A NEW RADIAL-INFLOW TURBINE TEST FACILITY

N C Baines and M Lavy
Imperial College
Department of Mechanical Engineering
Exhibition Road
London SW7 2BX
UK

ABSTRACT

A facility for testing small radial-inflow turbines has been constructed, and its use both for measuring turbine performance and the turbine flowfield has been demonstrated. This paper describes the rig and discusses some of the measuring techniques which have been used. Flowfield measurements in the vaneless volute of such a turbine are illustrated. Comparative measurements were made with a multi-hole pressure probe and a laser-2-focus anemometer. The results obtained are useful in revealing the strengths and weaknesses of each. The probe is intrusive, and is thus susceptible to problems of blockage, but the requirements of optical access limit the number of separate measurement points available to the laser.

A separate rig used for calibrating the probe is also described. It is capable of making a full three-dimensional calibration at representative turbine Mach and Reynolds numbers, and these are separately variable.

INTRODUCTION

Radial turbines are commonly used in small gas turbine engines and internal combustion engine turbochargers, because of their high specific power output, low manufacturing cost and, in small sizes, higher efficiencies than comparable axial turbines (due largely to the high tip clearance losses of the latter). In many radial turbine applications it is also possible to dispense with a separate ring of nozzle vanes and use the spiral shape of the turbine housing, or scroll, to generate the necessary swirl at entry to the rotor. This leads to a further simplification in design and reduction in manufacturing cost.

The test rig described here was designed with a two-fold purpose: to measure the performance of radial-inflow turbines (power output, efficiency, speed, mass flow rate, etc) under realistic operating conditions, and also to be able to make detailed measurements of the flowfield in the turbine passages. The second of these is particularly important, since the available aerodynamic data for radial turbines is currently very limited, and design tends to proceed largely by trial-and-error.

Measurement techniques to be used in such a rig require careful consideration, because of the small size of the components, the complex geometry of both stator and rotor passages, and the high gas velocities encountered. Two measuring techniques suitable for use in the stator are described here. One is a fairly conventional multi-hole pressure probe, which requires separate calibration, and for this purpose a rig was developed and is also described. The other is a laser-2-focus (or transit) anemometer which is, in principle, also suitable for making measurements in the rotating blade passages, although here its use is confined to the vaneless volute, for comparison with the probe measurements.

Description of the turbine test rig

A schematic diagram of the turbine test rig is shown in Fig. 1. The turbine is supplied with air at 5 bar and ambient temperature. It is finely filtered with cyclone and paper filters to remove particles above about 1 µm. This enables sensitive and delicate probes, such as hot-wire anemometers, to be used in the rig. An orifice plate is used to measure the air mass flow rate. The air is heated electrically to 400 K turbine inlet temperature. This does not reproduce the high inlet temperatures encountered in most applications, but has a number of advantages. It is very clean and does not introduce any solid particles in the flow, as a combustion chamber might. It is also very controllable (using a PID controller it is possible to regulate the inlet temperature to within 0.5 K, which is important when using temperature-sensitive instrumentation). The use of relatively low temperatures enables test turbine rotors and other components to be made out of low-cost and easily machined materials. The inlet temperature is sufficient to avoid any problems of condensation occuring in the turbine expansion.

At entry to the turbine the total temperature is measured by thermocouple, the total pressure by pitot probes, and the static pressure by tappings in the duct walls. The turbine exhausts via a silencer to atmosphere. The total temperature and static pressure are also measured here.

The turbine is loaded by means of a centrifugal compressor which draws in air from atmosphere and exhausts it through a throttle valve. This valve controls the load on the turbine. Compressor air mass flow, inlet and exit total temperatures and static pressures are recorded. The turbine output power is calculated from an energy balance of the whole system, and since there is significant power lost in the shaft bearings, the oil flow rate and temperature rise are also recorded. The whole rig can be thermally lagged to minimise stray heat losses.

