Flow measurement around a fan volute tongue using particle tracking velocimetry

by

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ABSTRACT

The primary function of the collecting volute of centrifugal fans and compressors is to collect the swirling flow issued from the upstream impeller and diffuser and deliver it to a single discharge duct. This can be achieved efficiently at the design flow rate only. At off-design flow rates a pressure distortion is generated around the vaneless diffuser and impeller discharge leading to reduced performance of both components. The tongue of the collecting volute acts as a single vane around which the flow is divided and directed down the discharge duct and/or forced to recirculate around the volute. At high flow rates the volute acts as a nozzle and accelerates the air velocity leading to a reduction in static pressure. This high air velocity impacts the leading edge of the tongue at a large incidence angle leading to flow separation. At low flow rates the volute decelerates the airflow leading to an increase in pressure through the volute. At these low flow rates separation or flow unsteadiness can occur from the underside of the tongue. This investigation concentrates on the measurement of the flow characteristic in the vicinity of the volute tongue. Three volute tongue designs were investigated. Volute A had a full tongue and did not allow any flow recirculation. Volute C had a reduced tongue length thereby opening the recirculation port. Finally the tongue of volute RT-60 had a rounded leading edge to make it less sensitive to off-design flow conditions. Volutes C and RT-60 showed poor performance at flow coefficients between 0.19 and 0.29. Typical flow patterns at the volute tongue of design C are shown in Fig.1 for a flow coefficient of 0.27. The flow from injection port C2 was unstable with the flow direction switching between the recirculation duct and the discharge duct.
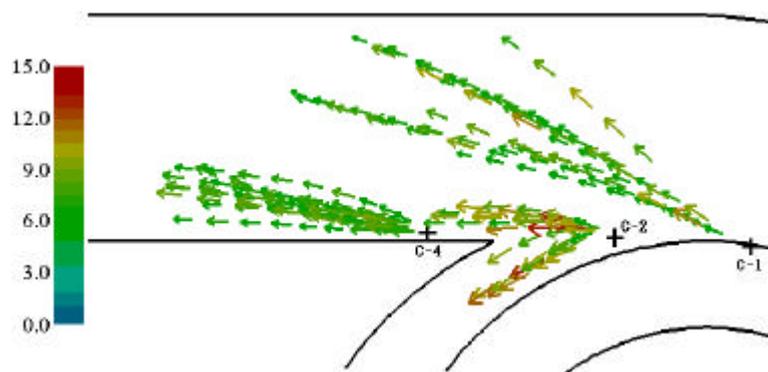
Fig.1 Velocity vectors illustrating unstable flow, Volute C, f = 0.27

1. INTRODUCTION

The collecting volute of centrifugal fans and compressors has been traditionally viewed as a simple collecting device, with all the required diffusion completed in the vaned or vaneless diffuser upstream of the volute. Many operating and installation requirements now demand compact designs with reduced diffuser size, and as a consequence the volute must provide efficient diffusion. The volute tongue acts as a single vane around which the airflow divides. At off-design flow rates large incidence angles occur leading to flow separation. At high flow rates the flow separation leads to a sharp reduction in stage efficiency, while at low flow rates the disturbed flow at the volute tongue is a possible trigger for compressor surge, Whitfield and Eynon(2000).

Irabu *et al*(1994) studied the flow around a volute tongue using a particle tracking procedure. Polystyrene balls were used in a water flow rig to investigate the flow through the vaneless diffuser and around the tongue of the collecting volute. The leading edge of the volute tongue had a variable vane attached so that it could be adjusted to match the incident flow conditions. The investigation concentrated on the low flow region where rotating stall vortices were discharged from the vaneless diffuser into the collecting volute. It was shown that at low flow rates vortices shed from the vaneless diffuser periodically created a large incidence angle at the volute tongue leading to separation. Separation occurred from both the upper and lower surfaces of the tongue leading to a pulsating flow condition. Application of the variable guide vane at the tongue leading edge suppressed the magnitude of the separation but did not eliminate it.

An ability to measure the nature of the flow structure at the volute tongue is essential if improved understanding of the impact of volute design on compressor efficiency and operating range is to be achieved. Such measurements will also provide essential data for the validation of CFD codes now being used for volute design, Dilin, Sakai *et al*(1998).
This flow structure near the volute tongue is difficult to determine by yaw probe traverse measurements. However, the development of optical equipment and image processing techniques, Particle tracking velocimetry (PTV), provides a useful technique for measuring this type of disturbed flow. For the application here a 2W Ar-ion laser was used to generate a laser sheet, and soap bubbles, which are close to the density of air and do not cause environmental pollution, were used to trace the airflow. The fluctuating flow structure was obtained through a series of superimposed particle traces obtained at any fixed flow rate.

