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Thermodynamic analysis and optimisation of Bagasse-Based Cogeneration in Mauritius

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Abstract
This paper aims at evaluating the possibility of improving the performance of cogeneration plants through typical performance parameters like the cogeneration plant efficiency, the steam consumption and the heat-to-power ratio. The ultimate objective of the investigation is to improve the performance of existing bagasse-based cogeneration plants and to influence the design considerations of future plants in order to meet the increasing demand in electrical energy requirements.The main performance parameters are analysed and compared in order to evaluate the potentiality and feasibility of maximising energy efficiency and exergy efficiency and minimising steam consumption, heat loss and exhaust gas emissions. The analysis is based on formulation and assumptions relative to the first and second laws of thermodynamics. Improvement of cogeneration efficiency up to 11% and maximum reduction of specific steam consumption by 40% have been observed.The paper focuses only on bagasse cogeneration and targets cogeneration plants equipped with condensing-type steam turbines with extraction, generating electricity and useful heat.Higher exergy efficiencies were observed by reducing the extraction temperature.

Keywords**:** bagasse, cogeneration,efficiency, exergy, optimisation.

1.0 INTRODUCTION

Electricity generation from bagasse has been a common practice in sugar industries for years. Traditionally, sugar factories generated sufficient electricity to meet their own needs from bagasse, a waste product of sugar cane milling processes, instead of importing electricity from the national grid. Howeverwith the possibility of exporting excess electricity, most sugar industries turned into independent power producers supplying electricity to the national grid. Cogeneration was introduced in Mauritius in 1957 and the first bagasse/coal cogeneration plant was erected at FlacqUnited Estates Limited(FUEL) in 1984. The potential of cogeneration was further exploited through one of the main component of the sugar reform to compensate for losses due to a fall in sugar prices and an increase in production cost. The steam generated from the combustion of bagasse is used to drive turbo-alternators to generate electricity as well as to drive factory equipment and thermal processes. The future of cogeneration in Mauritius is strongly related to the centralisation of sugar industries and a future boost in cogeneration may be expected. In order to meet the increasing demand in electricity at lower cost, plant performance has to be optimised such as to ensure maximum electrical output and maximum cogeneration plant efficiency at minimum steam consumption and process cost.

Bagasse cogeneration in sugar industries has enabled electricity generation well above their energy requirements. The excess electricity is then sold to the national grid which in return brings money to the company. Therefore, optimally exploiting cogeneration is an effective means of meeting the increasing demand in electricity at relatively low cost. In order to meet the increasing demand in electricity at lower production cost, the plant performance has to be regularly evaluated and optimised such as to ensure maximum electrical output and maximum cogeneration plant efficiency at minimum steam consumption and process cost. Innovative projects have already been proposed for electricity generation like the Biomass Integrated Gasification Combined Cycle power plant. These projects are expensive and take time to be concretised. In the meantime, the optimisation of actual power plants' performance is an essential part in increasing revenue through improvement in efficiency of power plants.

The paper aims at evaluating the possibilities of improving the performance of thermal plants through typical cogeneration performance parameters like the cogeneration plant efficiency; the steam consumption and the heat-to-power ratio. Optimisation procedures can then be proposed to optimise existing bagasse-based cogeneration plants or to support design considerations of future plants in order to meet the increasing demand in electrical energy requirements; to promote independent power producers and to enhance the energy potential of bagasse. The objectives of the paper are to:

1) Investigate the effect of different plant parameters on electrical and thermal output, cogeneration plant efficiency, steam consumption and heat-to-power ratio

2) Evaluate steam optimisation potential,

3) Investigate the effect of temperature and pressure on cogeneration plant exergy,

4) Assess exhaust gas emissions from bagasse combustion at different operating conditions.

The main attribute of this research works as compared to other similar studies made in the past is that the focus is on performance analysis of cogeneration; optimisation of cogeneration systems and energy conversion and management

2.0 Optimisation of cogeneration plant

Cogeneration is the simultaneous production of electricity and heat from the same fuel source. The waste heat generated from the prime mover is collected through the heat recovery system and becomes useful energy that can be used for heating purposes. The concept of cogeneration itself goes back as far as the twentieth century when steam was the main source of power. Since 1957, cogeneration is exploited in Mauritius for its high energy saving potential and energy utilisation efficiency. The interest for cogeneration rose by late 1970s with the need to conserve energy resources.

Plants using back-pressure condensing type steam turbines with extraction and using bagasse as fuel source will be favoured. These plants correspond to local cogeneration systems. This review will also note the thermodynamic analysis and formulae, based on the laws of thermodynamics, used in previous works. The information obtained will be adapted to the optimisation of bagasse-based cogeneration in Mauritius.

. The research databases employed for the literature review includes handbooks, dissertation abstracts and online papers based on work done in the past twenty years..

The overall thermodynamic efficiency, which is among the most important optimisation features of this paper, was defined by as the ratio of the sum of power and thermal energy to the fuel input[1]. This definition is confirmed in various handbooks on cogeneration and thermodynamics including the handbook on *Applied Thermodynamics for Engineering Technologists* by Eastop and McConkey[2]. In this present paper, the same analysis used by Dan Turner in the handbook of *Efficiency and Renewable Energy*[1].will be adapted to steam turbines instead of gas turbines to correspond to the local cogeneration situation. However, instead of evaluating the effect of exhaust temperature on entropy, its effect will be evaluated on enthalpy change in order to relate directly to heat extraction. In the handbook of *Energy Efficiency and Renewable Energy*, Dan Turnerobtained an overall efficiency of 64% for a given case study. However, the main investigations in the handbook of *Energy Efficiency and Renewable Energy* were about gas turbine cogeneration systems and one of the analyses of exhaust gas turbine temperature as a function of entropy showed an increase in entropy with increasing exhaust temperature[1].

