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Modelling and Simulation of Solar-Biomass Hybrid Trigeneration using ORC-VCC

Dr. Kamal Kishore Khatri[1], M. Sai Praneeth[2]
[1]Associate Professor and Head , [2]Undergraduate student,
Mechanical Engineering Dept
LNM Institute of Information Technology, Jaipur, India
Pondicherry Engineering College
Pondicherry-605014, India.
saiprnth87@gmail.com

Abstract— *In this paper, the feasibility of using a solar-biomass hybrid system in trigeneration plants is discussed through thermodynamic modelling and simulation analysis. The system consists of an Organic Rankine Cycle (ORC), a heating-process heat exchanger, and a Vapor Compression Cycle (VCC) system. This study illustrates key output parameters to assess the trigeneration systems considered. These parameters are energy efficiency, exergy efficiency, net electrical power, electrical to cooling ratio, and electrical to heating ratio. The system was modelled using EES software with CODEpro program for the analysis of Solar Flat plate Collector. The novelties of this paper can be summarized as:*

1. Small solar field size, in opposition to the current multi-MW trends, to reduce the footprint impact.

2. Organic rankine cycle in place of superheated steam driven Rankine cycle, allowing a reduced heat requirement to drive the prime mover, resulting in a smaller solar field.

3. Trigeneration (Electricity, Heating, cooling) and Cogeneration feasibility study.

Keywords: Trigeneration, Biomass, Organic Rankine Cycle, vapor compression cooling, Cogeneration.

I. INTRODUCTION *(HEADING 1)*

According to the 2011 census, 69% of India's population lived in the countryside and was sustained primarily by agriculture and small local industries. As of 2008, 47.5% of India's population living in rural areas did not have access to electricity [1]. Just fewer than 24,500 out of 112,401 villages in India without electricity were classified as being in remote and inaccessible areas. The financial viability of extending the electricity grid to these areas is poor due to a dispersed population with a low peak power demand. Currently, the grid already suffers from high transmission and distribution losses, blackouts and power theft. Progress to improve the grid has been slow due to India's rapidly growing energy demand and population. In 2008, India used 0.84 million GWh of electricity, demonstrating a tremendous growth in electrical energy usage in the past decade. India receives a high level of Direct Normal Irradiance (DNI), 4–7 kWh/m2 per day. Thus, there is a vast potential for off-grid decentralized solar energy applications. To take advantage of this resource, one option that is currently of much interest is Concentrating Solar thermal Power (CSP) technologies, also known as solar thermal collectors.

The potential for biomass boilers in India is vast with over 370 million tonnes of biomass being produced every year. Biomass is available from agricultural wastes, direct harvesting and as a by- product from industries such as rice mills, sugar mills and saw mills. Biomass is estimated to contribute 46% to the total energy consumption in India and 80% in rural areas. In industry, 40% of the fuel for boilers is supplied from biomass. However, due to problems with infrastructure and the seasonal variability of biomass in India, consumers are struggling to obtain a consistent fuel supply. Furthermore, while biomass is still competitive, prices have increased considerably in recent years

Trigeneration usually refers to the simultaneous production of cooling, heating, and power based on a single energy source. It is also known as combined cooling, heating and power (CCHP). Sometimes combined heating and power (CHP) refers to trigeneration. That is, if the heat produced from CHP is used for cooling, as well as heating, the plant is called a trigeneration plant. CHP could refer to a cogeneration plant if it produces only heat and power. In a trigeneration plant, the waste energy from a generation unit, such as a gas turbine, is used to drive both the heating and cooling systems. Therefore, the use of a trigeneration plant results in an improvement of the overall thermal efficiency and a reduction of the contamination to the environment. The degree of improvement of the plant is sensitive to the performance of each unit in the trigeneration plant and the approach of integrating the units of the plant. Trigeneration plants are usually used as decentralized plants in order to keep the cooling and heating demands at the needed temperatures.[2]

II. THERMODYNAMIC MODELLING OF THE SYSTEM

PROPOSED SYSTEM:

The proposed system consists of a Biomass boiler which generates steam by the combustion of low grade fuels such as wood residues, rice husk etc. In addition to the biomass boiler Solar flat plate collectors are also employed in order to utilize the solar energy as well as dependency on the biomass fuel. The prime mover in this system is the Organic rankine cyclic turbine which has Organic fluids like R134a, R123, R245fa, as the working fluids. A vapour compression cooling unit is coupled with the condenser of the turbine as well as it is driven by the electricity which is generated by the turbine.

