Impulse Reaction Turbine

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DESIGN OF IMPULSE-REACTION TURBINE
Contents:

1. Problem Statement.................................................................3

2. Introduction................................................................................3
   - Impulse principle.................................................................3
   - Reaction principle..............................................................3

3. Optimal design calculations......................................................5

4. Results......................................................................................10

5. Conclusion.................................................................................12
**Problem Statement:**

The steam turbine to be designed has 4 stages. The first two stages are impulse stages and the last two are reaction stages. The inlet angle to the turbine is given and velocity coefficient is given. The design parameters are to be adjusted to obtain an optimal design.

**Introduction:**

A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. Early turbine examples are windmills and waterwheels.

**Working Principle:**

**Impulse turbine:**

An impulse turbine has fixed nozzles that orient the steam flow into high speed jets. These jets contain significant kinetic energy, which is converted into shaft rotation by the bucket-like shaped rotor blades, as the steam jet changes direction. A pressure drop occurs across only the stationary blades, with a net increase in steam velocity across the stage. As the steam flows through the nozzle its pressure falls from inlet pressure to the exit pressure. They are usually used in the entrance high pressure stages of a steam turbine, when the specific volume of steam flow is low and requires much smaller flow area than at low pressures.

**Advantages of pressure compounded Impulse turbine:**

It has the advantage of reduced blade velocities, reduced steam velocities and equal work among stages, or equal work distribution among the stages as desired by the designer.

**Reaction turbine:**

In the reaction turbine, the rotor blades themselves are arranged to form convergent nozzles. This type of turbine makes use of the reaction force produced as the steam accelerates through the nozzles formed by the rotor. Steam is directed onto the rotor by the fixed vanes of the stator. It leaves the stator as a jet that fills the entire circumference of the rotor. The steam then changes direction and increases its speed relative to the speed of the blades. A pressure drop occurs across both the stator and the rotor, with steam accelerating through the stator and decelerating through the rotor, with no net change in steam velocity across the stage but with a decrease in both pressure and temperature, reflecting the work performed in the driving of the rotor. They are generally used in low pressure stages where the blades become progressively longer so the tip clearance becomes smaller to the blade height i.e., relative to steam volume.
Advantages of Reaction Turbine:

1. Capacity to use high pressure with high temperature.
2. Elevated capacity to weight ratio.
3. Oil free exhaust system.
4. High rotational speeds.
5. Lesser stage spacing.

A Schematic diagram and pressure velocity relationship of Impulse and Reaction turbines is shown in the figure1:

![Comparison of Impulse and reaction turbines](image)

*Figure 1: Comparison of Impulse and reaction turbines*
**Optimum Design Calculations:**

To reach an optimal blade velocity which would result in maximum work tried and get the fluid exit angle as close as possible to 90° so that the exit whirl velocity is zero and throughout the design process our main motive was to reach that target. However we also had to make sure that the angular velocity for all the blades remained the same considering the shaft rotates at the same speed. Our blade velocity ratios for each stage had to have the same ratio as the diameter of each stage. We decided to use the pressure compounding method for the Impulse stages of the turbine.

**Assumptions:**

1. The Nozzle Angles for the first two impulse turbines are the same.
2. The inlet angle of the reaction stages are the same as the nozzle angles of the impulse stage
3. The fixed blade angles of the two reaction turbines equal to the given inlet angle.
4. All the Blades are Symmetrical in Impulse turbine i.e Ø = Y.
5. In reaction turbine Fixed blade angle is equal to blade exit angle i.e \( \theta_3 = Y_3, \theta_4 = Y_4 \)
6. The 2\(^{nd}\) and 3\(^{rd}\) stage of the turbine are 50 % reaction stages.

\[ h_n = 1504.4 \text{ Btu/lbm} \]
\[ h_g = 923 \text{ Btu/lbm} \]

Total Enthalpy drop \( \Delta h_{total} = (1504.4 - 923) = 581.4 \text{ Bt/lbm} \)