The paper *Efficiency Analysis of a Cogeneration and District Energy System*proposed an efficiency analysis of a case study in the city of Edmonton in Canada. Different configurations were considered and overall energy efficiencies of 83% to 94% were obtained[3].Exergy efficiencies of 28% to 29% were observed in the above-mentioned paper. The high overall efficiency values obtained in the paper on *Efficiency Analysis of a Cogeneration and District Energy System* are not expected for the present project since the above-mentioned paper was based on a large scale analysis and some concepts like the integration of single-effect and double-effect absorption chillers have been considered[3]. These factors may also account for the difference in efficiency values obtained between Dan Turner's analysis and the above-mentioned paper.

Sahin and Kodalproposed an interesting approach for optimisation of cogeneration. The study was started in 1957, continued in 1975 and published in 1999 in a book named *Recent Advances in Finite-Time Thermodynamics*[4].The technique used was to consider the cogeneration cycle to operate between three heat reservoirs at temperatures T_H, T_L and T_K. *Recent Advances in Finite-Time Thermodynamics* was mainly focused on the exergy performance of cogeneration systems and this approach will be used for cogeneration optimisation based on the second law of thermodynamics[4] . Furthermore, the constant of proportionality of 1.065 proposed by Ward between fuel exergy and Lower Heating Value of fuel will be used in the exergy destruction analysis[5].

The paper *Thermodynamic Performance Evaluation of Combustion Gas Turbine Cogeneration System with Reheat* written by Khaliq and Kaushik (2004) indicates an increase in the power-to-heat ratio and exergy but a decrease in first-law efficiency with an increase in steam pressure[6]. Reheat results in an increase in electrical and thermal power output, fuel utilisation efficiency and exergy. The methodology used by Khaliq and Kaushik in evaluating the influence of steam pressure on performance will be adapted to steam turbines in this project and additional parameters like temperature and steam consumption will be considered[6].

The technical support document named *Cogeneration Unit Efficiency Calculations* established a minimum efficiency standard that should be met by cogeneration units regardless of the fuel used. A minimum efficiency standard of 42.5% has been established based on calculations and standards of the Public Utility Regulatory Policy Act (PURPA). Furthermore, it states that in extraction or condensing case, the greater the steam flow, the greater the efficiency will be. The PURPA minimum efficiency standard of 42.5% for cogeneration units defined in *Cogeneration Unit Efficiency Calculations*will be used for the comparison of efficiencies calculated in this paper[7].

Various papers have been written by Deepchand relating to bagasse cogeneration in Mauritius. One paper from Deepchandentitled: *Sugar Cane Bagasse Energy Cogeneration – Lessons from Mauritius*, illustrated an increase of 234 GWh of electricity generated from bagasse cogeneration was observed in Mauritius from 1995 to 2004[8]. The aim of the paper was to further optimise the use of bagasse for electricity generation and export to the grid. Furthermore, investigations into the use of other fractions of the sugar cane biomass were proposed.

Another paper from Deepchand (2001)entitled: *Bagasse Based Cogeneration in Mauritius – A Model for Eastern and Southern Africa*,provided more detailed information on cogeneration plants in Mauritius. Schematic representations and surveys of various power plants including Union St. Aubin, Savannah and FUEL were proposed[9]. However, at the time the paper was published, the centralisation of the sugar industry was not yet considered.

In a note on *Sustainable Energy Regulation Network*, Dreepaul (2010) mentioned the possibility of increasing electricity generation from bagasse especially from older sugar factories that are not as efficient as newer technology[10]. He referred to boilers burning bagasse at lower pressures of 30 – 40bar compared to power plants burning bagasse at 80bar.

Somduth (1998), in a report entitled: *A Combined Heat and Power System at Mon Trésor Mon Désert*Sugar,obtained an increase in Rankine cycle efficiency of 1.9% on superheating the steam at the turbine entry[11]. The steam quality was improved by 3.5% and the steam consumption reduced from 5.821 kg/kWh to 5.183 kg/kWh. The calculations were based on first law of thermodynamics.

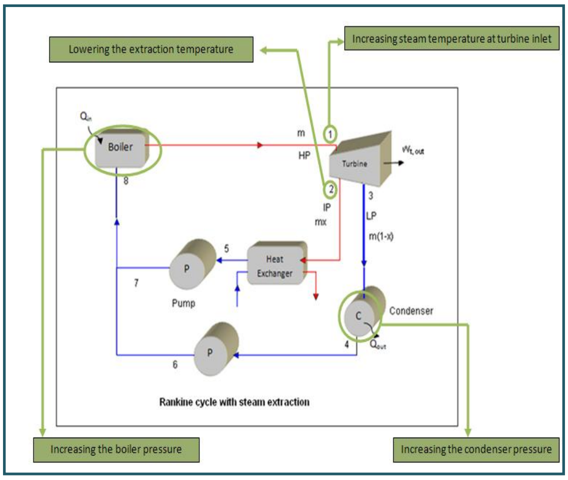

Figure 1. Schematic representation of the parameters evaluated.

