Utilization of Exhaust Gas Diesel Power Generation for Micro Turbine Organic Rankine Cycle (ORC)

Harry Indrawan¹ and Almas Aprilana¹

1 PT PLN (Persero) Research Institute, Jl. Duren Tiga 102, Jakarta 12760, Indonesia
E-mail: harry.indrawan@pln.co.id

Abstract. This study aims to study the reuse of heat from exhaust gas diesel by using micro turbine ORC to improve thermal efficiency of diesel. The methodology undertaken is as follows: conducting studies on heat exhaust potential, conduct a study of environmental conditions (dry and wet air temperature, availability of water source enhancer), design of working fluid thermodynamically appropriate to use and heating fluid type.

The results of the discussion and analysis obtained the following conclusions: the study of the utilization of exhaust gas Diesel Power Generation micro turbine takes place in Lombok. From field survey results and optimization results of available space in unit 2 & 3 engine configuration and or engine configuration of units 5 & 6 which will be utilized exhaust gas for generator micro turbine ORC; in this study it has been determined that the design of ORC to generate 100 kW electrical energy and will be used for its own use; system design has 2 alternative system design which are simple ORC and ORC with recuperator; 4 alternative working fluids are n-butane, n-pentane, R-134a and R-245fa; 4 thermal fluid alternatives are hot water, saturated steam, Dowtherm A and Thermo XT 32; based on simulation results to generate 100 kW electrical energy with the above design alternatives obtained optimal conditions on ORC system with recuperator, n-pentane working fluid, thermal fluid Thermo XT 32, with heat and mass balance model as follows; thermal efficiency 11.81%, mass flowrate n-pentane 1.92 kg / s and Thermo XT mass flowrate 3.67 kg / s and turbine inlet temperature 160°C.

1. Introduction
Diesel Generator is a power station where the electric generator drive is a Diesel motor. The energy equilibrium in Diesel motor generally ranges from 37.5% with cooling water, 31% as exhaust gas, 29.5% as useful power and the rest is lost for other reasons. Figure 1 and Table 1 are examples of studies conducted by Scoott J. Wallace, 2007[1]. The study comprises Diesel Fuel (D) and Biodiesel Fuel (B) versions of 250 kW Diesel engine performances. The power distribution occurs in the respective temperature range: cooling water (82 - 93 °C) with temperature difference (Tout - Tin = 11 °C), exhaust gas (549 - 560 °C) and ambient air around 25 °C.
By paying attention to the potential of waste heat in the cooling water and the exhaust gas, it is necessary to study the utilization. From the type and temperature of fluids that carry exhaust heat (cooling water and exhaust gas) there is techno-economical technology appropriate to use it, namely Organic Rankine Cycle, which is developed from geothermal power technology binary cycle.

The locations selected for this study is the Ampenan Diesel Power Generation located in Lombok, West Nusa Tenggara. During this study, there are 8 (eight) turbogenerator engine units operated in Ampenan Diesel Power Generation. Total installed capacity in Ampenan is about 55 MW. From field survey results, Diesel Power Generating units which capable installed waste heat recovery for ORC micro turbine are Diesel Power Station unit number 1 - 3 and Diesel Power Station units 5 & 6. Location of unit 4 isolated from other others, making it less potential to install waste heat recovery for ORC micro turbine. Diesel Power Units 7 and 8 currently have boiler units installed, which serve as Marine Fuel Oil (MFO) heaters. The boiler utilizes exhaust heat from units 7 and 8, so the units cannot be used for utilizing ORC micro turbine plants.

The exhaust gas temperature of Diesel Power Station is still high, between 300 °C and 500 °C, where this temperature can be used for waste heat recovery process. In this study will use ORC micro turbine.

2. Methodology
To produce the right ORC design then the stages of activities that need to be done are as follows:
- Undertake a study of potential exhaust heat which includes measurement of mass flow rate, temperature, pressure loss permitted by engine and exhaust gas composition. This parameter is
important for determining the physical and chemical properties of the exhaust gases to set the evaporative temperature of the working fluid as well as the selection of the water heater type.

- Conduct a study of environmental conditions (dry and wet air temperature, availability of water source enhancer). Environmental conditions are important to determine the working fluid conditions out of the turbine and the type of condenser used (water cooled system or water cooled condenser).
- Conduct the design of working fluid thermodynamically appropriate to use and heating fluid. However, it is also necessary to consider the availability of working fluid in Indonesia.

