# Evaluation of Gas-Steam Combined Cycle Generator Unit Using Mango Pit as Biogas

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### *Abstract*

**Mango pits, considered as waste materials in the Philippine farms and which are generally thrown out, contain energy and be used as biomass with the characteristics to reduce 0.02% of the CO2 emission. In 2020, the mango production in the Philippines reached to 27.53 thousand metric tons. For the conservation of environment, the use of organic wastes such as mango pit to produce biogas was explored on this study. With most of power plant using stand-alone turbines and its efficiency reaching only 35% of the total performance, the proposed alternative energy source delivered higher efficiency and adequate power supply. The combined cycle technology of steam and gas is appropriate to work together to provide higher efficiency. The Bryton-Rankine cycle was utilized in the design and evaluation of the combined gas generator intended to achieve higher efficiency compared to the stand-alone gas turbine and stand-alone steam turbine. From the evaluation done through simulation in MATLAB of the proposed design, efficiency of the stand-alone gas turbine ranged from 20% to 35%, the stand-alone steam turbine efficiency ranged from 26% to 35%, but the efficiency of the combined cycle ranged from 35% to 55% which emphasized the increase in the efficiency of the electricity production.**


***Keywords* —biomass, byrton-rankine cycle, gas-steamed cycle generator, mango pit**

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## I. Introduction

People rely on electricity so much that they cannot do much work without it. Machines and appliances need electricity to function and work as these are needed for the production in agriculture and other sectors of a country. A lot of studies have been made to start the use of renewable energy to reduce the cost of fuels and electricity and help the electrification of the rural areas and agricultural farms that have inadequate supply of electricity. One of the promising areas of alternative energy is the production of biogas from the organic waste of agricultural enterprises. If biomass will be used for the generation of electricity as an alternative source of energy, those who have less access to electricity will greatly benefit from it.

Waste materials in farms such as rice hulls, coconut shells, fruit peels sugarcane bagasse and even the waste of animals which are generally thrown out, without realizing that all these contain energy and can be used as biomass. Mango pit as a waste material can also be a primary biomass material in the Philippines since this is readily available.

Mango is one of the most popular fruits in the Philippines and its tree produces fruits in the months of March to June, though advancement in the agriculture made it possible for mango tree to bear fruits even beyond those months. In 2020, the mango production achieved 27.53 thousand metric tons' production compared to 27.78 thousand metric tons' production of 2019 [1]. Also, using mango pit as biomass can reduce the carbon dioxide emissions up to 0.02% [2].

While most of power plant uses stand-alone turbines with its efficiency only reaches 35% of the total performance, too much energy was used to produce small electrical energy only. The proposed alternative source aimed to address the poor efficiency of the existing system and be able to deliver higher ones and adequate power supply. Likewise, since the combined cycle technology works to provide higher efficiency that ranges 50% to 60% which is more efficient, identifying the best combination of cycle appropriate for mango pit was also the main concern of this study.

This study aimed to evaluate the performance of the combined gas and steam turbine generator using mango pit as biogas sources. Using MATLAB software programming as a means to evaluate the proposed system, the study intended to assess the efficiency and sensitivity of the gas turbine with respect to the heat recovery steam generator with various thermal parameters; and identified these thermal parameters that have the greatest impact on efficiency.

## II. Related Literature

For the conservation of environment, the use of organic wastes to produce biogas was explored on this study. The material balance analysis together with the methane production is essential factor in the analysis on the performance of the combined gas-steam generator.

### *A. Biomass*

Organic waste, which are basically thrown out, can be used effectively as biomass [1]. These organic wastes are not only readily available, but also, they are harmless to environment. These can also be efficient as feedstock for gasification.

Gasification is a thermo-chemical process for converting a solid fuel into a mixture of combustible gases known as "product gas". During the gasification, the complexity of the processes occurring inside the gasifier appears to be complicated from the point of regulatory forecasting parameters and elaboration of design solutions to create the installation. The dependence of composition and calorific value of the resulting mixture of combustible gases from the operating and constructive parameters requires a unique approach to the organization of the process and equipment design [2]. Modeling allows to determine the design parameters of the installation, the main technological parameters of the work and to forecast the parameters of a mixture of combustible gases at the exit of the gasifier.

The quality of the product gas depends on the design and operating parameters of the gasifier. The idea of gasifier design should be in such a way that it can convert the solid biomass like mango pit into the form of clean product gas.

The integrative biomass gasification with solid oxide fuel cell (SOFC) system using rice husk as feedstock was studied under various operations. It was found that the stand-alone mixed air-steam gasification provided significant higher benefit than alone air and steam gasification. The mathematical model was developed to predict the electrical, thermal and overall efficiency of the system. It was found that the SOFC with steam gasification provided the greatest overall efficiency of 96%. Hence, the steam gasification is a promising option for coupling with SOFC to generate electricity from biomass [3].