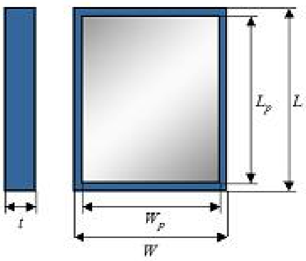
The biomass boiler can produce hot water as well as steam which runs by the combustion of Low Grade fuels such as rice husk, dried leaves etc. The hot water that is generated will be passed through a heat exchanger which in turn transfers heat to the organic fluid in different stages as economizer, Evaporator and Super Heater. The thermal energy produced in this system is calculated as the difference between the solar field production and the full-load needs. The fuel required to obtain the energy calculated with the previous consideration can be calculated assuming a performance of 88% for both systems at the full-load points. [6] The needs for auxiliary fuel are given by the following expression:

$M_f = (Q_{fl} - Q_{sl})/\eta * LHV$

Where:

- Q_{fl} Heat needed for full/load production.
- Q_{sl} Heat collected in the solar field.

SOLAR FLAT PLATE COLLECTOR MODEL:



Overall Dimensions	Length	L	2.491 [m]
	Width	W	1.221 [m]
	Thickness	t	0.079 [m]
Absorber Dimensions	Length	L_p	2.4 [m]
	Width	W_p	1.137 [m]
	Gross area	A_c	3.042 [m²]
	Absorber area	A_p	2.729 [m²]

Figure 1 Collector Dimensions

The flat-plate collector design program (CoDePro) [4] is a program that can help engineers to design flat-plate solar collectors. It has been developed so that most details of the collector configuration can be specified. The program has been developed with the professional version of EES and beta-tested from its development level by solar engineers. CoDePro calculates the instantaneous efficiency, incident angle modifier coefficient, and stagnation temperatures. These calculations are related flat-plate solar collector tests. This program can be used to investigate the thermal effect of the choices of geometric parameters and materials. It should be noted that many functions used in the program have been developed by Solar Energy Laboratory, University of Wisconsin-Madison.

The test conditions to calculate collector thermal performance are set. Input variables for test conditions are:
- Intensity of incident solar radiation
- Diffuse radiation proportion
- Incident angle of beam radiation
- Collector slope
- Wind speed It is assumed that the area of absorber is the same as the aperture area, i.e., the frontal transparent area. Input variables are:
- Overall Dimensions: Length, width, and thickness
- Absorber Dimensions: Length and width

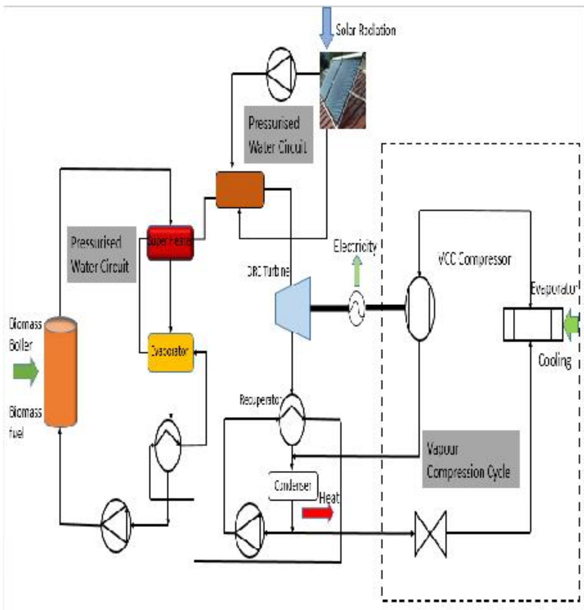


Figure 2 The proposed system for Solar-Biomass Hybrid trigeneration system using ORC-VCC

The cover and plate design needs the values of the optical and thermal properties of the covers and the absorber plate. The collector can have up to two covers

