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IN
TURBOMACHINE STATORS

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GTL Report No. 103 February 1971

GAS TURBINE LABORATORY

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ABSTRACT

The mechanism of rotor wake interaction with stators has been examined experimentally by using helium, injected into the rotor wakes, as a tracer for the wake fluid. Time averaged helium profiles downstream of the stator, measured with a thermal conductivity cell, indicate the time averaged distribution of rotor wake fluid at the stator exit. The results are in qualitative agreement with the wake transport theory of Kerrebrock and Mikolajczak, but indicate the need for accounting for differential radial drifts of the wake fluid which encounters the motion and pressure sides of the stator blades. They also indicate that the wake transport theory is valid only when the stators flow is not separated.

INTRODUCTION

As the blades of an axial-flow compressor or turbine pass through the convected wakes of an upstream blade row, they tend to collect the wake fluid against their pressure side. The collected fluid streams along the pressure side of the blade, and appears in or near the wake of the blade. It was demonstrated in Ref. (1) that, as results of this process, tangential variations of stagnation pressure and temperature may be found downstream of a blade row, which are directly ascribable to processes occurring, not on that blade row, but on the one upstream of it. Thus, for example, the profile of stagnation temperature downstream of a stator is directly related to the losses on the rotor upstream of that stator.

A model was suggested in Ref. (1), for the transport process by which the wake fluid of one blade row is collected by another, and a preliminary comparison of the theory to experiment suggested that with further development, the method might be used to infer rotor losses, under actual operating conditions, from stator-exit profiles. Such a quantitative application is, however, difficult because of the real complexities of the intra-stator-wake transport process, which were greatly idealized in the model of Ref. (1).

The present work was motivated by the idea of calibrating the wake transport process by addition of a small amount of a traceable fluid to the rotor wake, and determining by experiment how it is transported during passage through the downstream blade row. Since all convected properties of the fluid should be transported in the same way, the resultant calibration can be used to infer, for example, the stagnation temperature of rotor wake fluid from a stagnation temperature traverse at the stator exit.

Some preliminary results of this work were given in Ref. (1). A more extensive series of experiments will be described here, which show the effect of flow coefficient on the transport process, and the importance of radial drift of the wakes. While the results are still far from definitive, they will serve to indicate what steps must be taken to render the method useful for quantitative determination of rotor losses.

METHOD OF WAKE-TRACING

The basic idea of the wake tracing technique is to introduce a trace gas into the wake of the blade whose losses are to be determined, in such a way that the mole fraction of trace gas is proportional to the value of the convected property of the fluid which it is desired to trace. The stagnation temperature and stagnation pressure are two quantities of interest. The differences of both from inviscid values are proportional, in the small disturbance limit, to the momentum defect of the wake, thus it suffices to make the trace gas mole fraction proportional to the wake's momentum defect.

Of the many trace gases which might be used, helium was selected for these experiments because of its inertness, its ready availability, and the possibility of detecting it quantitatively in small mole fractions by means of a thermal conductivity cell. There may be much better choices of gas and detector.

1. Helium Detection System.

The helium mole fraction downstream of the stators was determined by drawing a flow of air and helium through one branch of a thermal conductivity cell, as indicated schematically in Fig. (1), by means of a vacuum pump. Air was drawn through the reference branch by the same pump so that the effect of flow would not unbalance the bridge in the absence of helium. Both the sampling and the reference orifice were choked, and the volume of the sampling system was kept as small as possible to minimize the response time of the system.

The thermal conductivity cell, a Gow Mac No. 9454, had four gold plated tungsten filaments, and was excited by a 5 volt D.C. power supply. Typically, the output from the cell unbalance caused by the helium was of the order of 0.1 mv. This signal was amplified by a D.C. vacuum tube voltmeter (Hewlett Packard 412), and fed to a Moseley X-Y recorder along with a potentiometer signal indicating the location on either a radial or a circumferential traverse.

Due to the low signal level, considerable difficulty with noise was experienced, as will be noted later, however with some refinement this sytem would be capable of quantitative measurement of very low helium mole fractions.

2. Wake Calibration.

To determine the distribution of helium in the blade wake, a single blade was mounted in a low speed wind tunnel, (100 fps compared to the compressor blade speed of 80 fps), and both stagnation pressure and helium concentration surveys were made. The helium was introduced through .0016 in holes drilled into either the leading edge, or into the pressure side of the blade near the trailing edge, as shown in Fig. (2). Helium distributions for both cases are compared to the velocity distribution of the wake in Fig. (2). As the pressure-side injection gave a profile very close to that of the velocity, this method was adopted for the compressor test.

3. Compressor Instrumentation.

Eleven of the 44 rotor blades were drilled for pressure-side injection at mid-span. The helium was conducted to the rotor through a teflon-sealed gland at a pressure of the order of 20 psig. This corresponded to a total flow rate, for all blades, of 0.08 gs^{-1}, compared to a compressor airflow of the order of 7 lbs^{-1} or 3200 gs^{-1}.

The sample was drawn through a Pitot tube (.040 in dia) aligned to the mean flow direction and located approximately 1/4 in (about 0.16 chord) downstream of the stators' trailing edge.

Additional instrumentation consisted of static pressure taps for determination of compressor pressure ratio and airflow, and a strobotac for speed measurement.

A more complete description of the compressor and instrumentation is given in Ref. (2).

EXPERIMENTAL RESULTS

Typical radial and circumferential surveys are shown in Fig. (3). Each measurement was conducted by first surveying with no helium flow, then (in the reverse direction) with helium flow. The first survey therefore provides a reference base, above which the helium concentration is measured.

