Hydropower Plants: Generating and Pumping Units
Solved Problems: Series 4

1 HYDROPOWER PLANT EQUIPPED WITH KAPLAN TURBINES

The Gezhouba power plant is located in the Hubei province, in China, where the frequency of the electrical grid is equal to f_{grid} = 50 Hz. It is equipped with 2 Kaplan turbines of 176 MW and 5 Kaplan turbines of 129 MW. In this problem, we will investigate the 176 MW units. A cut-view of the Kaplan unit is given in Figure 1.

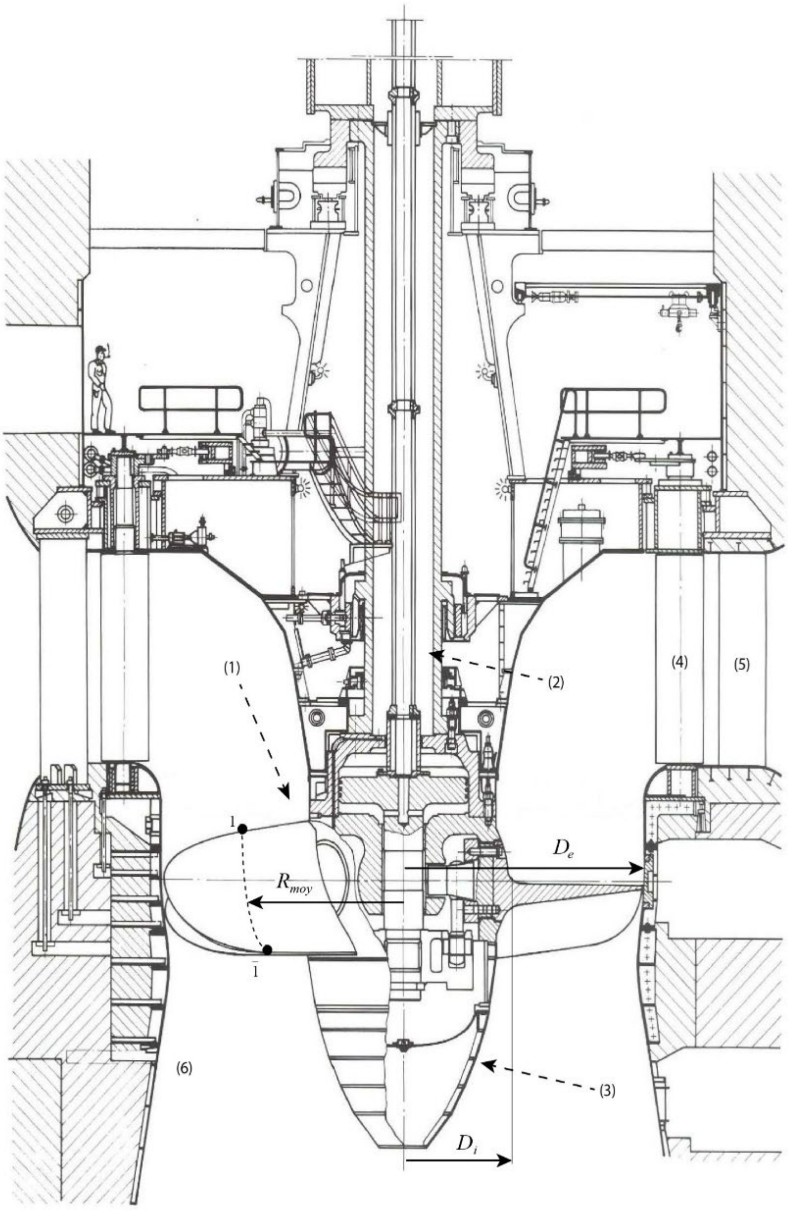

Figure 1 – Kaplan turbine unit from Gezhouba power plant.

1. Find the adequate name for the power plant components numbered in Figure 1:

Number	Name
(1)	
(2)	
(3)	
(4)	
(5)	
(6)	

2. Compute the specific potential energy of the installation for an upstream reservoir level of $Z_B = 45$ m and a downstream reservoir level of $Z_{\bar{B}} = 25$ m. The value of the gravitational constant in the Gezhouba power plant is $g = 9.794$ m s^{-2}.
3. For a nominal discharge of $Q = 1130$ m^{3}s^{-1}, the head losses of the installation have been measured and are equal to $\sum gH_r = 13.48$ J kg^{-1}. Compute the available specific energy of the turbine. Deduce the net head H of the turbine.
4. For this unit, the generator has a pole number equal to $Z_0 = 110$. Compute the runner frequency n and the specific speed ν of the runner.
5. Compute P_h, the hydraulic power. The value of the water density ρ is 998 kg m^{-3}.
6. We assume that the energy efficiency for this turbine is $\eta_e = 92$ %. Compute the transformed (or supplied) specific energy E_t.
7. Compute the torque experienced by the runner shaft T_t.
8. Compute the mechanical efficiency η_{me} and global machine efficiency. Neglect the generator losses.
9. The streamline $1-\bar{1}$ can be approximated as an open cylinder with a mean radius R_m. The internal and external diameters are equal to $D_i = 4.520$ m and $D_e = 11.3$ m, respectively. Compute the peripheral runner speed U_1 and $U_{\bar{1}}$.
10. By considering that the flow at the runner outlet is purely axial, compute Cu_1 the peripheral component of the absolute velocity at the runner inlet.
11. Compute the meridional components of the absolute velocity Cm_1 et $Cm_{\bar{1}}$.
12. From the previous results, compute the angles α_1 and β_1 at the runner inlet, and $\alpha_{\bar{1}}$ and $\beta_{\bar{1}}$ at the runner outlet.