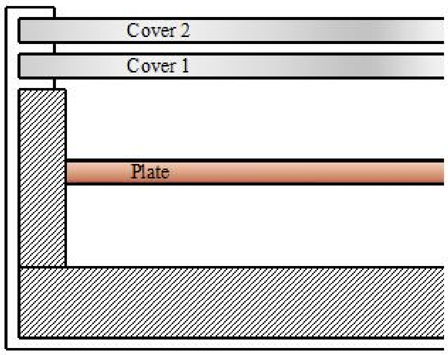


Figure 3 Cover and Plate of the solar flat plate collector

Number of covers			N_{cov}	1
Cover 2	Cover Material			Glass
	Properties of cover material			
	Solar spectrum	Refractive index	n	1.526
		Transmittance	$\tau_{c,s}$	0.891
	Long wave	Absorptance	ε_c	0.88
		Transmittance	$\tau_{c,IR}$	0
Cover 1	Cover Material			Glass
	Properties of cover material			
	Solar spectrum	Refractive index	n	1.526
		Transmittance	$\tau_{c,s}$	0.891
	Long-wave	Absorptance	ε_c	0.88
		Transmittance	$\tau_{c,IR}$	0
Cover-plate air spacing			d_{cp}	1.8 [cm]
Cover 1 - cover 2 air spacing			$d_{c1,c2}$	0.5 [cm]
Plate	Plate Material			Copper
	User-defined Conductivity		k_{pl}	380 [W/m-K]
	Thickness		t_p	0.02 [cm]
	Solar spectrum	Absorptance	α_n	0.88
	Long-wave	Emittance	ε_{pl}	0.15

Figure 4 The Cover and plate design parameters

To calculate the heat loss coefficient, it is necessary for the program to be provided with information about the edge and back insulation. This information is provided through as - Thickness and conductivity of back Insulation Thickness and conductivity of edge Insulation.

The working fluid is selected among water, ethylene glycol/water and propylene glycol/water. The bond conductivity represents the contact resistance between the tube and absorber plate. If the thermal conductance between them is high, its value should be larger than 400 W/mK. Input variables in this are

- Tube
- Number of Tubes

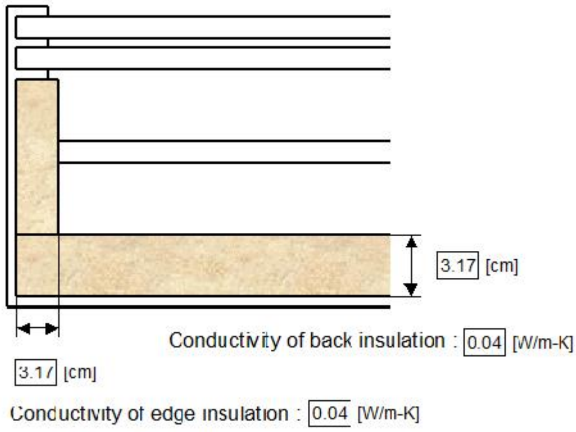
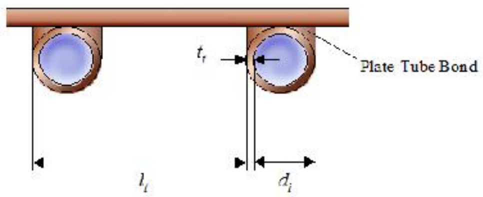


Figure 5 The Edge and back Insulation parameters

- Inner & outer diameter
- Fluid
- Material
- Percent Composition (for ethylene glycol/water and Propylene glycol/water)
- Volumetric flow rate
- Inlet Pressure
- Plate-Tube Bond Conductivity



Tube	Number of Tubes	N_t	10
	Inner Diameter	d_i	1.6 [cm]
	Outer Diameter	d_o	1.8 [cm]
	Tube-to-tube spacing	l_t	11.37 [cm]
Fluid	Material		Water
	Percent Composition*		20 [%]
	Volumetric flow rate	$\dot{V}$	4.75 [L/min]
	Inlet pressure	P_{in}	200 [kPa]
Plate-tube bond conductance		k_b	400 [W/m-K]

Figure 6 Tube and fluid input parameters

ORGANIC RANKINE CYCLE MODEL:

The thermodynamic modelling of the ORC presented in this section is for the system shown in Figure 5. The analysis is carried out by applying the governing equations to the control volumes enclosing each component of the system. For each component, mass, energy, and exergy balance equations are presented. The analysis starts with the ORC and then the cooling cycle. Some assumptions were made to carry out the analysis. It was assumed that the system is at steady state and pressure drops are neglected except in pumps, valves, and the turbine. Also, the kinetic and potential energies were neglected. Further assumptions for specific components are mentioned later where appropriate.[5]

