Aerodynamic design of advanced LP steam turbines

The complex nature of the three-dimensional and transonic flow in large LP steam turbines, especially in the last stages, has often made it difficult in the past to introduce new design features, mainly because the available design tools have been unable to predict the consequences with sufficient accuracy. Modern, fully three-dimensional software enables steam turbine designers to apply the new ideas to actual designs. By allowing an increase in the maximum exhaust area per flow, the new technology makes it possible to reduce the number of flows, and hence costs, as well as significantly increase the design point efficiency and extend the operating range.

As power plants and steam turbines have increased in size and rating, the total exhaust area of the LP turbines has had to be continually enlarged to enable them to handle the larger steam volumes. At the same time, design engineers have to try to reduce the number of flows in order to keep costs down. Efforts therefore concentrate on achieving a large exhaust area per flow.

Every type of LP steam turbine can be characterized by its outlet or exhaust area, S **2**.

$$S = \pi d_m^2 \frac{h}{d_m} \approx \pi r_t^2 \left(1 - \frac{r_h^2}{r_t^2}\right) \qquad (1)$$

where

d_m Mean diameter

h Blade height

r_h Hub radius

r_t Casing radius

For an LP steam turbine to be cost-competitive it has to have a small mean diameter. As long last-stage rotor blades are necessary to ensure the required exhaust area, either the blade height to diameter ratio, h/d_m, has to be high or the hub to tip ratio, r_h/r_t, has to be low. The value of h/d_m is an indicator of the three-dimensionality of the flow through the last stage of an LP steam turbine. Typical values for present-day designs are $0.35 < h/d_m < 0.40$ and $0.43 < r_h/r_t < 0.46$. The higher the chosen h/d_m, the more complex the aerodynamic design of the last-stage blade will be.

In addition to the aerodynamic problems, the probability of a natural mode being excited grows as the blade becomes longer. The stresses due to centrifugal forces increase and dictate the cross-sectional area distribution over the blade height. Thus, designing a last-stage blade which satisfies the aerodynamic and the mechanical requirements simultaneously can be a complex and demanding task.

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Approaches to these problems have been suggested in the literature [1,2] for many years. Calculation tools are available today with which these approaches can be applied to actual designs.

Flow through the last stage of a traditional large LP steam turbine

3 shows the radial flow distribution for a typical older design of the last stage of an LP turbine [3].

The task of a vane is to deflect the flow and generate swirl. This swirl downstream of the vane (1) causes a positive radial pressure gradient from the hub to the blade tip, which is responsible for the strong negative Mach number gradient at the vane exit (Ma_1). The low pressure at the hub leads to undesirable low hub reaction, which can cause local separation. The Mach number gradient at the vane exit subjects the last rotor blade to a high inlet Mach number at both the hub and the tip (Ma_{w1}). High inlet Mach numbers make it very difficult to avoid shock waves around the leading edge and also make the rotor blades very sensitive to off-design incidences. The combination of the vane exit Mach number profile and the radially increasing circumferential velocity leads to a huge variation in the inlet flow angle of the rotor blade (β_1), due to which a strongly twisted blade is required. This results in high shear stresses in the rotor blade, which are superimposed on the high normal stresses caused by centrifugal forces.

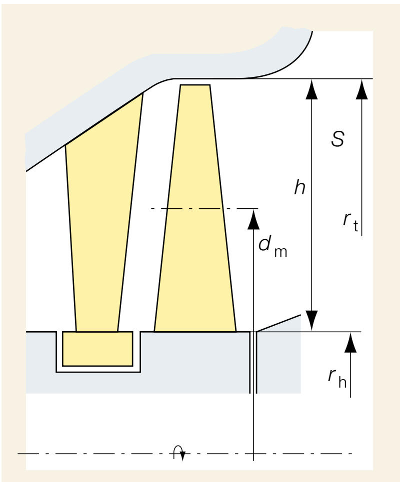
ABB advanced low-pressure turbine rotor. Modern, fully viscous 3-D calculation software allows a reduction in the number of flows plus a significant increase in the design point efficiency and an extended operating range. **1**

The described effects occur in every axial turbine. However, the higher the ratio h/d_m, the steeper the radial gradients and the more significant these undesirable effects will be.

Former LP turbine designs were normally restricted by having to have an almost constant hub radius **4** [4]. The rapidly increasing volume of steam leads to a large casing pitch angle and an undesirably high h/d_m ratio for the last stage. Due to the high tip speed, the flow conditions are transonic or supersonic and highly three-dimensional even when no consideration is given to the endwall flow phenomena. This three-dimensionality is caused by the strong radial variations in the flow parameters as well as by the large streamline pitch angles that occur.