The role of biomass and biofuel in the potential scalability for small usage was discussed particular on the potential benefits and applications of this biomass with emphasis on densified biowaste and organic Rankine cycle turbo generator. With an abundance of potential biomass resources in Sierra Leone, specifically mango pit, the waste stream of the local fruit processing facility as potential densified biofuel feedstock source was developed using low-resource and low-capital materials for industry standard fuel [4].

Cellulose is an organic compound and has important structural component of the primary cell wall of green plants, algae and the oomycetes. Cellulose solvent-based pretreatment for enhanced second-generation biofuel production has a core pretreatment step for improved bioprocessing of lignocellulose. Cellulose, in addition to hemicellulose and lignin, makes the major fraction of lignocellulosic biomass – the only sustainable feedstock to meet the long-term sustainable energy need of the world. This ability can be used as a core pretreatment step for improved bioprocessing of lignocelluloses. The cellulose solvent-based lignocellulosic fractionation technologies for enhanced enzymatic hydrolysis to improve biofuel and renewable chemical production were reviewed [5].

### *B. Biogas generator*

In the advancement of biogas in a gas-steam combined cycle, the gas turbine is the essential equipment of the combined cycle unit. The operating conditions of the gas turbine not only affect its performance but also affect the performance of the heat recovery steam generator and steam turbine. When studying the combined cycle, the first step is to analyze the gas turbine and its performance. The gas turbine is composed of a compressor, a combustion chamber, and a gas turbine. Therefore, the efficiency of the gas turbine is determined by the combined characteristics of the compressor, the combustion chamber, and the gas turbine.

A study conducted was focused on analyzing and comparing the performance efficiency of filtered fuel and the unfiltered fuel of the locally-made biogas generator. With the average flow rate of the locally-made biogas generator being 6.0 $m^3$/hr with 66% biogas initial concentration to 4.9 $m^3$/hr and 84% biogas concentration due to filtration system, the overall filtration efficiencies were increased by 18% [6].

With the mechanisms of combining the gas turbine (GT), a steam Rankine cycle (SRC), and an organic Rankine cycle (ORC) and were coupled together to obtain the maximum heat recovery of the GT exhaust gas. The introduced cycles were optimized simultaneously using multi-objective optimization with seven decision variables, including steam turbine inlet pressure and temperature, ORC turbine inlet pressure, ORC and steam turbine back pressures, and pinch point of heat exchangers. Under the design conditions, the exergy efficiency of 40.75% and product cost rate of 439 million $/year could be achieved [7].

To further enhance the performance of power generation systems, steam injection and adding steam turbine cycles to gas turbine with biomass can be substituted for fossil fuel when the gas turbine lowers its value. The results of energy and exergy analyses of two biomass integrated steam injection cycles and combined power cycles enhanced the performance of power generation systems. Even with its lower heat value, biomass can be substituted for fossil fuels [8].

The thermodynamic modeling of a combined cycle power plant for optimized performance was assessed using different cases. The effect of steam turbine outlet quality on the output power of a combined cycle power plant with dual pressure heat recovery steam generator was discussed [9]. Obtained results show that it is really important to keep the quality of the vapor at turbine outlet constant in 88% for the results to be more realistic and also optimization and data are more technically feasible and applicable.

The advancement of biogas effectiveness of the steam turbine unit work is largely determined by the efficiency of its condenser. Therefore, in the development of modern physical and mathematical models of steam turbines, the physical and mathematical models of the condenser should be used as one of the most important routines. The better model of the steam turbine unit is the more complicated interaction of the turbine and condenser in this model. the study showed that the magnitude enthalpy difference of the exhaust steam and the condensate is not constant and depends on many factors which can be considered only within the combined model of the condenser and the steam turbine unit. The study presented the equations of the condenser material and energy balance on the basis of which it is possible to calculate the condenser heat load taking into account all the components entering into the heat flow which substantially exceeds the calculated magnitude of the manufacturers [10].

## III. Methodology

The study started with the design of the system of mango pit-powered generator using MATLAB. This is followed by the integration of the gasifier with lenses for solar power heating. The evaluation of the system took place eventually focusing on the power output of the designed stand-alone gas turbine, the designed stand-alone steam turbine, and the evaluation of the combined gas and steam turbine.

The gasifier for biomass material was connected with condenser and filter to produce gas which was then connected to turbines and generator for the generation of electricity. Figure 1 presents the proposed design system process flow of the gas-steam combined cycle generator unit using mango pit as biomass.