From Fig. (3), the regions of maximum helium concentration are quite clear, in both survey directions. It will be noted, however, that there is considerable fluctuation even in the absence of helium flow. These fluctuations seem to be caused by the response of the sampling probe to velocity (stagnation pressure) fluctuations. They became larger compared to the helium signal as the compressor speed was increased, so that it was difficult to obtain useful results for speeds above 3000 rpm (the data of Fig. 3 is for 1600 rpm).

Variation with Flow Coefficient

As the flow coefficient was reduced at constant speed, the circumferential helium profiles changed as shown in Figs. (4a, b, c, d), while the radial profile broadened somewhat, as shown in Fig. (5). The peaks, which result from the rotor wake fluid streaming down the pressure side of the stators, were distinct until a flow coefficient of about 0.48 was reached, when they virtually disappeared. This suggests that the behavior of the stators changed markedly at this flow coefficient.

Radial Drift

Radial traverses were carried out at two circumferential locations, corresponding to the peak and the minimum of the circumferential traverse. A range of helium flows was used, to check for the effect of buoyancy on the radial drift. It is clear from Fig. (6) that such effects are negligible.

There is, however, some difference in the radial locations of the wake fluid at the two circumferential locations, the fluid intercepted by the pressure side of the stator being nearer the tip than that which is convected along the suction side of the stator. The radial shift is in each case about 5 percent of span, but in opposite directions from the mid-span injection radius. Because of the radial pressure gradient due to swirl, the boundary layers on the stator would be expected to move inward, while those on the rotor, and the rotor wakes, should move outward. Thus, a possible explanation for the observed shifts is that the wakes drift outward some 5 percent of span between rotor and stator, and the suction side boundary layer on the stator drifts some 10 percent of span in the opposite direction (inward).

Although these radial drifts seem rather small, they are sufficient to somewhat confuse the tracing of losses along streamlines, the loss associated with a given spanwise location on the rotor being distributed over a region encompassing 15 percent of the span at the stator exit. Furthermore, the data of Fig. (6) are for a flow coefficient ϕ = .529. It is probable that the drift on the stator would be larger for lower flow coefficients, although from Fig. (5) we see that the radial drift of the wakes, between rotor and stator, does not change appreciably with flow coefficient.

COMPARISON TO WAKE TRANSPORT MODEL

The wake transport model of Ref. (1) connects the time-averaged profile of convected fluid properties at the stator exit to the fluid properties at rotor exit. To make this connection the behavior of the wake as it is convected downstream from the rotor to the stator must be modeled, as well as the behavior of the wake in the stator passages.

For the former process, Ref. (1) used the wake correlation of Ref. (3), which was derived from data for an isolated airfoil. Thus, one question which must be raised is: just how realistic it is to use this correlation in a compressor? To get some information on this point we have supposed in what follows that the spreading of the helium in the radial direction is a measure of the spreading of the wake in the tangential direction, i.e., that the turbulence of the wake is nearly isotropic. The wake model gives the velocity defect at the center of the wake as

$$\alpha = 1 - \frac{w_m}{W} = \frac{2.42\ C_D^{1/2}}{2\xi^*/b_r + 0.3} \tag{1}$$

where w_m is the actual velocity at the center of the wake, W is the inviscid flow velocity at the blades trailing edge, $\xi^* = \xi - 0.35b_r$, where ξ is a coordinate along the wake with origin at mid chord, and b_r is the blade chord. The wake width is given by

$$z = \frac{b_r}{2}\left(\frac{2\ C_D\ \xi^*}{b_r}\right)^{1/2} \tag{2}$$

Finally we assume a wake profile,

$$1 - \frac{w}{W} = \left(1 - \frac{w_m}{W}\right)\ e^{-\pi(\zeta/z)^2} \tag{3}$$

where ζ is a coordinate perpendicular to the wake.

Fitting of this gaussian profile to the wake profiles of Fig. (5) leads to the wake widths (divided by the cross-wake blade spacing) shown in Fig. (7). We see that for the higher flow coefficient z/l is about 0.7 of the value given by the isolated airfoil wake model. In making this estimate, blade drag coefficients were taken from Ref. (4), which describes experiments on the same compressor. As the flow coefficient decreases, the wake thickens, relative to the isolated airfoil model, as might be expected.

As explained above, we assume that the helium in the rotor wake has concentration proportional to $1 - w/W$, i.e.,

$$n_{He} = n_{He,m}\, e^{-\pi(\zeta/z)^2} \tag{4}$$

and the theory of Ref. (1) then relates the stator-exit helium profile to α and the stage geometry. In particular, it indicates that the product of helium concentration and width for the region of high helium concentration near the pressure side, divided by the product of average helium concentration and blade spacing, should be given by,

$$\frac{\delta_s N_{He}(0)}{S_s \bar{N}_{He}} = \left(\frac{\sin(\beta_2 + \theta_3)}{\sqrt{2}} \frac{b_s}{S_s} \frac{W_2}{V_3}\right) \alpha \tag{5}$$

where W_2 denotes rotor exit relative velocity and V_3 stator entrance, velocity, β_2 and θ_3 are their respective angles from the axis, and b_s/S_s is the stator solidity. By comparing this formula to the data of Fig. (4), α can be estimated as a function of flow coefficient. The results are compared to the isolated airfoil correlation in Fig. (8).

Two points must be noted. First the values of α are about three times too large in comparison to the isolated airfoil correlation. An explanation for this discrepancy can be found in the different radial drifts of the fluid contributing to various portions of the circumferential profile. The circumferential survey was taken at the radius corresponding to peakof the radial profile of Fig. (6b), i.e., for the fluid which streamed along the pressure side. Referring to Fig. (6a), we see that the helium concentration near the suction side is considerably smaller at that radius than at its radial peak. Thus, the different radial drifts lead to an underestimate of the average helium concentration [denominator of Eq.(5)], hence to an overestimate of α. It is clear that to obtain quantitatively correct values of α one would have to either a) distribute the helium injection along the span, thus sacrificing radial resolution of the profiles, or b) survey both radially and circumferentially, and modify the analysis to account for the radial distribution.