2. APPARATUS AND EXPERIMENTAL PROCEDURE

2.1 Particle Tracking System

The apparatus used to generate the soap-bubble tracers is shown in Fig. 2. Compressed air was passed through an inner tube, and a water solution of detergent was passed through an outer tube. The two were then mixed at the end of a coaxial tube through which the generated soap bubbles were injected into the airflow. By adjusting the height of the water solution and the pressure of the compressed air supply appropriate bubbles were generated. The soap bubbles obtained had a diameter of approximately 1 mm, and a mass of the order of 10^9 kg. For the lighting system, Fig. 3, the Acousto-Optic Modulator (AOM) together with a cylindrical lens generated a pulsed laser sheet. As the flow was three-dimensional at the test section of the volute tongue the thickness of the laser sheet was adjusted to a width where a locus of a soap bubble was captured in a frame.
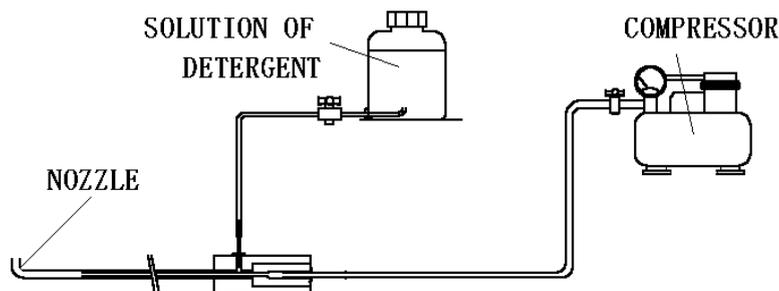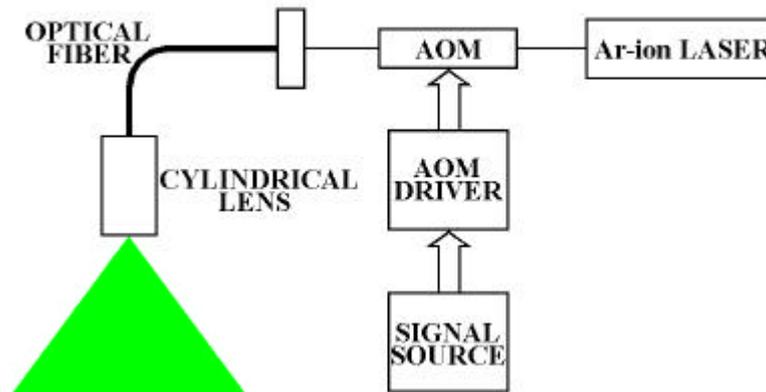

Fig.2 Soap bubble generator

Fig.3 Lighting system

The PTV system was calibrated in a steady airflow using an open wind tunnel, Fig. 4, which provided a uniform low turbulent flow. A 250 Hz pulsed laser sheet and a camera exposure time of 1/30 sec was found to be suitable to obtain satisfactory tracer images in one frame of the CCD camera. The camera images were video recorded and inputted into a computer through a frame grabber. The tracer images were extracted using image-processing techniques with the instrumentation set to select the brightest images in order to reduce noise. The velocity of a tracer was obtained from the co-ordinates of a frame that was calibrated in advance, and using a pattern matching technique.
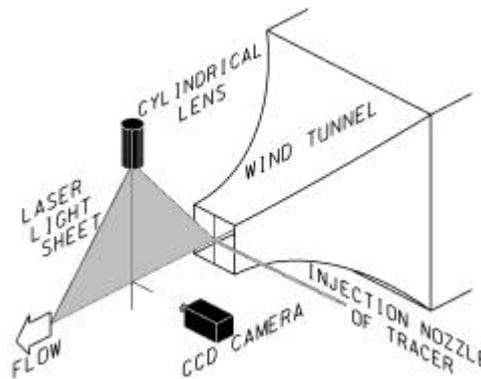

