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Modernizing Synthesis Gas Turbocompressor Units to increase Ammonia Production Capacity

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The paper presents actual examples of centrifugal compressor and turbine modernizations at large-capacity ammonia production sites in Russia and the CIS. In particular, a project to modernize, at minimum cost, the 103J synthesis gas compressor to raise its capacity from 1,360 to 1,700-2,000 tons of ammonia per day and to reduce its specific energy consumption is considered.

INTRODUCTION

The large-capacity ammonia production plants in Russia and the CIS that were constructed in the 1970s were equipped with turbocompressor units originally designed for a capacity of 1,360 tons of ammonia per day. These production processes were based on the technology of Toyo Engineering (TEC) of Japan or that of the Soviet State Institute of Nitrogen Industry (GIAP). The turbocompressors installed in these plants were built by such reputable machinery companies as Mitsubishi Heavy Industries, Dresser-Rand, Hitachi, Fuji and Nuovo Pignone, Nevsky (Saint-Petersburg) and Kazansky Plants.

As time went by it became desirable to expand these ammonia plants to a target capacity of 1,700-2,000 t/d. This was far beyond the design capability of the original turbocompressors: an increment of this size could not be accommodated merely by running them faster because their efficiency drops off on account of aerodynamic effects and the risk of damage reduces their reliability. In any case, the drive turbines did not meet latter-day standards of energy-efficiency (= steam consumption).

To replace these compressors with new ones would have been prohibitively expensive, so it was decided to modernize the existing machines' flow parts. The following machines are turbocompressors: process air (101J), synthesis gas (103J), natural gas (102J) and ammonia (105J).

Entechmach RPC has already previously done modernizations of the 101J and 103J centrifugal compressors going along with notable prime cost and operational specific energy consumption reduction. The most complex and power-intensive is the synthesis gas compressor, and it with that type of machine that this paper is mainly concerned.

ORIGINAL 1,360-T/D SYNGAS COMPRESSOR

As an example let us consider the basic points of 103J synthesis gas compressor modernization. This machine was originally designed for an inlet pressure of 2.5 MPa and a discharge pressure of 32 MPa. The volumetric suction capacity at STP (0°C, 0.1MPa) is 165,000 Nm³/h. The compressor has three cases: low-pressure (LP), medium-pressure (MP) and high-pressure (HP) cases. There are four synthesis gas sections and a recycle stage that returns gas remaining unconverted at the outlet of the synthesis column to its inlet with its pressure increased by 1.09 (Fig. 1). The drive is a two-stage steam turbine.

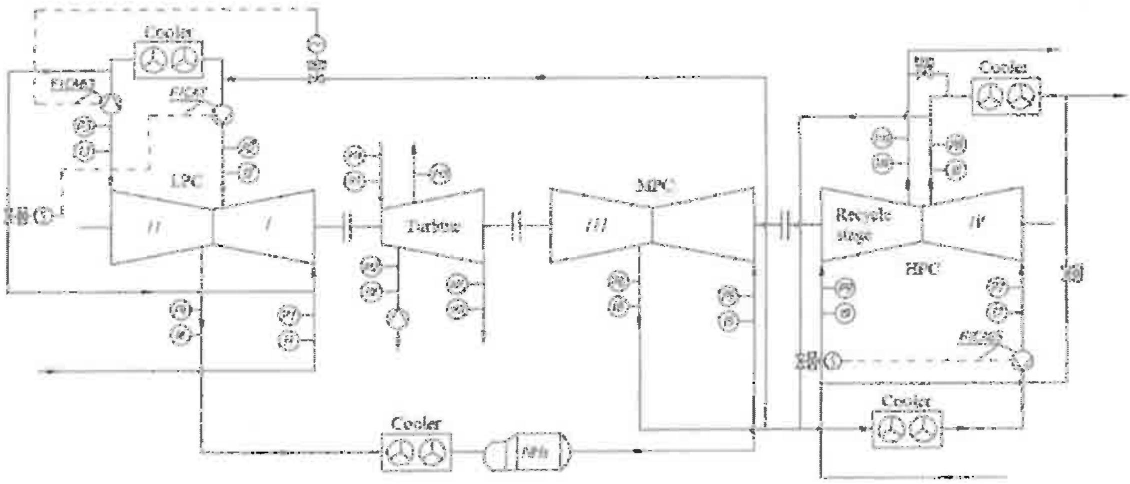

Fig. 1: Syn-gas compressor principle scheme

MODERNIZATION FOR 1,700 T/D AMMONIA PRODUCTION

In 2010, the Russian company **Entechmach RPC** worked on the modernization of a synthesis gas compressor to raise its capacity to the equivalent of 1,700 t/d of ammonia. By the 2014 three successful modernizations has been completed. The modernized compressor in the existing cases of the original one has the initial pressure 2.5 MPa and discharge pressure 23 MPa. The discharge pressure was reduced because the synthesis converter was loaded with a new catalyst that is effective at the lower pressure. The new compressor capacity is 202,000 Nm³/h, 22% higher than the old. A photograph of this synthesis gas compressor is given in Fig. 2.

