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Comparison of Partial vs Full Admission for Small Turbines at Low Specific Speeds (*)

ENNIO MACCHI
Professor
Dept. of Energetics
Politecnico di Milano
Milan, Italy

GIOVANNI LOZZA
Research Engineer
Dept. of Hydraulics
University of Pavia
Pavia, Italy

ABSTRACT

Several methods are available for the optimization of basic design parameters and the preliminary efficiency prediction of axial flow turbine stages. However, their application is often questionable for stages having low specific speed and/or small volume flow rates. In particular, the question may arise whether a better performance is achieved by a partial admission, impulse stage or by a full admission reaction stage having lower blade height.

The paper firstly reviews the available loss correlation methods applicable to partial admission turbines, then a comparison is performed between the efficiency achievable by partial and full admission stages designed for the same operating conditions. The turbine design procedure for both options is fully automatized by an efficiency optimization method similar to the one described in previous authors'papers.

The results of calculations are presented in the paper as a function of similarity parameters (specific speed, size parameter, expansion ratio). It is found that the results obtained with different correlations are relatively similar for "conventional" turbine stages (low expansion ratio, moderate size parameters), while important differences take place for very small sizes and/or in presence of important compressibility effects.

The presented results can be useful: 1) to decide whether selecting full or partial admission solutions; 2) to optimize the degree of admission and the other basic design parameters, and 3) to predict with reasonable accuracy the stage efficiency.

NOMENCLATURE

a	arc of admission, m
b	axial chord, m
d_b	rotor rim - housing clearance, m
d_h	disk - housing clearance, m
D	mean diameter, m
FL	flaring angle, deg
h	blade height, m
K_{is}	head coefficient = $2\Delta h_{is}/u^2$
k_s	blade surface roughness, m
$\dot{m}$	mass flow, kg/s
M_W	Mach number of relative velocity
MM	molecular mass of the working fluid
n	speed of revolution, rps
N_s	specific speed $= n\sqrt{\dot{V}_{ex}}/\Delta h_{is}^{3/4}$
o	blade throat opening, m
p	pressure, Pa
R	mean radius, m
Re	Reynolds number
s	blade spacing, m
t_n	trailing-edge thickness, m
T	temperature, K
r*	isentropic degree of reaction
u	peripheral speed, m/s
v	absolute velocity, m/s
w	relative velocity, m/s
VH	size parameter $= \sqrt{\dot{V}_{ex}}/\Delta h_{is}^{1/4}$, m
VR	volume ratio = $\dot{V}_{ex}/\dot{V}_{in}$
$\dot{V}_{in}$	volumetric flow rate at turbine inlet, m^3/s
$\dot{V}_{ex}$	volumetric flow rate, at turbine exit, for isentropic expansion, m^3/s
Z	number of blades
α	absolute flow angle, deg
β	relative flow angle, deg
γ	specific heat ratio
δ_r	radial tip clearance, m
δ_{SR}	axial clearance between stator and rotor, m
Δl	overlap of rotor blades, m
Δh_{is}	isentropic enthalpy drop, J/kg
Δv_t	variation of tangential velocity across the rotor, m/s
$\Delta\eta_l$	efficiency debit due to leakages, in PA operations
$\Delta\eta_s$	efficiency debit due to sector-end losses
$\Delta\eta_v$	efficiency debit due to ventilation losses
ε	degree of admission
ϕ	flow coefficient = v_a/u
η	efficiency, 50% leaving losses recovered
η_{ts}	total-static efficiency
ξ	loss coefficient

Subscripts

0	stator inlet
1	stator exit

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2	rotor exit
a	axial component
FA	full admission
PA	partial admission
opt	optimized value
t	tangential component
T	blade tip, or total

INTRODUCTION

The dimensions of turbomachinery bladings are primarily a function of the volume flow rates which pass through the machine. When a machine operates with dense fluids and/or low power levels, small volume flow rates take place and flow passage channels become small. In an "ideal" machine, for which it would be possible to maintain clearances, blade thicknesses, surface roughness in proper ratio to other geometrical parameters, small dimensions of blading would have a very limited influence on performance, since, according to similarity rules, only Reynolds number decrease plays a role on losses. A different situation occurs in a real machine, where the penalties related to small dimensions become much greater, as demonstrated both by experience and theory (1, 2).