The second point to be noted is that α decreases rapidly with decreasing ϕ, contrary to the prediction, which simply reflects a slightly increased drag coefficient with decreasing ϕ. It appears that this discrepancy results from a deviation of the intra-stator wake transport mechanism from that postulated in Ref. (1), as ϕ decreases. From flow visualization studies carried out by the hydrogen-bubble technique it has been found (5) that for large incidence, when the wake impinges on the leading edge of the stator, separation may occur on the suction side near the leading edge. A passage vortex forms which might contain much of the rotor wake fluid, so that it would not be transported to the pressure side of the passage, as modeled in Ref. (1).

Thus, it appears that the wake transport theory, as proposed, can give a quantitative relation between rotor losses and stator exit profiles only when the stators operate without severe separation.

CONCLUSIONS

1) The helium wake tracing technique does yield information about the transport of wakes, both between rotor and stator and within the stator passages.

2) In the GTL low speed compressor, the radial drifts of rotor wakes are of the order of $\pm$ 5 percent of span at the exit of the stators.

3) For high incidence, when the stators are periodically separated, the intra-stator wake transport mechanism is qualitatively different from that proposed by Kerrebrock and Mikolajczak, the transport of the rotor wakes to the stators' pressure side being markedly reduced.

4) In order to obtain radial variations of rotor losses from stator exit traverses, it will be necessary to account for differential radial drifts of the wake fluid which encounters pressure and suction side of the stators.

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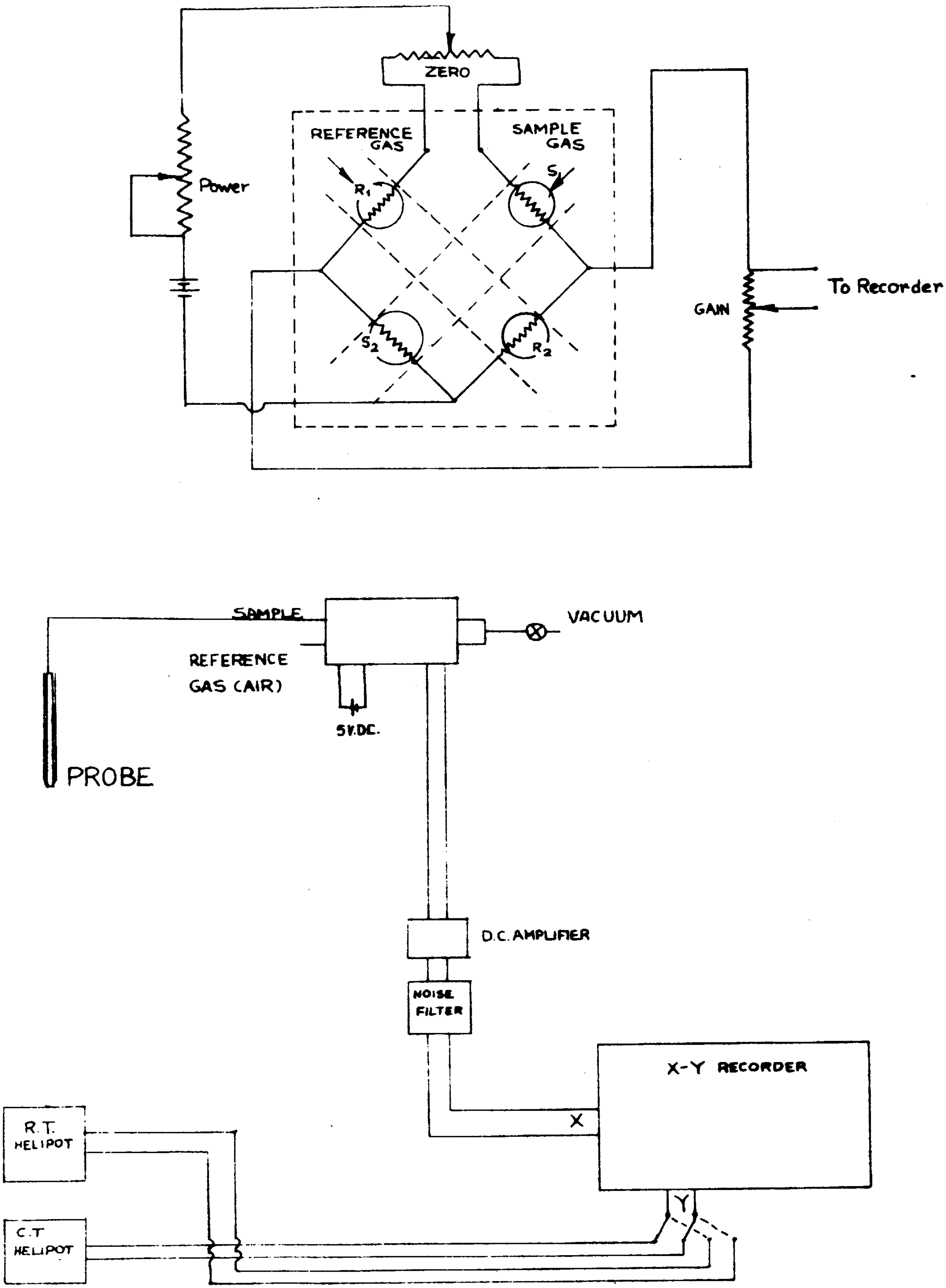


Figure 1: Schematic of the helium detection system.