3. Results And Discussion

3.1. Area Configuration

The exhaust gas that will be used for the ORC micro turbine plant comes from the chimney diesel generating unit number 1 - 4 and unit number 5 - 8. But due to limited free space, so it is necessary to optimize the area. Possible options for area optimization are to configure area of units 5 - 6 and units 2 - 3. Configurations of unit 5 - 6 have free space dimensions of 6.1 m (W) x 8.4 m (L). But on the wide side there is a transverse piping with a height of 1.5 m and 3.6 m wide from the wall. While the configuration of unit 2 & 3 have a free space dimension of 7.6 m (W) x 8.1 m (L). But on the wide side there is a transverse piping with a height of 1.5 m and 3.6 m wide from the wall. The two configurations will be used in designing the ORC micro turbine modular structure.

3.2. Selection of Working Fluid

3.2.1. First Selection Process. In the initial selection process of working fluid, there are several common criteria that must be considered, including critical temperature, condensation pressure, factor I, and safety considerations.

i. Critical temperature (CT) is the temperature at which the liquid and gas phases of a fluid cannot be distinguished anymore. The working fluid to be selected should have a lower CT than the CT of water. The water here is used as a reference as a heating fluid. The working fluid must be able to change to the vapor phase by taking heat from the heating fluid.

ii. Condensation pressure is the pressure at which a fluid begins to condense. The lower the pressure of the working fluid condensation will be the cheaper the cost of equipment (Heat exchanger and piping) and its operation (pumping cost), provided it is not lower than atmospheric pressure, because it can cause air to enter into the system.

iii. Factor I is a parameter that describes the phase conditions of the fluid when leaving the turbine, this parameter is defined by [2] in the form of equations.

\[
I = 1 - \frac{T_{\text{cond}}}{(dT/ds)_{\text{sat,vap}}} 
\]

where,

- \(T_{\text{cond}}\): Condensation temperature associated with condensate pressure.
- \(C\): Specific heat at constant pressure.
- \((dT/ds)_{\text{sat,vap}}\): Temperature gradient at saturated temperature in diagram T-s.

In the outlet turbine, the fluid has a vertical steam curve, \(I = 1\); fluid with wet mixture, \(I < 1\); and for superheated steam, \(I \geq 1\). The I-factor in the range of 0.65 ≤ 1 ≤ 1.50 will be selected to be the initial screening limit.

iv. Security considerations on the selection of working fluids include such things as toxicity, flammability, ODP (Ozone Depletion Potential), and GWP (Global Warming Parameter). Working fluids that tend to be unsafe and destructive are strongly discouraged for the power generation industry as they will cause far-reaching losses, especially environmental impacts. Based on the above criteria, fluids that have been reviewed by experts can be grouped into 4 groups, namely: carbon dioxide, ammonia, halocarbon and hydrocarbons.
In the initial selection process, the use of carbon dioxide and ammonia can be eliminated by reason of:
- Critical temperature of carbon dioxide is very low (31 °C).
- Although thermally stable, ammonia is a highly toxic and flammable fluid.

Halocarbon and hydrocarbon fluids show many advantages in terms of thermodynamic properties for their application in ORC. From the first selection process that takes into account the four criteria above, we get some working fluids that meet the requirements. The working fluid can be seen in Table 2. Although water (H₂O) is not included in the category of working fluid for ORC, it is still shown as a comparison.

| Fluid     | Formula | Molecular Weight | T<sub>critic</sub> (°C) | P<sub>critic</sub> (atm) | P<sub>cond. at 38 °C</sub> (atm) | Toxicity | Flam. | GWP/ODP |
|-----------|---------|------------------|-------------------------|--------------------------|---------------------------------|----------|-------|---------|
| Propane   | C₃H₈   | 44.1             | 96.7                    | 41.9                     | 12.8                            | Low      | High  | 20/0    |
| n-Butane  | C₄H₁₀  | 58.1             | 152.0                   | 37.5                     | 3.5                             | Low      | High  | 20/0    |
| n-Pentane | C₅H₁₂  | 72.2             | 196.6                   | 33.3                     | 1.0                             | Low      | High  | 20/0    |
| R-123     | C₂HCl₂F₃ | 152.9          | 183.8                   | 36.1                     | 1.2                             | High     | Non   | 120/0   |
| R-134a    | C₂H₂F₄  | 102              | 101.1                   | 40.1                     | 9.2                             | Low      | Non   | 1300/0  |
| R-245fa   | C₃H₃F₅  | 134              | 154.1                   | 43.7                     | 2.3                             | Med. high| Non   | 950/0   |
| Water     | H₂O     | 18               | 373.9                   | 217.7                    | 0.06                            | Non      | Non   | 0       |

