2000

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Whitfield, A., "Review of Variable Geometry Techniques Applied to Enhance the Performance of Centrifugal Compressors" (2000). *International Compressor Engineering Conference.* Paper 1368.
https://docs.lib.purdue.edu/icec/1368

REVIEW OF VARIABLE GEOMETRY TECHNIQUES APPLIED TO ENHANCE THE PERFORMANCE OF CENTRIFUGAL COMPRESSORS

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ABSTRACT

Most centrifugal compressors are required to operate over a broad range of flow rates and to provide a high pressure ratio with high efficiency. In order to meet these demands the application of variable geometry techniques is often considered and applied. The potential areas for the application of variable geometry procedures lie at inlet to and discharge from the impeller. This paper reviews the application of inducer preswirl, variable vaneless diffusers and variable vaned diffusers, and summarises some turbocharger compressor results obtained at the University of Bath.

INTRODUCTION

In many applications, e.g. small gas turbines, turbochargers and process compressors, the centrifugal compressor is required to provide a high pressure ratio with good efficiency together with a broad operating range. Developments in user technologies often lead to a demand for increased pressure ratio per stage, without sacrifice of efficiency or operating range. Yet as pressure ratio is increased both efficiency and operating range are inexorably reduced. The requirement for a broad operating range stems from the need for the compressor to match the operating range of the component for which the compressed gas is supplied. A process compressor must meet the demand for a wide range of flow rates and possible variations in the composition of the gas being compressed.

The objectives of applying variable geometry techniques are dependent on the operational requirements of the compressor. The requirement for a small turbocharger compressor will be for rapid response to changing operating conditions and to supply a broad range of flow rates as demanded by the engine. A large process compressor may not need to respond to rapid changes in operating conditions, but to operate at the best efficiency or deliver a constant pressure over a wide range of flow rates. Other applications may require variable geometry to suppress surge and ensure that the compressor can operate at lower flow rates than could be normally achieved. The requirement to respond to changing operational conditions may be a seasonal one where the changed conditions once set may remain fixed for a significant period. Such requirements could be met by manual operation of variable geometry components or even by the inclusion of alternative fixed components. In this case it is more a case of flexible design, allowing for component changes as required, rather than variable geometry.

Compressor operating range is limited at high flow rates by choking and at low flow rates by surge. An important aspect of many variable geometry applications is the suppression of surge so that the compressor can operate safely and efficiently at reduced flow rates. A simple criterion for the onset of surge is that it commences at the peak of the pressure ratio/mass flow characteristic, the positive gradient part of the curve defining the unstable operating region of the compressor. A stable characteristic is one where the pressure ratio increases as the flow rate is reduced; an impeller with a backward swept discharge blade is now routinely used to assist with this objective. The terms surge and stall are often used to describe unsteady flows, but can refer to quite different phenomena. Stall can be considered to be a local phenomenon affecting perhaps the impeller or diffuser only. Surge on the other hand is a system phenomenon with the flow pulsations passing through all components. Yoshinaka(1) concluded that surge occurred only when the inducer and diffuser are operated at or beyond stall. Techniques to suppress the onset of surge should act to delay, or better eliminate, the tendency for stall to develop in any component. The natural areas for the application of variable geometry devices are the regions immediately upstream and downstream of the impeller. Inlet guide vanes which generate a swirling flow in the direction of rotation of the impeller enhances the underlying stability by developing a rising characteristic. This approach has been extensively investigated, e.g. Steinke and Crouse (2), Whitfield et al (3) Rodgers (4,5) and Simon et al (6), but has only been widely adopted for process compressor applications. Downstream of the impeller the diffuser system, both vaneless and vaned, has been considered as an area for the application of variable geometry techniques. Abdel-Hamid(7,8,9) considered both the vaneless diffuser and the application of small guide vanes at diffuser discharge. The shape of the vaneless diffuser, in particular wall convergence, has been investigated by a number of researchers including Whitfield *et al*(10), Ludtke(11) and Yingkang and Sjolander(12). For vaned diffusers it is well accepted that they lead to improved efficiency but with reduced operating range. The desire to have both high efficiency and improved operating range has led to investigations of both vaned diffuser designs and variable geometry techniques. Variable geometry diffusers have been investigated by Simon *et al*(6), Salvage(13) and Sitram and Issac(14). Senoo *et al*(15) introduced the low solidity vaned diffuser which promised improved efficiency over the vaneless diffuser without reduced flow rate. Later variable geometry low solidity vaned diffusers were investigated by Sorokes and Welch(16) and by Eynon and Whitfield(17).

