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HIGH STAGE LOADING LOW PRESSURE TURBINES. A NEW PROPOSAL FOR AN EFFICENCY CHART

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ABSTRACT

In 1999, ITP (Industria de Turbopropulsores, S.A) launched a wide on-going research and development program to advance the state of the art in Low Pressure Turbines for use in future high bypass ratio aeroengines for long range civil transport.

The objectives of the program were very aggressive in order to satisfy the market demands. Enormous cost and weight savings (about 30% off) were required, equalling or even improving the efficiency and noise emissions.

Through that program, ITP has continuously reduced the components of the turbine, as the most adequate way to achieve the previous targets. As result of that reduction, High Stage Loading Turbine technology has being developed.

High stage loading turbines have less number of stages to produce the same work output (high stage loading), fewer numbers of blades to perform the same duty (high and ultra high lift blades) and low rotational velocities.

An overview of the two options of high stage loading turbines, high through flow and low through flow, is introduced and how both approaches allow an important reduction in weight and number of components (stages and blades). It is also shown that keeping the same levels of efficiency and noise than conventional turbines, is a technical challenge that demands improved aerodynamics or/and higher rotational velocity.

This paper describes the current technology limits that are exceeded by high stage loading turbines and the special aerodynamic and geometrical features that come up. Special attention must be highlighted when the stage loading is increased over 50%. In those cases the Mach number limit is exceeded and the pressure ratio per stage is risen as much than transonic blades can not be avoided.

Even on those extreme cases the pressure ratio levels and referred work are still far from typical values of high-pressure turbines and geared low-pressure turbines, and considering the high efficiencies achieved for those last two types of turbines, someone could wonder whether a specific research program is required. To conclude the paper, a new efficiency chart, alternative to Smith Chart, is presented to support the answer to the previous reasonable question.

INTRODUCTION

The design objectives for the future high by-pass ratio civil aeroengines require significant reductions in the weight of the engine, the cost of production, the loss of efficiency and the level of noise emissions.

Low Pressure Turbine is the largest simple component in the engine, it can comprise one third of the total engine weight and approximately a 15% of the total cost. The efficiency of the low-pressure turbine has also a large effect on the overall specific fuel consumption. Typically, a 1% increase in low-pressure turbine efficiency gives rise to 0.7% increase in engine overall efficiency (Wisler, 1998). Therefore, the reduction of LP turbine losses, weight and cost is very important to achieve the engine design targets.

However, it is very complicated for the low pressure turbine to help in obtaining the objectives, as it requires more number of stages because the new generation of large thrust civil engines demand fans of larger diameter that need more power and lower rotational speed.

Several approaches have been followed by ITP to fulfil those huge reductions: number of blade reduction (ultra high lift blades), number of stages reduction (high stage loading turbines), design improvements (blade pairs, integral vanes, etc.), new lighter materials (Ti-Al blades) and improved manufacturing processes.

In over 10 years of extensive research, the weight and manufacturing cost of the LP turbine was reduced by decreasing almost a 20% the number of airfoils. To date, that technology baptized as high lift is successfully used in modern turbines which have reduced the number of airfoils in a given blade row whilst maintaining efficiency (Schulte and Hodson, 1996 and Curtis, 1996). Recently, further attempts to increase even more the lift coefficient have been carried out by Howell and Hodson (2000) and by Brunner (2000). Although ITP is still researching to improve that technology, the maximum lift coefficient achievable does not seem to be far from the current levels, unless active boundary layer control mechanisms are used.

In view of the previous difficulties, new approaches like the reduction of stages for a same work output, referred as high stage loading turbines, are advised for further number of component reduction (Vázquez, 2001).

Most of the modern direct drive low-pressure turbines have been designed for a moderate stage loading ($\Delta H/U^2$ ~2), even when is well known that lower loaded stages may offer better efficiency. This accepted reduction in efficiency arises because of the need to use as few stages as possible in order to save weight and cost, but always maintaining efficiencies well above 90 percent. As the market is demanding now further cost and weigh savings, it seems a natural way to proceed an increase of the stage loading parameter and therefore to have a fewer number of stages.

ITP has already explored high stage loading turbines with a number of stages reduction up to 50% ($\Delta H/U^2$ ~3) and unit direct cost and weight savings around 20% or higher have been proved. Obviously the challenge of that technology is to achieve those benefits keeping the same level of turbine performances. However special attention should be paid to the following issues: firstly, we would expect a trend to efficiency reduction for higher loaded stages and secondly, the new basic aerodynamic characteristics of those turbines lie well beyond the current levels of technology. Due to the last issue even the estimation of the trend to efficiency reduction is complicated since the classical efficiency models need to be extrapolated.

The efficiency and noise reduction and therefore the aerodynamic improvement required for recovering, limits the maximum referred work and pressure ratio achievable. Although those maximum values mean a significant increase in relation to conventional turbines (25% and 10% respectively), they are still very far from typical values of high pressure or geared low-pressure turbines (>65% and >25% respectively). Nevertheless the much higher referred rotational velocity of those last two types of turbine change the trend of efficiency, even allowing better performances with conventional aerodynamics and higher Mach numbers.

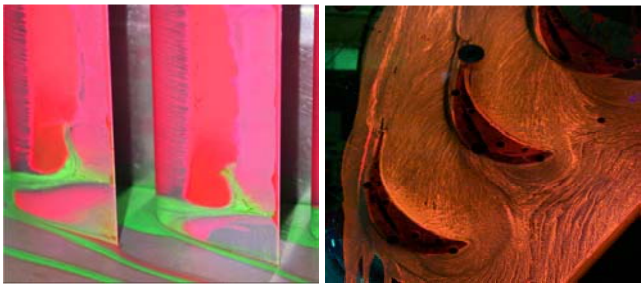

Figure 1, high turning (~120 deg.) unsteady compressible cascade, tested at Whittle Lab

In the open literature, very few works are known by the author about the subject of the current paper and just a couple of turbines that have tried to address the problem, one of them was the called E3 (Energy Efficient Engine) developed in USA twenty years ago.

Figure 2, single stage rig at the transonic tunnel.

Figure 3, hot films to explore the suction side boundary layer

Figure 4, miniature pneumatic probes, temperature rakes and surface pressure tapping.

A wide on-going research program is being developed by ITP to explore that technology. The program was launched in 1999 and final conclusions are expected by 2004. Several low and high speed unsteady linear cascades (fig. 1) will be tested at the Whittle Laboratory (University of Cambridge) and at the School of Aeronautics (Polytechnic University of Madrid), to get basic understanding of special aerodynamic characteristics connected to high stage loading designs. Also, at least three cold flow single stage rigs (fig. 2) with extensive advanced instrumentation (fig. 3 and 4) are being tested in a transonic test facility with stage loading around 3 and several features to validate the weight and number of components reduction as well as the efficiency behavior. Finally a four stage LP turbine for a full-scale engine is being designed as technology demonstrator, under the supporting of the European program, ANTLE. This turbine is a redesign of the Trent 500 LPT (Ulizar, 2001), with a 20% stages reduction, weight and cost savings higher than 25% are expected (fig. 5). During this year, before performance tests of the engine, a full-scale cold flow rig with advanced unsteady and steady instrumentation is running in an altitude test facility.