3.2.2. Second Selection Process. The second selection process is an advanced selection process of the working fluid that passes through the first selection process. Broadly speaking, the second selection process is the selection process between hydrocarbon group working fluid with the working fluid of refrigerant group.

There are several things to note from the working fluid properties, including:
- Working fluid has a large specific enthalpy change. It is intended to maximize thermal efficiency and reduce the flow rate of working fluid.
- The turbine inlet pressure is relatively small, as this can cut the cost of making heat transfer equipment.
- The working fluid has the smallest specific volume possible, to keep the turbine size small.
- Fluid has a high thermal conductivity coefficient of vapor and liquid. Because this can minimize the required heat transfer surface area.
- The viscosity of the working fluid must be low, thereby reducing the pressure due to friction can be minimized and the coefficient of convection heat transfer can be maximized.

The working fluid that can be used for ORC cycles include: n-pentane, n-butane, R-134a and R-245fa. n-Pentane and n-butane are included in the hydrocarbon class while R-134a and R-245fa belong to the refrigerant group. The four working fluids are simulated with a heat source, such as brine / hot water, and one will be selected for use in the ORC cycle. This simulation is done by computer modeling using software EES (Engineering Equation Solver).

From optimization results using EES software (Figure 2) can be seen net thermal efficiency (NTE) n-pentane to 90 °C temperature showed the lowest value among the three other working fluids. While n-butane and R-245fa show identical trends and values, but R-245fa requires more mass flowrate than n-butane. For turbine inlet temperatures above 110 °C, n-butane and n-pentane have the same characteristics for the value of NTE and the amount of mass flowrate required. Taking into account the high enough heat source temperature (above 150 °C), the suitable working fluid used in this ORC is n-pentane. n-Pentane has the highest temperature range of the other three fluids. The critical temperature of n-pentane reaches 196 °C so that it is suitable to be applied to heat sources whose temperatures are high enough.
3.2.3. ORC Simulation. The device used to determine the thermodynamic properties of the working fluid and calculate or run the heat mass balance for ORC is the Engineering Equation Solver (EES) Professional. This EES is a type of software that can solve linear, non-linear, complex and optimization problems.

Some parameters and assumptions need to be done to facilitate and obtain optimal results, here are the parameters and assumptions:

- Exhaust gas temperature of diesel
  \[ T_{\text{in}} = 350 \degree C \]
  From field observations, exhaust gas temperature ranges from 300 - 400 \degree C. In this calculation used average temperature 350 \degree C.
  \[ T_{\text{out}} = 200 \degree C \]
  Based on field data, the temperature of the gas to be discharged through the chimney into the atmosphere cannot be more than 200 \degree C due to environmental considerations.

- Heating fluid to be simulated in the calculation, among others: Saturated Steam; Hot Water; Dowtherm A; Thermo XT 32. Dowtherm A and Thermoxt 32 belong to a type of thermal fluid.
  \[ T_{\text{in}} = 200 \degree C \]
  \[ T_{\text{out}}: \text{Saturated Steam} = 150 \degree C \text{ (subcooled condition)} \]
  Hot water = 100 \degree C
  Dowtherm A = 100 \degree C
  Thermo XT 32 = 100 \degree C

- The cooling medium used is air. Based on the environmental conditions in the field, the inlet temperature of the inlet air cooler used is 33 \degree C while the outlet temperature is 40 \degree C.
- The working fluid used is n-pentane.
- 75\% turbine isentropic efficiency, 90\% generator efficiency, pump / motor efficiency 75\%.
- Working fluid flow rate used 2 kg / s.
- The ORC cycle operates at subcritical pressure.
- Pinch point temperature set minimum 6 \degree C.

