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Parametric Exergy Analysis of Coal Gasifier and Gas Turbine Combustion Chamber with Emission Study

T. Srinivas*[1], A.V.S.S.K.S. Gupta[+], and B.V. Reddy[#]

Abstract – *Coal gasification plays an important role in the power generation as it reduces environmental pollution. Direct burning of coal causes much irritation besides pollution to the environment. Clean synthetic gas, produced from partial combustion of coal can be burnt in the gas turbine combustion chamber to run the coal based combined cycle power plant. In this paper attention has been focused on studying the parameters which influence the operation of coal gasification and gas turbine combustion chamber. Pressurized circulating fluidized bed (PCFB) has been used to produce the synthetic gas from the coal. Steam has been internally produced by the heat generation of partial combustion in the coal gasifier.The effects of gasifier pressure, combustion chamber temperature, supplies of air and water/steam have been studied in this analysis. In this thermodynamic analysis it has been found that increasing the gasifier pressure and combustion chamber temperature will give desirable effects, but high amounts of air and water supply is not desirable as it increases the exergetic losses. The effect of the operating parameters as mentioned above is also carried out on the atmospheric emissions.*

Keywords – Coal-based combined cycle power generation, coal gasification, gas turbine combustion chamber, irreversibility.

1. INTRODUCTION

Gasification is the thermal decomposition of organic material at elevated temperatures in an oxygen restricted environment. The process, which requires an initial heat supply to get underway, produces a mixture of combustible gases (primarily methane, complex hydrocarbons, hydrogen and carbon monoxide). This producer gas can then either be used in boilers or cleaned up and used in combustion turbines or in generators. The major environmental benefit of these processes are that they retain pollutants (sulphur, heavy metals, and etc.) in the ash instead of them being moved to the gas phase and discharged to the atmosphere. Therefore the emissions form this technology are much lower than produced by conventional incineration and will require less flue gas treatment. In fact, there is often no need for a smoke stack as the emissions only come from the burning combustible gases in a turbine or boiler.

In a typical coal-based combined cycle, coal can be gasified either partially or wholly and the synthetic gas produced is to be supplied directly to the combustion chamber of the gas turbine. This high temperature flue gas can be used to run the combined cycle power plant. On an average, 4 kg of solid coal can give gas equivalent to 1 liter of petroleum fuel. The price of 4 kg solid fuel may vary between Rs.5.00 - 8.00 (0.1$ - 0.18$) whereas 1 liter of diesel costs Rs.35.00 - 38.00 (0.78$ - 0.84$). Corti and Lombardi [1] determined the main working conditions of biomass integrated gasification by means of exergetic analysis. In this analysis a sensitivity analysis with respect to the CO_2 absorbing solution composition has also been carried out. Duan *et al.* [2] proposed a novel integrated gasification combined cycle (IGCC) system with steam injected H_2/O_2 cycle and CO_2 recovery. He presented a new evaluation criterion for comprehensive performance of the IGCC system. Liebner and Ulber [3] proposed the Multi Purpose Gasification (MPG), which is a process for the partial oxidation of hydrocarbons delivering a synthesis gas composed mainly of carbon monoxide and hydrogen. In his model, different, and even unmixable hydrocarbon containing feeds can be gasified ranging from natural gas, tars and other coal gasification residues, refinery residues, asphalts to slurries and chemical wastes. Nag and Raha [4] thermodynamic analysis presented both the energetic and exergetic analyses in a coal based combined cycle power plant. The volumetric composition of the flue gas typical of a Lurgi gasifier given by [5] is taken constant for all conditions of operation. Andrews and Biblarz [6] developed the temperature dependence of gas properties in polynomial form to find the thermodynamic properties of the gas. These equations of curve fittings for various gases are used to determine the properties of the gases. Kwaj *et al.* [7] carried out the exergetic and thermo-economic analyses for 500 MW combined cycle power plant. The chemical and physical exergetic components are determined by the method given by [8]. Zaporowski [9] presented the complex energy analysis of technological systems of gas–steam power plants integrated with coal gasification. Dogru *et al.* [10] reported a full mass balance including the tar production rate as well as the composition of the produced gas as a function of feed rate. Hara *et al.* [11] examined the gasification characteristics such as product gas composition, cold gas efficiency and carbon conversion

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efficiency in a pressurized coal gasifier.

The present work aims to analyze the effects of operating parameters of coal gasifier in a coal based combined cycle power plant which consists of pressurized circulating fluidized bed (PCFB) partial gasification unit. Not much is reported on the operating parameters for combined cycle power generation unit, which employs fluidized bed units for partial gasification and char combustion in the literature. The objectives of the present work are to investigate the role of gasifier pressure, gas turbine combustion chamber (GTCC) temperature, air and water supplies to gasifier on the exergetic loss of gasifier and turbine combustion chamber, gasifier temperature, gasified fixed carbon and air requirement to gas turbine combustion chamber. The exergetic losses of the components are evaluated based on second law of thermodynamics. The effect of these parameters is extended on emissions of exhaust gas from gas turbine and into the atmosphere.