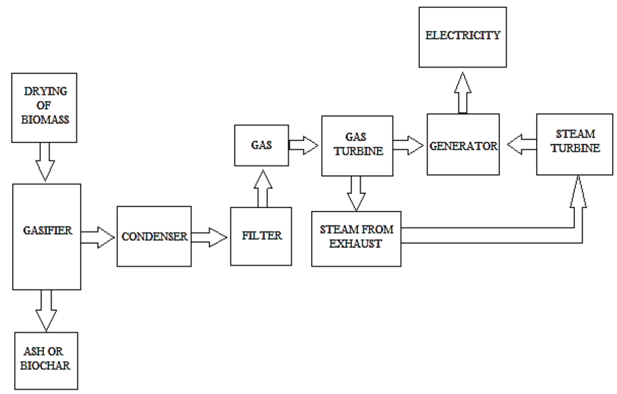


**Fig. 1.** Proposed design system process flow of the gas-steam combined cycle generator using mango pit as biomass

### *A. Details of the gasifier*

The gasifier used is based on the process of an updraft gasifier (or also called counter-current), which is one of the common and simplest type of gasifiers for biomass. The biomass was applied on the top part of the gasifier and entered the drying process. Air was applied near the bottom part and served as gasifying agent which eventually counter-currently flowed with the fuel. Fresh air aided the process of combustion, but there should be sufficient amount of air to avoid dangerous levels of carbon monoxide deposits.

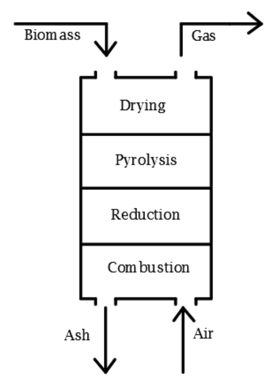


**Fig. 2.** Process flow diagram of the gasifier from biomass as its input to gas as its output

The description of the process in the gasifier are as follow: (1) Drying zone of the gasifier – the biomass entered the drying zone of the gasifier to reduce its moisture and a lower percentage of moisture was needed for a higher efficiency.; (2) Pyrolysis zone –decomposition of the biomass by high temperature took place. Pyrolysis produced ash or biochar, which can be used for soil enrichment. The carbon dioxide was removed from the atmosphere and was decomposed by bacteria.; (3) Reduction zone – the reduction occurred when the heat and CO2 from the combustion were released. Carbon monoxide was formed from the CO2.; and, (4) Combustion zone – charcoal from the biomass was combusted with the oxygen in air entering from the bottom part of the gasifier.

### B. *Solid materials in the process*

Dried small mango pits were used as biomass and fuel for this study. The mango pits were broken into smaller pieces for faster heating process since the gasifier used the sunlight through concentrated lenses to reduce its carbon dioxide emission.

### C. *Solar lenses heating in gasifier*

Heating the biomass was required to enter the gasification process. By achieving high temperature, the biomass was converted into biogas or syngas. The heating process is generated through concentrated solar lenses attached around the gasifier for solar-powered heating. Ceramic material is used for the system to generate faster gasification process.

Since concentrated solar power makes use of the sunlight as its energy source, it produces less GHG emissions compared to fossil fuel sources, requires low operating costs with its clean and natural energy, and it has sufficient energy to gasify the biomass.

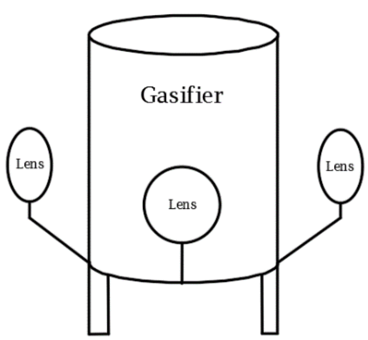


**Fig. 3.** Design of gasifier with installed concentrated lenses for heating process

### D. *Gas turbine model*

The gas turbine model is based from the Brayton cycle, a cycle using heat addition and constant pressure. A compressor and fuel in the combustor help to increase the heat and pressure of gas.

Air was taken in the compressor causing higher pressure and temperature of air. The compressed air was sent to the combustion chamber, and fuel was added, which was burned at a constant pressure. This resulted in higher temperate gases to be sent to the turbine. As the gas caused the turbine blades to spin, electricity was generated. Exhaust gases exit the turbine.