Main dimensions of the last stage of an LP steam turbine **2**

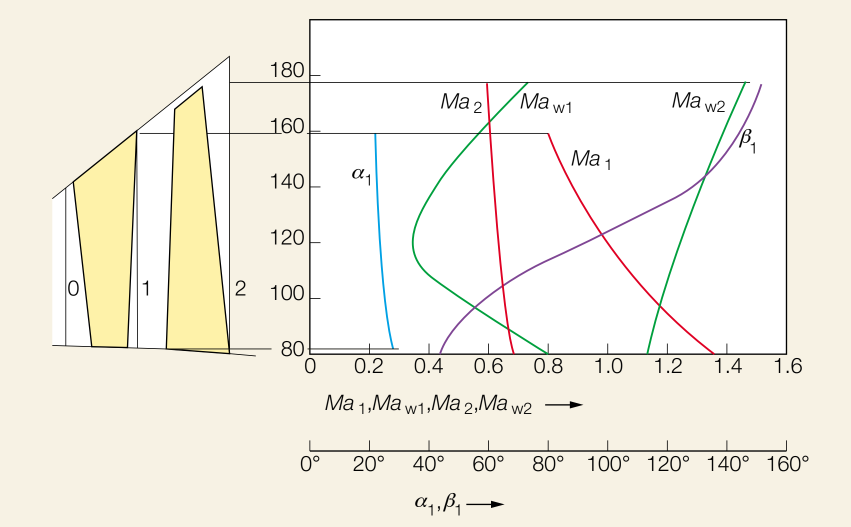
d_m Mean diameter of rotor
h Blade length
r_h Hub radius
r_t Casing radius
S Exhaust area



Design problems and their solutions

The main problem encountered when designing the last stage of a large LP turbine is the strong radial pressure gradient or the strong Mach number gradient after the vane, each of which is caused by the high h/d_m ratio. Cost considerations and stress limitations are the two main factors preventing a smaller h/d_m ratio from being chosen (increased d_m and reduced h). It is shown in [5] that when the rotor blade is made of steel, h/d_m has to be chosen in the range 0.35 to 0.40 to obtain a maximum exhaust area **5**. Thus, the aerodynamicist must find other ways of reducing the radial gradients:

It has been proved [2] that a concave upwards curvature of the stream-



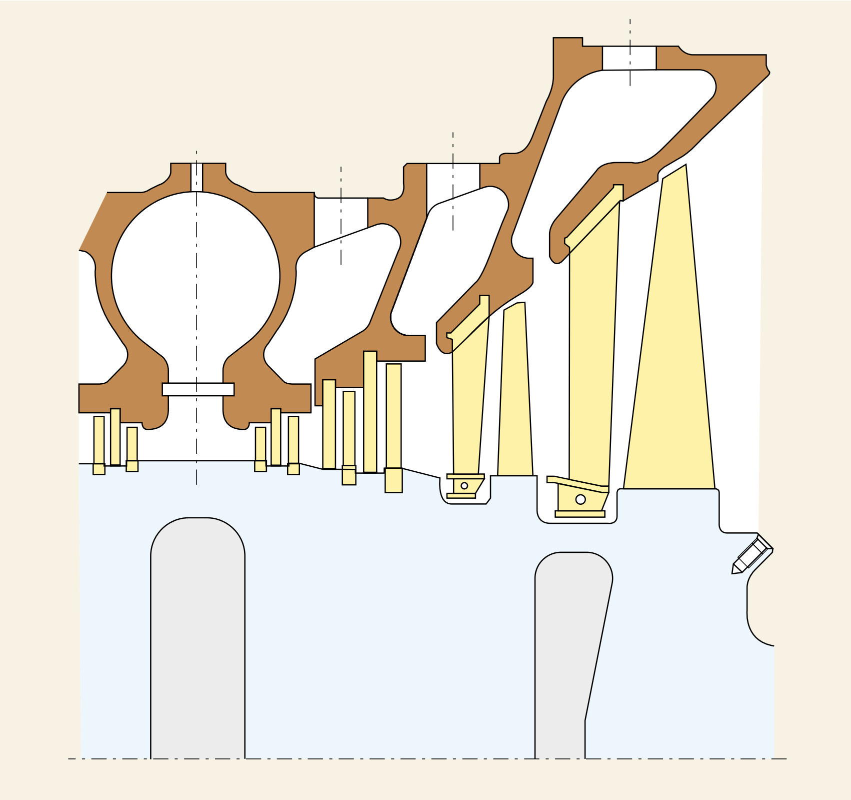
Flow conditions for a typical last stage of a high-speed LP steam turbine [3] **3**

