Numerical Simulation of Turboexpander on Organic Rankine Cycle with Different Working Fluids

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Abstract. Renewable energy is an alternative to overcome the energy crisis and dependence on fossil-fuel energy that has an environmental impact due to the greenhouse effect. Meanwhile, disadvantage of EBT is depend on weather periodically. Geothermal is a source of EBT that is independent with weather. Geothermal resources dominated by water (brine) can’t be directly utilized as a power generated, but it has to separated into water and steam phase. The high enthalpy owned by brine can still be utilized due to development of Organic Rankine Cycle. ORC uses organic refrigerant fluids or hydrocarbons as a working fluid because it has low boiling temperatures. The numerical simulation was analyzed using a CFD ANSYS CFX with turbulence model K-epsilon and Pentane, R245fa, and butane as working fluids with expansion ratio 5:1 and rotational speed variation at 2000 until 14000 rpm.

1. Introduction

Indonesia is a country that has the greatest geothermal potential in the world around 27 GW. But in application, it only about 1.2 GW and it is divided into 7 regions [1]. One of the areas that has the greatest potential and has been utilized is the Awibengkok area, West Java. Where, the installed plant is around 127 MWe with a reservoir temperature of 250°-290°C and reservoir pressure of 35-85 bar and brine temperature of 160°-180°C and brine pressure of 11 bar [2]. Can be seen the brine temperature needed, then the area of Awibengkok can be utilized as a combined heat generator. One of the combined heat plants is the application of the Organic Rankine Cycle (ORC) which uses organic fluids or hydrocarbons as a working fluids because it has a low boiling temperature point.

At present more than 200 ORC plants have been identified with more than 1800 MW installed worldwide [3]. Factors that causing ORC technology are still not utilized, because the components production is still very lack, especially turboexpander component that require very high costs to be developed and produced [4]. Turboexpander is a substantial component in ORC, where the energy of organic fluid flows into turbine shaft then the mechanical energi from rotating shaft is converted, which moves to the generator to produce electricity. Generally, there are two common turboexpanders, in terms of the direction of fluid passing through the turbine, axial turbine and radial turbine. In this research, the turboexpander type is radial turbine outflow or centrifugal radial turbine is used.

One way to develop ORC technology is to analyze ORC turboexpander. Simulation is a way to get optimal efficiency and is expected to produce maximum power as well. The expander simulation process with the flow that occurs in the turboexpander is done by the CFD method. Spadicini, et al
(2015) have performed numerical analysis with CFD on radial outflow turbines with pentane working fluid with inlet temperature parameters 130°C and 1.3 MPa inlet pressure, where the results of numerical analysis with CFD show the power that can be generated by turbines looking for 2MW at changes of 3000 rpm. Whereas [5] has conducted numerical analysis to discuss turboexpander with radial inflow type for 3.5 kW power by comparing ideal gas and real gas for R245fa fluid.

2. Methods
Awibengkok Geothermal Power Plant in West Java, Indonesia was chosen as a reference for reservoir conditions with a minimum estimated brine injection with a temperature range of 180° – 160°C. In this case, R245fa, Pentane and butane are selected as a working fluid based on ODP (Ozone Depletion Point) characteristics and (Global Warming Potential) GWP that match with ORC characteristics studied.

![Figure 1. T-s Diagram of working fluids](image)

In the fig 1 above, the three working fluids fall into the dry working fluid category, which is highly recommended for ORC applications to avoid erosion of turboexpander blades due to collision of liquid droplets during the expansion process [6].

2.1 Optimum Condition
Optimum conditions are very important on Organic Rankine Cycle, because in generally ORC has a low efficiency. To optimize the utilization of residual heat from brine PLTP, the cycle must be working at optimum conditions. According to [7] that the maximum output power will be obtained by utilizing the remaining heat as much as possible. Meanwhile according to [8] conducted a study to determine the optimum evaporator temperature in the subcritical cycle. The conditions of the turbine inlet fluid are assumed to be in a saturated vapor condition. The optimum point is determined by optimized the equation that represents the area of the T-s ORC (nett power) curve that is done iteratively. For the utilization of waste heat from brine, the ORC that can be made is limited by two temperature conditions. The brine reinjection temperature at 155°C for upper limit temperature and the cooling water temperature at 25°C as a lower limit temperature.
From this temperature limit, it can be used to determine the optimal conditions of the three working fluids with only one pressure variation. Furthermore, determined some properties of each fluid that obtained from NIST Refprop and some equations used.

\[ W_{turbine} = \dot{m}(\Delta h) \eta_{turbine} \] (1)
\[ Q_{in} = \dot{m}(\Delta h) \] (2)
\[ \dot{W}_{pump} = \frac{\dot{m}(\Delta h)}{\eta_{pump}} \] (3)

The table 1 is the optimum operating state from the calculation of the cycle tempo with the power parameters generated by each working fluid that is set at 5 kW with a thermal efficiency value of each working fluid less than 10%.

