CENTRIFUGAL COMPRESSOR IN HIGH FLOW AND LOW HEAD APPLICATIONS: AN IMPELLER DESIGN CONCEPT FOR COPING WITH THE INCREASING VOLUME FLOW IN POLYOLEFIN PROCESSES

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ABSTRACT

The paper discusses the development of a novel impeller design concept that addresses changing requirements for radial centrifugal compressors applied in the polymer/downstream petrochemical industry. The impeller design concept developed balances the need for low heads, while at the same time achieving higher flow volumes for the compressor. The approach is described in form of a case study.

INTRODUCTION

As plant capacities in the polymer/downstream petrochemical industry have increased over recent decades, the volume flow of the polypropylene/polyethylene (PP/PE) gas phase reaction process has similarly further increased. The head requirements, however, have remained the same. On the one hand, the recycle compressor used in this process is traditionally a radial centrifugal compressor. On the other hand, handling the ever-increasing volume flow is a challenge for the recycle compressor, and especially for the impeller and diffusor design.

Centrifugal compressors in the polymer/downstream petrochemical industry usually see a pressure ratio of above 1.2-2. Yet, the main loop compressors in gas phase reaction processes in the polypropylene and polyethylene industries require a head as low as 200 m to 450 m. The volume flow, in contrast, can reach up to 75,000 m3/h. The ASME PTC 10 testing procedure defines a performance test for a minimum pressure ratio of 1.05, but the main loop compressors are very close or even below this limit.

This paper will draw from a case study and describe one solution to the challenge of coping with the higher volume. The obvious solution is to increase the impeller's diameter until the flow coefficient is again within the flow coefficient range of the impeller. This can be achieved by either reducing the rotational speed of the impeller via the application of a gearbox – either free standing or integrally geared – or by using an impeller with a lower head coefficient to get a bigger impeller diameter. Obviously, the downside of a bigger impeller plus a bigger casing is increased investment costs.

A more economic approach, discussed in this paper, is to develop the centrifugal impeller design in a way that ensures it is suitable for a higher flow at the same tip diameter. This means the casing size does not need to be increased. Importantly, the efficiency level needs to be maintained and operational costs should not be increased.

MARKET SITUATION

Petrochemical complexes are these days often integrated into refinery plants. During the last few decades, this has led to increasing ethylene cracker capacities. Today, PP and PE are still in high demand and this is expected to grow further. In this regard, it has become quite normal that multiple PP/PE lines follow a cracker, enabling refineries to diversify their product mix. Similarly, the combination of PDH plant with at least one PP line has also become the norm. A consequence of the inclusion of the PP/PE plants has been increased economic pressure to increase line capacities. While a decade ago plant capacities of 300,000-400,000 tpy were the standard, today single-line plant capacities of 450,000–500,000 tpy are usual. Nowadays, licensors are already able to offer proven design capacities of up to 650,000 tpy per line and it is likely that in the near future PE and PP single-line capacity will advance to as high as 750,000 tpy.

PP/PE GAS PHASE POLYMERIZATION TECHNOLOGY

In principle, polyethylene and polypropylene are usually produced either by a gas phase process or a slurry process. This article focuses on the first, where a fluidized-bed gas phase reactor is used to produce the polymer or copolymer. There are some variances but in principle the technology of fluidized bed gas phase reactor is the same for both PP and PE. Crucial to the process is the recycle compressor, which circulates the gas through the reactor and keeps the particles bed lifted. The reactor volume has had to grow significantly over the years to enable the single-line reactor capacity to grow. Likewise, the recycle compressor flow capacity has had to keep up with the increasing reactor volume.