Steam temperature and pressure as well as the moisture content of bagasse are altered and the plant performance parameters are evaluated accordingly and compared. The steam temperature at the turbine inlet is varied from 500°C to 600°C. Two scenarios are considered for this study:

Scenario 1: Extraction temperature is varied from 150°C to 135°C,

Scenario 2: Extraction temperature is varied from 150°C to 120°C.

The parameters for the first scenario are as follows: Steam temperature and pressure at turbine inlet of 500°C and 80bar respectively and an extraction pressure of 3bar. The parameters for second scenario are: Steam temperature and pressure at turbine inlet of 400°C and 40bar respectively and an extraction pressure of 2bar. The average moisture content of bagasse is taken as 48% with a net calorific value of 8,000kJ/kg. The steam to bagasse ratio is taken as 2.2[9]. The basic calculation of cogeneration plant efficiency is as follows:

Step 1: The thermal energy associated with the fuel input is calculated based on its Net Calorific Value (NCV).
Step 2: The electrical energy output is calculated.
Step 3: The net useful thermal energy is calculated.
Step 4: The cogeneration efficiency is determined as follows [12]):
Cogeneration efficiency, **n_c = (electrical output + thermal output) / fuel input**
Fuel input = mass flow rate of fuel x Net Calorific Value of fuel

Based on the above methodology, the plant efficiency is calculated for decreasing values of turbine exhaust temperature and increasing values of steam temperature at turbine inlet and boiler pressure.Exergy is a measure of quantity and quality of energy unlike energy which is based on quantity only. Many engineers and scientists suggest that thermodynamic performance is best evaluated by performing an exergy analysis in addition to or in place of conventional energy analysis[13].Exergy analysis uses the principles of conservation of mass and of energy together with the second law of thermodynamics. Based on calculations of specific enthalpies and entropies for case 1, the cogeneration exergy efficiency is calculated. The following governing equations have been used throughout the analysis.

$$W_{net} = \left(\dot{m}(h1 - h2) + \dot{m}(1 - x)(h2 - h3)\right) - \left(\dot{m}xv5(P7 - P5) + \dot{m}(1 - x)v4(P6 - P4)\right) \quad (1)$$

$$\text{Thermal output} = \dot{m}x(h2 - h5) \quad (2)$$

Where W_{net} is the net work output, $\dot{m}$ is the mass flow rate of steam, $h1$, $h2$, $h3$, $h5$ are specific enthalpies of steam at the turbine inlet, at extraction, at the turbine exit and at the exit of the heat exchanger respectively. x represents the fraction of steam extracted, $v5$ and $v4$ are specific volume of steam at the entry of the pumps while $P5$ and $P4$ represent the steam pressures. $P7$ and $P6$ represent the steam pressures at the exit of the pumps.

$$\Psi_{cogen} = (W_{net} + Ex_H) / Ex_{PF} \quad ($$

Where Ψ_{cogen} is the cogeneration exergy efficiency, W_{net} is the net work output, Ex_H is the heat exergy and Ex_{PF} represents the exergy input to the system.

$$Ex_H = x(h2 - h5) - To(s2 - s5) \quad (4)$$

$$Ex_{PF} = (h1 - h8) - To(s1 - s8) \quad (5)$$

Where $h8$ represents the specific enthalpy of steam at the entry of the boiler, $s1$, $s2$, $s5$, $s8$ are specific entropies of steam at the turbine inlet, at extraction, at the exit of the heat exchanger and at the entry of the boiler respectively, To is the dead state temperature. Figure 1 below is a schematic representation of the parameters that have been altered and evaluated throughout the research.

3.0 PLANT PARAMETERS UNDER STUDY

The parameters for the first scenario are as follows: Steam temperature and pressure at turbine inlet of 500°C and 80 bar respectively and an extraction pressure of 3 bar. The parameters for second scenario are: Steam temperature and pressure at turbine inlet of 400°C and 40 bar respectively and an extraction pressure of 2 bar. The average moisture content of bagasse is taken as 48% with a net calorific value of 8,000kJ/kg. The steam to bagasse ratio is taken as 2.2[9].

4.0 RESULTS AND DISCUSSION

4.1 INCREASING THE STEAM TEMPERATURE AT TURBINE INLET

The performance analysis of bagasse cogeneration based on the first law of thermodynamics and the above-mentioned governing equations leads to an average increase of 0.7% in electrical output per degree Celsius when the steam temperature at the turbine inlet is increased. Raising the steam temperature at the turbine inlet can be achieved by the use of higher pressure and temperature boilers, increasing the super heater temperature within the super heater tubes temperature ratings and by minimising losses between the boiler, the super heater and the turbine. Increasing the superheated steam temperature also results in a better quality of dry steam due to an increase in its dryness fraction. The graph below illustrates the increase in electrical and thermal output against an increase in the steam temperature at the turbine inlet.