NOMENCLATURE

α	Flow Angle
ΔH	Stagnation enthalpy drop
$\Delta H/U^2$	Stage Loading Factor
$\Delta H/a^2$	Referred work
ϕ	Stage Flow Factor
γ	Gas Specific Heats Ratio
η	Isentropic efficiency
ν	Cinematic Viscosity
θ	Wake Momentum Thickness
ψ	Stage Loading Factor
ε	Gas deflection
ρ	Flow density
A_0, a	Stagnation Speed of Sound
AN^2	Mechanical Load
A_R	Blade Aspect Ratio
C_X	Axial Chord
C_L	Lift Coefficient
DNS	Direct Navier Stokes Numerical Simulations
E	Blade Section Maximum Thickness
f	Transfer Function of Efficiency
f_R	Reduced Frecuency
FSTI	Free Stream Turbulence Intentsity
H	Blade span
HTF	High Through Flow Design
KSI	Kinetic Energy Loss Coefficient
LPT	Low pressure Turbine
LTF	Low Through Flow Design
M	Mach Number
N	Number of Airfoils
OGV	Outlet Guide Vanes
P	Blade Pitch Spacing, Pressure
PR	Pressure ratio
p'	Unsteady pressure perturbation
R	Stage Reaction
r_m	Stage Mean Radius
Re_s	Reynolds Number based on suction surface length and exit conditions
S	Suction Surface Length
SPL	Sound Pressure Level
T	Exit Channel Thickness
u'	Unsteady velocity perturbation
U	Rotational velocity
U/a	Referred rotational velocity
V	Velocity. Volume.
Va	Axial velocity
Va/U	Stage Flow Factor

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Subscripts

1	Row Inlet
2	Row Exit
E	Row Exit
R	Rotor
ref	Reference
rel.	Relative
S	Stator

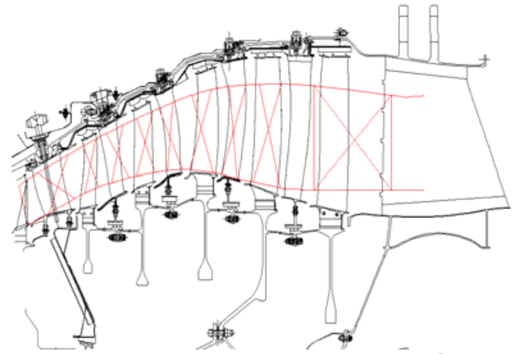

Figure 5a, Trent 500 vs. ANTLE LP turbines

Figures 5b, ANTLE LPT airfoils are characterized by low aspect ratio and long chords.

HIGH STAGE LOADING TURBINES

General Overview

As it was mentioned before, the first problem that must be addressed in order to know how much the high stage loading can be increased is to calculate the trend of the efficiency, especially if one of the targets is to keep similar performance levels. One would expect great efficiency dependence on the dimensionless work output or stage loading ($\Delta H/U^2$), because it is one of the main factors to determine the shape of the velocity triangles. Basing on that assumption, Smith (1965), presented the most widely known overall-stage performance method that related the efficiency of 70 turbine stages to the loading and flow factors.

In view of that correlation the efficiency varies very strongly with the stage loading, moving from conventional loading (~ 2) to high loading (~ 3) means about 4% efficiency penalty. Smith suggested that strong drop was related to larger gas deflections, which should be connected to higher losses.

Based on the previous numbers, reducing the number of stages seems to be nonsense, but further considerations must be taken into account before. The accuracy of the method can be ±2% and none of the 70 turbines tested have a stage loading larger than 2.4, so the correlation is extrapolating for high loaded turbines reducing even more the accuracy. Moreover, important factors for high stage loaded turbines, as compressibility, aspect ratios, Reynolds numbers, degrees of reaction, etc. are not considered in the correlation.

Others researches took into account some of the previous factors to update the Smith Chart, thereby Swindell introduced the aspect ratio. Swindell Chart for low pressure turbine (high aspect ratio) is quite similar but for a given efficiency curve the peak $\Delta H/U^2$ value is attained for a lower stage flow factor or dimensionless axial velocity (va/U). That conclusion has a physical sense, since that peak value is generated by counterbalance of 3D and 2D losses. So if only the experimental data of Smith´s correlation with higher aspect ratios are retained, the weight of the 3D losses in the total efficiency is lower and therefore the peak moves to higher deflections.

Kacker and Okapuu (1981), developed a new efficiency correlation, based on perhaps the most popular "loss component analysis method", Aienly and Mathieson (1951) modified by Dunham and Came (1970). That new overall method was tested against the known efficiency of 33 turbines and against Smith Chart. Although the results were satisfactory, the method presents the same drawbacks than Smith approach. On one hand, high scatter (± 1.5%) which is of the same order than the drop of the efficiency that is predicted by the method to go from conventional to advanced stage loading. On the other, just one of the 33 turbines has higher stage loading than 2.5, and it was not correlated, thus the method is only reliable for conventional loaded stages. Although those turbines are newer than Smith's ones, they are still far from the current technology.

Finally, Hourmourziadis (1989) accounted for compressibility, which is a main factor for efficiency calculations in high Mach numbers, through the referred rotational velocity (U/a). That new dimension of the Smith Chart is mandatory for high loaded low-pressure turbines, because the Mach numbers may be much higher. But also that method lacks experimental data for high referred work ($\Delta H/a^2$) and low referred rotational velocity, which is our area of interest.

In view of the lack of information to calculate the trend of efficiency for high stage loading turbines, the construction of a new loss model is the highest priority. To mitigate that priority several tests have been launched by ITP. Although a detail description of that new correlation is out of the scope of this paper, some guidelines will be highlighted in the rest of the paper.

Current Technology Limits

Obviously, that loss model must consider the new required technology to drive the aerodynamic and geometric features of high stage loading, that lie beyond the current levels of technology.

Some of those current levels can be represented on a Smith´s Chart, as shown in figure 6.

The first limit of technology that may be exceeded when the stages are overloaded is related to gas deflection. As Smith (1965) suggested, the figure 7 shows the gas deflections in a 50% reaction stage at various values of $\Delta H/U^2$ and va/U. Also, some data of individual stages, which are representative of LP turbine experience of different companies, have been drawn.

In view of the figure 7, two main conclusions may be highlighted: highest deflections must be expected for high stage loading and low flow factors and the conventional LP turbines are familiarized with gas deflections below 110 degrees. Thus, over that value we are out of experience, as it has been represented in the figure 6.

This border is exceeded (fig. 6) by a high stage-loading turbine ($\Delta H/U^2 \sim 3$), when the value of the flow factor is conventional o low (va/U $\leq$ 0.9). That type of high stage loading turbine will be referred as low through flow design and will be distinguished by its high turning blades (around 120 deg.) Those blades have the following special features that need to be studied:

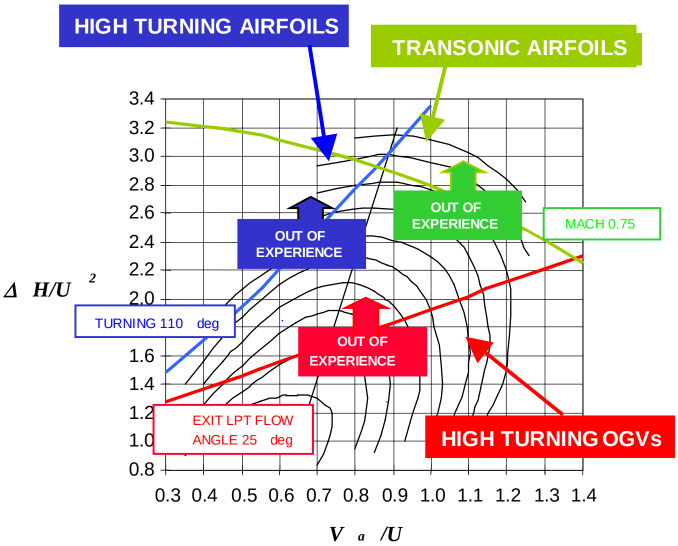

Figure 6, Edges of current technology.