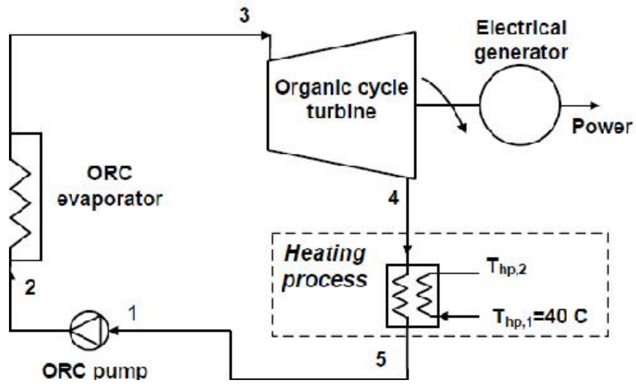


Figure 7 Organic rankine cycle

The mass flow rate is constant throughout the ORC. The mass balance equations are

$$M_1=M_2=M_3=M_4=M_5$$

ORC Pump:

The energy and exergy balance equations of the ORC pump are

$W_{op} = m_o. (h_2-h_1)$

$Ex_{d,op} = W_{op} + m_o . (ex_1-ex_2)$

Where, the subscript op indicates the ORC pump. The isentropic efficiency of the pump is defined as

$\eta_p = W_{op,is}/W_{op}$

Where, W_{op} is defined as

$W_{op,is} = m_o. (h_{s,2} – h_1)$

Where the subscript 'is' refers to isentropic.

ORC Turbine:

The energy and exergy balance equations of the ORC turbine are

$W_{ot} = m_o . (h_3 – h_1)$

$Ex_{d,ot} = -W_{ot} + m_o. (ex_3 - ex_4)$

Where the subscript 'ot' indicates the ORC turbine. The isentropic efficiency of the Turbine is

$\eta_{turbine} = W_{ot}/W_{ot,is}$

Heating Process

The energy and exergy balance equations of the heating process are

$Q_{hp} = m_o . (h_4 – h_5) = m_{hp} . (h_{hp,2} - h_{hp,1})$

$Ex_{d,hp} = m_{hp} . (ex_{hp,1}- ex_{hp,2}) + m_o. (ex_4 - ex_5)$

Where the subscript 'hp' indicates the heating process.

VAPOUR COMPRESSION REFRIGERATION SYSTEM MODEL:

Even there is an opportunity to employ an Absorption refrigeration cycle driven by the Waste heat generated by the condenser. The Organic rankine cycle may not be in superheated state and also the condenser pressures are not high enough so a Vapour compression refrigeration is proposed which runs on the part of the electricity generated. A simple vapor compression refrigeration system consists of the following equipments:

i) Compressor
ii) Condenser
iii) Expansion valve
iv)Evaporatortor

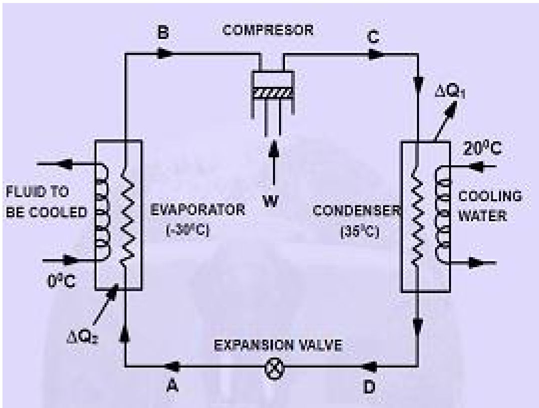


Figure 09 A simple Vapour Compression refrigeration cycle

Work done by the compressor is calculated by the expression:

$W= (h_c-h_b)$ (adiabatic compression)

The heat extracted at the low temperature = Heat transfer during the process A-B= refrigerating effect

$Q_2= (h_B-h_A)$

Now, heat rejected to the condenser,

$Q_1= w + Q_2$

$= (h_C–h_B)+(h_B-h_A)$

$= (h_C - h_A) = (h_C - h_D)$

The volumetric efficiency of a compressor η is defined as ratio between actual mass of vapor drawn at suction conditions and Theoritical mass that can be filled in the displacement volume.

