Thermodynamic Analysis of Torrefaction Process

M. Senthil Kumar*‡, Ashutosh Singh *, Jithu. V. P *, R. Anand Murali*, Aravind Revuru*, Anurag Das*

* School of Mechanical Engineering, VIT University, Vellore-14, Tamil Nadu, India

(msenthilkumar@vit.ac.in, ashutosh.singh2011@vit.ac.in, jithuv.p2012@vit.ac.in, ranand.murali2012@vit.ac.in, aravind.revuru@vit.ac.in, anuraag_das007@yahoo.co.in)

‡ Corresponding Author; M. Senthil Kumar, VIT University, Vellore-14, Tamil Nadu, India, msenthilkumar@vit.ac.in

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Abstract- This paper discusses the exergy and energy analysis of torrefaction process for four different residual biomass (wet leaf, rice husk, coconut shell and tree bark). Torrefaction is a thermo-chemical conversion process carried out in an inert atmosphere. The biomass samples are torrefied using waste heat from a diesel engine at a temperature of 240˚C for a duration of an hour. Exergy and Energy efficiencies, and exergy and energy saved are assessed with the help of the actual system data. The exergy saved in the overall system is found to be 0.258 kW, 0.702 kW, 1.812 kW, 2.486 kW for wet leaf, rice husk, coconut shell and tree bark respectively. The most efficient biomass in the torrefaction process is tree bark, yielding an energy efficiency of 58.76% whereas wet leaf is the least efficient biomass. It is found that maximum exergy efficiency is obtained from the reactor if the exhaust from the source is in the range 430-470˚C.

Keywords Torrefaction, Energy, Exergy, Waste Heat Recovery.

1. Introduction

Biomass is getting increased attention as a promising source of solid fuel due to its acceptable performance in thermal processes. Biomass accounts for 14% of the global energy and 38% of the energy in developing countries[1]. The International Energy Agency (IEA) indicated its confidence in biomass serving as a potentially competitive energy contributor by modelling Blue Map Scenario- a technology road map to attain a 'clean, clever and competitive energy future'. Biomass utilization, under the Blue Map scenario, is expected to become threefold by the year 2050 [2].

The torrefaction process requires low concentrations of oxygen at temperatures typically ranging between 200-300˚C and heating rates as low as 20˚C/min [3]. It leads to thermo chemical conversion of biomass which generates high density energy products. The end products of the process are synthetic gas and bio-char which are formed by the degradation of hemicelluloses, cellulose and lignin, following first order kinetics. It is observed that products such as wet leaves, rice husk, coconut shells and tree barks that previously had no calorific value can now be considered as a viable source of fuel.

With the intention of analysing the thermal degradation characteristics, Wei-Hsin Chen et al. [4] has performed torrefaction of five basic constituents (i.e. cellulose, lignin, hemicellulose, xylan and dextran) and two pure materials(glucose and xylose) . Performance analysis of biomass conducted at different temperatures (i.e. 230, 260 and 290˚C), provides an understanding of its pre-treatment through torrefaction. It is observed that torrefaction at 230˚C liberated some moisture and light volatiles from the samples and hence it is inferred that this operation has a relatively slight effect in enhancing the properties of biomass. At 260˚C, torrefaction results in the paralysis of some amount of hemicelluloses, whereas cellulose and lignin are found to be least reactive. Large amounts of hemicelluloses and celluloses are destroyed when biomass undergoes torrefaction at 290˚C . Since a major portion of biomass is consumed, the pre-treatment procedure is considered to have an adverse effect on the torrefied mass.

The Torrefaction process can be explained to some extent using various models. Ratte et al. [5] has investigated the physical and chemical process that takes place in a torrefaction column using a model. Two distinct scales are considered; the particle and the surrounding gas. However, since certain simplifications in the simulations are involved, the model is inaccurate.