Maximum use was made of components of the existing unit: power cases, piping gas lines, valves, lubrication system, etc.

Fig. 2: Synthesis gas compressor

Cross-sections of the LP, MP and HP cases of the modernized 103J compressor (1,700 t/day) are shown in Figs 3, 4 and 5. In the LP case the number of stages is 5/5. The number of stages was reduced from 5/5 to 4/4 in the MP case and from 7+1 to 6+1 in the HP case in order to diminish the discharge pressure from 32 to 23 MPa. The general concept of the original compressor was saved. The impeller's outlet width was increased and the width ratio between the vaneless diffuser and the impeller outlet width was increased from 0.8 to 1.2. The inclination angle of the impeller cover disks was increased to minimize losses at the inlet turn to each impeller.

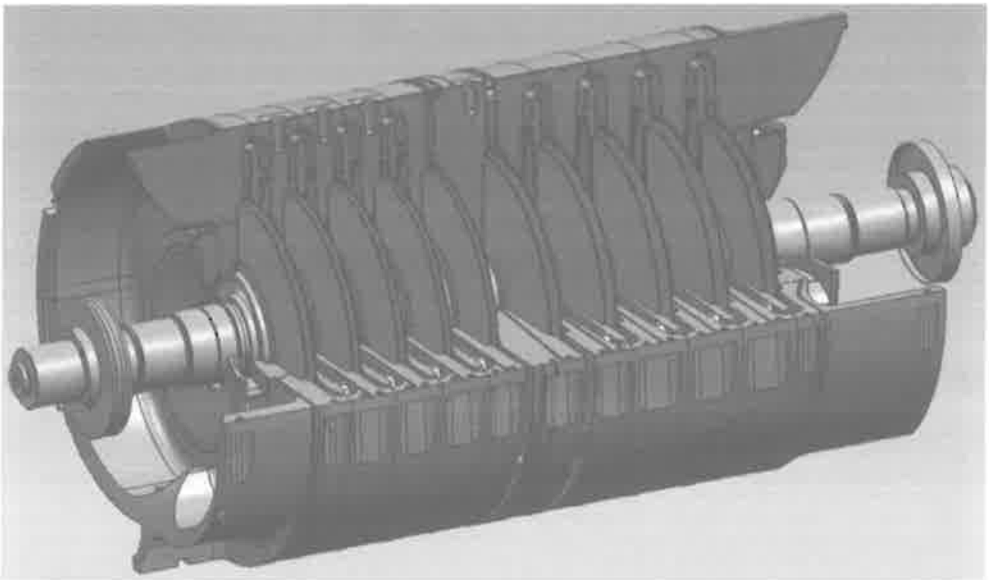

Fig. 3: Cross-section of low pressure case (LPC) of the modernized 103J compressor (1700 t/day)

