CITY COLLEGE

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PROJECT 2.0

IMPULSE STAGE STEAM TURBINE

Thermal System Analysis and Design

ME 430

Spring 2010

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Submitted By:

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May 18, 2010

Abstract

The steam turbine bade design is concept based on the stage for conversion of heat to work in which the thermal energy (potential Energy) is first converted to kinetic energy and then to shaft work. Hot air or steam is the medium through which this process takes place. Potential energy (pressure) is the required condition for the motion to occur while thermal effects (temperature) essentially help to enhance the quality of the compression process. The objective of this project was to determine the approximate number of turbine blades needed to obtain the desired power from the steam turbine and with partial knowledge based on project #1. Assuming that the impulse stages, the velocity triangles were drawn, efficiency and other design parameters were evaluated and theoretically an impulse stage of the steam turbine was designed.

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1.0 Nomenclature

$P = Pressure, (psi)$

$T = Temperature$ (°F)

$\eta_{th} = Efficiency$

$h = Specific\ enthalpy \left(\frac{Btu}{lbm}\right)$

$v = Specific\ volume \left(\frac{ft^3}{lbm}\right)$

$W = Power\ (KW)$

$\dot{m} = Mass\ flow\ rate, \left(\frac{lbm}{s}\right)$

$r_t = Radius\ of\ tip$ **(inch)**

$r_h = Radius\ of\ hub\ (inch)$

$s = Spacing\ between\ blades\ (inch)$

$c = Chord\ length\ (inch)$

$\frac{U}{V0} = Velocity\ ratio$

$V_0 = Adiabatic\ velocity\ (\frac{inch}{s})$

$U = Blade\ velocity\ (\frac{inch}{s})$

$V = Absolute\ velocity\ \left(\frac{inch}{s}\right)$

$w = Relative\ velocity\ (\frac{inch}{s})$

$\alpha = Angles\ made\ by\ absolute\ velocities$

$\beta = Angles\ made\ by\ relative\ velocities$

$g_c = Gravitational\ force\ (\frac{ft}{s^2})$

$N = Number\ of\ blade$

$r = Radius\ (mch)$

$d = diameter\ (inch)$

$\Psi = Loading\ factor$

$l = Length\ of\ the\ blade\ (inch)$

$R = Universal\ gas\ constant \left(\frac{Btu}{lbmol * R}\right)$

$\rho = Density \left(\frac{lbm}{ft^3}\right)$

Impulse Stage Turbine Design

1. Introduction

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam, and converts it into rotary motion. Its modern manifestation was invented by Sir Charles Parsons in 1884. It has almost completely replaced the reciprocating piston steam engine primarily because of its greater thermal efficiency and higher power-to-weight ratio. Because the turbine generates rotary motion, it is particularly suited to be used to drive an electrical generator – about 80% of all electricity generation in the world is by use of steam turbines. The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency through the use of multiple stages in the expansion of the steam, which results in a closer approach to the ideal reversible process.

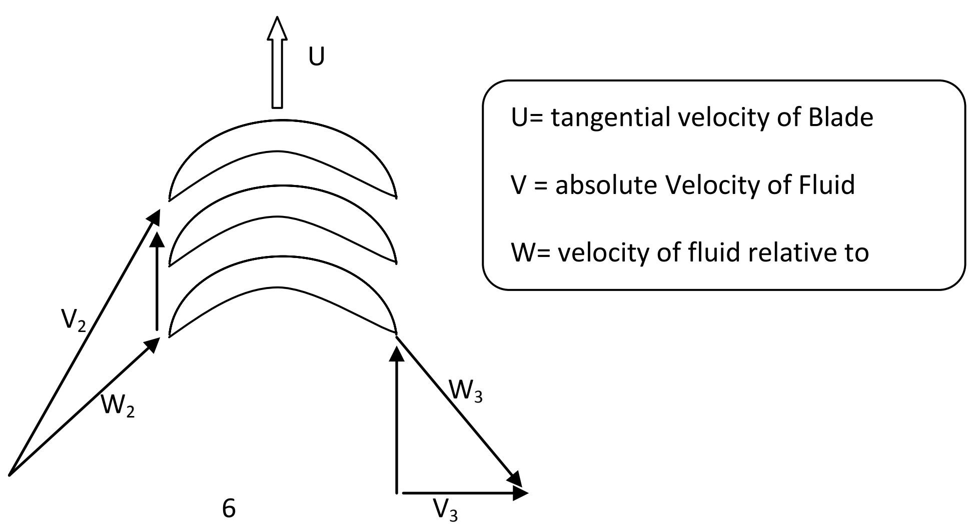
To maximize turbine efficiency the steam is expanded, generating work, in a number of stages. These stages are characterized by how the energy is extracted from them and are known as either *impulse* or *reaction* turbines. Most steam turbines use a mixture of the reaction and impulse designs: each stage behaves as either one or the other, but the overall turbine uses both. Typically, higher pressure sections are impulse type and lower pressure stages are reaction type.