Fig.4. Experimental apparatus for calibration of PTV system

Calibrations were carried out with air velocities of 4.4 and 8.4 m/s. Evaluated velocities were compared with the velocity measured by a standard Pitot probe, Fig. 5. The broken line is the theoretically evaluated velocity based on the equilibrium of inertial force and the viscous force of the soap particle for very small Reynolds number flow, Asakura (1986). It can be seen that the soap bubbles accelerated after leaving the generator nozzle, and significant distance was required to attain the flow velocity. The scatter of points in Fig.5 was not small due to poor clarity caused by a lack of laser power. Logarithmic and polynomial curve fitting techniques were applied to the experimental data, and it was found that the logarithmic fit was best. By plotting the results as a velocity ratio, velocity non-dimensionalized by that given by the Pitot probe, it can be seen that the calibration curve showed a similar tendency to the theoretical curve. The calibration curve, however, shows a steeper gradient at small distance from the injection point, and shows that a larger distance was necessary to attain a constant velocity. This can be attributed to slip between the tracer and the air, and to Reynolds number effects. It is, therefore, necessary to repeat the calibration at other air speeds to cover the range obtained in the volute tests. In this study, the average flow velocity was of the order of 8m/s and the calibration curve obtained at an air velocity of 8.4m/s proved to be satisfactory. The calibration was used to provide a velocity correction procedure to allow for the distance required to accelerate the soap bubbles.
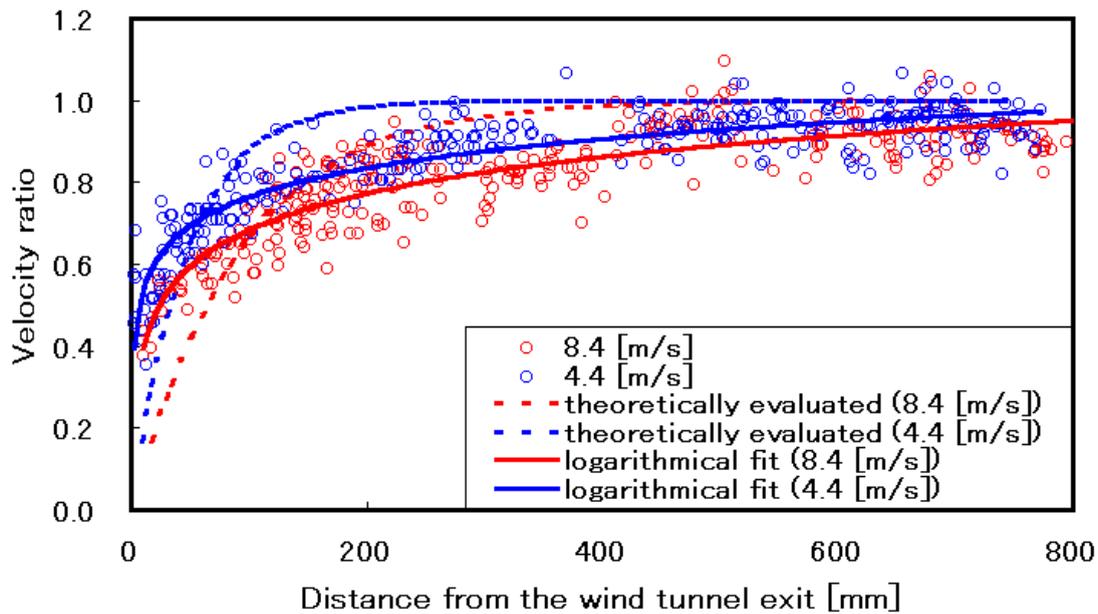
Fig.5 Calibration results

