

Design of n-Butane Radial Inflow Turbine for 100 kW Binary Cycle Power Plant

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ABSTRACT

Agency for the Assessment and Application of Technology (BBPT) has successfully developed a model of a 2 kW binary cycle power plant using brine as a heat source. The working fluid using in this model is n-pentane. The type of turbine used is a single stage axial flow. This model was tested at Wayang Windu geothermal field. Based on these successes experience, BPPT further develop larger models for binary cycle power plant i.e. 100 kW with a working fluid is n-butane. For the purposes of this study, the design of an n-butane radial inflow turbine was carried out. Turbines are designed to operate with the following data: inlet pressure 21.8 bar, outlet pressure 4.5 bar, inlet temperature 120 °C, mass flow 2.49 kg/s, electric power output 100 kW, and turbine power 141 kW. From a design analysis, the turbine used is a single stage radial inflow turbine, 500 mm rotor diameter, 26 number of blades, 9.7 mm inlet width of blade, and 4.9 mm outlet width of blade. This turbine is designed to operate at 6000 rpm and 79.43 % of turbine efficiency.

Keywords: binary cycle plants, brine, n-butane, radial inflow turbine.

1. INTRODUCTION

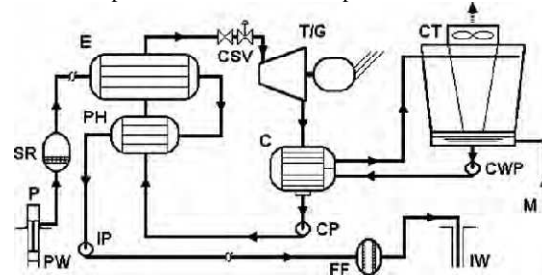
1.1. Binary Cycle Power Plant

In the conventional geothermal power plant almost 100% of the brine from a separator is re-injected into the earth in hot condition through a reinjection well. A brine of around 150° C with a mass flow rate at hundreds of tons per hour is potential of producing an estimate of several hundred MW of electric power. Similarly, a conducted industrial survey such as from chemical and petrochemical industries, energy industries and so forth indicates that potentially hundreds of MW of hot waste can still be extracted for other purposes.

A binary cycle geothermal power plant is an appropriate technology for taking advantages of hot waste or others thermal energy that has not yet been utilized, especially low temperature geo fluid (150° C). In the binary cycle power plant, thermal energy from brine or geo fluid is moved through a heat exchanger to the working fluid used in a Rankine cycle. The flow chart for a typical binary cycle geothermal power plant is shown in Figure 1.

Energy cycle components in the Figure 1 consist of pre-heater, evaporator, a set of control valves, turbine, condenser and filling pump. In addition, there is a water cycle that is used as condenser cooler. If a wet cooling

system is employed, water supply is necessary on location to provide source for makeup water



Legend: PW Production well, P (Well) Pump, SR Sand Remover, E Evaporator, PH Pre-heater, IP Injection Pump, FF Final Filter, IW Injection Well, CSV Control and Stop Valve, T/G Turbine/Generator, C Condenser, CP Condensate Pump, CT Cooling Tower, CWP Cooling Water Pump, M Makeup Water

Figure 1: Schematic of the binary cycle geothermal power plant, Thomas C. Elliot et. all. (1989)

Agency for the Assessment and Application of Technology (BBPT) has successfully developed a model of a 2 kW binary cycle plant using brine as a heat source and the working fluid is n-pentane (Fig. 2). The type of turbine used is a single stage axial flow. This model was tested at Wayang Windu geothermal field, Bambang Teguh P. et. all (2010). Based on these successes experience, BPPT further develop larger models for binary cycle power plant i.e. 100 kW with a working fluid is n-butane. For the purposes of this study, the design of an n-butane radial inflow turbine was carried out.