2. THERMODYNAMIC MODEL OF GASIFIER AND GAS TURBINE COMBUSTION CHAMBER

Assumptions used in the Analysis

The reference temperature and pressure for the analysis are taken at 25^0C and 1.01325 bar respectively. The exhaust gas is assumed to be as an ideal gas and its properties are taken as a function of temperature. It is assumed that the steam enters into the gasifier at a saturation temperature corresponding to the pressure of the incoming compressed air. The steam is generated in gasifier for partial combustion by taking the heat that evolved in partial combustion. Only a part of hydrogen undergoes in gasification process and the rest escapes with char and ash. The coal is fed at atmospheric conditions. The gasifier pressure is maintained at 12 bar and the combustion chamber temperature is taken at 1100^0C. The pressure drop and the heat loss are neglected in the gasifier.

Analysis of Coal

The schematic diagram of coal gasifier and gas turbine combustion chamber is shown in Figure 1. Since the gasifier is pressurized and air blown, a Lurgi gasifier has been considered for this analysis. The volumetric composition of the flue gas typical of a Lurgi gasifier as given below by [5] is taken constant for all conditions of operations.

CO_2: 13.5%, CO: 16.5%, H_2: 23.8%, CH_4: 4.0%,
N2: 41.3%, and others 0.9% (by volume)

The coal fed to the gasifier has been assumed to be of the following composition.

Proximate analysis: Fixed carbon 42.6%, volatile matter 35.4%, moisture 8.8% and ash 13.2% (by mass)

Ultimate analysis: carbon 62.2%, hydrogen 5.2%, oxygen 14.3%, sulphur 3.8%, nitrogen 1.3% and ash 13.2% (by mass on dry basis).

In a 100 kg of coal, the fixed carbon is 42.6 kg. The mass of carbon present in the volatile matter is (62.2-42.6) i.e. 19.6 kg. It is assumed that the whole mass of carbon in volatile matter and 10 % of fixed carbon, (19.6 + 4.26) or 23.86 kg get gasified, while the remainder (42.6 - 4.26) i.e. 38.34 kg escaped as char.

Coal + air + steam = fuel gas + steam + char
Fixed carbon = 42.6 % (by mass)
Carbon = 62.2 % (by mass, dry basis)
Gasified carbon / 100 kg coal = mass of carbon in volatile matter + 10% of fixed carbon
= (62.2 - 42.6) + 10% of 42.6
= 19.6 + 4.26
= 23.86 kg / kg coal

Char = remained carbon = 42.6 – 4.26
= 38.34 kg / kg coal
= 38.34 / 12
= 3.2 kg mol / kg coal

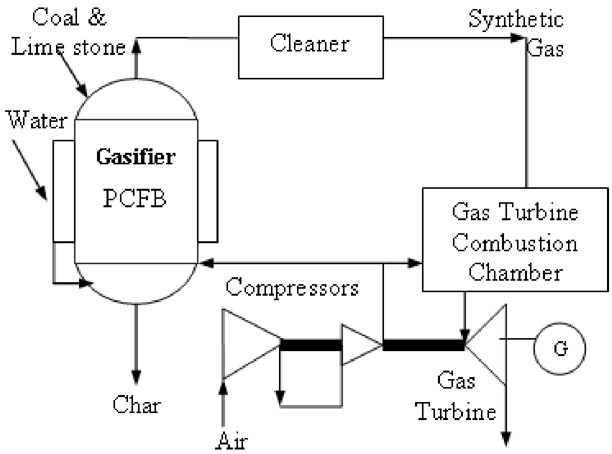

Fig. 1. Schematic diagram of coal gasifier and gas turbine combustion chamber

From the ultimate analysis of the coal on the mass basis the conversion of gravimetric to volumetric is as follows:

C: 62.2 / 12 = 5.18 kg mol
H_2: 5.2 / 2 = 2.6 kg mol
O_2: 14.3 / 32 = 0.45 kg mol
S: 3.8 / 32 = 0.12 kg mol
N_2: 1.3 / 28 = 0.05 kg mol
H_2O: 8 / 18 = 0.44 kg mol

Coal: air: steam = 100: 86: 57.6

The heating value of coal is obtained from stoichiometric quantity of air being used for complete combustion of unit mass of coal yielding the following reaction.

Stoichiometric equation:

$$(5.18C + 2.6H_2 + 0.05N_2 + 0.45O_2 + 0.12S + 0.44\ H_2O) + 6.15\ (O_2 + 3.76N_2) = 5.18CO_2 + 3.044H_2O + 0.12\ SO_2 + 23.174\ N_2 \quad (1)$$

Net calorific value:

$h_R = 0$
$h_P = 5.18\ (h_fCO_2) + 3.044\ (h_fH_2O)$
$= 5.18(393520) + 3.044(241820)$
$= 2774533.68$ kJ / 100 kg coal
$= 27745.3368$ kJ / kg coal

Therefore L.H.V. = 27745.3368 kJ/kg coal
(Neglecting energy released by the oxidation of sulphur)

Standard Chemical Exergy (ϵ^0) and the Ratio ϕ of the Coal

The chemical availability or exergy of a fuel is the maximum theoretical work obtainable by allowing the fuel to react with oxygen from the environment to produce environmental components of carbon dioxide and water vapor. When a difference in availability between states of the same composition is evaluated, the chemical contribution cancels, leaving just the thermo mechanical contributions. This will be the case while doing availability analyses for compressors and turbines. However, the chemical contribution will come into picture during analyses of the gasifier and fuel gas combustor.