---

1. **First Stage Impulse**

Nozzle inlet angle \( \theta_1 = 20^\circ \)
\( \Delta h_1 = 39.5 \text{ Btu/lbm} \)

\( V_{s1} = \sqrt{2 \times 32.2 \times 778.1 \times [(\Delta h_1 \times \eta)]} = 1336.813 \text{ ft/s} \)

\( V_{b1} = \frac{V_{s1} \times \cos(\theta_1)}{2} = 628.1 \text{ ft/s} \)

\( V_{s1} \sin \phi_1 = V_{s1} \sin \theta_1 \ldots \ldots \text{eq}(1) \)

\( V_{s1} \cos \phi_1 = V_{s1} \cos \theta_1 - V_{b1} \ldots \ldots \text{eq}(2) \)

Solve equation 1 and 2 to find:

\( \phi_1 = 36.052 \)

\( V_1 = 776.9 \text{ ft/s} \)

\( V_2 = K_1 \times V_1 = 738.04 \text{ ft/s} \)

\( \phi_1 = Y_1 \)
\[ V_{r2} \sin \gamma_1 = V_{s2} \sin \delta_1 \quad \text{......eq(3)} \quad \text{and} \quad V_{r2} \cos \gamma_1 + V_{s2} \cos \delta_1 = V_{b1} \quad \text{......eq(4)} \]

Solve equation 3 and 4 to find:

\[ V_{s2} = 435.49 \text{ ft/s and } \delta_1 = 85.865 \]

**Work done in Impulse Stage 1:**

\[
\dot{W} = \frac{m}{2 \cdot g_c} \left[ (v_{s1}^2 - v_{s2}^2) - (v_{r1}^2 - v_{r2}^2) \right] = 23890.84 \text{ ft.lbf/s}
\]

**Stage Efficiency:**

\[
\eta_{\text{stage}} = \frac{\dot{W}}{\Delta h_1 \cdot 778.16} = 77.73\%
\]

**Blade Efficiency:**

\[
\eta_b = \frac{\dot{W}}{\frac{v_{s1}^2}{2 \cdot g_c}} = 86.095\%
\]

**2. Second Stage Impulse**

\[ \theta_2 = 20^\circ \]

\[ \Delta h_2 = 66 \text{ Btu / lbm} \]

\[ V_{s3} = \sqrt{2 \cdot 32.2 \cdot 778.1 \cdot \left( \Delta h_2 \cdot \eta \right) + \frac{V_{s2}^2}{2}} = 1782.03 \text{ ft/s} \]

\[ V_{b2} = \frac{V_{s3} \cdot \cos \theta_2}{2} = 837.281 \text{ ft/s} \]

\[ V_{s3} \sin \varnothing_2 = V_{s3} \sin \theta_2 \quad \text{......eq(1)} \]

\[ V_{s3} \cos \varnothing_2 = V_{s3} \cos \theta_2 - V_{b2} \quad \text{......eq(2)} \]

Solve equation 1 and 2 to find:

\[ \varnothing_2 = 36.052 \]

\[ V_{s3} = 1035.625 \text{ ft/s} \]

\[ V_{r4} = K_v \cdot V_{s3} = 983.84 \text{ ft/s} \]
\[ \varphi_2 = \gamma_2 \]

\[ V_{s4} \sin \gamma_2 = V_{s4} \sin \delta_2 \quad \text{eq}(3) \]

\[ V_{s4} \cos \gamma_2 + V_{s4} \cos \delta_2 = V_{b2} \quad \text{eq}(4) \]

Solve equation 3 and 4 to find:

\[ V_{s4} = 580.528 \text{ ft/s and } \delta_2 = 85.86^\circ \]

**Work done in Impulse Stage2:**

\[ \dot{w} = \frac{m}{2 \cdot g_c} \left[ (v_{s3}^2 - v_{s4}^2) - (v_{r3}^2 - v_{r4}^2) \right] = 42454.27 \text{ ft.lbf/s} \]