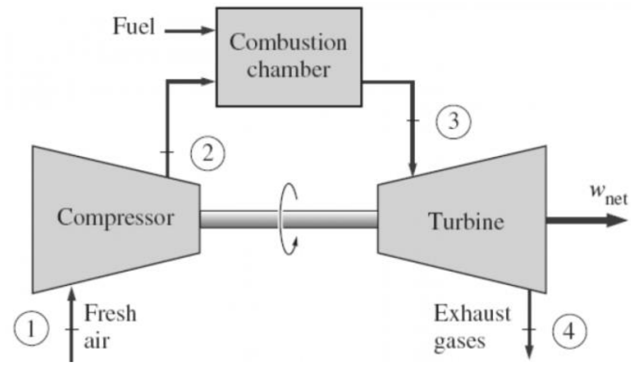


**Fig. 4.** Design of the open cycle gas turbine to achieve higher temperate gases

### E. *Combined Brayton-Rankine Cycle*

The figure below shows the process of combined Brayton and Rankine cycle. The Brayton-Rankine power cycle was utilized to further achieve a higher efficiency compared to the stand-alone gas turbine and stand-alone steam turbine. On the process of the combined Brayton-Rankine cycle, the exhaust gases from the gas turbine were sent to drive the steam turbine, wherein the boiler and fluid play significant roles for the Rankine cycle. Air, entering the inlet, was compressed and sent out to the combustion chamber. Fuel was added in the combustion chamber that drove the turbine, and the exhaust gases exit the turbine. The exhaust gases drove the steam turbine.

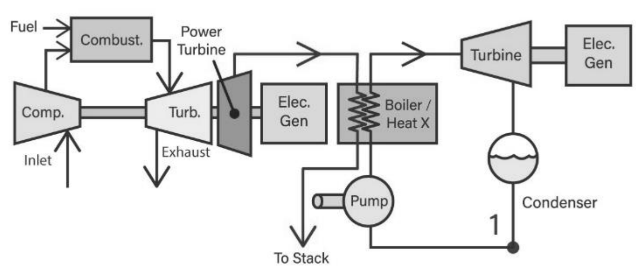


**Fig. 5.** Process of combined Brayton-Rankine cycle

## IV. EXPERIMENTS AND RESULTS

### A. *2D Model Design*

The 2D model design of the system is presented in figure 6. With the gasification system design, the mango pit was fed in the feeder. After the gas went through condensing and filtering, it was injected in the combustion chamber in the gas turbine. Boiler was connected in gas turbine to catch the exhaust gas, and the pump supplied water that was pressurized by the boiler. High pressured steam flowed into the steam turbine, while the condenser converted the steam from gas to its liquid state.

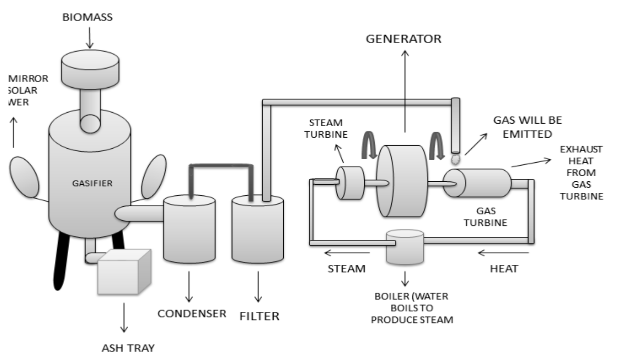


**Fig. 6.** Design of the gas-steamed combined cycle generator system using mango pit as its biomass

## B. MATLAB Design

The stand-alone gas turbine design was run in MATLAB using Brayton cycle as its model since compressor and the turbine are included in Simscape Foundation Gas Library. Heat was added in the combustor as power input and the parts of the gas turbine, such as the upstream compressor, combustor and downstream turbine were separated for the evaluation of the process. Air was the working fluid in this cycle. Fresh air was taken by the upstream rotating gas compressor, compressed to increase its pressure. The fuel gas produced from gasifier through biochemical processes was sent to combustor of the gas turbine. Fuel gas together with the pressurized air was heated in the combustor at a high pressure. Higher temperate gases were now fed into the downstream turbine. APU or auxiliary power unit acted as addition supply of energy.

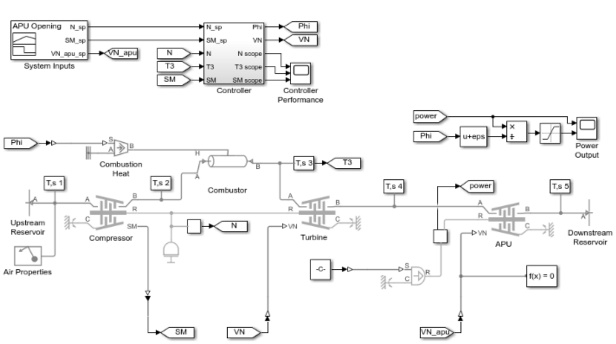

**Fig. 7.** Gas turbine design using MATLAB

## C. Gas Turbine Results

The line graph of the shaft speed in revolutions per minute (rpm) is presented below with the yellow line representing the demand output for the gas turbine and the blue line representing output through simulation. Shaft is important in transmitting power from one part to another. The output increased from 6000 rpm to 10000 rpm, and that the demand output of 10000 rpm is achieved.