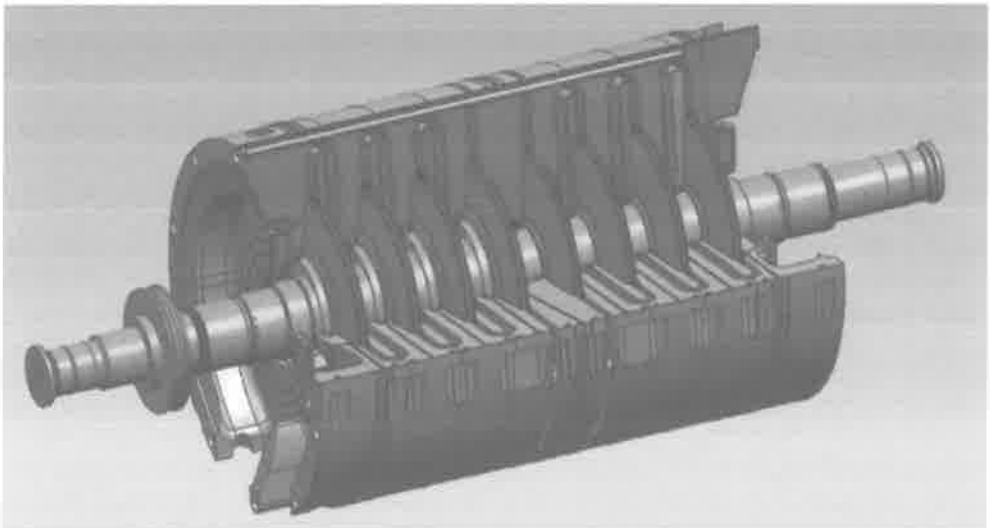

Fig. 4: Cross-section of medium pressure case (MPC) of the modernized 103J compressor (1700 t/day)

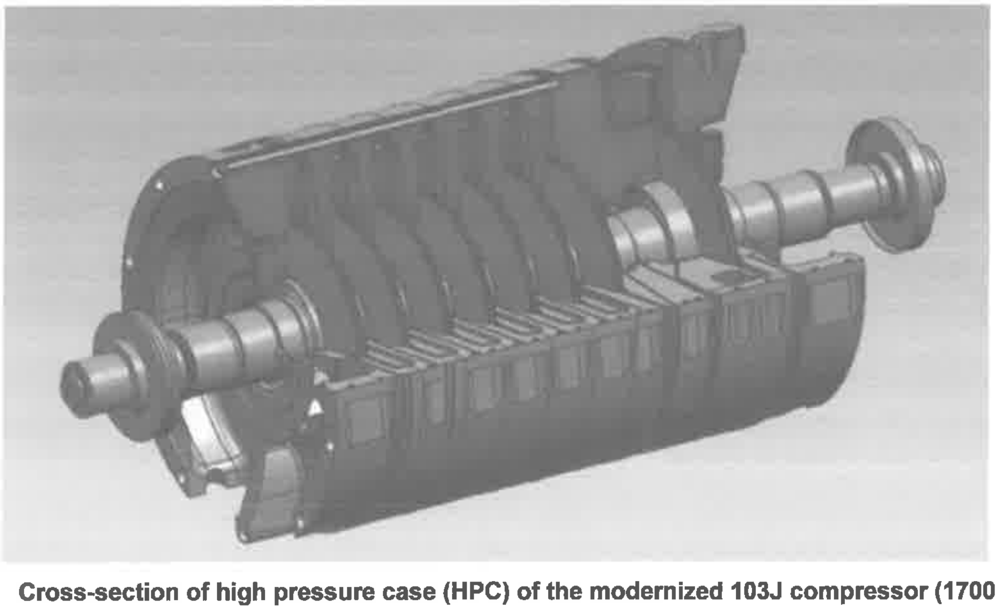

Fig. 5: Cross-section of high pressure case (HPC) of the modernized 103J compressor (1700 t/day)

The power consumption of the modernized compressor under comparable conditions is 10% lower than that of the one being operated now.

MODERNIZATION FOR 2,000 T/D AMMONIA PRODUCTION

Project description

With the benefit of this experience, in 2011 **Entechmach**, the Polish company **ALSTOM Power** and the Ukrainian company **TRIZ** started a joint development project on modernizing compressors and turbines to meet the requirements of the producers for 2,000 t/d of ammonia – the "Ammonia 2000" project. The project would be implemented in 2014.

Such a huge hike in production (more than 45% above the original design value) demands careful study of the changes which need to be made both in the process and in the compressors and turbines. The task of determining just how to accomplish it was carried out by design organizations such as **Ammonia Casale**, which undertook a minute analysis of the complete process plant in co-operation with the plant operators, whose long-term experience of operating the process and its machinery is invaluable in defining the exact combination of changes in the equipment and in the process conditions that will make it possible to achieve the objectives of the revamp.

The Ammonia 2000 project is based on several main requirements for the dynamic equipment, namely:

- to adjust the characteristics of the synthesis gas and air compressors to attain the target capacity;
- to obtain from the turbine drives the requisite power and speed matching the optimal requirments of the compressors for the minimum steam consumption;
- to ensure continuous uninterrupted and smooth operation within the safety margins specified in the API 612 and API 617 standards;
- to increase the efficiency of compressors and their turbines and thereby reduce the specific energy consumption in the ammonia production.