APPLICATION OF INLET SWIRL

The effect of inlet swirl on the performance of centrifugal compressors has been studied and presented by many investigators; for example, Rodgers(4,5) for small gas turbines, Whitfield *et al*(3, 18) for turbochargers, and Simon(6) and Williams (19) for process compressors. The objective of the inclusion of preswirl maybe to improve the compressor pressure ratio over the full operating range, in which case negative swirl is applied at high flow rates. Alternatively the objective maybe to suppress the tendency to surge and positive inlet swirl will be applied at low flow rates only. At the low flow rates associated with surge it is necessary to operate at high swirl angles if a significant effect is to be achieved. The inlet guide vanes adopted to generate the swirling flow must then operate through a wide range of setting angles including zero. This requirement to generate no swirl over part of the operating range has led to the general adoption of flat plate vanes which generate little disturbance to the flow when set in the axial direction.

The effect of prewhirl on the overall performance of a gas turbine compressor with a vaneless diffuser, Rodgers(4), is shown in Fig.1. The application of 40° of positive prewhirl provided a significant shift of the surge line to reduced flow rates over much of the operating range. It is notable, however, that the movement of the surge line at 60% speed is small. The performance of a compressor with a vaned diffuser and an impeller with a 40° backswept blade was presented by Rodgers(5). Significant displacement of the surge line, with up to 27° of prewhirl, occurred at pressure ratios in excess of 4 only. At pressure ratios below 3.5 there was no measurable shift of the surge line through the application of 27° of preswirl. For these gas turbine compressors operating at high pressure ratio the inlet relative Mach number was in excess of unity. As a consequent a low swirl angle was particularly affective as it reduced the inlet relative Mach number to subsonic levels.

For a turbocharger compressor, pressure ratios up to 2.8, Whitfield *et al*(18) observed only a small shift in the surge line through the application of 40° of swirl. Through an analysis of these data, and the results of Rodgers, Whitfield and Abdullah(20) concluded that swirl angles of the order of 70° were required if the surge line were to be shifted to reduced flow rates for pressure ratios below 3.0. For a single stage process compressor Williams (19) showed that inlet swirl coupled with impellers with large backsweep can produce a significant shift of the surge line at pressure ratios of only 1.6 to 1.7. In this case, however, large swirl angles were used, 60° to 70°, and a clear drop in efficiency was shown as a consequence. The application of flat plate vanes at high incidence angles lead to significant pressure loss and reduced stage efficiency. There is, therefore, a need to generate high swirl angles efficiently.

Recognising the need for low loss inlet guide vanes Swain(21) designed a tandem vane design located in a converging spherical inlet section. The tandem vane design made it possible to develop high swirl angles without the losses associated with high incidence angles. The spherical inlet passage eliminated the blade hub and tip clearance necessary in a conventional cylindrical duct, and led to reduced losses. Through the application of a CFD analysis Coppinger and Swain(22) carried out a detailed design of the tandem vane cascade and spherical duct arrangement and showed a significant reduction in pressure loss across the guide vane with swirl angles up to 60°.

Whitfield and Abdullah(23) investigated the development of swirling flow through a vaneless volute design. Vaneless volutes, used to generate high swirl rates efficiently at inlet to radial inflow turbines, were applied to generate the swirl at compressor inlet, Fig.2. Two variable geometry techniques were applied to the inlet volute. That shown in Fig.2 provided maximum swirl when y_l=0, no core flow, and zero swirl with a fully open axial core flow. A mix of volute and core flows was also investigated. With a full volute flow, maximum swirl, the surge flow rate was reduced by 40%, Fig.3. At high flow rates the efficiency was substantially reduced due to large impeller incidence angles and the swirl would not be used in this region. At low flow rates the measured efficiency, Fig.3, was off the same order as that achieved with zero swirl. As the main objective was the suppression of the tendency to surge it was envisioned that the application would be one for zero swirl or full swirl without the need to develop intermediate swirl flows. The main disadvantage of the arrangement was the need for a dual inlet, one providing the axial swirl free flow and the other the high swirl flow through the volute inlet. This arrangement could be acceptable for an air compressor but would lead to a complex inlet design for a gas compressor.