0 *Stator blade inlet*
1 *Stator blade outlet (rotor blade inlet)*
2 *Rotor blade outlet*

Ma_1, Ma_2 *Mach numbers, absolute reference frame*
Ma_{w1}, Ma_{w2} *Mach numbers, relative reference frame*

α_1 *Exit flow angle, absolute reference frame*
β_1 *Inlet flow angle, relative reference frame*

Flow path through a typical large LP steam turbine [4] **4**



lines (towards the casing) must be introduced upstream of the rotor. Such a curvature generates a negative radial pressure gradient which counteracts the positive pressure gradient caused by the swirl.

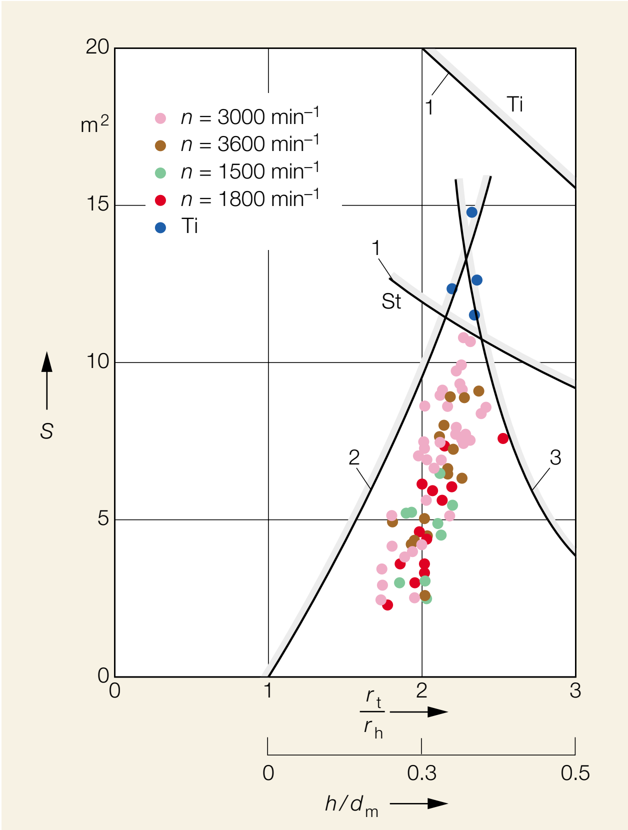
The issue confronting the designer is: How can this curvature be achieved?

Several approaches are possible:

- The simplest way is to open the vane at the hub and close it at the tip in what is known as a ‘forced vortex’ design. The radial mass flow distribution is coupled directly to the radial throat area distribution, with the result that the designer has to accept the resulting mass flow distribution, including a maximum mass flow near the hub. This method has nevertheless been chosen for many designs.
- An additional degree of freedom is gained by giving the vane a certain angle of lean, such that the pressure surface faces down towards the hub **6a**. A leaned vane generates an additional radial force that acts on the flow, pushing it downwards in the direction of the hub. The streamlines are thus given the desired upward curvature, which partly balances the radial pressure gradient due to the swirl.
- A similar effect can be imposed on the flow by sweeping the vane backwards from the hub to the tip. The non-radial stacking of the blockage (ie, profile sections) within the annulus generates a radial force which is directed towards the hub, accompanied by the same effect on the streamlines that blade lean produces **6b**.

In addition, the streamline curvature can be dictated directly by the shape of the hub contour **7**.

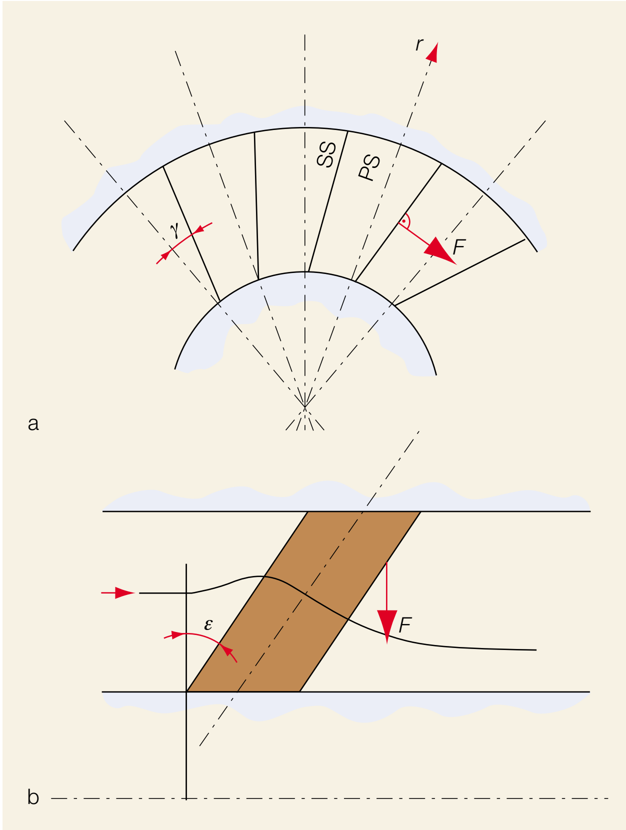
Combinations of the above design features are of course possible, thus providing the steam turbine designer with addi-