Ibrahim et al. [6] has been able to explain the portion of thermodynamics that emphasizes the intersection of energy, exergy and entropy fields. Adrian Bejan [7] provides insights on the fundamentals of exergy analysis and minimization of entropy generation. These works are aimed at giving a clear-cut explanation on thermodynamic analysis.

2. Thermodynamic Analysis of Systems

Thermodynamic analysis, also known as energy and exergy analysis is considered as an important determinant for energy conversion and to understand the behaviour of a system. It reveals the domain of dissipation of thermal energy in a system and helps in optimizing designs [8]. The conventional thermodynamic analysis called energy analysis is based on the first law of thermodynamics whereas second law of thermodynamics is employed for exergy which gives the quantitative nature of energy flow. On application to a practical process such as torrefaction that is dealt with in this study, exergy analysis gives an insight on the practicality of the particular process and highlights its deviation from the ideal nature. Reduction in energy losses results in an eco friendly and efficient system, which is the primary motive behind any research activity in the current decade. The work is focussed upon emphasizing the potential of energy and exergy analysis to recognize the energy lost and wasted in torrefaction process, through a systematic approach.

2.1. System Description

Fig. 1 shows a schematic diagram of torrefaction chamber. The experiment unit is made up of a diesel engine, a waste heat recovery unit (WHRU), reactor containing biomass and a syngas support pipe. A 7.32 kW twin cylinder diesel engine is considered for the analysis. The waste heat recovery unit recovers heat from hot stream with potentially high heat content, such as hot flue gas from a diesel generator. The exhaust from the diesel engine is nearly at 400^{0}C at full load conditions. A bypass valve installed in the main exhaust line taps the exhaust gas. Simple diversion line with a "T" joint is fabricated and installed. The piping is fitted with 32 mm gauge ball valves made of gunmetal to withstand velocity, temperature and pressure of the exhaust gas. The reactor consists of two concentric cylinder vessels. The inner reactor is made up of aluminium whereas the external reactor is made up of stainless steel. To facilitate venting out of synthetic gas and to supply nitrogen to the inner reactor, a synthetic gas pipe is developed. A muffler helps in maintaining back pressure in the experimental system and the engine. Both K-type and J-type thermocouples are used to measure temperature at regular intervals. A bellow tube pressure gauge is used to measure pressure inside the reactor chamber.

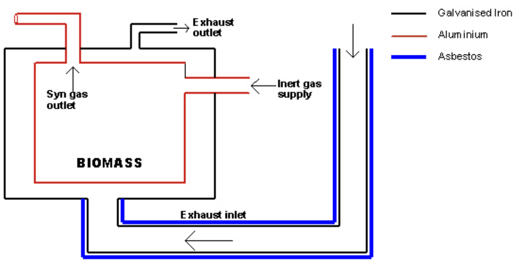


Fig. 1. Schematic diagram of torrefaction chamber

2.2. Storing of Energy

Four biomasses are torrefied using the aforementioned setup. Heat from the exhaust gas of a Kirloskar TV 2, 7.5 kW engine, is used for the torrefaction process. Under observation, about 5.12 kW of energy is lost as exhaust from the specified engine. Biomass within the reactor consisted of (in separate readings) coconut shells, tree bark, rice husk, wet leaves. The materials chosen are known to have a less calorific value that excludes them as a viable fuel source. Pyrolysis of the biomass with temperature varied between 200°C to 280°C results in the formation of synthetic gas and bio-char due to the first order degradation of hemicelluloses, cellulose and lignin. A substantial increase of calorific density is observed and the torrefied products resembled coal in mechanical characteristics since it is easily pelletized and grind-able. Hence, the waste heat from exhaust is successfully utilized in improving the energy content of biomass.

3. Exergy and Energy Analysis

The energy analysis of diesel engine and storage system is carried out with the help of first law of Thermodynamics, whereas second law of thermodynamics is employed for exergy assessment. The assumptions made in the process of exergy analysis are as follows:

- The analysis does not include changes in kinetic, potential, electrostatic and electromagnetic exergies since it is assumed to be negligible.
- Reference pressure is 1 bar and reference temperature is 303 K.
- Steady flow is assumed for engine and energy storage devices.