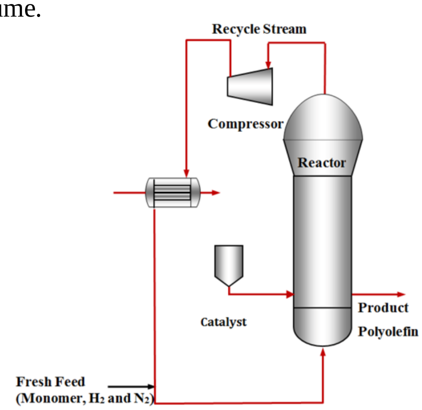


Figure 1: Typical polyolefin gas phase reactor process

THE RECYCLE GAS COMPRESSOR IN PP/PE GAS PHASE REACTOR

The recycle compressor in PP/PE gas phase reaction is traditionally an API 617 style turbo compressor with a radial impeller. In this set up, the open impeller overhangs beyond the bearings. The suction pressure is relatively high and the gas molecular weight is also on the higher side. A single stage directly coupled to the motor is sufficient to produce the relatively low head required. Due to the mechanical reliability, a geared solution is not desired by the end-user or the licensor. This means the compressor is usually driven by an induction motor. The capacity regulation is done via completely sealed and purged inlet guide vanes, enabling an efficient control of the machine with a turndown of approximately 50%.

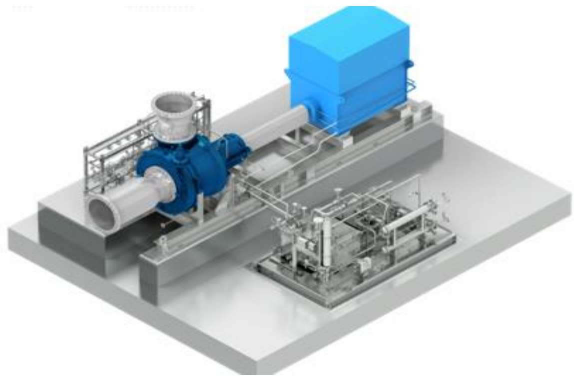


Figure 2: Typical recycle compressor package in PP/PE

The impeller tip speed is at around 90 m/s-120 m/s, which is relatively low for a centrifugal compressor. Despite the higher volume flow, the shaft power is moderate and ranges from about 600 kW to up to around 6,500 kW.

In general, as this compressor is a critical component with no back up, the licensor requires a robust, reliable compressor design which can handle the polymer dust in the gas stream. An anti-surge compressor control including a bypass valve is not part of the system since the gas is circulated in an open loop. In general, unscheduled shut-downs and uncontrolled trips should be avoided by all means.

PROCESS PARAMETERS

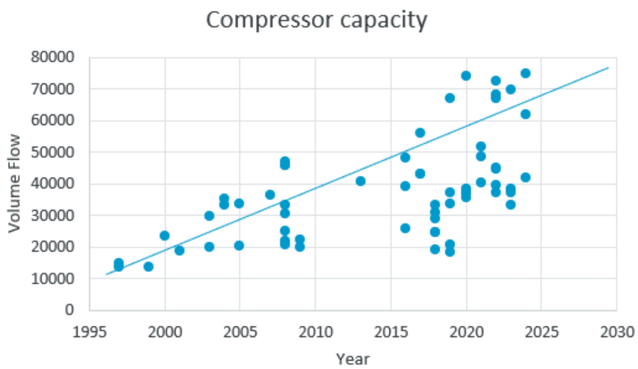
The process requires a high flow rate at relatively low head (see Table 1). This can be recognized by the fact that the ASME PTC 10 performance test code (which provides test procedures for an axial or centrifugal compressor) describes a minimum pressure ratio of 1.05.

Nevertheless, the main loop compressors are very close or even below this limit. This demonstrates that this compressor type differs from other, typical compression methods.