Experimental database

Entechmach RPC has been able to increase the polytropic efficiency of the modernized compressor's sections and improve the characteristics of the intermediate gas coolers by a sufficient amount to make it possible to achieve the desired 45% increase in ammonia production. Gas flow through the modernized 103J compressor has been streamlined by the use of high-efficiency components such as impellers with cylindrical backward-curved blades and vane diffusers. Compressor stages have been designed using Entechmach's in-house database of information obtained from the company's model rig (Fig. 6).

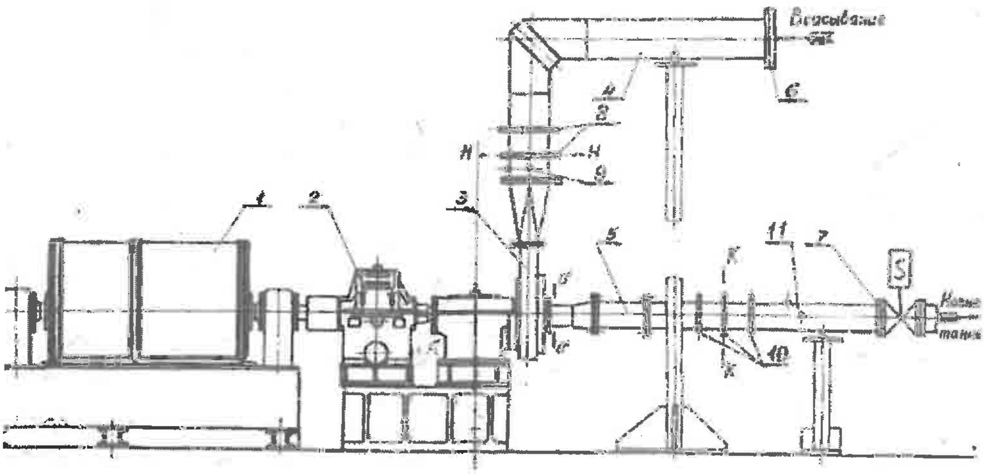

Fig. 6: Model rig for centrifugal compressor stage:
1: Electric motor. 2: Multiplier. 3: Model stage. 4: Suction tube. 5: Pressure line. 6: Diaphragm. 7: Throttle. 8, 10: Sampling tubes for measuring suction and discharge pressure. 9, 11: Chambers for suction and discharge temperature measurement

High-efficiency centrifugal stages with impeller exit angles β_2 = 48° and 32° and vane diffusers are used in the modernized 101J and 103J compressors. The 5% diffuser airfoil blades have been created after careful experimental research and have a leading blade angle which provides 'bumpless' entry in the normal operation.

CFD analysis

Besides the experimental method of obtaining gas-dynamic characteristics of stages, **Entechmach** also uses the modern finite element method. An example of a calculation of speed distribution in the first stage of the modernized 103J compressor (2000 t/day) with a vane diffuser is shown in Figs 7 and 8. This was worked out in co-operation with **Numeca Russia**. The calculated polytropic efficiency of a stage is equal to 85%, and that is confirmed as well by Entechmach's experimental data on model stages, which gives 83% with reduced geometry close to that one in simulation. The calculation results indicate a high guarantee efficiency for the stages used.

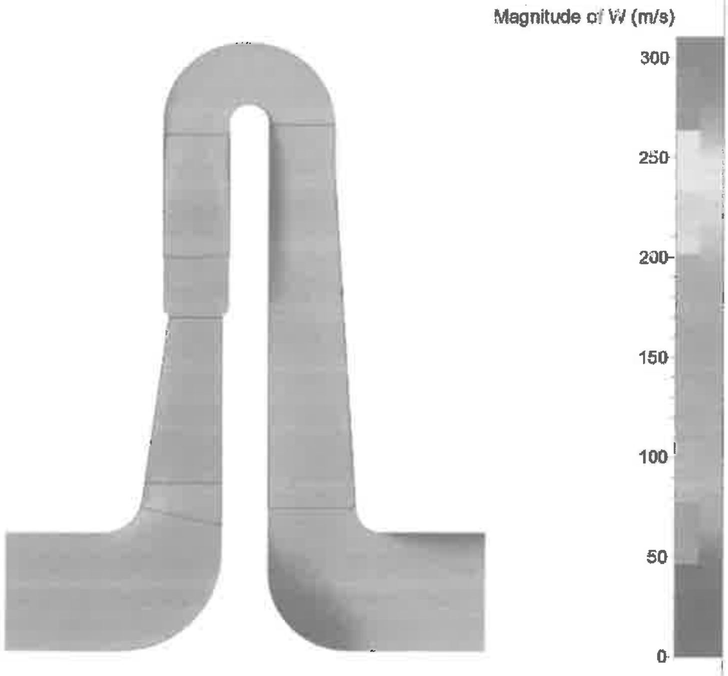

Fig. 7: Calculation results (meridional section)

