Thermodynamic analysis of a power plant integrated with fogging inlet cooling and a biomass gasification

H. Athari (Department of Mechanical Engineering, University of Ataturk, 25240 Erzurum, Turkey)

S. Soltani (Faculty of Mechanical Engineering, University of Tabriz, Iran)

M.A. Rosen (Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada)

S.M.S Mahmoudi (Faculty of Mechanical Engineering, University of Tabriz, Iran)

T. Morosuk (Institute for Energy Engineering, Technische Universität Berlin, Marchstr 18, 10587 Berlin, Germany)

Outline

1. Introduction
2. System Description
3. Thermodynamic Modeling
4. Results and Discussions
5. Conclusions

1. Introduction

Why fog cooling?

The performance of a gas turbine, particularly output power and energy efficiency, is significantly affected by ambient temperature, especially during hot and humid summer periods when power demands often peak

The fog inlet cooling, which is one of way to increase energy efficiency, involves spraying water droplets into the compressor inlet air to reduce its temperature towards the corresponding wet-bulb temperature

1. Introduction

What is biomass

- Biomass is a renewable energy source that is derived from living or recently living organisms.

- Biomass includes biological material, not organic material like coal.

- Energy derived from biomass is mostly used to generate electricity or to produce heat.

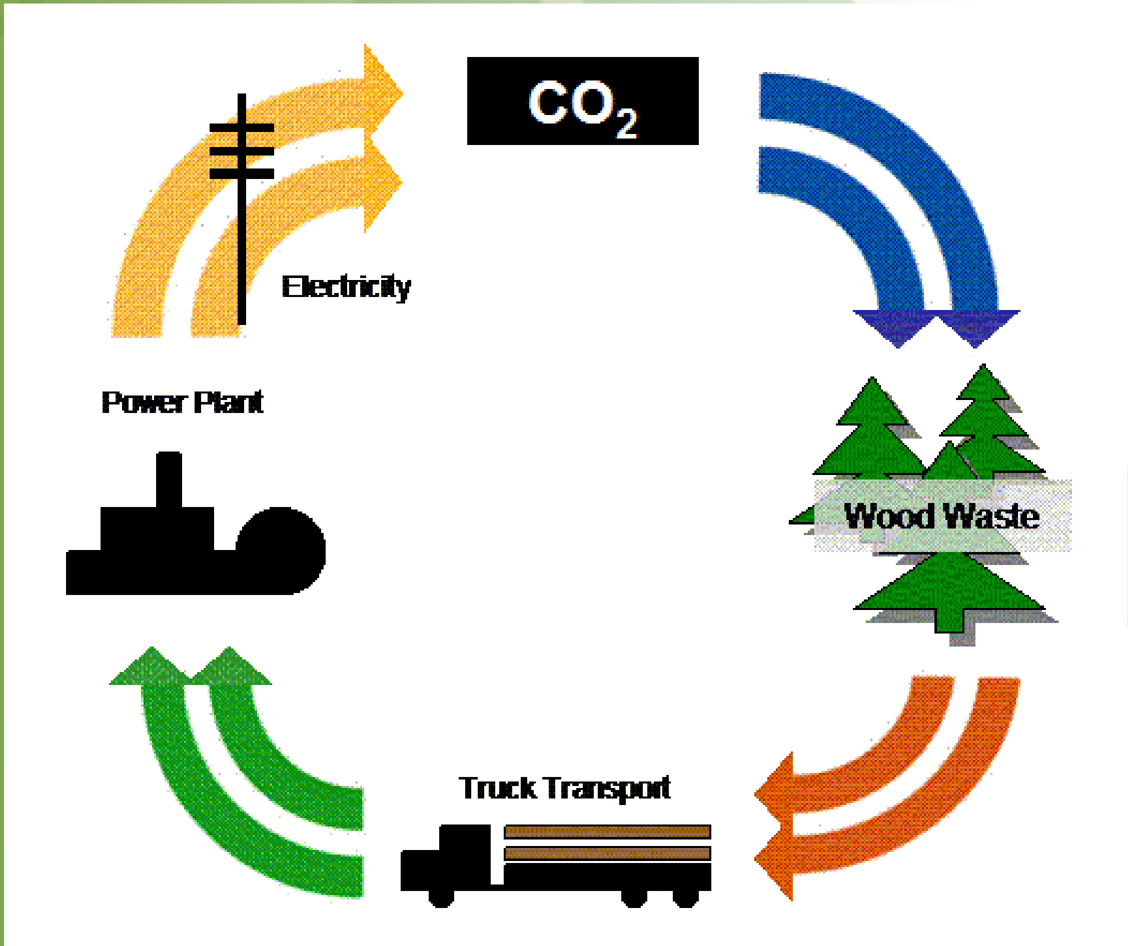
- Biomass can be chemically and biochemically treated to convert it to a energy-rich fuel.

1. Introduction

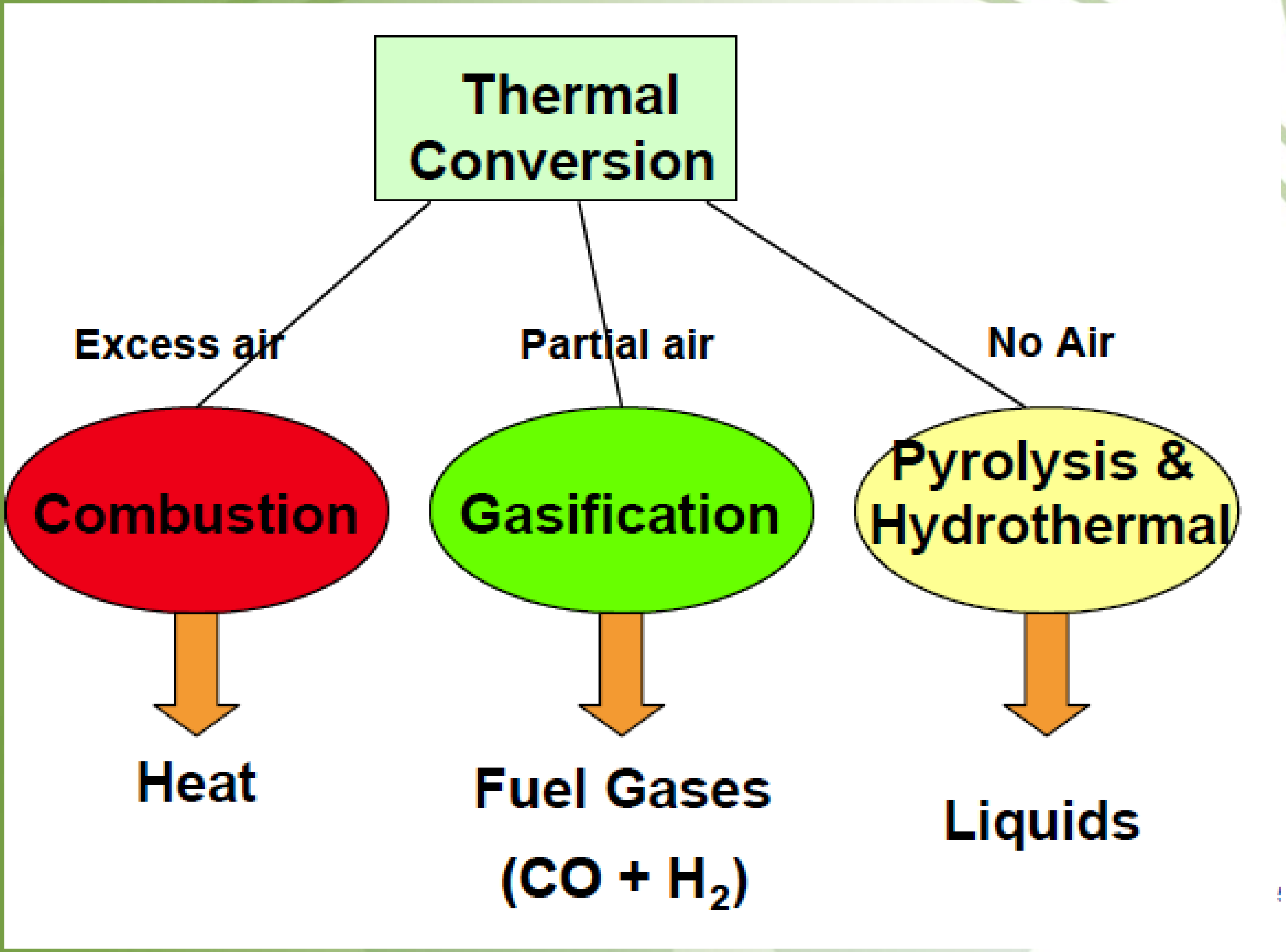
What makes it green (ideally)?