1.2. Radial Inflow Turbines for Binary Cycle Plant using N-Butane as Working Fluid

Process data for binary cycle are ideal for radial inflow turbines. Pressure ratios, flows and temperatures ensure an operation very close to the maximum achievable isentropic efficiency. Other losses in gear boxes, generator and bearings typically do not exceed in total 10% of the total enthalpy drop. For this reason the larger units can recover almost 85% electricity compared to the total isentropic enthalpy drop. Another benefit in using radial inflow turbine in standard execution with variable inlet nozzles is the ability to smooth seasonal variations inherent to geothermal process, Frederic Marcuccilli and Samuel Zouaghi (2007).



Figure 2. Installation of 2 kW binary cycle power plant model, Bambang Teguh P. et. al (2010)

The advantage of operating at higher pressure levels and with lighter organic fluid than usual is explained. It increases the recovered electrical power, whilst decreasing the expander frame size and price. In most of the cases there is a large benefit to optimize the binary cycle process data together with the turbine design to offer the best net cycle efficiency Frederic Marcuccili and Samuel Zouaghi (2007).

The main components of such radial inflow turbine are described in Figure 3.

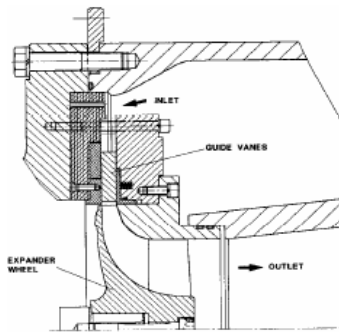


Figure 3. Cross section of expander wheel of radial inflow turbine showing the flow passage from inlet to outlet, Frederic Marcuccili and Samuel Zouaghi (2007)

- A high pressure barrel housing from which the gas first expands through guide vane or nozzles arrangement that is located in the circumference of the wheel.
- The gas is accelerated in the guide vanes and enters the turbine wheel. It converts the kinetic portion of energy contained in the gas by means of deflection in to mechanical energy.
- The gas leaves the wheel axially at the low pressure level and subsequently passes through the discharge diffuser where velocities are converted into pressure and reduced to normal pipeline velocities.
- The power generated by the wheel is given to shaft which runs in high speed bearings. This power can be recovered by driving a compressor or a generator.

1.3. Calculation procedure

1.3.1 Specific speed n_s

The radial inflow turbine must be designed at optimum specific speed n_s which represents a shape factor for the passage of the wheel. Ronald H. Aungier (2006) gives the formula:

$$n_s = \frac{2\pi N}{60} \sqrt{\frac{Q_5}{(\Delta H_{id})^{0.75}}} \quad (1)$$

With ΔH_{id} isentropic enthalpy drop (kJ/kg), Q_5 volumetric flow-rate at the outlet of turbine (m^3/s), N rotation velocity of turbine wheel (rpm). The volumetric flow-rate is defined as $Q_5 = \dot{m}/\rho_{t5}$ where \dot{m} mass flow rate (kg/s), ρ_{t5} gas density in section 5 (kg/m^3).

Figure 4 from Ronald H. Aungier (2006) describe the relation of specific speeds with turbine efficiency. The maximum turbine efficiency is obtained at n_s around 0.5

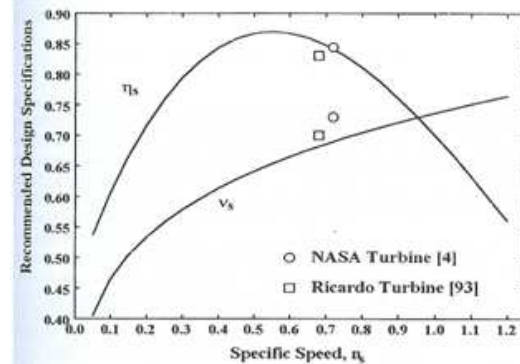


Figure 4. Efficiency is a function of n_s for radial inflow turbine, Ronald H. Aungier (2006)

After determining n_s and Q_5 , and ΔH_{id} the next stage of calculating the dimensions shown in the flow chart Figure 5. The nomenclature according to Ronald H. Aungier (2006), is as follows:

Q	: volumetric flow rate (m^3/s)
\dot{m}	: mass flow rate (kg/s)
ρ	: density (kg/m^3)
ΔH	: enthalpy drop (kJ/kg)
v	: velocity ratio (U_4/C_0)
U	: local blade speed (m/s)
C_0	: Spouting velocity (m/s)
α	: flow angle with respect to tangent (rad)
C	: absolute velocity (m/s)
b	: passage width; also maximum chamber (m)
r	: radius (m)
z	: axial coordinate
Δz_R	: circular-arc radius of curvature

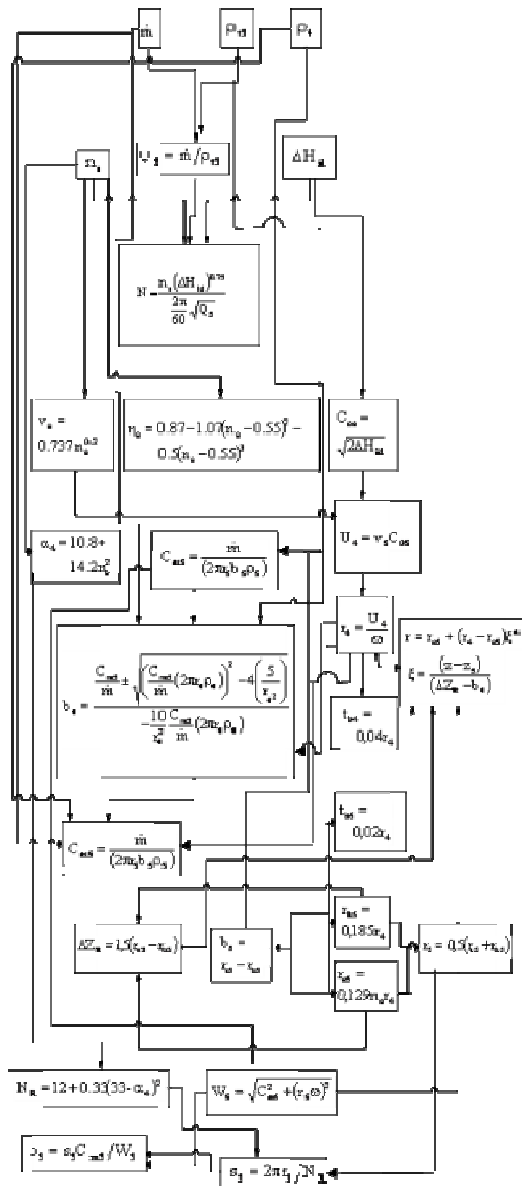


Figure 5. Calculation process of radial inflow turbine

- N_R : Number of blades (including the splitter blade)
- W : relative velocity (m/s)
- o : blade passage throat width
- s : blade pitch $2\pi/N$ (m)
- N : rotation speed (rpm)

Subscripts:

- id : ideal (no loss) parameter
- t : total thermodynamic condition
- s : total-to-static condition; also a shroud condition
- R : rotor parameter
- 1 : volute inlet parameter
- 2 : volute exit and nozzle inlet parameter
- 3 : nozzle exit parameter
- 4 : rotor inlet parameter
- 5 : rotor exit parameter

The following figures show the geometric dimensions mentioned in the list nomenclature:

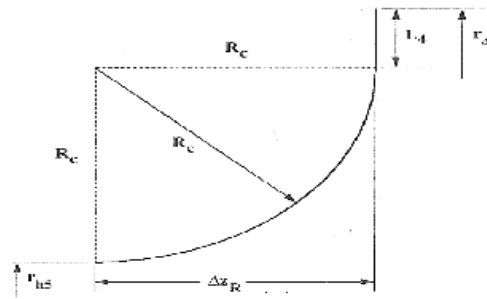


Figure 6. Circular-Arc Hub Construction, Ronal H. Aungier (2006)