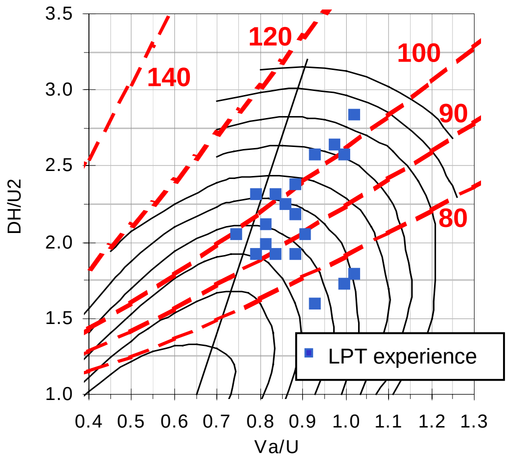

Figure 7, Gas Deflections.

- For a 50% reaction stage, both inlet and exit flow angles increase, but the inlet angle increment is much higher than the exit one (fig. 8). That requires a careful design of the leading edge, to avoid a very thick profile or a very big pressure side bubble. Moreover, due to the lift increase, the stagnation point tries to move towards pressure side, claiming for a positive incidence design.

- In ultra high lift blades, the trailing edge velocity was suppressed, therefore the back suction diffusions are higher than expected (Howell, 2000). Really, that physical fact is related to aft loaded profiles regardless of whether the lift coefficient is high, ultra high or conventional. That effect is due to potential interactions between adjacent blades. In high turning blades, the thickness of channel between blades (t= p cosα_2), is lower due to the higher exit flow angle, and therefore that potential effect is stronger. For those levels of deflections, it must be taken into account because it forces a lift coefficient reduction to avoid the increment of the deceleration required by the flow on the suction side.
- According with the classical theories (Gregory Smith, 1982 and 1988), the secondary flow is produced when a streamwise component of vorticity is developed from the deflection of an initial sheared flow. Therefore, it is expected an important dependence on gas deflection of secondary flows. In high turning profiles, that effect produces a non negligible impact on secondary flows due to the increase of streamwise vorticity, caused by potential effects as well as by the interaction between the massive pressure side bubble and the horse shoe and passage vortices. The previous impact is estimated to be bigger than the one predicted by some conventional loss model.

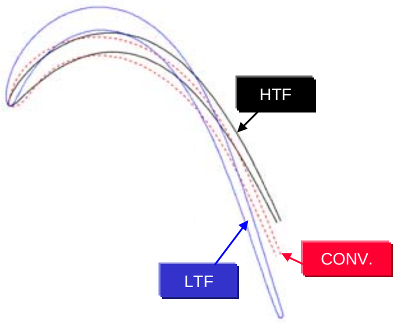

Figure 8, Airfoil geometry comparison.

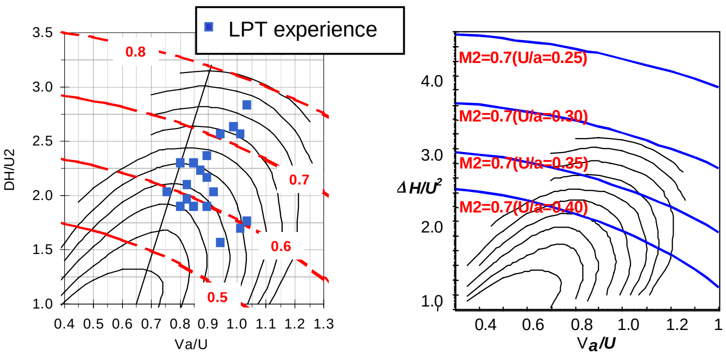

Figure 9, Mach Numbers.

The second limit of the current LP turbine technology (fig. 6) is Mach number. Figure 9 shows how the Mach number varies trough the Smith Chart, for a typical referred rotational velocity of direct drive LP turbines. The influence of U/a on Mach number values can also be seen in same figure.

In the same way as in the first technology limit, again, some conclusions can be concluded from figure 9:

1. Highest Mach numbers are related to high loaded stages.
2. For a same stage loading, the higher the flow factors, the bigger Mach number.
3. The fan direct driven low-pressure turbines are attributed to moderate subsonic Mach numbers ($M \leq 0.8$), as it can be inferred from the figure 9.

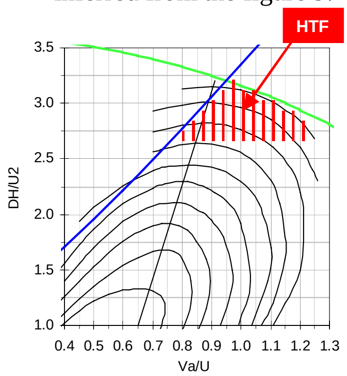

Figure 10,
High Trough Flow Design

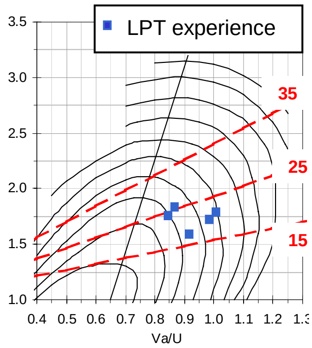

Figure 11,
OGV Gas deflection

Based on that conclusion, the green line in figure 6 is the Mach number limit for a typical U/a (0.3), which means values over that line lead to transonic flow conditions in regions around the Mach peak of the suction side. This new feature also needs to be considered in the loss model. However, latest experiments carried out by ITP have showed that the impact of the compressibility on the kinetic energy losses of high lift airfoils is negligible up to exit Mach number of 0.9, if the pressure distribution is kept constant. Therefore this experience limit can be slightly exceeded with low risk.

Figure 10 shows the region below the two technology limits described. Inside that area the aerodynamic parameters are quite similar than in conventional design, and it is possible to design a high stage-loading turbine without any special technology development if a penalty in efficiency is assumed. The right side of that region, where the flow parameter is higher than usual and gas deflection are closer, even lower, than conventional ones will be referred as High Through Flow Design. While the LTF design is geometrically characterized by high turning airfoils, the HTF is distinguished by the reduced annulus cross section.

The last limit to be considered, is related with the OGV (outlet guide vanes). That boundary is due to the lack of experience, more than a real technological need. When one stage is removed, the work done by that stage is distributed between the rest of stages. If extra work is assigned to the last stage of the turbine, the exit flow angle of that stage is increased putting more load on the OGV, if not the other stages of the turbine have to do more work, damaging the turbine efficiency and noise. Therefore, an optimization exercise is required to get the optimum LPT+OGV performances, as result of that exercise the gas deflection through the OGV uses to be increased.

The figure 11 shows that gas deflection at various values of $\Delta H/U^2$ and va/U and some points representative of last stages of LP turbine experience of several companies.