An **impulse turbine** has fixed nozzles that orient the steam flow into high speed jets. These jets contain significant kinetic energy, which the rotor blades, shaped like buckets, convert into shaft rotation 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 (atmospheric pressure, or more usually, the condenser vacuum). Due to this higher ratio of expansion of steam in the nozzle the steam leaves the nozzle with a very high velocity. The steam leaving the moving blades is a large portion of the maximum velocity of the steam when leaving the nozzle. The loss of energy due to this higher exit velocity is commonly called the "carry over velocity" or "leaving loss".

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.

2. Theory

The first stage, including a convergent-divergent inlet nozzle is shown. Ideally there is no change in the magnitude of the relative velocities W_2 and W_3 between inlet and exit respectively. The large inlet absolute velocity V_2 has been reduced to a small absolute velocity V_3, which ideally is in the axial direction.



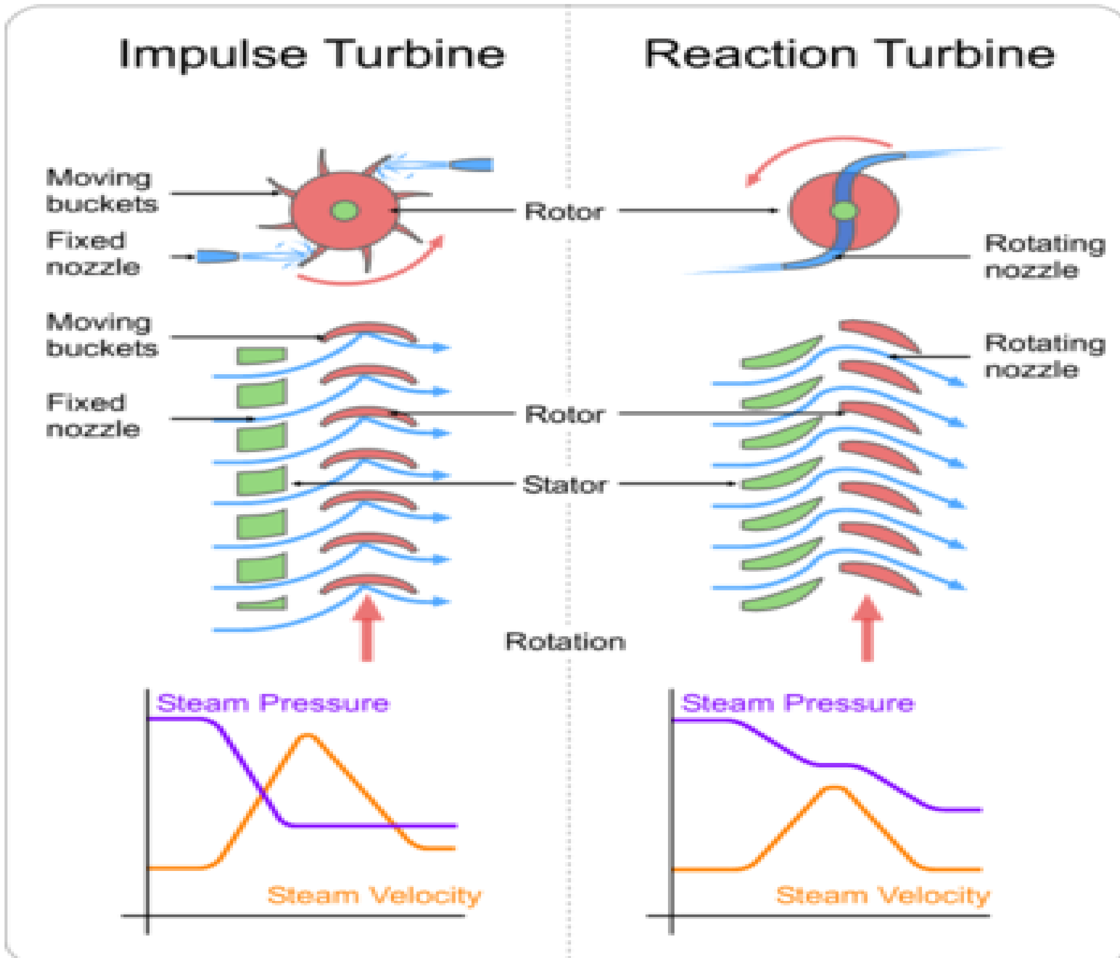


Fig 1.0

Availability of heat in static form, there is a need of some kind of mechanism in between process which creates motion or some form of dynamics. This dynamics will impact kinetic energy to the medium which then impact blades and rotate the shaft. No work can occur when there is some kind of rotation since work is equals to force time distance. $[w = \int f.ds]$

