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## ABSTRACT

An investigation has been carried out to assess the effect of volute design on the performance of a centrifugal compressor. Three volutes, based on a turbocharger compressor volute, have been fabricated and tested. These volutes provided two that were larger than the original design, and one that was smaller. The alternative volute designs were fabricated from sheet steel and had a square cross-section. A common centre core, which provided the impeller cover, was copied from the original cast design and manufactured as a separate piece. This single centre core was used with each of the fabricated volutes. A scroll design, which was 25% larger than the original cast design, gave improved performance throughout the operating range. Scroll designs with a reduced discharge area did not perform well at high flow rates; this was attributed primarily to excessive flow separation from the leading edge of the tongue. The volute design also modified the performance of the upstream vaneless diffuser. The pressure recovery coefficient for the vaneless diffuser with the original cast design showed a clear maximum, whilst with the fabricated designs the pressure recovery coefficient increased throughout the flow range.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| $B_4$ | Vaneless diffuser discharge passage height | $R_4$ | diffuser discharge radius |
| $C_{\theta 4}$ | Tangential component of velocity at diffuser discharge | $r$ | Radius of volute passage |
| $C_{r4}$ | Radial component of velocity at diffuser discharge | $\alpha$ | Absolute flow angle |
| $q_v$ | Volume flow rate | $\theta$ | Azimuth angle |

## INTRODUCTION

It is well established that volutes of centrifugal compressors cause a circumferential pressure distortion around the impeller at all flow rates other than that at design. The design objective, Eck(1), is to achieve a uniform flow at volute inlet. At off-design conditions the volute is either too small or too large and a pressure distortion develops circumferentially around the volute passage. At low flow rates the pressure increases with azimuth angle while at high flow rates the pressure decreases. These circumferential pressure distortions are transmitted back to the impeller discharge and have been observed at impeller inlet, Fink *et al*(2). These circumferential pressure distortions reduce the stage performance and have a direct impact on diffuser and impeller flow stability. Roberts and Whitfield (3) showed that the flow rate at which the peak efficiency operating point of the compressor occurred was closely related to the flow rate at which

minimum pressure distortion was generated by the volute. A similar observation was made by Young(4) where he concluded that volute circumferential pressure distortion, which is influenced by tongue location, has a strong affect on efficiency. Mishina and Gyobu(5) showed that the effect of the cross-sectional shape of the flow passage was small, whilst the loss coefficient was a function of the volute area ratio and radius ratio. Reducing the radius ratio to provide an overhung volute, typical of that used for turbocharger compressors, led to an increase in the loss coefficient. Whitfield and Eynon (6) observed that the volute of a turbocharger compressor provided a significant pressure rise at the best efficiency point, and at flow rates down to full surge. They showed that the volute performance plays a significant role in setting both the best efficiency flow rate and the operating range of the compressor.
The purpose of the present study was to develop a technique to fabricate volute so that alternative designs could be quickly made and tested. Three volutes, based on a turbocharger compressor volute, have been fabricated and tested. These volutes provided two that were larger than the original design, and one that was smaller.

## VOLUTE DESIGN AND FABRICATION

The design of the fabricated volutes was based on the existing turbocharger volute design. The basic volute design procedure followed that given by Eck(1).Eck showed that the radius of the volute passage for a circular section is given as a function of azimuth angle, θ, by

$$r = \sqrt{\frac{\theta R_c q_v}{360\pi C_{\theta 4} R_4} - \left(\frac{\theta q_v}{720\pi C_{\theta 4} R_4}\right)^2}$$

With the volume flow rate into the volute given by $q_v = 2\pi R_4 B_4 C_{r4}$ and the absolute flow angle given by $\tan\alpha_4 = C_{\theta 4}/C_{r4}$ the above expression can be developed to

$$r = \sqrt{\frac{\theta B_4}{180\tan\alpha_4}(R_4 - r) - \left(\frac{\theta B_4}{360\tan\alpha_4}\right)^2}$$

where the radius to the centre of the volute passage was assumed to be given by $R_c = R_4 + r$
By using the dimensions for $B_4$ and $R_4$ of the original cast volute, and applying a flow angle $\alpha_4$ of 65° the calculated variation of $r$ with azimuth angle closely followed that of the original turbocharger design.

The above design procedure was then used as the basis for the design of the fabricated volutes with a square cross-section. The size of the square section being set equal to the diameter of the calculated circular section. An example of a fabricated volute is shown in Fig.1. This shows the centre core separated from the fabricated volute. The centre core, which provided the impeller cover, was copied from the original cast design and manufactured as a separate piece. This single centre core was used as the impeller shroud for each of the fabricated volutes. The volute can be considered as three sections, see Fig.1:

i) The scroll, where the cross-sectional area increased with azimuth angle from a minimum at the tongue recirculation port to a maximum at an azimuth angle of 360°.
ii) The scroll discharge, which is a square section duct, that increases in area, from an azimuth angle of 360° to the discharge flange, and
iii) The exit duct, which was an adapter piece forming the connection from the square volute discharge flange to the circular section discharge pipe.