In view of that figure, the technology limit for the OGV can be identified (gas deflection $\leq$ 25 degrees), as it was illustrated in the figure 6, obviously that boundary only affects to the last stage position on the Smith Chart. Also, it can be concluded that in LTF turbines the limit is exceeded more easily than in HTF, for the same high stage loading.

When the limit is exceeded more vanes or longer chords are required by the OGV to leave the flow axial, and that leads to increase the cost, weight and loss. Taking into account that the OGV is one of the most expensive and heavy components of the turbine, the previous increment can mean a penalty for the turbine weight and cost of about 5%.

Parameters that affect the LPT performances

Turbine efficiency may be expected to be function of non-dimensional parameters such as:

$$\eta=\eta(\Delta H/U^2, va/U, U/a, Re, C_L, R, f_R, A_R) \quad (1)$$

It is obvious that the efficiency also depends on other factors, like some geometric parameters (trailing edge thickness, tip clearance, wedge angles, etc.), FSTI, applied technology and so on. Nevertheless, only the parameters of the expression (1) are been considered, mainly because the other parameters are kept almost constant or their contribution is less important.

If the turbine boundary conditions are known, the variables of the equation (1) define the major geometric parameters of the turbine: number of blades, airfoil span, profile thickness, axial chord, etc. Therefore the weight, cost and level of noise can be inferred from the same parameters

Although quantitative shapes of previous function (1) will be shown later on, some important guidelines will be highlighted now.

The influence of the stage loading has been extensively explained before as well as the influence of the flow parameter. Based on the later factor, the high stage loading turbines have been classified in two groups: HTF and LTF. Although, same division can be done for conventional loading, it does not make sense because is widely demonstrated that the optimum efficiency is achieved for LTF designs (low flow factors ~ 0.75, see Smith Chart, or even a little bit lower if the Swindell correlation is used instead). Moreover, at those levels of loading the efficiency is very sensitive to modifications of va/U as it is well shown in the Smith Chart. Smith (1965) justified the previous behaviour on a stronger variation of the shaft output to the kinetic energy ratio, which is a measurement of how favorable the working conditions of the turbine are. The figure 12 shows how small flow parameter variations cause big increase on Mach number or dynamic pressure, at low stage loading regions.

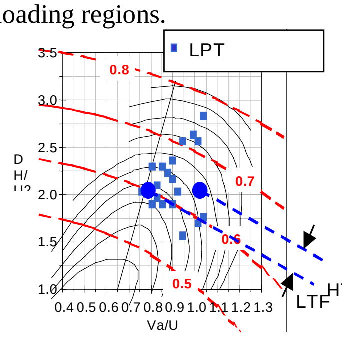

Figure 12,
Conventional Turbines:
Efficiency dependence on va/U

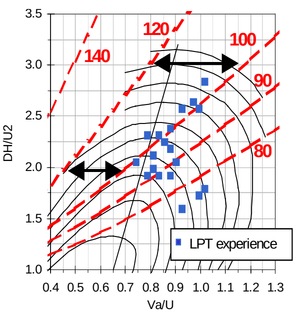

Figure 13,
Efficiency dependence
on gas deflection

However, at high stage loading, HTF designs are suitable since a smoother variation of the efficiency is expected with the stage flow factor. That fact that can be seen in the Kacker (1981) correlation is based on the physical explanation that the flow properties vary smoother with the flow factor, as it can be seen in figures 13 and 14. In the figure 13, it is shown how at high stage loading the gradient of the gas deflection with the flow parameter is lower than at conventional stage loading. Whereas the figure 14 shows how the velocity ratio between HTF and LTF turbines tends to 1 as the stage loading parameter is increasing. As Kacker also suggested that fact can move towards higher va/U the optimum of efficiency, for a given high stage loading, with regard to the Smith correlation. Those reasons, together, with the larger weight savings against LTF designs, as it will justified below, makes very attractive the HTF option.

Others advantages for the HTF turbine, are lower AN^2, lower tip to hub ratio and lower outer wall slope. All of them come from the annular cross section reduction.

The influence of U/a on turbine performances is less important than the flow and stage loading parameters, if the modification of U/a is achieved by mean radius changes, but that influence is of first order when the variation of U/a is achieved by shaft speed modifications. To justify previous assumption a simple example can be given. If the high stage loading ($\Delta H/U^2$ ~ 3) is imposed by a decrease of rotational speed instead of stagnation enthalpy rise, the number of stages is not reduced and therefore the high weight and cost savings mentioned before are not achievable.

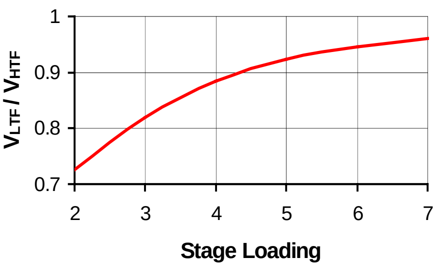

Figure 14, LTF to HTF velocity ratio vs. stage loading

The rest of parameters of the expression (1) are not as important as the preceding ones, although they must be considered to optimize the turbine. Nevertheless, there can be exceptions, as for instance the Reynolds number can be as important as the flow parameter for some type turbines when the weight wants to be reduced.

Then, the geometric and aerodynamic features of high stage loading against conventional turbines will be obtained and from them the performances of the high stage loading turbines will be inferred to demonstrate the previous assumptions. The referred rotational velocity will be kept constant and with a characteristic value of direct driven turbines (~0,3).

Geometric and Aerodynamic Parameters

The increase of the work per stage in high loaded turbines takes to very important changes in the geometric and aerodynamic parameters of the airfoils that directly affect to their design. The performances, area properties and number of components are determined by these changes. The two ways of increasing the loading, either increasing the deflection of the flow (LTF) or increasing the dynamic head (HTF) have completely different effects and have to be analysed separately.

As the mechanism of increasing the loading is to increase the variation of the tangential velocity through the blade, very high flow angles result in LTF configurations. The inlet angle is more affected as is takes three quarters of the total increase in turning (fig. 8 and 15). That high inlet flow angle has very important effects on the design of the leading edge.

The HTF configuration is defined to have almost the same total turning than a conventional loading design, nevertheless the different flow parameter takes to different velocity triangles and the inlet angle increases whilst the outlet angle reduces taking to profiles with smaller stagger angle (fig. 8 and 15).

As it was mentioned before, increasing the stage loading parameter as well as the flow coefficient rises the exit Mach number. Obviously the increase is greater in the HTF configuration (fig. 16). A reasonable limit is set to an exit Mach number of 0.8 to keep in the high subsonic zone, bounding the achievable loading. This limit is very sensitive to referred rotational velocity (U/a), see figure 16.