Coming to axial flow turbines, and referring to the loss breakdown usually adopted in these machines (3), it is generally found that small blade dimensions penalize all loss components. In fact, they cause an increase of: 1) profile losses, due to high values of relative roughness and trailing edge thickness/opening ratio; 2) secondary losses, due to low blade aspect ratios; 3) leakage losses, due to high clearance/blade height ratio; 4) disk windage losses, due to low hub/tip ratios. Two ways are available to turbine designer to decrease these losses: the adoption of very high speeds of revolution and/or the partialization of the machine. The first procedure is always beneficial from an aerodynamic point of view, up to optimum values of specific speed , but the resulting speed of revolution is not always allowed by practical limitations (seals, bearings, matching to other stages in multistage machines, coupling to utilizer, etc.). A typical example of these limitations is represented by small steam turbines for industrial applications, which often run at specific speeds lower than optimum by an order of magnitude. For instance, a 500 kW turbine operating between 40 and 4 bar would require about 200,000 rpm, while the speed of revolution of existing machines ranges between 3000 and 20000 rpm (4).

The second procedure improves the situation as far as losses related to blade dimensions are concerned,but brings about some new losses. It is purpose of the present paper to discuss the merits of partialization and to present a simple method to decide whether a turbine should or not be partialized and to select the basic design parameters of a partialized turbine stage.

METHOD OF ANALYSIS

The design method used in the analysis is similar to the one described in previous papers (1, 2), modified to incorporate the influence of partialization and various loss correlations to be tested: it is based on a computer program which performs a contemporary optimization of the basic design parameters of an axial-flow turbine stage, within specified boundaries, introduced in order to keep the solution within realistic assumptions (see tab. 1). It should be noted that the isentropic degree of reaction r^*, which is usually an optimizing variable for full admission stages, becomes a fixed input for partial admission; the degree of admission ε can be either an input or an optimizing variable.

In all cases, the loss correlation of Craig and Cox (3) is used to predict all losses but the partiali-

TAB. 1 : COMPUTER PROGRAM INPUT DATA AND OPTIMIZATION BOUNDARIES.

INDEPENDENT VARIABLES	FLUID PROPERTIES AND OPERATING CONDITIONS	FIXED GEOMETRIC DIMENSIONS	OPTIMIZATION BOUNDARIES
$(o/s)_1$	γ	t_n = max(0.05 o,0.0002)	2.0 < K_{is} < 10.0
o_1	MM	δ_r = max(0.002 R,0.0002)	- 0.01 < r^* < 0.8$^{(c)}$
b_1	Re	k_s = 0.000002	0.225 < $(o/s)_{1,2}$ < 0.8
$(o/s)_2$	P_{TU}	α_0 = 90°	2 $o_{1,2}$ < $b_{1,2}$ < 0.1
o_2	T_{TO}	δ_{SR} = 0.2 b_1	0.0015 < $o_{1,2}$ < 0.05
b_2	P_2	$\Delta 1$ = max(0.1 h_1,0.002)	10 < $Z_{1,2}$ <150
K_{is}	$\dot{m}$	R_2 = R_1	0.001 < h/D_2 < 0.25
$r^{*(a)}$	n	d_b = 0.75 δ_{SR}	0 < M_{w1} < 1.4
$\varepsilon^{(b)}$		d_h = d_b	0° < FL < 30°

a Only for full admission.

b Only for partial admission, if not specified as input.

c r^* = 0 for partial admission stages.

zation ones. In the authors' experience, this correlation yields reliable results in a wide range of turbine characteristics and dimensions, with an exception for the prediction of tip clearance losses in impulse stages with unshrouded blades, which seem to be systematically underestimated. For this reason, an option to utilize the Kacker-Okapuu (5) relation just for this specific item is included in the program.

ANALYSIS OF EXISTING CORRELATIONS OF PARTIALIZATION LOSSES

To the authors' knowledge, only a few correlations on partialization losses have appeared in the open literature during the last two decades (6 - 10). As shown in tab. 2, they differ both on classification of various types of losses and on parameters involved in the analysis. For this reason, a direct comparison among them is not straightforward, and a different approach will be followed. The analysis will be limited to correlations proposed by Traupel (6), Baljè and Binsley (7) and Yahya and Doyle (8), which seem to be the most comprehensive methods today available to predict partialization losses. The relations suggested by the various authors and used in the present paper are given in tab. 3.