The alternative method of measuring turbine power is by means of a high-speed dynamometer, usually of an oil drag or eddy-current type. By comparison, the present method is inexpensive, since it uses standard commercial components, and has proved to be trouble-free in operation. Its principal disadvantages are that the turbine operating range is restricted by the compressor surge and choke points, unless a series of compressors of different sizes is used, and the method of deducing the power output is indirect and relies on a number of more basic measurements. Considerable attention had to be paid to the instrumentation in order to minimise experimental uncertainties.

The present bearing system is conventional, with plain, oil-lubricated bearings. The bearing clearances are generous, giving good damping, but limiting the scope for adjusting the turbine rotor radial tip clearance. It is hoped to change these bearings for high-speed rolling element bearings at a later date.

Laser anemometer arrangements

For the series of tests discussed here, arrangements were made to measure the flowfield in the vaneless volute of a radial turbine. For this purpose, optical windows were set into the turbine housing (Fig. 2). The housing is a complex shape, being doubly-curved in the regions of interest, and is not dimensionally precise. Curved windows were rejected on the grounds of cost and the difficulty of calculating the optical path through them. Instead, small plane windows were used. Although these introduced discontinuities in the inner surface in which they were set, they were judged to be sufficiently small that they would not invalidate the experiment. It was not possible to find a way to make the windows removable, and they were set in place using RTV to allow for any differential thermal expansion. Fortunately, no problems of the seeding material obscuring the windows were encountered, and it was only necessary to clean them occasionally.

The instrument used was a Polytec L2F velocimeter and signal processor; the principle of operation is adequately described elsewhere, e.g. by Schodl (1985).

The pressure probe and its calibration

A multi-hole pressure probe was also used for comparative measurements in the turbine volute. A four-hole wedge probe was designed, manufactured and calibrated (Fig. 3). In form it is similar to one of the two probes used for the Workshop on Probe Calibrations (Fransson, 1983). A single, forward-facing sensor records the total pressure, the static pressure is a function of the average of two tappings, one on either side of the wedge, the yaw angle is a function of the difference between these two tappings, and the pitch angle is calibrated against the difference between the forward-facing tapping and the one at the rear of the wedge.

In order to calibrate this and similar probes a special calibration channel was constructed. This uses the identical air supply as the turbine rig, thereby avoiding any problems of temperature and fluid property variations. The test section is a constant-area, straight, hydraulically smooth pipe of diameter 50 mm (Fig. 4). This is fed from a plenum chamber containing honeycombs and gauzes to smooth and straighten the flow, followed by a smooth, separation-free contraction into the test section. The total pressure loss between the plenum and the test section was checked and found to be negligible. The static pressure variation across the test section was also found to be constant. The reference pressures, against which the probe is calibrated, are therefore a total pressure measured by pitot probe in the plenum, and a static pressure tapping in the sidewall in the plane of the probe itself. The probe can be traversed across the test section (to investigate wall proximity effects, for example), and can be yawed and pitched relative to the flow.

Valves are located upstream and downstream of the calibration rig. By means of these the reference total and static pressures in the test section can be varied independently, and hence also the reference Mach and Reynolds numbers.

Comparison of results

A brief presentation of a few measurements of the volute flowfield are presented here in order to judge and compare the usefulness of the various measurement techniques in the turbine test rig. No attempt is made here to explore the full details of the volute flow.

Using the pressure probe it was possible to make a detailed survey of the volute in the radial, tangential and axial directions. A large number of access holes were drilled in the volute (not the identical volute to that containing the optical windows, but one of the same design). The probe was inserted in each hole in turn, traversed in the axial direction, and total and static pressures, and the velocity vector, were measured. A single set of results at one axial location is shown in Fig. 5.

The single most obvious feature here is that, while the flows are reasonably similar, in both magnitude and direction, with radius around most of the volute, at the smallest radius (and very close to the rotor tip), there are very large and surprising variations in flow angle in particular around the circumference. If the tangential velocity is integrated around the periphery of the rotor, it becomes apparent that this is wholely incompatible with the actual power output of the turbine at this condition. It would appear that the proximity of the rotor to these measuring locations makes the probe very unreliable in this region.