- CO_2 emissions/per energy produced is similar to petroleum.
- However, CO_2 released is recaptured by next years crops. So, there is no net CO_2 added.

1. Introduction



1. Introduction



1. Introduction

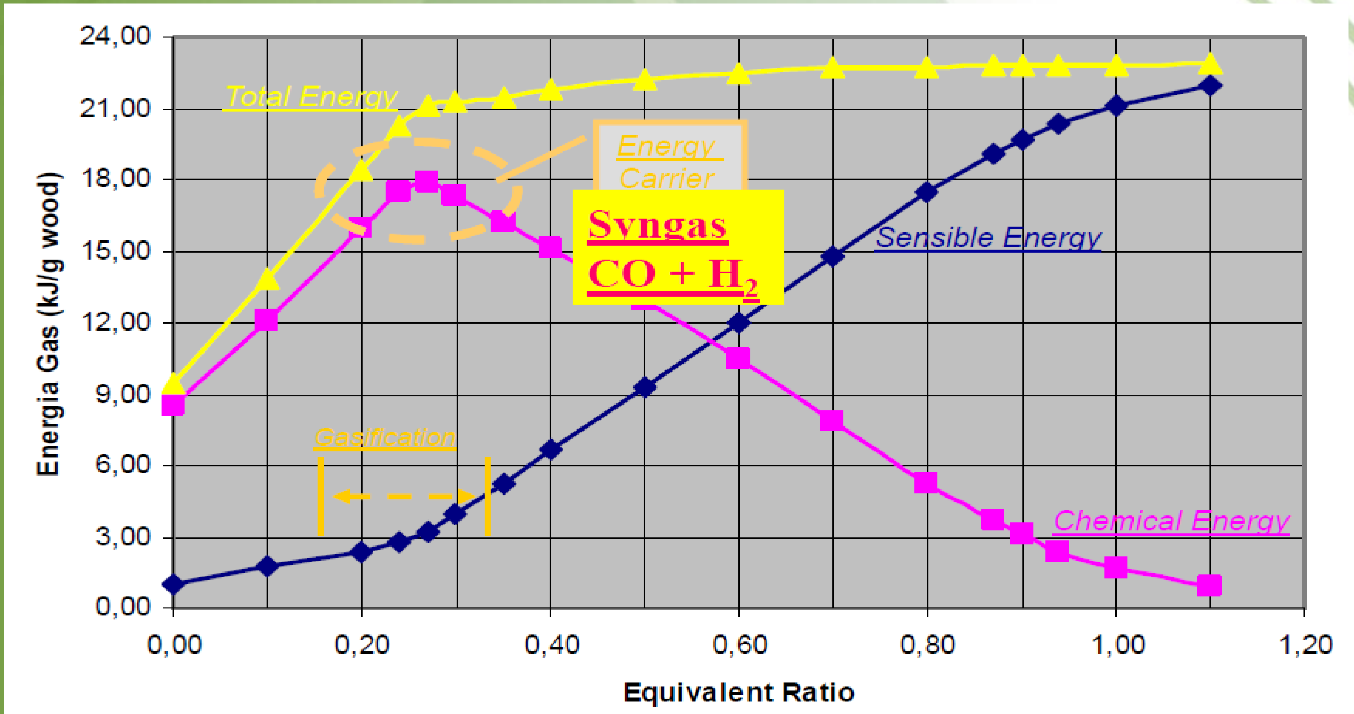
What is Biomass Gasification?

Basic Process Chemistry

- Conversion of solid fuels into combustible gas mixture called producer gas ($CO + H_2 + CH_4$)
- Involves partial combustion of biomass
- Four distinct process in the gasifier viz.
  - Drying
  - Pyrolysis
  - Combustion
  - Reduction