TAB. 2 : PARAMETERS INVOLVED IN THE LOSS CORRELATIONS

AUTHORS	SOURCE OF LOSSES: BLADE PUMPING or VENTILATION	SOURCE OF LOSSES: SECTOR-END and/or SCAVENGING FILLING-EMPTYING	SOURCE OF LOSSES: LEAKAGE
TRAUPEL (6)	$\varepsilon, K_{is}, \phi_1, \frac{h_2}{D}$	$\varepsilon, K_{is}, \frac{b_2}{D}$	not considered
BALJE BINSLEY (7)	$\varepsilon, K_{is}, \phi_1, \frac{h_2}{D}, Re_T$	$K_{is}, \phi_1, \frac{b_2}{a}, \frac{s_2}{a}$	$r^*, \frac{h_2}{D}, \frac{b_2}{D}, \frac{d_b}{a}, \frac{d_h}{h_2}, \phi_1, \phi_2, K_{is}, \frac{\Delta v_t}{u}$
YAHYA DOYLE (8)	not evaluated	$\frac{s_2}{a}, \frac{o_2}{a}, b_2, u, w_1, \beta_1, \beta_2, \xi_2$	included in sector-end losses
DEICH TROJANOVSKI (9)	$\varepsilon, K_{is}, \phi_1$	included in blade pumping losses	not considered
KOREMATSU HIRAYAMA (10)	ref. to Traupel (6)	function of stipulated velocity distribution along the arc of admission	$\frac{h_2}{D}, \frac{b_2}{a}, u, w_1, d_h$

It is not the purpose of this paper to test the validity of these correlations against experiments, a procedure which would require a large number of tests on turbine stages of various (and all specified) geometric characteristics, performing detailed and reliable measurements of losses at various degree of partialization. However, a check of the adopted calculation procedure and loss correlations was performed on two single stage axial flow turbines tested by NASA (11,12) at various degrees of admission. The two turbines have the characteristics summarized in tab. 4. As shown in fig. 1, an excellent agreement between experiments and calculations is obtained for both turbines at full admission, a further confirmation of the validity of the Craig and Cox correlation, even in presence of unusual values of Mach numbers and deviations. For the transonic turbine, the measured efficiency decrease related to partialization is very well predicted by all three correlation methods, if the sharp increase of leakage losses due to the non zero theoretical degree of reaction reported in Baljè - Binsley correlation is not accounted for. No influence of partialization was measured for the supersonic turbine in (12), a result in contrast with theory and correlation predictions. It should however be pointed out that the predicted efficiency drop due to partialization is relatively small (and within experimental uncertainties) for a great part of the investigated range. Some further tests on correlations reliability were run on industrial steam turbines. However, no evidence of advantages of one correlation vs the others was found, due both to insufficient accuracy of available measurements and uncertainties on actual clearances and geometrical details of seals.

While the question about the accuracy of the loss correlations cannot be answered, let's try to solve these other two points:

a) how different are the efficiency predictions based on various loss correlations ?
b) which is the influence of the adopted loss correlation on the results of the optimization of a turbine stage?

To give an answer to the above questions, the behavior of loss correlations is to be investigated in the whole field of interest, by varying all relevant parameters. In (1, 2), it was demonstrated that the maximum efficiency achievable by a turbine stage operating at optimum peripheral speed is primarily a function of: 1) the specific speed N_S, 2) the "size" parameter VH, which accounts for the actual turbine dimensions, and 3) the compressibility parameter VR, which accounts for volume flow rate variations through the machine and Mach number influence. For partialized turbines, a further va-