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13. Finally, sketch the corresponding velocity triangles at the runner inlet and outlet.

2 FUNDAMENTAL STUDY FOR TRANSFORMED SPECIFIC ENERGY

Here, the fundamentals of hydraulic power plants and the calculation of the transformed specific energy E_t are studied. The general sketch of a hydraulic power plant with a pump-turbine unit is shown in Figure 2, where the numeric values of the operating condition are shown as well. The pump-turbine is operated in turbine mode at the best efficiency point. The points 1 and $\bar{1}$ correspond to the inlet and the outlet of the turbine, respectively. For gravity acceleration and density, use the following values:

$$g = 9.81 \text{ m s}^{-2},\ \rho = 1'000 \text{ kg m}^{-3}$$

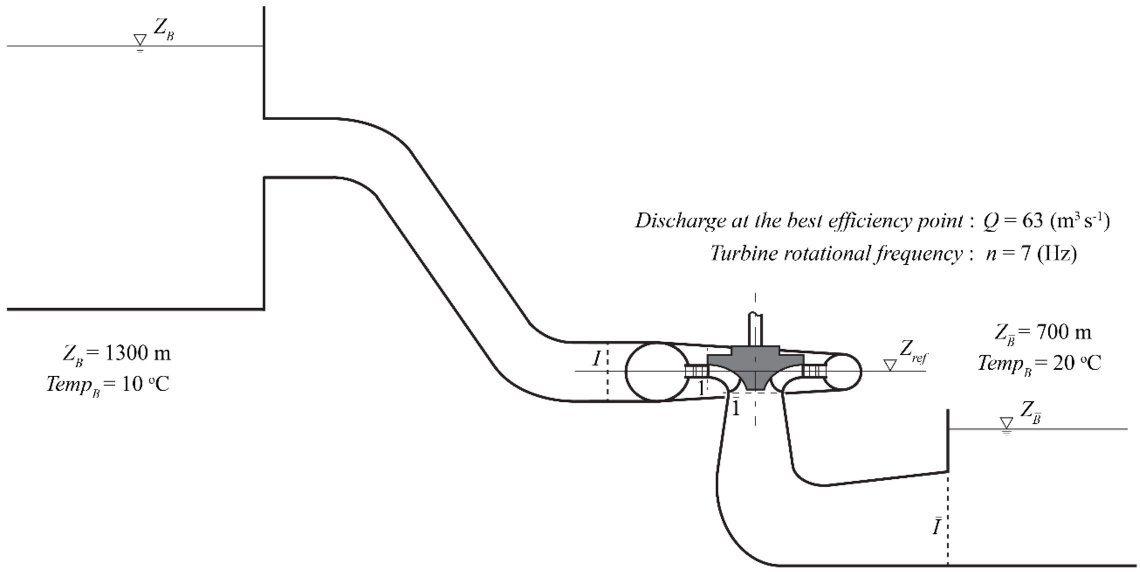

Figure 2 Layout of a pump-turbine installation

1) Assuming that an atmosphere pressure p_a is constant, express the potential specific energy $E_{potential}$ by g, Z_B and $Z_{\bar{B}}$. Then, calculate its value.

2) Assuming a constant atmospheric pressure is a good first approximation. However, in reality, the atmosphere pressure changes with altitude and temperature. Considering the difference of atmosphere pressure between both reservoirs, express the potential specific energy $E_{potential}$ as a function of $g, \rho, Z_B, Z_{\bar{B}}, p_{a\_B}$ and $p_{a\_\bar{B}}$. Then, calculate the value of $E_{potential}$.

   The atmospheric pressure can be calculated as a function of the altitude h (in meters) and the temperature T (in ºC) using the following equation:

$$p_a = p_0 \left(1 - \frac{0.0065h}{T_0 + 273.15}\right)^{5.257}$$

$$p_0 = 101.3\text{kPa},\ \ T_0 = T + 0.0065h$$

3) Express the available specific energy E selecting the necessary variables among $E_{potential}$, $gH_{rB\div I}$, $gH_{rI\div 1}$, $gH_{r\bar{1}\div\bar{I}}$, and $gH_{r\bar{I}\div\bar{B}}$.