Using the above parameters, we calculate the heat mass balance for both ORC models, simple ORC and ORC using recuperator. The calculation of heat mass balance is also done by using 4 different types of heating fluid. The results of the calculations are then poured in the form of graphs that can be seen in Figures 3 and 4.
From Figure 3 and 4, it can be seen that ORC with recuperator produces Net Power Output and Net Thermal Efficiency higher than simple ORC. Heating fluid in the form of saturated steam produces the highest efficiency followed by hot water, Dowtherm A and Thermo XT 32, but the difference is not too significant. Dowtherm A and Thermo XT 32 produce similar efficiency.
The maximum Net Power Output and Net Thermal Efficiency of both models are obtained in turbine inlet temperatures of approximately 180 - 190 °C. To reach the temperature, a pump can pump the working fluid from a small suction pressure (about 1 bara) until it reaches its saturation pressure (about 30 bara) at a small flow rate (about 2 kg / s).

Furthermore, by determining the generator's net capacity of 100 kW, heat mass balance for each model can be calculated. The results can be seen in Table 3. It can be seen that ORC with recuperator produce higher efficiency compared to simple ORC. Heating fluid saturated steam produces the highest efficiency followed by hot water, Dowtherm A and Thermo XT 32. Saturated steam and subsequent hot water are not selected as heating fluid because both of these fluids operate at atmospheric pressure so they are easy to operate. Due to consideration of price and availability issues in Indonesia, Thermo XT 32 was chosen to be heating fluid because it is much cheaper than Dowtherm A and is easily available in Indonesia.

With the results of the considerations mentioned, ORC with recuperator and heating fluid use Thermo XT 32 is then selected as the ORC micro turbine generator system concept.

### Table 3. Comparison of heat mass balance calculation result for simple ORC and ORC with recuperator

| Heating Fluid | ORC without recuperator | ORC with recuperator |
|---------------|-------------------------|-----------------------|
|               |                         | % eff. Mass flow (kg/s) | % eff. Mass flow (kg/s) |
|               |                         | n-pentane | heating fluid | Gas | Air | n-pentane | heating fluid | Gas | Air |
| Steam         | 9,37                    | 2,03      | 0,49        | 6,8 | 130,82 | 11,87 | 1,92 | 0,39 | 5,37 | 99,98 |
| Hot water     | 9,34                    | 2,04      | 2,48        | 6,82 | 131,17 | 11,85 | 1,92 | 1,95 | 5,38 | 100,19 |
| Dowtherm A    | 9,31                    | 2,04      | 5,54        | 6,85 | 131,69 | 11,81 | 1,93 | 4,37 | 5,39 | 100,5 |
| Thermo XT 32  | 9,32                    | 2,04      | 3,71        | 6,84 | 131,55 | 11,81 | 1,93 | 3,67 | 5,4  | 100,6 |

4. Conclusion

From the analysis it can be concluded as follows:

- From the results of field survey and optimization results of available space engine configuration units selected 2 & 3 and or engine configuration units 5 & 6 which will be utilized exhaust gas for generator micro turbine ORC.

- System design has 2 alternative system design which are simple ORC and ORC with recuperator; 4 alternative working fluids are n-butane, n-pentane, R-134a and R-245fa; 4 thermal fluid alternatives ie hot water, saturated steam, Dowtherm A and Thermo XT 32.

- Based on the simulation result to produce 100 kW electrical energy with the above design alternatives obtained optimal conditions on ORC system with precuperator, n-pentane working fluid, thermal fluid Thermo XT 32, with heat and mass balance model as follows; thermal efficiency 11,81%, mass flowrate n-pentane 1,92 kg / s and thermo XT mass flowrate 32 3,67 kg / s and turbine inlet temperature 160 °C.

5. References

[1] Wallace, Scott J., June 2007, Modeling of the Exhaust Gas Temperature for diesel Engine, MS thesis report Russ College of Engineering and Technology of Ohio University.

[2] Kihara, D. H. and Fukunaga, 2013 (1975), Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, 3.

[3] Sinnott, R., 1998, Coulson and Richardson's Chemical Engineering Design, vol. 6.
[4] Aprilana, A and Indrawan, H, 2013, Kajian Pemanfaatan Gas Buang PLTD untuk Mikroturbin Organic Rankine Cycle (ORC), PT PLN (Persero) Research Institute

Acknowledgments
The authors give high appreciation to the General Manager of PT PLN (Persero) Research Institute that has given permission for this study. Also, Mr. Bambang Teguh and team from BPPT who help authors to completed this study. To my colleague, high gratitude for the amount of time to finish this study.