_{T22}^{T21} c_{p,HAT}dT$ (32)

$W_{HAT,net} = (W_{HAT,tur} - W_{air,comp} - W_{f,comp} - W_{pump})$ (33)

$\eta_{HAT} = \frac{W_{HAT,net}}{Q_{HAT}}$ (34)

Where $Q_{HAT} = Q_{tot} - W_{SOFC,DC} = Q_{comb} + m_{14}h_{14} + m_{15}h_{15} - m_9h_9 - m_{13}h_{13}$

3.12 Waste Heat Boiler

Effectiveness of waste heat boiler, $\varepsilon = \frac{T_C - T_{27}}{T_{26} - T_{27}}$ (35)

3.13 Supercritical carbon dioxide cycle

The heat balance equation for waste heat boiler is given as below;
$\eta_{whb}(m_{26}h_{26} - m_{27}h_{27}) = m_{sCO2}(h_c - h_b)$ (36)

Power from sCO_2 turbine will be, $W_{sCO2,tur} = m_{sCO2}(h_c - h_d)$ (37)

The heat rejection in the heat exchanger is given as:

$Q_{heatex} = m_{sCO2}(h_d - h_a)$ (38)

The power required for compressing sCO_2 is, $W_{sCO2,comp} = m_{sCO2}(h_b - h_a)$ (39)

Net power output: $W_{sCO2,net} = W_{sCO2,tur} - W_{sCO2,comp}$ (40)

Efficiency: $\frac{(h_c - h_d) - (h_b - h_a)}{(h_c - h_b)}$ (41)

3.14 SOFC-HAT

Mass balance for SOFC-HAT

Mass balance: $m_1 + m_2 + m_3 + m_{18} - m_{19} = m_{21}$ (42)

where,

$m_1 = m_4 = m_3 = m_{14} = m_{17}$

$m_2 = m_5 = m_{10}$

$m_7 = m_{11}$

$m_{21} = m_{22} = m_{23} = m_{24} = m_{25} = m_{26} = m_{27}$

Energy balance for SOFC-HAT

Total Work output : $W_{net,1} = W_{sofc,ac} + W_{HAT,net}$ (43)

Total thermal efficiency: $\eta_{cyc,1} = W_{net,1} / Q_{tot}$ (44)

where

$Q_{tot} = (m_f U_f LHV + Q_{comb})$

3.15 SOFC-HAT-sCO$_2$

Same mass balance equations as used in SOFC-HAT-sCO_2 are used in SOFC-HAT combination. The sCO_2 mass equations are given as:

$m_a = m_b = m_c = m_d$ (45)

Total work output and thermal efficiency of the SOFC-HAT-sCO_2 combined cycle are respectively:

$W_{net,2} = W_{sofc,ac} + W_{HAT,net} + W_{sCO2,net}$ (46)

$\eta_{cyc,2} = W_{net,2} / Q_{tot}$ (47)

Where $Q_{tot} = (m_f U_f LHV + Q_{comb})$ (48)

Based on mathematical model described above a computer program is written in C language for performance assessment with various input parameters. Thermophysical properties required in thermodynamic analysis are obtained by REFROP 9.0.

4. Result and Discussion

SOFC-HAT combined cycle and SOFC-HAT-sCO_2 combined cycle arrangements are analysed through the computer simulation based on the input parameters given in Table1.

Table 1 - Input parameters [6,11,13,14 and 19]

Parameter	Value
Compressor polytropic efficiency, %	90
Inlet temperature, K	298
Cycle pressure ratio	8
Polytropic efficiency of turbine, %	92
Turbine inlet temperature, K	1400
LCV of fuel, kJ/kg	50000
Fuel utilization factor	0.85
Current density, A m^{-2}	4628
Area of cell,cm^2	220
Cell voltage, V	0.614
Operating temperature, K	1138
No. of cell, N	50000
Air/fuel ratio	13.5
Humidification ratio	0.186
Effectiveness of waste heat boiler	0.95
DC-AC inverter efficiency, %	90
Combustion efficiency, %	95
Steam/natural gas ratio	2.5
Pre-reformer operating temperature, K	700
Gravimetric composition of air	O_2=21%, N_2=79%
Fuel	100% CH_4
sCO_2 compressor inlet temperature (K)	305.15
sCO_2 compressor outlet pressure (MPa)	20.4
sCO_2 compressor inlet pressure (MPa)	7.2
sCO_2 turbine isentropic efficiency	90%
sCO_2 compressor isentropic efficiency	89%
Water flow rate in humidifier, kg/sec	3.27
Water inlet temperature, K	420
Water exit temperature, K	346
Inlet Water flow rate in humidifier, kg/sec	3.27