4) Express the transformed specific energy E_t selecting the necessary variables among $E_{potential}$, $gH_{rB\div I}$, $gH_{rI\div 1}$, $gH_{r\bar{1}\div\bar{I}}$, and $gH_{r\bar{I}\div\bar{B}}$.

5) The transformed power P_t is defined by $P_t = \rho Q_t E_t$, where Q_t is the discharge passing through the turbine, which is lower than the discharge Q. Give an explanation of this difference.

6) The transformed power P_t is related to the output power P as $P_t = \frac{1}{\eta_{me}} P$ (with η_{me} the mechanical efficiency defined by $\eta_{me} = \eta_m \eta_{rm}$, where η_m is the efficiency of the bearing and η_{rm} the efficiency of the disc friction). Express the transformed power P_t by the mechanical efficiency η_{me}, global efficiency η, density ρ, discharge Q, available energy E.

7) Introducing the volumetric efficiency and the energetic efficiency defined as $\eta_q = \frac{Q_t}{Q}$ and $\eta_e = \frac{E_t}{E}$ respectively, express the global efficiency η by η_e, η_q, η_m, and η_{rm}.

8) Assuming that the losses $gH_{rB \div I} + gH_{r\bar{I} \div \bar{B}}$ correspond to 5% of the potential specific energy, calculate the hydraulic power P_h.

For the calculation of the transformed specific energy E_t, the velocity triangle representing the relationship of the discharge velocity with the turbine rotational velocity and the Euler equation play a decisive role. The schematics of the pump-turbine and an example of the velocity triangle are shown in Figure 3. In this section, we set the values of k_{Cu1e} and $k_{Cu\bar{1}e}$ such that $k_{Cu1e} = 1$ and $k_{Cu\bar{1}e} = \frac{1}{2}$. If necessary, use the following values: $D_{1e} = 4.0\,\mathrm{m}$, $D_{\bar{1}e} = 1.6\,\mathrm{m}$, $B = 0.234\,\mathrm{m}$

$$E_t = k_{Cu1e}\left(\vec{C}_{1e} \cdot \vec{U}_{1e}\right) - k_{Cu\bar{1}e}\left(\vec{C}_{\bar{1}e} \cdot \vec{U}_{\bar{1}e}\right) = \left(\vec{C}_{1e} \cdot \vec{U}_{1e}\right) - \frac{1}{2}\left(\vec{C}_{\bar{1}e} \cdot \vec{U}_{\bar{1}e}\right)$$

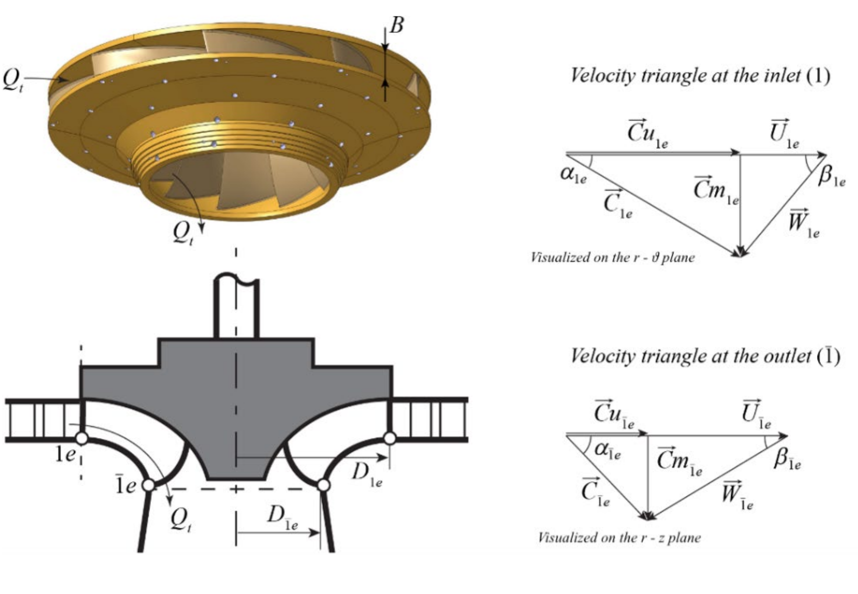

Figure 3: Velocity triangle of the pump-turbine in turbine mode

9) Referring to the vectorial relationship in Figure 3, deduce the scalar form of the Euler equation using the necessary variables among Cu_{1e}, Cm_{1e}, U_{1e}, $Cu_{\bar{1}e}$, $Cm_{\bar{1}e}$, and $U_{\bar{1}e}$.

10) Calculate the meridional velocity component Cm_{1e} and the turbine rotational velocity U_{1e} assuming a volumetric efficiency $\eta_q = 0.99$.