Gas Mix	Ethane, Ethylene, Propylen, Propane, Hydrogen
Mole-weight KG/KMOL	24 - 42
Suction volume (m3/h)	up to 72.000
Suction pressure (barg)	12 - 33
Mass flow (kg/h)	Up to 2.200.000
Suction Temperature (DegC)	70-100
Discharge pressure (barg)	13 - 32
Motor Speed (rpm)	1500 / 3000
Required head (meter)	200 - 800

Table 1: Typical process parameter range in PP/PE gas phase reaction

The history of the PP/PE recycle compressors that Atlas Copco has delivered, for example, shows that growing plant capacities have required the compressor capacity to likewise increase (see Figure 3). In contrast, the required head/pressure ratio has remained stable at the same level (see Figure 4). And because the single-line plant capacity is expected to grow up to 750,000 tpy, the required compressor capacity is predicted to increase to reach 90,000 m3/h the future.



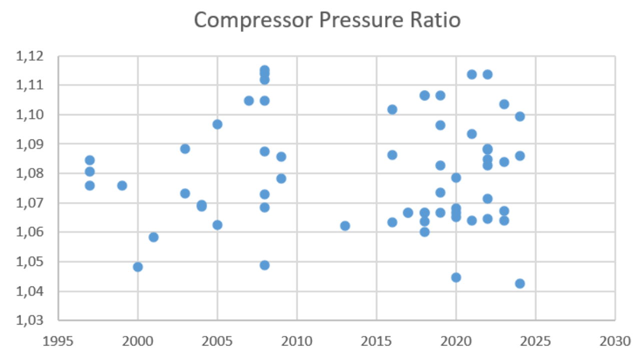


Figure 3: Compressor capacity of delivered and quoted units predicted

Figure 4: Pressure ratio of compressors in PP/PE in the past and predicted for the future

TASK DEFINITION FOR THE IMPELLER DEVELOPMENT

Seeing these market needs from an aerodynamic R&D perspective, the challenge is mainly to develop an impeller that stays compact and competitive at a given speed. The speed is fixed as the machine is traditionally driven with an electric induction motor with either 50 Hz or 60 Hz. The motor is two or four pole, which results in 2,960 rpm or 3,552 rpm and 1,480 rpm or 1,776 rpm respectively.

The increasing volume flow calls for a larger inlet area and therefore a larger impeller eye diameter. When the flow increases, the ratio of the impeller eye diameter to the impeller outlet diameter becomes smaller, until the impeller eye diameter becomes bigger than the impeller tip diameter. Therefore, this ratio is limited by a dimensionless number called phi or flow coefficient. The maximum flow coefficient is a specific figure for a certain type of impeller.

$$flow\ coefficient = \varphi = \frac{4 * V_1}{\pi * D_2^2 * u_2} (Formula\ 1)$$

The tip speed u_2 is equivalent to the isentropic head when keeping the same isentropic head coefficient or PSI.

$$head\ coefficient = \psi = \frac{2 * y_s}{u_2^2} \quad (Formula\ 2)$$

For a certain type of impeller, the isentropic head coefficient is a more or less fixed number, depending on special geometry variables, such as the impeller blade outlet angle and the ratio of inlet area to outlet area. By keeping the head coefficient constant, the u_2 is equivalent to the customer's specified isentropic head of the machine.

To keep the flow coefficient within permitted parameters, the normal solution is to reduce the pinion speed in order to increase the outlet diameter at nearly the same eye diameter. This reduces the flow coefficient, and it is also the solution for a traditional integrally geared compressor. Obviously, the disadvantage of this solution is a bigger impeller plus a bigger casing. Furthermore, licensors do not want the application of a gear box, the increased investment costs of the gear box or the increased cost of the bigger impeller and casing required to accommodate the bigger impeller outlet diameter. Similarly, increasing the number of motor poles from two to four will result in the same disadvantages. Therefore, a different approach needs to be taken and the speed of the machine shell remain fixed.

A more economical solution is to develop the impeller in a way that ensures it is suitable for a higher flow at the same impeller outlet diameter – therefore, for higher flow coefficients, without the need to increase the impeller and casing size. The efficiency level has to be maintained and operational costs should not increase. Naturally, with the increased volume flow, the train power will rise, but this can be accommodated easily by modifying the mechanical design.