Let c, h, o and n are mass fractions of C, H, O and N respectively.

$$\varphi_{dry} = 1.0437 + 1.882\frac{h}{c} + 0.0610\frac{o}{c} + 0.0404\frac{n}{c} \quad (2)$$

$$= 1.0437 + \frac{1.882 \times 5.2 + 0.0610 \times 14.3 + 0.0404 \times 1.3}{62.2}$$

$$= 1.2159$$

For moist fuel, standard chemical exergy, ε^0

$$\varepsilon^0 \text{ (kJ/kg)} = [NCV^0 \text{ (kJ/kg)} + 2442\, w]\, \phi_{dry} + 9417\, S \quad (3)$$

In this equation, w is the mass fraction of moisture in the fuel. The value 2442 is the enthalpy of evaporation for water at standard temperature, T_0 in kJ/kg steam. The NCV is taken from the LHV of the coal.

$$\varepsilon^0 = (27745.3368 + 2442 \times 0.08)1.2159 + 9417 \times 0.038$$

$$= 34330.94 \text{ kJ / kg}$$

$$\text{Ratio, } \phi = \frac{\varepsilon^0}{NCV^0} \quad (4)$$

$$= \frac{34330.94}{27745.3368} = 1.237$$

The values of the standard chemical exergy at reference state for the components are taken from [8]. These are in kJ/kg mol and as follows:

$\overline{\varepsilon^0}_{CH4} = 836510$

$\overline{\varepsilon^0}_{CO} = 275430$

$\overline{\varepsilon^0}_{CO2} = 20140$

$\overline{\varepsilon^0}_{H2} = 238490$

$\overline{\varepsilon^0}_{H2O(l)} = 3120$

$\overline{\varepsilon^0}_{H2O(g)} = 11710$

$\overline{\varepsilon^0}_{N2} = 720$

$\overline{\varepsilon^0}_{O2} = 3970$

Reaction in Coal Gasifier

Weight of the steam into gasifier:
= 57.6 kg / 100 kg coal
= 3.2 kg mol / 100 kg coal

The following reaction takes place in the Lurgi high pressure gasifier:

$$(5.18C + 2.6H_2 + 0.05N_2 + 0.45O_2 + 0.12S + 0.44\, H_2O) + 0.6281(O_2 + 3.76N_2) + 3.2(H_2O)$$
$$= 5.8235\,(0.135CO_2 + 0.165CO + 0.238H_2 + 0.04CH_4 + 0.4141N_2) + 3.2591(H_2O) + (3.2C + 1.129H_2 + 0.12S + \text{ash}) \quad (5)$$

The temperature of gasifier after partial combustion is determined from the application of first law of thermodynamics. The gasifier temperature is determined from the energy balance equation of the reaction with the iterative method.

Reaction in Gas Turbine Combustion Chamber

The following combustion equation takes place in the GTCC.

$$5.8235\,(0.135CO_2 + 0.165CO + 0.238H_2 + 0.04CH_4 + 0.4141N_2) + 3.2591(H_2O) + x\,(O_2 + 3.76N_2)$$
$$= a\, CO_2 + b\, H_2O + (3.76\, x + 5.8235 \text{ X } 0.4141)\, N_2 + y\, O_2 \quad (6)$$

From the mass balance of the above chemical reaction, the coefficients of a, b and y is calculated. The heat loss in the gas turbine combustion chamber is assumed to be 2.5% of energy released by the coal.

$$h_R = q_{loss\ GTCC} + h_P \quad (7)$$

From the above energy balance equation the amount of air required for combustion (x) is calculated.

Irreversibility of Gasifier

Chemical exergy of coal = $e_{ch,\,c}$

= 3433094 kJ / 100 kg coal (as determined above)

Coal and water are supplied at reference temperature. i.e. at 25^{0}C, therefore the physical exergies of coal and water have been treated to zero.

Chemical exergy of air supplied to gasifier,

$$e_{ch,\,aga} = \sum_k n_k \overline{\varepsilon^0}_k + \overline{R}T_0 \Sigma_k \ln.[P.x_k] \quad (8)$$

x_k is the mole fraction of kth component in the chemical equation.

Physical exergy of air supplied to gasifier,

$$e_{ph,\,aga} = h_{aga} - \Sigma_k T_0 s_k \quad (9)$$

Chemical exergy water supplied at 25^{0}C,

$$e_{ch,\,w} = 3.2 \text{ x } 3120$$

Chemical exergy of fuel gas ($e_{ch,fg}$) is determined from the Equation (8).

Physical exergy of fuel gas,

$$e_{ph,\,fg} = h_{fg} - \Sigma_k T_0 s_k \quad (10)$$

The chemical exergy of char,

$$e_{ch,\,char} = \sum_k n_k \overline{\varepsilon^0}_k \quad (11)$$

Physical exergy of char,

$$e_{ph,\,char} = h_{char} - \Sigma_k T_0 s_k \quad (12)$$

Irreversibility of gasifier,

$$i_{gasifier} = e_{ch,\,c} + e_{ch,\,aga} + e_{ph,\,aga} + e_{ch,\,w}$$

$$-(e_{ch,\,fg} + e_{ph,\,fg} + e_{ch,\,char} + e_{ph,\,char}) \quad (13)$$

Irreversibility of GTCC

The chemical exergy of air supplied to GTCC ($e_{ch,\,agt}$) is determined from the Equation (8).

Physical exergy of air supplied to GTCC,

$$e_{ph,\,agt} = h_{agt} - \Sigma_k T_0 s_k \quad (14)$$

The chemical and physical exergy of fuel gas are taken from coal gasifier equations.