Unfortunately, the restrictions of the turbine housing geometry meant that it was not possible to locate windows so as to obtain laser measurements this close to the rotor, so that these data cannot be compared directly. At a larger radius, however, a comparison of laser and probe-measured velocities around the circumference at constant radial and axial position was possible, Fig. 6. In general the agreement between the two is encouraging, although some discrepancies particularly at the higher pressure ratio remain to be resolved. Most significantly, it is clearly possible to achieve a better spatial resolution with the probe due to the larger number of measuring points. In the region of the tongue (at azimuth 0°, where the remaining flow which has performed a complete circumference of the turbine re-enters and mixes with the entering stream) there are detail variations of the flow conditions. These are not seen by the laser because of the limited number of viewing windows available. In practice it is found that the presence and location of the tongue have an important influence on the performance of a vaneless radial turbine, and the flow details in this region are of considerable interest (see Scrimshaw and Williams, 1984, and Lymberopoulis *et al*, 1988).

Conclusions

A radial turbine test rig and an associated probe calibration rig have been constructed, and have been used for turbine performance and flowfield measurements. A comparison of measuring techniques applied to the vaneless volute of the turbine has revealed their suitability, strengths and weaknesses in this application. The particular features of the volute are its small size and complex geometry, both of which cause measuring problems.

Measurements of total and static pressure, and magnitude and direction of velocity, have been demonstrated using a four-hole pressure probe. The manufacture, calibration, and use of the probe is relatively straightforward, and a good spatial resolution is possible by using a large number of measurement points. The preparation of the volute for such measurements involves little more than drilling the necessary access holes for the probe (and plugging those not currently in use). The principal disadvantage of this technique is that it is intrusive, and in particular measurements in the proximity of the rotor are very unreliable.

A laser-2-focus velocimeter has also been used to measure flow speed and direction at a number of points in the volute. Being non-intrusive, it does not suffer from the same problems as the probe. There are, however, considerable difficulties in obtaining adequate optical access. In a curved casing, plane windows must be small to reduce the discontinuities introduced in the inner surface, and this has limited the number of measuring points available. In particular, it was not possible to "see" into areas important in understanding the fluid mechanics of the vaneless volute.

Acknowledgements

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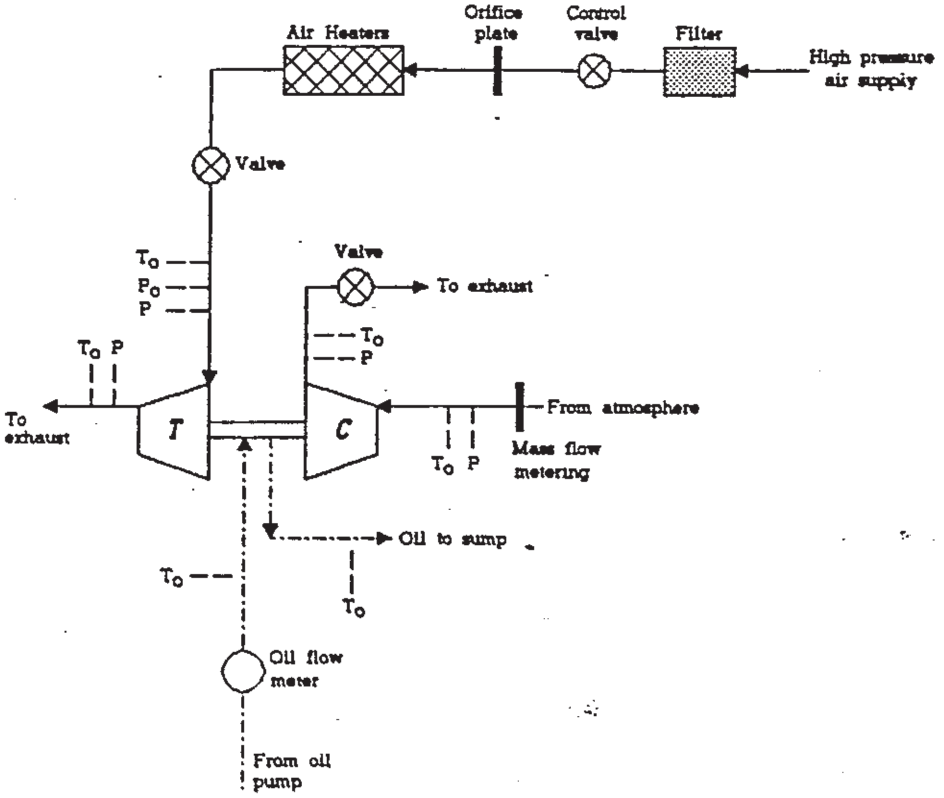