2.2 Volute designs and tracer injection points

The flow patterns around three volute tongue designs were investigated. For volute A, see Fig.7a, a full tongue was used and it was not possible for the air to recirculate around the volute. For volute C the tongue was cut back, Fig.7b, thereby allowing for flow recirculation. Finally for the third design the leading edge of the tongue was rounded and designated RT-60, Fig.7c. The tracer injection points are indicated for each volute with the exact locations given on the figures. A 500-Hz pulsed laser sheet with a thickness of 10 mm was applied at the centre cross section of the volute tongue, Fig. 6. The exposure time of the CCD camera was adjusted in the range 1/30 to 1/60 sec so that satisfactory tracer images were obtained in a single frame. Soap bubble tracers were injected at the exit of the fan's vaneless diffuser, and downstream of the volute tongue leading edge, through the points shown in Fig.7. The tracer injection points were selected to provide full coverage of the flow in the volute tongue region.
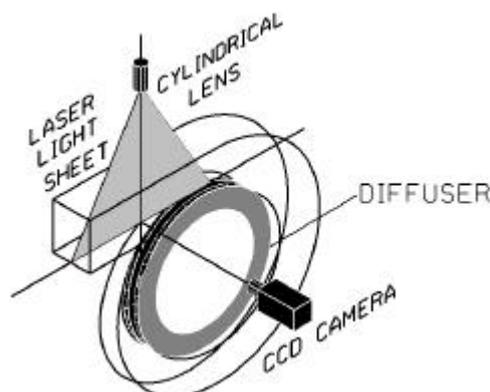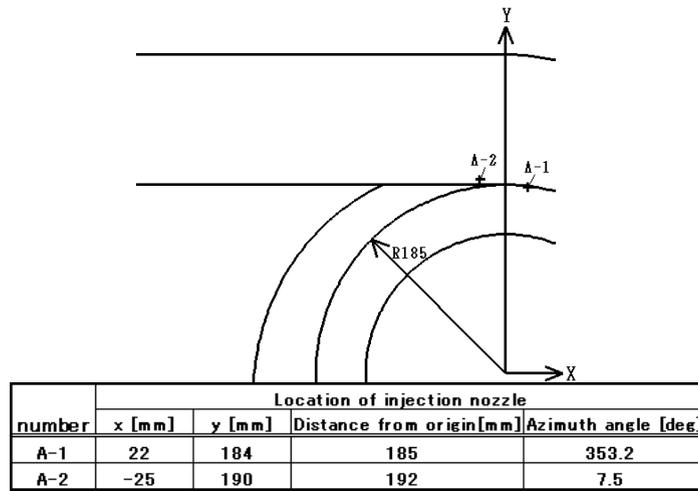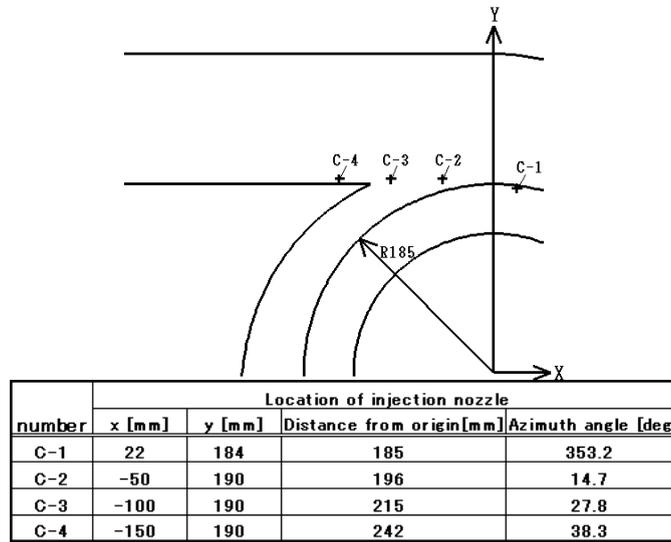

Fig.6 Volute tongue flow measurement system

4

	Location of injection nozzle			
number	x [mm]	y [mm]	Distance from origin[mm]	Azimuth angle [deg]
A-1	22	184	185	353.2
A-2	-25	190	192	7.5

Fig.7a Volute tongue design, A

	Location of injection nozzle			
number	x [mm]	y [mm]	Distance from origin[mm]	Azimuth angle [deg]
C-1	22	184	185	353.2
C-2	-50	190	196	14.7
C-3	-100	190	215	27.8
C-4	-150	190	242	38.3

Fig.7b Volute tongue design, C

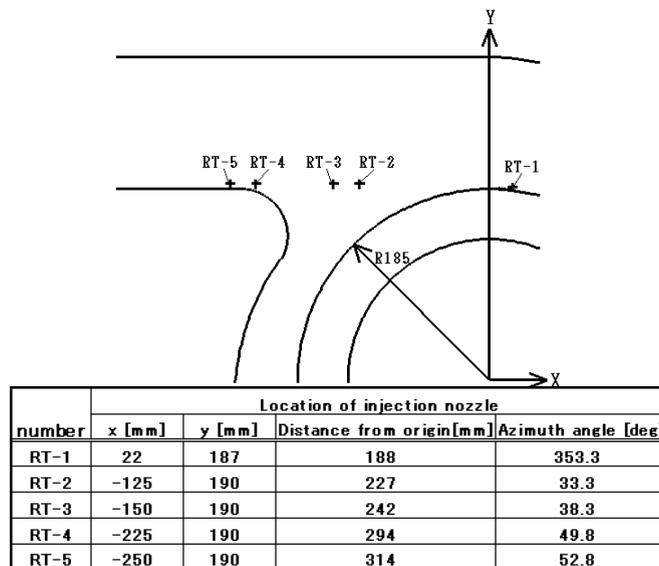|	Location of injection nozzle			
number	x [mm]	y [mm]	Distance from origin[mm]	Azimuth angle [deg]
RT-1	22	187	188	353.3
RT-2	-125	190	227	33.3
RT-3	-150	190	242	38.3
RT-4	-225	190	294	49.8
RT-5	-250	190	314	52.8