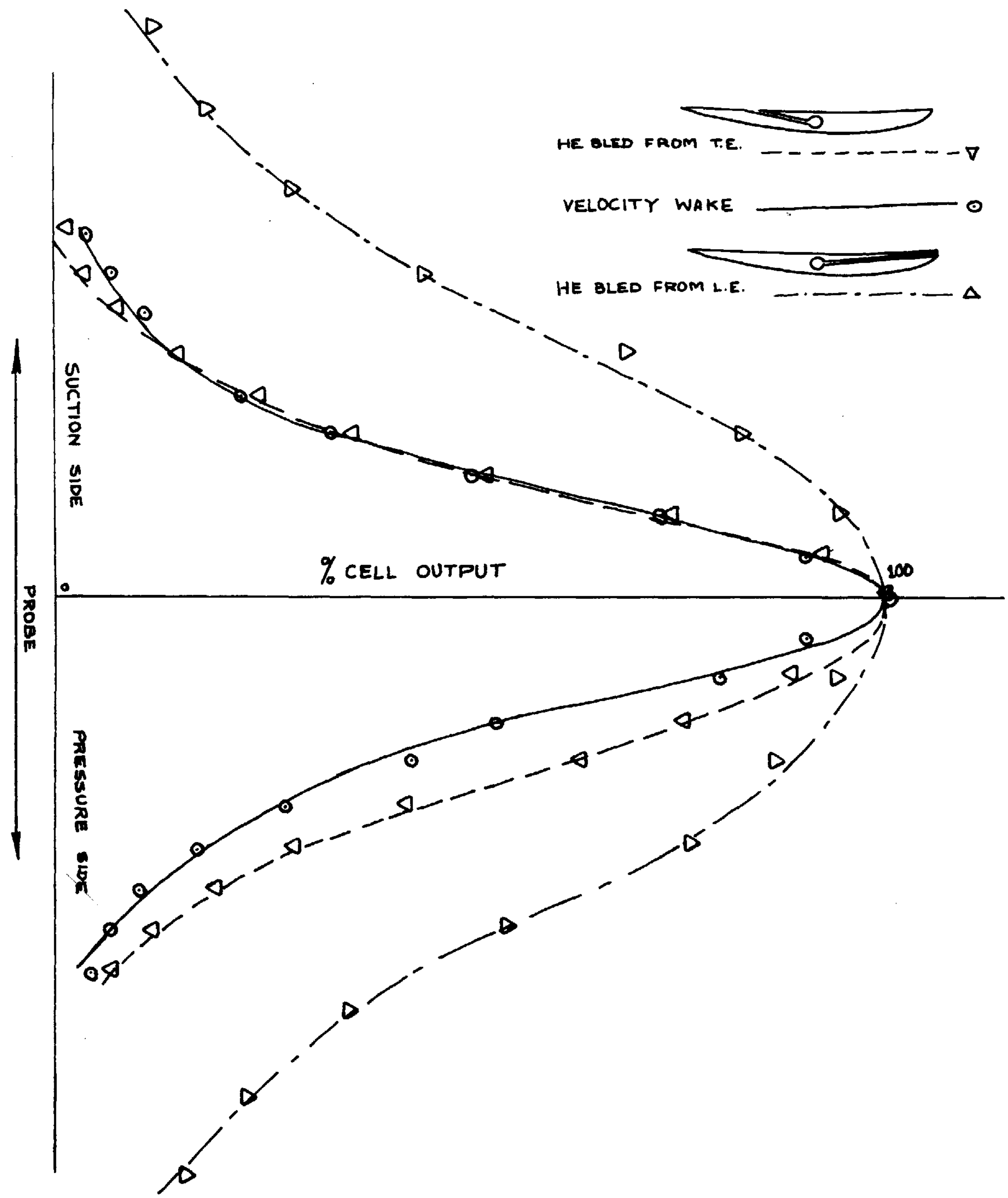
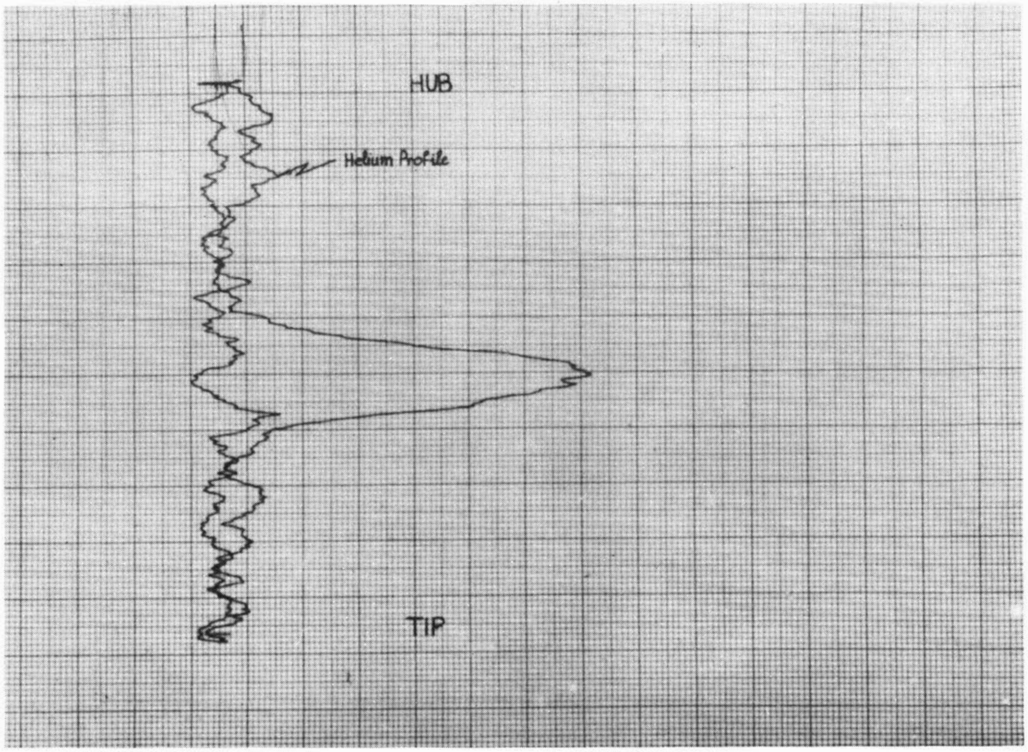