Compilation of actual last-stage parameters of different manufacturers [5] **5**

1 Combined blade stress and cascade geometry limit
2 Rotor stress limit
3 Blade frequency limit

St	*Steel*	h	*Blade height*
Ti	*Titanium*	r_h	*Hub radius*
S	*Exhaust area*	r_t	*Tip radius*
d_m	*Mean diameter of rotor*	n	*Rotational speed*



Blade lean (a) and sweep (b) **6**

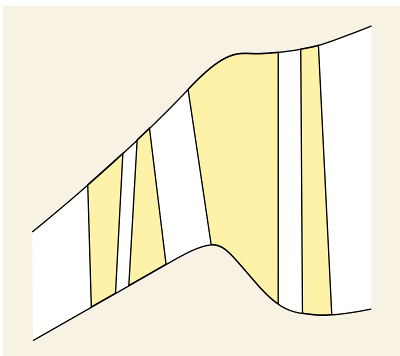
r	*Radius*
F	*Radial force*
PS	*Pressure side*
SS	*Suction side*
γ	*Lean angle*
ε	*Sweep angle*

tional degrees of freedom for improving the last-stage flow conditions and efficiency in spite of the disadvantageous length to diameter ratio.

The design tools available in the past had too many shortcomings and were not able to predict the effects of the above-described design features with the accuracy required for use in an actual design. Calculation tools as well as computer hardware have meanwhile improved significantly. Nowadays, one or more stages can be calculated simultaneously using a fully 3-D Navier-Stokes code, enabling the described approach to be used as part of the daily design process.

Three-dimensional design features can therefore be applied to advanced LP turbines.

Hub contouring suggested by Denton [2] **7**



Advanced LP turbine design philosophy

8 and **9** show an ABB advanced LP turbine design and its most striking feature – the highly three-dimensional geometry of the last vane.

In a classical design the pitch angles of the streamlines can reach 60° **10**. The flow tends to separate from the hub, while the mass flow concentrates near the casing. The streamlines cut the radially stacked vane at angles ⩽90°, ie they experience a significant sweep angle. In the case of the leaned and swept vane (the lean is not visible in the meridional cut), the inclination angles tend to be perpendicu-

