ANALYSE DE L'ECOULEMENT MERIDIEN DANS LES TURBINES FONCTIONNANT EN INJECTION PARTIELLE

THROUGH-FLOW ANALYSIS OF STEAM TURBINES OPERATING UNDER PARTIAL ADMISSION

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SYNTHÈSE :

Afin de produire l'énergie électrique avec un rendement amélioré, Electricité de France doit vérifier les performances du matériel que proposent les constructeurs. Dans le domaine spécifique des turbines à vapeur, l'un des principaux outils d'analyse est le code de calcul de l'écoulement méridien quasi-3D CAPTUR qui permet de calculer tous les paramètres aéro-thermo-dynamiques d'une turbine.

Le dernier développement dont CAPTUR a fait l'objet est une extension permettant de calculer l'écoulement méridien dans une turbine fonctionnant en injection partielle. Pour ces turbines, il est désormais possible de calculer l'écoulement interne et de déterminer le rendement d'une façon beaucoup plus précise que par les méthodes précédentes qui consistent en une correction de rendement arbitraire appliquée en 1D à un calcul moyenné.

Du point de vue aérodynamique, l'injection partielle implique des pertes spécifiques dans le premier étage, puis un remplissage et un mélange turbulent immédiatement en aval du premier étage.

Les pertes au sein du premier étage sont de types très différents : ventilation, pompage et remplissage aux extrémités d'un secteur d'injection. Leurs valeurs ont été estimées à l'aide de résultats expérimentaux, puis exprimées sous forme d'un coefficient de ralentissement appliqué à la vitesse relative en sortie des ailettes.

En ce qui concerne l'écoulement à l'aval du premier étage, une analyse a été effectuée à l'aide de codes 2D et 3D spécifiques. Elle a conduit à définir le traitement numérique mis en place dans le code CAPTUR.

Certains problèmes ont dû être résolus pour rendre compatible une formulation quasi 3D avec un phénomène entièrement 3D. Certaines limitations des conditions de fonctionnement ont été adoptées au départ, mais une généralisation est en cours.

Le calcul d'une turbine à vapeur nucléaire HP fonctionnant en injection partielle a été effectué. Les résultats des calculs présentent une correspondance satisfaisante avec les résultats d'essais, notamment en ce qui concerne la ligne de détente le long des étages.

Le code CAPTUR sera particulièrement utile pour le calcul des nouveaux types de turbines HP à monoflux de forte puissance, conçues à la fois avec une injection partielle à l'étage de contrôle et des ailettes vrillées dans les derniers étages.

EXECUTIVE SUMMARY :

In order to produce electric energy with improved efficiency, Electricité de France has to check the performances of equipment proposed by manufacturers. In the specific field of steam turbines, one of the main tools of analysis is the quasi 3D through flow computer code CAPTUR, which enables the calculation of all the aerothermodynamics parameters in a steam turbine.

The last development that has been performed on CAPTUR is the extension to a calculation of a flow within a turbine operating under partial admission. For such turbines, it is now possible to calculate an internal flow field, and determine the efficiency, in a much more accurate way than with previous methods, which consist in an arbitrary efficiency correction on an averaged 1D flow calculation.

From the aerodynamic point of view, partial admission involves specific losses in the first stage, then expansion and turbulent mixing just downstream of the first stage.

Losses in the first stage are of very different types : windage, pumping and expansion at the ends of an admission sector. Their values have been estimated, with help of experimental results, and then expressed as a slow down coefficient applied to the relative velocity at the blade outlet.

As for the flow downstream the first stage, a computational analysis has been made with specific 2D and 3D codes. It has lead to define the numerical treatment established in the CAPTUR code.

Some problems had to be solved to make compatible a quasi 3D formulation, making an average in the azimutal direction and using a streamline curvature method, with an absolute 3D phenomenon. Certain limitations of the working conditions were first adopted, but a generalization is on hand.

The calculation of a nuclear HP steam turbine operating under partial admission has been performed. Calculation results are in good accordance with tests results, especially as regards the expansion line along the stages.

The code CAPTUR will be particularly useful for the calculation of the new types of high output single flow HP turbines, designed with both partial injection in the control stage and twisted blades in the last stages.

Through-flow analysis of steam turbines operating under partial admission

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SUMMARY

This paper describes the code used at the Research Direction of EdF to analyse the flow within a steam turbine operating under partial admission.