Fig.2a shows that at any cycle pressure ratio, the SOFC-HAT combination yields more work output as compared to SOFC alone. While in SOFC-HAT-sCO_2 combination, the increasing cycle pressure ratio shows a gradual increase in the work output. However, at any cycle pressure ratio, the work output of SOFC-HAT-sCO_2 is highest as compared to the SOFC-HAT cycle. At TIT of 1400 K, the maximum work output from SOFC-HAT-sCO_2 is 1690.432 kJ/kg of air while that of SOFC-HAT is 1639.946 kJ/kg of air at a cycle pressure ratio of 14, fuel utilization factor of 0.85, and humidification ratio of 0.186.

Fig.2b depicts the cycle efficiency at fixed TIT, fuel utilization factor, and humidification ratio of 1400 K, 0.85, and 0.186 respectively for SOFC, HAT, SOFC-HAT, and SOFC-HAT-sCO_2 at different pressure ratio. Here the increase in cycle pressure ratio yields the increase in efficiency of SOFC, HAT, SOFC-HAT, and SOFC-HAT-sCO_2 cycle arrangements. The highest efficiency value of 64.81 % is obtained for the SOFC-HAT-sCO_2 cycle and 62.84 % for the SOFC-HAT cycle at a cycle pressure ratio of 14.

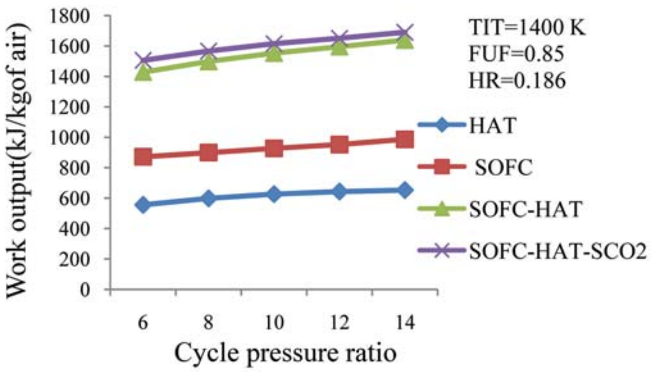


Fig.2a Effect of cycle pressure ratio on work output

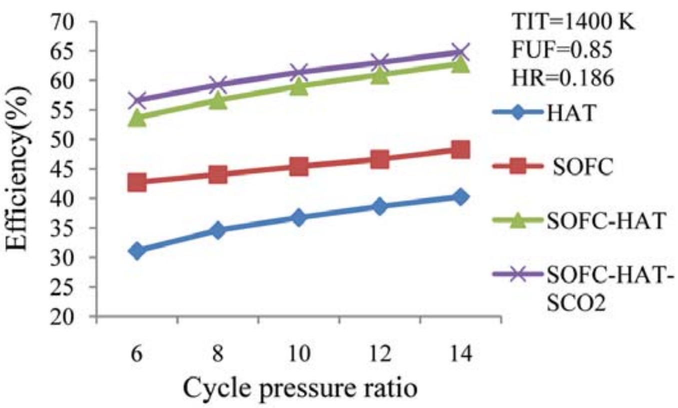


Fig.2b Effect of cycle pressure ratio on efficiency

Fig.3a shows the effect of turbine inlet temperature on work output at cycle pressure ratio, fuel utilization factor and humidification ratio of 8, 0.85, and 0.186 respectively. Here the increase of turbine inlet temperature causes an increase in work output for fixed utilization factor due to an increase in work output of humid air turbine at higher turbine inlet temperature for SOFC, HAT, SOFC-HAT, and SOFC-HAT-sCO_2 cycle arrangements. The maximum work output is 1632.42 kJ/kg of air for the SOFC-HAT-sCO_2 cycle due to 96 kJ/kg of air work contribution of supercritical carbon dioxide. The higher turbine inlet temperature yields waste gases with higher energy content in the SOFC-HAT cycle arrangement.