DETERMINING THE CORRECT IMPELLER SHAPE

Generally, a high flow and low heads impeller suggests the use of an axial shape. In contrast, experience with radial stages shows that an intermediate approach makes sense. Moreover, less radial shape also results in lower head and allows higher flows.

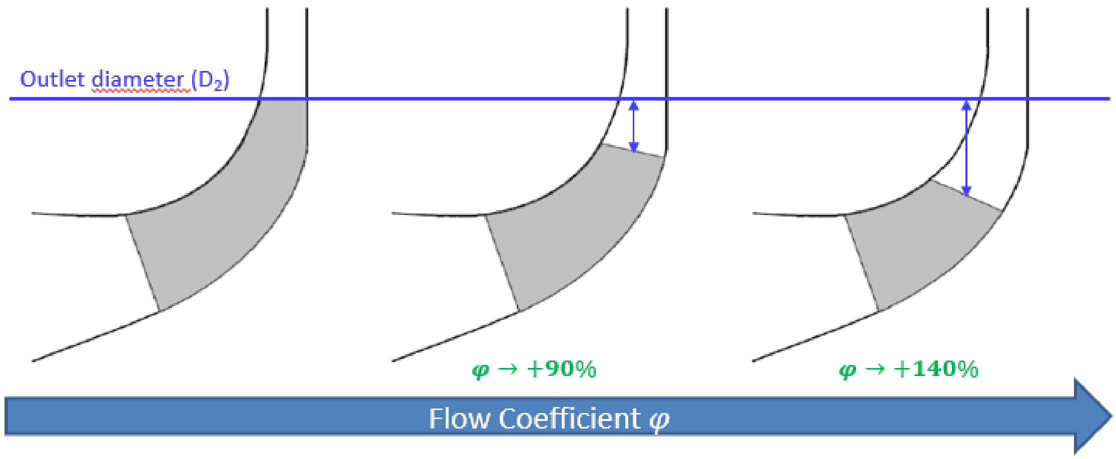
The initial idea in the past was to take a well-known radial impeller and start cutting the diameter until a more half-radial, half-axial shape is reached. This results in an increasing flow coefficient as the volume flow is fixed and the diameter is reduced. The reduction in head with the less radial shape of the impeller is also beneficial. This, specifically, means a reduction of the general capability of the impeller to create head, which in turn results in a lower head coefficient of the impeller (see the head coefficient, Formula 2).

This lower head coefficient causes an increase of u_2 at a fixed head y_s and a bigger D_2 at a fixed pinion/motor speed (see the flow coefficient, Formula 1). A bigger outlet diameter lowers the flow coefficient and makes it easier for the impeller to handle the flow. Therefore, the approach is two times more beneficial.

FURTHER DEVELOPMENT

To cope with the always increasing plants sizes and subsequent increasing flows, a further development of the half-axial impeller needs to be taken. The latest developments mainly focus on increasing flow capacity and keeping the same efficiencies. The result is an optimized flow path with an even more axial shape.

Figure 5: The shaded area represents the blade shape in a meridional view. Shown is the development coming from the pure radial impeller (left) into the direction of a more axial shape (right) to cope with the further increasing flow demand. The head required for the process over recent decades has been more or less constant. The flow coefficient increases with the increasing axial shape. (From left to right)



$$\varphi = \frac{4 \cdot \dot{V}_1}{\pi \cdot D_2^{\,2} \cdot u_2}$$

Figure 5: Increase of axial shape with increasing flow coefficient

A CLOSER LOOK AT THE IMPELLER AND RELATED DESIGN FEATURES

The new diameter cut, with the more axial shape, requires a complete review of the flow path of the impeller and reshape of the impeller blade. With the help of state-of-the-art CFD tools, the flow path and blade shapes were designed to cope with the new conditions.