NOMENCLATURE

b	blade axial chord
c	available enthalpy drop
C	absolute velocity. C_r, C_θ, C_z radial, azimutal and axial component
D_m	average steam path diameter
H	static enthalpy
$\dot{m}$	mass flow
P	static pressure
r	radius
s	pitch
S	entropy
TG	tg(ε)
U	blade peripheral velocity
$V_{1_{is}}$	isentropic absolute velocity at the nozzle outlet
W	relative velocity
x	axial distance between nozzle outlet and rotor inlet
z	axial coordinate
α	fraction of admission
ε	meridional pitch angle
ρ	density
ϕ	blade height
ψ	loss slow-down coefficient
η_{TS}	total to static efficiency
η_{is}	isentropic efficiency

SUBSCRIPT:

i	streamline index
j	calculation plane index
r	radial direction
z	axial direction

I. INTRODUCTION

In order to produce electric energy with improved efficiency, Electricité de France has to check the performances of equipments proposed by manufacturers. In the specific field of steam turbines, one of the main tools of analysis is the through-flow computer code CAPTUR, which enables the calculation of all the aerothermodynamic parameters in a steam turbine.

The last development that has been performed on CAPTUR is the extension to a calculation of a flow within a turbine operating under partial admission. For such turbines, it is now possible to calculate an internal flow field, and determine the efficiency, in a much more accurate way than with previous methods, which consist in an arbitrary efficiency correction in an averaged 1D flow calculation.

This paper first presents the general calculation methods used in the code, then describes the phenomena occurring in case of partial admission, and their taking into account in the code, and at last, analyses results of a calculation performed on specific turbines.

II. COMPUTER CODE CAPTUR: GENERAL THEORY

CAPTUR enables the calculation of a steam turbine's internal flow for full load or part load operating conditions, knowing geometrical data of the machine and inlet/outlet fluid boundary conditions:

- total pressure and total enthalpy at the turbine inlet
- static pressure at the turbine outlet.

Results of calculation are:

- global characteristics of the turbine: flow, output, efficiency, expansion line
- aerothermodynamic parameters at every point of the mesh.

A detailed presentation of the code can be found in [1]

1/ Equations

The formulation of the code assumes that the flow is steady, inviscid and axisymmetrical. The steam is in thermodynamic equilibrium. In a cylindrical frame of reference, the corresponding equations in the annular regions between blade rows are:

- **Continuity equation:** $\frac{\partial \rho r C_z}{\partial z} + \frac{\partial \rho r C_r}{\partial r} = 0$
- **Momentum equation:**

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = -\left(C_z \frac{\partial C_z}{\partial z} + C_r \frac{\partial C_z}{\partial r}\right)$$

$$\frac{1}{\rho}\frac{\partial P}{\partial r} = \frac{C_\theta^2}{r} - \left(C_z \frac{\partial C_r}{\partial z} + C_r \frac{\partial C_r}{\partial r}\right)$$

- **Energy equation:** $H + \frac{1}{2}(W^2 - U^2)$ = constant along a stream surface
- **State equation:** $\rho = f(H, S)$

2/ Method of resolution

The code applies the streamline curvature method, coupled with an iterative process:
After the n^{th} iteration, the aerothermodynamic parameters are known along equiflow streamsurfaces, whose geometry (radius, slope, curvature values) are definite. Those streamsurfaces are only valid for that iteration, since they match to a non-converged velocity field.

$(n+1)^{th}$ iteration starts with the calculation of the pressure gradients normal to the streamsurfaces, using their slope and curvature values to solve the discretized momentum equation. Knowing new pressure gradients, energy, state and continuity equations are applied from upstream to downstream of the turbine, to determine new values of aerothermodynamic parameters; iterative process on the values of flowrate, and over-expansion pressure after choked rows in transonic turbines, is required to reach the outlet pressure.

$(n+1)^{th}$ iteration ends with calculation of new equiflow streamsurfaces. The process is stopped when the streamsurfaces pattern does not vary anymore: between n^{th} and $(n+1)^{th}$ iteration, if the maximum relative variation of radii is inferior to 0.001, and the maximum relative variation of streamsurfaces width is inferior to 0.01, at any point of the grid, numerical convergence is obtained, and the calculated streamsurfaces are definitive. If not, a new iteration starts.