Fig.3b describes the efficiency varying with turbine inlet temperature in the case of SOFC, HAT, SOFC-HAT, and SOFC-HAT-sCO_2 cycle arrangements at a cycle pressure ratio of 8, fuel utilization factor 0.85 and humidification ratio 0.186 respectively. It demonstrates that the increase in turbine inlet temperature leads to a decrease in efficiency of the SOFC-HAT cycle for a fixed fuel utilization factor as the increase in turbine inlet temperature demands for additional fuel supply. The decrease in efficiency with increasing turbine inlet temperature is due to the additional heat supply being more than the increase in the corresponding work output.

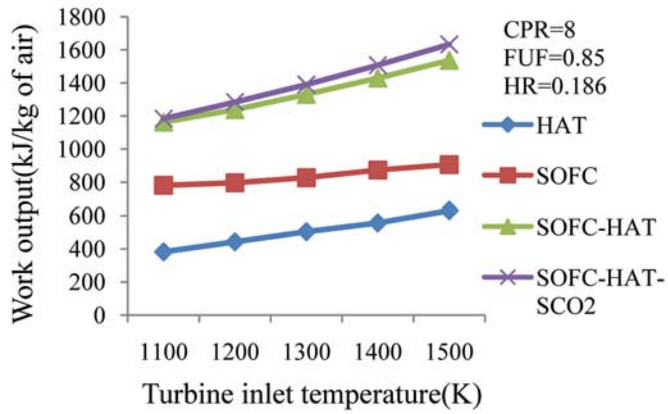


Fig.3a Effect of turbine inlet temperature on work output

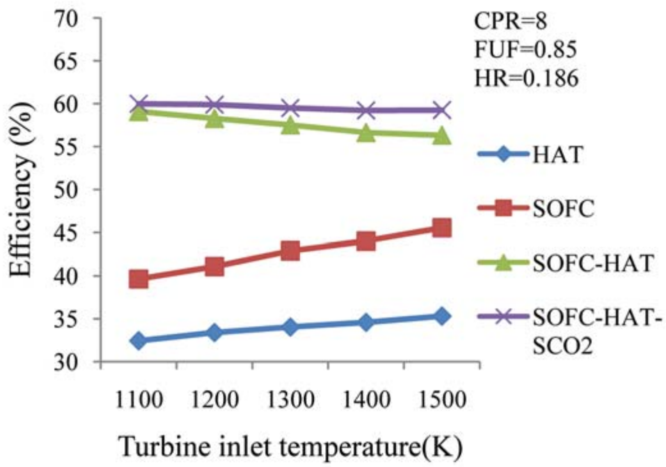


Fig.3b Effect of turbine inlet temperature on efficiency

Fig.4a shows the variation of work output with fuel utilization factor for SOFC, HAT, SOFC-HAT and SOFC-HAT-sCO_2 cycle arrangements at cycle pressure ratio, turbine inlet temperature, and humidification ratio of 8, 1400 K, and 0.186 respectively. Graphically, the work output increases with increasing fuel utilization factor in the SOFC-HAT cycle due to an increase in SOFC work output because of better fuel utilization while HAT work output remains constant. Hence the SOFC-HAT cycle work output increases with an increase in work output and the same is evident upon the SOFC-HAT-sCO_2 cycle arrangement, however the magnitude of work output from the SOFC-HAT-sCO_2 combined cycle is more than that of the SOFC-HAT cycle.

Fig.4b gives the efficiency of SOFC, HAT, SOFC-HAT, and SOFC-HAT-sCO_2 cycle arrangements varying with fuel utilization factor at cycle