Chemical exergy of flue gas,

$$e_{ch,\,flg} = \sum_k n_k \overline{\varepsilon^0{}_k} + \overline{R} T_0 \Sigma_k n_k \ln.[P.x_k] \quad (15)$$

Physical exergy of flue gas at combustion chamber temperature,

$$e_{ph\,,flg} = h_{flg} - \Sigma_k T_0 s_k \quad (16)$$

Irreversibility of GTCC,

$$i_{GTCC} = e_{ch,\,fg} + e_{ph,\,fg} + e_{ch,\,agt} + e_{ph,\,agt} - (e_{ch,\,flg} + e_{ph,\,flg}) \quad (17)$$

3. RESULTS AND DISCUSSIONS

The system operating parameters for the thermodynamic analysis of coal gasifier and gas turbine combustion chamber are gasifier pressure, combustion chamber temperature, air and water supplies to the gasifier. The effect of these four parameters has been studied on the variations of the exergetic losses in coal gasifier and gas combustion chamber. The parametric analysis is carried out to study the variations in gasifier temperature, air supply to the combustion chamber and gasified fixed carbon. The emissions of carbon dioxide, water vapor, nitrogen and oxygen in the products from the combustion chamber are discussed with the above mentioned parameters. The irreversibility due to chemical reaction is determined from the exergy difference between the reactants and the products.

Effect of Gasifier Pressure

Figure 2 shows the effect of gasifier pressure on exergetic loss in the coal gasifier and gas turbine combustion chamber. The figure also depicts the variation in the gasifier temperature with the gasifier pressure. The temperature of the compressed air at the inlet of the gasifier increases with increase in the pressure ratio of the cycle. Therefore the gasifier temperature increases with increase in the gasifier pressure. The gasifier's exergetic loss is a considerable loss even though the heat loss in gasifier is neglected. The gasifier and GTCC exergetic loss decreases with increase in the gasifier pressure. The effect of gasifier pressure on the exergetic losses of gasifier and gas turbine combustion chamber is insignificant due to its slight variation. In this work, the temperature of gasifier due to partial oxidation of coal is found as 960^{0}C at a pressure of 16 bar. This result is nearer to the gasifier temperature (980^{0}C) obtained by [9] at the same pressure of air supplied to the coal gasifier. The exergy rise in the products of gasifier is much more than the rise in the reactants of the partial combustion with increase in the gasifier pressure. Therefore the gasifier exergetic loss decreases slightly with increase in the gasifier pressure. Similarly in combustion chamber the exergetic loss also decreases with increase in the gasifier pressure.

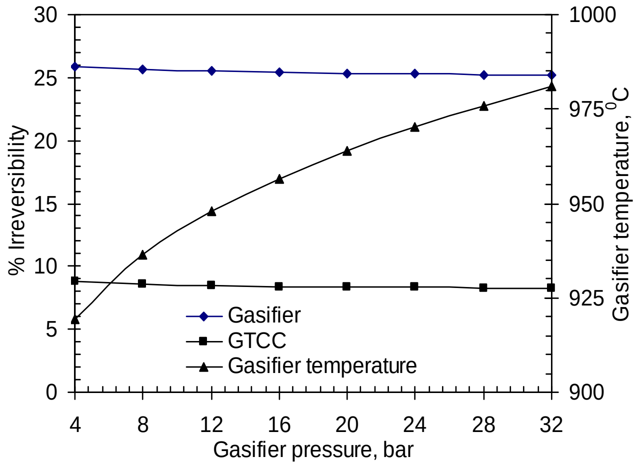

Fig. 2. Effect of gasifier pressure on its temperature and exergetic losses

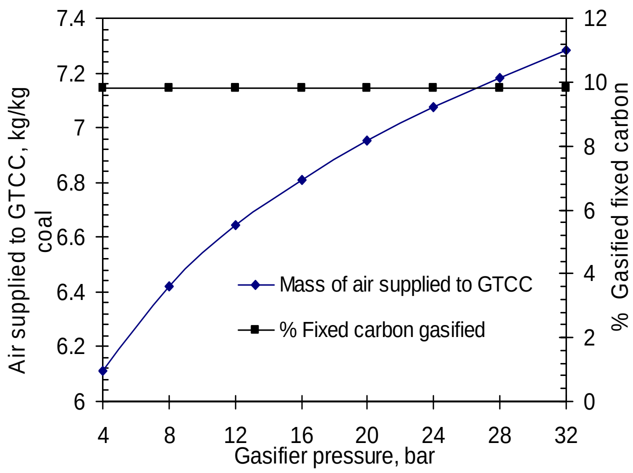

Fig. 3. Effect of gasifier pressure on air supply to GTCC and gasified fixed carbon

Figure 3 shows the influence of gasifier pressure on air supply to GTCC and the amount of gasified fixed carbon. Combustion chamber temperature generally increases with increase in the gasifier pressure and the temperature. The gasifier pressure is varied from 4 to 32 bar with the constant GTCC temperature. To maintain constant combustion chamber temperature, the air supply to the combustion has to be increased. Combustion chamber temperature decreases with the increase in the air supply for combustion. The excess air provides the cooling effect in the chamber. Therefore the mass of air to GTCC should be increase with increase in the gasifier pressure to keep the constant combustion temperature. The amount of gasified fixed carbon remains unchanged with increase in the gasifier pressure. The mass of air supplied to the gasifier is kept constant. It keeps the constant gasified fixed carbon in the coal gasifier.