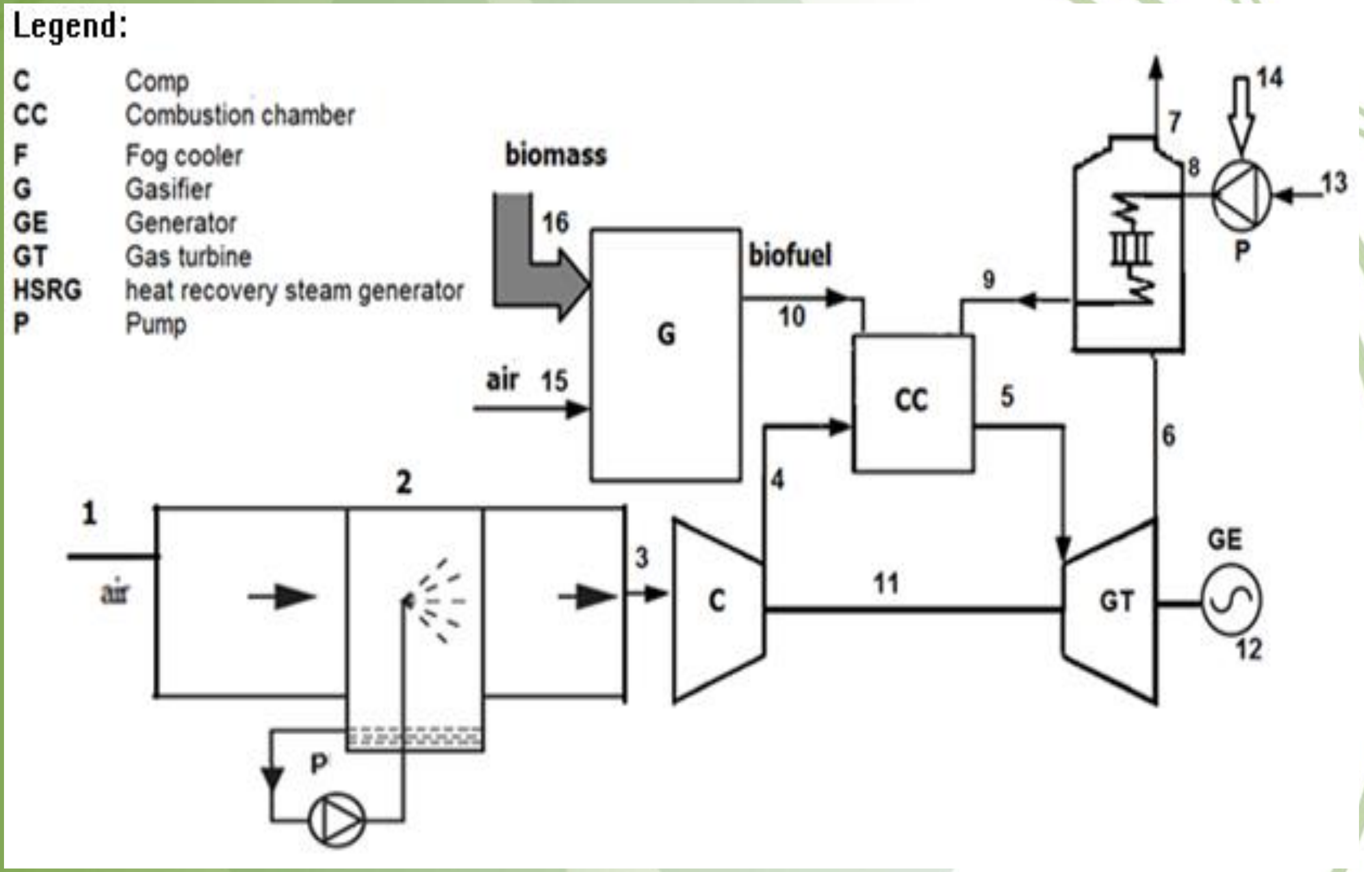
1. Introduction

WHY GASIFICATION



It maximize the Chemical Energy in the produced gases

2. System Description



Gas turbine cycle with steam injection and inlet fogging cooler (BIFSTIG)

2. System Description

BIFSTIG (biomass integrated fog cooling steam injection gas turbine)

FSTIG (fog cooling steam injection gas turbine with firing of natural gas)

BISTIG (biomass integrated gas turbine with steam injection)

BIFGT (biomass integrated gas turbine with fog cooling)

BIGT (biomass integrated simple gas turbine)

3. Thermodynamic Modeling

$$\dot{m}_{a3}h_{a3}+\dot{m}_{v3}h_{v3}+\dot{m}_{f3}h_{f3}=\dot{m}_{a1}h_{a1}+\dot{m}_{v1}h_{v1}+\dot{m}_{w}h_{w}$$

The both side of equation are divided by $\dot{m}_{a3}$ or $\dot{m}_{a1}$ (because they are equal to each other)

(W (specific humidity) is equal to $\dot{m}_v / \dot{m}_a$ and overspray is equal to $\dot{m}_{f3} / \dot{m}_{a3}$)

$$h_{a3}+w_3h_{v3}+(\dot{m}_{f3} / \dot{m}_{a3})h_{f3}=h_{a1}+w_1h_{v1}+(\dot{m}_w / \dot{m}_{a3})h_w$$

$\dot{m}_w = \dot{m}_3 + \dot{m}_{f3} - \dot{m}_1$ (In point 3 there are air and liquid water)

$$ha_3+w_3hv_3+\text{overspray}\times h_{f3}=ha_1+w_1hv_1+(w_3-w_1+\text{overspray})h_f$$

3. Thermodynamic Modeling

Equilibrium model[1]

$C + CO_2 \Leftrightarrow 2CO$

$C + H_2O \Leftrightarrow CO + H_2$

$CO + H_2O \Leftrightarrow CO_2 + H_2$ — $K_2 = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}}$

$C + H_2 \Leftrightarrow CH_4$ — $K_1 = \frac{P_{CH_4}}{(P_{H2})^2}$

K_i: equilibrium constants for methane formation and shift reaction

Global gasification process can be expressed as the global reaction:

$$C_xH_yO_z + w\,H_2O + m\,O_2 + 3.76m\,N_2 = x_1\,H_2 + x_2\,CO + x_3\,CO_2 + x_4\,H_2O + x_5\,CH_4 + 3.76m\,N_2$$

3. Thermodynamic Modeling

Part A: Fogging cooler			**Part B: Biomass gasification**			
Comparsion conditions	Comparison of reported and computed results for selected conditions: TIT = 1122°C, compressor pressure ratio = 11.84, inlet mass rate of turbine = 374.59 kg/s, overspray = 2%		Comparsion conditions	Comparison between model and experimental constituent breakdown (in %) for wood at 20% moisture content and a gasification temperature of 800 °C		
Parameter	**Reported in [6]**	**Computed here**	**Parameter**	**Computed here**	**Reported in [26]**	**Reporte in [25]**
CIT (°C)	30.00	30.08	Hydrogen	18.01	15.23	21.06
CDT (°C)	293	286.9	Carbon monoxide	18.77	23.04	19.61
$\dot{W}_{net}$ (MW)	133	136	Methane	0.68	1.58	0.64
TOT (°C)	553	577	Carbon dioxide	13.84	16.42	12.01
Heat rate (kJ/kWh)	10,609	10,653	Nitrogen	48.7	42.31	46.68
			Oxygen	0.00	1.42	0.00

3. Thermodynamic Modeling

Thermodynamics

- The First Law
  - The energy of the universe is constant
- The Second Law
  - The Entropy of the universe is constantly increasing.

3. Thermodynamic Modeling

Energy-based methods are not suitable for answering some questions because the only thermodynamic inefficiencies identified by energy-based methods are the transfer of energy to the environment. However, *the inefficiencies caused by the irreversibilities within the system* being considered are, in general, by far the most important thermodynamic inefficiencies and are identifiable with the aid of an exergetic analysis.

Exergy-based methods reveal the location, the magnitude and the sources of inefficiencies and costs impact and allow us to study the interconnections between them.

3. Thermodynamic Modeling

Exergetic Variables: E_P and E_F

Exergy of product: $\dot{E}_P$

The desired result, expressed in exergy terms, achieved by the system (the *k*-th component) being considered.