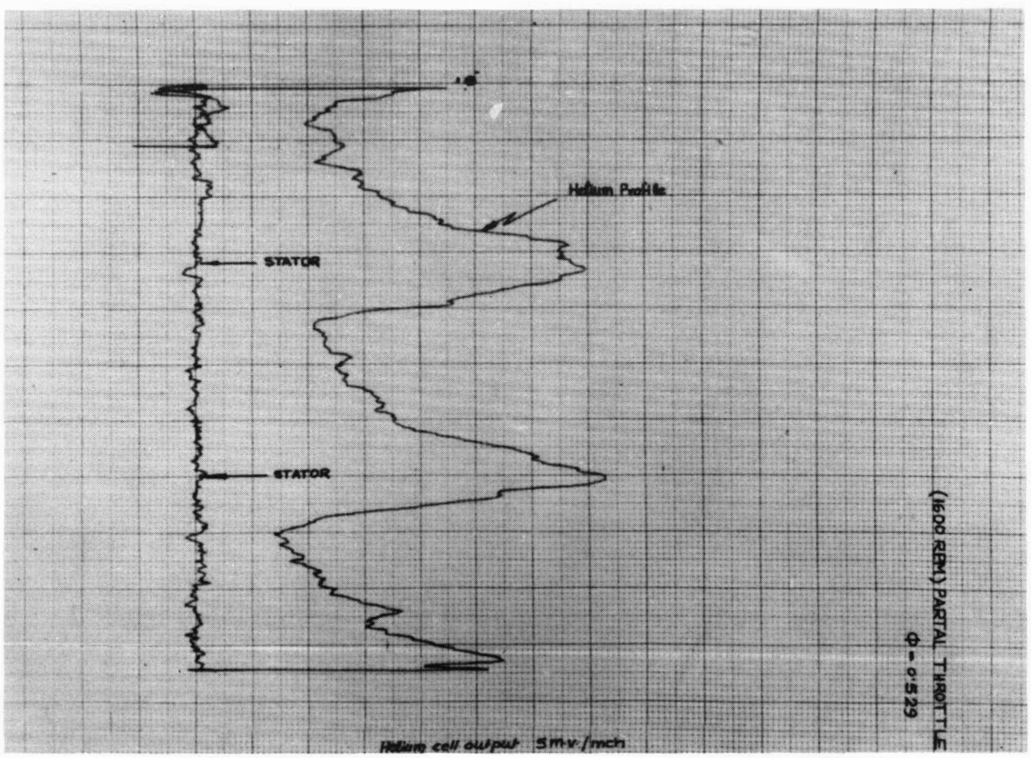


