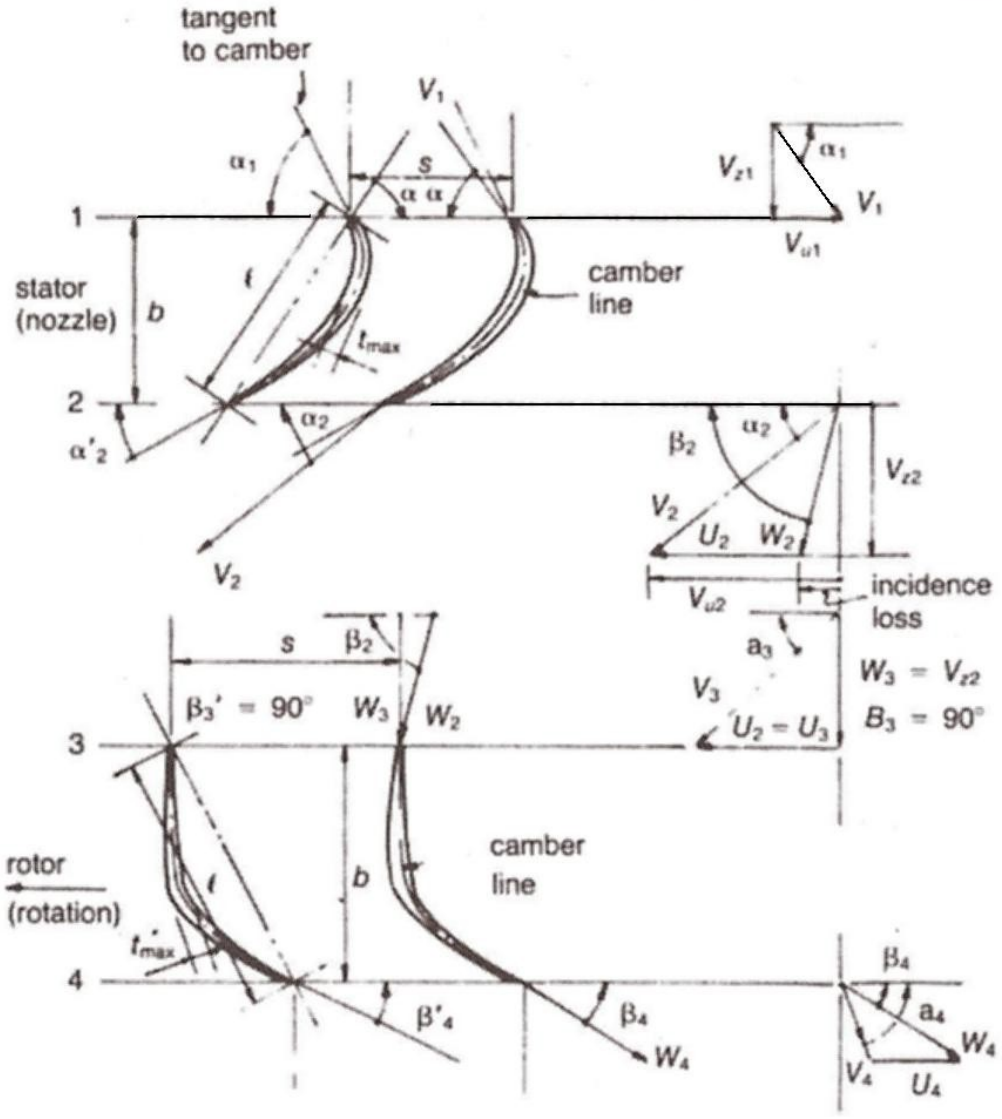
The new gas turbines being designed for the new millennium are investigating the use of steam as a cooling agent for the first and second stages of the turbines. Steam cooling is possible in the new combined cycle power plants, which is the base of most of the new high performance gas turbines. Steam, as part of the cooling as well as part of the cycle power, will be used in the new gas turbines in the combined cycle mode. The extra power obtained by the use of steam is the cheapest MW/$ available. The injection of about 5% of steam by weight of air amounts to about 12% more power. The pressure of the injected steam must be at least 40 Bar above the compressor discharge. The way steam is injected must be done very carefully so as to avoid compressor surge. These are not new concepts and have been used and demonstrated in the past. Steam cooling for example was the basis of the cooling schemes proposed by the team of United Technology and Stal-Laval in their conceptual study for the U.S. Department Of Energy study on the High Turbine Temperature Technology Program, which was investigating Firing Temperatures of 3000 °F (1649 °C), in the early 1980s.

There are three state points within a turbine that are important when analyzing the flow. They are located at the nozzle entrance, the rotor entrance, and at the rotor exit. Fluid velocity is an important variable governing the flow and energy transfer within a turbine. The absolute velocity (V) is the fluid velocity relative to some stationary point. Absolute velocity is important when analyzing the flow across a stationary blade such as a nozzle. When considering the flow across a rotating element or rotor blade, the relative velocity W is important. Vectorially, the relative velocity is defined

$$\vec{W} = \vec{V} - \vec{U} \tag{9-1}$$

where U is the tangential velocity of the blade. This relationship is shown in Figure 9-2.

Two angles are defined in Figure 9-2. The first angle is the air angle α, which is defined with respect to the tangential direction. The air angle α represents the direction of the flow leaving the nozzle. In the rotor, the air angle α represents the angle of the absolute velocity leaving the rotor. The blade angle β is the angle the relative velocity makes with the tangential direction. It is the angle of the rotor blade under ideal conditions (no incidence angle).