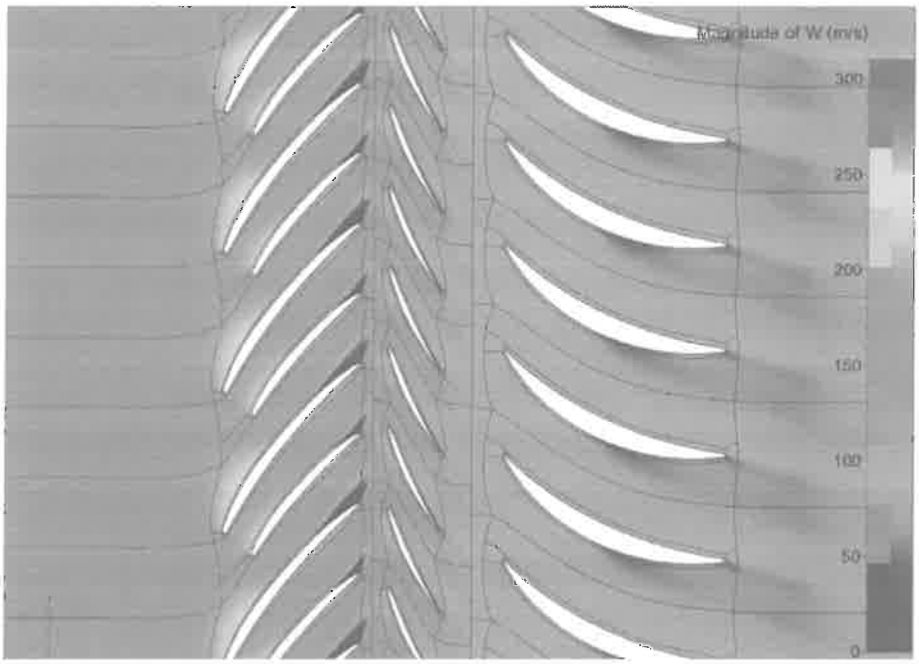

Fig. 8: Calculation results (conformal mapping)

Modernized compressor

The modernized compressor in the existing cases of the original one has the initial pressure 2.5 MPa and discharge pressure 23 MPa. The compressor capacity at STP is 245,000 m³/h, which is about 45% higher than that of the original, unmodified compressor. Cross-sections of LP, MP and HP cases of the modernized 103J compressor (2,000 t/d) are shown in Figs 9, 10 and 11.

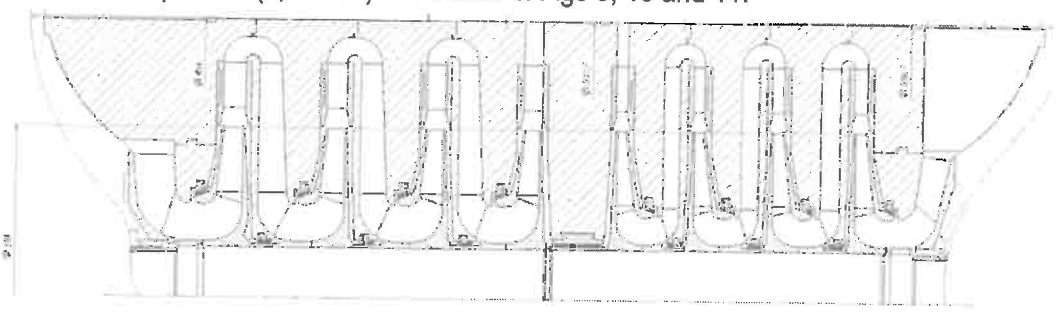

Fig. 9: Cross-section of low pressure (LP) case of the modernized 103J compressor (2,000 t/d)