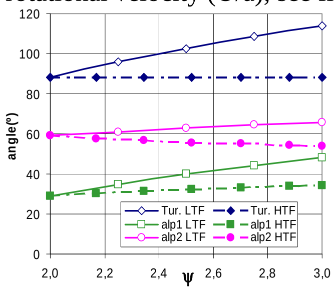

Figure 15, Flow angles vs. Stage loading

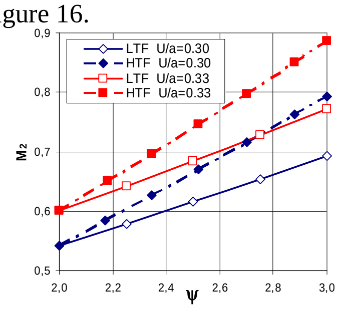

Figure 16, Mach number vs. stage loading

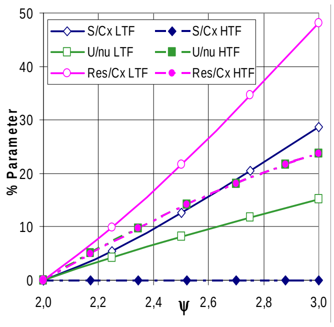

Figure 17, Reynolds based on perimeter vs. stage loading

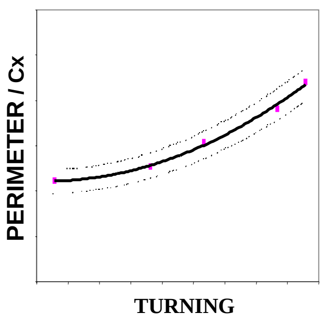

Figure 18, blade perimeter vs. gas deflection

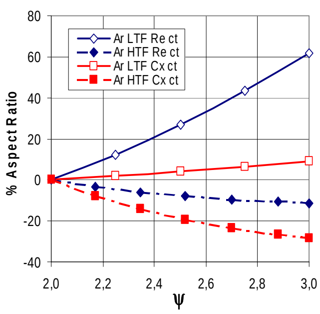

Figure 19, Aspect Ratio vs. stage loading

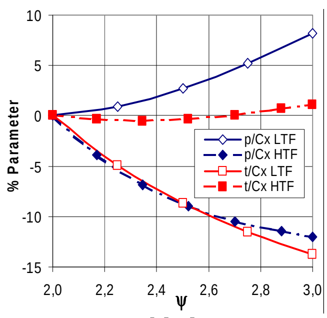

Figure 20, blade spacing & channel thickness vs. stage loading

The airfoil chord is selected based on optimisation procedure of turbine equivalent cost. The result of this procedure is not at all obvious and it depends strongly on the engine application, which defines the weight factors between efficiency, cost, weight and noise of the turbine. In future, two different possibilities are considered to make a simple analysis; to maintain the Reynolds number (perimeter of the suction side based) or to maintain the axial chord. The difference may be relatively small in terms of efficiency but it is critical in number of components, weight and cost.

The perimeter based Reynolds number – Axial Chord ratio may be decomposed as $Re_S/C_X = V/\nu \cdot S/C_X$. The evolution of these parameters is plotted in figure 17. The perimeter-axial chord ratio is a function of the turning that has been correlated in the figure 18, it keeps constant in HTF configurations but increases dramatically for LTF ones. To conclude, if the axial chord is held constant, the Reynolds number will increase a 50% in LTF and a 25% in HTF, on the other hand, if the Reynolds number is kept constant, 33% in LTF and 20% in HTF reductions in chord would be required. Since the span in each configuration is fixed given the mass flow, the change in chord changes significantly the aspect ratio (fig. 19)

The number of airfoils required for each configuration can be calculated setting a value for the lift coefficient. In this analysis it is kept constant for simplicity, however, the lift coefficient that maximises the efficiency is in first approach a function of the Reynolds number, Considering the equivalent cost, the optimum lift coefficient also depends on the engine trades and it is coupled with the axial chord selection.

Assuming a constant lift coefficient, the pitch spacing - axial chord ratio is presented in figure 20, together with the exit channel thickness - axial chord ratio ($t/Cx = p/C_X \cos \alpha_2$) that influences the 2D losses. To explain the results the 2D incompressible expression is considered:

$$C_L = 2 \cdot p/C_X \cdot (\tan\alpha_1 + \tan\alpha_2) \cdot \cos^2\alpha_2$$

The term $\cos^2\alpha_2$ is always dominant and the pitch – chord ratio increases an 8% for LTF but reduces a 12% for HTF with the opposite effect in blade counting.

Finally figure 21 shows the dimensional geometric parameters per stage comparing the cases with constant chord or Reynolds number. The total volume of the airfoils is obtained with $V = N \cdot h \cdot S \cdot e = N \cdot h \cdot S \cdot C_X \cdot e/C_X$, where a constant value of e/C_X is assumed.

In view of the figure 21, the main conclusions are:

- HTF turbines allow biggest weight savings (>30% per stage than conventional turbines).
- LTF turbines with constant axial chord allow biggest blade counting reductions (>10% per stage than conventional turbines).
- Following the tendency of the HTF drawings, it can be deduced that a further axial chord increases lead to a HTF turbine lighter and with fewer number of components per stage than conventional turbines.

The previous benefits are much higher when the whole turbine is taking into account and savings from the removed stages are added. To show the order of reduction that can be achieved, let us suppose for instance a 6 stages conventional turbine. If one of the stages is eliminated, a weight and number of component charts can be calculated (figure 22 and 23 respectively) from the preceding results, which show how the whole turbine weight and number of component vary from conventional to high stage loading turbine.

Because it is the most promising case analysed before, the axial chord has been kept constant and further considerations have been considered, like: mechanical loads, containment requirements, etc. The variation of referred rotational velocity is only achieved through turbine mean radius modifications, thus the chart is not reliable for shaft speed changes.

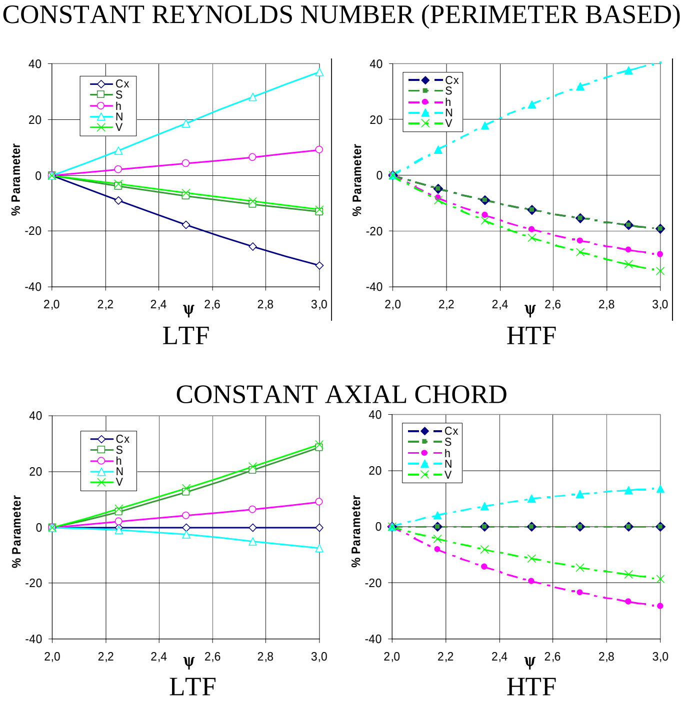

Figure 21, dimensional geometric parameters for constant axial chord and constant Reynolds number against stage loading

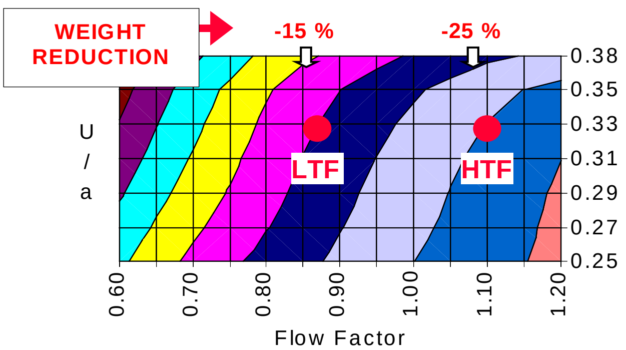

Figure 22, Weight vs. Rotational Velocity and Flow Factor for high stage loading referred to conventional turbines. ΔW=5%

In view of the figures 22 and 23, the following conclusions can be highlighted:

- The high stage loading turbines offer a big capacity to reduce weight and number of components.
- The superiority of HTF turbines to reduce weight is unquestionable, leading to total weight savings above 25% referred to conventional turbines.
- The LTF turbines allow a total blade counting reduction of 25% for this turbine, while HTF option only achieve a 10%.
- The weight of the turbine is more sensitive to flow parameter than mean radius variation.
- The number of component is equally sensitive to flow factor and mean radius.