Fig. 1 Schematic diagram of radial turbine test rig

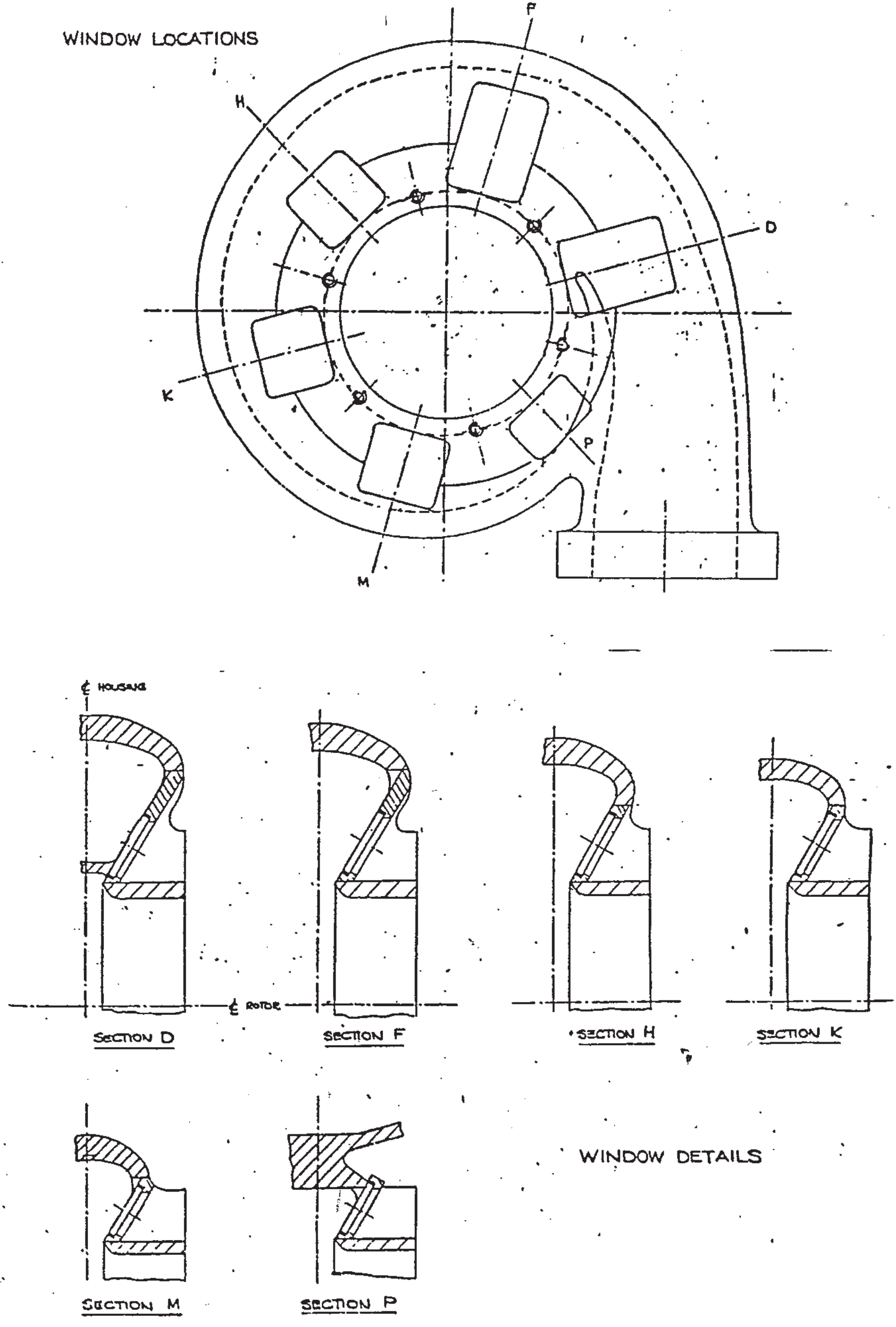

Fig. 2 Optical windows in turbine volute