DIFFUSER SYSTEMS

Vaneless Diffusers

A wide range of diffusing system designs has been used downstream of the impeller. The vaneless diffuser is the simplest and most commonly used when a wide operating range is required. Diffusion is accomplished through the conservation of the angular momentum and the reduction of the tangential component of velocity. Narrowing of the diffuser passage width has been investigated as a means of suppressing surge and extending the operating range by Whitfield *et al*(10) for turbochargers and Ludtke(11) for process compressors; in both cases a radial bladed impeller was used. It was found that a parallel diffuser had the highest efficiency and the most unfavourable surge characteristic, whilst a constant area diffuser improved the surge characteristic with little detrimental impact on the efficiency level. Further reduction of the passage width gave further improvement in the surge characteristic but at reduced peak efficiency levels. Whitfield *et al*(10) considered the application of a flexing diffuser wall to provide a variable geometry diffuser that could be utilised to improve the surge characteristic only.

As a simpler alternative to the flexing diffuser wall Abdel-Hamid(7,8) reported the use of a variable throttle ring at diffuser exit. This was applied to a turbocharger compressor by Whitfield and Sutton(24), and whilst substantial reductions in efficiency occurred at high flow rates significant gains in surge margin were achieved. A retractable throttle ring, which would only be introduced at the near surge flow conditions, was considered to be a more practical option than a flexing sidewall. Hagelstein *et al*(25) showed that the use of a throttle ring at discharge from a vaneless diffuser improved the circumferential static pressure distribution at impeller discharge. This may contribute to the improved surge margin obtained with the use of a throttle ring.

Vaned Diffusers

Vaned diffusers provide an improved efficiency and reduced operating range. A variable geometry design must be adopted if a broad operating range is to be achieved. Aerodynamically shaped vanes and thin flat vanes lend themselves to a swivelling design that can be adjusted to ensure a low incidence angle for a wide range of flow rates. Simon *et al*(6) used aerodynamically shaped diffuser vane profiles and adjusted the blade angle in conjunction with variable inlet prewhirl vanes. They showed that the simultaneously adjustment of the inlet guide vanes and diffuser vanes provided not only an expansion in the operating range, but also efficiency improvements over the entire operating range of the compressor.

For a military turbocharger Harp and Oatway(26) described an application for wedged shaped vanes. The diffuser vanes were pivoted close to the leading edge and the vane angle set by pins sliding in slots along the chord of the vane. The vane pivot position was chosen so that the diffuser throat area was maximized at the minimum stagger angle to allow a high choked flow rate. The result was a variable channel diffuser which provided surge free operation over a broad flow range when used with a backswept impeller.

Two variable geometry techniques used with pipe diffusers were described by Salvage(13). It is difficult, probably impossible, to adjust the leading edge of a pipe diffuser to accommodate the varying flow conditions. The first design used a split ring arrangement so that one ring could be rotated relative to the other, with the dividing radius at 1.223 times the impeller radius. This arrangement acted as a throttle when one ring was rotated, and whilst it was predicted that increased losses would be generated it was found that surge occurred at reduced flow rates with only 4° of rotation. The second design, shown in Fig.4, was referred to as 'the recirculating diffuser'. A portion of the gas flow was recirculated from the collector back to the impeller discharge. The flow from the collector passed through deswirl vanes, a swirl chamber located above the impeller, and a vaned channel before mixing with the impeller exit flow and entering the pipe diffuser. The objective was to maintain a near constant flow through the pipe diffuser as the impeller flow rate varied. A shut-off ring that could be used in conjunction with the impeller inlet guide vanes controlled the recirculating flow rate. The design was developed through a theoretical analysis and a sample of the experimental results is shown in Fig.5. With the recirculating flow passage fully open there was a substantial shift of the surge line to reduced flow rates at all inlet guide vane settings. Investigation of the effect of varying the rate of recirculating flow showed that it was necessary to open the shut-off ring more than 10% before any beneficial shift in the surge line was measured. The maximum shift in the surge line occurred with the shut-off ring open 50%.