Fig.7c. Volute tongue design, RT-60

3. PRESENTATION AND DISCUSSION OF RESULTS

The performance of the fan in terms of pressure coefficient as a function of the flow coefficient is shown in Fig.8 for the 3 volutes tested. Flow coefficient f is defined as the ratio of radical component of velocity C_{r2} and impeller tip speed u_2. It can be seen that as the flow rate was increased the initial rise in pressure coefficient was followed by a stepped reduction, region 'a', at a flow coefficient between 0.19 and 0.29. This is particularly prominent with volutes C and RT-60 and is not shown with volute A. At the high flow rates volutes C and RT-60 provided an improved pressure coefficient compared to that for volute A, Fig.8 region 'b'. Use of the volute with the rounded tongue provided improved performance throughout the flow range except in region 'a', where there is a stepped reduction in pressure coefficient. In this region the rounded tongue led to the poorest fan performance.

The characteristics of the flow around the volute tongue were obtained over the full operating range of the volute with particular attention being paid to 1) the high flow region, 2) the low flow region, and 3) a flow region were the pressure coefficient showed a stepped reduction in performance. All traces are shown at the centre cross section of the volute. The figures generally show the superimposition of a series of tracer paths from one injection point. In addition the resultant traces from a number of injection points are presented on a single figure in order to illustrate the flow pattern.
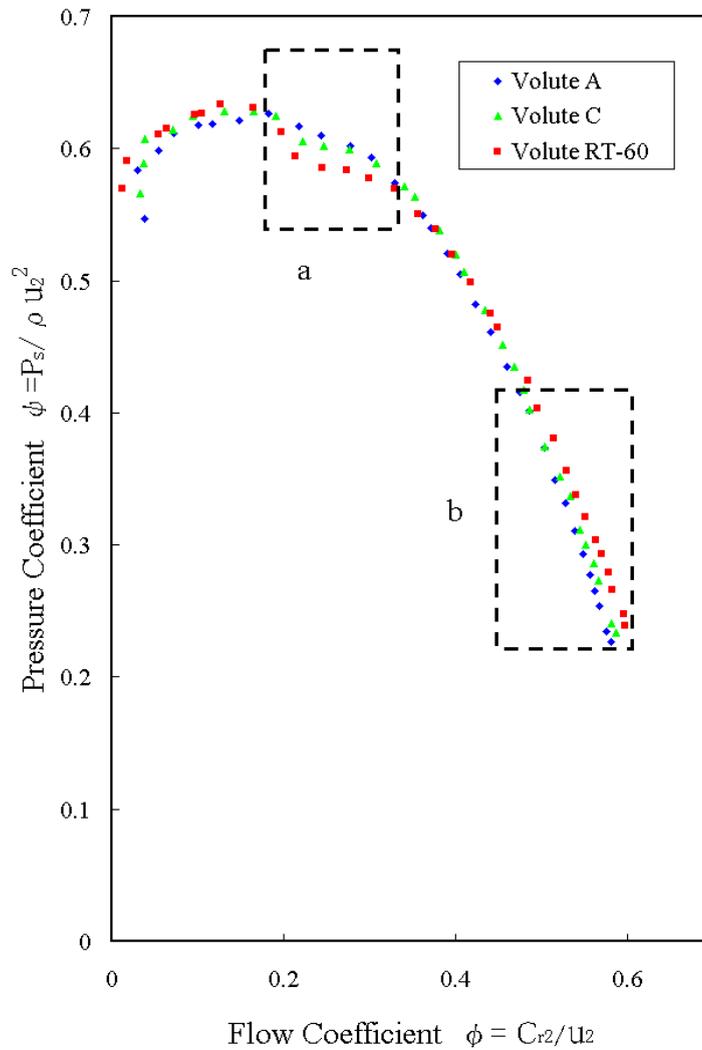