TAB. 3 : LOSS CORRELATIONS USED IN THE PAPER

<table>
<tr><th>AUTHORS</th><th>BLADE PUMPING
(or VANTILATION)</th><th>SECTOR-END
or SCAVENGING
FILLING-EMPTYING</th><th>LEAKAGE</th></tr>
<tr><td>TRAUPEL</td><td>Ventilation losses:
$\Delta\eta_v = C_{b1}\frac{1-\varepsilon}{\varepsilon}\frac{1}{\phi_1 K_{is}}$
where:
$C_{b1} = 0.019 + 1.1(0.125 - h_2/D)^2$</td><td>Sector-end losses:
$\Delta\eta_s = \frac{0.30}{\varepsilon\sqrt{K_{is}}}\frac{b_2}{D}$</td><td>-</td></tr>
<tr><td>YAHYA-DOYLE</td><td colspan="3">Mixing and sudden expansion losses:
$\Delta\eta_s = \frac{u w_1}{\Delta h_{is}}(\cos\beta_1 + \cos\beta_2)(1 - \frac{s_2}{2a})(1 - n) - \frac{\xi_2 w_1^2}{2\Delta h_{is}}\cdot(1 - m(1 - \frac{s_2}{2a})) + (\frac{s_2}{4a})\frac{u w_1 \cos\beta_2}{\Delta h_{is}}$
where:
$m = -1 - \frac{1}{Kt_1} + \frac{2}{Kt_1}\ln(\frac{1 + e^{Kt_1}}{2}) + \frac{4e^{Kt_1}}{Kt_1(1 + e^{Kt_1})}$
$n = 1 + \frac{4}{Kt_1(1 + e^{Kt_1})} - \frac{2}{Kt_1}$
$Kt_1 = \frac{2w_1}{u}\frac{a}{b_2}$</td></tr>
<tr><td>BALJE'-
BINSLEY</td><td>Blade pumping losses:
$\Delta\eta_v = C_{b1}\frac{1-\varepsilon}{\varepsilon}\frac{1}{\phi_1 K_{is}}$
where:
$C_{b1} = .04568\ (\frac{h_2}{D_T})^{-0.4}\ Re_T^{-1/7}$</td><td>Scavenging losses:
$\Delta\eta_s = 1.4\frac{b_2}{a}\frac{1}{\phi_1 K_{is}}$
Filling and Emptying losses (accounted by modifying the rotor loss coefficient):
$\frac{1 - \xi_{2,PA}}{1 - \xi_{2,FA}} = 1 - \frac{s_2}{2a}$</td><td>Leakage losses:
$\Delta\eta_L = \frac{2}{K_{is}}\frac{\Delta v_t}{u}(L_A + L_B + L_C + L_D)$
where:
$L_A = C_1\frac{d_b}{a}\sqrt{r^*}$
$L_B = C_1\sqrt{r^*}\frac{d_h}{h_2}\frac{(D - h_2)}{D}$
$L_C = C_1\frac{d_b}{a}\sqrt{1 - \xi_1}\ (1 - r^*)$
$L_D = 0.21\frac{h_2}{D}\frac{b_2}{D}\frac{1}{\phi_2}$
$C_1 = 0.66\frac{\sqrt{K_{is}}}{\phi_1}$</td></tr>
</table>

TAB. 4 : CHARACTERISTICS OF TURBINES OF FIG 1

Reference	Mean diameter,m	Pressure ratio	Relative Mach number at rotor inlet	Range of admission,%	η_{ts} at full admission,%
(11)	0.095	3	0.8	12-100	68
(12)	0.260	30	2.0	12.5-100	42.5

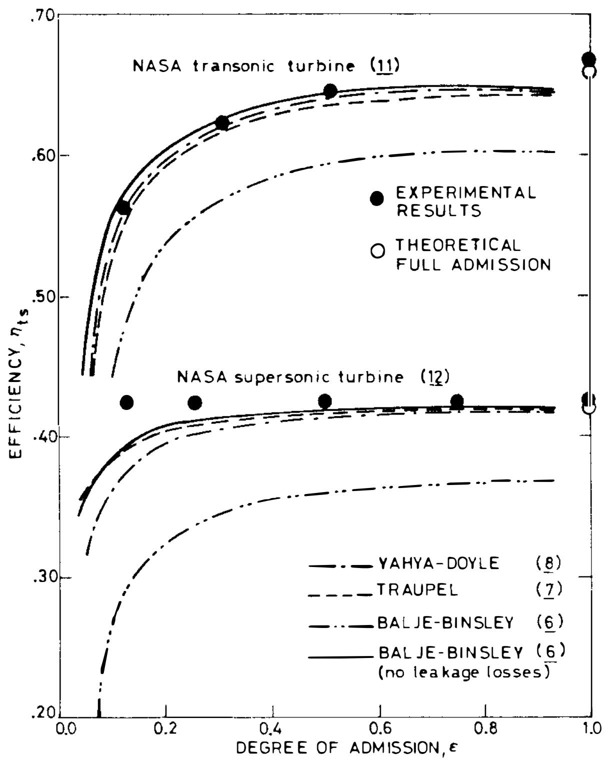

FIG. 1 COMPARISON BETWEEN EXPERIMENTAL DATA AND CALCULATIONS PERFORMED USING VARIOUS LOSS CORRELATIONS, FOR TWO PARTIALIZED TURBINES.

riable, namely the degree of admission ε, should be added.

Let's now consider the results represented in fig. 2, where,according to previous point, all four relevant parameters are varied. The curves in fig. 2 represent the result of the optimization of the efficiency of a turbine stage as a function of ε, for the specified combination of parameters VR, VH, N_s. Since the resulting optimizing variables depend upon ε and loss correlation, the turbine characteristics vary from point to point. The following considerations can be drawn from fig. 2:

- for nearly incompressible cases and relatively large turbines (VH = 0.10 m), the three correlations yield similar results at various N_s and ε, both on terms of efficiency and optimum degree of admission;
- for small turbines (VH = 0.02 m), some differences are found among the three correlations at low ε; in general there is a good agreement between (6) and (7), while (8) yields more optimistic results;
- when high compressibility effects are considered (VR = 4) , larger discrepancies among the results appear. Again, higher efficiencies are predicted with (8), while the correlation in (6) strongly penalizes small degrees of admission, owing to the sharp increase of ventilation losses. It should be pointed out that these results are strongly influenced by the assumed constraint on M_{W1}, which requires the adoption of head coefficients much lower than for incompressible case (K_{is} = 4 - 4.5 vs 6.5 - 7).

