Comparison of the performance of slotted and solid aerofoil blades in a centrifugal impeller

Rueter, F.; Giroux, G. J.; Fowler, H. S.

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E.H. Dudgeon

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SECURITY CLASSIFICATION OPEN

SUBJECT COMPARISON OF THE PERFORMANCE OF SLOTTED AND SOLID AEROFOIL BLADES IN A CENTRIFUGAL IMPELLER

PREPARED BY F. RUETER
G.J. GIROUX
H.S. FOWLER

ISSUED TO

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ILLUSTRATIONS

1.0 INTRODUCTION

An extensive experimental study of the flow in centrifugal impellers, using a low speed centrifugal compressor rig, has been carried out in the Engine Laboratory, and is reported in References 1 to 4. The major conclusions drawn from this test programme were that flow detachment from the blade surfaces constitutes one of the major causes of poor distribution and flow instability, and that slotted blades offered the most promising means of delaying flow detachment. The optimum slot configuration was determined experimentally, and the behaviour of slotted and unslotted blades was compared on the low speed rig.

The present memorandum describes an experiment conducted on a high speed centrifugal compressor rig to compare the performance of uncambered aerofoil blades with and without slots.

2.0 HIGH SPEED CENTRIFUGAL COMPRESSOR RIG

The high speed test rig shown in Fig. 1 was assembled for the tests. The impeller was driven by an air turbine via a positive belt drive with a reduction ratio of 1,8:1 and a quill shaft for measuring the torque required to drive the rotor. The test impeller inhaled atmospheric air through a wooden bellmouth and a straight, cylindrical duct 221 mm in diameter and some 1,5 m long, and discharged through a volute equipped with a motor-driven sliding plate valve at its exit.

Rotor speed was controlled by throttling the compressed air supply to the drive turbine, and the fan pressure ratio was varied by adjusting the plate valve at the volute exit.

2.1 INSTRUMENTATION

Instrumentation throughout was simple and direct. Pressures were measured with a bank of manometers, inlet air temperature with a resistance thermometer, and fan speed with an electronic counter triggered by a proximity pickup and a notched wheel on the fan drive shaft. Atmospheric pressure was measured for each test with a mercury barometer.

Flush wall tappings provided the static pressures at the fan inlet and outlet. The total pressure at the outlet was sensed by a traversing total head probe mounted at the same radial position as the outlet static tapping, and was measured at five axial positions so chosen that each was at the centre of an element of equal circumferential area. The probe was yawed to find the maximum value for each of these positions.

The torsional deflection of the quill shaft was measured to find the impeller drive torque, using the system of mirrors shown in Fig. 1. A laser beam trained on a plane mirror mounted at the driven end of the quill shaft was reflected to a fixed section of cylindrical mirror, thence to a plane mirror at the other end of the quill shaft, and finally to a fixed scale visible from the observer's position. A static calibration gave the conversion from scale reading to torque.

3.0 DESCRIPTION OF BLADING

The blades used were identical, in all but size, with those designated VB2 A and VB2 B in Reference 4, and are sketched in Fig. 2. Each impeller carried eleven uncambered blades of C-4 aerofoil section (see Reference 4) riveted and cemented between two aluminium discs of 458 mm diameter comprising the impeller. The span of each blade, and hence the spacing between the discs, was 25 mm. The two sets of blades were identical except for the slots in the VB2 B blades. The design of these slots is described in Reference 2.

4.0 DESCRIPTION OF EXPERIMENT

4.1 TEST PROCEDURE

The parameter for each test run, comprising five or six points, was the "non-dimensional" speed, $N/\sqrt{T}$, which was maintained constant by continual adjustment of the throttling valve in the air supply to the driving turbine. Mechanical considerations dictated an upper rotational speed limit of 5000 revolutions per minute, thus restricting the pressure ratio to quite low values.

For each speed, the fan outlet throttle was used to vary the delivery pressure from a minimum at full open throttle to the maximum that could be reached without surging. Surge could usually be detected by ear, the airborne vibration being clearly audible even though ear defenders were worn. An additional, though less definite, indication was provided by the increased vibration of the laser beam spot on the torque meter scale. Surge was not readily detectable at the lowest speeds, where it was often possible to close the throttle completely without noticeable distress.