The first part in fig 1 is named as Stator and second part is named as Rotor. It is assumed that there is no loss of heat from casing of the turbine. The work is obtained from rotor and that will be equal to the change in energy. A combination of stator and rotor is called a stage. Generally, a typical steam turbine is made of combination of many stages to obtain ideal process and high thermal efficiency.

3. Design Parameters

- $Impulse\ Stage\ enthalpy\ \Delta h\ =\ 25 \sim 30\ Btu\ /\ lbm$
- $Revolution\ per\ minute\ of\ the\ turbine, RPM\ =\ 1800 \sim 3600$
- $The\ ration\ of, \frac{U}{V0}\ = 0.30 \sim 0.38$
- $Angel\ of\ absolute\ velocity\ \alpha_2\ =\ 10° \sim 15°$
- $Angel\ of\ relative\ velocity\ w_2\ = w_3\ and\ \beta_2\ = \beta_3$
- $Chord\ Length\ \sim 0.5$
- $\frac{c}{s} \sim 1$
- $Radius\ of\ the\ turbine\ interior\ are\ represented\ in\ ft$

4. Design Assumptions

- $The\ mass\ flow\ rate\ in\ the\ entrance\ region\ of\ the\ turbine = 286.9\ lbm/s$
- $Power\ produced\ in\ the\ Power\ Plant, P\ =\ 161{,}236.78\ Btu/s$
- $The\ Work\ produced\ by\ the\ Turbine = 563.38\ Btu/lbm$
- $Degree\ of\ reaction\ (R) =\ 0$
- $Rotor\ blade\ of\ the\ turbine\ are\ sysmetric$
- $Blades\ of\ the\ turbine\ are\ evenly\ spaced$
- $A\ turbine\ in\ steady\ state\ continiously\ spin$
- $Cascade\ to\ analyse\ flow\ through\ blade\ passages$
- $Relative\ inlet\ velocity\ and\ exit\ velocity\ and\ corresponding\ angle\ are\ equal$