Figure 4 generates the mole fractions of the emissions from the GTCC with the gasifier pressure.

Nitrogen occupies the major portion of the species in the products of the combustion due to the air supply for oxidation of fuel. The complete combustion in the GTCC is assumed in this analysis. Therefore there is no any carbon monoxide content in the exhaust of the gas turbine. The main pollutant in this exhaust gas is carbon dioxide and it increases with fuel supply for the combustion. The air supply to GTCC increases with increase in the gasifier pressure. Therefore the nitrogen and oxygen content in the exhaust gas increases with increase in the gasifier pressure. The amount of carbon dioxide and water vapor is independent of the gasifier pressure for fixed fuel supply. The mole fraction of the carbon dioxide and water vapor decreases with increase in the gasifier pressure as the quantity of exhaust increases. The results of these emissions are same as the results obtained by dogru [10]. In his experimental gasifier, the nitrogen is 59 % of mole fraction where as in this work it is 66 % at same pressure of the gasifier.

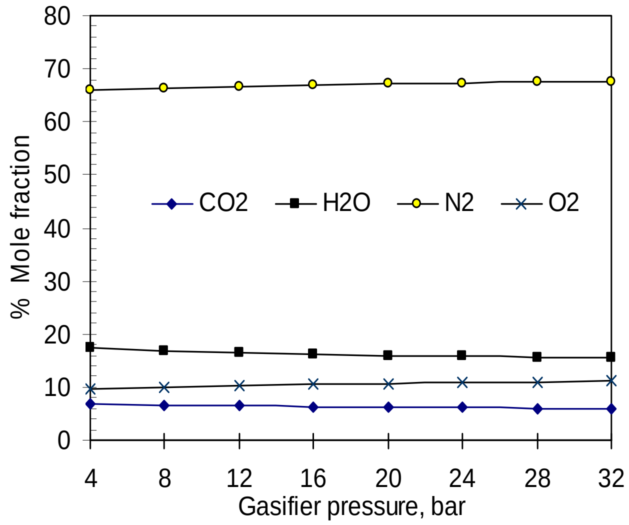

Fig. 4. Effect of gasifier pressure on emissions of combustion chamber

Effect of G.T. Combustion Chamber Temperature

Figure 5 depicts the influence of GTCC temperature on exergetic losses and the gasifier temperature. The gasifier temperature and irreversibility does not depend on combustion chamber temperature, and so they remain constant. But the gas turbine inlet temperature has an important significance on the performance of the cycle. The irreversibility of GTCC decreases with increase in the combustion chamber temperature. The air supply decreases with increase in the GTCC temperature and so it decreases the reactants availability than the products. On the overall basis the exergetic loss in GTCC decreases with increase in its temperature.

Figure 6 illustrates the effect of GTCC temperature on the air supply to the GTCC and gasified fixed carbon in the gasifier. The gasified fixed carbon in the coal gasifier is independent of GTCC temperature therefore it is fixed with the change in the GTCC temperature. The additional air supply for the combustion decreases the combustion adiabatic flame temperature. The excess air supply cools the combustion as it does not participate in the combustion. Therefore the mass of air required to GTCC decreases with increase in the temperature.

Figure 7 shows the effect of combustion chamber temperature on the emissions of the products from GTCC. The air supply to GTCC decreases with increase in the temperature. The mole fraction of the oxygen and nitrogen decreases with increase in the GTCC temperature. The total mass of the products from combustion chamber decreases with increase in the temperature. This increases the mole fraction of carbon dioxide and water vapor with increase in the combustion chamber temperature.

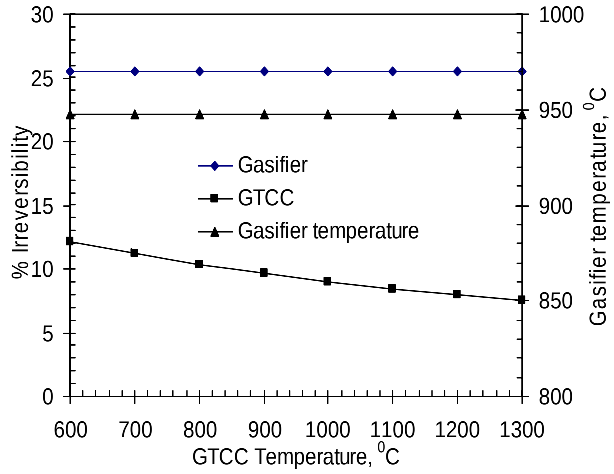

Fig. 5 Effect of GTCC temperature on gasifier temperature and exergetic losses

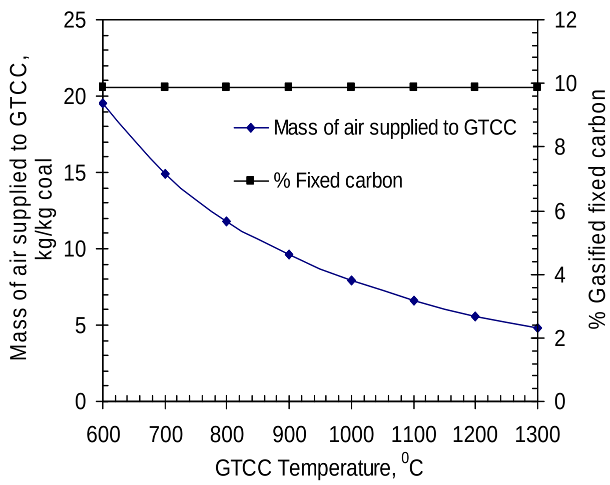

Fig. 6. Effect of GTCC temperature on air supply to GTCC and gasified fixed carbon