Figure 2: Cross-wake traverses of stagnation pressure, (circles), and helium concentration, found for a single blade in a low speed wind tunnel, showing similarity of velocity and helium wakes for pressure-side injection of helium.





<u>Figure 3</u>: Typical radial (top) and circumferential traverses of helium concentration behind the stators.

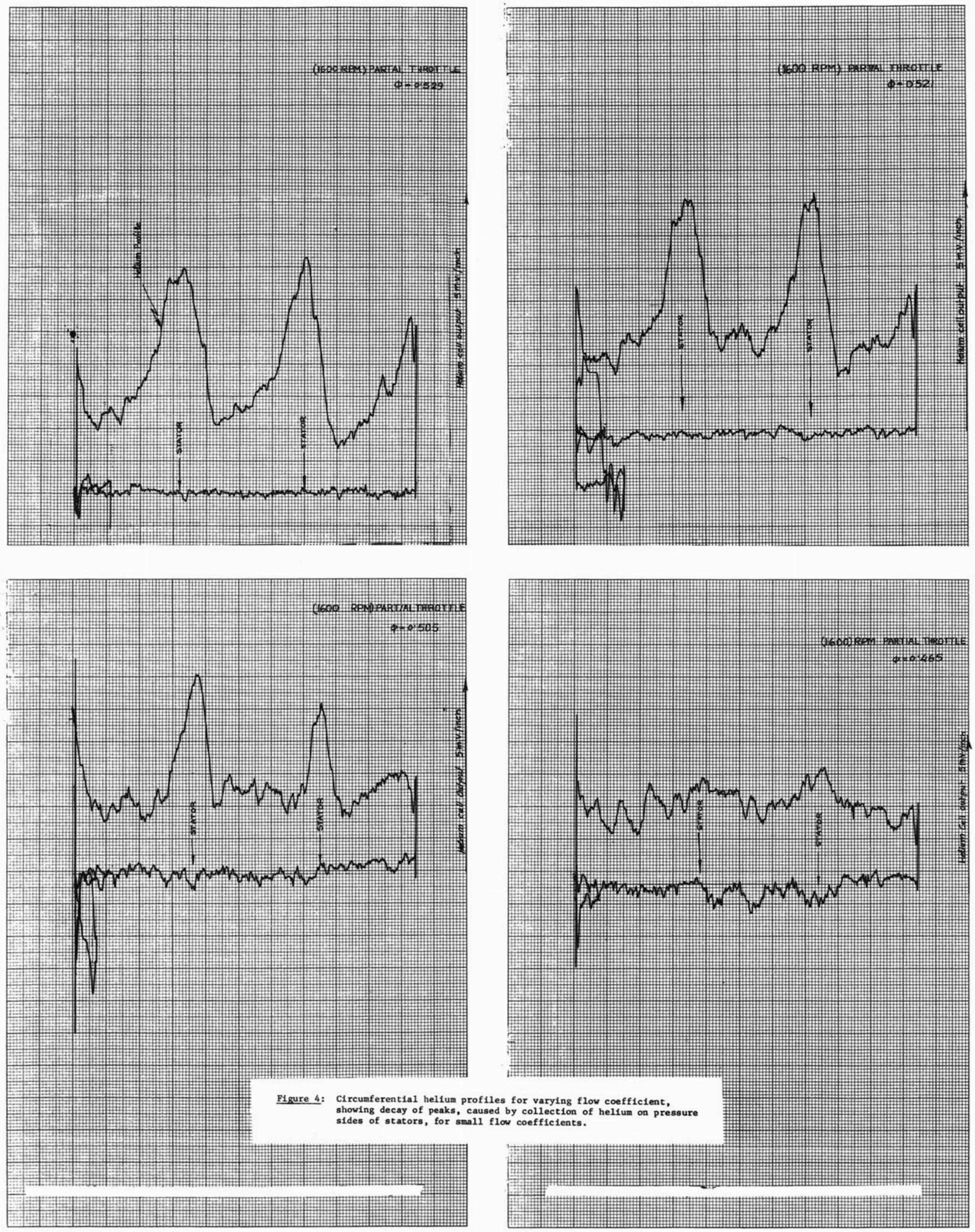
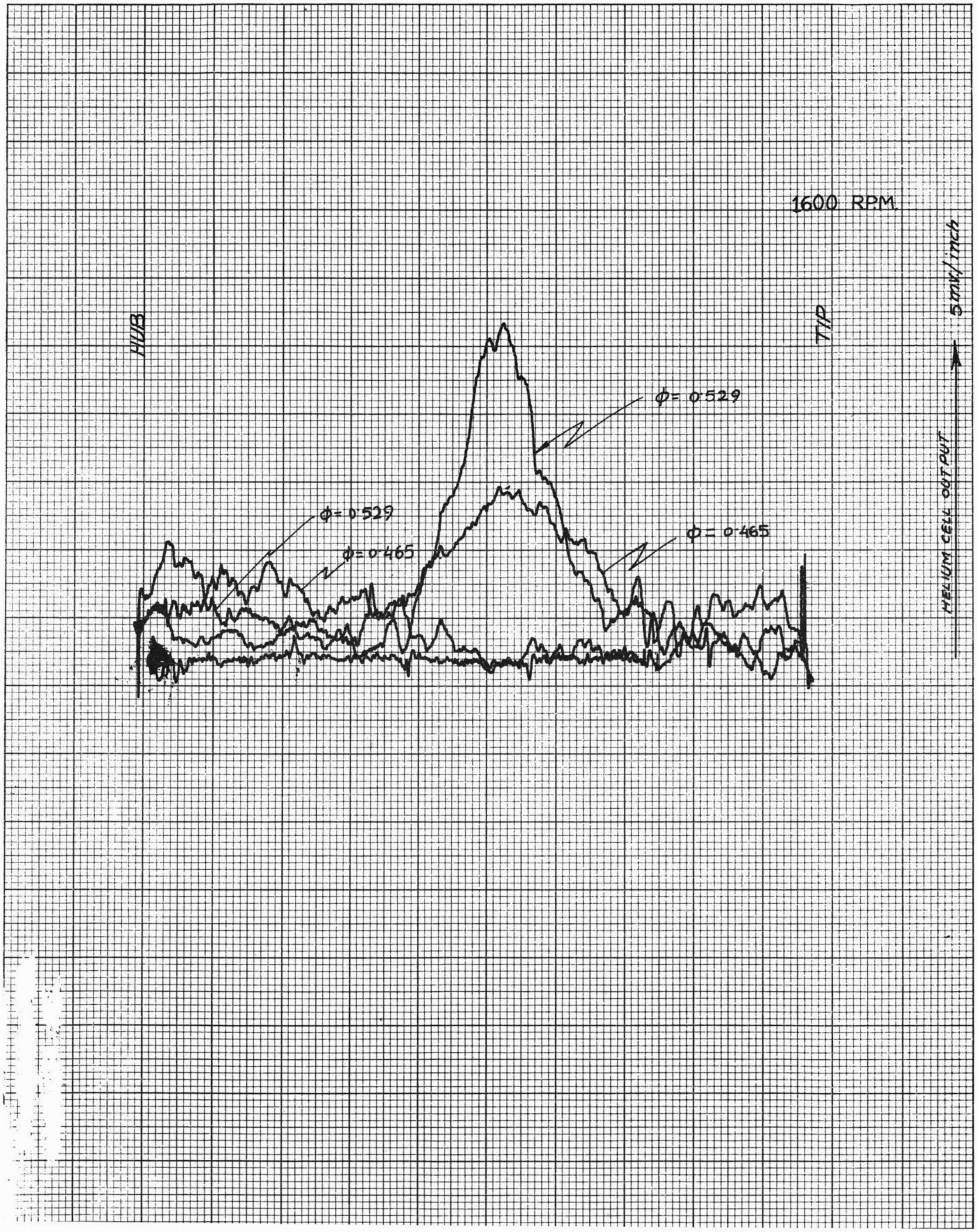


Figure 4: Circumferential helium profiles for varying flow coefficient, showing decay of peaks, caused by collection of helium on pressure sides of stators, for small flow coefficients.



<u>Figure 5</u>: Radial surveys of helium concentration for flow coefficients near design (.529) and near stall (.465), showing slight broadening at the latter condition.