Exergy of fuel: $\dot{E}_F$

The exergetic resources expended to generate the exergy of the product.

The concepts of product and fuel are used in a consistent way not only in *exergetic analyses* but also in the *exergoeconomic* and *exergoenvironmental* analyses.

3. Thermodynamic Modeling

Exergetic Variables: E_D and E_L

Exergy destruction: $\dot{E}_D$

Exergy destroyed due to irreversibilities within a system (the k-th component).

Exergy loss: $\dot{E}_L$

Exergy transfer to the system surroundings. This exergy transfer is not further used in the installation being considered or in another one.

Exergy balance:

$$\dot{E}_F = \dot{E}_P + \dot{E}_D \left(+ \dot{E}_L \right)$$

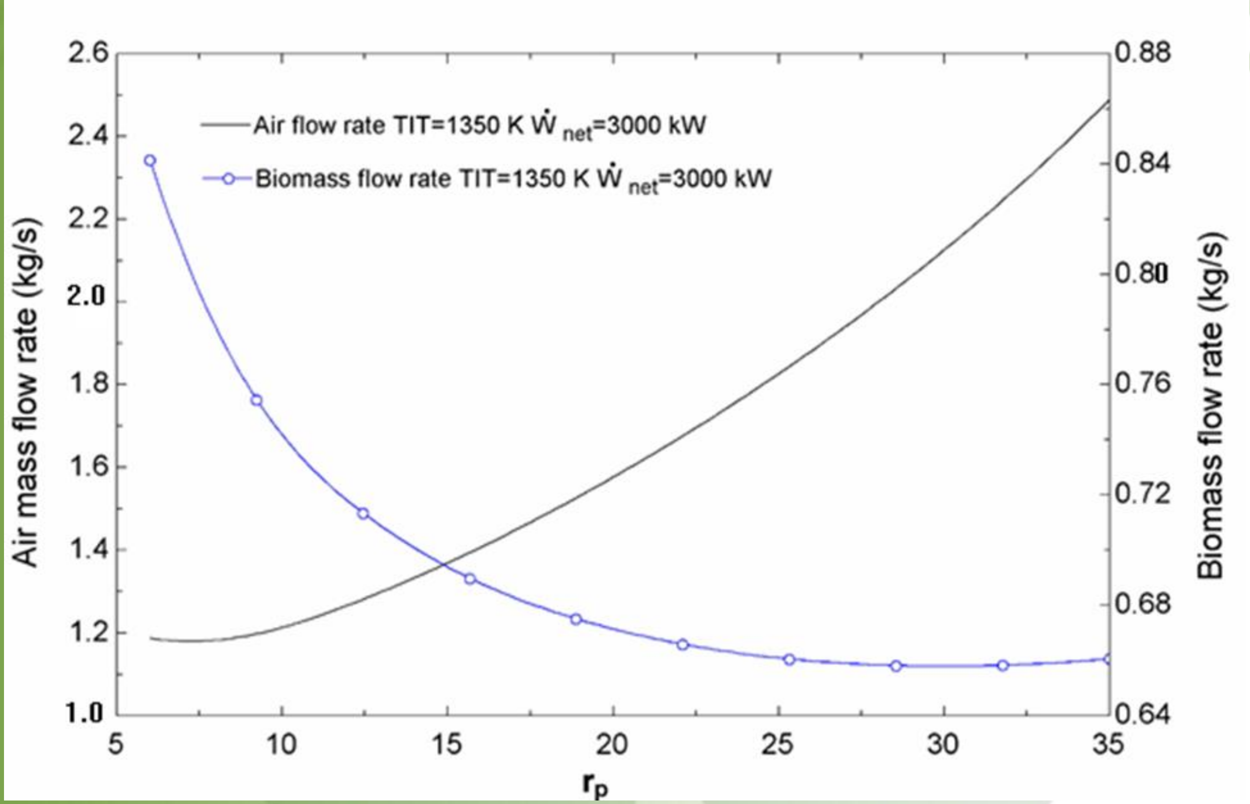
$\dot{E}_D$ and $\dot{E}_L$ are absolute measures of the thermodynamic inefficiencies.

3. Thermodynamic Modeling

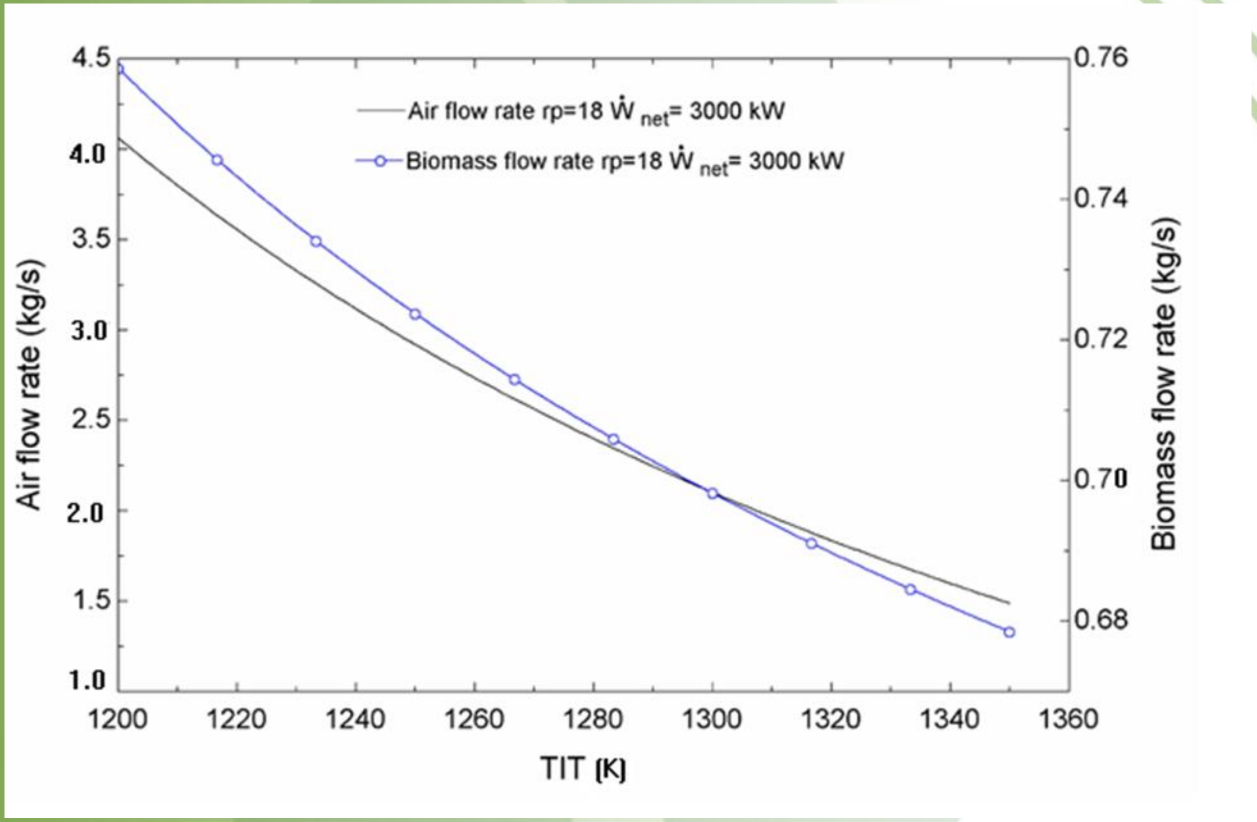
$$\eta = \frac{\dot{W}_{net,cycle}}{\dot{m}_{fuel} LHV_{fuel}}$$

