A SIMPLE APPARATUS FOR THE EXPERIMENTAL STUDY OF NON-STEADY FLOW THRUST-AUGMENTER EJECTOR CONFIGURATIONS

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ABSTRACT

Some advantages of non-steady flow ejectors as thrust augmenters are reviewed briefly. It appears that the main benfits to be derived from non-steady flow ejectors stem from the relatively small primary-to-secondary (cross-sectional) area ratios, and short "mixing" lengths, required, for prescribed thrust augmentation ratios, compared with those of steady flow ejectors. The fundamental benefit of a non-steady as compared with a steady flow ejector results from the nature of the process by which energy is transferred from the primary to secondary streams. In a non-steady flow ejector a component of pressure-exchange is involved in addition to the conventional mixing processes of steady flow ejectors. It is shown that the combined pressure-exchange flow-mixing mechanism presents substantial analytical difficulties even for so called one-dimensional systems in which the primary stream intensity, but not direction, is modulated. This suggests the need for an adaptable test rig to investigate experimentally the performance of non-steady flow ejectors.

A flexible, and easily modified, test rig is described which allows a one-dimensional non-steady flow stream to be generated, economically from a steady flow source of compressed air. This non-steady flow is used as the primary stream in a non-steady flow ejector constituting part of the test equipment. Standard piezo-electric pressure transducers etc. allow local pressures to be studied, as functions of time, in both the primary and secondary ("mixed") flow portions of the apparatus. Provision is also made for measuring the primary and secondary mass flows and the thrust generated. Sample results obtained with the equipment are presented.

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NOMENCLATURE

a	acoustic velocity
D	internal diameter of primary flow channel
L	length of primary flow channel
$\dot{m}$	mass flow
m'	dimensionless Riemann variable [$\equiv \frac{a}{a_{ref}} - (\frac{\gamma-1}{2}) \frac{u}{a_{ref}}$]
n'	dimensionless Riemann variable [$\equiv \frac{a}{a_{ref}} + (\frac{\gamma-1}{2}) \frac{u}{a_{ref}}$]
p	static pressure
P	stagnation pressure
p'	normalised pressure [$\equiv \frac{p}{p_{ref}}$]
t	time
t'	normalised time [$\equiv \frac{t\ a_{ref}}{L}$]
u	fluid (particle) velocity
u'	normalised velocity [$\equiv \frac{u}{a_{ref}}$]
x	distance along primary channel from rotary valve
x'	normalised distance [$\equiv \frac{x}{L}$]
z	gap between primary and secondary channels
z'	normalised gap [$\equiv \frac{z}{D}$]
β	mass flow ratio [$\equiv \frac{\dot{m}_S}{\dot{m}_P}$]
θ	pressure parameter: $(p_D - P_S)/(P_P - P_S)$
Φ	augmentation ratio: (thrust with augmenter)/(thrust due to primary mass flow when expanded isentropically from receiver-to-surroundings pressure)
Φ_A	augmentation ratio: (thrust with augmenter)/(thrust due to primary stream with augmenter present)

Φ_B augmentation ratio: (thrust with augmenter)/(thrust due to primary stream with augmenter removed)

Subscripts

D exit of secondary flow channel

P primary stream

S secondary stream

ref reference conditions

INTRODUCTION

The renewed interest, in recent years, in the use of ejectors as thrust augmenters appears to have arisen because of remarkable progress in the field of ejector design which allows (static) thrust augmentation ratios (Φ) in the region of 2:1 to be achieved in practice (1,2,3,4). One of the problems of modern, improved, high augmentation ratio ejectors is the large area ratio required. A primary-to-secondary area ratio of approximately 24:1 is necessary in order to achieve a (static) thrust augmentation ratio of about 2:1 (1,2,3,4).