Low Solidity Vaned Diffusers

As the flow conditions at the throat of a vaned diffuser passage controls both the maximum and minimum flow rates Senoo *et al*(15) suggested the removal of the throat by using low solidity vane cascades. They found that low solidity vaned diffusers applied downstream of a backswept blower provided a comparable flow range to that of the vaneless diffuser with improved pressure recovery. Sorokes and Welch(16) applied an adjustable low solidity vaned diffuser to a single stage process compressor of pressure ratio 2 to 1. The vanes could be adjusted from an inlet angle of 58° to 78°. Two sets of vanes were investigated; one set had 20 short vanes, and the other 10 long vanes to give identical solidities. The vanes were located at radius ratios relative to the impeller of 1.08 and 1.15. It was found that the long vanes located at a radius ratio of 1.08 gave the better results, and by rotating the vanes to adjust the inlet angle the surge margin was enhanced. The low solidity diffuser design influenced the performance of the downstream return channel and further work was suggested to optimise the vaned diffuser design with the return channel.

Eynon and Whitfield(17) investigated the application of low solidity vaned diffusers to a turbocharger compressor and found that a variable geometry arrangement was necessary in order to obtain a broad operating range. A 10-vane design with a solidity of 0.69 and a circular arc camber line was used to investigate the effect of vane leading and trailing edge angles. Specifying a range of angles through which the vanes turned varied the trailing edge angle. Vanes with leading edge angles of 65, 70 and 80° were considered together with turning angles of 10, 15 and 20°. Fixed designs were used, the term 'turning angle' referring to the difference between the vane leading edge and trailing edge angles. The effect on compressor performance of varying the leading edge angle, for a vane with 10° of turning, is compared with the use of a vaneless diffuser in Fig.6. With the standard vaneless diffuser the peak efficiency occurred at an inlet flow angle of approximately 65°. When diffuser vanes with a leading edge angle of 65° were applied a premature surge occurred. With vane leading edge angles of 75 and 80° surge occurred at reduced flow rates but the operating range was reduced due to poor efficiency at high flow rates; a variable geometry arrangement would, therefore have to be deployed. By increasing the vane turning angle the rate of reduction of the tangential component of velocity is increased and improved diffusion should follow. With a leading edge angle of 80° the effect of increasing the vane turning angle is shown in Fig.7. By increasing the vane turning the pressure recovery across the vanes was increased leading to increased pressure ratio and improved operating range. With the vaneless diffuser design a significant pressure rise occurred across the collecting volute, over 50% at near surge flow rates. This was reduced by the introduction of the diffuser vanes with the volute pressure rise decreasing as the vane trailing edge angle was reduced from 70 to 45°, Whitfield and Eynon(27). For this low solidity diffuser design the diffuser/volute matching needs further consideration.

CONCLUSIONS

A review of the application of variable geometry techniques has shown that enhanced compressor operating range can be achieved. With inlet guide vanes significant losses can be generated by the high incidence conditions required and low loss cascade designs are required. For the application of variable vaned diffusers the impact on the operating conditions of the downstream components, collecting volute or crossover duct, needs to be considered as part of the design process. In the cases reviewed here the variable diffusers techniques were applied to existing design configurations which were not designed with the application of variable diffusers in mind. Alternative approaches to those conventionally adopted require further consideration, in particular the variable gas flow path techniques adopted by Whitfield and Abdullah at impeller inlet and by Salvage at impeller discharge.