For given operating conditions, the selection of the optimum degree of admission is not only influenced by the assumed loss correlation for partial admission effects, but also by all other assumptions on losses. The situation is illustrated in fig. 3, where the results of two optimizations obtained with different correlations on tip leakage losses are given. It can be seen that not only the predicted efficiency is different, both for the initial and final solutions, but also that the degree of admission, initially set to a common value of 15%, reaches significantly different values during the optimization process: in fact, lower arcs of admission are selected, in the cases showing higher tip clearances losses.

PRESENTATION OF RESULTS

Even with the uncertainties and limitations outlined in the previous section, it is of interest to perform an attempt to obtain a correlation which enables the turbine designer to decide whether or not to use a partialized stage and to select the optimum degree of admission. The results of such an attempt are given in the next series of diagrams, which were derived for shrouded blades, by arbitrarily assuming the Traupel (6) loss correlation for partial admission losses. As stated before, the stage efficiency is primarily a function of four parameters. However, if compressibility effects are not considered (small VR) and the degree of admission is taken as an optimizing variable, the results can be simply presented in a plane having N_s and VH as coordinates.

In the first diagram (fig. 4), the efficiencies of optimized turbine stages, both with partial and full admission, are presented in the N_s - VH plane. It can be seen that for low N_s (less than 0.035 to 0.07, depending upon the VH values), partial admission yields better results than full admission. A typical breakdown of losses, both for full or partial admission turbines, is shown in fig. 5, for a case at low specific speed (N_s = 0.01). It should be noted that additional losses, due to partial admission, are much lower than the gain in efficiency, caused by a significant reduction of secondary and tip clearance losses.

The optimum degree of admission is strongly influenced by N_s (fig. 6) and reaches values close to 0.5 in the vicinity of the line where partial and full admission give equivalent results. The optimum head coefficients (fig. 7) increase at low N_s and VH, i.e. lower diameters are adopted to obtain a better aspect ratio, even if the velocity triangles experience an unconventional deformation. The use of partial admission limits this effect, owing to the increase of blade height. The variation of K_{is} is a further demonstration that the design parameters of a turbine stage cannot be individually optimized, say first select the velocity triangles, then the degree of admission. The turbine design is to be looked at as a contemporary optimization of a multivariable function, owing to mutual influence of optimizing variables.

The beneficial effects of partialization are evident in fig. 8, where the blade height variations at nozzle exit are shown in the N_s - VH plane. At constant VH, the blade height of full admission stages decreases by lowering the specific speed. When a partialized solution is adopted, the blade height is kept to a constant optimum value (about 50% of VH), by decreasing the degree of admission. The resulting efficiency improvements are particularly relevant for low VH, where corresponding blade heights at full admission stages are very low .

All above results were derived for VR = 1.05, i.e. for a nearly incompressible case. In this situation it was shown that all loss correlations give similar predictions, and it can therefore be assumed that the presented results are of general validity.

The influence of compressibility is rather complex. Let's consider the results of fig. 9, where the effect