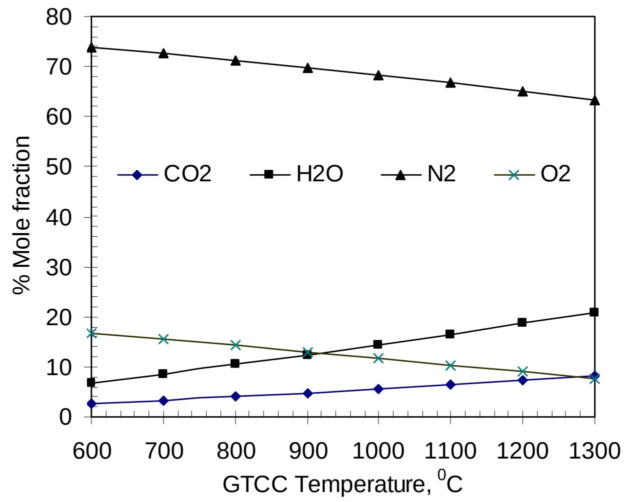

Fig. 7. Effect of GTCC temperature on emissions

Effect of Air Supply to Gasifier

Figure 8 generates the effect of air supply to the gasifier on exergetic losses and gasifier temperature. The gasifier temperature decreases with increase in the air supply to the gasifier. This relationship is similar to the result obtained by [11]. He plotted the higher heating value of the synthetic gas with respect to the gasifier air ratio. This parameter is proportional to the gasifier temperature. He proved that the higher heating value of the synthetic gas decreases with increase in the gasifier air ratio. Therefore the theoretical result obtained in this work is same as the experimental trend obtained by [11]. The exergy of the reactants increases and the exergy of the products decreases with increase in the air supply to the gasifier. Therefore, the exergetic loss in the gasifier increases with the increase in the air flow to the gasifier. At high quantity of air supply, these losses are very high as shown in Figure 8. In GTCC, the exergy of products increases and the exergy of the reactants decreases with the increase in the air supply to the gasifier. Therefore the exergetic loss in GTCC decreases with increase in the air supply to the gasifier.

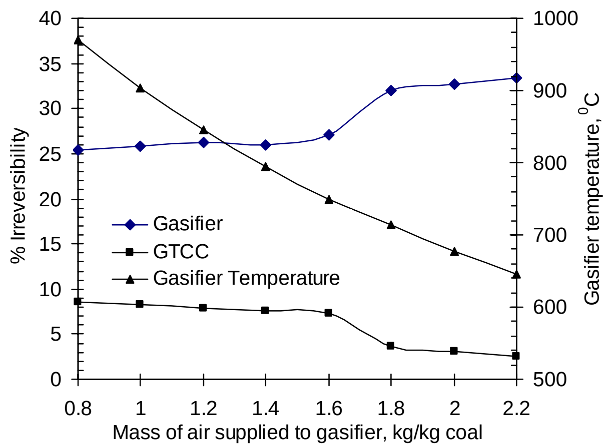

Fig. 8. Effect of air supply on gasifier temperature and exergetic losses

Figure 9 presents the effect of air supply to gasifier on the air flow rate for the GTCC and the amount of gasified fixed carbon in the gasifier. In this analysis the air supply is varied with the pre assumption of complete combustion of volatile carbon in the coal. The gasification of the fixed carbon starts after exhausting of the volatile carbon in the coal. The conversion of the coal in to the synthetic gas increases with increase in the air supply to the gasifier. Therefore the air supply for GTCC also increases with increase in the air supply to the gasifier.

Figure 10 represents the effect of gasifier air on the emissions of the products form the combustion chamber. The amount of synthetic in the gasifier and also the air for GTCC increases with increase in the gasifier air. Therefore the oxygen and nitrogen content in the products increases with increase in the air supply to the gasifier. The mole fraction of carbon dioxide and water vapor decreases with increase in the gasifier air.

Effect of Steam Supply to Gasifier

In this system the steam for the gasification of coal has been generated internally using the heat from the partial combustion of coal in the gasifier. The water supplied to the coal gasifier absorbs heat from the partial combustion and converts in to the steam. This steam enters into the gasifier for the partial oxidation of coal in the gasifier. Figure 11 develops the effect of water/steam supply to the gasifier on the irreversibilities and the gasifier temperature. The gasifier temperature decreases with increase in the steam supply to the gasifier. The heat produced due to the partial gasification is used for steam generation. Therefore the gasifier temperature decreases with increase in the steam supply. The availability of the reactants increases where as the availability of the products decreases with increase in the steam supply. The exergetic loss in the gasifier increases with increase steam supply to the gasifier. The decreasing effect of availability of products is more than the reactants with the increase in the steam supply for the gasifier. Therefore the irreversibility of GTCC increases with increase in the steam addition.