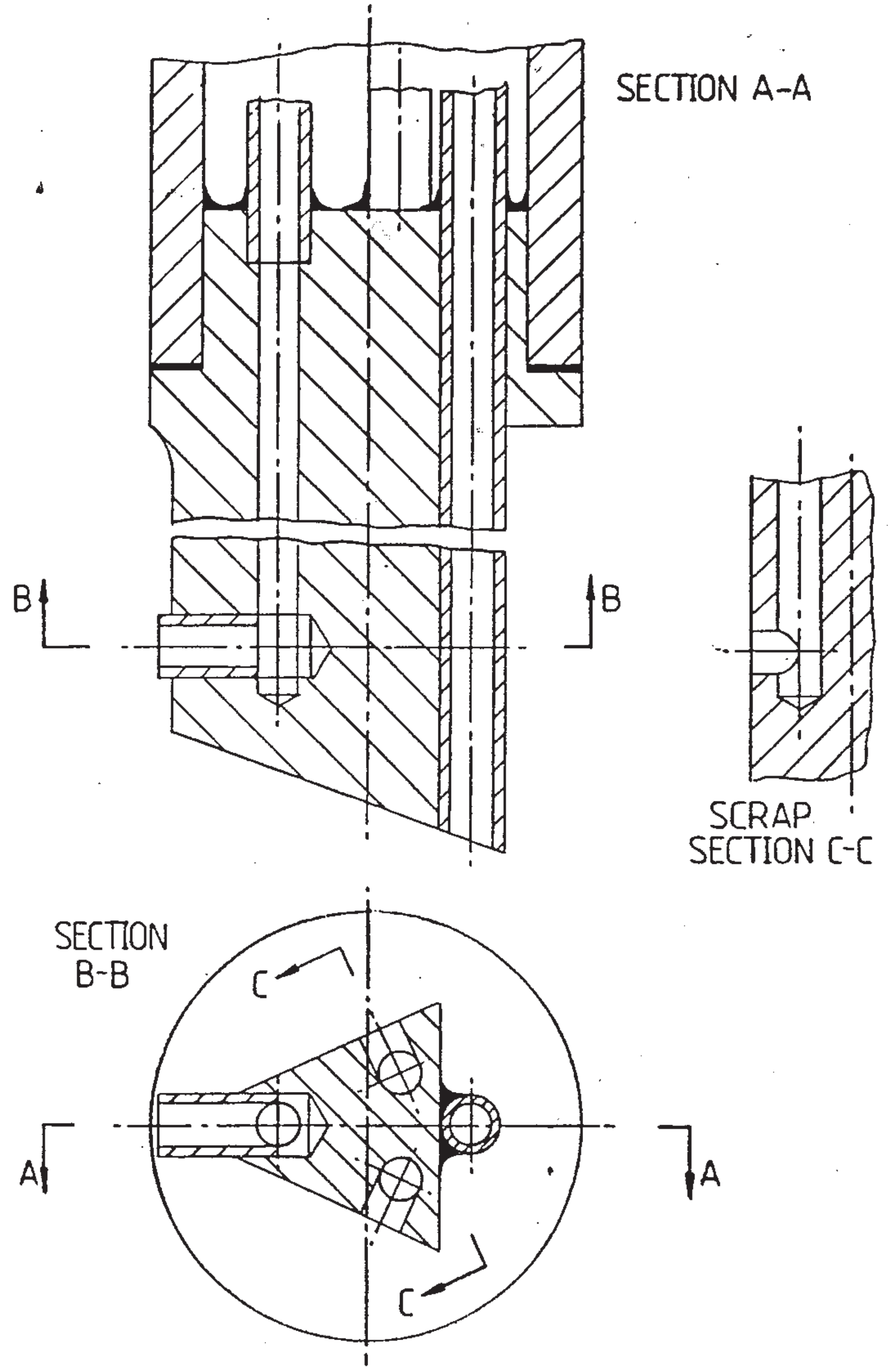

Fig. 3 4-hole wedge probe

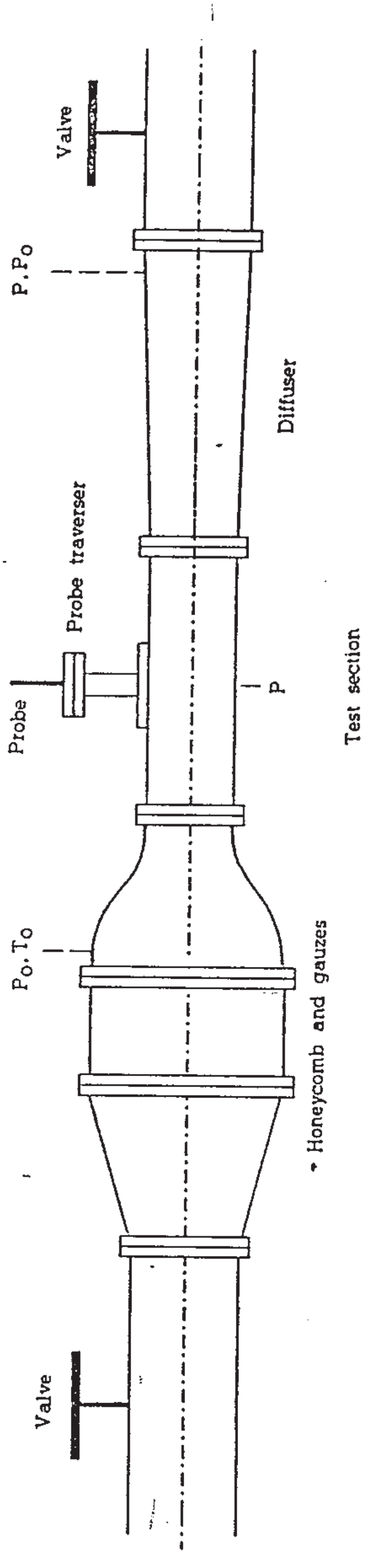

Fig. 4 Calibration rig