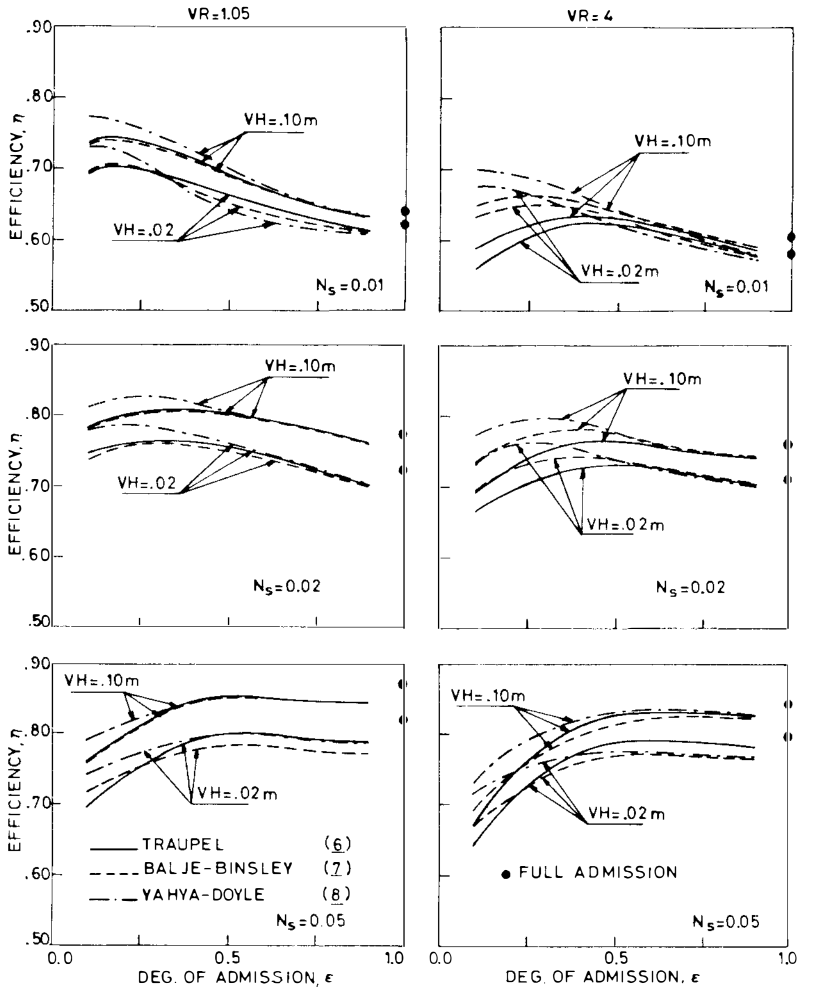

FIG. 2 OPTIMIZED EFFICIENCIES FOR TURBINE STAGES AT VARIOUS N_s, VH, VR, AS A FUNCTION OF THE DEGREE OF ADMISSION.

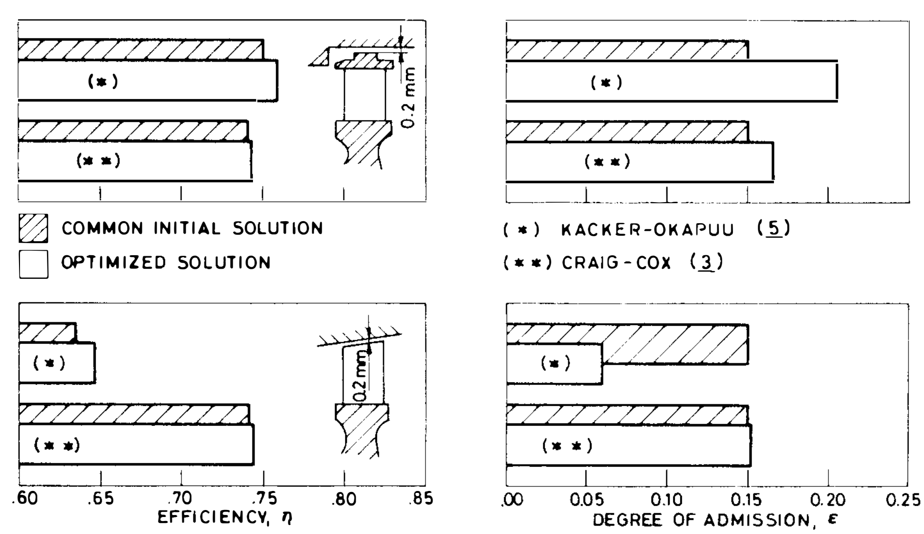

FIG. 3 INFLUENCE OF THE TIP CLEARANCE LOSSES ON THE EFFICIENCY AND THE OPTIMIZED DEGREE OF ADMISSION, FOR A TURBINE HAVING N_s = 0.01, VH = 0.1, VR = 1.05.

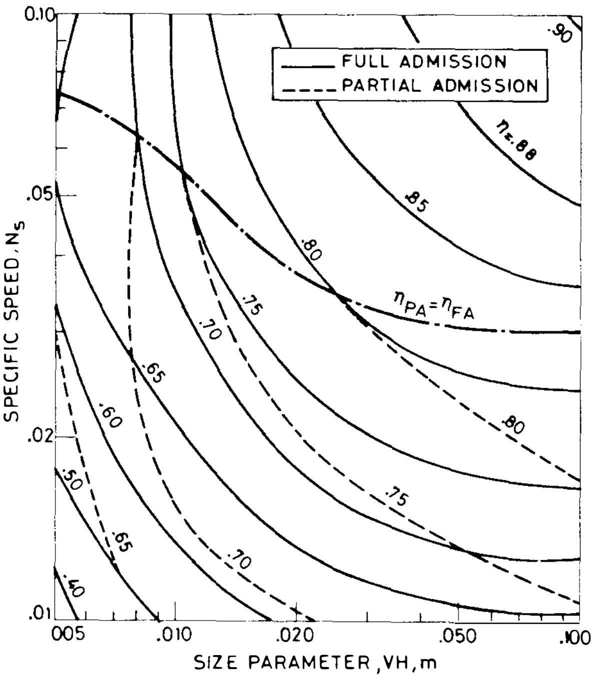

FIG. 4 OPTIMIZED EFFICIENCY OF PARTIAL AND FULL ADMISSION TURBINES, IN THE VH – N_s PLANE, FOR NEARLY INCOMPRESSIBLE FLOW.