3/ Mesh

The flow is computed on a two dimensional grid in the meridional plane: "vertical part" of the grid is fixed, and consists of planes including the geometrical lines joining leading edges and trailing edges of every blade. Those planes are called "quasi orthogonal" planes.

"Horizontal part" of this grid moves with the iterations, and consists in fact of the equiflow streamsurfaces pattern, defined at the end of every iteration, using the continuity equation. Slope and curvature values of those surfaces are calculated, and will then be used in the discretized momentum equation.

All aerothermodynamic parameters are known at each grid point.

4/ Equation discretization

Subscript M means an average value on the streamsurface.

- **Continuity equation:**

It is first expressed in an integral form along quasi orthogonal planes, and then discretized:

$$\sum_{i=1}^{n} \pi\,(r_{i+1} + r_i)\,\rho_i \left[C_{z,i}\,(r_{i+1} - r_i) - C_{r,i}\,(z_{i+1} - z_i)\right] = \dot{m}$$

with n number of streamsurfaces.

- **Momentum equation:**

Radial derivatives are simply discretized using centered finite differences between grid points. Indeed grid points are close enough to each other in the radial direction to obtain a good representation of any gradients with that method.

$$\frac{\partial C_z}{\partial r} = (C_{z_{i+1}} - C_{z_i})/(r_{i+1} - r_i)$$

$$\frac{\partial C_r}{\partial r} = \frac{\partial (C_z\, tg\varepsilon)}{\partial r}$$
$$= (TG_{i+1}\, C_{z\,i+1} - TG_i\, C_{zi})/(r_{i+1} - r_i)$$

Axial derivatives are computed using streamlines slope and curvature values. Moreover, grid points in the axial direction may be too "far" from each others to simply discretize $\partial C_z/\partial z$ by finite differences between them. So a special treatment is applied on that term.

- First, C_z is evaluated in virtual sections S_{j-p} and S_{j+q}, using Taylor's expansion, in which $\partial C_z/\partial z$ appears clearly. Respective axial coordinates of S_{j-p} and S_{j+q} are $(z_j - dz_p)$ and $(z_j + dz_q)$.
- Then the mass conservation law through surfaces S_{j-p} and S_{j+q} is expressed.
- At last, it comes:

$$\frac{\partial C_z}{\partial z} = C_{z_M} \frac{\left[\rho_{j-p}\, S_{j-p} - \rho_{j+q}\, S_{j+q}\right]}{\rho_{j-p}\, S_{j-p}\, dz_p + \rho_{j+q}\, S_{j+q}\, dz_q}$$

The different values of ρ and S are obtained with the help of Taylor's expansions, in which slope and second derivative of the streamsurfaces take place.

That result will also be used to express $\partial C_r/\partial z$, since we have:

$$\frac{\partial C_r}{\partial z} = \frac{\partial (C_z\, tg\varepsilon)}{\partial z}$$
$$= TG_M \frac{\partial C_z}{\partial z} + C_{z_M} \frac{\partial (tg\varepsilon)}{\partial z}$$

the two terms TG_M and $\frac{\partial (tg\varepsilon)}{\partial z}$ being known through streamsurfaces geometry.

Tangential derivatives are set to zero because of the axisymmetrical flow hypothesis.

- **Energy equation:**

It is written along a stream surface.

$$H_{j+1} + \frac{1}{2} C_{j+1}^2 = H_j + \frac{1}{2} C_j^2 \text{ for a fixed blade row}$$

$$(H_{j+1} + \frac{1}{2} C_{j+1}^2) - (H_j + \frac{1}{2} C_j^2) = U_{j+1} C_{\theta\, j+1} - U_j C_{\theta\, j} \text{ for a moving blade row}$$

Enthalpy values are coming from the state equation.

5/ Particularities of the code

- Losses: they are taken into account through a slow down coefficient applied either to the absolute or the relative velocity at the blade outlet. This coefficient is based on experimental cascade results. Wetness losses are evaluated using a pseudo-Baumann rule.

- Outlet flow angle: up to Mach 1, an experimental correlation is used. It takes into account blade geometry elements, and flow parameters. If the exit flow is supersonic, the flow angle downstream the trailing edge is calculated through Denton's method, which basically consists in satisfying the continuity requirement between throat and trailing edge.
The inlet flow angle is computed applying angular momentum conservation in duct regions between blade rows.