Fig.1 Fabricated Volute

The cross-sectional area at the discharge flange was the same for all fabricated volutes and as a consequence only one exit duct was necessary. The area at the scroll discharge, the 360° azimuth angle position, was systematically varied relative to that of the original cast design. In terms of area ratio, (defined as the ratio of the area at scroll discharge, the 360° azimuth angle position, to that at volute inlet), Design 1 was 50% larger, Design 2 was 25% larger and Design 4 was 25% smaller, than the cast design. As the scroll discharge area was different for each design and all designs had the same area at the discharge flange, the scroll discharge duct had different area ratios for each design. The scroll discharge duct area ratio was 1.18, 1.41, 2.36 for designs 1, 2 and 4 respectively. In effect diffusion in the volute was transferred from the scroll section to the scroll discharge as the volute size was reduced.

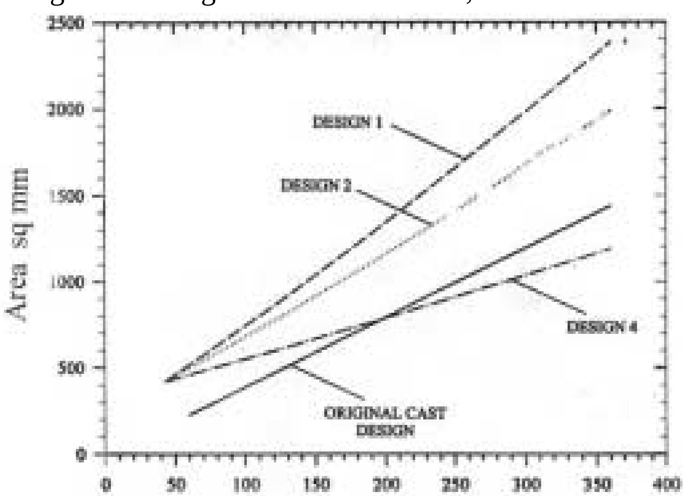

Fig.2 Volute area as a function of azimuth angle

The variation of scroll area with azimuth angle is shown in Fig.2 for the 3 fabricated volutes and the original cast design. Due to fabrication constraints it was necessary to increase the minimum area of the scroll section at the tongue from that of the cast designs. Consequently the area of the recirculation port on the fabricated volutes was larger than that of the cast volute.

## PRESENTATION AND DISCUSSION OF RESULTS

The impact of the alternative volute designs on the performance of the compressor is illustrated in Fig.3. The performance obtained with the fabricated rectangular section volutes is of the same order as that of the cast volute and there was no measurable reduction in performance due to the adoption of the rectangular cross-section. As expected the size of the volute had a direct impact on the stage performance, particularly at high mass flow rates. As the size of the volute was reduced, design 1 to design 4, the stage efficiency and pressure ratio decreased at high flow rates. If the limit of operating efficiency is set at a minimum of 60% there was a significant reduction in operating range as the volute size was reduced. As the volute size was reduced from that of design 1 to design 4 there was a reduction in maximum flow rate of 13%. Compared to the original cast volute design, design 1 showed an increase in high mass flow rate of 5%. The impact of volute size on performance at low mass flow rates is not as clearly defined as that at high flow rates. It is indicated, however, that the smallest volute provided the better performance in terms of pressure ratio and efficiency. Relative to the original cast volute the application of Design 2, which had an area ratio 25% greater than the cast design, led to improved performance throughout the operating range.

