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Energy and exergy analyses of an externally fired gas turbine (EFGT) cycle integrated with biomass gasifier for distributed power generation

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A B S T R A C T

Biomass based decentralized power generation using externally fired gas turbine (EFGT) can be a technically feasible option. In this work, thermal performance and sizing of such plants have been analyzed at different cycle pressure ratio ($r_p = 2-8$), turbine inlet temperature (TIT = 1050–1350 K) and the heat exchanger cold end temperature difference (CETD = 200–300 K). It is found that the thermal efficiency of the EFGT plant reaches a maximum at an optimum pressure ratio depending upon the TIT and heat exchanger CETD. For a particular pressure ratio, thermal efficiency increases either with the increase in TIT or with the decrease in heat exchanger CETD. The specific air flow, associated with the size of the plant equipment, decreases with the increase in pressure ratio. This decrease is rapid at the lower end of the pressure ratio ($r_p < 4$) but levels-off at higher r_p values. An increase in the TIT reduces the specific air flow, while a change in the heat exchanger CETD has no influence on it. Based on this comparison, the performance of a 100 kW EFGT plant has been analyzed for three sets of operating parameters and a trade-off in the operating condition is reached.

1. Introduction

Small scale decentralized power generation is gaining importance for distributing electricity in the remote areas far from the centralized grid [1–4]. The delivery of grid power to the remote areas, particularly in the hilly terrain, is extremely uneconomic [5]. On the contrary, the installation of small capacity plants catering to the local needs using the local resource can be an attractive alternative for remote places. Biomass is one of the important available primary resources, which generally exists in abundance in the villages and already serves as the source of energy e.g. in cooking.

Energy from the biomass can be thermochemically recovered for the generation of electricity either through direct combustion or through gasification and subsequent combustion of the producer gas. In large scale, biomass gasification can be used for power generation in a combined cycle [6,7]. On the other hand, piston engines or micro gas turbines are suitable for small capacity distributed generation. Producer gas can be used in conventional diesel engines in the dual fuel mode or in producer gas engines for the generation of power [8]. However, such engines having reciprocating components require more maintenance and abundance of cooling water, which make them unsuitable for remote locations.

The use of biomass as fuel in conventional (internally fired) gas turbine engines entails various problems [9]. Firstly, the gas turbines are sensitive machines that require extremely clean gas to avoid damage to the turbine blades (such as erosion, incrustation, and corrosion) and blockage of filters and fuel injectors. This requires installation of expensive gas clean up system, consisting of scrubbers, ceramic filters, cyclones etc., at the gasifier outlet. Secondly, the low calorific value of the producer gas, obtained from biomass gasification, necessitates a high fuel flow. It calls for a design modification in the combustor and the turbine inlet guide vanes, otherwise the change in the mass balance between the compressor and the turbine moves the compressor operating point towards surge [9]. These problems are resolved, if the biomass can be conveniently used as a fuel in an externally fired gas turbine (EFGT) engine.

In an EFGT cycle [9], the high pressure air from the compressor is heated in a heat exchanger before admitting to the turbine. The turbine essentially handles clean air and the turbine exhaust air is subsequently used to burn the fuel in a combustion chamber. The combustion product is employed as the hot stream of the heat exchanger, before being released from the power cycle. The cycle can employ dirty and low cost fuels, as the combustion products do

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Nomenclature

A_{HE}	Heat exchanger surface area
AF_{St}	Stoichiometric Air-fuel ratio
CETD	Cold End Temperature Difference of heat exchanger
C_p	Specific heat at constant pressure
e_i	Specific thermomechanical flow exergy at state *i*
e^{ch}	Specific chemical exergy
EFGT	Externally Fired Gas Turbine
EN	Energy released with exhaust gas
h	Enthalpy
h_f	Enthalpy of formation
K	Equilibrium constant
M_j	Molecular weight of species *j*
P_i	Pressure at state *i* or Partial pressure for species *i*
ΔP	Pressure drop
r_p	Pressure ratio
$\overline{R}$	Universal gas constant
s	Entropy
T_i	Temperature at state *i*
TIT	Turbine Inlet Temperature
U	Overall heat transfer coefficient of heat exchanger
w	Specific work
W	Work
X	Number of moles
Z	Moisture content in the as-fired biomass (by mass)