Fig.8 Fan performance characteristics

For volute A relatively poor performance was shown at high flow coefficients, and it was in this region where the interesting flow characteristics were observed. The flow traces at the highest flow coefficient of 0.57 are shown in Fig.9. Tracers are shown from injection ports A1 and A2. Injection port A2 was downstream of the tongue leading edge and the tracers show a clear flow reversal back to injection port A1. The tracers from port A1 did not show a flow reversal, but were carried around into the positive flow direction by the reversing downstream flow swirling back into the discharge direction. It is clear that a separation eddy existed downstream of the leading edge of the tongue, although the experimental investigation has not been done in sufficient detail to show this in full. This clear reversal of the flow was not observed with volute designs C and RT-60.
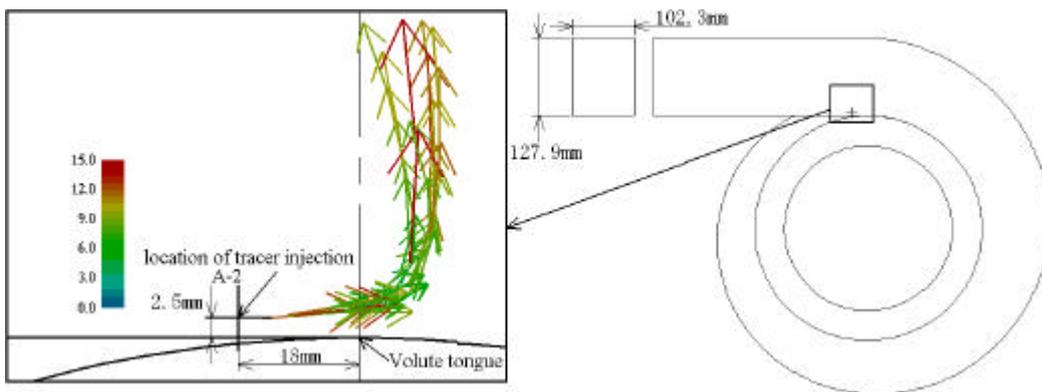

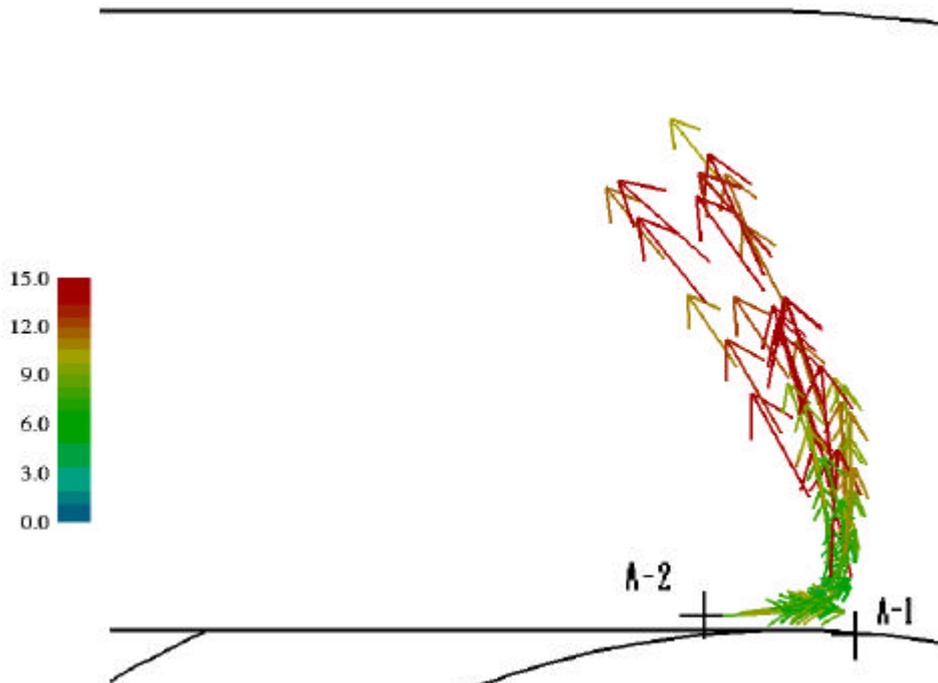Fig.9a Velocity vectors from upstream of volute tongue A f = 0.57

Fig.9b Velocity vectors showing flow reversal upstream of the tongue leading edge

7

Figure 10 shows the high flow coefficient conditions obtained with volute C. In this case the traces from three injection points, C1, C3 and C4, are shown. The high flow rate and consequent large flow angle, from the tangential direction, again leads to separation from the leading edge of the tongue. However, there is no evidence of a flow reversal downstream of the leading edge. The large flow angle, as shown by the tracers from port C1, leads to clear fluctuations in the flow direction.