The possibility appears to exist of utilising unsteady-flow ejectors of relatively modest area ratio to achieve Φ values in the region of 2:1. On the basis of available experimental data, for one type of non-steady flow ejector, a primary-to-secondary area ratio of only about 6:1 will be necessary to achieve a Φ value approaching 2:1 (5). When consideration is given to the fact that, for the device in question, flow passes through the primary nozzle for only about 50% of the ejecter running time, it can be seen that it should be possible to reduce the secondary duct cross-sectional area, for a prescribed value of Φ, to about half that necessary for a comparable steady flow system.

The inherent advantage of non-steady flow ejectors appears to stem from the nature of the primary-to-secondary stream energy transfer process which, for most types of non-steady flow ejectors, seems to involve a component of pressure-exchange. Pressure-exchange is an energy transfer process, independent of mixing, in which the primary and secondary flows interact via an interface normal, or substantially normal, to the (local) flow direction. Quantitative prediction of the flow field in the secondary zone becomes particularly difficult when the pressure-exchange mechanism is combined intimately with mixing. This situation appears to prevail in most non-steady flow ejectors and suggests the desirability of an experimental approach to performance investigation.

TYPES OF NON-STEADY FLOW EJECTOR

There are at least three classes of ejector in which organised non-steady flow is an essential feature of the device. Each type is illustrated diagrammatically in Fig. 1. In every case the primary stream is the source of the flow non-steadiness.

Crypto-Steady Ejector

Perhaps the best known form of thrust augmenter involving non-steady flow (at least flow which is non-steady relative to a stationary observer) is the crypto-steady device due to Foa (6,7,8). In this system, illustrated in Fig. 1(a), "pseudo-blades" formed from fluid issuing from orifices in a self-driven, freely spinning, hub constitute the primary stream of the ejector. This type of machine, which is axi-symmetric, relies upon the "pseudo-blades" pumping the secondary flow somewhat along the lines of a turbo-machine with, of course, the important difference that the blades are non-rigid and are not attached to the hub. In part, at least, energy is transferred from the primary to the secondary stream by pressure-exchange. Presumably both the primary and secondary streams leave the apparatus at least partially mixed. An inherent advantage of the Foa device, relative to some other types of non-steady flow ejector, is that the expansion of the primary flow can be executed efficiently.

Oscillating Jet Ejector

A form of non-steady flow device which is not constrained to be axi-symmetric is an ejector in which the primary flow oscillates laterally in the secondary flow zone: a device of this type is shown in Fig. 1(b). Preferably, from an operational view point, the primary stream is caused to oscillate by fluidic means thereby eliminating the need for mechanical moving parts. Again a pressure-exchange mechanism can be seen to come into play in the transfer of energy between the primary and secondary flow. It appears that a major problem of the oscillating jet system is irreversibility in the fluidic primary nozzle (9).

One-Dimensional Non-Steady Flow Ejector

Perhaps the most simple form of non-steady flow ejector is that in which the intensity of the primary stream is modulated as a function of time. An ejector of this type is shown in Fig. 1(c). It was an ejector of this kind, subjected it seems to but little prior development, which was shown, by Lockwood (5) to be capable of producing a basic augmentation ratio, ϕ_B, of 1.95:1 with a primary-to-ejector-thrust area ratio of only 2.2:1. Lockwood used a flow converter which converted a steady flow into four, separate, non-steady streams one of which constituted the primary stream of the ejector. The thrust augmentation ratio ϕ was substantially lower than ϕ_B due to losses in the conversion device. However the best converter performance coefficient obtained was 0.91 (5). The converter performance coefficient was defined by Lockwood to be the time-averaged non-steady flow thrust (without the augmenter) divided by the thrust which would be obtained by expanding the same primary mass flow, isentropically, to the surroundings pressure. The value of ϕ_A lay between the values of ϕ_B and ϕ: the presence of the augmenter obviously affected the primary flow.