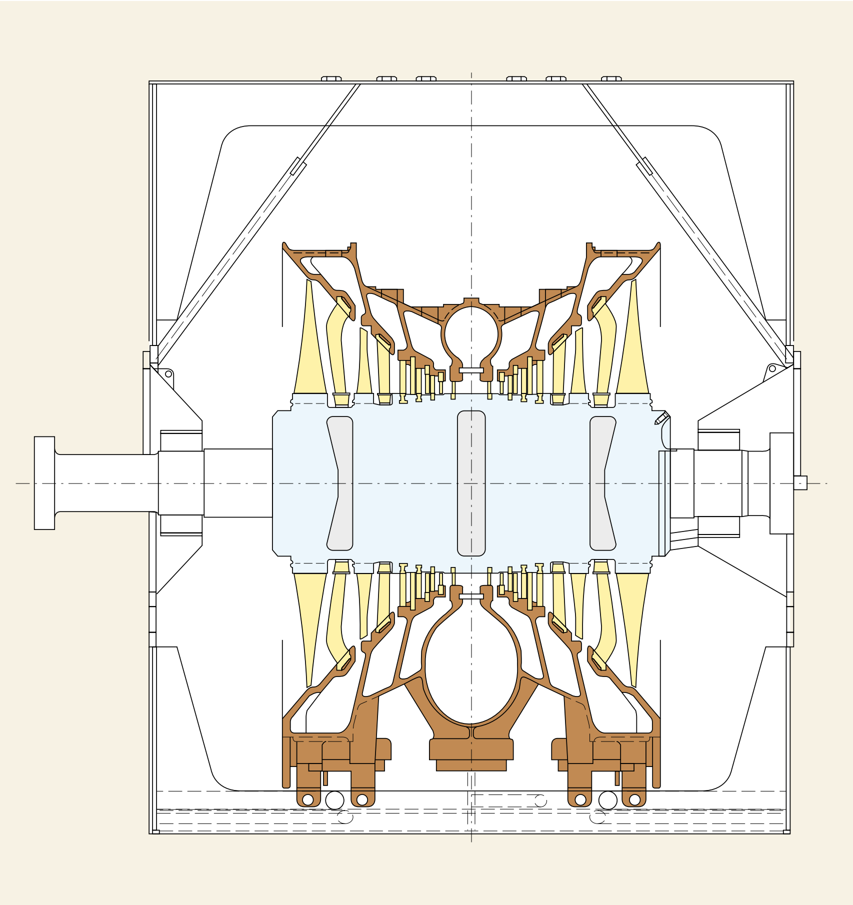
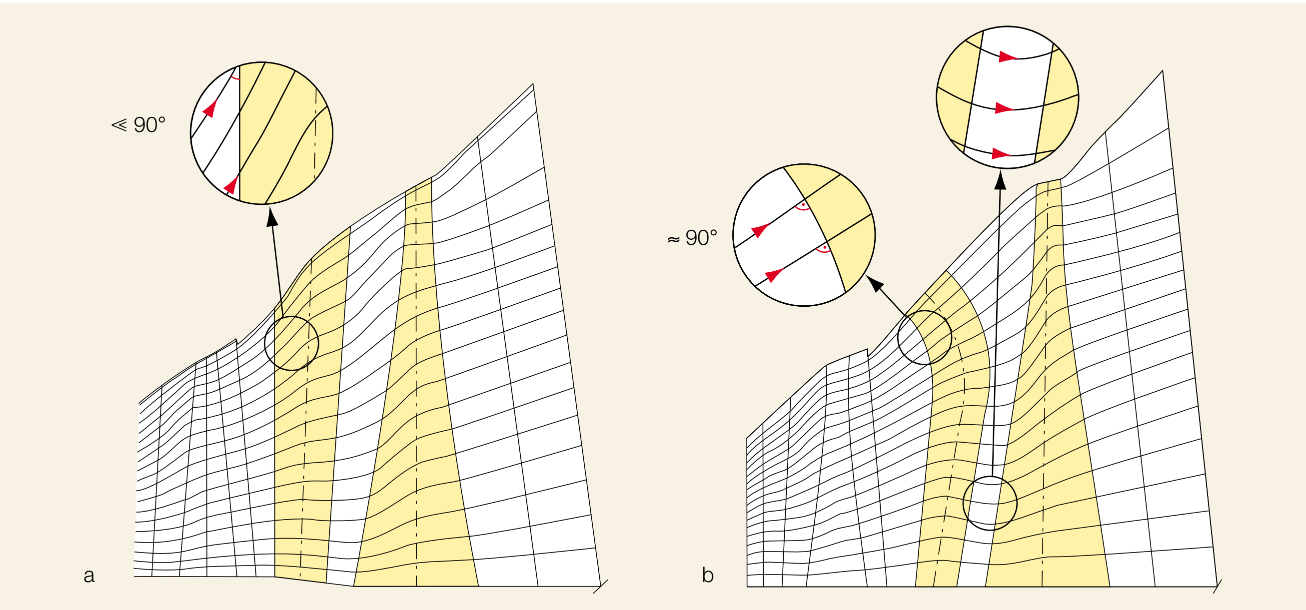