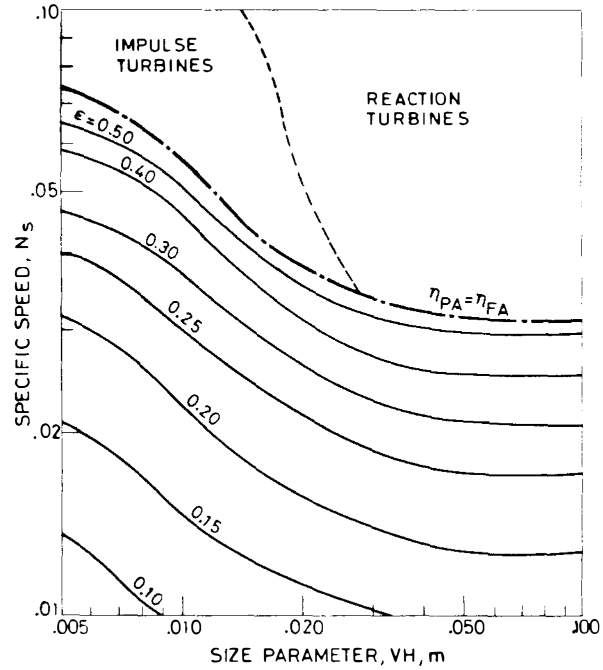

FIG. 6 OPTIMUM DEGREE OF ADMISSION, IN THE VH – N_s PLANE

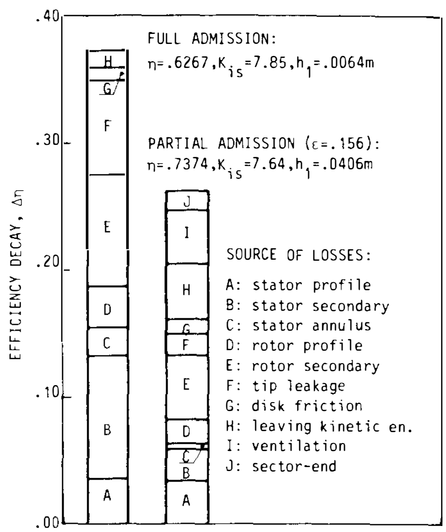

FIG. 5 BREAKDOWN OF LOSSES FOR TURBINES, HAVING N_s = 0.01 VH = 0.1, VR = 1.05 FOR FULL AND PARTIAL ADMISSION

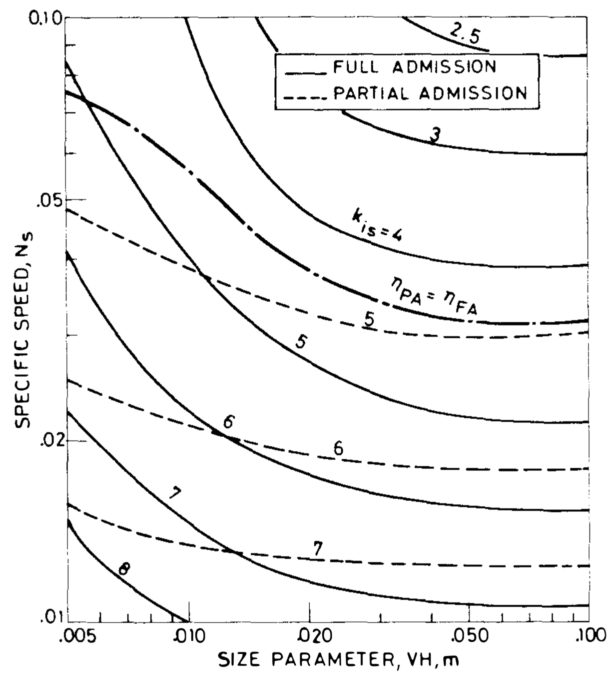

FIG. 7 OPTIMIZED HEAD COEFFICIENT, FOR FA AND PA TURBINES, IN THE VH – N_s PLANE.