It would seem, therefore, that provided an efficient means can be found to generate the non-steady primary stream, an ejector of the type shown in Fig. 1(c) can be very effective. In the case of an application as a thrust augmenter for a pulse-jet, for example, the ejector primary stream (i.e. outflow from the pulse-jet) is modulated in intensity automatically and this problem vanishes. For applications in which the primary stream originates from a steady flow source a spinning primary jet, on the lines of that of Foa's ejector (6), entering sequentially a cluster of secondary flow channels, Fig. 2, may be acceptable for some thrust augmenter applications. The rigorous phase control of such a system may serve to minimise noise and vibration both of which tend to be problems with non-steady flow equipment.

The merits of one-dimensional (dynamic) pressure-exchange processes are, when isolated from the complexities associated with significant mixing, well understood and are amenable to analysis by the method-of-characteristics as applied to non-steady flows (6,10). In fact when a machine is designed to utilise dynamic pressure-exchange processes exclusively it is possible to achieve isentropic efficiencies of expansion and compression comparable, at least for some operating conditions, with those of turbines and compressors (10,11,12). The dynamic pressure-exchanger counterpart of an ejector is a machine termed an equaliser. However this device appears to be relatively unattractive as a large-scale thrust augmenter because of the size, and complexity, of the major moving component (11,12).

A special test rig was constructed in order to assist in obtaining an understanding of devices of the type shown in Fig. 1(c) in which internal events represent a combination of pressure-exchange and flow mixing.

TEST RIG

A prime consideration during the conceptual stage of planning the test rig for testing one-dimensional type ejectors was that the device should make efficient use of the primary flow available. This prevented the application of a multi-channel flow converter as used by Lockwood (5) and it is believed, although it is not stated explicity, also by Johnson and Yang (13). Another important factor was that the time-averaged thrust generated should be measurable, by simple means, with instrumentation etc. connected to the apparatus. It was, therefore, decided to use a suspended-plate type thrust meter. The thrust meter essentially turned through a right angle all flow impinging on the plate normal to the working face. A justification for the use of this type of thrust measuring device will be found elsewhere (14).

Other considerations were that it should be possible to measure the (average) primary and secondary mass flow rates, the pressures and temperatures of both the primary and secondary flows (i.e. reservoir conditions) and pressures, as a function of time, within the primary and secondary flow channels. It was felt that the provision of a heated air supply for the primary stream would have been desirable but to equip the apparatus with this facility would have complicated the system substantially.

Accordingly no provision was made to control the temperature of the primary, or secondary, stream. The apparatus is shown in diagrammatic form in Fig. 3.

Figure 4 shows details of the slotted, drum-type rotary valve used for creating the pulsing primary flow. The valve was driven by a variable speed electric motor (Fig. 3). The transition section, connecting the rotary valve stator to the primary tube, and the primary tube itself are shown in Fig. 5. Further details of the apparatus are available (15).

ANALYSIS OF PRIMARY-TUBE FLOW

One of the first tasks undertaken with the rig was to compare actual with theoretical pressure $\sim$ time traces in the primary tube. In this way it should be possible to detect any major shortcomings of the simple rotary valve mechanism as these should show up as major discrepancies between the theoretical (predicted) and actual (measured) pressure or time records.

Figure 6 shows a wave diagram (method-of-characteristics) constructed, ignoring wall friction, for the flow within the primary tube. Two operational cycles are depicted, the first cycle (duration $\Delta t'_{cycle\ 1}$) was based on uniform initial conditions, with the air at rest, within the primary tube at $t' = 0$. The second cycle was constructed with its initial conditions based on the final conditions of the first cycle. The second cycle should, therefore, be much more representative of the cyclic operation of the apparatus. Figures 7 and 8 show theoretical and experimental pressure traces in the primary tube at x = 2" and x = 10" respectively. For the case of the theoretical prediction (solid line) the pressure trace is shown for cycles 1 and 2. For the experimental case (dotted line) the comparison is made with the second cycle since this is more representative of cyclic operation, the conditions for which the experimental measurements were made. Figures 7 and 8 implied that the operation of the rotary valve appeared to be quite satisfactory. Figures 6, 7 and 8 correspond to a nominal design-speed operation of the rotary valve at 1800 rev/min. The design speed of the rotary valve was based on a cycle duration of $\Delta t'_{cycle\ 2}$.