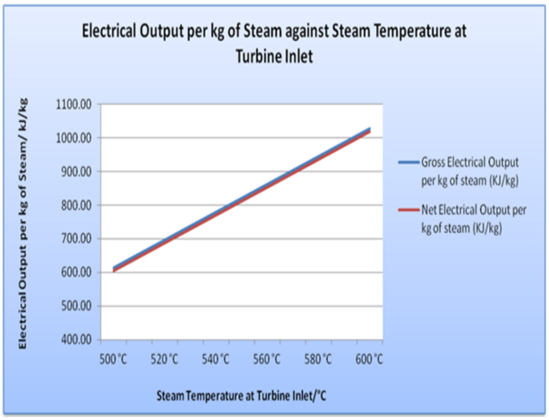

Figure2. Electrical output against steam temperature at turbine inlet.

Consequently,an increase of 0.1% in the plant efficiency per degree Celsius increase in steam temperature at turbine inlet is observed.The variation of plant efficiency against steam temperature at the turbine inlet is illustrated in figure 3.

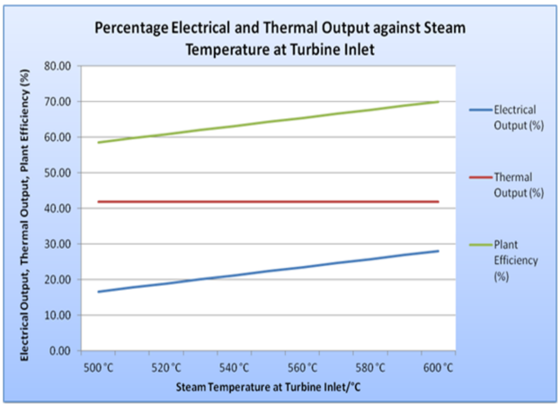

Figure3. Plant efficiency against steam temperature at turbine inlet.

Furthermore, the heat-to-power ratio decreases by 0.4% per degree Celsius increase in steam temperature at the turbine inlet.The following graph illustrates the decrease in heat-to-power ratio. Since the major desired output of topping systems is to generate electricity, higher heat-to-power ratio, that is, higher potential for electricity generation should be favoured for these systems. Therefore, in such cases, raising the steam temperature and pressure at the turbine inlet is recommended for the considerable decrease in heat-to-power ratio obtained.

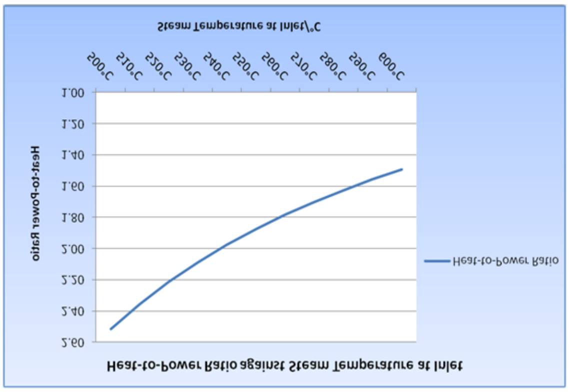

Figure4. Heat-to-power ratio against steam temperature at turbine inlet.

The specific steam consumption decreases by 0.4% per degree Celsius increase in superheated temperature at the turbine inlet. The specific steam consumption is defined as the steam flow developing unit power output[2]. It is an important criterion of plant performance since it relates directly to the amount of steam required to generate power. The lower the specific steam consumption, the lower will be the amount of steam required for power generation. The graph in figure 5 represents the decrease in specific steam consumption while increasing the steam temperature at the turbine inlet.

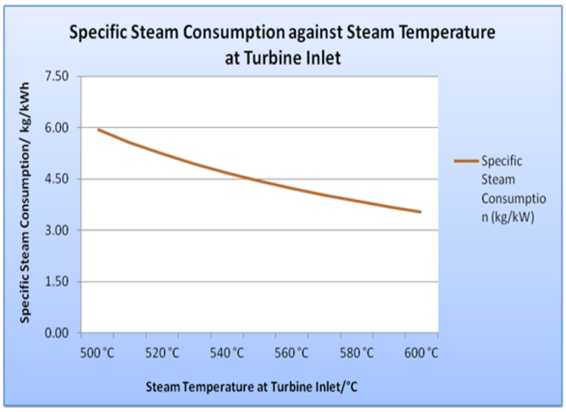

Figure5. Specific steam consumption against steam temperature at turbine inlet.

Upon increasing the steam temperature at turbine inlet, the second law analysis leads to an increase of 3% in the cogeneration exergy efficiency. The higher the exergy efficiency the lower is the carbon dioxide emission. The following graph shows the corresponding increase in cogeneration exergy efficiency.

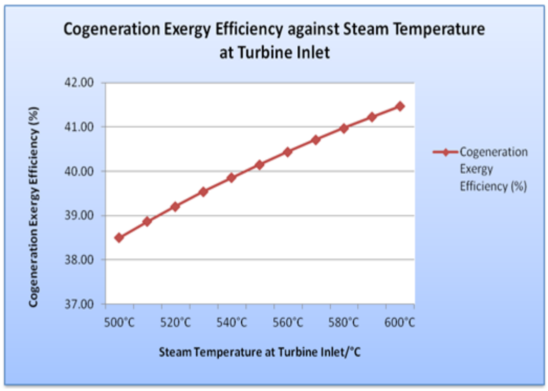

Figure6. Cogeneration exergy efficiency against steam temperature at turbine inlet.