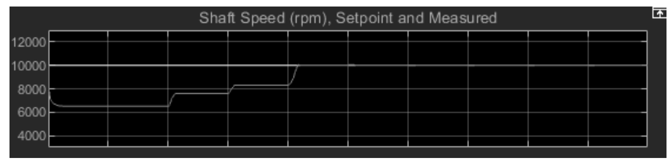


**Fig. 8.** MATLAB-generated line graph of shaft speed

Turbine inlet temperature or TIT is an important parameter affecting the performance of the system. As the turbine inlet temperature increases, efficiency and its power output will also increase. TIT was decreasing from 1800$^{O}$K to approximately 1200 $^{O}$K because of the decreasing heat transfer rate.

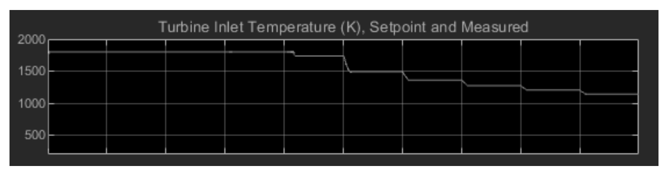


**Fig. 9a.** MATLAB generated line graph of turbine inlet temperature

Surge may affect the performance of the whole machine. Figure 9b shows the surge margin of the gas turbine, where it stayed on 0.3. This is the measurement of how close the operation is to surge.

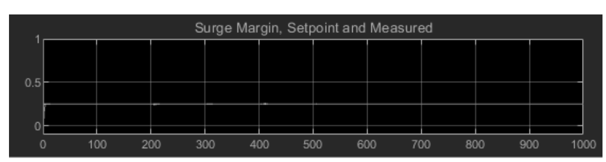


**Fig. 9b.** MATLAB-generated line graph of surge margin

The ambient temperature has an effect to the power output of gas turbine. For each degree Fahrenheit increase in ambient temperature, there is 0.3% to 0.5% drop in power output. The figure below shows that the power output was increasing from 20kW up to 100kW, but eventually decreases from 100kW to 40kW. Given such, the efficiency gained by the system ranges from 20% to 35%.

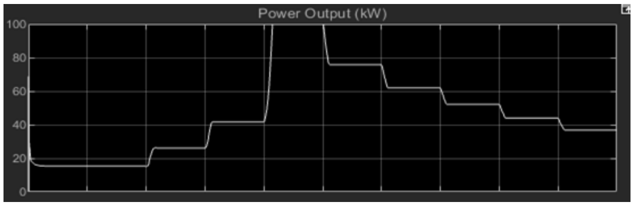


**Fig. 9c.** MATLAB-generated power output graph of gas turbine


**Fig. 9d.** MATLAB-generated efficiency graph of gas turbine

Figure 10 shows the relationship of the temperature and specific entropy. The cycle points indicate the processes involved in the T-s diagram. The isentropic compression takes place from cycle point 1 to cycle point 2, cycle point 2 to cycle point 3 is where heat is added, cycle point 3 to cycle point 5 is isentropic expansion, and cycle point 5 to cycle point 1 is where heat will be rejected.

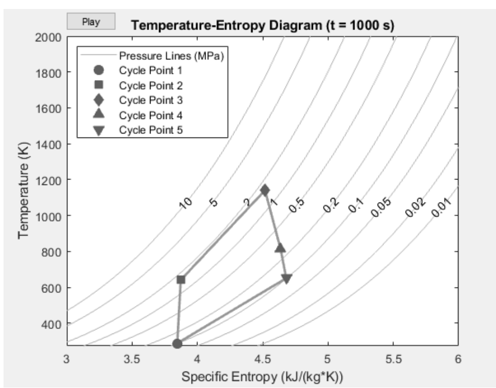


**Fig. 10.** Temperature-Entropy diagram of Brayton cycle (T-s diagram) generated by MATLAB

Compressor maps are significant to assess the performance of the engine. The area above the surge line is where unstable flow occurs and, therefore, it is best to avoid this area. Corrected speed lines are the measurement of the Mach number of the rotor blade tip or the ratio of flow of velocity to the speed of sound. The lines vary from 5000 rpm and increases to 12000 rpm. The operating line is the locus of operating points in the engine. The isentropic efficiency shows the relationship of efficiency with the flow.