III. PARTIAL ADMISSION PHENOMENA ANALYSIS

When partial admission takes place in a turbine, nozzles in the first stage are divided into separate nozzle areas, each connected independently to a control valve. Load is adjusted by opening and closing the valves.
From the aerodynamic point of view, partial admission involves specific losses in the control stage, then expansion and turbulent mixing just downstream of the control stage.

1/ Review of existing theories, and quantification of the losses

Aerodynamic losses result from the fact that active flow in the rotor can only be found downstream nozzle sectors which are fed with steam: there are first windage losses in the areas where the blades move non working steam downstream nozzle sectors of no admission; then losses at the ends of an admission sector, where blades do not work under flow design conditions.
Some authors have elaborated theories and run out some tests in order to quantify those losses:

- <u>Windage losses:</u>

Most theories rely on dimensional analyse, which makes it possible to express the lost power in fonction of gemetrical and flow parameters:

$$P_W = C_1 \underbrace{(1 - \alpha)\, \pi\, D_m\, \phi\, \rho}_{\text{mass of non working steam per width unit}} \frac{U^3}{2}$$

Several expressions have been proposed for C_1, all of them are based on experimental results:

$$C_1 = 0.04 + 0.52 \frac{\phi}{D_m} : \text{Suter and Traupel's correlation [2]}$$

$$C_1 = 0.034 - 0.0061 \frac{x}{\phi} : \text{Walzer's correlation [3]}$$

The evaluation of the windage lost power for the high pressure steam turbine described in section IV reveals that the value obtained using Walzer's correlation is half as much as the one using Suter and Traupel's, which is quite close to another type of evaluation, due to Stodola.

- <u>Losses at the ends of an admission sector:</u>

Two main theories have been elaborated.

- According to Stenning [4], the corresponding loss of power P_s consists of a loss P_p used to pump not active steam out of the blade channel and a loss P_e meaning the expansion of the flow across blade chanels entering or leaving an admission sector.

$$P_p = C_2\, b\, \rho\, \phi \frac{U^3}{2}$$

$$P_e = \frac{\psi}{1 + \psi} \frac{s}{3\pi\alpha D_m} \eta_{TS}\, c\, \dot{m}$$

$$P_s = P_e + P_p$$

Stenning uses $C_2 = 1.4$; Walzer [3] proposed another evaluation for C_2, which leads to under-estimate the loss.

- For their part, Suter and Traupel [2] think that P_s may be expressed in fonction of the width of the admission sector where the flow is in an alternative state, between stagnant and working.

$$P_s = C_3 \frac{\dot{m}\, b}{\alpha\, \pi\, D_m} V_{1_{is}}\, U \quad \text{where } C_3 = 0.47$$

Ohlsson [5], Yahya [6] and Doyle [7] have established similar expressions.

- Both analyses evaluate similar loss of power due to ends of sector phenomena for the high pressure steam turbine described in section IV.

2/ Flow downstream the first stage

Downstream the first stage of a partial admission turbine, the flow generally enters a wide expansion annular room, generally called equalizing chamber, where turbulent mixing and azimutal repartition take place. Mixing losses are more important than in classical annular space, and a specific calculation or experiment is required to describe the flow.
For this purpose, a computational study has been engaged. Part of an equalizing chamber, as well as second stage nozzles have been modelled, in order to performe a flow calculation with a 2D finite elements compressible code, which has been developped by EdF. Unlike standard blade to blade calculations, an area of no admission exists in the inlet section. The influences of different parameters on the flow and on the mixing loss value will be analysed: fraction of admission, chamber's geometrical dimensions, angle between absolute flow velocity and axial direction at the inlet section, expansion rate through the nozzles. It will lead to the general rules governing the chamber working.
The study is on hand, some results are available: Fig 1 shows the velocity field, under a specific expansion rate. Azimutal repartition resulting from the acceleration through the nozzles appears clearly.
A similar 3D modelling has also been engaged, in order to take into account radial components of velocity in the equalizing chamber, imposed by some steam path geometrical design.