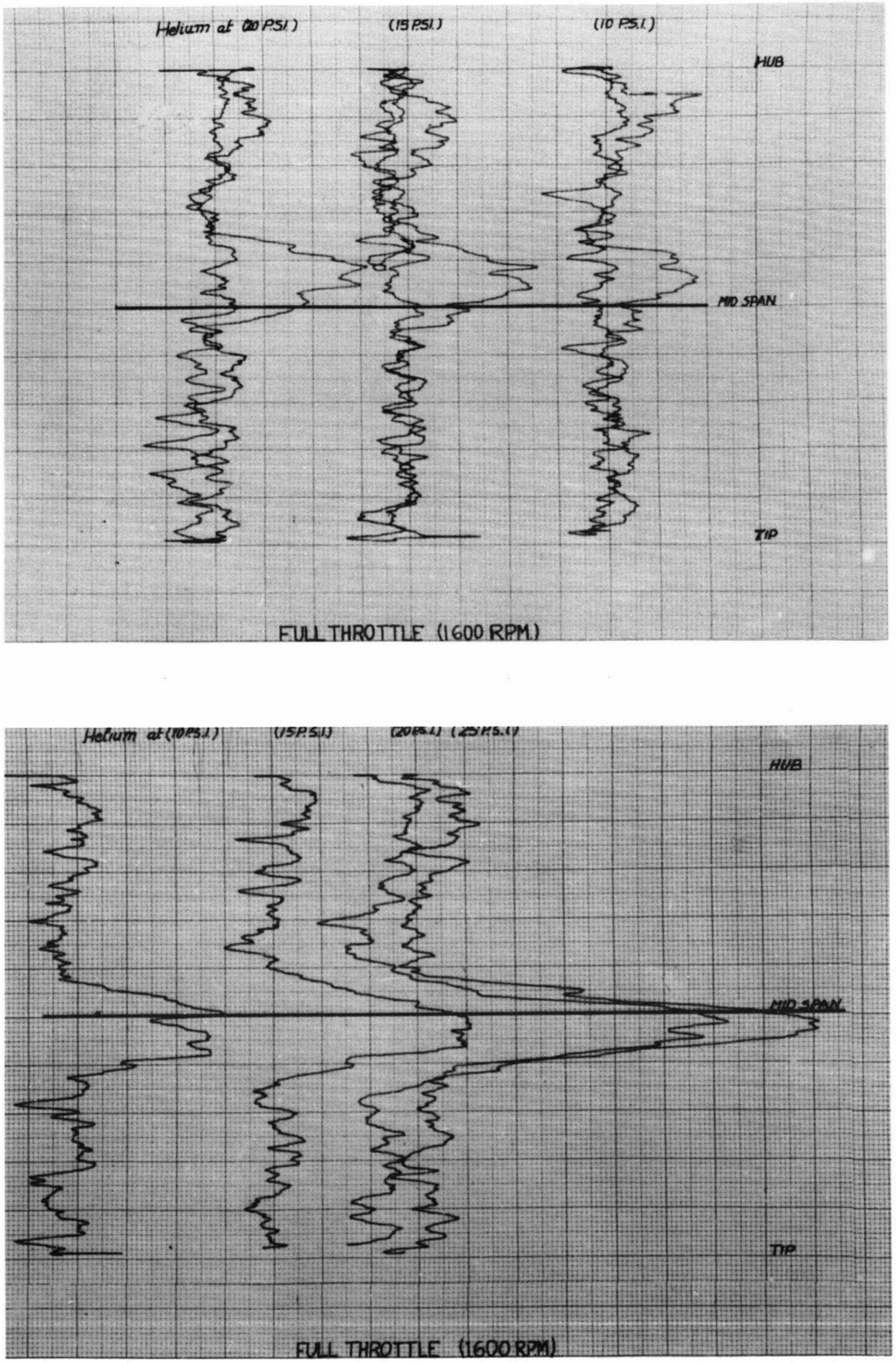


Figure 6: Radial profiles for different helium concentrations, and at two circumferential locations, near the pressure side of the stators (bottom) and near the suction side (top).