**Stage Efficiency:**

\[ \eta_{\text{stage}} = \frac{\dot{w}}{\Delta h_f \cdot 778.16} = 82.66\% \]

**Blade Efficiency:**

\[ \eta_b = \frac{\dot{w}}{\frac{v_{s3}^2}{2 \cdot g_c}} = 86.095\% \]

3. **Third Stage Reaction**

\[ \theta_3 = 20^\circ \]

\[ \Delta h_{m1} = 93 \text{ Btu / lbm} \]

\[ \Delta h_{f1} = 93 \text{ Btu / lbm} \]

\[ V_{s5} = \sqrt{2 \cdot 32.2 \cdot 778.1 \cdot \Delta h_{f1} + V_{s4}^2} = 2238.8 \text{ ft/s} \]

\[ V_{b3} = \frac{V_{s5} \cdot \cos \theta_3}{2} = 1051.9 \text{ ft/s} \]

\[ V_{s5} \sin \varnothing_3 = V_{s5} \sin \theta_3 \quad \text{eq}(1) \]

\[ V_{r5} \cos \varnothing_3 = V_{s5} \cos \theta_3 - V_{b3} \quad \text{eq}(2) \]

Solve equation 1 and 2 to find:

\[ \varnothing_3 = 36.052 \]

\[ V_{r5} = 1301.05 \text{ ft/s} \]

\[ V_{r6} = \sqrt{2 \cdot g_c \cdot 778.1 \cdot \Delta h_{m1} + V_{r5}^2} = 2523.443 \text{ ft/s} \]
\[ \theta_3 = \gamma_3 \]

\[ V_{s6}\sin \gamma_3 = V_{ss6}\sin \delta_3 \quad \text{......eq}(3) \quad \text{and} \quad V_{r6}\cos \gamma_3 + V_{ss6}\cos \delta_3 = V_{b6} \quad \text{......eq}(4) \]

Solve equation 3 and 4 to find:

\[ V_{s6} = 1576.6 \text{ ft/s and } \delta_3 = -33.190 = 146.8 \text{ degrees} \]

**Work done in Reaction Stage3:**

\[ \dot{w} = \frac{m}{2*gc} \left[ (v_{s5}^2 - v_{s6}^2) - (v_{r5}^2 - v_{r6}^2) \right] = 111822.99 \text{ ft.lbf/s} \]

**Stage Efficiency:**

\[ \eta_{\text{stage}} = \frac{\dot{w}}{(\Delta h_{m1} + \Delta h_{f1}) + 778.16} = 77.26\% \]

**Blade Efficiency:**

\[ \eta_{b} = \frac{\dot{w}}{\left[ \frac{v_{s5}^2}{2*gc} + \Delta h_{m1} + 778.16 \right]} = 74.452\% \]

**4. Fourth Stage Reaction**

\[ \theta_4 = 20^\circ \]

\[ \Delta h_{m2} = 145 \text{ Btu / lbm} \]

\[ \Delta h_{f2} = 145 \text{ Btu / lbm} \]

\[ V_{s7} = \sqrt{2 * 32.2 * 778.1 * \Delta h_{f2} + V_{s6}^2} = 2700 \text{ ft/s} \]

\[ V_{b4} = \frac{V_{r7}*\cos \theta_4}{2} = 1268.5 \text{ ft/s} \]

\[ V_{r7}\sin \phi_4 = V_{s7}\sin \theta_4 \quad \text{......eq}(1) \quad \text{and} \quad V_{r7}\cos \phi_4 = V_{s7}\cos \theta_4 - V_{b4} \quad \text{......eq}(2) \]

Solve equation 1 and 2 to find:
\( \varphi_4 = 36.052 \)

\( V_{r7} = 1569 \text{ ft/s} \)

\[ V_{r8} = \sqrt{2 \cdot g_c \cdot 778.1 \cdot \Delta h_m2 + V_{r7}^2} = 3122.623 \text{ ft/s} \]