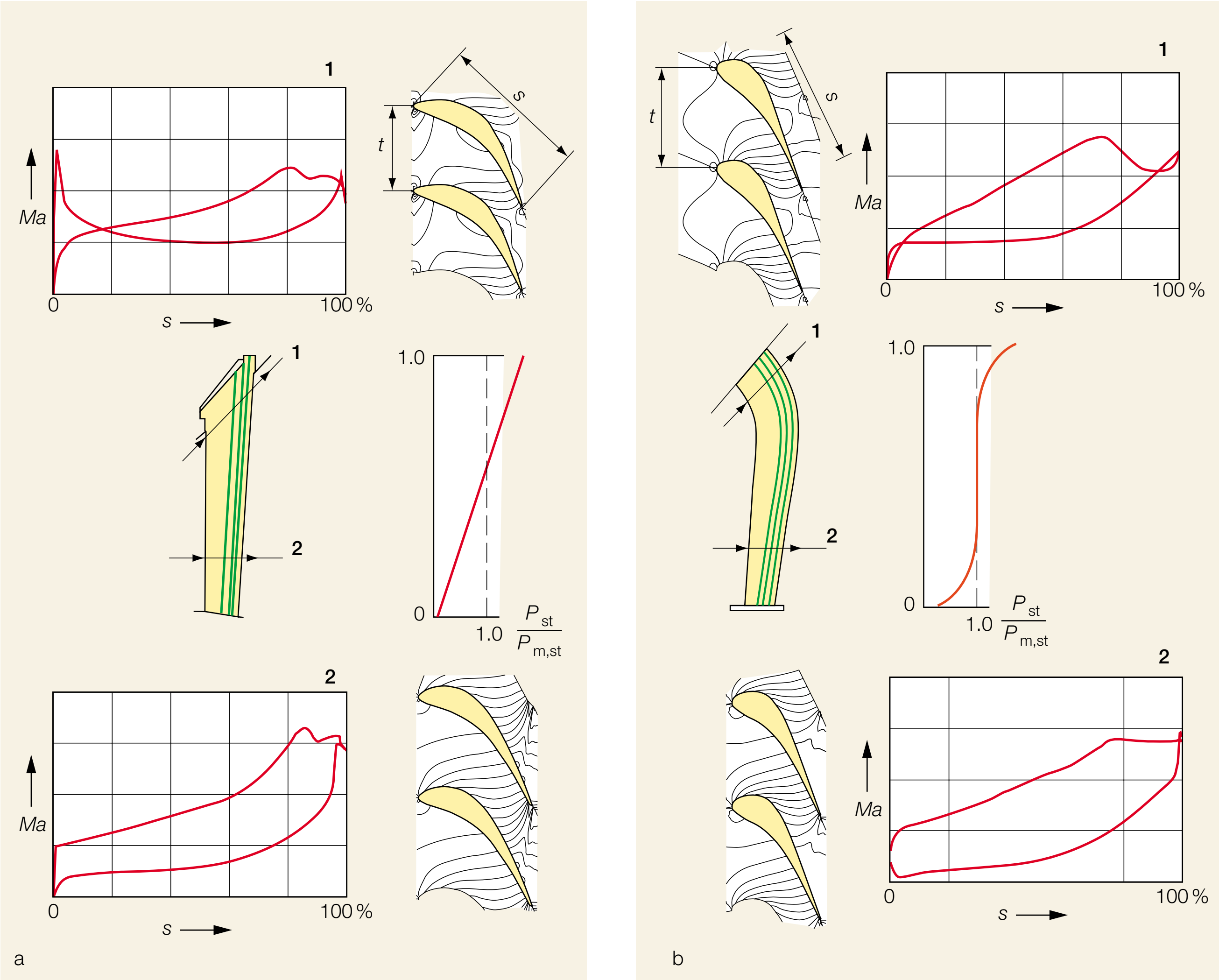
ABB advanced LP turbine featuring highly three-dimensional geometry for the last-stage vanes **8**

Full-scale model of the advanced 3-D vane **9**

Effects of the 3-D vane on meridional flow behaviour **10**

a 'Classical' vane b Last vane with lean and sweep





Benefits of 3-D vane geometry **11**

a *Classically designed vane*
b *Blade with lean and sweep (optimized t/s)*

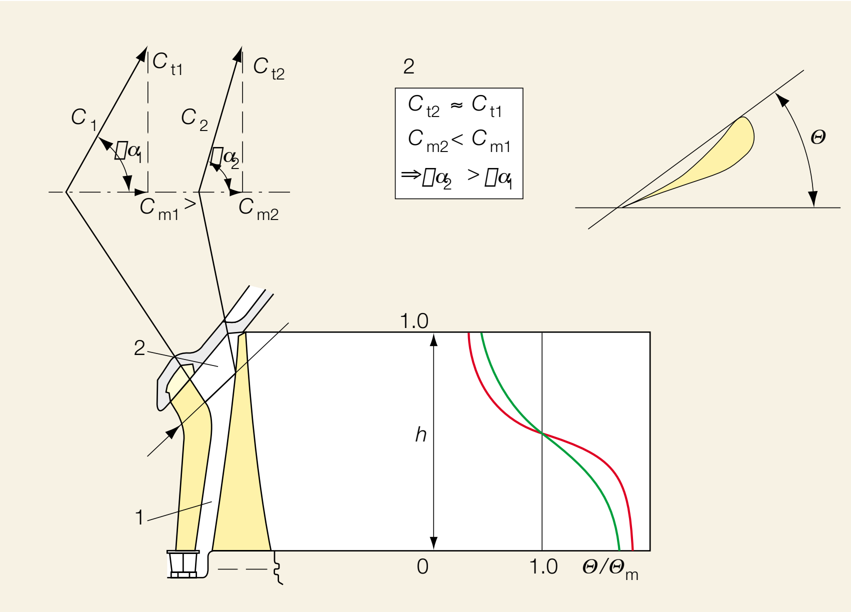
1 *Casing streamline*
2 *Hub streamline*