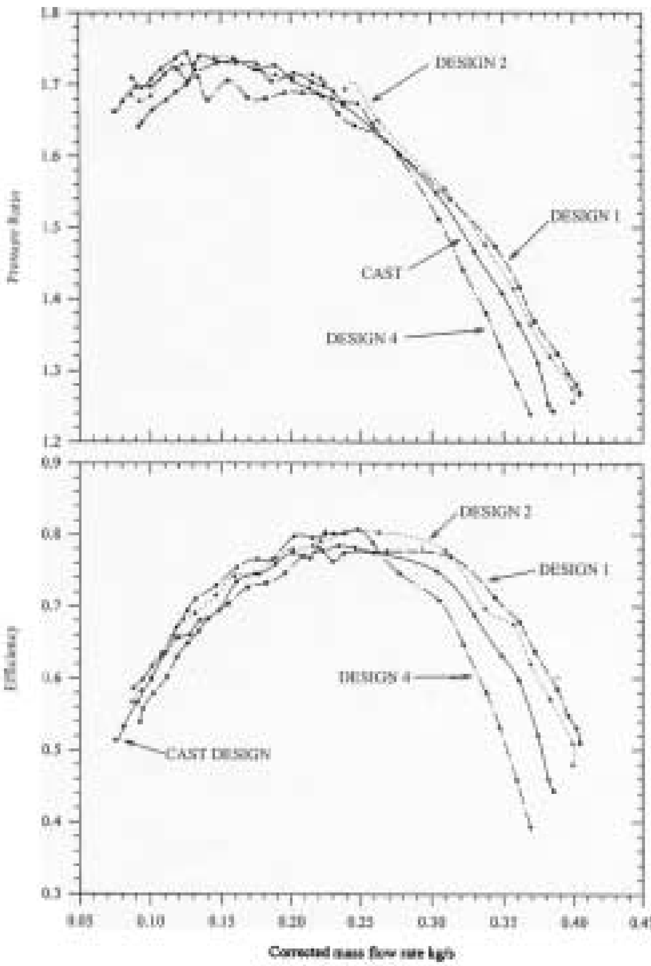

Figure 3. Effect of Volute Design on Compressor Stage Performance

To assess the impact of the volute designs further static pressure measurements were made at impeller discharge, vaneless diffuser discharge and throughout the volute to stage discharge. The complete diffuser system downstream of the impeller is illustrated in Fig.4. This shows the vaneless diffuser from station 3 to station 4, the scroll section from station 4 to station 4a, the scroll discharge duct, station 4a to 4b, and finally the exit duct from station 4b to station d. The pressure recovery coefficient across the vaneless diffuser, as a function of mean inlet flow angle, is shown in Fig.5. The pressure recovery coefficient with the fabricated volutes shows a steady increase with increasing flow rate (reducing flow angle), whereas that for the cast volute rises to a peak and then decreases with further increase in mass flow rate. The mass flow rate at which the peak stage efficiency occurred, with the cast volute, was very close to that at the peak pressure recovery coefficient for the vaneless

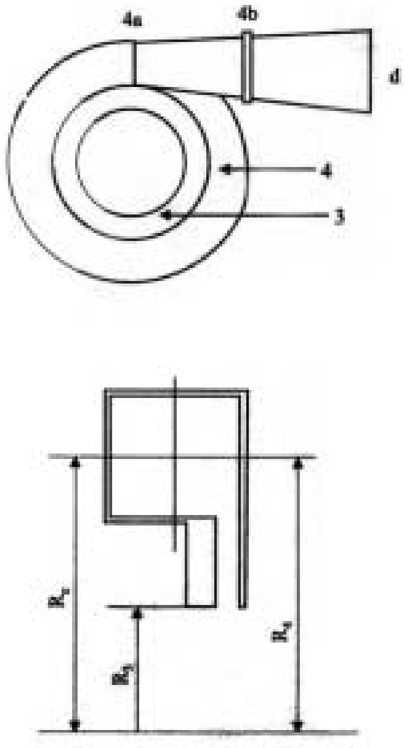


Fig.4 Compressor Diffusion System

diffuser. The vaneless diffuser when tested in association with the fabricated volutes did not exhibited a clear peak in the pressure recovery coefficient.

The pressure recovery through the scroll (4-4a), the scroll discharge duct (4a-4b) is shown in Fig.6 together with the pressure recovery coefficient for the full volute from volute inlet through to the stage discharge (4-d). The effect of reducing the scroll size on scroll pressure recovery coefficient is clearly shown. As the area ratio of the scroll was decreased the pressure recovery coefficient, at high flow rates, decreased. Each volute design showed a distinct peak pressure recovery coefficient and the mass flow rate at which the peak occurred decreased as the scroll size was reduced. Further pressure recovery occurred in the scroll discharge duct (4a-4b), Fig.6b. As the final discharge area of the volute was the same for all designs the rate of increase in area of the duct from scroll discharge to volute discharge was largest for the smallest area ratio designs, i.e. design 4. As a consequence the pressure recovery across the discharge duct was largest for design 4 and negligible for design 1. At high mass flow rates the pressure recovery falls sharply below zero due to flow separation from the leading edge of the tongue; this was shown by Dilin *et al*(7) both experimentally and theoretically. Finally the overall pressure recovery coefficient for the volute is shown in Fig.6c.