TRIGENERATION ASSESSMENT:

The Electrical generator power

$W_g = \eta_g.W_{ot}$

The net work output from the power cycle = Wnet

The net electrical efficiency

$\eta_{el} = W_{net}/Q_{in}$

Where Q_{in} is the total input heat to the system by Solar radiation and Biomass fuel

The heating Cogeneration,

$\eta_{cog,h} = W_{net}+Q_h/Q_{in}$

Where, the Q_h refers to the heat generated from the turbine outlet.

It is expressed as

$$Q_h = m_{hp} \cdot (h_{hp,2} - h_{hp,1})$$

The cooling cogeneration,

$$\eta_{cog,c} = W_{net} + Q_{ev} / Q_{in}$$

Where, Q_{ev} refers to the cooling energy produced by the system through the evaporator

$$Q_{ev} = m_{ev} \cdot (h_{ev,1} - h_{ev,2})$$

$h_{ev,1}$, $h_{ev,2}$ are the specific enthalpy of water at the inlet and exit of the cooling evaporator

The efficiency of the trigeneration

$$\eta_{tri} = W_{net} + Q_{ev} + Q_h / Q_{in}$$

The ORC efficiency , η_{ORC}

$$W_{ot} - W_{op} / Qin$$

Electrical to heating ratio,

$$r_{el,h} = W_{net} / Q_h$$

Electrical to cooling ratio,

$$r_{el,c} = W_{net} / Q_{ev}$$

RESULTS & DISCUSSION:

The following figures are the process cycle diagram that are plotted with the help of the calculated T-S values during the diagram, At first R245fa is chosen as working fluid and then the process is modelled using R123 as the working fluid.

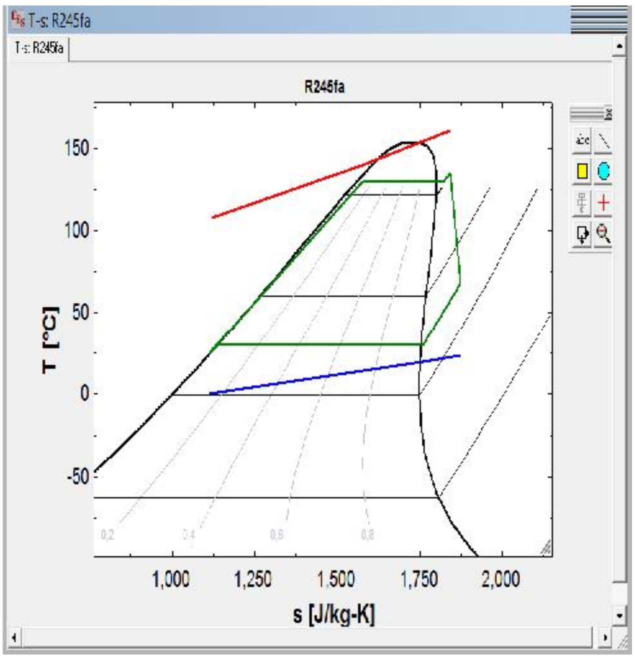


Figure 10 Organic rankine cycle with R245fa as working fluid

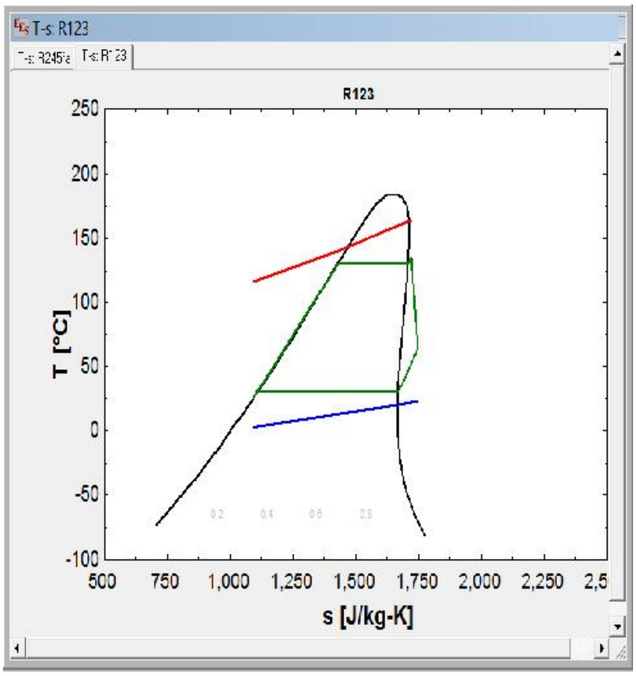


Figure 11 Organic rankine cycle using R123 as working fluid

The following figures summarizes the results calculated by CODePro with the given test conditions and collector configuration. It shows the efficiency equations with calculated coefficients and the incident angle modifier equation with calculated incident angle modifier coefficient.