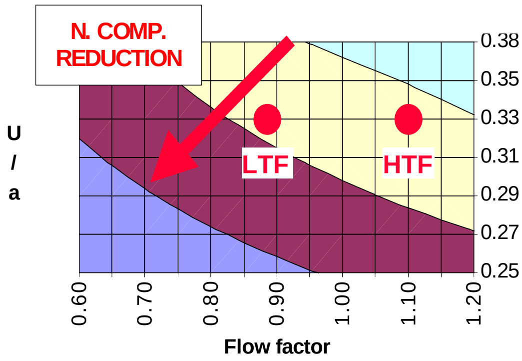

Figure 23, Number of components vs. Rotational Velocity and Flow Factor for high stage loading referred to conventional turbines. ΔN=10%

Efficiency

Following a similar approach than Lewis (1978), but considering the flow compressibility, the efficiency of the stage may be expressed as (3):

$$\eta_{stage}=\frac{(\gamma-1)\cdot\Psi\cdot\left(U/a_0\right)^2}{1-\left(1-(\gamma-1)\cdot\Psi\cdot\left(U/a_0\right)^2\right)\cdot\left(1-\frac{\gamma-1}{2}M_{e,S}^2\frac{KSI_S}{1-KSI_S}\right)\cdot\left(1-\frac{\gamma-1}{2}M_{e,rel,R}^2\frac{KSI_R}{1-KSI_R}\right)}$$

, assuming $KSI_R = KSI_S \ll 1$ and $M_{e,rel,R} = M_{e,S}$ the expression can be simplified to:

$$\eta_{stage}=1-\left(\frac{1}{\Psi\cdot\left(U/a_0\right)^2}-(\gamma-1)\right)\cdot M_e^2\cdot KSI$$

$$\eta_{stage}=1-f_1\left(\Psi\, (U/a_0)^2\right)\cdot M_e^2\cdot KSI=1-f\left(\Psi,\phi,U/a_0\right)\cdot KSI$$

being ´f´ the transfer function between the airfoil energy loss coefficient and the stage efficiency. Figure 24 shows how those functions change moving through Smith Chart. The function ´f_1´ reduces as the loading parameter increases, but the M^2 has the opposite trend. Both terms cancel for LTF but the second one is stronger for HTF, in consequence, the airfoil energy loss of HTF turbines is amplified by a 40% referred to the baseline configuration (figure 27).

However, the airfoil kinetic energy loss coefficient has first order changes that have to be considered. It strongly depends on the same parameters highlighted on expression (1).

Using the following simplified models and the variations of geometric parameters commented before, the KSI behaviour (fig. 25 and 26) can be explained.

$KSI = KSI_{2D} + KSI_{3D}$

$$KSI_{2D}\approx\frac{2\cdot\theta}{p\cdot\cos\alpha_2}=\frac{2\cdot\theta/S(\mathrm{Re}_S,C_L)}{p/C_X(C_L)\cdot\cos\alpha_2}\cdot S/C_X$$

$$KSI_{3D}\propto\frac{f(\alpha_1+\alpha_2)}{A_r}$$

If Reynolds number is unchanged, the KSI_{2D} keeps quite constant in HTF, but may increase around a 50% in LTF, mainly due to the greater perimeter (longer wetted area), see figure 25. If the axial chord had been kept constant, the result is in first approach the same because, although in LTF the Reynolds number is amplified by 1.5, a factor close to 10 would be required to counterbalanced the increase in 2D losses.

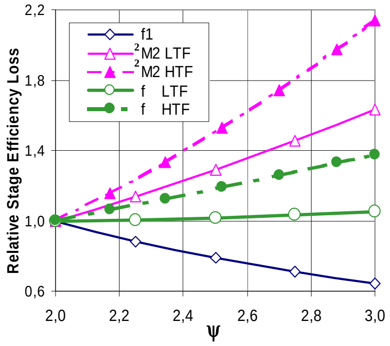

Figure 24, Efficiency transfer function vs. stage loading

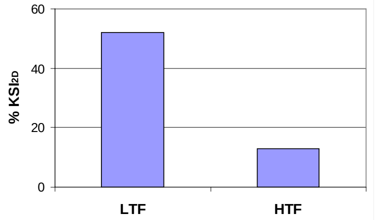

Figure 25, KSI_{2D} referred to conventional turbines

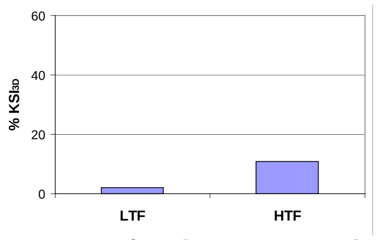

Figure 26, KSI_{3D} referred to conventional turbines

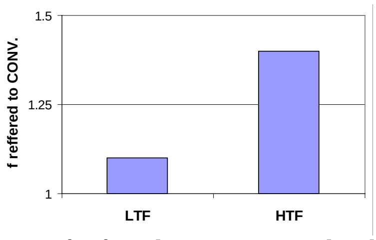

Figure 27, f referred to conventional turbines

If Reynolds number is unchanged, the KSI_{3D} keeps quite constant in LTF (the improved aspect ratio counterbalances the increase of gas deflection), but may be increase a little bit in HTF (figure 26) because of the aspect ratio reduction. For constant axial chord, both types of turbines behave similar, anyway the comparison between figures 25 and 26 remarks the small contribution of 3D losses in these high aspect ratio turbines.

To summarise, it is clear that high stage loading parameters implies a severe penalty in efficiency, considering the conventional technology. In view of figures 25, 26 and 27, LTF and HTF turbines achieve similar levels of efficiency, due to either working conditions of the turbine for HTF or the aerodynamics for LTF.

Noise

As it was remarked before, higher Mach numbers than conventional turbines characterize the high stage loading stages. As it is well known that Mach number is a first order factor for noise emissions, an important penalty in noise is expected for that turbines, which will have to be recovered somehow.

If HTF turbines are compared to LTF turbines, one may suppose that first ones are worse because theirs Mach numbers are higher than in LTF (see figure 16). However, it is very important to realise that the aerodynamic design point analysed, typically cruise, is not one of the noise legislation performance points. Those points use to be approach, flyover and sideline. For a LPT point of view, approach is the most important point because in those conditions the turbine is one of the engine components that have more contribution to the noise emissions. In approach, the first stage has bigger contribution in noise than other stages, because its loading is the highest of the turbine.