4.2 ANALYSIS

The volumetric flow rate through the fan was calculated from the inlet duct static depression, using a discharge coefficient of 0,991 obtained from Reference 6 for a typical inlet pipe Reynolds number of $2 \cdot 10^5$. For incompressible flow, the velocity,

$$v = c_d \cdot \sqrt{\frac{2}{\rho} \cdot (P_{1t} - P_{1s})} \text{ m/s} \qquad (1)$$

for any coherent system of units.

Substituting $v = Q/A$ and $\rho = \frac{P_s}{R \cdot T}$

where R is the gas constant for air = 287,011 N·m/kg·K,

$$Q = 0{,}9108 \sqrt{\frac{T}{P_{1s}} \cdot (P_{1t} - P_{1s})} \text{ m}^3\text{/s} \qquad (2)$$

where all pressures are in the same units and T is in kelvin.

The equivalent total pressure at the fan exit was calculated from the five measured fan outlet total pressures by an adaptation of the mass-weighted method described in Reference 5.

Equating the product of pressure head and mass flow for the equivalent pressure and the five measured pressures gives

$$\frac{P_{2t\ eq}}{\rho \cdot g} \cdot M = \sum_{i=1}^{i=5} \frac{P_{2ti}}{\rho \cdot g} \cdot M_i \qquad (3)$$

Since all five elemental areas are equal,

$$\begin{aligned} M_i &= \rho \cdot \frac{A_2}{5} \cdot v_{2i} \\ &= \rho \cdot \frac{A_2}{5} \sqrt{\frac{2\ (P_{2ti} - P_{2s})}{\rho}} \\ &= \sqrt{2\rho} \cdot \frac{A_2}{5} \cdot \sqrt{P_{2ti} - P_{2s}} \end{aligned}$$

Substituting in (3) and simplifying gives

$$P_{2t\ eq} = \frac{\sqrt{\frac{2}{\rho}}}{5 \cdot v_{2eq}} \cdot \sum_{i=1}^{i=5} P_{2ti} \cdot \sqrt{P_{2ti} - P_{2s}} \qquad (4)$$

Substituting $v_{2eq} = \sqrt{\frac{2}{\rho} \cdot (P_{2t\ eq} - P_{2s})}$ yields

$$P_{2t\ eq} = \frac{\sum_{i=1}^{i=5} P_{2ti} \cdot \sqrt{P_{2ti} - P_{2s}}}{5 \cdot \sqrt{P_{2t\ eq} - P_{2s}}} \qquad (5)$$

Since the required $P_{2t\ eq}$ appears on both sides of this equation, an iterative solution was employed, using the arithmetic average of the five measured pressures as the first trial value.

The aerodynamic power delivered by the fan in watts is simply the product of the flow rate in cubic metres per second and the pressure rise across the fan in pascals.

Similarly, the shaft power absorbed by the fan is the product of shaft torque in newton metres and the rotational speed expressed in radians per second.

The overall efficiency of the fan is then the quotient of delivered power by shaft power.

4.3 PRESENTATION AND DISUCSSION OF RESULTS

The test results for both the slotted and unslotted blades are superimposed for comparison in Fig. 3. The conventional presentation has been employed, in which fan pressure ratio is plotted against "non-dimensional" volumetric flow rate, with "non-dimensional" speed as parameter. Superimposed on this plot, for each impeller, are lines of constant efficiency.

Examination of Fig. 3 shows that both the pressure ratio and the surge characteristic are improved by the addition of slots. While the improvement is significant at the higher pressure ratios, the performance at low pressures is practically unaffected. More surprisingly, the slots improve the peak efficiency from about 75% to almost 85%. The lowest efficiency, with fully-opened throttle, is unaffected by the slots, and remains at about 40%.

5.0 CONCLUSIONS

The tests described suggest that a useful improvement in the surge limit and some increase in pressure ratio may be expected from the addition of slots to the blades, and that this improved performance is attended by a significant increase in efficiency.