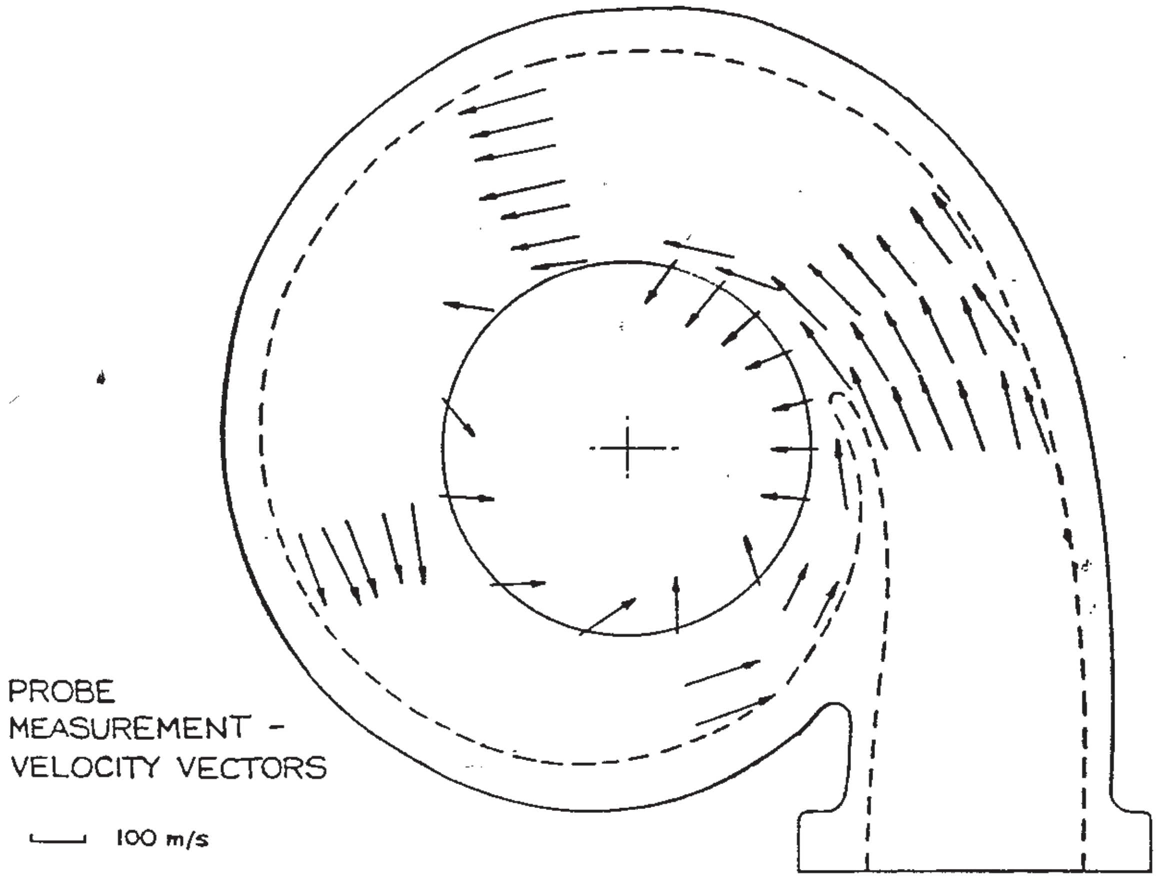

Fig. 5 Probe measurement - velocity vectors at a mid-passage axial plane in the volute