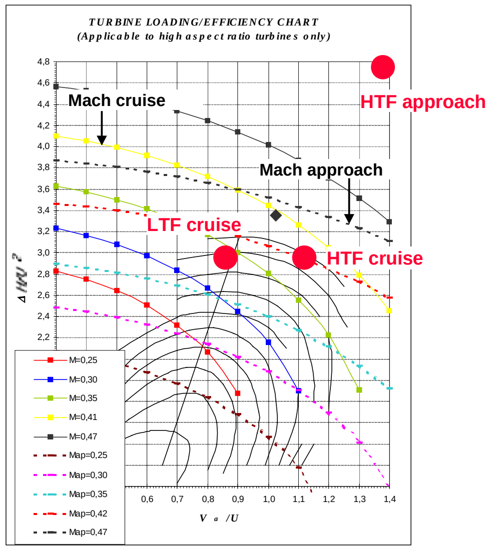

Figure 28, Smith Chart with Mach numbers for cruise and for approach

To understand how is the Mach number of both options in approach, the Smith Chart is reproduced in figure 28. The first stage Mach numbers are represented for cruise and approach.

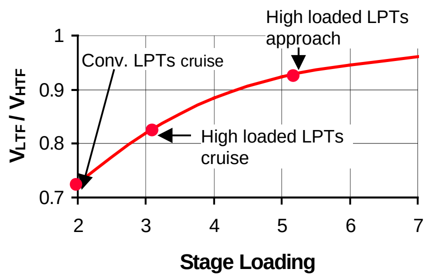

Figure 29, LTF to HTF velocity ratio vs. stage loading

Comparing the dashed lines (approach) in figure 28 with the solid lines (cruise), it is clear than the Mach numbers in approach vary smoother with the flow factor, allowing at high stage loading similar Mach number levels for HTF and LTF.

This conclusion can also be deduced from the figure 29, which represents the ratio between LTF and HTF velocities against the stage loading parameter. In approach the stage loading grows and that ratio is closer to 1.

The physical reason is very intuitive. The Mach number in approach conditions for HTF turbines is high because of the high Mach numbers in cruise, whereas for LTF turbines, the approach Mach number is high because of the velocity triangles (high flow angles), even being the cruise Mach number similar than in conventional turbines.

If a simple expression to calculate the level of noise is considered (4):

$$SPL(dB) = \underbrace{20\log\left(\frac{p'}{\rho_2 V_2^2\left(\frac{u'}{U_1}\right)}\right)}_{Noise\ Source} + \underbrace{20\log\left(\frac{\rho_2 V_2^2}{P_{ref}}\right)}_{Dynamic\ \mathrm{Pressure}} + \underbrace{20\log\left(\frac{u'}{U_1}\right)}_{Wake} - Acoustic\ decay$$

four components can be highlighted. The first and third ones that are associated to the noise source and wake depth respectively do not depend on first approach on the Mach number. Their contribution to the noise level is not clear yet. It seems that small differences must be expected in the third factor between conventional and HTF turbines, because both have similar wakes, however wider differences can be found with LTF turbines due to the bigger wakes produced by the worse kinetic energy losses.

The second factor represents the noise increase due to the dynamic pressure and it is the factor more linked to the Mach number. The rise of Mach number suffered by the high stage loading turbines, both HTF and LTF, can reach an increase of noise higher than 2,5 dB.

The acoustic decay in gaps also is connected to the Mach number, highest Mach numbers reduce the decay of the mode, and its contribution, although less significant, can be not negligible.

U/a impact on efficiency: a new proposal for an efficiency chart.

As it has been shown along the paper, High Stage Loading Turbines have higher referred work, pressure ratio and Mach numbers than conventional Low Pressure Turbines (fan direct driven), nevertheless those values are still far from the ones achieved by geared LPT and High Pressure Turbines. If as it well known some of these last turbines have efficiency as good as conventional LPT, why such ambitious research program is required. On other words, for a conventional LPT, why the number of stages is selected to have a pressure ratio of 1.4 whereas for geared turbines achieve pressure ratio of 1.65 or higher are acceptable. And moreover, if these geared turbines are designed with efficiencies enough high, why a research program is needed to keep that level of efficiency when the pressure ratio of conventional turbines only raise up to 1,5 or so.

To answer the preceding questions a new efficiency map is mandatory. Returning to the expression (1) and replacing some of the variables by others more familiar for the turbine designer and that allow taking apart the dynamic pressure impact, the stage efficiency can be written as:

$$\eta=\eta(PR, \varepsilon, M, Re, C_L, R, f_R, A_R) \quad (5)$$

The stage loading parameter has been replaced by the stage pressure ratio, although the referred work can also be used.

At least, the efficiency Chart has to take into account the variation of the three first variables (PR, ε and M), because their effect is the most important. The rest of variables will be fixed to a characteristic value for modern Low Pressure Turbines. Their value should be the optimum for each application, anyway it will be demonstrated later on that their have a second order contribution to the efficiency.

The efficiency model makes use of an extensive experimental database from linear and annular cascades, moreover it has been validated against several cold flow rig data.

The new efficiency Chart is plotted in the figure 30 for a gas deflection of 95 degrees. The contour lines are efficiency increments with regard to a modern conventional Low Pressure Turbine. The conventional turbines are located in the bottom-left corner (low-pressure ratio and Mach number), figure 34. The black dashed line in figure 30 is the zero efficiency increment, so if the turbine is located above this line the efficiency decreases while the efficiency increases below this line. High Stage Loading Turbines are placed above that line with pressure ratio higher than conventional turbine (fig. 34), however the geared turbines and located below the line. Because of that the geared turbines have better efficiency than the high stage loading turbines even having much higher stage pressure ratio, therefore much lower relative number of stages.

But, what should we do to move a high stage loading turbine below the line?. The figure 31 represents the contour lines for the referred rotational velocity together with the back dashed line of the figure 30. Based on this figure, the referred rotational velocity for high stage loading turbines should rise significantly, through an increase of shaft speed or mean radius or both. As high stage loading turbines use to keep similar rotational velocity than conventional turbines, no options exits to avoid the efficiency penalty and therefore a research program is required to improve the aerodynamics looking for an efficiency recovery.

In the figure 32, the efficiency Chart has been plotted for a gas deflection of 115 degrees. The contour lines have moved downwards. The location of LTF has been remarked and it can be corroborated that HTF (figure 30) and LTF (figure 32) have similar level of efficiency.

In the figure 33 the efficiency map have been drawn for a Reynolds number of 10^5, although there are differences with figure 30, it is clearly seen that the Reynolds contribution is much more smaller than either Mach number or gas deflection, as it was claimed before. One could expect a stronger impact of Reynolds number on efficiency, particularly for small gas turbines, but because of the unsteadiness (fig. 35) the modern LPTs show slight dependence on Re.