\( \theta_4 = \gamma_4 \)

\[ V_{r8} \sin \gamma_4 = V_{s8} \sin \delta_4 \ldots \text{eq(3)} \quad V_{r8} \cos \gamma_4 + V_{s8} \cos \delta_4 = V_{b4} \ldots \text{eq(4)} \]

Solve equation 3 and 4 to find:

\( V_{s8} = 1979 \text{ ft/s} \) and \( \delta_4 = -32.665 = 147.3 \) degrees

**Work done in Reaction Stage4:**

\[
\dot{W} = \frac{\dot{m}}{2 \cdot g_c} \left[ (v_{s5}^2 - v_{s6}^2) - (v_{r5}^2 - v_{r6}^2) \right] = 165567.07 \text{ ft.lbf/s}
\]

**Stage Efficiency:**

\[
\eta_{\text{stage}} = \frac{\dot{W}}{(\Delta h_m2 + \Delta h_f2) \cdot 778.16} = 73.37\%
\]

**Blade Efficiency:**

\[
\eta_b = \frac{\dot{W}}{\left[ \frac{v_{s7}^2}{2 \cdot g_c} + \Delta h_m2 \cdot 778.16 \right]} = 73.254\%
\]

**Overall Efficiency:**

\[
\eta_{\text{overall}} = \frac{W_{\text{total}}}{\Delta h_{\text{total}}} = 75.96\%
\]
Results:

After several iterations with different enthalpy drops for each stage we obtained results for the optimal design which also yielded the accurate blade velocity ratios. The results are shown in table 1. Other iterations are shown in the appendix.

<table>
<thead>
<tr>
<th>Diameter, ft</th>
<th>Nozzle angle Θ1</th>
<th>Θ2</th>
<th>Θ3</th>
<th>V₃</th>
<th>Vb₁</th>
<th>Blade entrance angle, Ø₁</th>
<th>Vr₁</th>
<th>Vr₂</th>
<th>Blad e exit angle, Y₁</th>
<th>Fluid exit angle, 91</th>
<th>Vs2</th>
<th>Velocity ratio, Vb₁/Vb₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>20.00</td>
<td>1504.4</td>
<td>1467.4</td>
<td>37.00</td>
<td>1293.8</td>
<td>607.89</td>
<td>5</td>
<td>36.05</td>
<td>9</td>
<td>751.89</td>
<td>714.30</td>
<td>36.05</td>
</tr>
<tr>
<td>3.333</td>
<td>20.00</td>
<td>1504.4</td>
<td>1405.9</td>
<td>61.50</td>
<td>1720.4</td>
<td>808.36</td>
<td>0</td>
<td>60.05</td>
<td>3</td>
<td>999.85</td>
<td>949.86</td>
<td>36.05</td>
</tr>
<tr>
<td>4.1666</td>
<td>20.00</td>
<td>1504.4</td>
<td>1310.4</td>
<td>95.50</td>
<td>2152.8</td>
<td>1011.5</td>
<td>9</td>
<td>36.05</td>
<td>2</td>
<td>1251.1</td>
<td>2426.0</td>
<td>36.05</td>
</tr>
<tr>
<td>5</td>
<td>20.00</td>
<td>1504.4</td>
<td>1069.0</td>
<td>146.0</td>
<td>2570.0</td>
<td>1207.5</td>
<td>47</td>
<td>36.05</td>
<td>2</td>
<td>1493.6</td>
<td>2972.5</td>
<td>20.00</td>
</tr>
</tbody>
</table>

Table 1: Tabulated results
Once we obtained our results we calculated the pressure for each stage using a Moiller Diagram. The Moiller diagram with the pressure stages of our calculated enthalpy drops is attached in the appendix. Once we obtained the pressure drops we tabulated and graphed the pressures and velocities for each stage as shown in table 2 and figure 2 respectively.