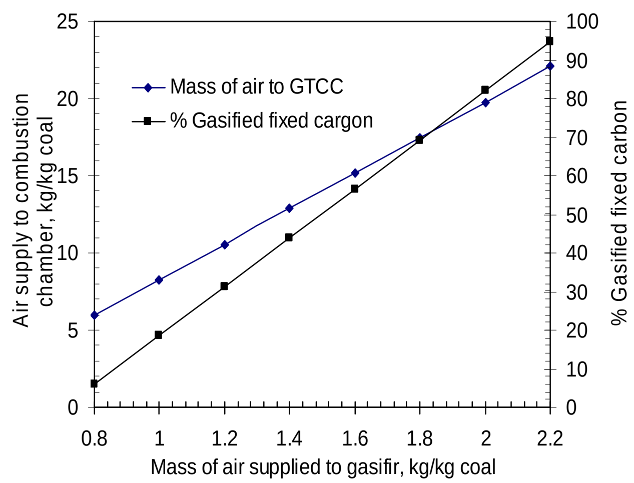

Fig. 9. Effect of gasifier air on air supply of GTCC and gasified fixed carbon

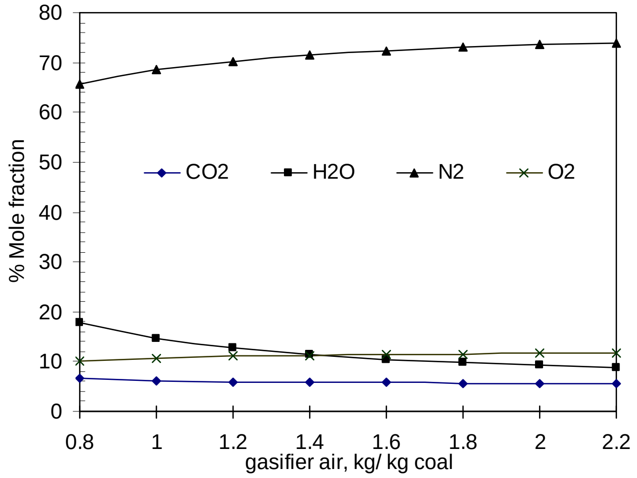

Fig. 10. Effect of gasifier air on emissions

Figure 12 depicts the effect of steam addition on the air supply to the GTCC and the gasified fixed carbon. The temperature of the gasifier and the GTCC decreases with increase in the steam supply to the gasifier. To maintain the fixed combustion chamber temperature, air supply to the combustion chamber should be decrease. Therefore air supply to GTCC decreases with increase in the steam addition. The gasified fixed carbon remains same with the variation in steam addition as the air supply to the gasifier get fixed.

Figure 13 represents the effect of steam supply on emissions of the system. The air supply to the GTCC decreases with increase in the steam supply. Therefore the emissions of nitrogen and oxygen in the product gas of GTCC decreases. The water vapor in the products and its mole fraction increases with increase in the steam supply to the gasifier. Only the mole fraction of carbon oxide increases with the increase in the water addition to the gasifier.

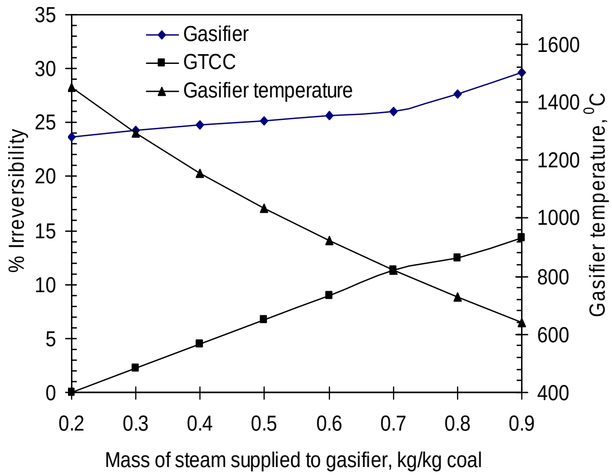

Fig. 11. Effect of steam supply on gasifier temperature and exergetic losses (gasifier and GTCC)

