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A Waste Heat Recovery Steam Power Generation System. A Case Study of Jabana II Power Plant Station in Rwanda

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Abstract

The increasingly worldwide problem regarding rapid economy development and a relative shortage of energy, the internal combustion engine exhaust waste heat and environmental pollution has been more emphasized heavily recently. Out of the total heat supplied to the engine in the form of fuel, approximately, 30 to 40% is converted into useful mechanical work; the remaining heat is expelled to the environment through exhaust gases and engine cooling systems, resulting into entropy rise and serious environmental pollution, so it is required to utilize waste heat into useful work. The recovery and utilization of waste heat not only conserves fuel but also reduces the amount of waste heat and greenhouse gases damped to environment. The study shows the availability and possibility of waste heat from internal combustion engine, also describe loss of exhaust gas energy of an internal combustion engine. Possible methods to recover the waste heat from internal combustion engine and performance and emissions of the internal combustion engine. Waste heat recovery system is the best way to recover waste heat and saving the fuel.

Key words:Waste Heat Recovery Steam, Power Generation, Power Plant, JabanaII, Kigali, Rwanda.

1. General Overview

Jabana II thermal Power Plant is a Government Power Plant in Rwanda commissioned in 2009 with a capacity of 20.5MW net electrical power output, supplying electricity to the national grid with a minimum guaranteed energy amount of 180072MW per year, which is equivalent to nearly 8784 hours per year of full load operation. The Power Plant is equipped with 3 Wartsila18V32 engines running on heavy fuel oil, each with a rated power capacity of 7.0 MW; and the generated electricity is supplied to national grid station via 110KV transmission line. The entire operations and maintenance work of power plant is carried out with local expertise under ISO 9001:2008, ISO 14001:2004,OHSAS 18001:2007 management systems and industrial housekeeping standard.

The overall efficiency of the energy conversion typically falls below 42% with much of the energy lost as waste heat taken away by the exhaust gas and sunk by the other waste heat flow streams of the turbocharged Wartsila 18V32 engines. In an attempt to recover waste heat, we need install three numbers of thermal oil boilers operated with waste heat recovery from the exhaust gas of three engines units and the recovered heat is used for process heating of heavy fuel oil with the purpose of additional electricity generation by a steam cycle, and selecting a suitable standard steam turbine according to heat estimated recovery capacity.

By considering climate change, which becoming more unpredictable due to global warming. Rwanda focuses on thermal electricity generation in order to sustain the national electricity grid especially during dry seasons. The country is 100% dependent on expensive imported heavy fuel to be used for thermal power generation as alternative to the locally available hydro power.

Therefore, it is of vital importance that the thermal power plants of Rwanda make the most out of the imported energy sources of fuel. At the same time, protecting the environment as much as possible, by reducing greenhouse gases emissions which is very indispensable recently.

The first aim is to enhance the overall efficiency of fuel utilization through optimized waste heat recovery for electricity generation by a steam bottoming cycle, thus also minimizing the release of rejected heat to the environment.

During normal full load running conditions one Wartsila 18V32 engine emits heated exhaust gas at 350^0c to 450^0c with a mass flow rate of 16.14 kg/sec. It was estimated that the energy waste due to current practice is approximately 11317.2066MJ/h of operation as thermal energy lost to the environment with the hot exhaust gas, which corresponds to a 1330KW thermal load of rejected heat just by the exhaust gases per each engine unit.

This study completely disregarded any possibilities for waste heat utilization from other available low temperature waste heat streams from the engines such as:

- Jacket HT circuit
- Charge air HT circuit
- Charge air LT circuit
- Lube oil LT circuit
- Radiation due to the clearly expressed unwillingness of the Jabana II plant management to consider any feasible investment options other than high temperature heat recovery from exhaust gas only.

The aim of this work is to put in place a study and to investigate the possibility of increasing the energy efficiency of Jabana thermal power plant by suitably utilizing the waste heat of the exhaust gases produced by three of the engine units, which is at present directly exhausted to the environment.

The objective of the study is to model a heat recovery steam generator and chose suitable and a matching commercially available steam turbine in order to improve the performance of the thermal power plant by optimizing the waste heat recovery from the exhaust gas streams of the available HFO fired medium speed four stroke Diesel engines. Additional power would be generated by a technically and economically optimum solution in the form of a steam bottoming cycle.