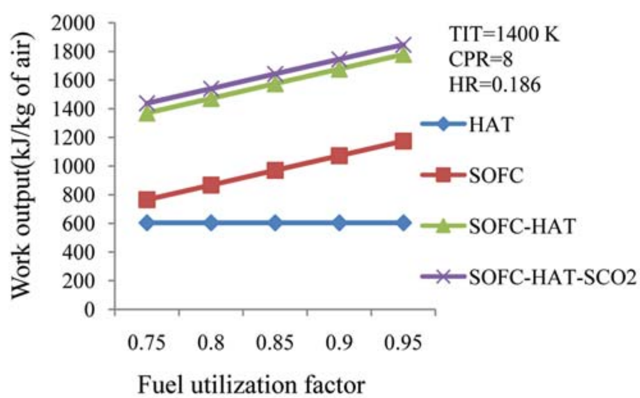


Fig.4a Effect of fuel utilization factor on work output

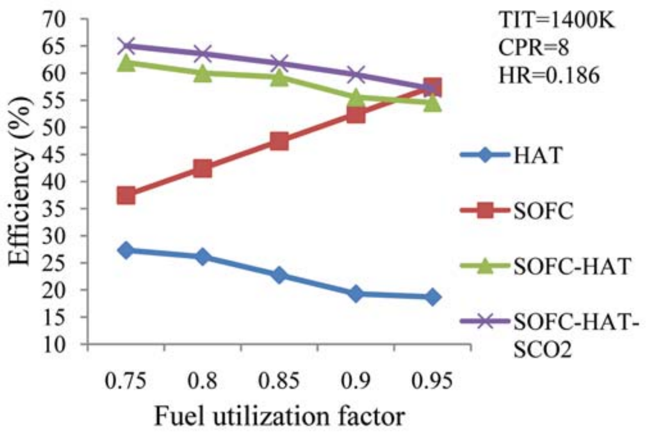


Fig.4b Effect of fuel utilization factor on efficiency

pressure ratio of 8, the turbine inlet temperature of 1400 K, and humidification ratio of 0.186. The better fuel utilization provides improved efficiency of SOFC, but the amount of left out fuel for the afterburner will get reduced with higher fuel utilization, therefore extra fuel requirement increases in the afterburner. Hence the efficiency of HAT, SOFC-HAT, and SOFC-HAT-sCO_2 cycle arrangements decrease as indicated in the graphical depiction. At FUF of 0.95, the efficiency of SOFC is highest as more amount of fuel undergoes electrochemical reaction while SOFC-HAT and SOFC-HAT-sCO_2 efficiency are lowest. This is attributed to the fact that though the SOFC, HAT work outputs increase with an increase in FUF but the fuel requirement also increases in afterburner thus the net efficiency decreases with an increase in FUF.

The implication of the humidification ratio on the work output is shown in figure 5a at the cycle pressure ratio of 8, the turbine inlet temperature of 1400 K, and fuel utilization factor of 0.85. It is seen that the work output increases with increase in the humidification ratio in the SOFC-HAT cycle due to the increase in mass flow rate yielding an increase in turbine work output and the same predominate the variation of SOFC-HAT-sCO_2. Graphically it is evident that the overall work output is 1576 kJ/kg of air for TIT 1400K, cycle pressure ratio of 8, fuel utilization factor of 0.85, and 0.186 humidification ratio. The SOFC-HAT-sCO_2 system offers a gain in work output by 4.54 % as compared to the SOFC-HAT cycle.

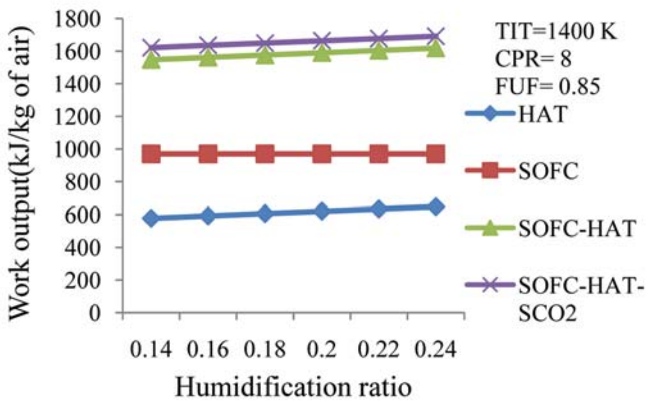


Fig.5a Effect of humidification ratio on work output

The influence of the variation of humidification ratio on the efficiency is shown in figure 5b at the fixed cycle pressure ratio of 8, turbine inlet temperature 1400 K, and fuel utilization factor 0.85. The increase in humidification ratio results not only in the increase in work output of humid air turbine but also increases the additional fuel requirement in afterburner leading to a drooping trend of efficiency in HAT cycle. However, the SOFC efficiency remains unaffected with increase in humidification ratio. The efficiency of the SOFC-HAT and SOFC-HAT-sCO_2 combined system also decrease as evident from the drooping trend of efficiency in HAT cycle with increase in humidification ratio.