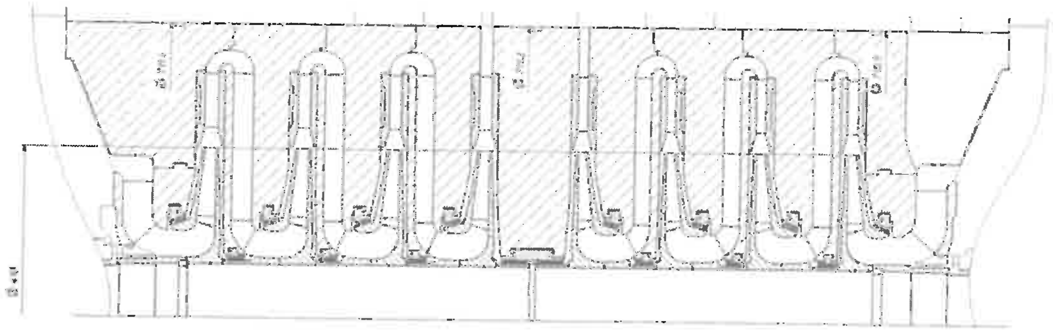

Fig. 10: Cross-section of medium pressure (MP) case of the modernized 103J compressor (2,000 t/d)

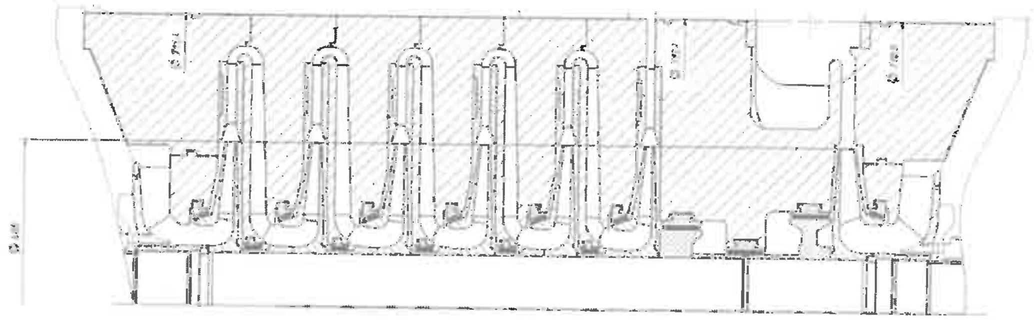

Fig. 11: Cross-section of high pressure (HP) case of the modernized 103J compressor (2,000 t/d)

The concept of the original compressor has been completely reviewed.

First, vane diffusers instead of the original short vaneless diffusers have been used. The original vaneless diffuser was so short that the outlet gas velocity was about 160 m/s. Vane diffusers work better when the dimensions are small, effectively decelerating the flow to 85 m/s. Since losses are proportional to the square of the velocity, and the velocity has been approximately halved, the polytropic efficiency drop in the crossover and return chanal have been reduced by almost three quarters. That is attributable to the 'steady gas flow' of the 5% airfoil blades – the low-pressure zone around the outlet of the diffuser is very small. 'Bumpless' vane diffuser angles are chosen so losses due to the stator are at a minimum at the optimal impeller mode. The relative width of the diffusers in relation to the impeller outlet width has been increased to 1.25. All these factors increase the efficiency of each stage by about 3% and also raise the head.

Second, increasing the head (=enthalpy rise) in every single stage, one stage from every section has been removed. The number of stages has been reduced from 5/5 to 4/4 in both LP and MP cases, and from 7+1 to 6+1 in the HP case.

Third, the remaining free axial space has been used to create optimal entry to the impellers, increasing efficiency and capacity potential. The flow at the inlet of each impeller has been optimized to reduce losses by the following expedients:

- increasing the inclination angle of the cover disks;
- increasing the inlet diameter 3% higher than the optimal (the original compressor had $D_0=0.9 \cdot D_{0opt}$);
- setting the inlet turn radius to the optimum value (not less than half of the width b_1 at inlet).

Fourth, the additional axial space has allowed a labyrinth seal with more fins to be used instead of a flat one, decreasing gas leakage and specific power consumption.

Fifth, the capacity of the impellers has been increased without changing their dimensions by using two-cascade multi-lattice impeller blading.

Sixth, the return channel works better as it does not diffuse the flow; it just turns it into the next stage.

Seventh, the outlet width b_2 has been increased while the outlet diameter D_2 has been diminished, thus increasing the reduced impeller's width b_2/D_2 and thus raising the polytropic efficiency.

The polytropic efficiency of first section of the syngas compressor is **83%** guarantee. *And that is unequalled by any other revamped synthesis gas compressor in an old case.*

The polytropic efficiencies of the original and modernized 103J compressor sections are specified in Table 1.