2. Heat Exchanger Design Methodology

The heat exchangers will be purchased from the market. They will then be fitted into the exhaust system of the engine and experiments will conduct to estimate the additional power conceivable with this setup. As these heat exchangers were not optimized for this particular application, attempts were made to design heat exchangers that can achieve maximum additional power. Simulation tools were used to simulate the current heat exchangers using experimental data. After acquiring adequate agreement of simulation results with the experimental results, the effects of important parameters of heat exchanger such as length, diameter of the shell, number and diameter of tubes on the performance of the heat exchangers will be investigated. The potential additional power was then calculated using actual turbine efficiency. As steam expands in turbines, the steam in this application needed to be super-heated. Therefore, two heat exchangers were used: one heat exchanger was used to generate vapor from the liquid namely vapor generator and the second heat exchanger was used to generate superheated vapor namely super heater.

3. Waste heat recovery potential calculation for W18V32

According to the exhaust gas temperature diagram of W18V32, the average temperature is 437^0C.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	B8	B9
Temperature	435	446	414	448	470	388	449	458	459	417	458	431	410	440	420	447	442	434
Deviation	-2	8	-23	11	33	-49	12	21	22	-20	21	-6	-27	3	-17	9	5	-3

Active power 6861 kW
Engine speed 744 rpm

Fig3.1: Average temperature of W18V32 at full load condition

Considering the average temperature of Wartsila 18V32 engine at full load, it can be practically used for effective recovery of waste heat from exhaust gas by any type of a waste heat boiler unit.

W18V32 engine waste heat estimation

In the internal combustion engine, most of the energy in the fuel burned is lost in the environment as waste heat (exhaust gases) without contributing to the productivity of the engine. In principle some of this lost energy could be captured and used to increase the engine's fuel efficiency by fitting a waste heat recovery system.

W18V32 is an internal combustion engine running with Heavy fuel oil

- LHV is the Lower heating value of HFO.

$$= \quad . \quad /$$

- Fuel oil flow supplied the engine (recorded from operation, engine at full load.
- $mf = 1452\ Kg/h$

The heat energy expected to be generated by combustion in three W18V32 can be calculated as follow:

$$Qf = 3 \times mf\ \times LHV \text{ .... } (1)$$

$$Qf = 3 \times 1452 \times 41.01 = 178,639.56 \frac{}{}$$

$$= \quad .$$

The total energy loss

$$Ql_{tot} = Qf - Qe \text{ .... } (2)$$

Where is the electrical energy output of three W18V32

$=\quad .$ *Running at 6.9MW each engine

$$Ql_{tot} = 49.623 - 20.7 = 28.923\ MW$$

The efficiency of the power plant

$$= \frac{Qe}{} \times 100 \text{ .... } (3)$$

$$\eta_{pp} = \frac{.}{49.623} \times 100 = 41.71\%$$

In medium internal combustion engines, heat energy is lost to the environment without useful work in the forms of :(see Appendice2)

Table3.1 :Wartsila 18V32 technical Data.

Loss of energy	**Value for W18V32 in KW**
Exhaust gas	-
ENERGY BALANCE	
Jacket HT water circuit	1512
Charge air HT water circuit	1440
Charge air LT water circuit	1193
Lube oil, LT water circuit	1091
Radiation	260
Total of energy balance losses per one engine	**5496**

Knowing the total energy lost from heat balance $\boldsymbol{Ql_{hb} = 3 \times 5.496 = 16.488\ MW}$, we can compute the total energy that is wasted to the environment through exhaust gases by:

$$\boldsymbol{Ql_{Exh} = Ql_{tot} - Ql_{hb}} \quad \textbf{... (4)}$$

$$\boldsymbol{Ql_{Exh} = 28.923 - 16.488 = 12.435MW}$$

Theoretically, the recoverable heat energy for three W18V32 when running at full load can be estimated as follow.

$$= \frac{\boldsymbol{Ql_{Exh}}}{} \times 100 \quad \text{... (5)}$$

$$Q_{rec} = \frac{12.435}{49.623} \times 100 = \mathbf{25.05\%}$$

4. Modeling of HRSG

4.1 HRSG Temperature profile and steam generation

The starting point for determining gas and steam temperature profile and steam generation is the assumption of pinch an approach points, as discussed above. The value that are known are gas flow rate (m_g), gas temperature at HRSG inlet (tg1), feed water temperature (tw1), temperature of steam leaving the superheater (ts2), and steam pressure (ps). Assuming a reasonable pressure drop in the superheater, we can determine the saturation temperature (ts) at the evaporator. Once the pinch point is selected, we know the temperature of the gas leaving the evaporator (tg3) and the approach point gives the temperature of the water leaving the economizer (tw2), since the saturation temperature is known. For typical unfired HRSG hardware that can be built and shipped economically in terms of size and complexity, both the pinch and approach point temperature difference vary between7°C to 25°C, usually.