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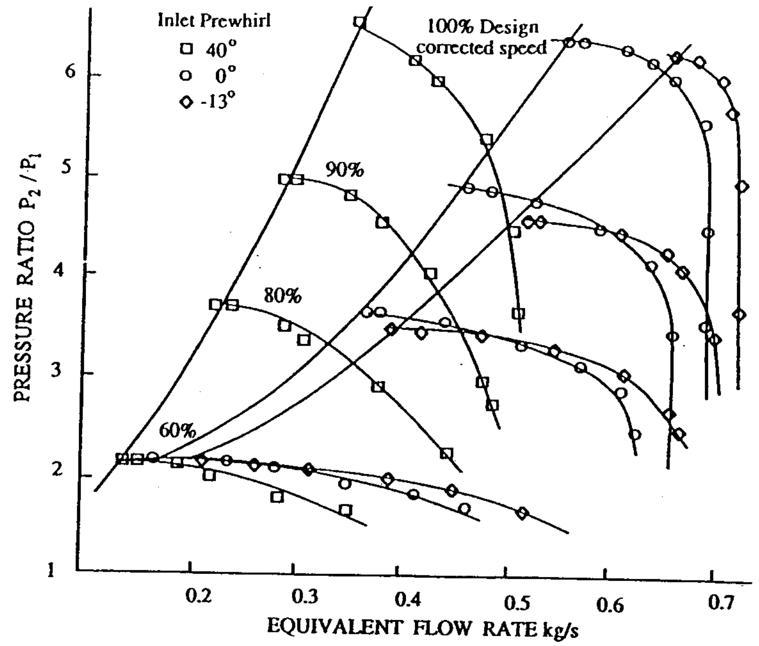