Table 1
Polytropic efficiency of 103J compressor sections

Section №	1	2	3	4	5
Compressed gas	Syngas	Syngas	Syngas	Syngas	Recycle
Polytropic efficiency (2000 t/day) modernized	0.83	0.79	0.77	0.75	0.80
Polytropic efficiency (1700 t/day) modernized	0.79	0.76	0.75	0.74	0.78
Polytropic efficiency (1360 t/day) original compressor	0.77	0.74	0.7	0.73	0.75

Table 2 shows the parameters of the original centrifugal compressors for 1,360 t/d and the modernized centrifugal compressors for 1,700 and 2,000 t/d production. *The power 28.5 MW of the 2,000 t/d compressor is less than the original one, and that is a breakthrough.*

Table 2
General parameters of 103J compressor sections

Naming	Value	**Ammonia 1360 (original)**	**Ammonia 1700 (modernized)**	**Ammonia 2000 (modernized)**
Suction syngas pressure	MPa, abs	25	25	25
Discharge syngas pressure		320	245	250
Suction recycle gas pressure		302	226	225
Discharge recycle gas pressure		321	246	246
Displacement at STP (0°C, 0.1 MPa), Q_g, Nm^3/h - at the 1st syn-gas section discharge - at the recycle gas suction	m^3/h	165000 ~480000	212000 653000	245000 705000
Shaft power	MW	**29**	**27.5**	**28.5**
Rotor speed	rpm	11268	11000	11000

Most companies, when doing a revamp, increase the impeller diameter and rotor speed, so making the operational conditions harder. However, we reduced and the number of impellers and their diameter and the speed, lowering the mass of the rotor. That has helped to solve problem of vibration in the LP case. A more rigid rotor with reduced mass improves run-up on launch and run-down on stop, suffers minimal vibration during operation, and has a good critical speed margin.

103JT STEAM TURBINE MODERNIZATION

The spectacular results achieved by modernizing the compressor casings have been compounded by revamping the turbine drive as well.

ALSTOM Power in Elblag possesses vast experience in the production and modernization of high-speed turbines, using different technologies (active and reactive). The company has also adopted the production technologies of high-speed turbines developed in the centre in La Courneuve/France.

The 103JT turbine drive for the 103J synthesis gas compressor is a high-speed machine designed to operate in condensing mode. The turbine is an axial one-case reactive machine. Reconstruction for 1800-2000 t/d case comprises replacing the existing reactive blading part with a new modern blading possessing highest efficiency such as 8000 or 9000 (3D stages), as shown in Fig. 12.

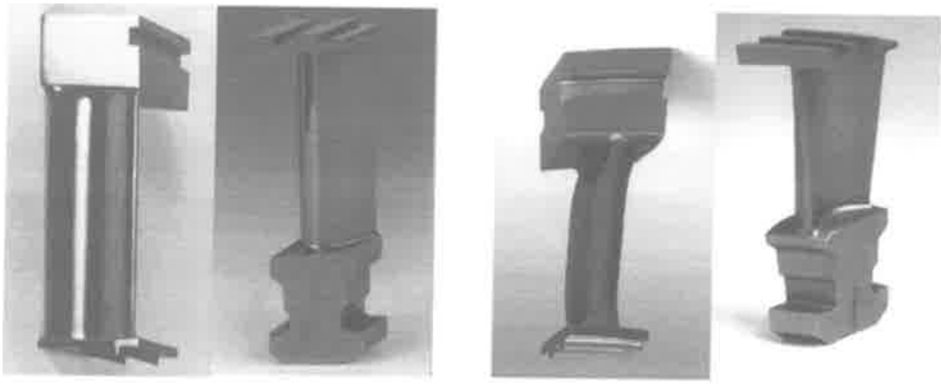

Fig. 12: Blading 8000 (2D) and 9000 (3D)

The revamped turbine achieves the capacities and speed specified in Table 3. The turbine is characterized by the high extent of detuning from a blading resonance on working speed ranges. The turbine on high speed balancing tool is shown in Fig. 14.

Already 9 modernizations has been completed. The modernized turbine has the increased isentropic efficiency and is saving more than 15 tonns of steam per hour.