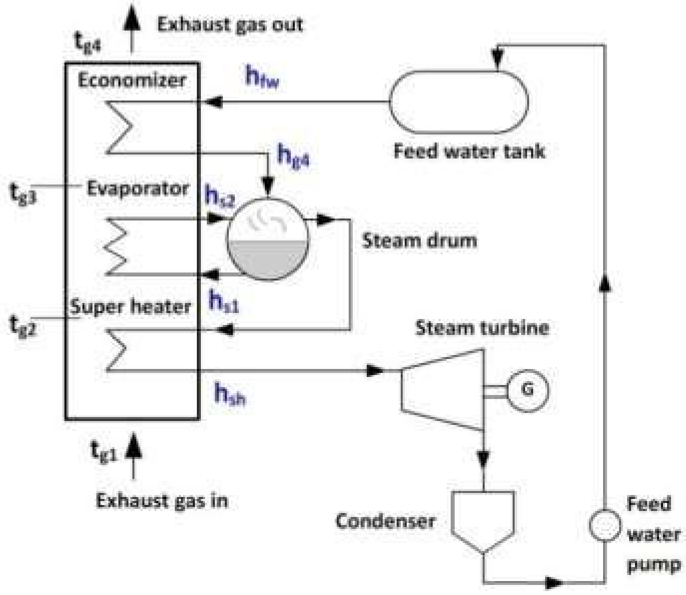

Fig4.1: Temperature and steam generation

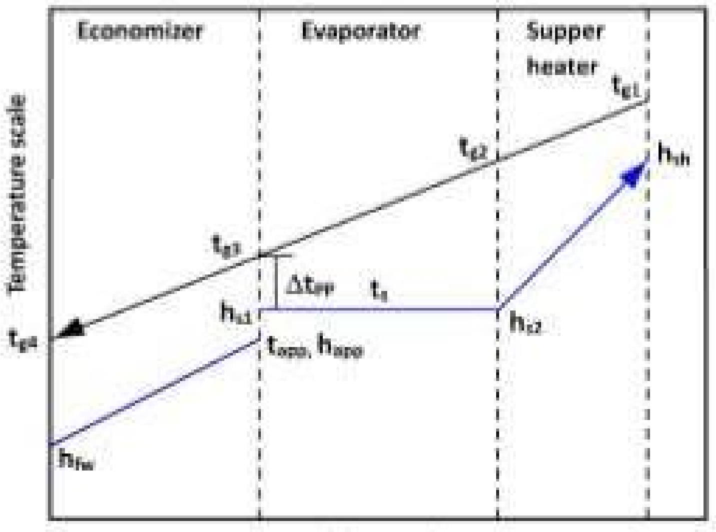

Fig 4.2: Temperature profile

4.2 Optimization of heat recovery steam generator

1. HRSG parameters

Known are the parameters for exhaust gas of three Wartsila 18V32 engines when operating at full load,

- ✓ Exhaust gas flow rate ($\mathbf{m_g}$) = 48.42 Kg/s
- ✓ Exhaust gas input temperature ($\mathbf{tg_1}$) = 437°C

To optimize the suitable heat recovery steam generator, the following parameters were assumed for calculations

- ✓ Inlet steam: superheated at 30 bar and 400°C
- ✓ Condenser pressure: 0.2 bar
- ✓ Steam turbine power output (P_{st}): 2.5 MW
- ✓ Mechanical efficiency of steam turbine (η_m): 0.98
- ✓ Approach temperature of the HRSG: 10°C
- ✓ Heat losses of the HRSG: 2%