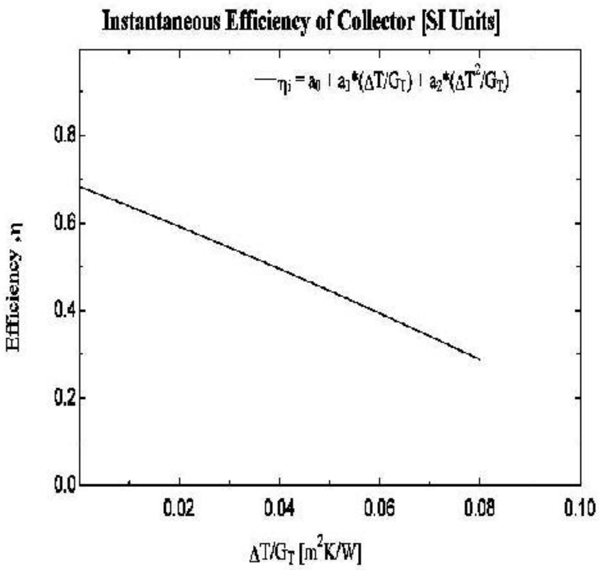


Figure 12 The efficiency vs Change in Temperature

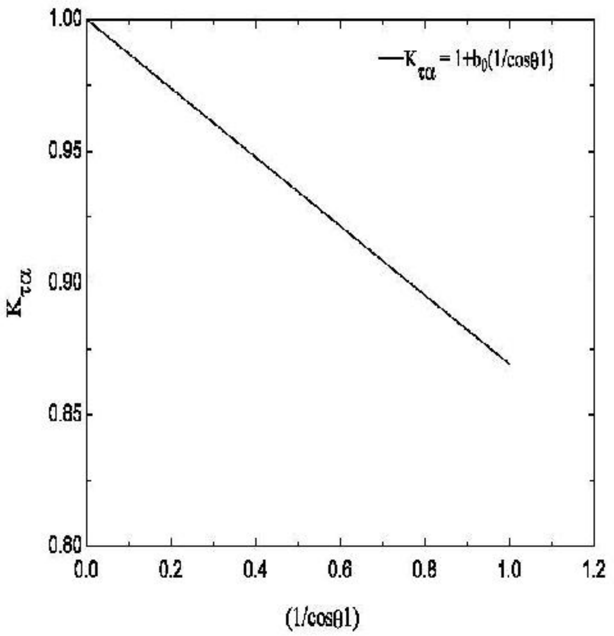


Figure 13 The calculated coefficient vs the incident angle modifier

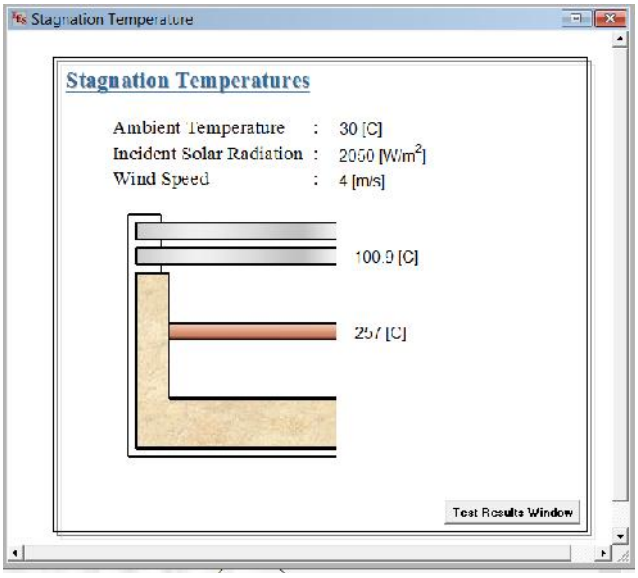


Figure 14 Steady state stagnation temperatures

The above figure refers to the stagnation temperatures that are calculated in the steady state of the applied solar radiation It indicates the liquid temperatures and also the test conditions that re imposed at the beginning of the simulation.