$$w_2\ = w_3\ and\ \beta_2\ = \beta_3$$

5. Design Procedure

5.1 Geometric Modeling

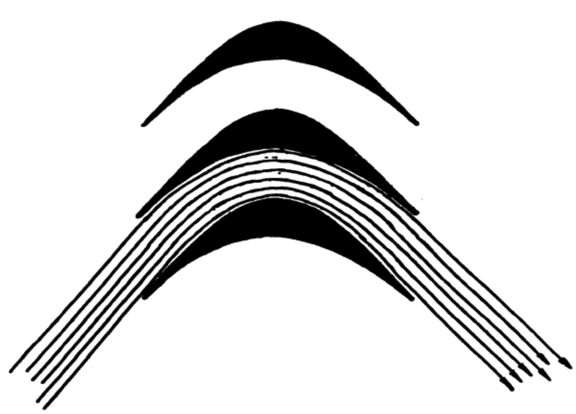
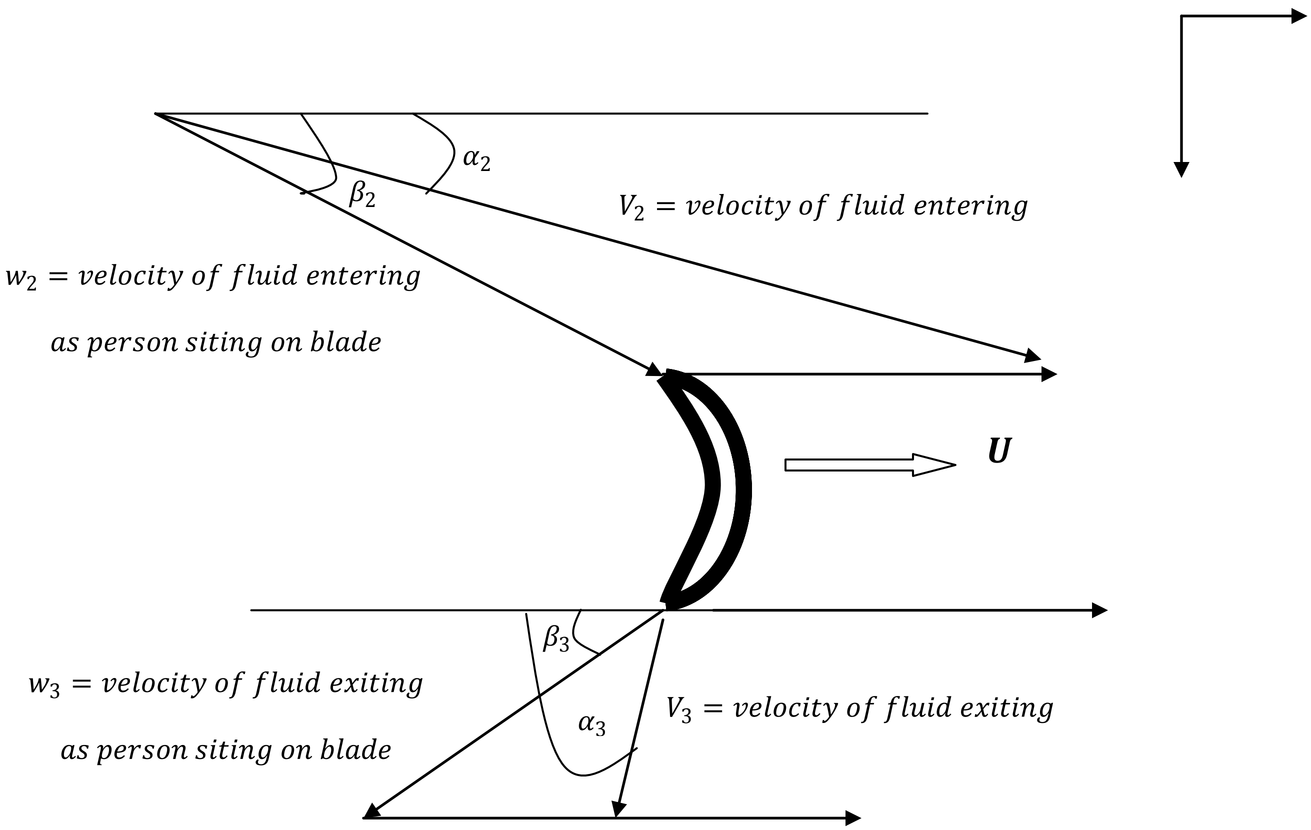