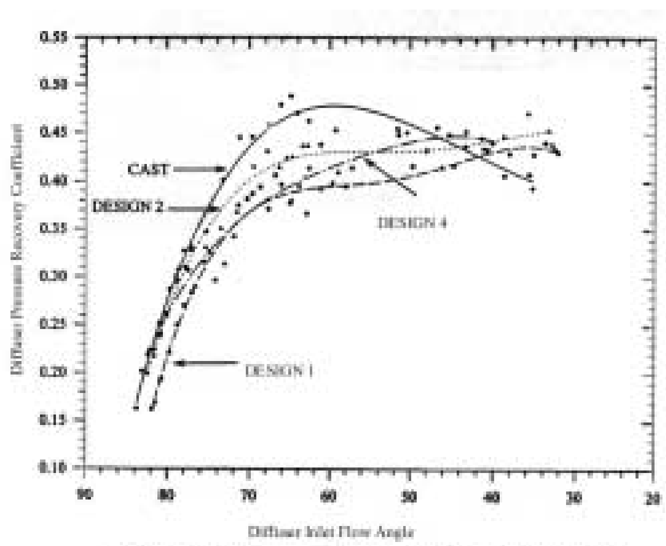


Fig.5 Variation of Diffuser Pressure Recovery Coefficient with Inlet Flow Angle

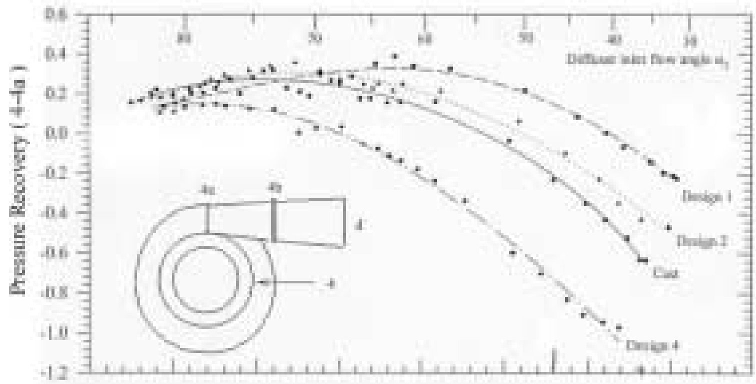


Fig.6a  Pressure Recovery of Scroll (4-4a)

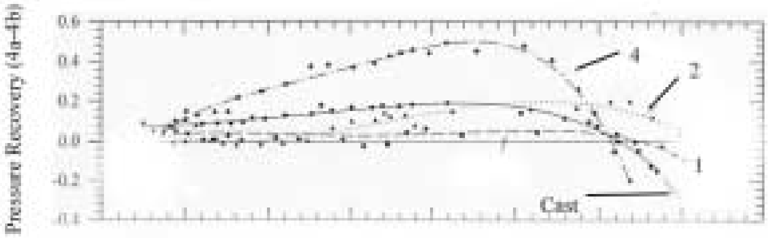


Fig.6b  Pressure Recovery of Scroll Discharge (4a-4b)

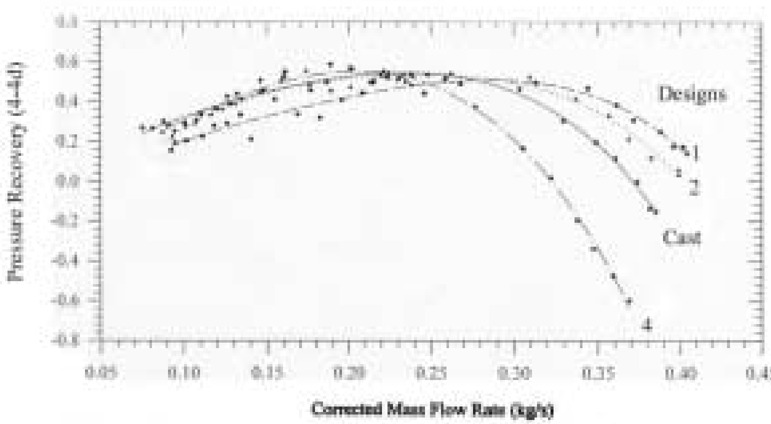


Fig.6c  Volute Pressure Recovery (4-d) as a function of mass flow rate

## CONCLUSIONS

A satisfactory fabrication procedure for volutes has been demonstrated and it has been shown that the use of a square section did not have a significant adverse effect on volute performance. The area profile of the volute scroll was modified by maintaining the same minimum area at the tongue and modifying the area progression to the scroll discharge. The effect of the scroll design on compressor performance was significant, particularly on the operating range. A scroll design which was 25% larger than the original cast design gave improved performance throughout the operating range. Scroll designs with a reduced discharge area did not perform well at high flow rates; this was attributed primarily to excessive flow separation from the leading edge of the tongue. The volute design also modified the performance of the upstream vaneless diffuser. The pressure recovery coefficient for the vaneless diffuser with the original cast design showed a clear maximum, whilst with the fabricated designs the pressure recovery coefficient increased throughout the flow range, albeit very little at high flow rates.

The investigation has provided a means to fabricate prototype volutes which can be used to investigate alternative designs, and in particular investigate variable geometry and variable flow control techniques in order to improve the performance over the full operating range.

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