Trigeneration Assessment results:

The performance of the trigeneration system based on the solar-biomass hybrid energy sources and ORC is examined under the variation of some variables. These variables are the ORC evaporator temperature, pump inlet temperature and turbine inlet pressure.

At first the efficiency of the system is analysed by the pump inlet temperature variation The plot as in the figure indicates the efficiencies dependency on the Pump inlet temperature.

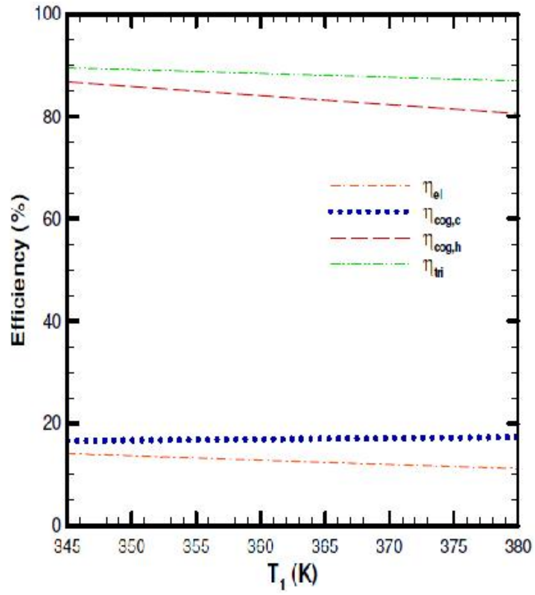


Figure 14 effect of the ORC pump inlet temperature on the efficiency at P_s at 2000 Kpa

Further the electrical to cooling ratio and the electrical to heating ratio are modelled against the pump inlet temperature. It can be noticed that the electrical to cooling ratio is sensitive to the change in the pump inlet

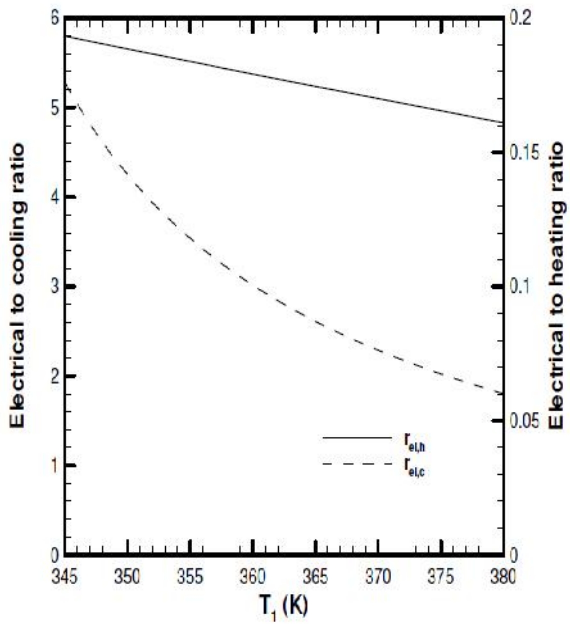


Figure 15 effect of the ORC pump inlet temperature on the electrical to heating

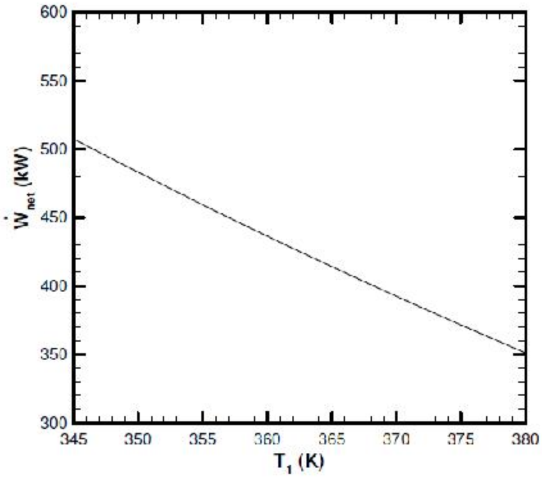


Figure 8 effect of the ORC pump inlet temperature on the electrical power

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