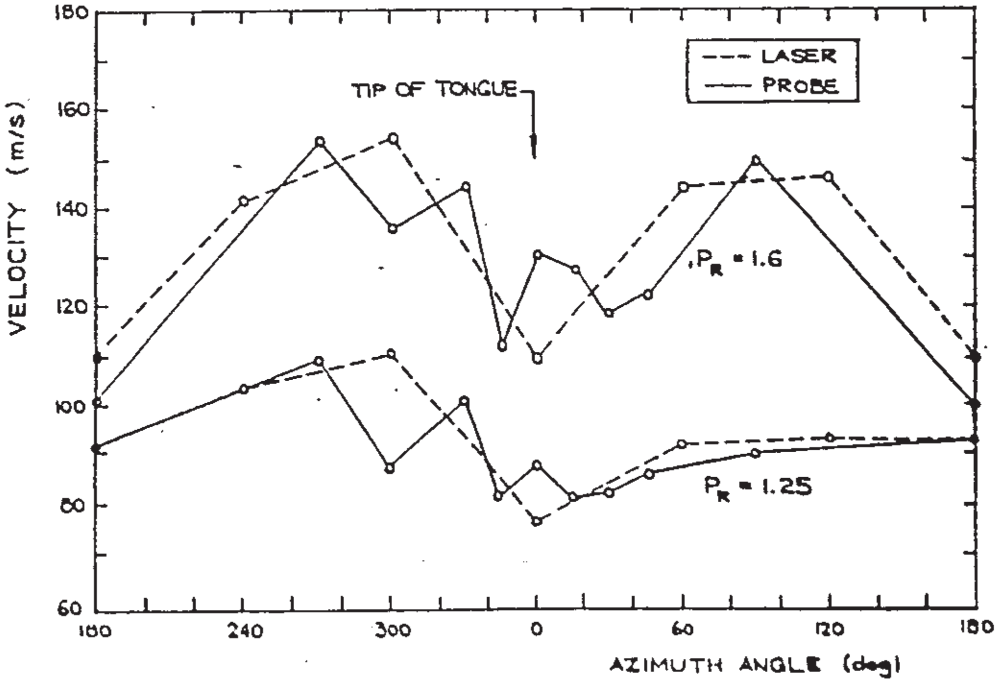

Fig. 6 Comparison of laser-2-focus and probe measurements of the circumferential variation of velocity