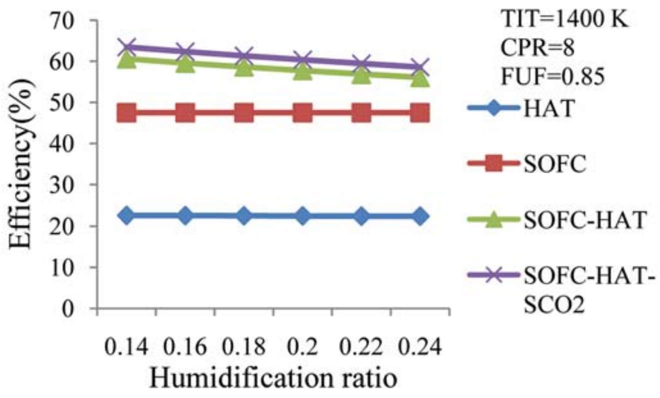


Fig.5b Effect of humidification ratio on efficiency

Fig.6 shows the validation of results obtained from the present thermodynamic modelling. In view of no evidence of the published work of the SOFC-HAT-sCO_2 cycle being available, the validation of

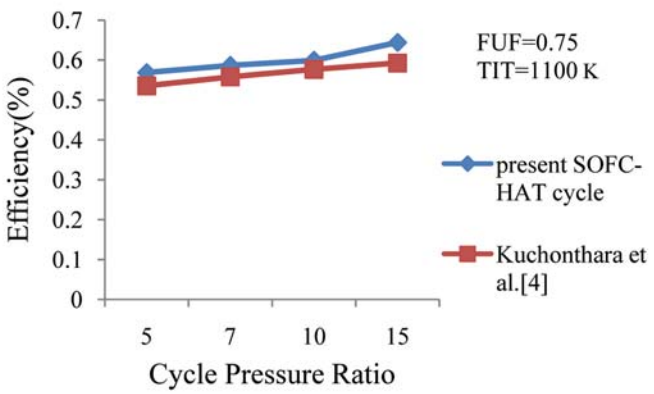


Fig.6 Validation with results of Kuchonthara et al. [3]

modelling has been done for the efficiency estimations for the SOFC-HAT cycle arrangement as reported in the published work of Kuchonthara et al. [3]. For the same operating parameters of fuel utilization factor of 0.75, turbine inlet temperature of 1100 K, and cycle pressure ratio varying from 5 to 15, the results obtained from the present study are nearly similar to those in the published work. The slight deviation is due to the difference in basic modelling assumptions. The deviation of the present work is 3.4 % from published work.

5. Conclusion

The following conclusions have been obtained from the comparative thermodynamic evaluation of SOFC-HAT and SOFC-HAT-sCO_2 cycle arrangements.

- The SOFC-HAT-sCO_2 cycle based combined power system has significantly higher specific power output and efficiency as compared to the SOFC-HAT combined cycle.
- SOFC-HAT-sCO_2 combined cycle offers thermal efficiency of 59.23% at a turbine inlet temperature of 1400 K and a cycle pressure ratio of 8 which is 2.58 % more than that available from SOFC-HAT combined cycle arrangement.
- The work output from SOFC-HAT-sCO_2 combined cycle is found to be 1576 kJ/kg of air at turbine inlet temperature 1400 K, cycle pressure ratio of 8, fuel utilization factor of 0.85, and humidification ratio of 0.186 which is 4.54 % more than the SOFC-HAT combined cycle.
- The maximum effect of integrating supercritical carbon dioxide cycle for optimal utilization of waste heat is estimated as the additional sCO_2 cycle work output of 96.68 kJ/kg of air and increment in the thermal efficiency of 3.35 % due to it.

- The increase in cycle pressure ratio results in higher work output, and an increase in efficiency at the considered turbine inlet temperature, fuel utilization factor, and humidification ratio.
- In SOFC-HAT-sCO_2 combined cycle, the increase in turbine inlet temperature leads to an increase in work output, while the efficiency decreases with an increase in turbine inlet temperature for fixed fuel utilization factor, cycle pressure ratio, and humidification ratio.

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