4.2 REDUCING THE STEAM TEMPERATURE AT EXTRACTION

Upon decreasing the steam temperature at extraction, an average increase of 0.1% in electrical output is obtained per degree Celsius. However, the extraction temperature is limited by the temperature required for the thermal processes, taking into account heat loss. Another main limitation is the saturation temperature of steam. This temperature limit is responsible for the low increase in overall work output obtained for scenarios 1 and 2. The following graphs illustrate the increase in electrical output against extraction temperature for both cases.

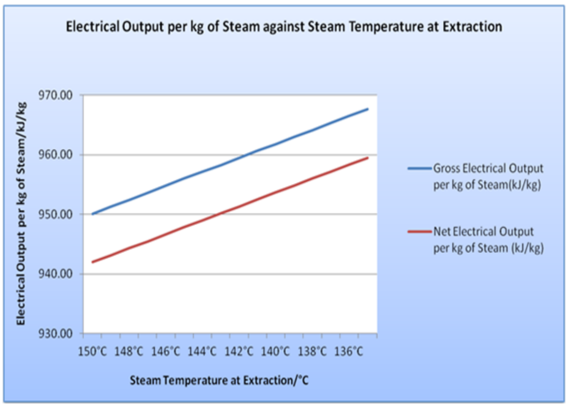

Figure7. Electrical output against steam temperature at extraction for scenario 1

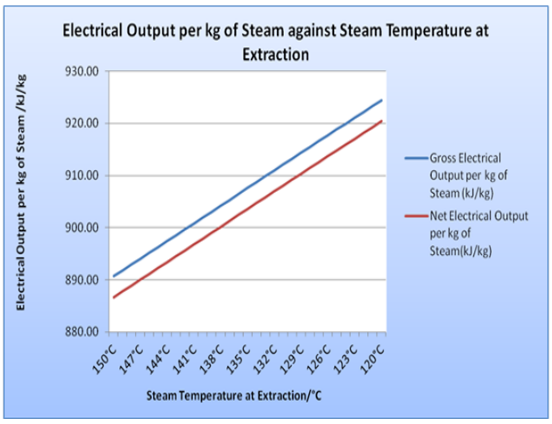

Figure8. Electrical output against steam temperature at extraction for scenario 2.

When the extraction temperature is lowered, the cogeneration exergy efficiency increases. An increase of 0.5% is observed upon lowering the extraction temperature from 150°C to 135°C. The exergy efficiency is lower than the energy efficiency. The increase in cogeneration exergy efficiency is illustrated in figure 9.

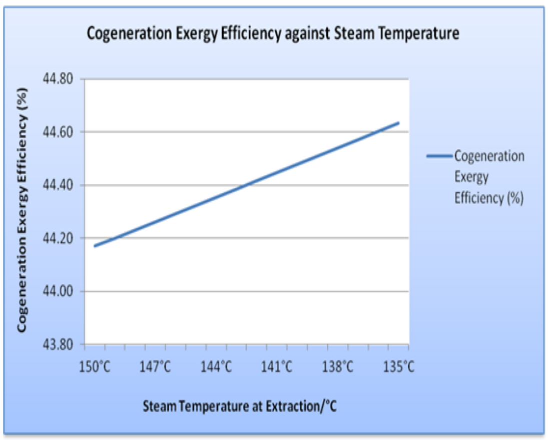

Figure9. Cogeneration exergy efficiency against steam temperature at extraction.

4.3 INCREASING THE BOILER PRESSURE

Increasing the pressure of the live steam will result in an increase in overall efficiency.However,the pressure is limited by the pressure the boiler and tubing network can withstand and eachturbine is designed for a specific steam inlet pressure. Upgrading the boiler to a high-pressure boiler is a common alternative but it implies large investment. The most economically appropriate solution would be to maintain the steam inlet pressure as close as possible to the design pressure such as to reach design efficiency. Initially, the pressure and temperature at the boiler was of 80bar and 500°C respectively, but when the system was operated at a pressure of 85bar and a temperature of 525°C, which correspond to the design pressure and temperature, an increase in the plant efficiency of 4.4% was obtained. Figure 10 illustrates an increase in the plant efficiency when the system is operated at conditions closer to design conditions.

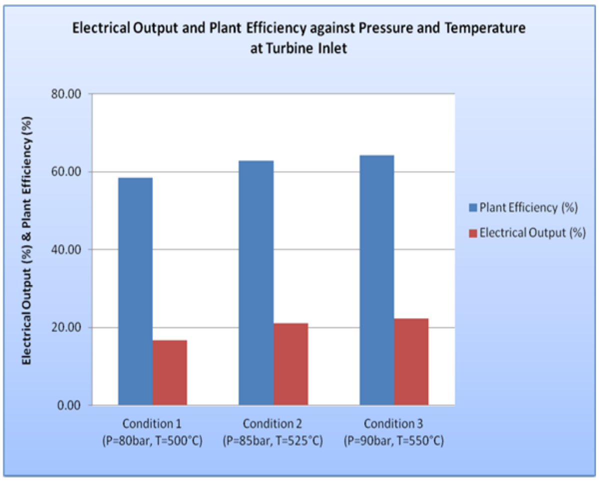

Figure10. Plant efficiency against steam pressure at turbine inlet.