The ratio of the primary-flow settling-tank pressure to the surroundings pressure was 1.5:1. This value was invoked in the construction of the wave diagram (Fig. 6) and was maintained constant for all the tests carried out with the apparatus.

SAMPLE RESULTS FROM EJECTOR TESTS

For preliminary tests of the complete ejector system three, simple, augmenter ducts were made, each of uniform diameter, provided with a bellmouth at the upstream end. The augmenter ducts were each 20 inches long, equal to the length of the primary tube, and were not provided with diffusers. The internal cross-sectional area of each augmenter tube divided by the internal cross-sectional area of the primary tube were as follows:

Augmenter Duct # 1	:	3.35
Augmenter Duct # 2	:	5.35
Augmenter Duct # 3	:	9.40

The initial tests were generally of an exploratory nature and were not intended to produce optimised performance characteristics. The first operational parameter investigated was the influence on performance of valve speed. This investigation was carried out using Augmenter Duct #1. The influence of valve speed on the thrust produced is shown in Fig. 9. From this diagram it can be seen that the thrust of the system increases steadily as the valve speed is increased from 50% to 150% of the nominal design-speed of 1800 rev/min. Exactly the opposite influence of valve speed is apparent in Fig. 10 which shows the ratio, β, of the secondary (induced) mass flow to the primary mass flow. It is apparent from Fig. 11 that the pressure parameter θ, representing the non-dimensional pressure-gain, is a maximum at the design valve-speed. The sensitivity of θ to a variation of valve speed is quite strong.

The results of a simple investigation to establish the optimum axial gap, z, between the open end of the primary tube and the face of the bellmouth of the augmenter duct are presented in Fig. 12. The diagram shows that β is relatively insensitive to changes in z'; the optimum value of z' is about 1.3. The finding that β is maximised with a positive value of z' is, qualitatively at least, in agreement with the findings of Lockwood (5).

It remains to offer an explanation of the performance characteristics displayed in Fig. 9 and 10.

The Influence of Valve Speed on the Primary Mass Flow

Figure 13 presents simplified wave (left hand side) and state (right hand side) diagrams constructed to show that the effective primary tube exit velocity can be expected to increase as the valve speed increases. The wave and state diagrams at the top of the figure depict conditions in the primary tube when the valve is operating at its design speed. The outflow velocity is represented by point 3, in the u ~ a chart, for 50% of the cycle duration with a low velocity inflow, state point 1, for the remainder of the cycle.

The lower pair of diagrams in Fig. 13 shows what happens when the valve is operated at twice the design speed. The outflow velocity for 50% of the cycle duration is given by state point D (a velocity much greater than that corresponding to state point 3 in the upper diagram) and for the remainder of the cycle the inflow velocity, noted in the upper diagram, is reduced to zero (state point B). The consequence of doubling the valve speed is, therefore, to increase very substantially the average flow velocity, and hence the mass flow, through the primary tube.

The foregoing characteristics offer an explanation of the increase of thrust with increasing valve speed apparent in Fig. 9 and, at the same time, account, in part, for the trend observed in Fig. 10.

CONCLUSIONS

Three classes of non-steady ejectors were surveyed briefly and it was found that the one-dimensional type, sometimes also known as a pulse-jet ejector, offered considerable promise in that it appears to permit a reduction in the secondary, or augmenter, duct cross-sectional area to about half that of a steady flow ejector of equal augmentation ratio.

It was further concluded that because of uncertainties associated with the analysis of the flow field in pulse-jet ejectors an experimental technique was preferred to a wholly theoretical one for investigative performance analysis. An apparatus designed specifically for studying the performance of pulse-jet ejectors was described and sample test results were presented. It was found that these results were, in general, in accordance with theoretically based expectations.