<table>
<thead>
<tr>
<th>State</th>
<th>Pressure (psia)</th>
<th>Absolute Velocity (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>700</td>
<td>2169.145</td>
</tr>
<tr>
<td>1.25</td>
<td>700</td>
<td>2169.145</td>
</tr>
<tr>
<td>2.25</td>
<td>700</td>
<td>706.637</td>
</tr>
<tr>
<td>3.25</td>
<td>700</td>
<td>706.637</td>
</tr>
<tr>
<td>4.25</td>
<td>400.000</td>
<td>2891.369</td>
</tr>
<tr>
<td>4.5</td>
<td>400</td>
<td>2891.369</td>
</tr>
<tr>
<td>5.5</td>
<td>400</td>
<td>941.913</td>
</tr>
<tr>
<td>6.5</td>
<td>202</td>
<td>3619.766</td>
</tr>
<tr>
<td>6.75</td>
<td>202</td>
<td>3619.766</td>
</tr>
<tr>
<td>7.75</td>
<td>90</td>
<td>3236.015</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>3236.015</td>
</tr>
<tr>
<td>9</td>
<td>18</td>
<td>4351.435</td>
</tr>
<tr>
<td>9.25</td>
<td>18.000</td>
<td>4351.435</td>
</tr>
<tr>
<td>10.25</td>
<td>1</td>
<td>1859.527</td>
</tr>
</tbody>
</table>

*Table 2: Pressure and velocity at each state*
We can observe from the graph that in the impulse stages the pressure drops only in the nozzles and remains constant in the moving blades. The fluid inlet velocity in pressure compounding should remain the same however in our design it increases considering the pitch diameter of each stage increases. There is a velocity increase and then once it enter the moving blade some kinetic energy is used up by the blades which decreases the velocity. This remaining velocity or the remaining kinetic energy is added to the next stage along with the kinetic energy it produces itself from the enthalpy drop. In the reaction stage we can observe that there is a pressure drop twice in each stage, one pressure drop in the fixed blade and the other in the moving blade. The velocities in the reaction act in a similar way as the pressure compounding stages except the drop in the velocity in very less as compared to the impulse stages. The reason behind this is that in the reaction stage the enthalpy drop gets divided in to 2 (since we are assuming a 50% reaction stage) which reduces the velocity drop as well.

The velocity diagram is attached in the appendix.
Conclusion:

As all the turbines are mounted on same shaft the angular velocity of all of them should match:

\[ \frac{V_{b1}}{D_1} = \frac{V_{b2}}{D_2} = \frac{V_{b3}}{D_3} = \frac{V_{b4}}{D_4} \]

<table>
<thead>
<tr>
<th>Stages</th>
<th>Enthalpy drop</th>
<th>Blade velocity</th>
<th>Various Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>btu/lbm</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( \Delta h_1 = 39.5 )</td>
<td>628.1</td>
<td>( \Theta=20, \varnothing=36.052, Y=36.052, \delta=85.865 )</td>
</tr>
<tr>
<td>2</td>
<td>( \Delta h_2 = 66 )</td>
<td>1782.03</td>
<td>( \Theta=20, \varnothing=36.052, Y=36.052, \delta=85.865 )</td>
</tr>
<tr>
<td>3</td>
<td>( \Delta h_{m1} = \Delta h_{m2} = 93 )</td>
<td>1051.9</td>
<td>( \Theta=20, \varnothing=36.052, Y=20, \delta=146.8 )</td>
</tr>
<tr>
<td>4</td>
<td>( \Delta h_{m2} = \Delta h_{m2} = 145 )</td>
<td>1268.5</td>
<td>( \Theta=20, \varnothing=36.052, Y=20, \delta=147.3 )</td>
</tr>
</tbody>
</table>

The results we obtained are in complete agreement with the above notion. The blade velocity is increased with increasing blade diameter which is evident from the pressure-velocity diagram shown in the appendix. After calculating the efficiency of all stages our overall efficiency of the entire turbine ended up being approximately 76%. This design yields a relatively good efficiency however several non-practical assumptions were made therefore in reality this efficiency would decrease a little bit.

Furthermore if we were to improve the efficiency of the turbine even more, we could add further stages in the process.