Ma *Mach number*
P_{st} *Static pressure*
$P_{m,st}$ *Mean static pressure*
s *Chord*
t *Pitch*

lar. The more uniform streamline fanning shows that the radial mass flow distribution is equalized. The lean and sweep angle of the vane produce an additional radial force which acts on the flow, increasing the hub reaction and preventing flow separation. This additional radial force is visible as the upward curvature of the streamlines close to the rotor hub **10**.

As already mentioned, the main problems involved in designing the last stage of an LP turbine are the steep pressure and the velocity gradients at the vane exit. In the case of a classically designed vane **11a** they cannot be avoided, but by introducing blade lean and sweep a pressure distribution which is at least partly constant can be achieved **11b**. The hub reaction is increased and the tip reaction is lowered as a result.

Although the radially stacked vane is regarded as being ‘unswept’, the casing streamlines nevertheless experience a significant sweep angle. The profile shape as well as the Mach number distribution vary radially **11a**. In the case of the swept vane, all the streamlines cut the isobars nearly perpendicularly. Since the leading and trailing edges neither have to be straight nor radial, the pitch (*t*) to chord (*s*) ratio, *t/s*, can be optimized on the basis of the radial loading distribution. Consequently, the profile shape and the Mach number distribution are



Twisting of last rotor blade **12**

1 *Elimination of axial diffuser effects*
2 *Exploitation of axial diffuser effects*

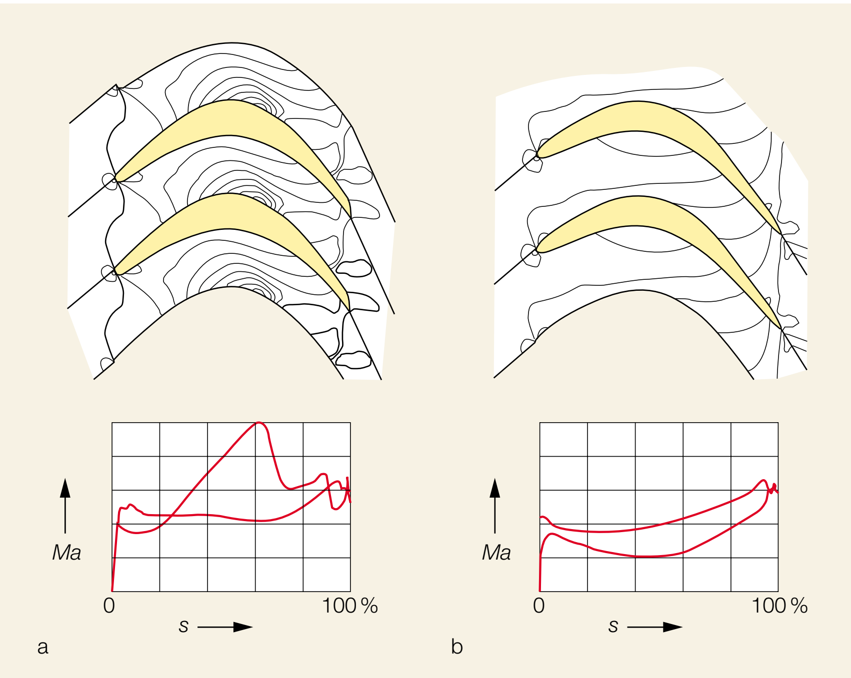
Red *Downstream of a 'classical' vane geometry*
Green *Downstream of a 3-D vane geometry*

α_1, α_2 *Flow angles (absolute reference frame)*
C_1, C_2 *Absolute velocity*
C_{t1}, C_{t2} *Tangential velocity*
C_{m1}, C_{m2} *Meridional velocity*
h *Blade height*
Θ *Stagger angle, rotor blade*
Θ_m *Mean stagger angle*

very similar along the full length of the swept vane. Also, transverse pressure gradients are practically eliminated. The surprising result of the highly three-dimensional vane geometry is that the flow conditions become more two-dimensional.