3/ Introduction of partial admission in the through flow code CAPTUR

The first point was to elaborate a simplified description of the flow in the first stage, in order to make compatible axisymmetrical formulation and partial admission. The basic idea of the model was to assume that the rotor consists in an infinite number of thin blades.
The hypothesis of modelling are the following ones:

- Only the first stage operates under partial admission. As soon as the leading edge of the second stage nozzle, the flow is supposed to be axisymmetrical.
- The flow in the first stage consists of as many independant and non interactive flows as existing separated admission sectors.
- Each of those flows follows the same expansion line. That is restrictive and non representative of general partial admission mode, but it was intended to qualify first the modelling of sectors of no admission for specific working points of the turbine, before trying to extend the method.
- The fraction of admission through the first stage blade is supposed to be exacty the same as the one through the first stage nozzle. That is based on the fact that ends of sector losses will be taken into account in the global loss coefficient.

Including all those hypothesis, we can consider that the flow in the first stage is similar to part of a fictive axisymmetrical flow, which would follow the same expansion line, taking into account partial admission losses.
That description does not change the formulation and discretization of the momentum and energy equations used in the code, except in the equalizing chamber, where angular momentum conservation has to take into account the fraction of admission existing in the calculation plane just downstream the control stage rotor. On the other hand, changes affect the continuity equation, which has to be applied in the first stage only in the areas which are really filled with active steam.

Suter and Traupel's correlation was selected to calculate windage losses, as well as Stenning's formulations for ends of sector losses. Thoses losses had to be expressed as slow down velocity coefficients.

Losses in the equalizing room were expressed considering a classical annular room basis, modified according to the first 2D calculation results available.

Introduction of all the above-mentioned elements in CAPTUR makes it possible to run a through flow calculation of a turbine operating under partial admission.

IV. THROUGH FLOW ANALYSIS OF A NUCLEAR STEAM TURBINE H.P. CYLINDER

1/ Description of the analysis case

The steam turbine in question is a 900MW output machine. The high pressure turbine is a double flow module, consisting of two symmetrical steam pathes of seven stages each. That turbine is designed to operate under partial admission: the inlet area is divided into six separate admission sectors, each one being fed by a control valve. Its operating mode is very specific: on full load conditions, only four adjacent sectors are fed, which represent 67% admission. On part load conditions, the fraction of admission does not vary, but the flow regulation is carried out by parallel steam throttling with the four corresponding control valves. The feeding of the six sectors (full arc admission) only occurs to admit an extra flow rate at the end of life of the nuclear fuel.

HP turbine flow calculations have been performed with the code CAPTUR, on full load conditions, then on 70%, 50% and 30% part load conditions. Boundary condition values corresponding to those different loads are coming from measurements carried out during the acceptance testings of the turbine.
The HP flow has also been calculated for the turbine operating under full arc admission, assuming the same expansion line than the full load conditions one.

2/ Results analysis

Results of calculation concerning global parameters of the turbine (mass flow, power output, extraction pressure values) were confronted with the corresponding measurement values available: the agreement is better than 2%, even in case of low load conditions, which validate both the feasibility of taking into account partial admission in a through flow code, and part of the modelling methods used.
Aerodynamic losses due to partial admission are equivalent to 0.6% of the total turbine nominal output, and their relative importance are inferior to the average gap between measurement and calculation: tests results available are too global to validate those calculated losses with accuracy.

Fig. 2 shows the meridional steamlines pattern on full load conditions. That pattern does not vary very much when the load dicreases. The streamlines follow the hub and shroud geometry without distortion, which is expected for such a steam path geometry.

Fig 3 shows the calculated pressure repartition along the stages, on one hand with 67% admission (nominal load), on the other hand with full arc admission. Available test values have been plotted in the same chart: they are in very good accordance with calculated values, though the equalizing chamber modelling has been extremely simplified.
The very important enthalpy drop in the first stage, which is characteristic of partial admission, appears in the calculation results. The corresponding expansion has been well evaluated. Such good results are also observed for the three part load calculations performed.

The examining of the results shows that the HP turbine aerodynamic performances and efficiency are satisfactory, and that the blades design is globally well adapted to the flow. However, the calculation enables to exhibit local areas where a mis-match between flow and optimal design can be noticed, under specific conditions.

Fig 4 shows the average fluid outlet angle, downstream active moving blades of the control stage, for 67% partial admision arc, and for full admission arc. A quite important swirl is to be found in case of partial admission. That swirl may be useful to establish an azimutal flow repartition, but it implies that the rotor blades efficiency is not optimal. That is not due to the specific aerodynamic phenomena occuring with partial admission, but to the design of the blade, better adapted to relative velocity values resulting from full arc admission.