$$\varepsilon = \frac{\dot{W}_{net,cycle}}{\dot{E}_{in,cycle}}$$

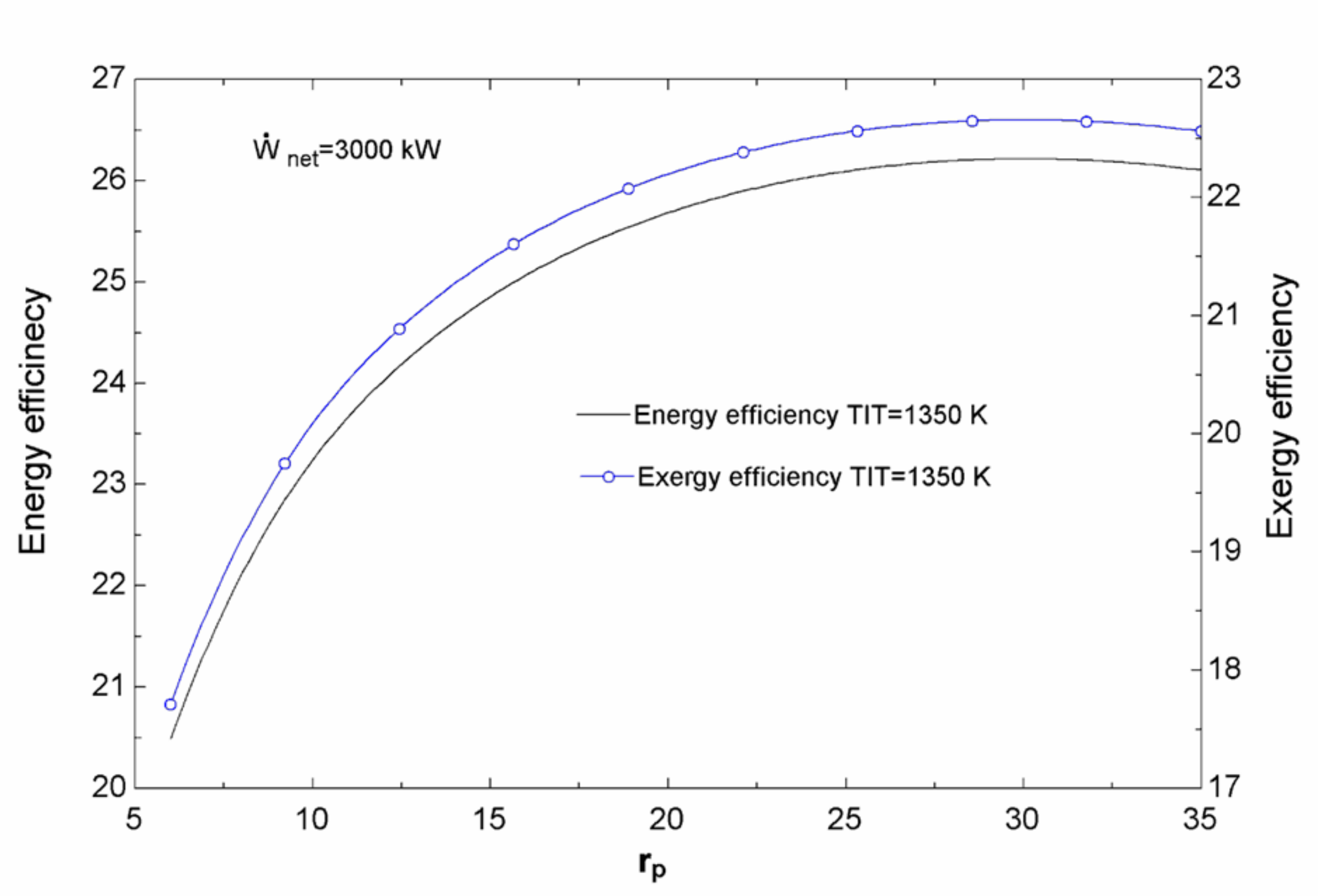
4. Results and discussions



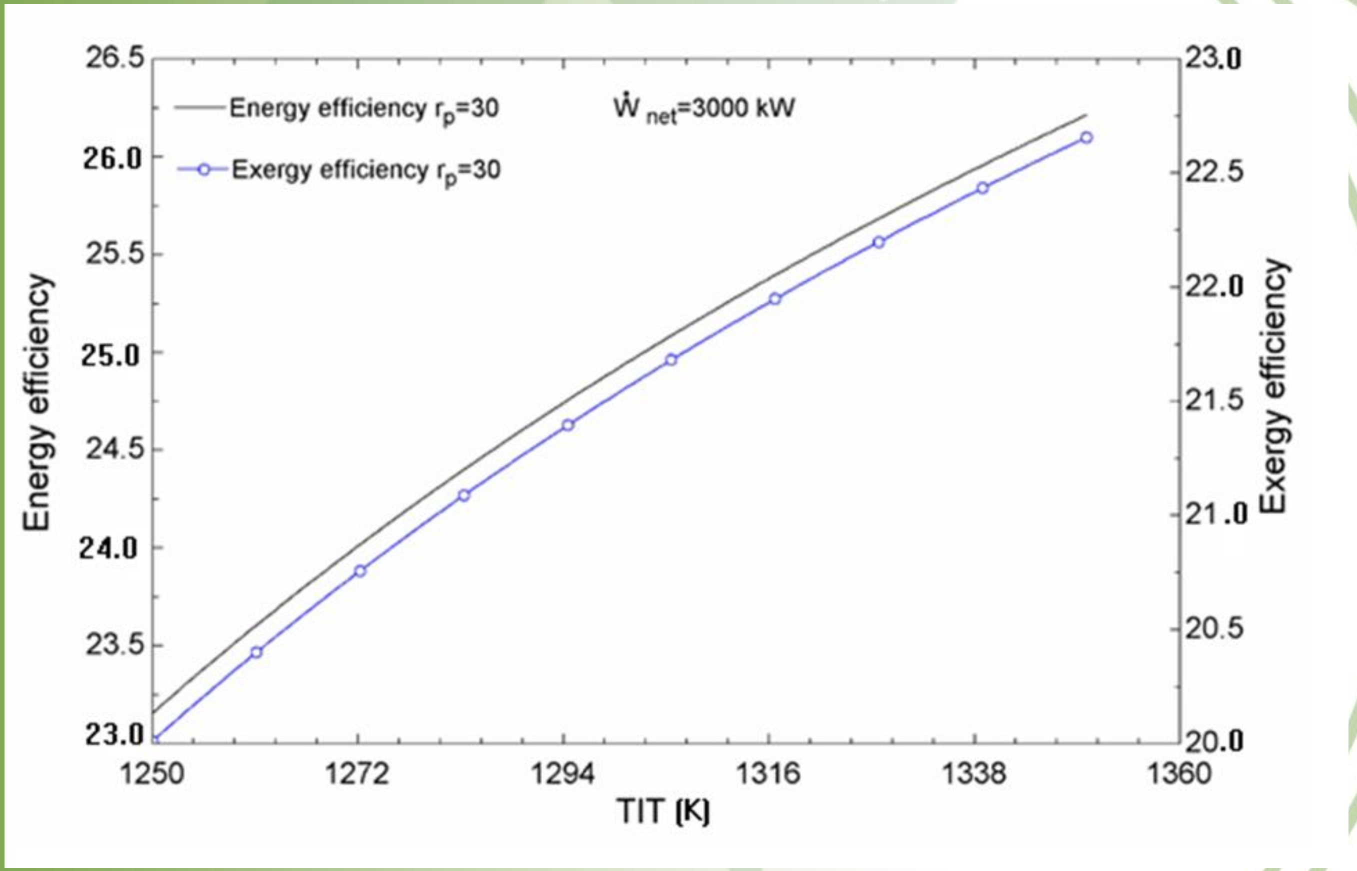
4. Results and discussions



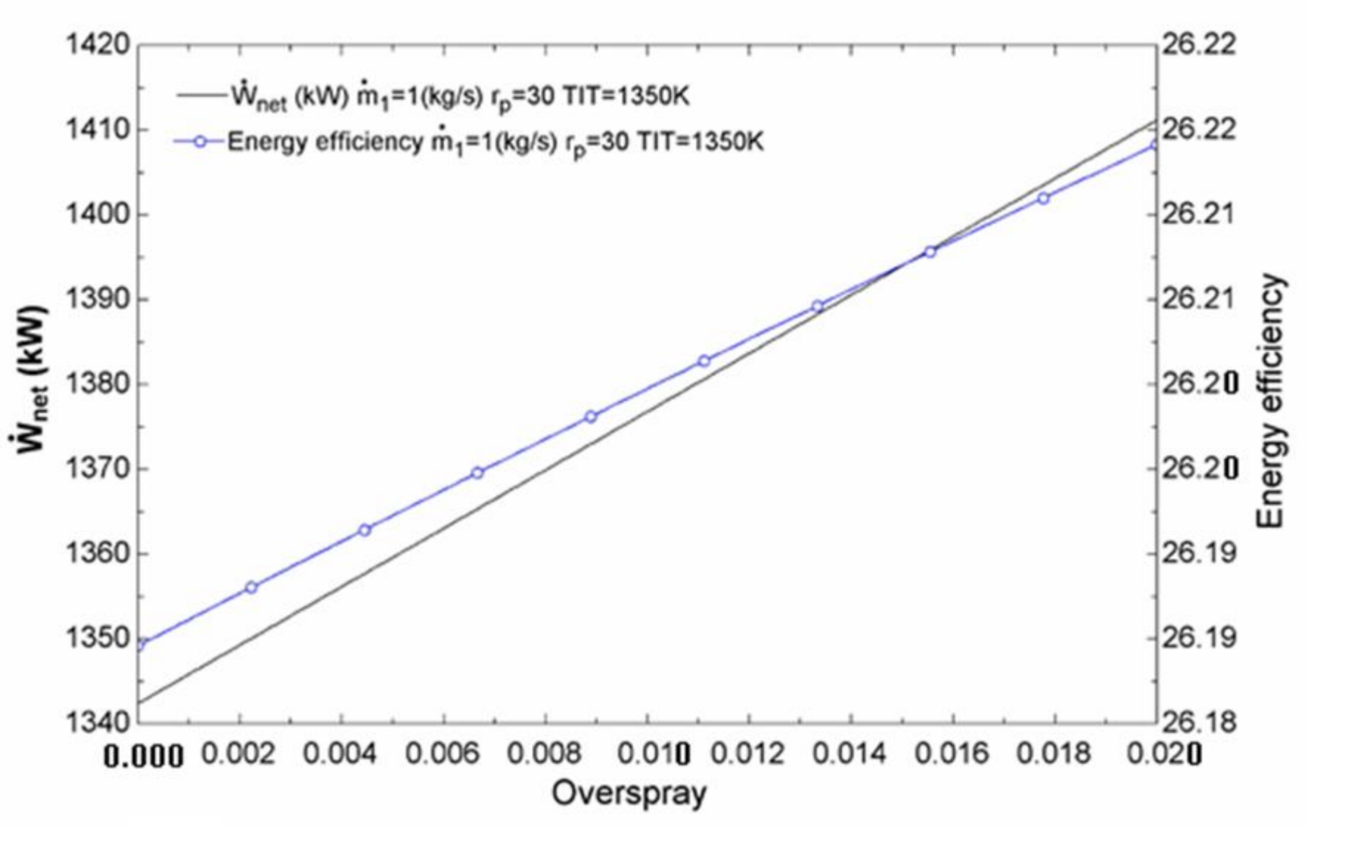
4. Results and discussions



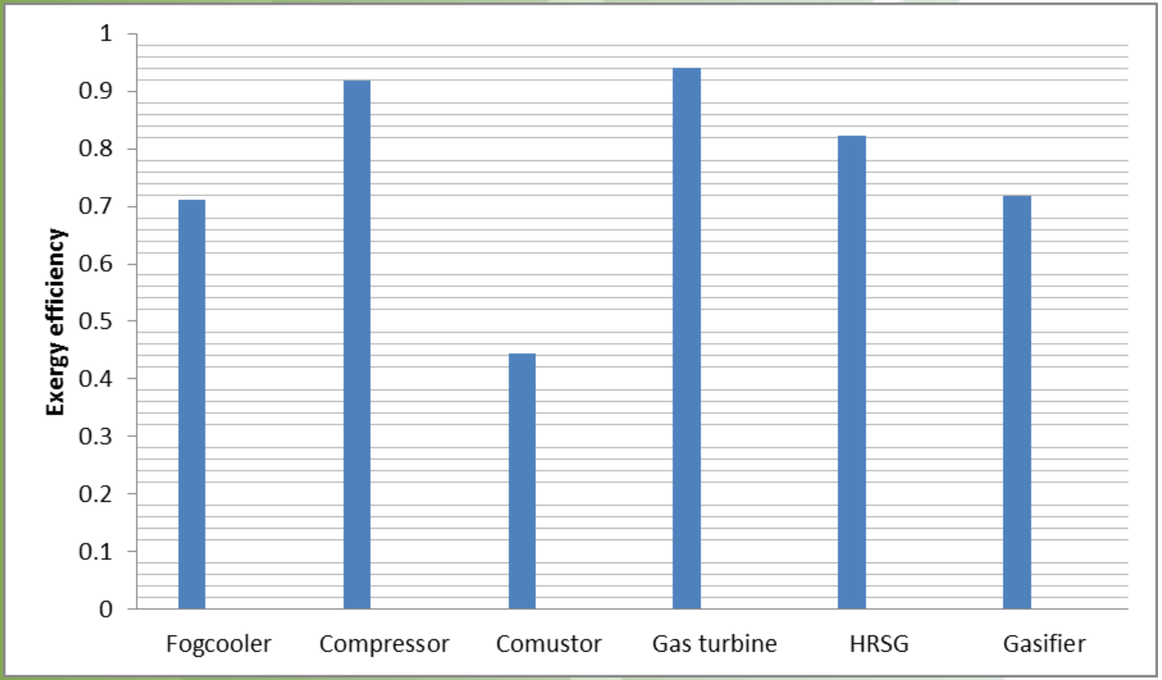
4. Results and discussions



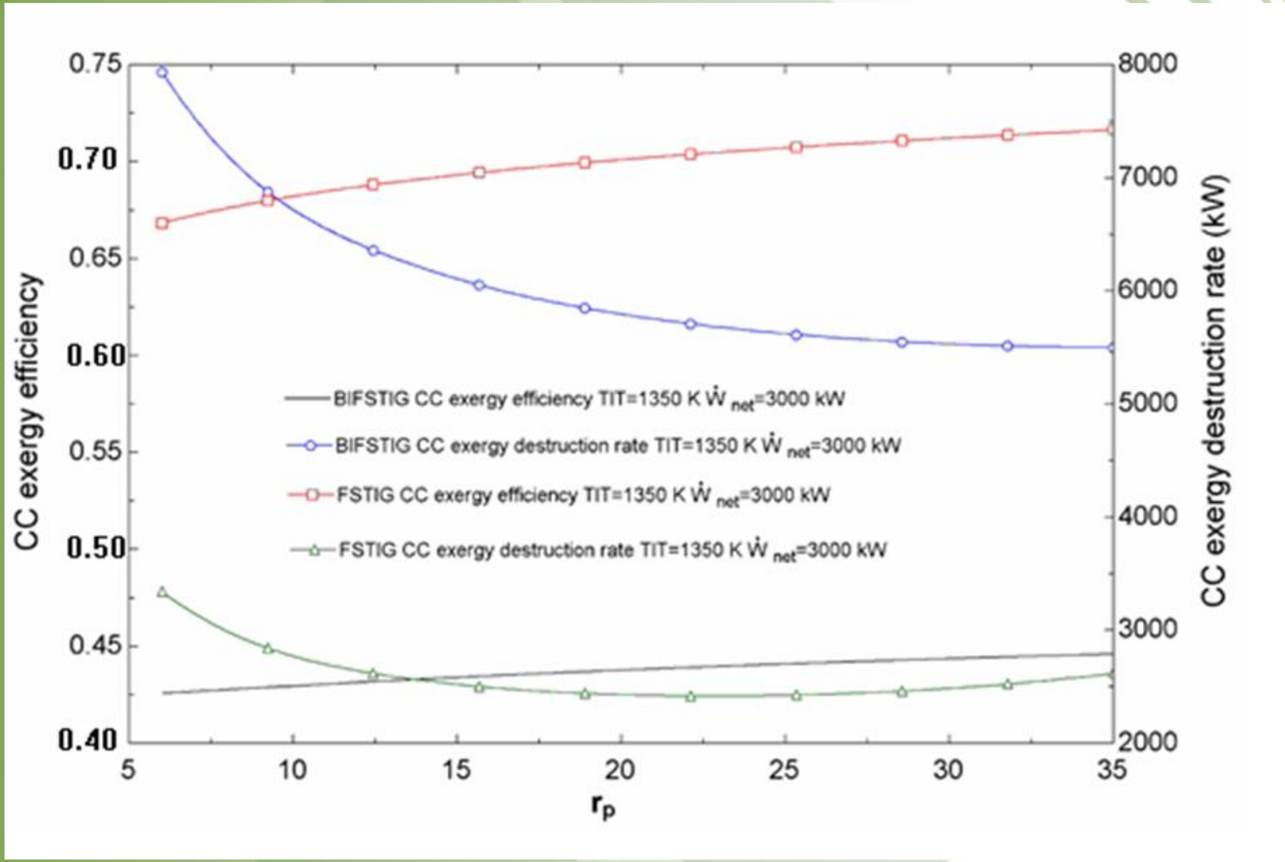
4. Results and discussions