The Energy possessed by the fuel (E_f) is given by:

$$E_f = \dot{m}_f \times LCV \quad (1)$$

where $\dot{m}_f$ is the mass flow rate of fuel and LCV is the lower calorific value of the same.
The energy carried by the exhaust gases (E_{ex}) is:

$$E_{ex}= \dot{m}_{ex}*Cp_{ex}(T_{out}- T_{in}) \quad (2)$$

where $\dot{m}_{ex}$ is the mass flow rate of exhaust gases, Cp_{ex} is the specific heat of exhaust gases at constant pressure, T_{out} is the outlet temperature whereas T_{in} is the inlet temperature of the exhaust gas.
The energy possessed by the reactor (E_{tp})is:

$$E_{tp}=\dot{m}_{ex}*Cp_{ex}(T_{in}-T_{out}) \quad (3)$$

The energy absorbed by cooling water (E_{cw}) is given by:

$$E_{cw}= \dot{m}_{cw}*C\,p_{cw}(T_{co}- T_{ci}) \quad (4)$$

where $\dot{m}_{cw}$ is the mass flow rate of cooling water, Cp_{cw} represents the specific heat of cooling water at constant pressure, T_{co} and T_{ci} are the outlet and inlet temperatures of cooling water.

The storing energy is the energy stored in form of torrefied mass. It is the ratio of energy in the torrefied mass which increases the calorific value to the time required for process. The storing energy(E_{st}) is:

$$E_{st} = m_b * CV_b / t \qquad (5)$$

where m_b is the mass of biomass, CV_b is the calorific value of biomass, and t is the time required to attain maximum temperature. The total useful energy (E_t) is:

$$E_t = W_d + E_{st} \qquad (6)$$

where W_d is the power output of the diesel engine. The energy efficiency of diesel engine (ηd) is given by:

$$\eta_d = W_d / E_f \qquad (7)$$

The Integrated system has energy efficiency (η_i) which is given by:

$$\eta_i = E_t / E_f \qquad (8)$$

The energy saved (E_s) is:

$$E_s = E_{st} / E_f \qquad (9)$$

The chemical availability or input availability of a fuel (A_f) can be computed by the following expression [9]:

$$A_f = LCV*1.04\times\dot{m}_f \qquad (10)$$

The exergy loss in exhaust gas (A_{ex}) is:

$$A_{ex} = \dot{m}_{ex}\{(h_i - h_o) - T_o(s_i - s_o)\} \qquad (11)$$

where h_i and h_o are the specific enthalpies at inlet and outlet. Terms s_i and s_o represent the inlet and out specific entropies, and T_o represents outlet temperature. The exergy recovered by system (A_{rec}) is:

$$A_{rec} = \dot{m}_{ex}\times Cp_{ex}\{(T_1 - T_2) - T_o \ln(T_1/T_2)\} \qquad (12)$$

where T_1 and T_2 are the temperatures of the exhaust gas entering and leaving the reactor. The exergy lost to cooling water (A_{cv}) is:

$$A_{cw} = \dot{m}_{cw}\times Cp_{cw}\{(T_4 - T_3) - T_o \ln(T_4/T_3)\} \qquad (13)$$

where T_3 and T_4 are inlet and outlet temperatures of the cooling water. The exergy of storage in the system (A_{st}) is:

$$A_{st} = m_b*(CV_b - T_o(CV_b/T_b))/2100 \qquad (14)$$

where T_b is the temperature of the biomass. The total useful exergy (At) is:

$$A_t = W_d + A_{st} \qquad (15)$$

The Exergy efficiency of diesel engine (ψ_d) is:

$$\psi_d = W_d / A_f \qquad (16)$$

The integrated system has exergy efficiency (ψ_i) which is given by:

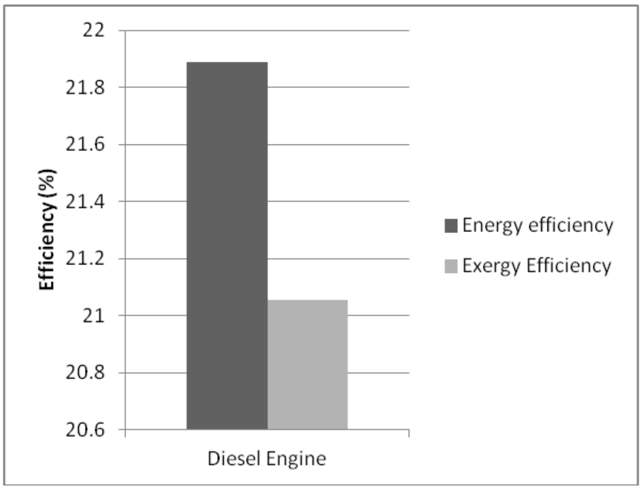
$$\psi_i = A_t / A_f \qquad (17)$$

The Exergy saved (Es) is:

$$Es = A_{st} / A_f \qquad (18)$$

4. Results and Discussions

Fig.2 shows that exergy efficiency of the diesel engine takes a lower value than that of the energy efficiency as the chemical availability of the fuel is slightly higher than its input energy [10].



Analysis o

Fig. 2. Thermodynamic efficiencies of diesel engine

Fig. 3. shows the exergy and energy efficiency of various torrefied samples in a diesel engine coupled with a waste heat recovery unit. The highest efficiency is achieved by tree bark sample.

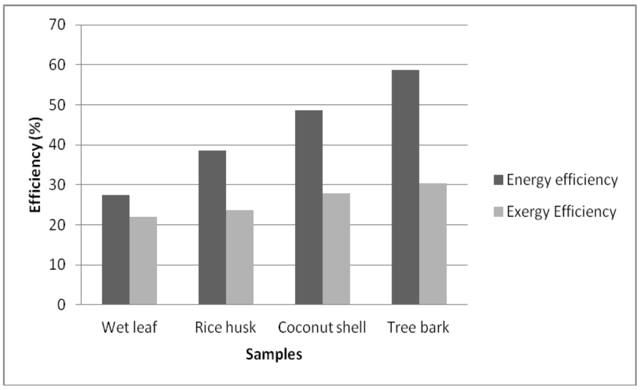


Fig. 3. Thermodynamic efficiencies of various samples

It is evident from Fig. 4. that both exergy and energy efficiencies take a high value when compared to a system that uses no energy storage unit.

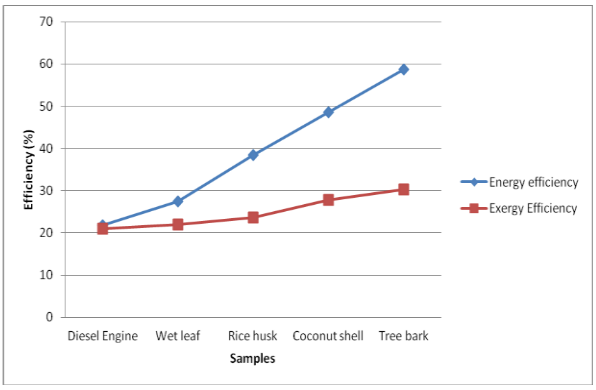


Fig. 4. Comparison of efficiency of systems with and without energy storage unit

Fig. 5 shows the energy and exergy saved by the torrefaction reactor from exhaust gas. It is observed that energy saved from exhaust gas varies from 1.425 kW to 9.462 kW for various samples. However, exergy that is obtainable to generate useful mechanical work is only between 0.258 kW to 2.486 kW.