Moreover, a decrease in the heat-to-power ratio is observed when the system is operated at conditions closer to design conditions. From condition 1, that is, at an operating pressure of 80bar and temperature of 500°C to condition 2, which corresponds to an operating pressure of 85bar and temperature of 525°C, a reduction of 21% in the heat-to-power ratio is obtained. The variation of the heat-to-power ratio at three different operating conditions is illustrated in the following chart.

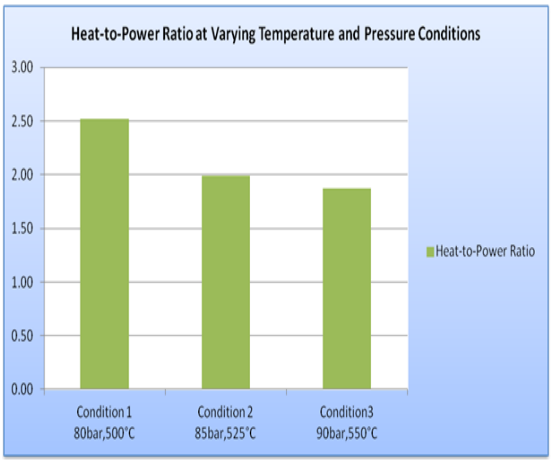

Figure11. Heat-to-power ratio against steam pressure at turbine inlet.

Furthermore, upon operation of the system at conditions closer to design condition, a decrease in the steam consumption is observed. From condition 1 to condition 2, a reduction in the specific steam consumption from 5.95 kg/kWh to 4.71 kg/kWh is observed. The following chart illustrates the drop in specific steam consumption against increasing boiler pressure and temperature.

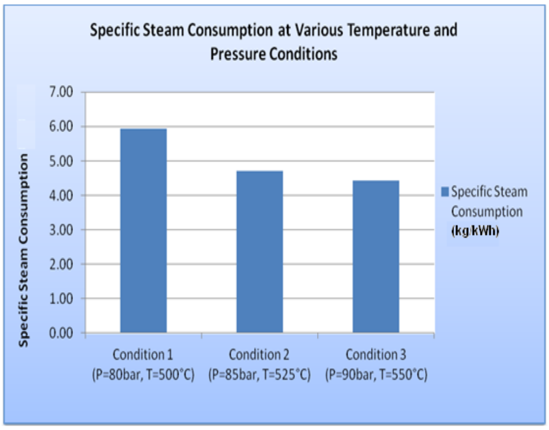

Figure12. Specific steam consumption against steam pressure at turbine inlet.

4.4 OPPORTUNITIES FOR STEAM RECOVERY

In addition to the reduction in steam consumption through the variation of temperature and pressure at the various steam points illustrated and explained above, steam recovery is an effective method of reducing steam consumption through the re-use of steam. A typical example of steam recovery appropriate for sugar mills is heat recovery from hot condensate. For instance, the evaporator and vacuum pans release hot condensate which can be used to heat part of the cane juice instead of extracting steam from a back-pressure condensing-type steam turbine, which corresponds to most cases in Mauritius. Condensate heat recovered from evaporators and vacuum pans, which require large amount of steam, being supplied to juice heaters can hence, result in a decrease in steam consumption.

Flash steam recovery is another mean of recovering steam and reducing steam consumption. Flash steam is formed from the discharged of hot condensate at a higher pressure into a lower pressure area. At the reduced pressure of the vessel, water tends to reduce its temperature and its heat content and hence, heat is released. The latent heat is absorbed and causes some of the condensate to flash into steam. Therefore, flash steam is a valuable source of heat which can be exploited for thermal processes. An example of flash steam recovery in sugar mills is the collection of flash steam from the evaporator in a flash tank and the use of the recovered steam to heat water supplied to the re-heater.

Another mean of reducing steam consumption is through the use of falling film evaporators. The juice flow velocity and heat transfer coefficient are higher and hence, and the possibility of having a high temperature condensate, with lower temperature difference, enhances the opportunity of pre-heating of juice. Hence, the steam consumption for the heating of juice decreases. In other words, replacing typical evaporators by falling film evaporators contributes to energy savings.

Furthermore, studies demonstrated that the use of continuous vacuum pans instead of discontinuous pans results in a reduction in steam consumption. For instance, continuous vacuum pans, compared to discontinuous pans where massecuite is boiled in stages one batch at a time, are known for their lower steam consumption and constant steam load (Ogden J.M *et al.*,1990).

4.5 EXERGY ANALYSIS

Exergy is a measure of quantity and quality of energy unlike energy which is based on quantity only. Many engineers and scientists suggest that thermodynamic performance is best evaluated by performing an exergy analysis in addition to or in place of conventional energy analysis[13]. Exergy analysis uses the principles of conservation of mass and of energy together with the second law of thermodynamics.