Fig.1 Effect of prewhirl on the surge line

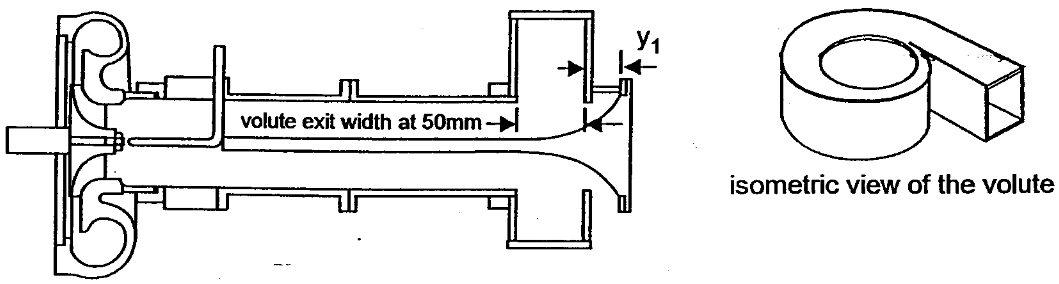

Fig.2 Volute with variable core flow

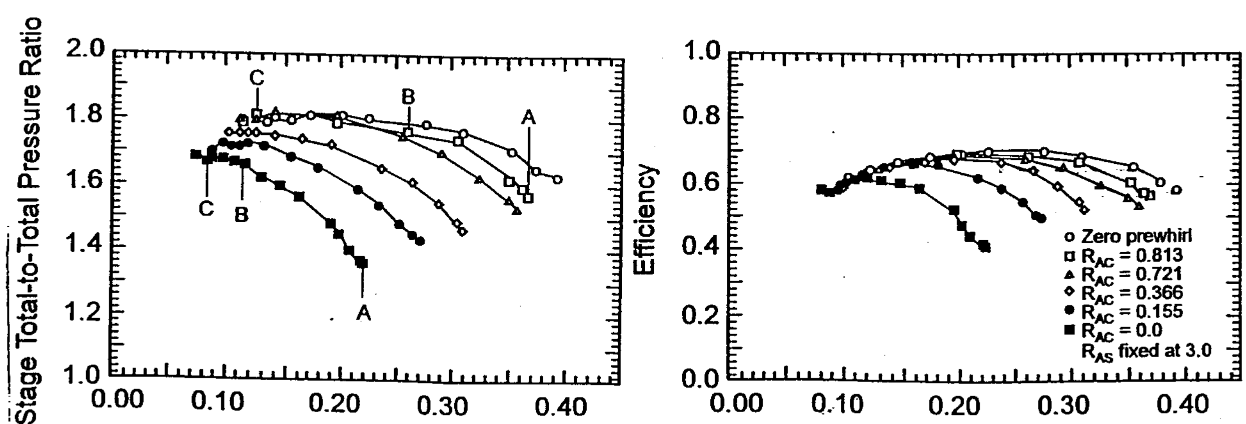

Fig.3 Compressor performance with varying core flow

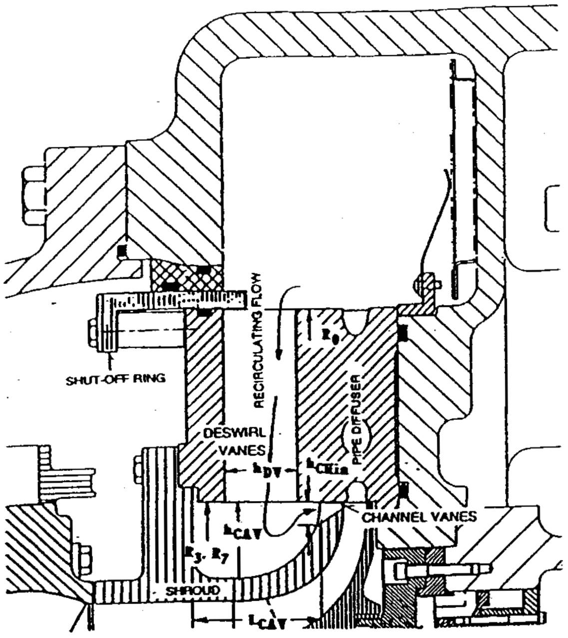

Fig.4 Recirculating diffuser geometry

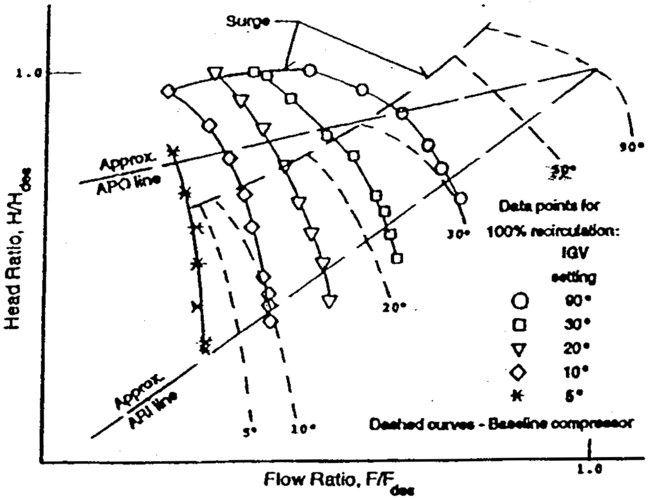

Fig.5 Test results with the recirculating volute

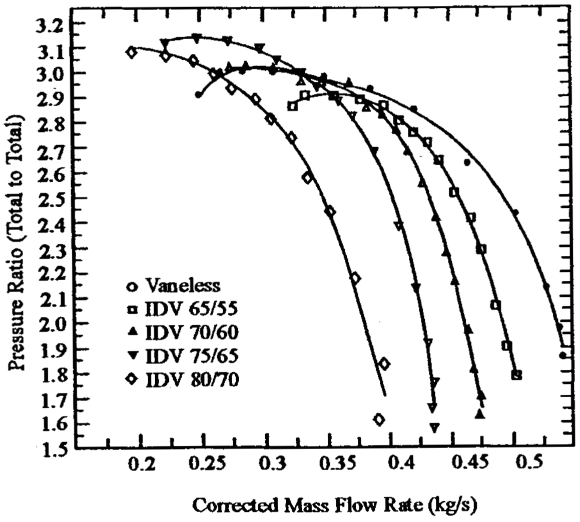

Fig. 6 Compressor performance with a vane turning angle of 10°

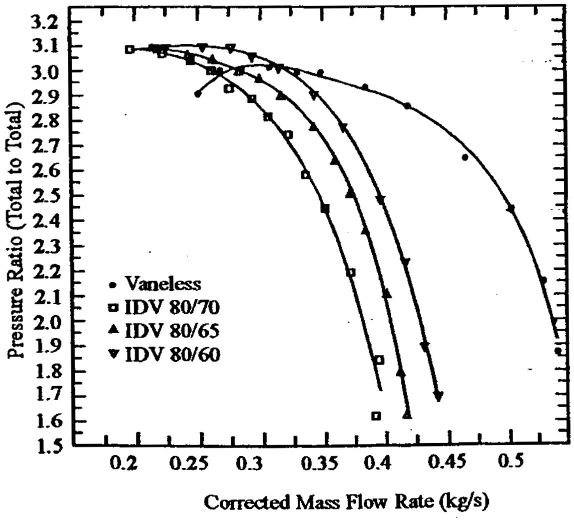

Fig. 7 Compressor performance with a vane leading edge angle of 80°