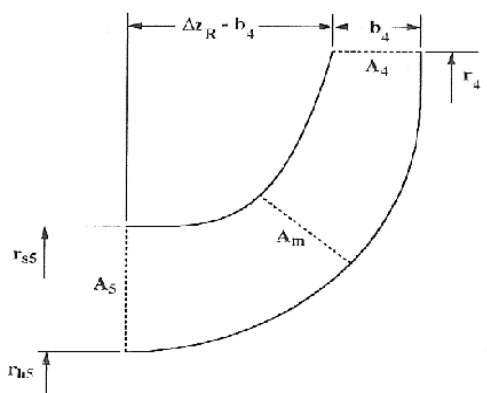


Figure 7. Power Law Shroud Contour, Ronal H. Aungier (2006)

2. METHODOLOGY

The methodology used in developing the hydrocarbon radial inflow turbines are as follows:

- Analysis approach
This activity uses the approach of data analysis and numerical analysis. Data analysis was performed with the initial design of data collection and calculation of its design. The numerical analysis carried out by processing the data using the software with the aim of knowing the initial conditions as well as the optimization opportunities that can be done
- Optimization techniques
Optimization techniques can be done in several ways iterations until obtained more optimum results. Calculation process can be seen in the Figure 4.

2.1 System design

Design of the 100 kW binary cycle geothermal power plant model is shown in Figure 8. Heat exchangers in the 100 kW binary cycle plant model include an evaporator, a condenser and a cooling tower. The wet cooling tower is chosen to cool down n-butane as condenser coolant. The chosen evaporator and condenser are shell and tube types. These types are preferred since

there are simpler in terms of design and easily manufactured locally in Indonesia.

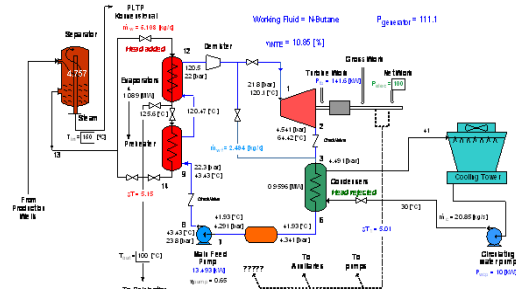


Figure 8. Diagram of 100 kW binary cycle plant model and design parameter,

The thermal designs of evaporator and condenser have been done using the temperature-Enthalpy diagram (T-h) method. This method is selected since both heat exchangers involve phase change of the respected working fluids, so that conventional approach is not applicable. Brackenbury has developed a software to design heat exchangers applying this method, H. J. Brackenbury et. all. (1993). A mechanical design calculation has been done accordingly with TEMA (1998) and other standards.

3. RESULTS

Based on the parameters optimization of the Process Flow Diagram (PFD) in Figure 6, the n-butane radial inflow turbine was designed with an enthalpy drop of 58.41 kJ/kg and flow rate of 2.494 kg/s. The estimated turbine thermal power is around 145.65 kW. The rotation velocity of shaft is designed to be 6000 rpm. The results of design calculations give the main dimensions of the turbine as shown in Table 1.

Table 1. The results of turbine design calculations

Nomenclature	Property Name	Units	Value
z	number of blades	-	26
l_{c1}	channel inlet width	mm	11.8
D_1	channel inlet mean diameter	mm	486
D_{2t}	channel outlet shroud diameter	mm	379.2
D_{2h}	channel outlet hub diameter	mm	90
B	flow path axial length	mm	217.2
i_{dShaft}	shaft index	-	
n	Rotation per minute	rpm	6000

From the data in Table 1, using the simulation software "exstream" can be done depiction rotor profiles, stators and other images as shown in Figure 9 - 15 in the appendix chapter.

4. CONCLUSIONS AND SUGGESTIONS

Based on the results of design calculations, considering the dimensions of a small turbine and turbine rotation velocity is high, it is necessary to study further

about the proper analysis of material to manufacture the hydrocarbon turbines.