Fig 2. Fluid Flow path



<u>For Inlet:</u>

$$\vec{V_2} = \vec{w_2} + \vec{U}$$

Resolving in Rectangular components:

$$V_2 Cos\alpha_2 + V_2 Sin\alpha_2 = w_2 cos\beta_2 + w_2 Sin\beta_2 + U cos\ 0$$

<u>For Exit:</u>

$$\vec{V_3} = \vec{w_3} + \vec{U}$$

Resolving in Rectangular components:

$$-V_3 Cos\alpha_3 + V_3 Sin\alpha_3 = -w_3 cos\beta_3 + w_3 Sin\beta_3 + U cos\ 0$$

5.2 Results

Step 1:

$Assumed\ available\ heat\ (\Delta h) = 30\ \frac{Btu}{lbm}$

Step 2:

$Absolute\ Velocity\ of\ attack\ of\ fluid\ on\ blade\ (V_2)$

$$= \sqrt{2 * g_c * \Delta h * 778} = 1226.0\ \frac{ft}{sec}$$

Step 3:

$Tangential\ Velocity\ of\ the\ Blade\ (U)$

$$= V_2 * 0.38 = 0.38 * 1226.0 = 465.88\frac{ft}{sec}$$

Step 4:

Assumed angular velocity $(N) = 2400\ rpm = \frac{2\pi*2400}{60} = 251.32\ \frac{rad}{s}$

Step 5:

Tangential Velocity $(U) = N * r_m$

Step 6:

$mean\ radius\ (r_m) = \frac{U}{N} = \frac{465.88}{251.32} = 1.85\ ft$

Step 7:

$Absolute\ velocity\ anlge\ of\ attack\ at\ inlet\ (\alpha_2) = 12°$

Step 8:

$For\ inlet\ in\ Axial\ direction$

$$W_2\ sin\ \beta_2 = V_2\ sin\ \propto_2$$

$$W_2\ sin\ \beta_2 = 1226.0 * \sin(12) = 254.89\frac{ft}{s}$$

$For\ inlet\ in\ tangential\ direction$

$$W_2\ cos\ \beta_2 + U = V_2\ cos\ \propto_2$$

$$W_2 \cos\beta_2 = 1226.0 * \cos(12) - 465.88 = 733.32\frac{\text{ft}}{\text{s}}$$

Step 9:

$$Relative\ \ inlet\ velocity\ angle\ (\beta_2)$$

$$\frac{W_2 * sin\,\beta_2}{W_2 * cos\beta_2} = \frac{254.89}{733.32}$$

$$Tan\beta_2 = 0.35$$

$$\beta_2 = 19.1°$$

Step 10:

$$Relative\ \ inlet\ velocity\ (w_2) = \frac{254.89}{sin\,\beta_2} = 776.35\frac{ft}{s}$$

Step 11:

$$For\ exit\ in\ Axial\ direction$$

$$W_3\ sin\,\beta_3 = V_3\ sin\,\alpha_3\ [w_2 = w_3\ and\ \beta_2 = \beta_3]$$

$$V_3\ sin\,\alpha_3 = 776.35 * \sin(19.1) = 254.03\frac{ft}{s}$$

$$For\ exit\ in\ tangential\ direction$$

$$U - W_3\ cos\,\beta_3 = -V_3\ cos\,\alpha_3$$

$$V_3\ cos\,\alpha_3 = 776.35 * cos(19.1) - 465.88 = 267.73\frac{ft}{s}$$

Step 12:

$$\frac{V_3 * sin\,\alpha_3}{V_3 * cos\alpha_3} = \frac{254.03}{276.55}$$

$$Tan\alpha_3 = 0.91$$

$$\alpha_3 = 42.57°$$

$$\alpha_3 = 42.57°$$

Step 13:

$$Relative\ \ inlet\ velocity\ (V_3) = \frac{254.03}{\sin\,\alpha_3}$$

$$V_3 = 375.51\frac{ft}{s}$$

Step 14:

$Work\ done$:

$$W = (W_2 \cos\beta_2 + W_3 \cos\beta_3) * \frac{U}{g_c}$$

$$= 2 * 772.35 * cos\ 16 * \frac{465.88}{32.2}$$

$$W = 21{,}228.24\ \frac{Btu}{lbm}$$

Step 15:

$Efficiency$:

$$\eta = \frac{W}{(\frac{V_2^2}{2 * g_c})} = \frac{21{,}228.24}{\frac{1226.0^2}{2 * 32.2}} = 0.9009 = 90\ \%$$

Step 16:

$Specific\ Volume$:

$$Given\ Case: Inlet\ Pressure\ (P_2) = 1800\ psi$$

$$Inlet\ Temperature\ (T_2) = 1000\ F$$

$$From, superheated\ Table$$

$$v_2 = 0.44471 \frac{ft^3}{lbm}$$

Step 17:

$Length\ of\ blade$

$$l_1 = \frac{\mathring{m} * v_2}{2 * \pi * r_m * V_2 * \sin\alpha_2} = \frac{319 * 0.44471}{2 * \pi * 1.85 * 1226.00 * \sin(12)}$$

$$= 0.57\ inch$$

Step 18:

$Assume\ chord\ length\ (c) = 0.5\ inch$

Step 19:

$Blade\ spacing:$

$$0.85 = 2 * \frac{S}{c} (tan\ \propto_2 + tan\ \propto_3) * \cos^2\ \propto_3$$

$$S = \frac{0.85 * 0.5}{2 * (\tan(12) + \tan(42.57)) * (\cos(42.57))^2} = 1.35\ inch$$

Step 20:

$Number\ of\ blade:$

$$N * s = 2 * r_m * \pi$$

$$N = \frac{2 * 1.85 * \pi * 12}{1.35} = 104$$

Step 21:

$Loading\ Factor:$

$\psi = \frac{\Delta w}{U^2} = \frac{21228.45 * 32.2}{(465.88)^2} = 3.14 > 3$ (Approximately around the SAFE value)

5.3 Optimization

Though in most case it was found that loading factor was below the maximum allowable values however, some data gave huge value for number of blade or sometime very small length for the turbine blade. Hence multiple cases were tried for the best result that suited the requirements of single stage impulse steam turbine.

6. Discussion

- The Turbine can develop under the conditions above discussed, but this project is for only one stage of the design.
- The length of the blades seems reasonable for this kind of design because the Toque produce into this blade needs to be transformed into movement in the shaft.
- The Work Produced by the Turbine can be useful for electric generator of medium Power.

- The steam mass flow rate must be adequate at the entrance region for better performance in the cycle. The mass flow rate varies from millions of pounds per hour, it depends the total energy produced in the whole process cycle.
- From the calculation loading factor is less than giving condition so overall calculations and the results are desirable.

7. Conclusion

We can conclude that in a steam turbine there will be two parts, the first will convert heat to kinetic energy and the second part will convert the kinetic so obtained to work. The numerical values found at the calculations are acceptable for this kind of design because the design is based in the entrance region of the Impulse Stage at the Turbine. The obtained values widely varied as there are uncertain changes in other given parameters. The design of turbine must be done with accuracy and precision, as the turbine is one of the most indispensable parts at the Power Plant. The turbine requires more development and precision than the other parts because the blades bears the centrifugal force and any fatigue deformation can created substantial damage to entire structure of the turbine. Nowadays electrical power is one of the essential for human beings. The simple steam power plants are the predominant producer of electricity in the world and most fundamental industrial gear.

For the design of this turbine the following requirements are needed such as: the mass flow rate which is found at the turbine entrance, the power required keeping working in excellent conditions the turbine cycle, and perhaps the amount of energy or work produced during the turbine cycle.

8. Reference

1. http://en.wikipedia.org/wiki/Steam_turbine
2. Rishi S. Raj, Preliminary Steam Turbine Design, chapter 14.