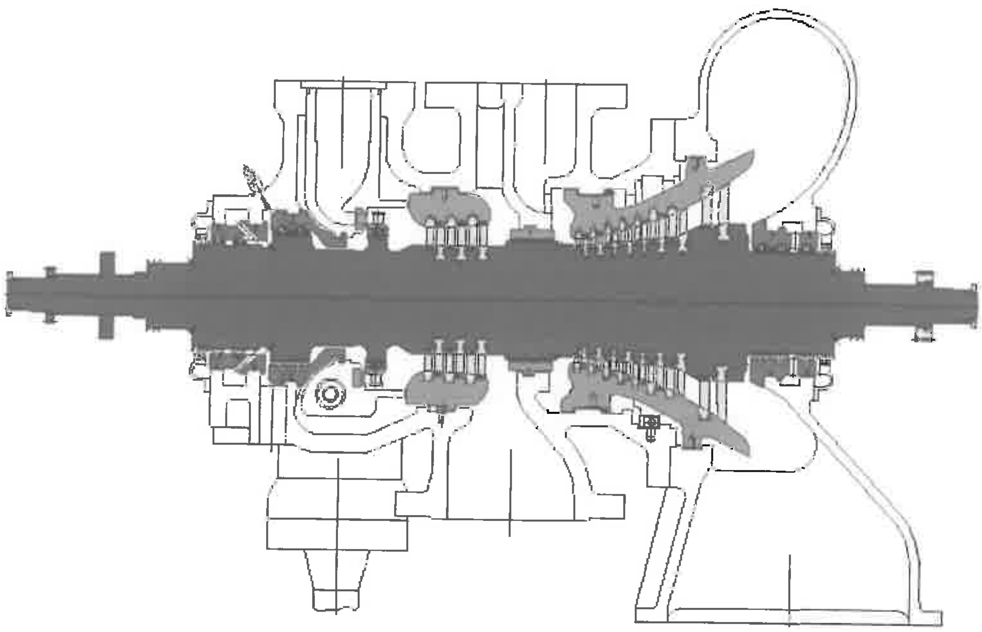

Fig. 13: Cross-section of 103JT turbine after revamping

Table 3
General parameters of 103JT steam turbine (1800-2000 t/d)

Parameter	Notation	Unit	Normal	Max power
Turbine speed	n	rpm	11000	11450
Shaft power	N	MW	28.5	31.4
Inlet pressure	p_{in}	MPa	9.9	
Exhaust pressure	p_{out}	MPa	0.049	
Inlet temperature	t_{in}	°C	480	
Inleat steam consumption	m	t/h	358	

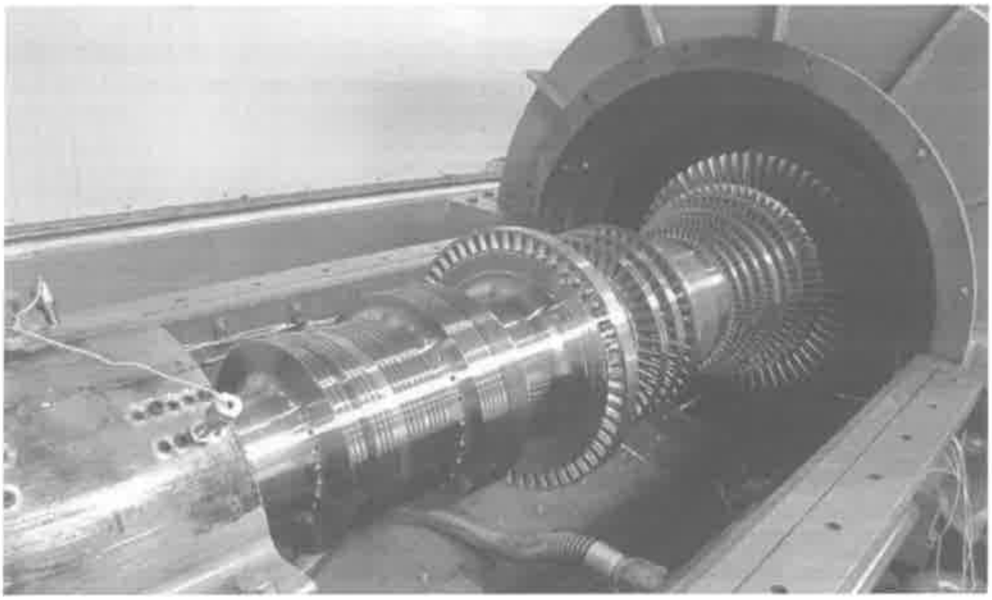

Fig. 14: 103JT turbine on the high speed balancing tool

Entechmach and **ALSTOM Power** also have joint modernization projects for air compressors.

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