6.0 REFERENCES

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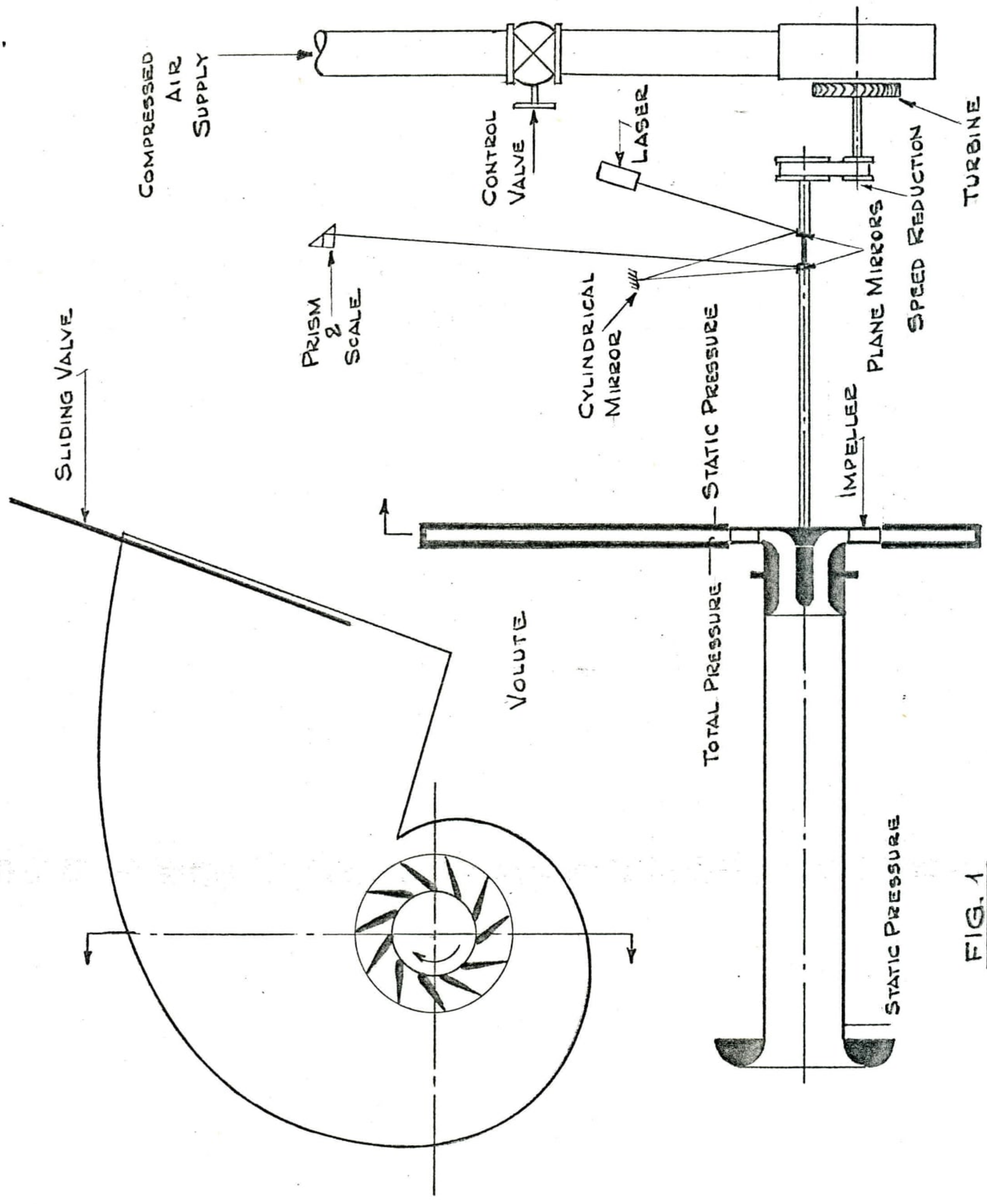