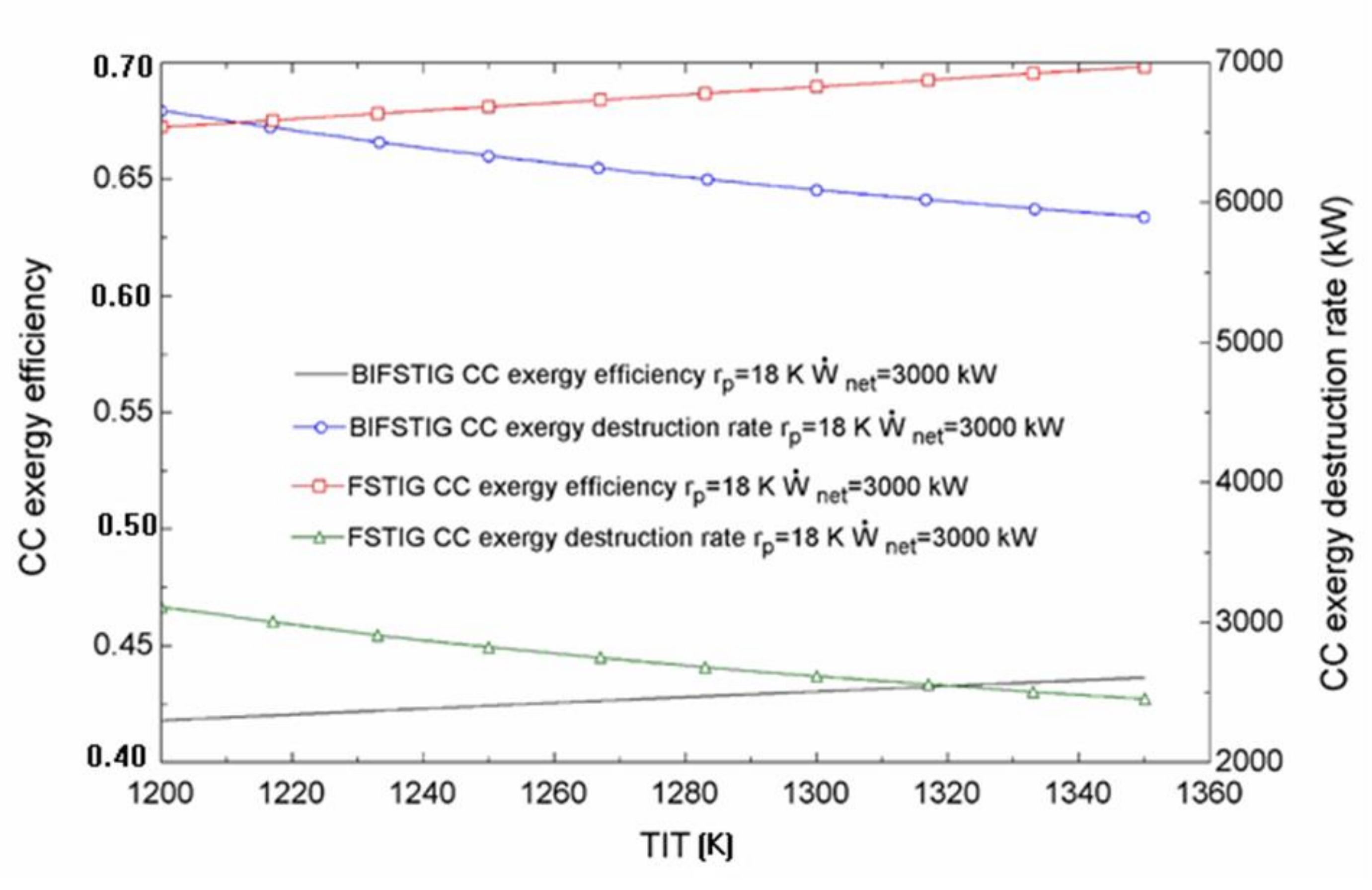
4. Results and discussions



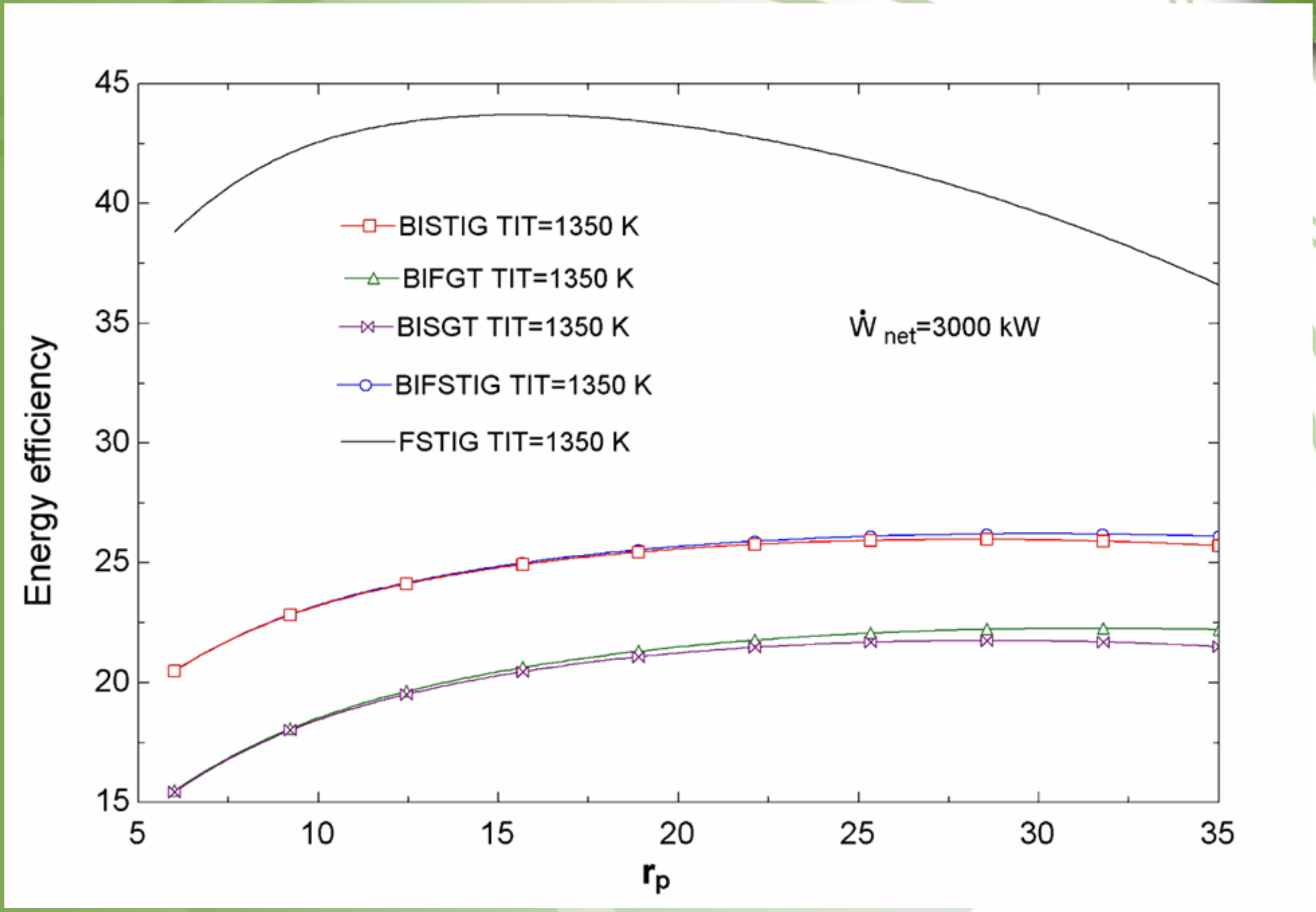
4. Results and discussions



4. Results and discussions



4. Results and discussions



5. Conclusion

- Increasing the compressor pressure ratio and gas turbine inlet temperature increases the energy and exergy efficiencies.

- Also, increasing compressor pressure ratio and gas turbine inlet temperature decreases the biomass flow rate, while the air mass flow rate increases with increasing compressor pressure ratio and decreases with increasing gas turbine inlet temperature.

- Overspray raises the net power output and the energy efficiency, with the influence on former being more significant.

5. Conclusion

- Increasing the compressor pressure ratio and gas turbine inlet temperature raises the combustor exergy efficiency for the BIFSTIG plant, while increasing the pressure ratio raises the energy efficiency. However, there is an optimum point in terms of a specific pressure value in the natural gas fired plant (FSTIG).

- For the maximum energy efficiency condition of the BIFSTIG plant, the component exergy efficiency is highest for the turbine and the lowest for the combustor. The BIFSTIG combustor exergy efficiency is lower than for a similar plant fired with natural gas.

Many thanks for your attention