of VR on turbine efficiency, degree of admission and head coefficient is given for a particular set of operating conditions (N_s = 0.015, VR = 0.2 m). For large VR values, supersonic relative velocity at rotor inlet takes place. This can be avoided, by increasing the peripheral speed, with an increase of losses related to ventilation and exit kinetic energy. If M_{W1} values in excess of unity are accepted, the influence of VR on obtained results is not very strong (dotted lines in fig. 9), owing to the small density variation experienced by the fluid across the rotor in impulse stages. If constraints on M_{W1} are introduced, the compressibility effects become very strong. Of course, the most correct approach to this problem should be the introduction of correlations to quantify the influence of M_{W1} on losses. The only suggestion on this regard found in the literature is the one given by (5). However, an attempt to utilize

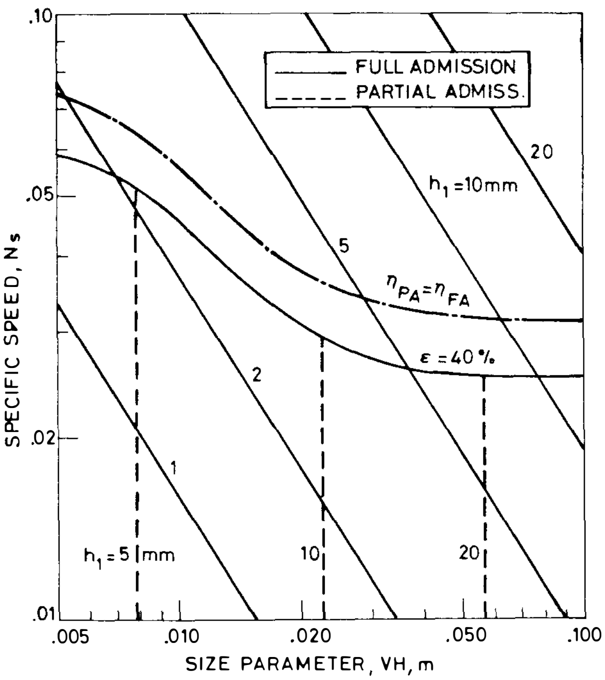

FIG. 8 OPTIMIZED BLADE HEIGHT, AT STATOR EXIT, FOR FA AND PA TURBINES, IN THE VH - N_S PLANE.

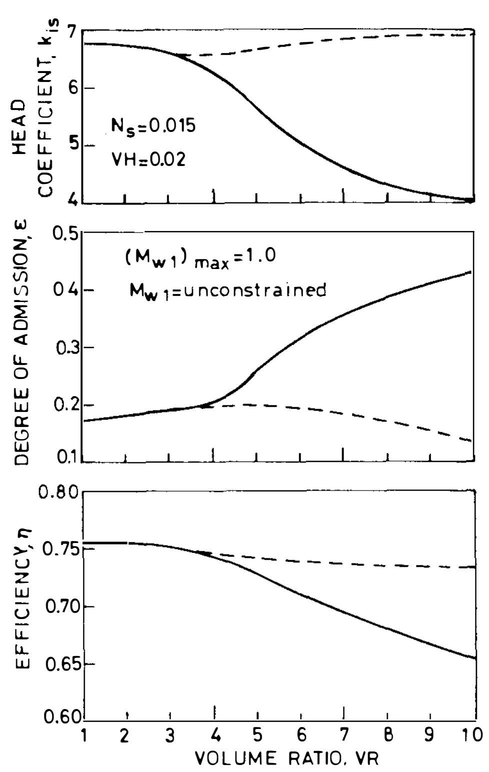

FIG. 9 INFLUENCE OF THE FLOW COMPRESSIBILITY ON THE EFFICIENCY AND THE DESIGN PARAMETERS OF PARTIALIZED TURBINES.

their penalization coefficient was not successful, since exceedingly high values of losses were obtained. In conclusion, it can be stated that the presented results hold for values of VR up to about 3.

CONCLUSIONS

The use of presented diagrams allows the turbine designer: 1) to decide whether to select full or partial admission stages and to predict the stage efficiency with reasonable accuracy (fig. 4); 2) to optimize the degree of admission (fig. 6) and 3) the stage head coefficient (fig. 7). The diagrams were derived under particular hypotheses, i.e. shrouded blades with small (0.2 mm) radial clearances, low compressibility effects, and other assumptions stated in tab. 1. For significantly different operating conditions, the obtained results would be not valid, and ad hoc optimizations should be performed. In this case, it is recommended to utilize a contemporary optimization of all relavant variables, since mutual influences can be very strong for turbine stages of small size.

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