By reducing the flow rate to a flow coefficient of 0.27 the fan operation is in the region where a stepped reduction in the pressure coefficient was observed, region 'a' Fig.8. The corresponding tongue flow conditions are illustrated in Fig.11 through the traces obtained from three injection ports, C1, C2 and C4. The traces from the middle injection point, C2, that above the recirculation port, show the passage of tracers through both the discharge and recirculation duct. A fluctuating flow condition existed with the tracers periodically switching from one duct to the other. Downstream from the tongue leading edge, injection port C4, the flow is orderly with no indication of reverse flow. This phenomenon corresponds with that described by Irabu *et al*(1994) where the fluctuations were attributed to the passage of vortices generated by a rotating stall pattern in the vaneless diffuser. In this investigation the measurements have not included the vaneless diffuser and no attempt has been made to measure the stall cells.
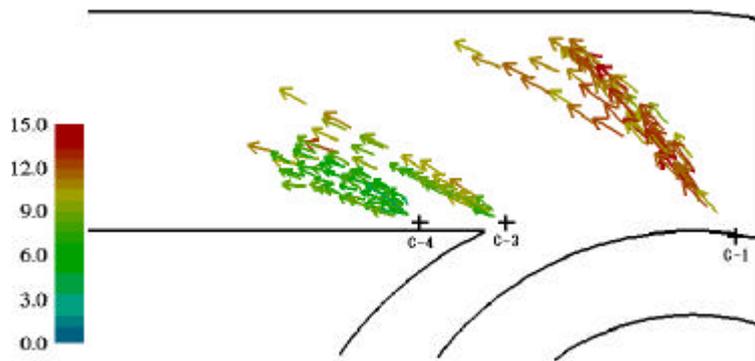

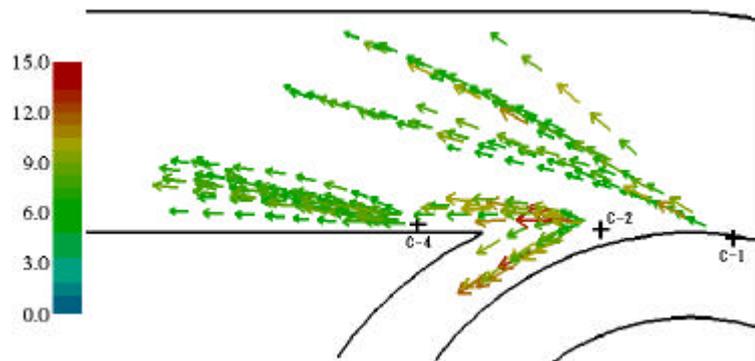Fig.10 Velocity vectors from 3 injection points, Volute C, $f = 0.57$

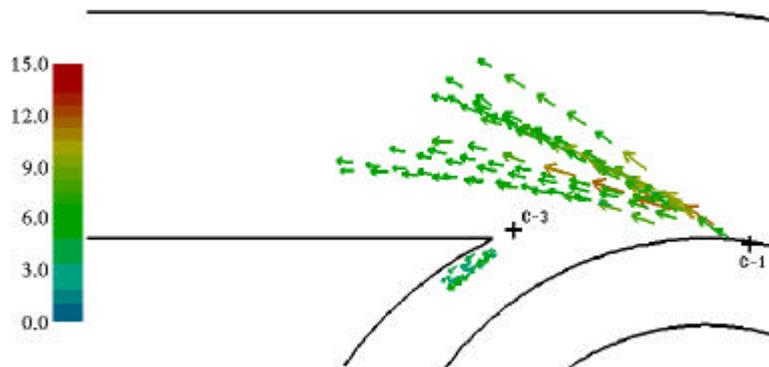Fig.11 Velocity vectors illustrating unstable flow, Volute C, $f = 0.27$