Stator: incidence $t_s = \alpha_1 - \alpha_1'$ $t_s > 0$ when $\alpha_1 > \alpha_1'$
deviation $\sigma_s = \alpha_2' - \alpha_2$
deflection $t_s = \alpha_1 + \alpha_2$ camber $\theta_s = \alpha_1' + \alpha_2'$
Rotor: incidence $t_r = \beta_2 - \beta_3'$ $t_r > 0$ when $\beta_2 > \beta_3'$
deviation $\sigma_r = \beta_4' - \beta_4$
deflection $t_r = \beta_2 - \beta_4$ camber $\theta_r = \beta_3' + \beta_4'$

Figure 9-2. Stage nomenclature and velocity triangles.

Degree of Reaction

The degree of reaction in an axial-flow turbine is the ratio of change in the static enthalpy to the change in total enthalpy

$$R = \frac{h_1 - h_4}{h_{01} - h_{04}} \tag{9-2}$$

A rotor with a constant radius and an axial velocity constant throughout can be written

$$R = \frac{\left(W_4^2 - W_3^2\right)}{\left(V_3^2 - V_4^2\right) + \left(W_4^2 - W_3^2\right)} \tag{9-3}$$

From the previous relationship, it is obvious that for a zero-reaction turbine (impulse turbine) the relative exit velocity is equal to the relative inlet velocity. Most turbines have a degree of reaction between 0 and 1; negative reaction turbines have much lower efficiencies and are not usually used.

Utilization Factor

In a turbine, not all energy supplied can be converted into useful work—even with an ideal fluid. There must be some kinetic energy at the exit that is discharged due to the exit velocity. Thus, the utilization factor is defined as the ratio of ideal work to the energy supplied

$$E = \frac{H_{id}}{H_{id} + \dfrac{{V_4}^2}{2g}} \tag{9-4}$$

and it can be written in terms of the velocity for a single rotor with constant radius

$$E = \frac{\left({V_3}^2 - {V_4}^2\right) + \left({W_4}^2 - {W_3}^2\right)}{{V_3}^2 + \left({W_4}^2 - {W_3}^2\right)} \tag{9-5}$$

Work Factor

In addition to the degree of reaction and the utilization factor, another parameter used to determine the blade loading is the work factor

$$\Gamma \equiv \frac{\Delta h_\theta}{U^2} \tag{9-6}$$

and it can be written for a constant radius turbine

$$\Gamma = \frac{V_{\theta 3} - V_{\theta 4}}{U} \tag{9-7}$$

The previous equation can be further modified for the maximum utilization factor where the absolute exit velocity is axial and no exit swirl exists

$$\Gamma = \frac{V_{\theta 3}}{U} \tag{9-8}$$

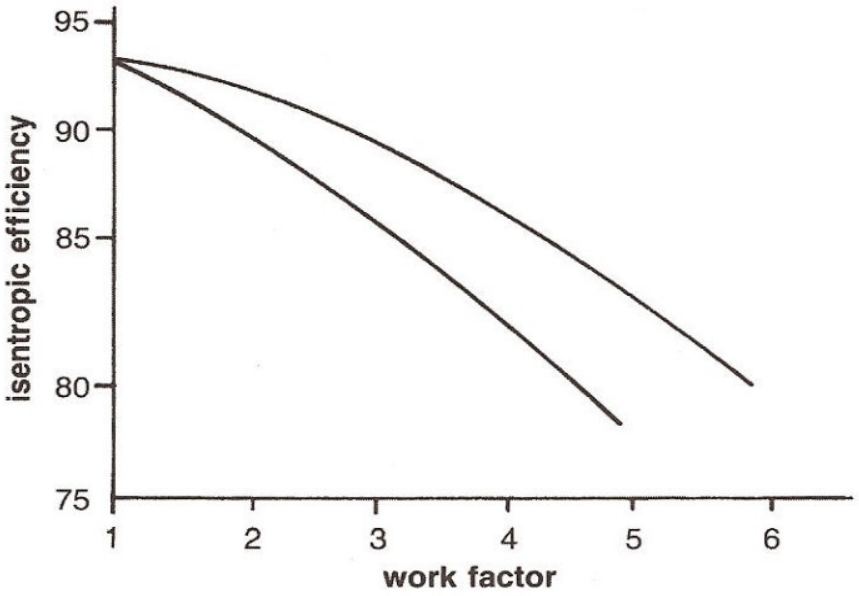


Figure 9-3. Effect of stage work on efficiency.

The value of the work factor for an impulse turbine (zero reaction) with a maximum utilization factor is two. In a 50% reaction turbine with a maximum utilization factor the work factor is one.

In recent years the trend has been toward high work factor turbines. The high work factor indicates that the blade loading in the turbine is high. The trend in many fan engines is toward a high by-pass ratio for lower fuel consumption and lower noise levels. As the by-pass ratio increases, the relative diameter of the direct-drive fan turbine decreases, resulting in lower blade tip speeds. Lower blade tip speeds mean that with conventional work factors, the number of turbine stages increases. Considerable research is being conducted to develop turbines with high work factors, high blade loadings, and high efficiencies. Figure 9-3 shows the effect of turbine stage work and efficiency. This diagram indicates that efficiency drops considerably as the work factor increases. There is little information on turbines with work factors over two.