FIG. 1
DIAGRAM OF HIGH SPEED CENTRIFUGAL COMPRESSOR RIG

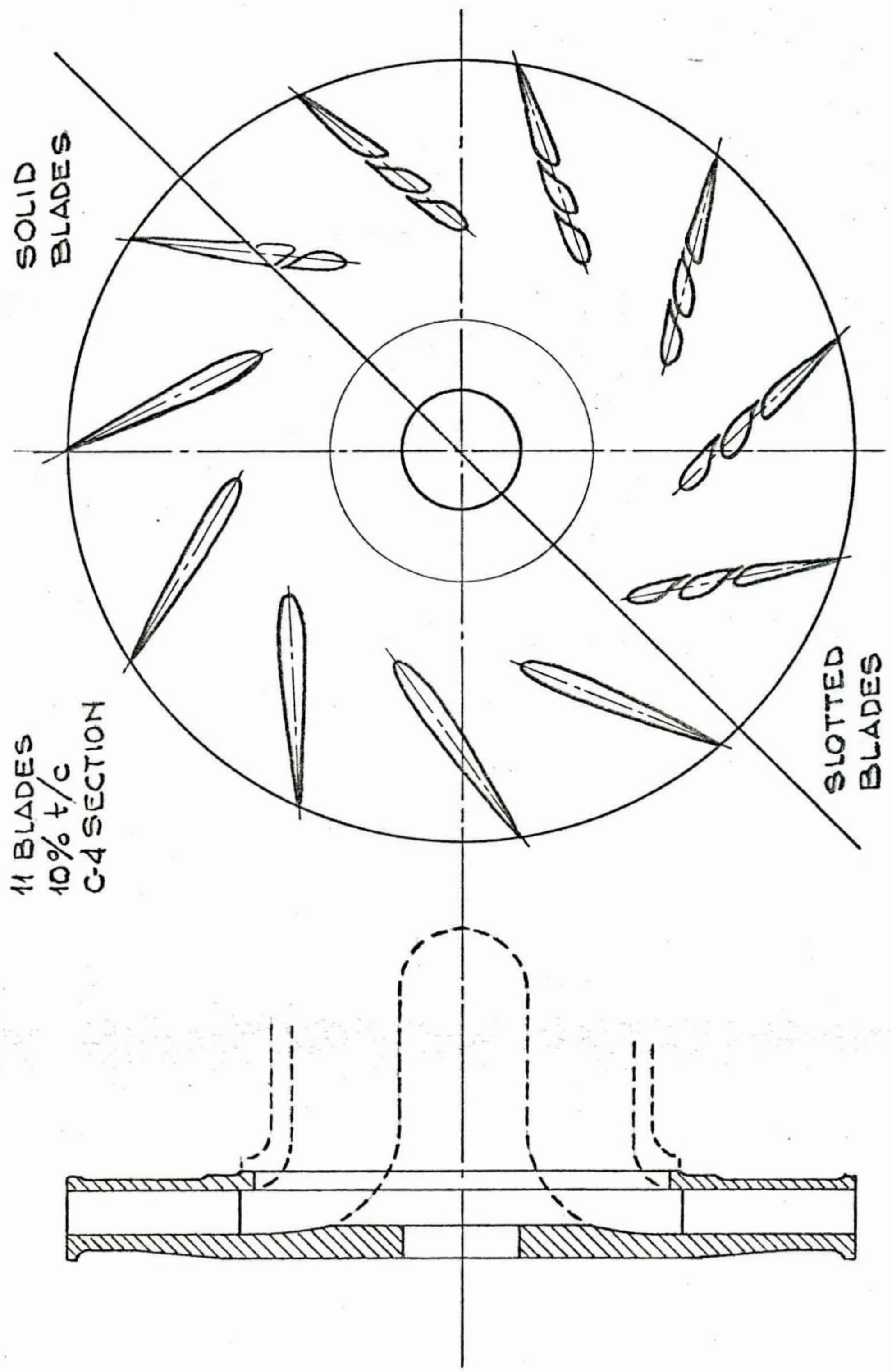
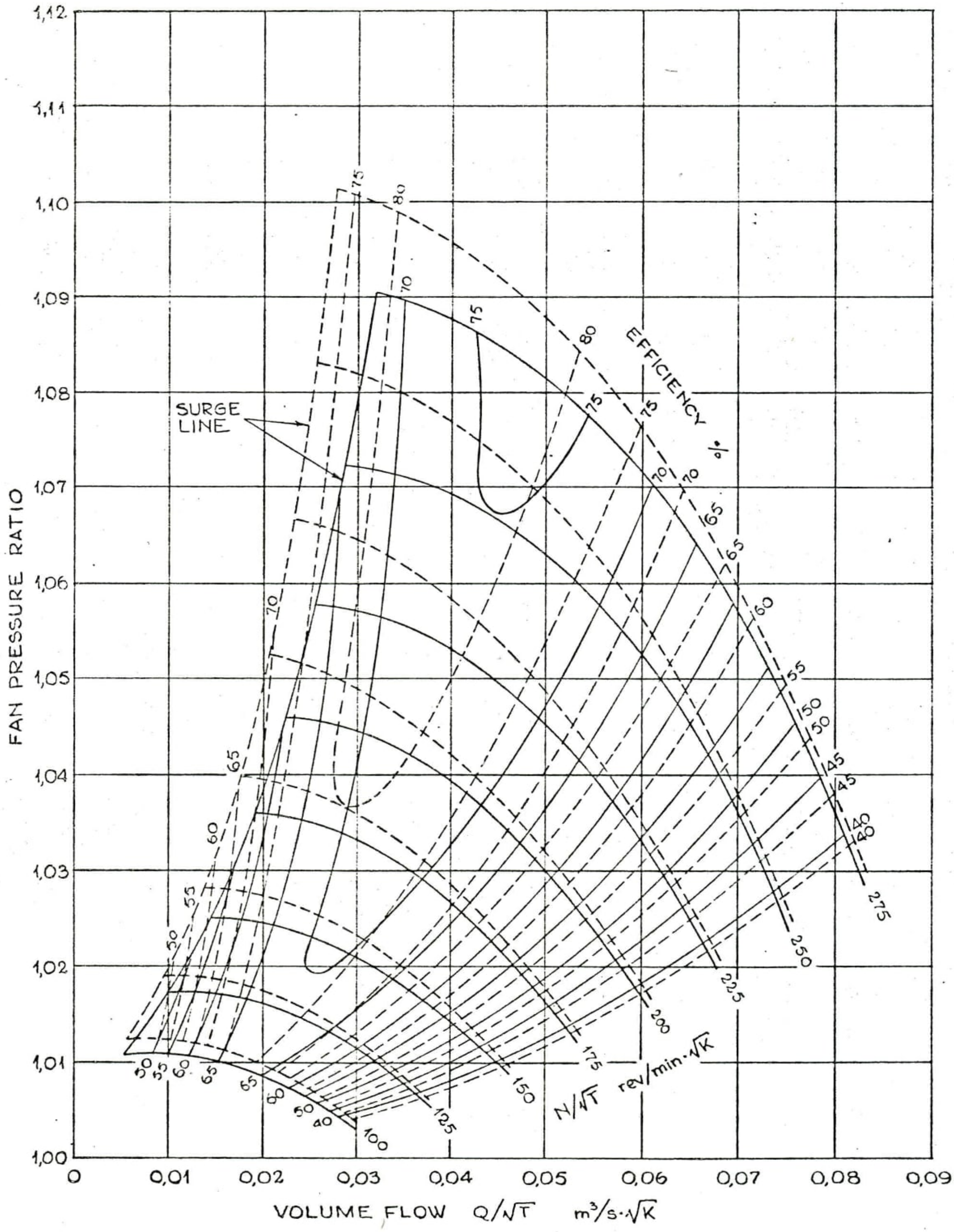


FIG. 2 SOLID AND SLOTTED BLADES

FIG. 3



FAN PERFORMANCE

——— SOLID BLADES - - - - - SLOTTED BLADES