Fig. 5 shows the flow incidence at the last moving blade, and Fig. 6 the angle at the turbine exhaust, for different load conditions. For any load condition between full load and 50% part load, there is little change on those values. But when the load decreases down under 50%, important negative incidence may appear at the last moving blade, as well as a tangential velocity component at the exhaust. That is mainly due to a modification of the turbine expansion rate at very low load conditions, which influences the last stage in particular. Changes in Mach number values are also to be noticed.

3/ Other types of results

The code may also be used in order to check the performances of a machine according to the fraction of admission α. That kind of calculation was of little interest for the previous HP turbine, which operates with a constant admission value, but was made for another turbine. Fig. 7 shows the variations of the Mach number at the trailing edge of the control stage active nozzles, and Fig. 8 the partial admission efficiency versus the fraction of admission, assuming constant turbine expansion rate.
The partial admission efficiency η_{ip} is defined by: $\eta_{is_{\text{first stage, partial injection}}} = \eta_{ip}\ \eta_{is_{\text{first stage, full arc admission}}}$

It is now possible to evaluate specific η_{ip} values for each turbine, and so to draw comparisons between different machines.

V. CONCLUSION

The through flow code CAPTUR enables the prediction of the aerothermodynamic parameters of a steam turbine operating under partial admission, when similar inlet pressure and enthalpy conditions exist upstream each nozzle sector, where steam is admitted. A comparison with test measurements proved the satisfying accuracy of global caculated results.
The modelling of the equalizing chamber dowstream the control stage may still be improved, in order to evaluate the turbulent mixing losses with more accuracy, and then to extend the use of the code to most general partial admission modes. For this purpose, computational analysis with specific 2D and 3D codes are on hand.
The code will be particularly useful to analyse the performances of the new types of high output single flow HP turbines, designed at once with a control stage allowing partial admission, and twisted blades in the last stages.

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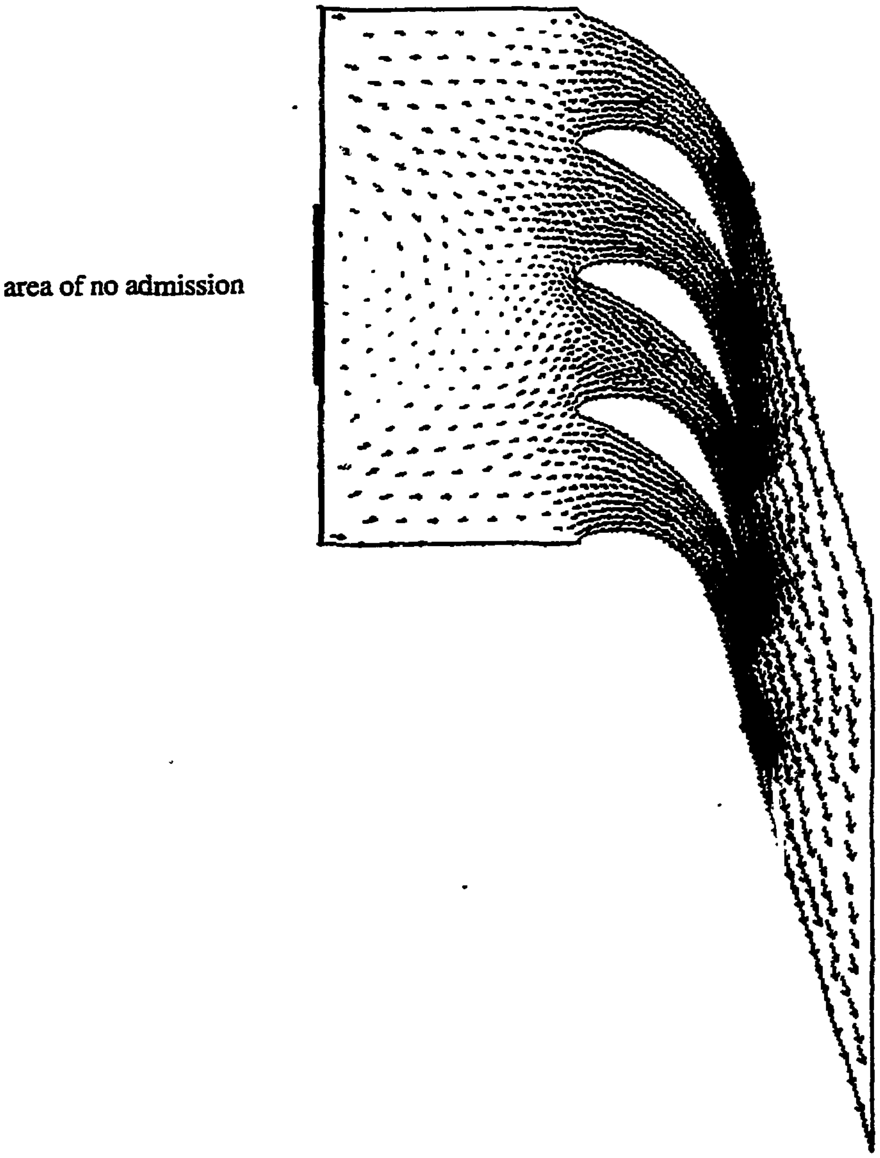