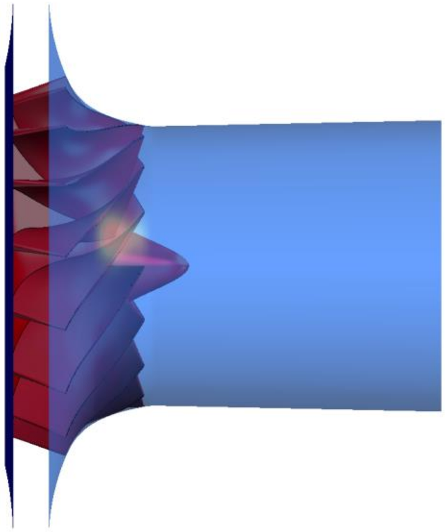


Figure 6: Flow path meridional view

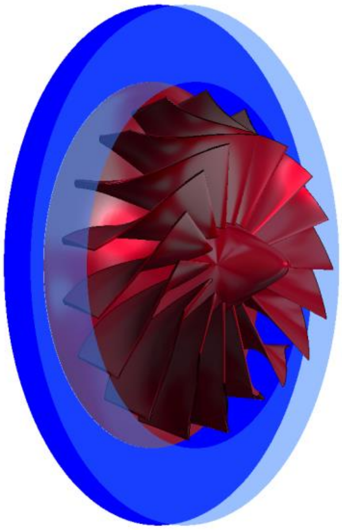


Figure 7: Flow path 3D view

Areas with flow separation need to be reduced by a homogeneous flow cut and optimized blade shape. The dark blue color in the flow path shown in Figure 8 are flow separations caused by a sub-optimal blade shape and flow cut. In Figure 9, the Mach Number equivalent to the flow velocity is more homogeneous, and the velocity never drops close to zero and flow separations does not occur. Under these circumstances the maximum efficiency is reached.

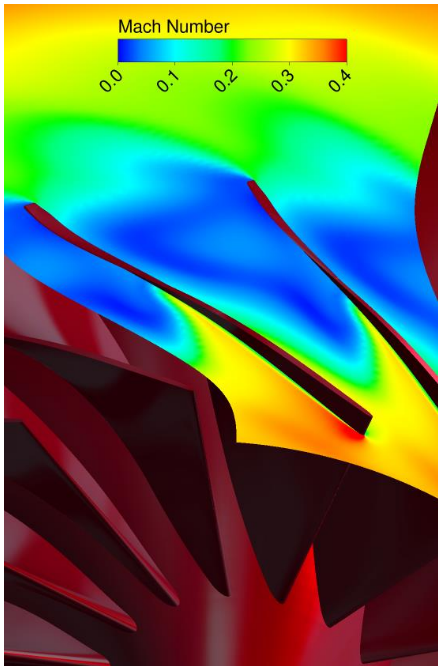


Figure 8: Flow separation (slightly exaggerated for better visibility)

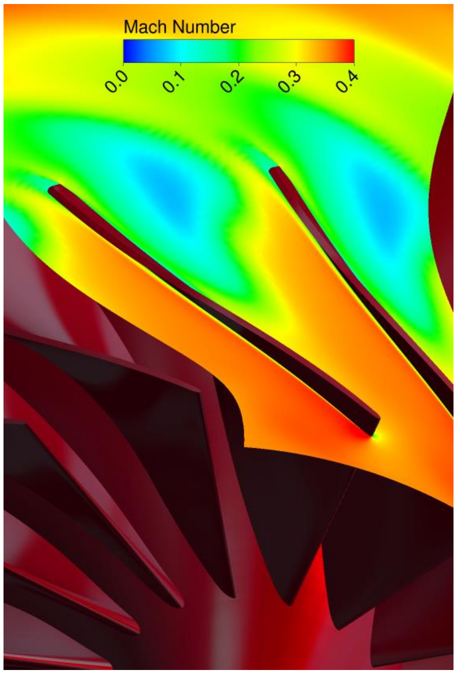


Figure 9: Homogenous flow through the flow pass

Figure 10 shows one of these improved impellers, which was milled from one piece, and it was ready to be incorporated into a customer machine. And Figure 11 shows a normal radial shape impeller.