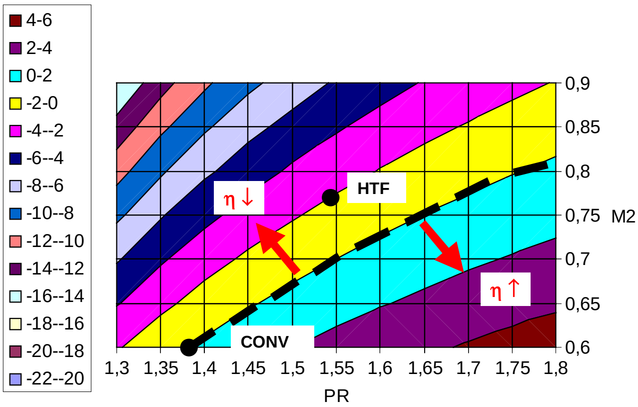

Figure 30, Efficiency Chart: $\Delta\eta=\eta-\eta_{ref}$ contour lines for ε = 95 deg., Re = 2 10^5, R = 50%

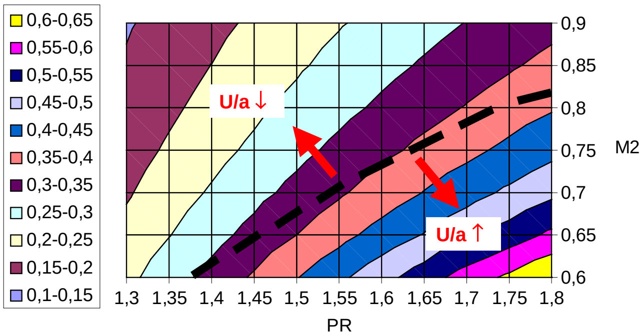

Figure 31, Efficiency Chart: U/a contours lines for ε = 95 deg., Re = 2 10^5, R = 50%

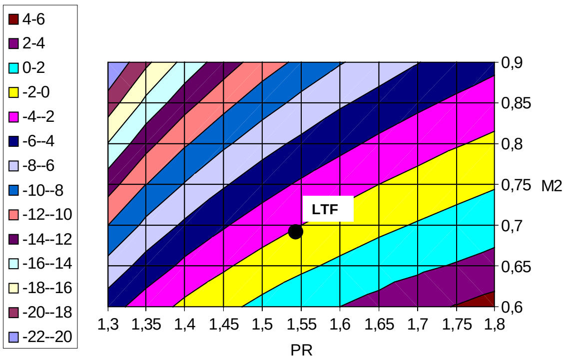

Figure 32, Efficiency Chart: $\Delta\eta=\eta-\eta_{ref}$ contour lines for ε = 115 deg, Re = 2 10^5, R = 50%

The new efficiency Chart also allows to select the number of stages for any type of turbine. For a given referred rotational velocity, for instance 0.3, the respective contours line (U/a = 0.3) is obtained from the figure 31. If this line is plotted on the efficiency Chart (red solid line in figure 34) and the target efficiency is known (point A in figure 34), the stage pressure ratio can be calculated (1.5 for point A). Both the overall pressure ratio and the stage pressure ratio give the number of stages required. In view of the efficiency Chart, if the design point is located to the right of A, the number of stages required will be lower but a decrement in efficiency must be assumed. Opposite trend it is found for design points placed to the left.

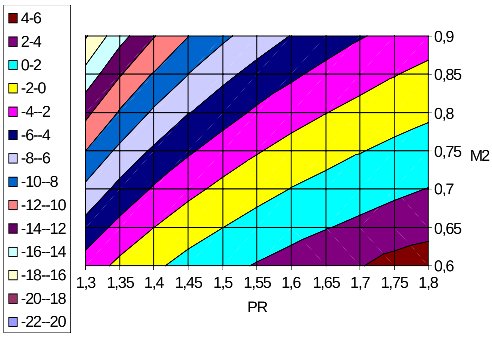

Figure 33, Efficiency Chart: $\Delta\eta=\eta-\eta_{ref}$ contour lines for ε = 94 deg, Re = 10^5, R = 50%

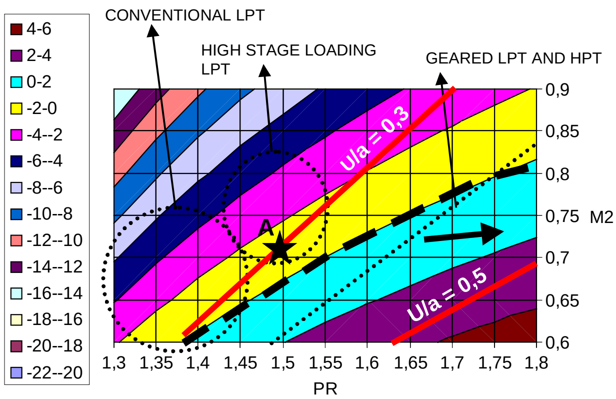

Figure 34, Efficiency Chart, location of each type of turbine

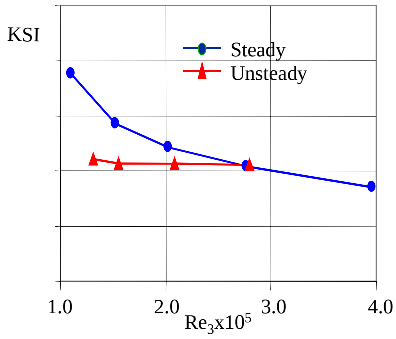

Figure 35, KSI vs. Reynolds no. for a representative airfoil of modern LPT (experimental data)

It is interesting to note that higher U/a lines, for instance 0.5 (see figure 34) have smaller slopes, which are closer to the efficiency contour lines. Because of that the pressure ratio can be risen in relation to the target and therefore the number of stages can be reduced with smaller impact in efficiency than for low U/a.

To conclude, the figure 34 shows that Geared or High Pressure turbines can achieve similar efficiency than conventional turbines with very high Mach numbers, such as 0.85 or higher than 0.9 for pressure ratios above 2, and with fewer number of stages. Although attention must be paid to the trailing edge losses for high trailing edge to channel thickness (T) ratio.

CONCLUSIONS

An overview of High Stage Loading Turbines Technology ($\Delta H/U^2 \sim 3$) has been introduced. Important potential benefits of about 30% in cost and weigh and 20% in stage number reduction can be achieved.

The drawbacks of that technology are efficiency and noise emissions, great penalties must be assumed based on the state of art experience on LPT.

A review of the current technology limits (gas deflection, Mach numbers and OGV flow turning) and how high stage loading turbines can exceed all of them have been shown. When that happens, new geometric and aerodynamic features come up, as for instance: suppression of trailing edge velocity, advanced OGVs, high turning blades, etc.

New loss model is highly required because classical loss models have not enough accuracy to predict the efficiency at high stage loading and they can not evaluate the previous aerodynamic features.

Two approaches for high stage loading turbines have been presented: High Through Flow and Low Through Flow. A comparison on geometric parameters, efficiency, weight, number of components and noise has been carried out. As main conclusions of those comparisons can be highlighted that:

- Similar levels of efficiency are obtained for HTF and LTF, due to either the aerodynamics for LTF or turbine working conditions for HTF.
- HTF designs are very attractive because they have higher potential in weight reduction, together with other characteristics as: similar aerodynamics than conventional turbines, much lower mechanical loads, lower wall slope, lower tip to hub radius ratio, etc.
- LTF turbines allow bigger blade counting reduction.
- In term of dynamic pressure contribution to noise, HTF and LTF have similar behavior, because they almost have same Mach number in approach conditions, in spite of their Mach numbers are quite different in cruise.

Finally a new efficiency chart has been presented. The authors suggest replacing the Smith Chart by this new proposal, because it offers the following two advantage:

- The state of the art technology is considered.
- By means of the referred rotational velocity, the new chart allows selecting the number of stages to achieve target efficiency for all types of turbine, regardless of whether the turbine is geared or fan direct driven. However, only these last ones can be handled by the Smith Chart whenever the referred rotational velocity is close to 0.3

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