Given the working fluid used is a flammable hydrocarbon fluid, it is necessary to study an analysis of the seal to overcome the leakage so as to minimize the potential for fires.

Expected there is cooperation between government and small to medium manufacturing industry in terms of coaching and empowerment of the domestic industry.

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APPENDIX

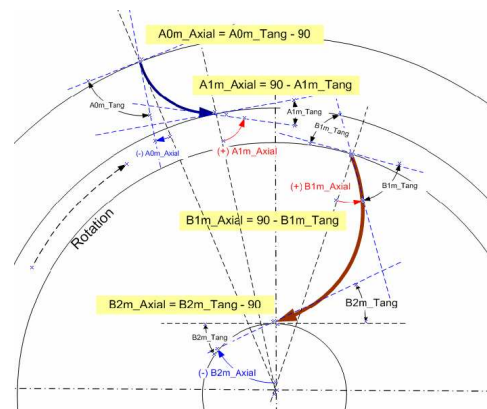


Figure 9. Magnitude tangential to the turbine (exstream software)

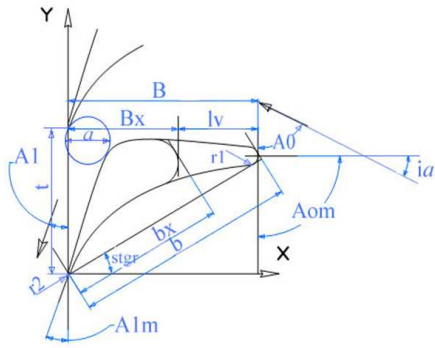


Figure 10. Nozzle Cascades (exstream software)

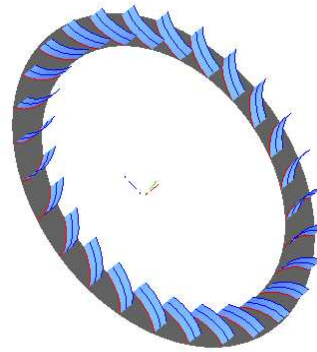


Figure 13. Stator Vane (exstream software)

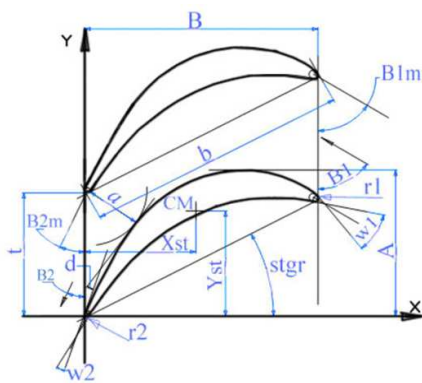


Figure 11. Blade Cascades (exstream software)

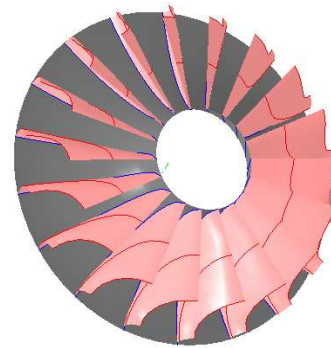


Figure 14. Blade Rotor (exstream software)

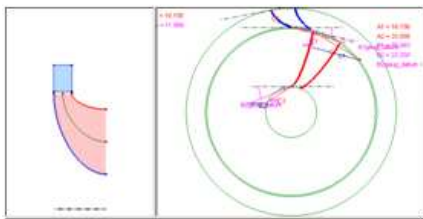


Figure 12. Flow path and velocity triangles (exstream software)

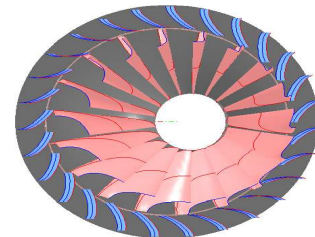


Figure 15. Rotor dan Stator (exstream software)