Figure 10: Ready milled half-axial impeller

Figure 11: Ready milled traditional radial open impeller

As shown in Figure 10, the large inlet volume causes a high blade height at the inlet. The low head of this application, with its low volume reduction from inlet to outlet, causes a large blade height also at the impeller outlet. Clearly visible in the photograph is the half axial shape of the impeller.

THE DIFFUSOR

With the increased flow coefficient of the impeller, the diffusor and the housing need to be prepared for this higher flow. The R&D-Team performed several optimization cycles to increase the diffusor efficiency. Traditionally, and also to prevent particle agglomeration, the diffusor is vaneless.

Calculations revealed that a thinner diffuser and the transition between impeller outlet and diffusor inlet, as well as volute inlet, becomes more important the higher the flow coefficient of the stage.

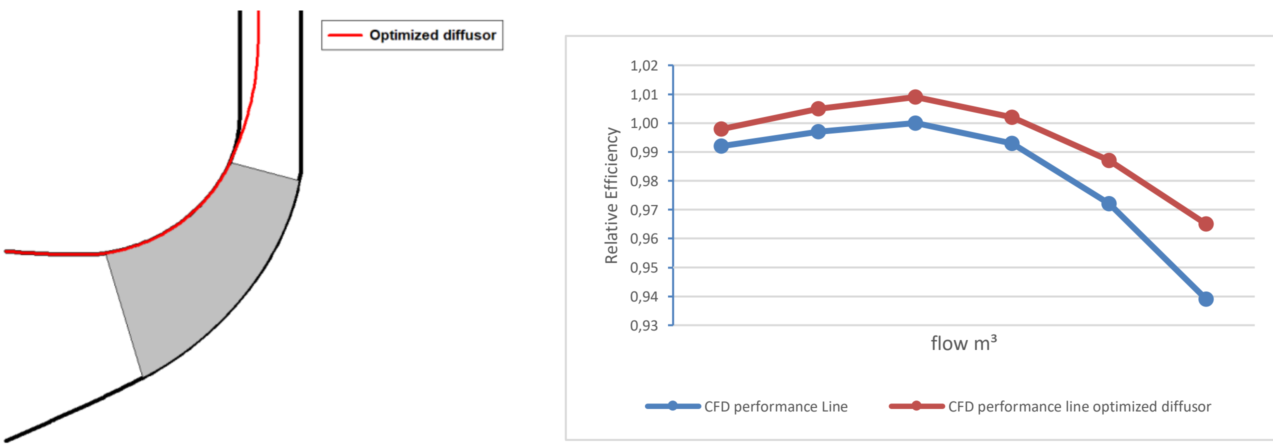


Figure 12a: Meridional impeller view with old and new diffusor shape and b) Relative efficiency comparison between old and new diffusor shaping

THE HOUSING

The Aerodynamic R&D team optimized the housing to keep a high efficiency level for the overall stage. This means the ratio between the outlet diameter of the impeller and volute inlet needs to be large enough, and the area along the flow path of the spiral housing needs to be increased with the higher flows. In addition, the aforementioned area should not deviate too much from the calculated optimum for the customer requested machine. Figure 14 is showing the core unit with all its components.

Figure 15 shows the housing's isentropic compression efficiency. It also reveals where potential efficiency losses are and where there is room for improvement. High flow velocities as well as sharp edges lead to a loss in efficiency. The diffusor in particular and the flow path from the diffusor into the spiral casing are crucial for a high efficiency level here.