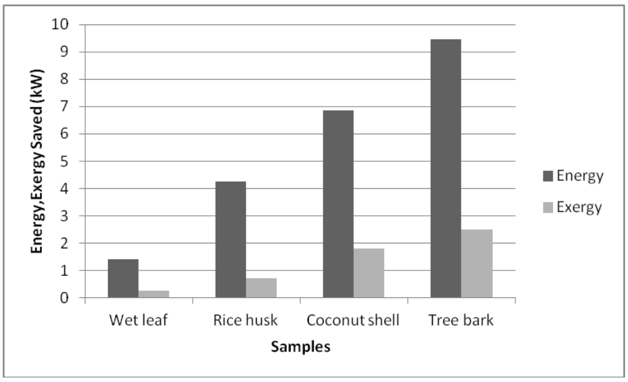


Fig. 5. Energy and Exergy saved from the exhaust gas

Fig. 6(a),6(b),6(c) and 6(d) gives an insight on the variation of exergy efficiency of four samples (wet leaf, rice husk, coconut shell and tree bark respectively) with exhaust gas temperature. This helps in optimization of the system.

Fig. 6(a). shows that wet leaf gives maximum exergy efficiency when the exhaust gas temperature is in the range 460-470 ˚C.

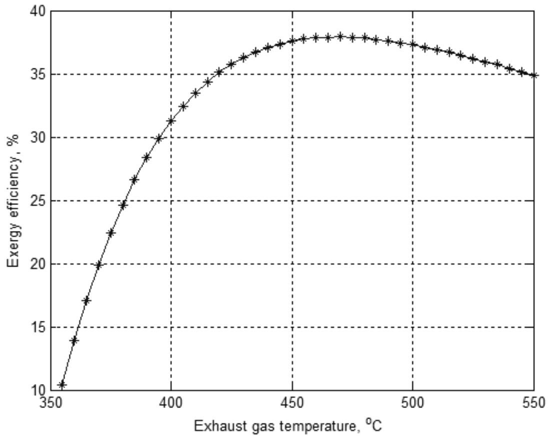


Fig. 6(a). Variation of Exergy efficiency of wet leaf sample with exhaust gas temperature

Maximum exergy efficiency can be obtained from rice husk when the exhaust gas temperature is 450 ˚C. It is shown in Fig. 6(b).

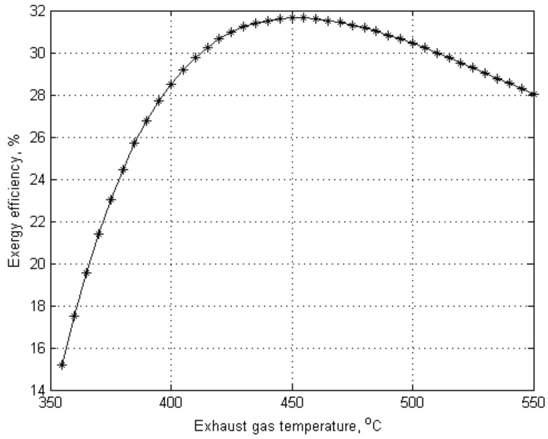


Fig. 6(b). Variation of exergy efficiency of rice husk sample with exhaust gas temperature

Whereas coconut shell requires an optimum temperature of about 455˚C to obtain maximum exergy efficiency.

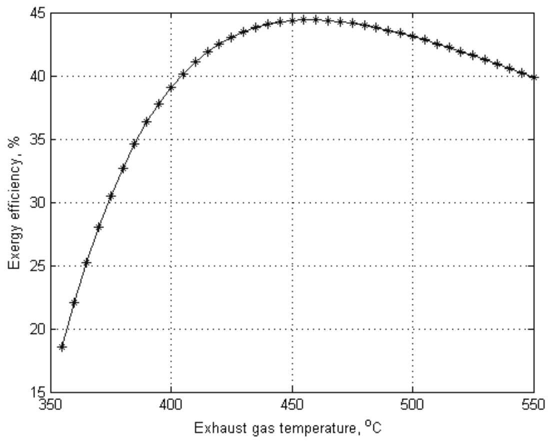


Fig 6(c). Variation of exergy efficiency of coconut shell sample with exhaust gas temperature

It is observed from Fig. 6(d). that tree bark at exhaust gas temperature of about 435˚C, gives maximum exergy efficiency which is equal to 65.2%.