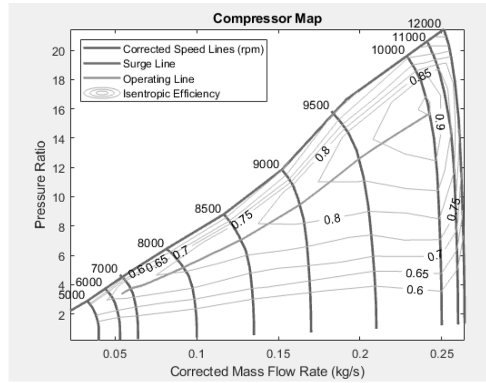


**Fig. 11.** Compressor map of gas turbine generated by MATLAB

The turbine map shows that the isentropic efficiency dropped from 0.85 to 0.7 at pressure ratio 1. The vane opening (on percentage) is a guide to know the needed flow system to reduce its hydraulic loss or head pressure loss. The operating line started from 30% and increased to 40%. The choked refers to the compressible flow effect, wherein changes in fluid density occurs.

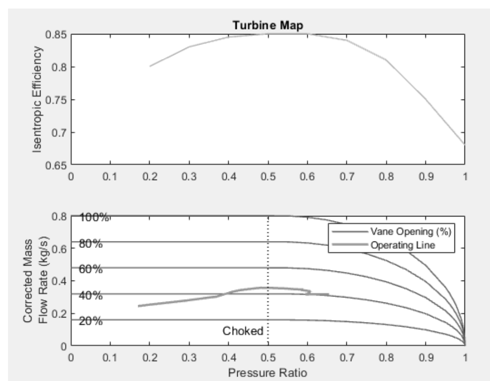


**Fig. 12.** Turbine map of gas turbine generated by MATLAB

## D. *Steam turbine results*

The turbine and the saturated fluid chamber block were included in Simscape Foundation Two Fluid Library. The model included superheating to prevent condensation in the high-pressure turbine and low-pressure turbine. Turbines were separated into high pressure turbine and low-pressure turbine since it was impossible for a single turbine to drop the pressure. With water as the working fluid, high pressure took place on the pump, where fluid was compressed, heated, and converted to steam. The steam expanded from the high-pressure being an impulsive turbine to the low-pressure turbines being the reaction turbine. Check valve was used to allow liquid to flow through, and the throttle valve was used to regulate the flow of steam that flows from the boiler. On the other hand, extraction valve was used to discharge the excess steam.

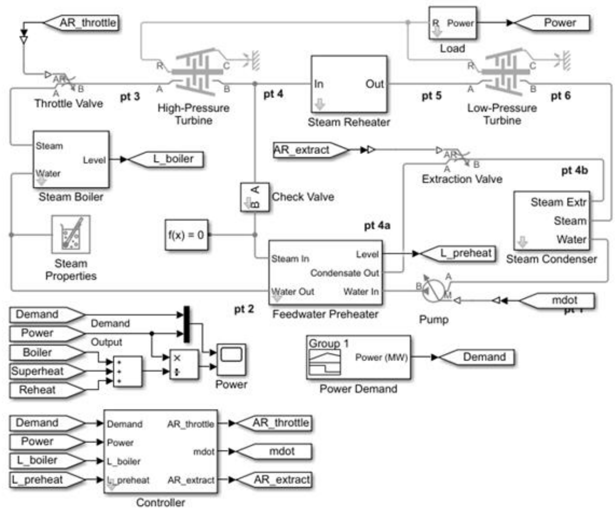


**Fig. 13.** Stand-alone steam turbine design generated by MATLAB

With the yellow line representing the demand output of the steam turbine and the blue line for the real output, the power output started from 1.15MW and increased to 1.2MW, where the demand line rests. The output line gradually decreases and reached 1.15MW. With this, its efficiency ranges from 22% to 25%.

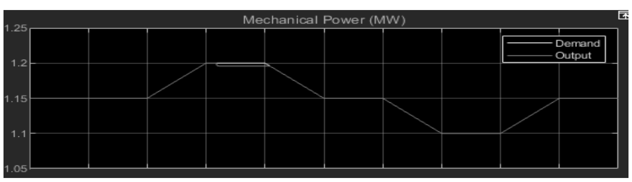


**Fig. 14a.** MATLAB-generated power output graph of steam turbine


**Fig. 14b.** MATLAB-generated efficiency graph of steam turbine

Since small amount of work was produced in the pump, it resulted with very small amount of energy. The boiler heat produced a high energy rate that varies from approx. 3600 kW to 3800 kW. The condensation process also produced a high energy rate that varies from 3500 kW to 3700 kW.