Fig.12 Velocity vectors at low flow coefficient, Volute C, $f = 0.21$

The tongue flow conditions at the lowest flow coefficient of 0.21 are shown in Fig.12 by the tracers from injection points C1 and C3. In this case there was no measured evidence of the flow immediately upstream of the tongue oscillating between the flow passages. The tracers indicated a continuous flow into the recirculation duct.
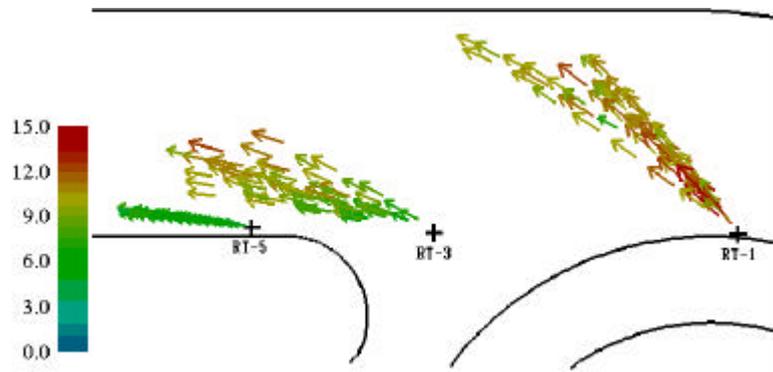
Fig.13 Velocity vectors at high flow coefficients, Volute RT-60, f = 0.57

Application of the design with a rounded leading edge, volute RT-60, led to improved fan performance at high flow rates. The passage of tracers from three injection points, RT1, RT3 and RT5, is shown in Fig.13 for a flow coefficient of 0.57. At the high flow rates the flow discharges from the vaneless diffuser with a large flow angle, measured from the tangential direction, as shown by the tracers from injection point RT1. In the vicinity of the tongue, however, there is no evidence of flow separation or of reverse flow. The rounded leading edge has led to improved tongue flow conditions and an improvement in the overall performance of the fan.
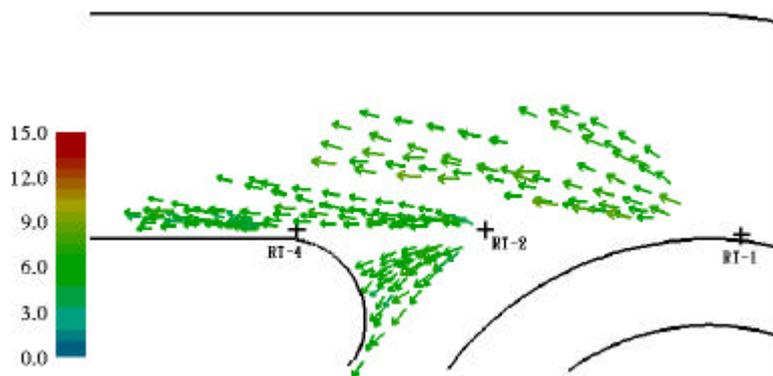
Fig.14 Velocity vectors at a flow coefficient of 0.27, volute RT-60

At the reduced flow coefficient of 0.27 the fan operated in the region that showed a stepped reduction in pressure coefficient, region 'a' Fig.8. In this region the volute with the rounded tongue provided the poorest pressure coefficient. The tracers from injection point RT2, Fig.14, show a stagnation point on the rounded tongue with the flow dividing to enter the recirculation passage. There is evidence of a stagnant zone with an unstable stagnation point on the rounded tongue. The fluctuation in flow direction at the volute tongue of RT-60, as observed from the video results, was wider ranging than that observed with volute design C. Due to this unstable stagnation point the flow over the rounded surface was severely disturbed. This disturbance affected the upstream flow as shown by the tracers from injection point RT1. In Fig.14 the tracers from point RT1 have a much wider spread than those at the high flow rate, Fig.13. The flow from the upstream injection point for volute C, Fig.11 point C1, is less disturbed than that shown by the corresponding tracers for the rounded tongue, Fig.14. The rotating stall vortices shed from the vaneless diffuser can impinge on to the volute tongue, see Irabu *et al*(1994). With the rounded tongue design it is possible that these vortices have an affect right across the curved surface, and cause a greater disturbance to the surrounding flow than that created with tongue design C. This seems to be the reason why the rounded tongue provided the poorest pressure coefficient at the flow coefficient of 0.27. These results suggest that it would be possible to remove this stagnant zone by re-designing the

tongue to be similar to that of volute C. This would improve the performance for flow coefficients in the range 0.19 to 0.29, but not at high flow coefficients.

4. CONCLUSION

It has been shown that the PTV system with an Ar-ion laser and a soap-bubble tracer can be successfully applied to the measurement of flow in the volute of a radial flow fan. The system provided good measurement of the flow direction, separation and flow unsteadiness around the leading edge of the tongue. The flow visualization has shown that the flow separation from the leading edge of the tongue was reduced by the design modifications. By cutting back the volute tongue both the volute and fan performance was improved. The performance was then further improved by providing a rounded leading edge to the volute tongue. The exception to this general improvement was in the flow region 'a' of Fig.8, the reason for this poor performance of design RT-60 was attributed to the development of an unstable stagnant zone at the tongue.

5. REFERENCES

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