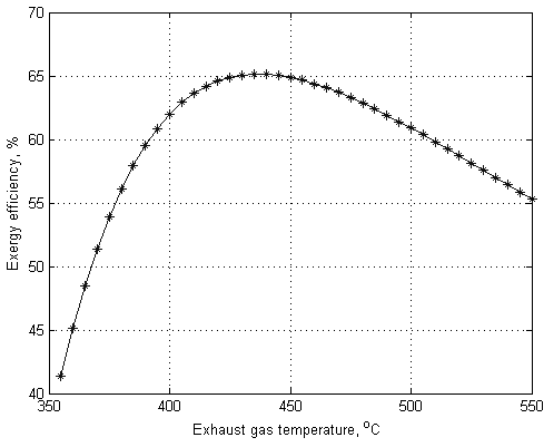


Fig. 6(d). Variation of exergy efficiency of tree bark sample with exhaust gas temperature.

5. Conclusion

Energy and Exergy analyses are performed using first and second laws of thermodynamics. The process helps in identifying areas of major energy losses in thermal devices. It is experimentally verified that a system with an energy storage device has comparatively higher thermodynamic efficiencies than a system without an energy storage device.
The most compromising biomass is tree bark with respect to the efficiency obtained. It gives remarkable exergy efficiency at an exhaust gas temperature of about 435˚C. Analyses of optimal operating conditions are performed and it shows that the torrefaction process gives maximum exergy efficiency when the inlet gas to the reactor (i.e. exhaust gas from the source) is in the range 430-470˚C.

Acknowledgements

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References

[1] Hall D.O, Rosillo-Calle F, Williams R and Woods J. ,1993, “Biomass for Energy: Supply Prospects, in Renewable Energy- Sources of Fuels and Electricity,” (Eds. Johansson T.B, Kelly H, Reddy A.K.N and Williams R.H), Island Press, Washington D.C.

[2] IEA, Energy Technology Perspectives, 2008, “Scenarios and strategies to 2050,” ExecutiveSummary,ACTscenarios,p-2

[3] P. Basu, 2010, "Biomass gasification and pyrolysis: practical design and theory", pp. 64-96

[4] Wei-Hsin Chen and Po-Chih Kuo, 2010, “A study on torrefaction of various biomass materials and its impact on lignocellulose structure simulated by a thermo gravimetry” Applied Energy, Vol.23: 368-375.

[5] J. Ratte, E. Fardet, D. Mateos, J.-S. Héry, 2011, “Mathematical modelling of a continuous biomass torrefaction reactor: TORSPYD™ column Biomass Bioenergy”, Vol.35 , pp. 3481–3495

[6] Ibrahim Dincer and Yunus A. Cengel, “Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering”

[7] Adrian Bejan,2010,”Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture”, Volume 26, Issue 7, pages 0–43,

[8] Najem, N.M., Diab, J.M., 1992, “Energy-Exergy analysis of a diesel engine, Heat Recovery systems & CHP”, Vol.12, pp. 525 – 529.

[9] Kotas T.J.,1995, “The Exergy Method of Power Plant Analysis, Reprint Edition, Krieger, NewYork”.

[10] K.Nantha Gopal, Rayapati Subbarao, V.Pandiyarajan and R. Velraj, 2010,”Thermodynamic Analysis of a Diesel Engine Integrated with a PCM Based Energy Storage System”, Vol. 13 (No. 1), pp. 15-21