Total exergy per unit mass = (physical + kinetic + potential + chemical) exergy[2].

$$e_T = e_{PH} + e_K + e_P + e_{CH}$$
$$= (h1 - h_0) - T_0\,(s1 - s_0) + \tfrac{1}{2} V^2 + gh + E_{CH} \qquad (6)$$

Where:

e: specific exergy (kJ/kg)

V: specific velocity (m/s)

h: specific enthalpy (kJ/kg)

g: acceleration due to gravity (m/s²)

s: specific entropy (kJ/kg K)

h: height (m)

T_0: Ambient temperature (K)

Based on calculations of specific enthalpies and entropies for case 1 described, the cogeneration exergy efficiency can be calculated. Using the source-sink exergy model for steady-flow and considering only physical exergies, the following equations can be applied:

Cogeneration exergy efficiency = $\Psi_{cogen} = (W_{net} + Ex_H) / Ex_{PF}$ (7)

Where:

Exergy input to system, $Ex_{PF} = (h1 - h8) - T_0\,(s1 - s8)$ (8)

Net workoutput, $W_{net} = W_{Turbine} - W_{pump}$ (9)

Heat exergy, $Ex_H = x\,[(h2 - h5) - T_0\,(s2 - s5)]$ (10)

When the steam temperature at extraction is lowered, the cogeneration exergy efficiency increases. An increase of 0.5% is observed between when the extraction temperature is lowered from 150°C to 135°C. The increase in exergy efficiency is illustrated in the following graph in figure 13.

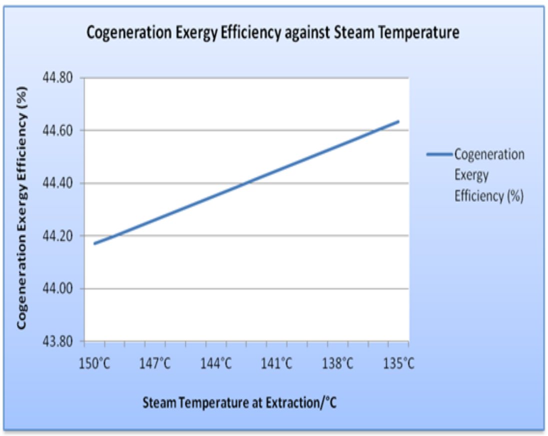

Figure13. Graph of cogeneration exergy efficiency against steam temperature at extraction.

Furthermore, the cogeneration exergy efficiency increases by 3% upon increasing the steam temperature at the turbine inlet from 500°C to 600°C.The following graph shows the relationship between cogeneration exergy efficiency and steam temperature at the turbine inlet.

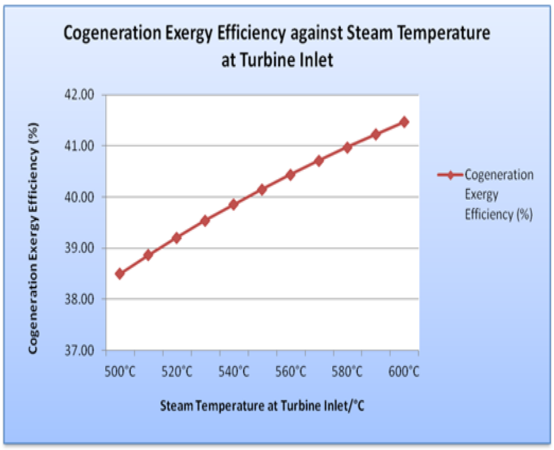

Figure14. Graph of cogeneration exergy efficiency against steam temperature at turbine inlet.

Conversely to exergy analysis, the exergy destruction analysis is based on the individual assessment of each components of the system in order to identify the components causing the largest exergy loss.The exergy destruction can be calculated for each component of the cogeneration plant if appropriate data is available. However, in this paper, the exergy destruction in three components, namely the turbine, boiler and condenser, has been calculated and compared.The source-sink approach is used together with the following assumptions:

1. The cogeneration system operates in steady state steady flow.
2. The dead state temperature of air, T_0, is 25°C.
3. Kinetic and potential exergies are negligible.
4. The Low Heating Value (LHV) of bagasse with 48% moisture content is 7750 kJ/kg.
5. The proportionality constant between fuel exergy and LHV is 1.065[5].

The mass flow rate of steam and bleed steam are taken as 175t/h and 140t/h respectively. Bagasse flow rate is 78,800kg/h (2005). Figure 15 illustrates the exergy of source and exergy destruction calculated for the turbine, the boiler and the condenser.

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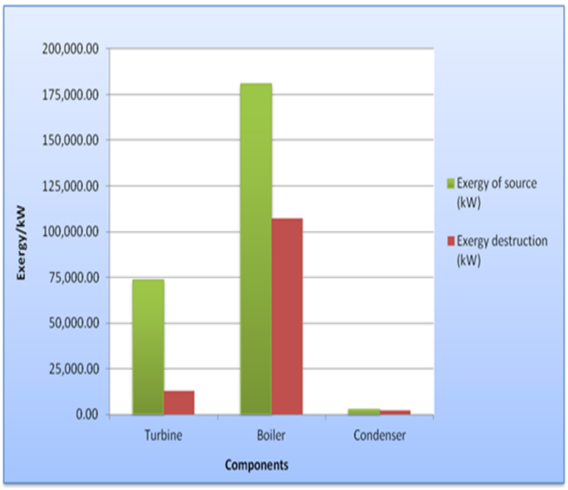

Figure15. Exergy of source and exergy destruction of different components.