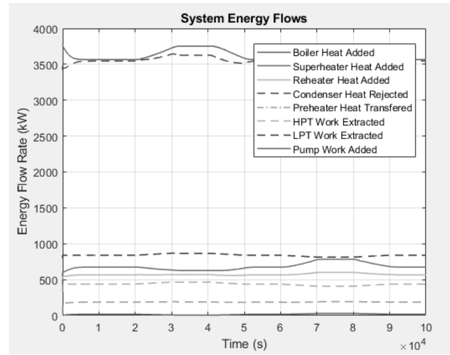


**Fig. 15.** System energy flow graph of steam turbine generated by MATLAB

In this case, extraction valve is approximately 0.1 kg/s or less because of fewer fluid that occurs in the valve. The high-pressure turbine (HPT) and the pump can be seen to equally share the same mass of fluid at 1.6 kg/s to 1.7 kg/s, while the low-pressure turbine (LPT) varies from approx. 1.4 kg/s to 1.59 kg/s.

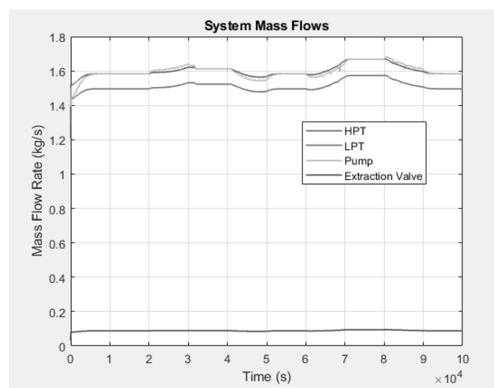


**Fig. 16.** System mass flow graphs of steam turbine generated by MATLAB

Figure 21 presents the result of the relationship between temperature (in Celsius) and specific entropy (in kJ/(kg*K)). From the cycle point 1 to 4a, the temperature is increasing since high pressure liquid enters the boiler from the pump with cycle 1 starting from 100 $^{O}$C increasing up to 250 $^{O}$C. The pressure from the boiler is assumed to be constant, thus the diagram shows a straight line near the 5MPa pressure line. Cycle 3 to 4 is the exit of pressure from the boiler and expansion of steam in the turbine, and this is the reason why temperature in the cycle 3 is approximately 400 $^{O}$C. Heat addition occurs in the cycle 4 and 5 from 230 $^{O}$C to 400 $^{O}$C due to reheating process to remove excess moisture with intermediate pressure. Cycle points 5 to 6 indicates the isentropic compression of the steam.

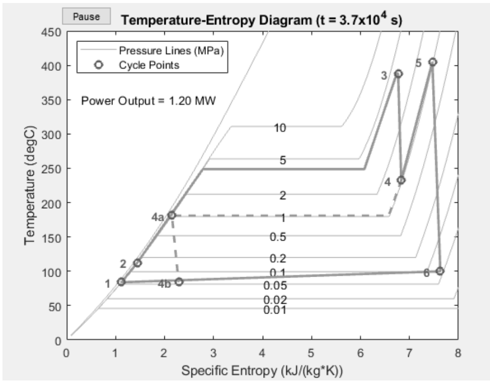


**Fig. 17.** Temperature-entropy diagram of steam turbine generated by MATLAB

*E. Combined gas and steam turbine results*

Temperature is higher in gas turbine inlet or Brayton cycle because it is a topping cycle, and the steam turbine or Rankine cycle is the bottoming cycle. Inlet temperature increases as the heat supplied increases. The inlet temperature of the gas turbine increased from approx. 870 $^{O}$K to 970 $^{O}$K while steam turbine increased from approx. 770 $^{O}$K to 830 $^{O}$K.

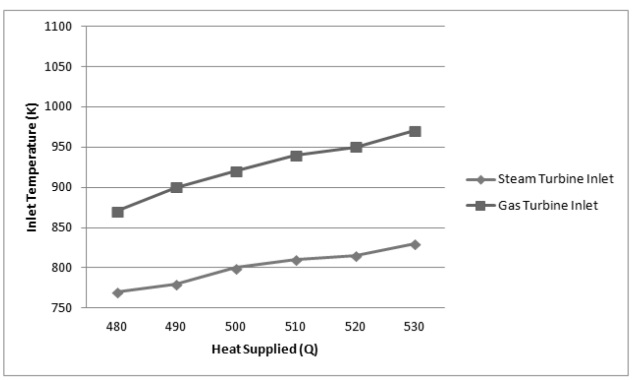


**Fig. 18.** MATLAB-generated relation graph of inlet temperature to supplied heat

The relationship of inlet temperature (y-axis) with the heat applied (x-axis) is presented in figure 18. The work output of the combined cycle is higher than that of gas turbine and steam turbine. The compressor in the gas turbine consumes more work therefore it will not produce more work output. The pump in the steam turbine consumes small amount of work, thus it produces high power output than the gas turbine.