The pinch point temperature difference, Δtpp:

$$\Delta tpp = Tg3 - Ts \quad \text{.......} \quad (6)$$

Ts, is found saturation tables for water/steam at pressure of 30 bar @ 400 °C

$$= 233.85$$

The mass flow rate of the steam can be found,

$Pst = mst\ (s \quad - out\ )\eta m$ …………………………………………………… (7)

Where,

$=$

$=$

$=$

$=$

$=$

From steam saturation and superheated tables,

$= 3231.7\ —$

$1 = 2357.5\ \_\_$

$= 2608.9\ —\ (@ \qquad 0.2 \quad)$

$= \frac{251.42}{}$

Now, $2500 = mst(3231.7 - 2608.9)$

$$= 4 \quad /$$

To determine the value of Tg3, we use this heat balance formula

$mg \times cp \times (Tg1 - Tg3) = mst\ (s \quad - app\ )$………………………………………… (8)

With $app \quad = cp(water) \times (Ts - Tapp) = 4.187 \times (233.85 - 10) = 937.25\ kj/kg$

For Tg3,

$$16.14 \times 3 \times 1.05 \times (437 - Tg3) = 4 \times (3231.7 - 937.25)$$

$3 = 256.4$

$\Delta tpp = Tg3 - Ts = 256.4 - 233.85 = \mathbf{22.55oC}$

For Tg4,

$mg \times cp \times (Tg1 - Tg4) \times (1 - l\ ) = mst \times (s \quad - fw\ )$ …………………………… (9)

$$16.14 \times 3 \times 1.05 \times 0.98 \times (437 - Tg4) = 4 \times (3231.7 - 251.42)$$

$$4 = \quad .$$

$$Qg = mg \times cp \times (Tg1 - Tg4) \ldots\ldots \text{(10)}$$

$$Qg = 16.14 \times 3 \times 1.05 \times 3600 \times (437 - 197.75)$$

$$= 43789353.3 \quad /$$

$$Qrec = \frac{Qg}{} \times 100 \ldots\ldots \text{(11)}$$

$$= \frac{43789353.3}{178639560} \times 100 = \mathbf{24.5\%}$$

4.3 Selection of steam turbine

Considering the average temperature and exhaust masse flow rate of Wartsila Engine W18V32 at full load condition and after selecting the HRSG able to produce needed steam to recover the lost energy in exhaust system, the back pressure steam turbine-model B1.6~B3 was selected as suitable steam turbine at Jabana Thermal Power Plant. (See Appendice5).The steam turbine power output is 2.5MW at steam inlet pressure of 30bar and condenser pressure of 0.2bar.

5. Summary & Conclusions

The deregulation of electric power market has introduced a strong element of competition. To meet this challenge, power plant operators must strive to develop advanced operational strategies to minimize the profitability in dynamic electric power market. The objective of this research is to identify if there are large potentials of energy savings through the use of waste heat recovery technologies from Warstila engines at Jabana Thermal power plant. Waste heat recovery defines capturing and reusing the waste heat from internal combustion engine for heating, generating mechanical or electrical work and refrigeration system. It would also help to recognize the improvement in performance and emissions of the engine. In this regard, the HRSG is the main and the most important component for generating steam used for driving steam turbine or in heat services. The selection of HRSG should be based on the concept of pinch point approach point that specify the temperature profile of fuel gas, water and steam. The pinch point is difference between the gas temperature leaving the evaporator and saturated steam. The approach point is the difference between the temperature of saturated steam and the temperature of the water entering the evaporator. Pinch and approach point affect both thermodynamic and economic view points of the HRSG optimization. The aim in introducing the pinch point temperature difference into HRSG designs is to avoid a temperature cross situation.A temperature cross situation results when part of the economizer and part of the evaporator virtually heat the exhaust gas which is thermodynamically impossible.

The total energy from fuel at Jabana power plant is 49.623MW =178642.8MJ/h which is 100% of total energy without loss. The total energy is 28.923MW = 104122.8MJ/h and the lost energy through exhaust gas only is 12.435Mw = 44766MJ/h which is 25% of total energy from fuel per hour. The 44766MJ/h is the estimated theoretical power output without any loss into environment which is practically impossible because there is a gas that can never be covered going into the atmosphere. The approach point selected is 10°C to avoid the temperature cross situation and the maximum practical power output of steam cycle is 2.5 MW for that, the recoverable energy from selected steam turbine is 9000MJ/h equal to 20.1% of total energy in fuel gas in power plant.

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