Besides the described effects on the stator flow itself, the non-radial stacking of the vane profiles also provides the designer with an additional degree of freedom for optimizing the rotor inflow conditions **12**. By reducing the axial distance between the trailing edge of the vane and the leading edge of the rotor in the lower ⅔ of the annulus (1) and increasing the distance in the upper ⅓ of the annulus, axial diffuser (2) effects can be eliminated in the lower ⅔ or exploited in the upper ⅓. The deceleration of the meridional velocity within the interstage axial diffuser is used to control the rotor inlet angle distribution. In contrast to the classically stacked vane, the vane exit angle distribution, rotor inlet angle distribution and radial mass flow distributions are at least partially decoupled in the case of a swept vane, allowing them to be optimized simultaneously. The main benefit of this is that the rotor blade is less twisted. Together, the reduced twist and the smaller gradient of the radial twist distribution effectively reduce the shear stresses in the rotor blade.

A large proportion of the losses in the last stage of an LP steam turbine is generated by the compression shocks that occur within and downstream of the blade passages. **13** compares an older design

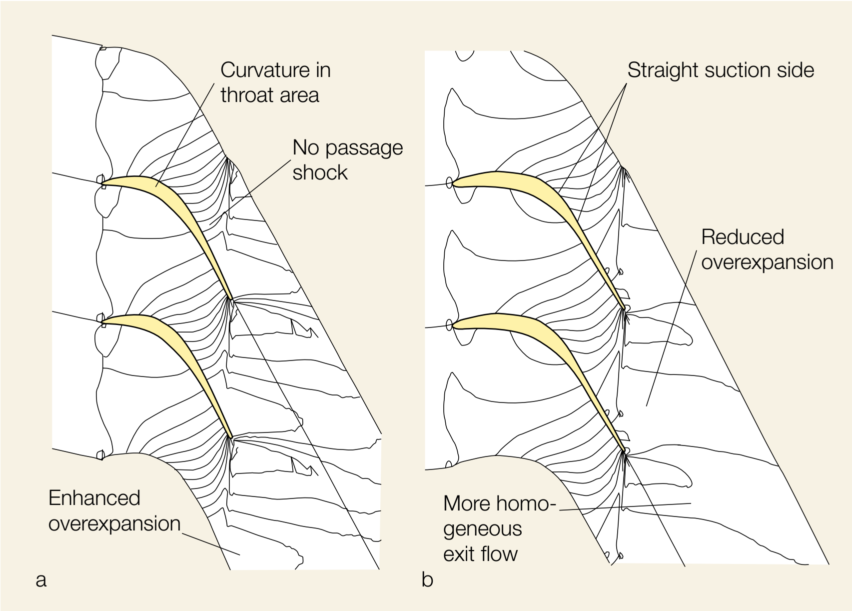


Optimization of the last-stage rotor hub section **13**

a *Older design with strong inter-passage shock*
b *Optimized design*

Ma *Mach number*
s *Chord*

and an optimized design of a last-stage rotor blade root section. Classical rotor hub sections were found to be very sensitive to inlet or inter-passage shocks under certain operating conditions. The advanced 3-D vane geometry substantially improves the inlet conditions for the rotor, allowing advanced rotor blade profiles to be applied which prevent inlet as well as inter-passage shocks over the entire operating range. Mid-height profile sections of the last-stage blades are characterized by low subsonic inlet Mach numbers and high supersonic exit Mach numbers **14**. Hence, shock losses make a major contribution to the overall losses. Straightening the suction side in the region of the throat and downstream of it allows a reduction in the peak Mach number as well as in the overexpansion, and the exit flow becomes far more uniform. The shock and mixing losses decrease significantly as a result.



Optimized transonic rotor blading **14**

a *Classical profile design*

b *Optimized profile design*

Conclusions

The solution to problems encountered when designing the last stages of large LP steam turbines is a concave upwards curvature of the streamlines, introduced upstream of the rotor. Several approaches to the problem are possible. The complexity of the highly three-dimensional and transonic flow prevented these approaches from being adopted in the past due to the available calculation and design tools being unable to predict and evaluate the effects with the required accuracy.

Modern fully viscous 3-D calculation tools are in use nowadays which have been validated by measurements and are therefore trustworthy. They enable steam turbine designers to adopt the described approaches for actual designs. Due to this new technology, the maximum exhaust area per flow can be increased, allowing the number of flows, and hence costs, to be reduced. In addition, they allow a remarkable increase in the design point efficiency plus an extended operating range.

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