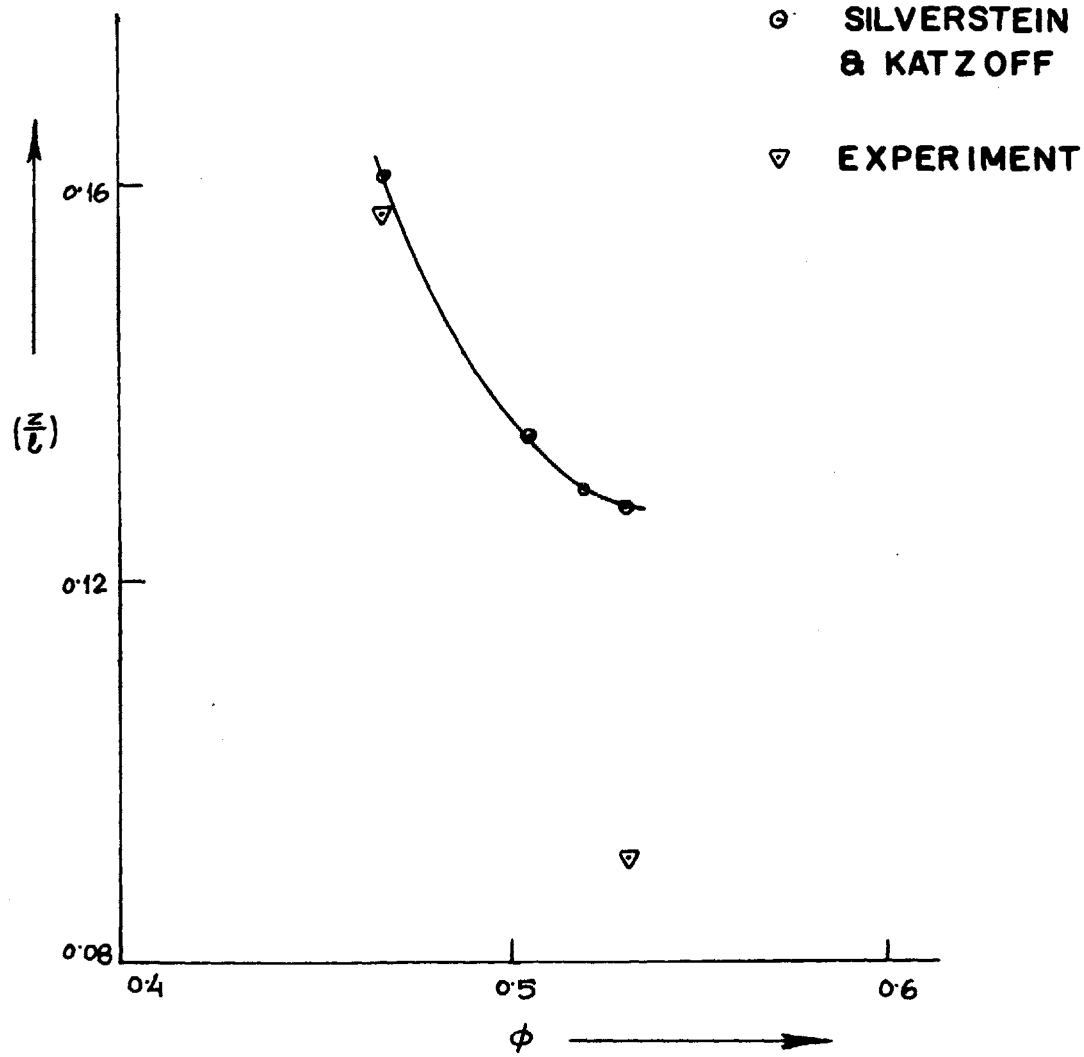


Figure 7: Comparison of wake widths, determined from Fig. (5), to predictions of wake model of Ref. (3).

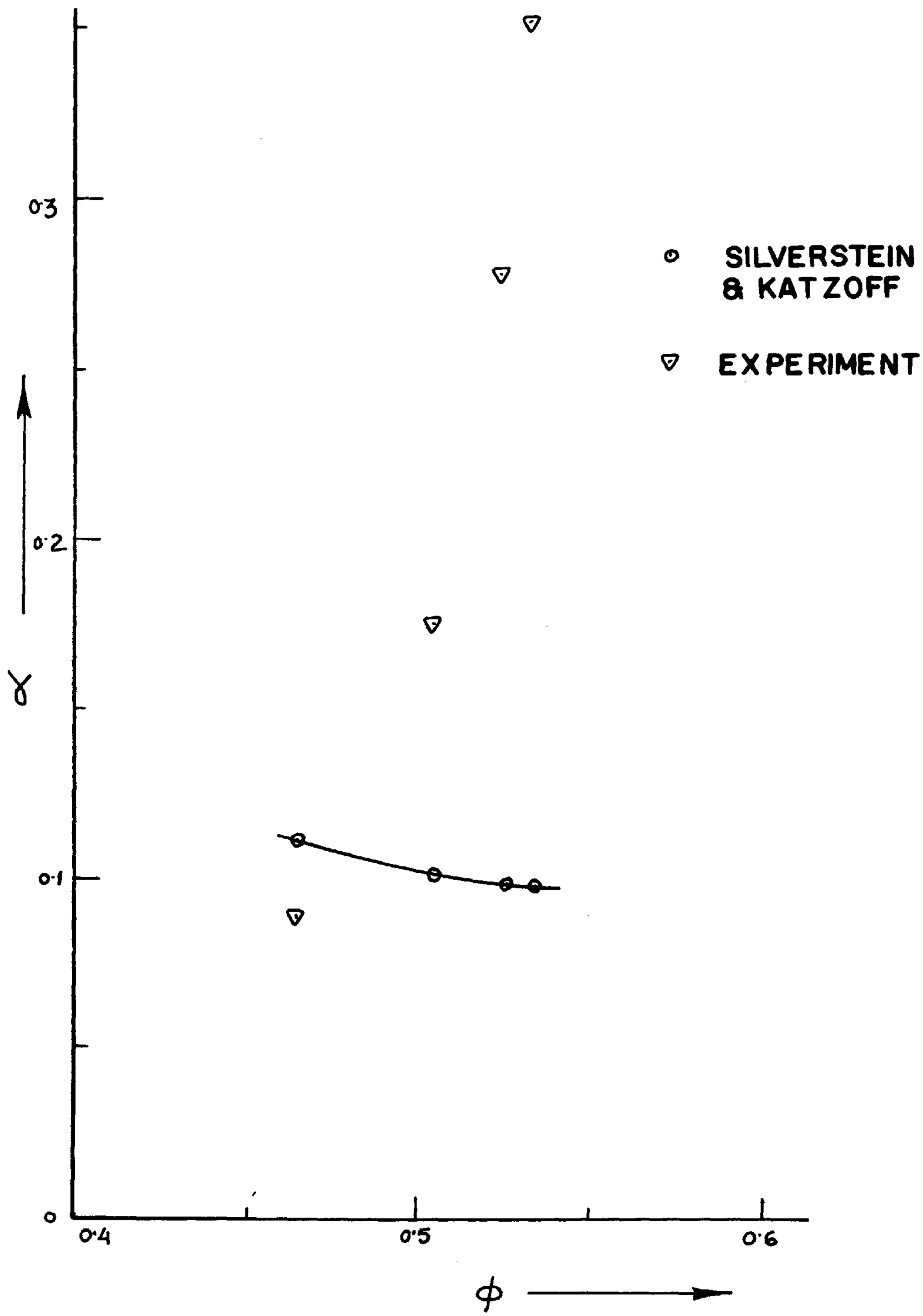


Figure 8: Comparison of magnitude of pressure side peaks of circumferential helium profile to prediction of Ref. (1). The rapid decrease at low flow flow coefficients, is attributed to differential radial drifts at different circumferential points.