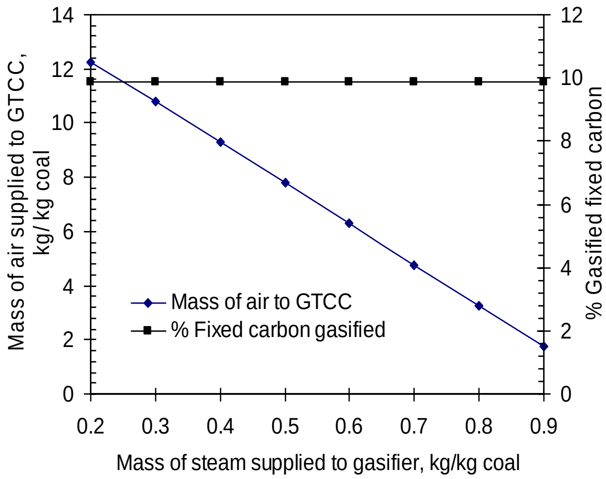

Fig. 12. Effect of steam supply on air supply to GTCC and gasified fixed carbon

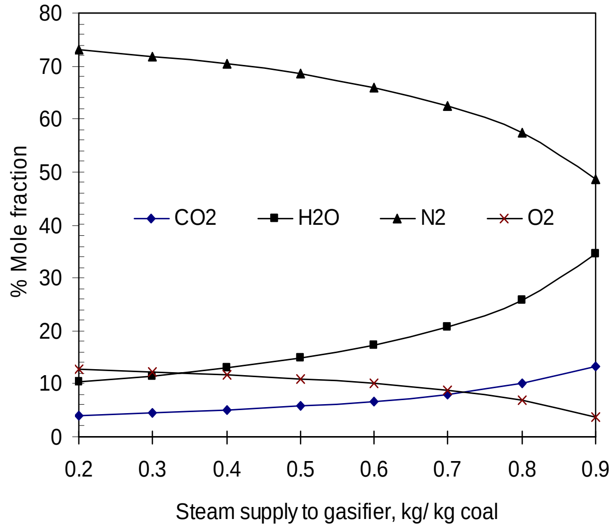

Fig. 13. Effect of Steam Supply to Gasifier on Emissions

4. CONCLUSION

Gasifier irreversibility decreases with increase of gasifier pressure. It is constant (25.5%) with variation in the combustion chamber temperature. It increases with both air and water supply rates to the gasifier. Irreversibility of the GTCC decreases with increase in the gasifier pressure, combustion chamber temperature and air supply to the gasifier. But it increases with rise in the water supply to the gasifier. Gasifier temperature increases with increase in the gasifier pressure. Gasifier temperature remains constant at 950^0C even the combustion chamber temperature changes. It decreases with both air and water supplies. The air supply to GTCC increases with increase in gasifier pressure but decreases with increase in combustion chamber temperature. Similarly its value increases with increase in air supply of gasifier but decreases with water supply. Gasified fixed carbon is independent of gasifier pressure, combustion chamber temperature and water supply but it increases with increase in air supply to the gasifier.

High pressure for gasifier has been recommended as the exergetic losses of both gasifier and combustion chamber decreases with increase in the gasifier pressure, but mechanical considerations of gasifier should be taken in to account. The increase in the gasifier pressure also increases the gasifier temperature. High temperature for combustion chamber has been also recommended as it reduces the combustion exergetic losses but metallurgical considerations of material should be taken in to account. The increase in the air supply to gasifier increases the total exergetic losses of the gasifier and GTCC. Therefore high amount of air supply is not desirable. Similarly increase in water supply to gasifier increases both the exergetic losses; therefore high water supply is also not desirable. But it can be used to control the gasifier temperature.

Carbon dioxide creates pollution to the environment. The mole fraction of carbon dioxide decreases with increase in gasifier pressure and the air supply. The carbon dioxide emission increases with increase in combustion chamber temperature and the steam supply to the gasifier.

NOMENCLATURE

e	= specific exergy, kJ/kg mole
h	= specific enthalpy, kJ/kg mole
i	= specific irreversibility, kJ/kg
LHV	= lower heating value, kJ/kg
m	= mass, kg
n	= molecular number, kg mol
NCV	= net calorific value, kJ/ kg
P	= pressure, k. Pa.
q	= heat loss, kJ/kg
$\bar{R}$	= universal gas constant, kJ/kg mol. K
s	= specific entropy, kJ/kg K
T	= temperature, K
$\bar{\varepsilon}$	= standard chemical exergy kJ/kg
ϕ	= ratio of exergy to the NCV of the fuel

Subscripts

aga	= air supplied to gasifier
agt	= air supplied to GTCC
c	= coal
ch	= chemical
fg	= fuel gas
flg	= flue gas
GTCC	= gas turbine combustion chamber
P	= products
ph	= physical
R	= reactants
w	= water

REFERENCES

[1] Corti, A., and Lombardi, L. 2004. Biomass integrated gasification combined cycle with reduced CO_2 emissions: Performance analysis and life cycle assessment (LCA). *Energy* (29): 2109–2124.

[2] Duan, L., Lin, R., Deng, S., Jin, H., Cai, R. 2004. A novel IGCC system with steam injected H_2/O_2 cycle and CO_2 recovery. *Energy Conversion and Management* (45): 797–809.

[3] Liebner, W., and Ulber. 2000. MPG-Lurgi multi purpose gasification: application in gas-gasification, In *Gasification Technologies Conference*, California, USA, October. IChemE Publications.

[4] Nag, P.K., and Raha, D. 1995. Thermodynamic analysis of a coal-based combined cycle power plant. *Heat Recovery Systems and CHP* 15 (2): 115-129.

[5] Perry, R.H., and Green, D. 1984. *Perry's Chemical Engineers' Handbook,* 6th Edition, 9-23. McGraw-Hill.

[6] Andrews, J.R., and Biblarz, O. January 1981. Temperature dependence of gas properties in polynomial form. Noval Postgraduate School, Defense Technical Information Center No. APA096388.

[7] Kwaj, H.Y., Kim, D.J., and Jeon, J.S. 2003. Exergetic and thermo economic analyses of power plants. *Energy* (28): 343–360.

[8] Kotas, T.J. 1985. *The exergy method of thermal plant analysis.* Butterworths, London.

[9] Zaporowski, B. 2003. Analysis of energy-conversion processes in gas–steam power-plants integrated with coal gasification. *Applied Energy* (74): 297–304.

[10] Dogru, M., Howarth, C.R., Akay, G., Keskinler, B., and Malik, A.A. 2002. Gasification of hazelnut shells in a downdraft gasifier. *Energy* (27): 415–427.

[11] Hara, S., Inumaru, J., Ashizawa, M., and Ichikawa, K. 2002. A study on gasification reactivity of pressurized two-stage entrained flow coal gasifier, *JSME International Journal*, series B 45(3): 518-522