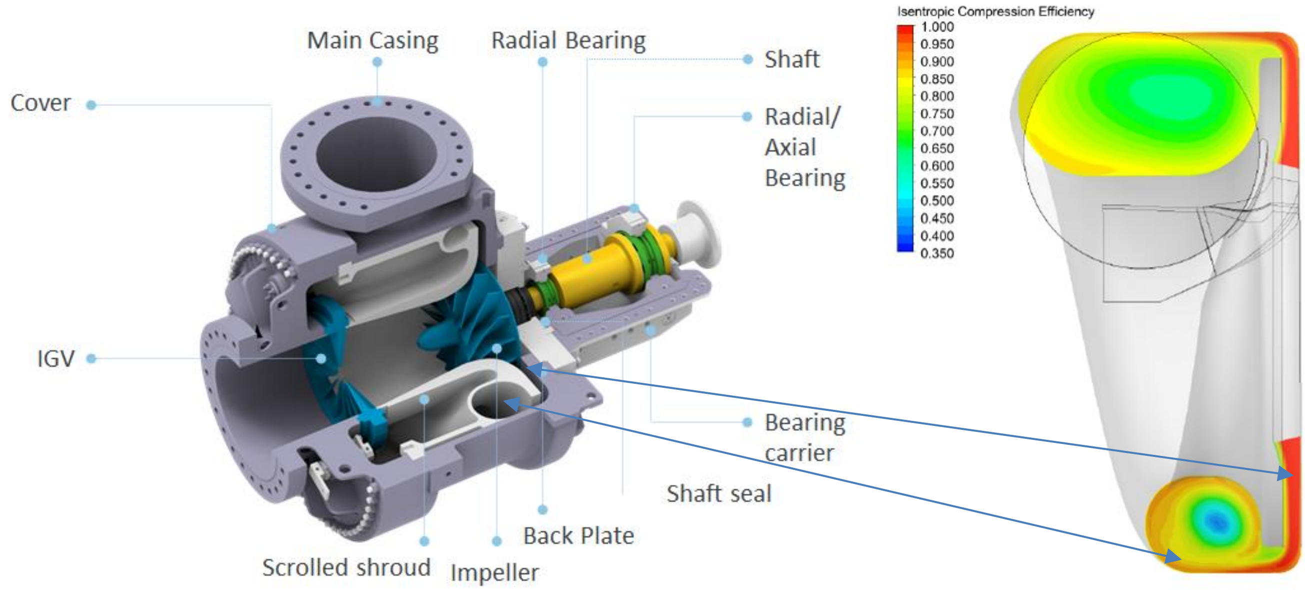


Figure 14a: Core Unit with its components and b) Meridional cut of the housing flow path and the diffusor, showing isentropic compression efficiency distribution

PERFORMANCE RESULTS

With the new configuration of the impeller and the further adaption of the diffusor and the housing, a flow coefficient well above the 0.33 region was achieved, at the same time as maintaining a very high efficiency level. These improvements have already been applied to several recycle compressors in the PP/PE field, generating savings in capex per machine of approximately 30%. In the near future, a flow coefficient in the range of approx. 0,5 maintaining a good flow to efficiency ratio could be possible.

SUMMARY AND OUTLOOK

Due to economic pressures, increased plant capacities are expected to further increase many processes in the petrochemical world. Applications with traditionally centrifugal compressors will need to adapt compressor capacities in an economical way. Multiplying compressor lines or increasing their size has economical disadvantages. The specific development of the radial impellers to be able to handle higher volume flows helps to successfully master the challenge.

The general principle of extending centrifugal radial impellers for higher volume flows can be applied to similar applications with high flow and low head. In general, the industry foresees bigger plant capacities. Therefore, centrifugal turbomachinery design must accommodate such developments and meet this challenge in an economical way. This PP/PE case study demonstrates one way how this can be accomplished.

Nomenclature

ASME PTC 10 = The American Society of Mechanical Engineers' Performance Test Code
PDH plant = propane dehydrogenation plant
TPY = Tons per Year
PP = Polypropylene
PE=Polyethylene
D2= Impeller outlet diameter
ys = isentropic head
u2= impeller outlet tip speed
V1= effective stage inlet suction flow
PSI= impeller isentropic head coefficient
PHI = impeller flow coefficient