Fig. 1: Velocity field in a cascade, with area of no admission at the inlet

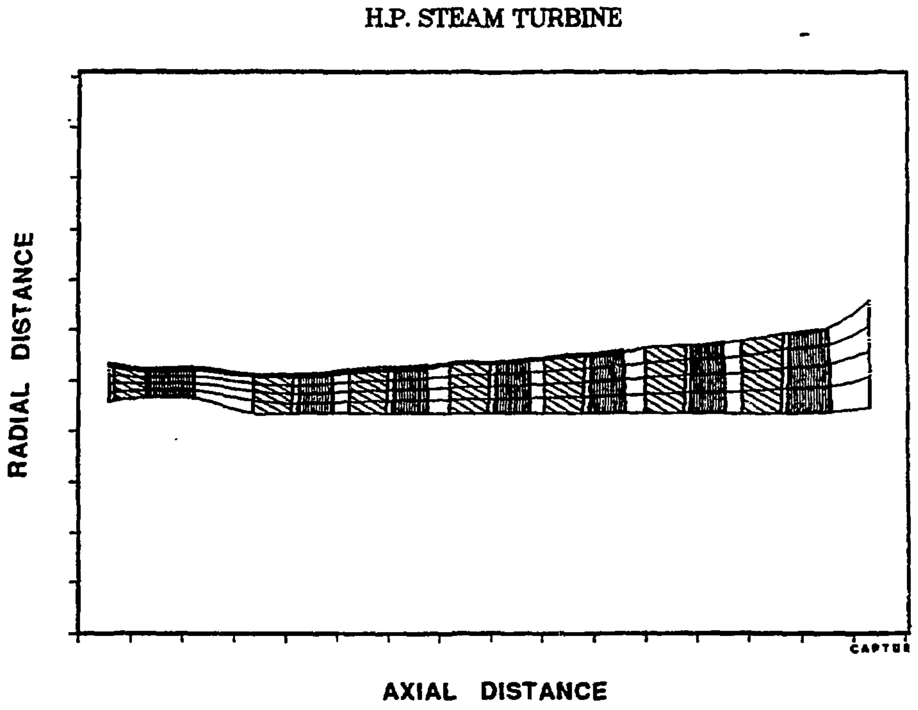

Fig. 2: Meridional streamlines pattern for full load conditions

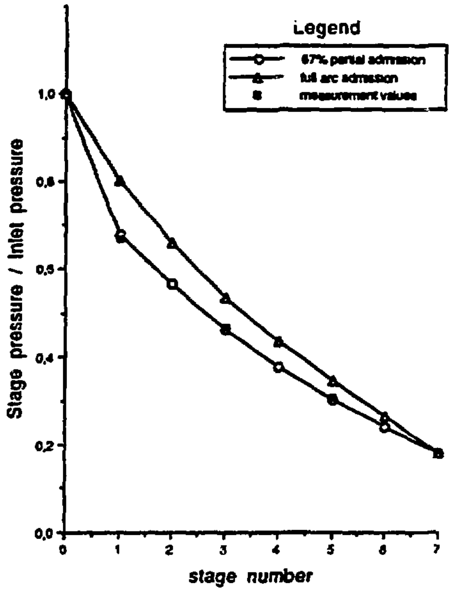

Fig. 3: Pressure repartition along the stages

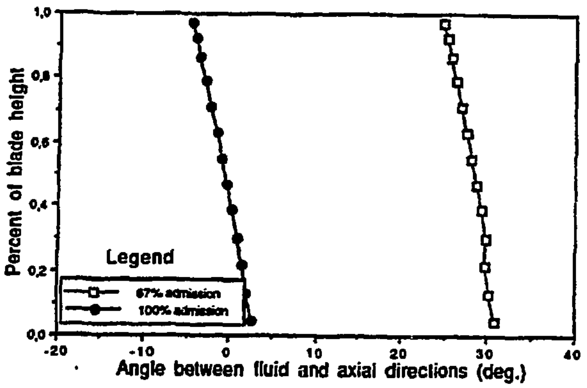

Fig. 4: Fluid angle at exit from control stage