| Parameters                        | Units | Pentane | R245fa | Butane |
|-----------------------------------|-------|---------|--------|--------|
| Inlet Pressure Brine              | MPa   | 1       | 1      | 1      |
| Temperature Brine                 | ºC    | 180     | 180    | 180    |
| \( \dot{m} \)                     | Kg/s  | 0.307   | 0.307  | 0.307  |
| Inlet Temperature turboexpander   | ºC    | 155     | 155    | 155    |
| Outlet Temperature turboexpander  | ºC    | 139.8   | 123.8  | 132.8  |
| Outlet Temperature condenser      | ºC    | 30      | 30     | 30     |
| Inlet Pressure turboexpander      | MPa   | 0.4     | 0.88   | 1.4    |
| Outlet Pressure turboexpander     | MPa   | 0.082   | 0.179  | 0.284  |
| Output Power                      | kW    | 5       | 5      | 5      |
| Power used by pump                | kW    | 0.28    | 0.22   | 1.13   |
| \( Q_{in} \)                      | kW    | 176.69  | 91.97  | 176    |

2.2 Modeling

The turbexpander that will be simulated in this study is the type of radial outflow turbine produced by infinitive turbine. Turboexpander sizes range from 12.7 cm with an output power is around 5 kW. Turboexpander from infinitive turbine has the advantage, that is not a gearbox needed [9]. Because the turboexander rotation value is low. Radial outflow turbine has two main parts, namely stator and rotor. The two main components have the shape of impulse blade.
Figure 3. Turboexpander parts: rotor (left), stator (right)

This component has the role of carrying out the process of expansion. The expansion process in the Radial Outflow Turbine occurs entirely due to the flow rate of the working fluid. The flow rate with a certain pressure enters through the inlet section and its expanded to a several levels. At the inlet side, the working fluid is directly header by the first level of stator which also act as a nozzle. Then after exiting from guide blade or stator at the first level, the working fluid flow enters the next level to rotate the moving blade or rotor section. Whereas for numerical analysis using software only the fluid parts are visible with the purpose of simplified numerical calculations of CFD.

Figure 4. Turboexpander CFD Modeling

Before the simulation process begins, a modeling must be divided into tiny elements or volumes with the purpose of convinient numerical calculations. The number of elements / volumes produced from the meshing results greatly affects to simulation process and results. As for meshing in this turboexpander model, it is in a good category, where the skewness criteria value is around 0.36 and the orthogonal quality value is around 0.78 [10].

In this simulation the software used is ANSYS CFX, where the features in ANSYS CFX are specifically used for the turbomachinery simulation process. But there is disadvantage of working fluid’s data especially for R245fa, so that the material tabs need to add the required properties such as molar mass, critical temperature, critical pressure, critical volume, acentric factor and boiling temperature. These properties can be found at NIST Refprop. Not only that, because R245fa is in the real gas category, the variables of the fourth order polynomial need to be entered for the correct calculation of the turbulence model of the standard redlich kwong or can be obtained by a linear regression approach. Therefore the coefficient values are.
\[ \frac{C_P}{R} = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^5 \]  
\[ a_1 = 432.29 ; a_2 = 15334 ; a_3 = 0 ; a_4 = 0 ; a_5 = 0 \]

3. CFD Results

3.1 Simulation Results
The simulation results from CFD of Turboexpander, give different results when compared with the data of specifications. The operating parameters being compared are turboexpander rotation from 2000 to 14000 rpm with three working fluids of R245fa, Butane and Pentane respectively.

3.2 Analysis of Fluids Contour
The expansion process that occurs in turboexpander involves several parameters when operating. These parameters include pressure, temperature, and velocity. Simulations performed on the ANSYS CFX software provide these parameters.
From figure 6, the contour of the static pressure of each fluid at turboexpander rotation speed which reaches the highest power and efficiency. The three pressure contour images show the symptoms of expansion in the same place where the fluid is expanded when it enters the leading edge of guide vane and exits through the trailing edge of rotor, the only difference from the expansions is reduction of pressure that occurs. This corresponds to the impulse blade with a zero reaction where a pressure drop occurs at stator or guide vane [12].

From figure 7, the contour of temperature of each fluid where the turboexpander rotation reaches the highest power and efficiency. The three working fluids (Pentane, Butane, R245fa) exhibited the same phenomenon, those are uniform decrease in temperature occurs after the fluid passes through the leading edge of the guide vane with different temperature range values. The small range of temperature reduction that occurs in Pentane compared to other working fluids, is an indication of the low power and efficiency produced.
Figure 7. Temperature contour of each fluid: (a) Pentane 12000 rpm, (b) butane 14000 rpm, (c) R245fa 10000 rpm

Figure 8. Fluids flow: (a) Pentane 12000 rpm, (b) butane 14000 rpm, (c) R245fa 10000 rpm
Figure 8 is the direction of flow for each fluid which reaches the highest power and efficiency. It can be seen, there is a secondary flow for each fluid when going through the stator or guide vane. Secondary flow is the losses that often occur in turbines with a percentage of losses of around 30% after leakage losses and friction losses [13]. In this research leak and friction losses are ignored, so secondary flow is the only losses that occurs.

4. Conclusion
The conclusion of this study, there are different results between calculations using the cycle tempo for each working fluid (Pentane, Butane, R254fa) which produces 5 kW of power with CFD simulation results, where Pentane working fluid produces power around 3.71 kW at 12000 rpm, butane produces power around 5.95 kW at 6000 rpm and R245fa produces power around 4.8 kW at 4000 rpm. Whereas Butane obtained the most efficient working fluid at rotational speed, Butane which produces power of 8.24 kW and 53.5% efficiency at 14000 rpm.

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