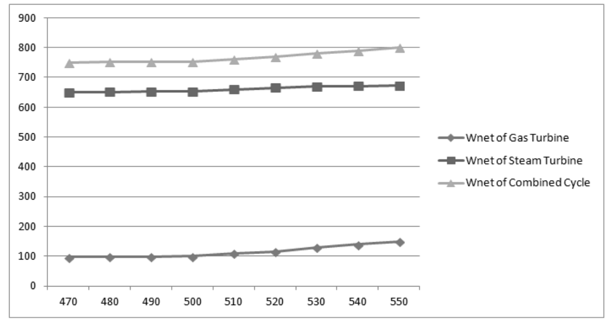


**Fig. 19.** MATLAB generated Wnet graph comparison of the three cycles

With the x-axis stands for the heat supplied and the y-axis stands for the efficiency, the steam turbine or Rankine in this case is higher than that of gas turbine or Brayton. But the combined cycle is higher since it is the sum of two cycles.

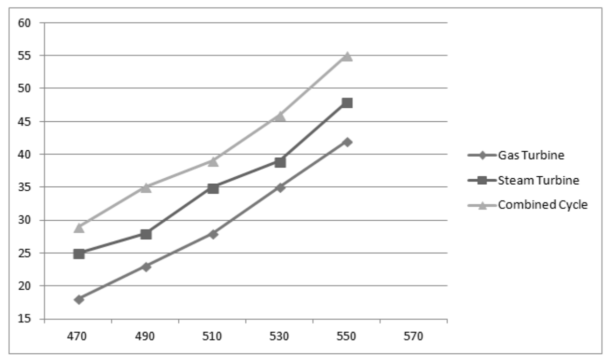


**Fig. 20.** MATLAB-generated efficiency graph of the three cycles

## V. Conclusion

The parameters of the cycles, such as input temperature and input pressure, affect the efficiency of the whole system. The efficiency of the stand-alone gas turbine was measured ranging from 20% to 35%, the stand-alone steam turbine efficiency was from 26% to 35%, and the efficiency of the combined cycle ranges was from 35% to 55%. Combining the advantage of one to the other increases the efficiency of the electricity production.

Therefore, the efficiency of stand-alone turbines can be improved through the combined cycle technology such as gas and steam cycle. Also, this technology is not hazardous because it uses mango pit as its biomass.

It is suggested that the system be tested for the diffusive burning effects against flash back and risk of engine failure for the next study.

## Acknowledgment

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## References

[1] https://psa.gov.ph/fruits-crops-bulletin/mango?fbclid=IwAR2rLnqmLhxvg1ZcyDyjT_F-CDkYdpQDUmphIGiiDtZVSAgvi4uiu6k0mW0 https://www.americanscientist.org/article/making-biofuel-from-microalgae?fbclid=IwAR3Y24uNY_9IifriNBh7QVzdLEk8_pLxZQCwrEBs1mglGhdIvn4HXVKMuqk

[2] Tapasvi, D., Kempegowda, R. S., Tran, K. Q., Skreiberg, Ø., & Grønli, M. (2015). A simulation study on the torrefied biomass gasification. Energy Conversion and Management, 90, 446-457.

[3] Rumple, C. R., Maley, S., & Mehta, K. (2016, October). Densified mango residues as biofuel from low-resource agricultural processing. In 2016 IEEE Global Humanitarian Technology Conference (GHTC) (pp. 27-32). IEEE.

[4] Satari, B., Karimi, K., & Kumar, R. (2019). Cellulose solvent-based pretreatment for enhanced second-generation biofuel production: a review. Sustainable Energy & Fuels, 3(1), 11-62.

[5] Paglinawan, A. C., & Mojica, E. E. (2016, October). Electrical performance analysis of biogas fuelled generator with purifier. In 2016 International SoC Design Conference (ISOCC) (pp. 3-4). IEEE.

[6] Mehrpooya, M., Ashouri, M., & Mohammadi, A. (2017). Thermoeconomic analysis and optimization of a regenerative two-stage organic Rankine cycle coupled with liquefied natural gas and solar energy. Energy, 126, 899-914.

[7] Athari, H., Soltani, S., Rosen, M. A., Gavifekr, M. K., & Morosuk, T. (2016). Exergoeconomic study of gas turbine steam injection and combined power cycles using fog inlet cooling and biomass fuel. Renewable Energy, 96, 715-726.

[8] Ganjehkaviri, A., Jaafar, M. M., Ahmadi, P., & Barzegaravval, H. (2014). Modelling and optimization of combined cycle power plant based on exergoeconomic and environmental analyses. Applied Thermal Engineering, 67(1-2), 566-578.

[9] Shempelev, A., Iglin, P., & Tatarinova, N. (2017, May). On condenser mathematical model method introduction into steam turbine unit mathematical model. In 2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) (pp. 1-4). IEEE.