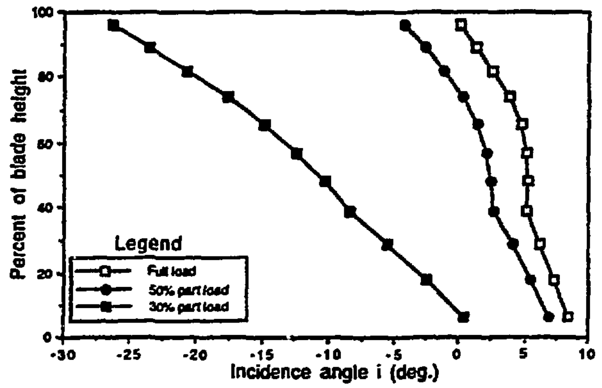

Fig. 5: Flow incidence at the last moving blade

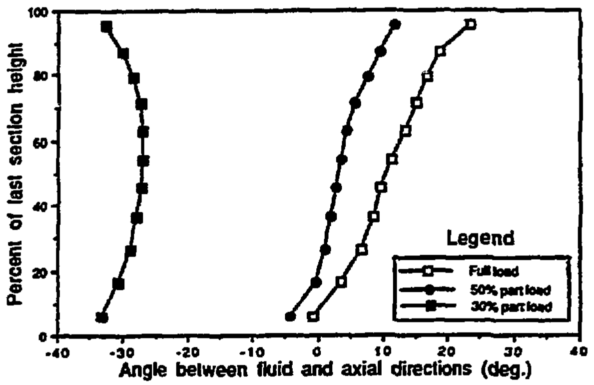

Fig. 6: Fluid angle at turbine outlet

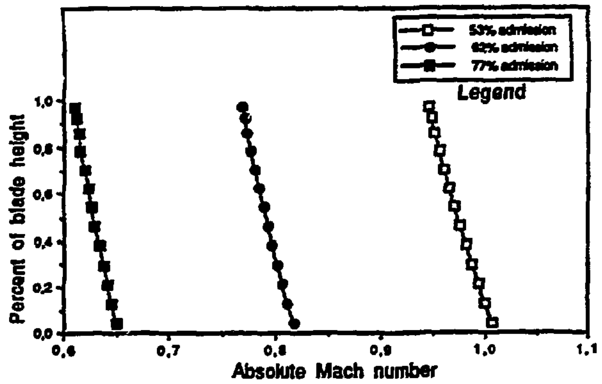

Fig. 7: Mach number at exit from first stage nozzle

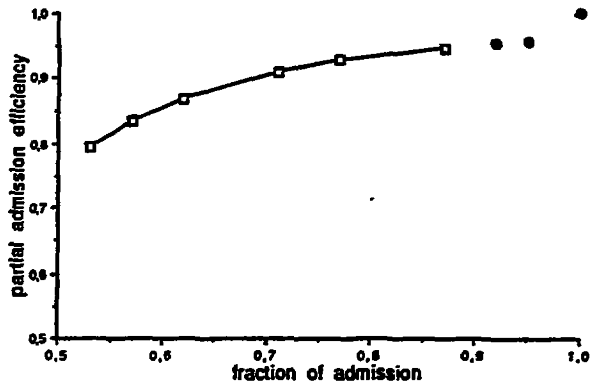

Fig. 8: Partial admission efficiency evolution