Greek Letters

φ	Equivalence ratio
γ	Ratio of specific heats
$\eta_{c,isen}$	Isentropic efficiency of compressor
$\eta_{t,isen}$	Isentropic efficiency of turbine
η	Efficiency

Sub-scripts

a	Air
B	Producer gas after gasification of biomass
C	Compressor
CC	Combustion chamber
f	Fuel
G	Gasifier
g	Product gas
HE	Heat exchanger
in	Input
i	Index for thermodynamic state point
o	Reference state
T	Turbine
w	Water

Super-scripts

c	Cold side of the heat exchanger
h	Hot side of the heat exchanger

not enter the turbine. Although the presence of ash in the products may cause erosion and fouling of the heat exchanger tubes, while corrosive products eats away the tube material, maintenance of the heat exchanger is much less troublesome than that for the turbine.

Anheden [10] presented thermodynamic and economic analyses of closed and open cycle externally fired gas turbine plants with direct combustion of biomass in a circulating fluidized bed furnace. It is found that the efficiency reaches a maximum value at an optimum pressure ratio of the cycle. Ferreira and Pilidis [9] compared the thermodynamic performance of an externally fired gas turbine cycle with direct combustion of biomass against an internally fired cycle firing either natural gas or producer gas from biomass gasification. The study was performed for the simple gas turbine cycle as well as for the combined cycle operation with a steam based Rankine cycle at the bottom. The results showed promising performance for the EFGT plant particularly considering the renewable and environment-friendly attributes of the biomass fuel. Bram et al. [11] reviewed the technological and economic feasibility of the external firing of biomass in gas turbines. The authors concluded that cogeneration based on EFGT on the scale of 100–200 kW$_e$ offers good prospects from both economic and technical aspects. Cocoa et al. [12] evaluated the performance of a 100 kW externally fired gas turbine plant fuelled with biomass and having an integral dryer for biomass. The influence of parameters like pressure ratio, turbine inlet temperature and temperature difference in the heat exchanger on the thermal efficiency for electrical generation was analyzed. It was found that the dry biomass produces efficiency in the range of 22–33% and the integration of the dryer improves flexibility in the plant operation. Traverso et al. [13] presented the steady state and transient performance of an externally fired micro gas turbine pilot plant of 80 kW capacity fired with natural gas. The paper demonstrated the feasibility of operation and control of the gas turbine plant of small capacity.

All the literatures on EFGT universally claim that one of the biggest challenges in the design lies in developing the high temperature heat exchanger that is capable of achieving high turbine inlet temperature and at the same time withstands the stresses imposed by the working conditions and the constituent of the combustion product [9–12]. The size of the heat exchanger and the cost of material are the two important considerations that decide the economy of the plant. The use of nickel based super alloys in the heat exchanger allows the turbine inlet temperature to reach 800–825 °C, while more advanced oxide dispersion (ODS) alloys withstand temperature up to 1100 °C at the turbine inlet [10]. The turbine inlet temperature may be as high as 1300 °C with ceramic heat exchanger materials [14], but prolonged operation with such exchangers is yet to be firmly tested. Increase in the turbine inlet temperature is favorable towards achieving higher plant efficiency but it complicates the equipment design. An uncooled micro gas turbine can sustain a maximum turbine inlet temperature of 950 °C, while further increase in the temperature requires turbine blade cooling arrangement [13]. Since all these modifications towards performance improvement bear considerable cost implications, such modifications always needs a priori evaluation, based on energy and exergy based performance analysis of the cycle.

In the present work, we have conducted the energy and exergy based performance analysis of an externally fired gas turbine cycle running on biomass as fuel. The effects of operating parameters, like pressure ratio, turbine inlet temperature, heat exchanger cold end temperature difference, on the thermal efficiency and specific air flow for the cycle have been analyzed. The main focus of the present study is to identify the ideal operating parameters for the use of a EFGT plant for decentralized power generation supplying the local needs in the remote areas, where extending the grid power is uneconomic. Accordingly, the performance parameters for a 100 kW gas turbine plant have been evaluated with selective sets