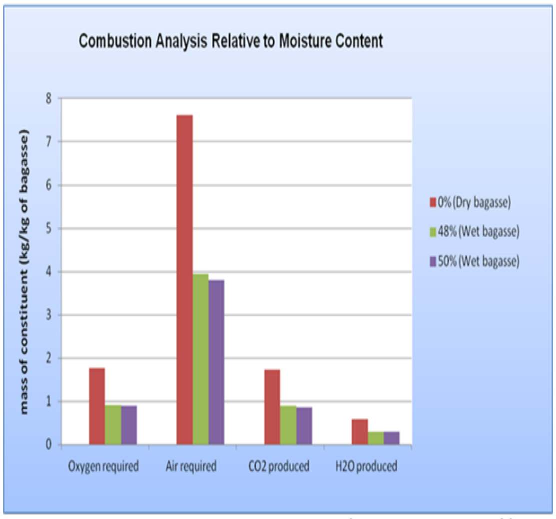

Figure16. Combustion analysis of bagasse at different moisture content.

The relatively low exergy destruction, of 17.4% calculated for the turbine, demonstrates a highexergy efficiency of this component.Conversely, high exergy destruction, of 87.3%, occurs in the condenser as compared to the exergy supplied to the mentioned-component. It suggests that improvements should be done mainly in this component in order to increase the overall plant exergy efficiency.

4.6 EXHAUST GAS ANALYSIS

The moisture content of bagasse affects the amount of air required for the combustion and the carbon dioxide emission. The higher the moisture content, the lower is the amount of air required and the carbon dioxide released upon combustion of bagasse. The moisture content of local bagasse varies between 45% and 52% depending on the quality of milling[8]. At higher moisture content, the amount of air required and carbon dioxide emission decreases. The following chart illustrates the variation in oxygen required and carbon dioxide released at varying moisture content assuming complete combustion of carbon and an oxygen-content of 23.3% of air[2].

However, increasing the moisture content of bagasse will have an adverse impact on the boiler efficiency, as well as the overall plant efficiency, since the moisture content influences the calorific value of bagasse.Therefore, other alternatives like the use of electrostatic precipitators can reduce the carbon dioxide emission without affecting the cogeneration plant efficiency.

Another parameter to be considered in considering exhaust gas emission is the flue gas ejection velocity. Flue gas dispersion can be estimated by complex equations and dispersion modelling that will not be covered in this paper. However, it is obvious that the dispersion of flue gas will be influence by the gas ejection velocity and emission flow rate in addition to the height of stack, temperature of effluent and meteorological conditions. Most of these parameters are either fixed parameters or uncontrolled parameters. The only parameter that can be controlled is the flue gas ejection velocity. It can be increased by the use of additional blowers in order to enhance the dispersion of carbon dioxidein the atmosphere. Since local cogeneration plants also involve the combustion of coal during intercrop season, the flue gas ejection velocity should not be less than 20 m/s for optimum dispersion and desulphurisation of sulphur dioxide, a product of combustion of coal.

In the cane industry, uncontrolled burning occurs during the burning of sugarcane before harvesting and Methane gas, CH_4, is produced by the uncontrolled burning and natural anaerobic decay of bagasse. Its contribution to global climate change is not negligible. Uncontrolled burning of bagasse is not covered in this paper. However, methane emission from trash decay can be reduced by reducing the amount of trash. This can be achieved by using cane trash in addition to bagasse for additional electricity generation.

5.0 CONCLUSION

The gain in electrical efficiency is indisputable in lowering extraction temperature, even though the cogeneration efficiency remains nearly unchanged due to the quasi-equivalent decrease in thermal output to increase in electrical output. Furthermore, the limit in reducing steam temperature at extraction is set by the saturation temperature of steam at the operating pressure and the temperature requirement of the thermal processes as well as heat losses.

Upon increasing the steam temperature at the turbine inlet, the cogeneration plant efficiency increases by 11.4% directly due to an increase in electrical efficiency. The thermal output remains nearly constant since the temperature change has no direct incidence on the enthalpy change in the heat recovery unit. The increase in boiler operating pressure to a condition close to the design condition results in an increase of 4% in cogeneration plant efficiency and a reduction of 21% in the heat-to-power ratio. This demonstrates the higher power than heat generation potential of this procedure.

The maximum decrease in specific steam consumption is observed upon increasing the steam temperature at the turbine inlet. The lower specific steam consumption is explained by the higher heat extraction from the turbine at higher inlet temperatures.

Only 0.5% increase in exergy efficiency has been obtained by decreasing steam temperature at extraction and 3% increase by raising steam temperature at the turbine inlet. The higher the exergy, the lower will be the carbon dioxide emission. The investigation leads to the conclusion that increasing the steam temperature and pressure at the turbine inlet has a better impact on plant performance and steam consumption as compared to decreasing the steam temperature at extraction. In addition, the reduction of condenser pressure leads to even higher cogeneration efficiency. Furthermore, the increase in the heat-to-power ratio indicates a higher potential to generate electricity rather than thermal output, which makes this alternative more suitable to topping systems where the major aim is the generation of electricity.

Also, the exergy efficiency increases by increasing the steam temperature at the turbine inlet as well as by decreasing the steam temperature at extraction. However, higher exergy efficiencies were observed by reducing the extraction temperature. The relationship between exergy destruction and entropy can be an explanation for this observation since this alternative implies lower entropy changes. Hence, it is the most effective process based on wasting as little work as possible from the given input. In all the alternatives evaluated, the exergy efficiency was lower than the first law efficiency since thermal energy cannot be completely converted to work.

Maximum benefits can be achieved from cogeneration optimisation for existing and future bagasse cogeneration plants in increasing plant performance and resource utilisation.

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