ACKNOWLEDGEMENT

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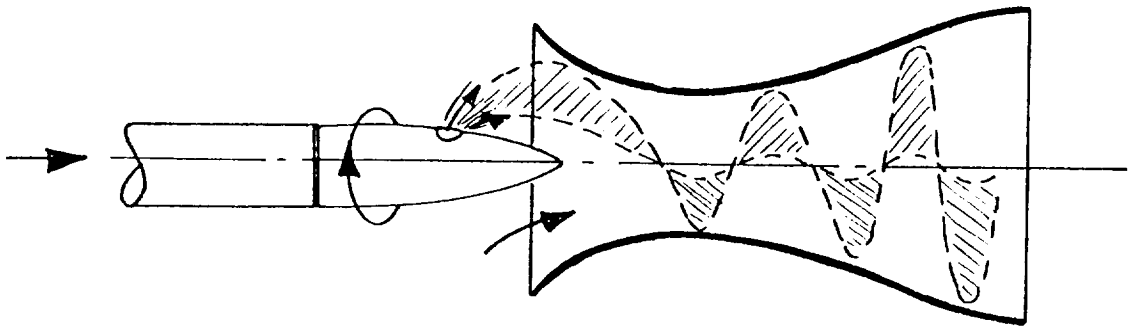
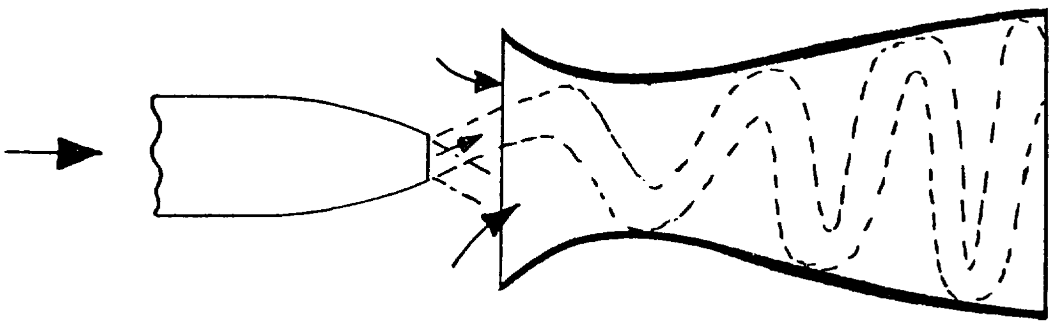
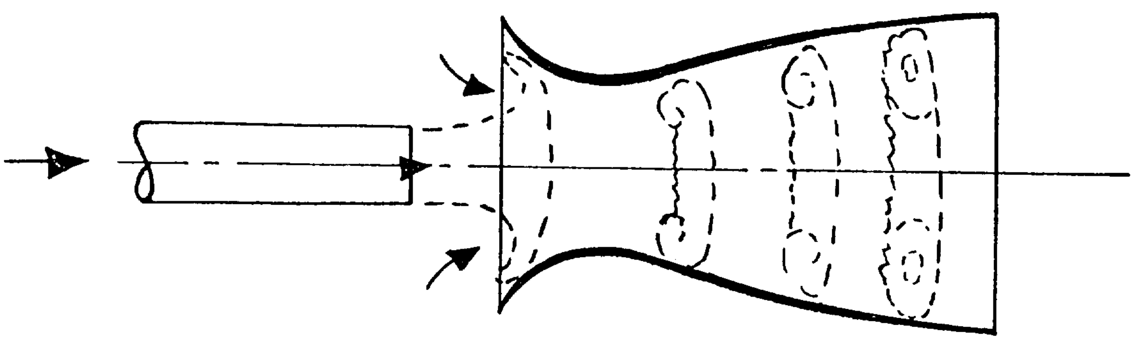


(a) Crypto-Steady, or Spin-Jet, Ejector (Foa).



(b) Ejector with Oscillating Primary Jet.



(c) One-Dimensional, or Pulse-Jet, Ejector.

Fig. 1 Types of Non-Steady-Flow Thrust-Augmentation Ejectors.

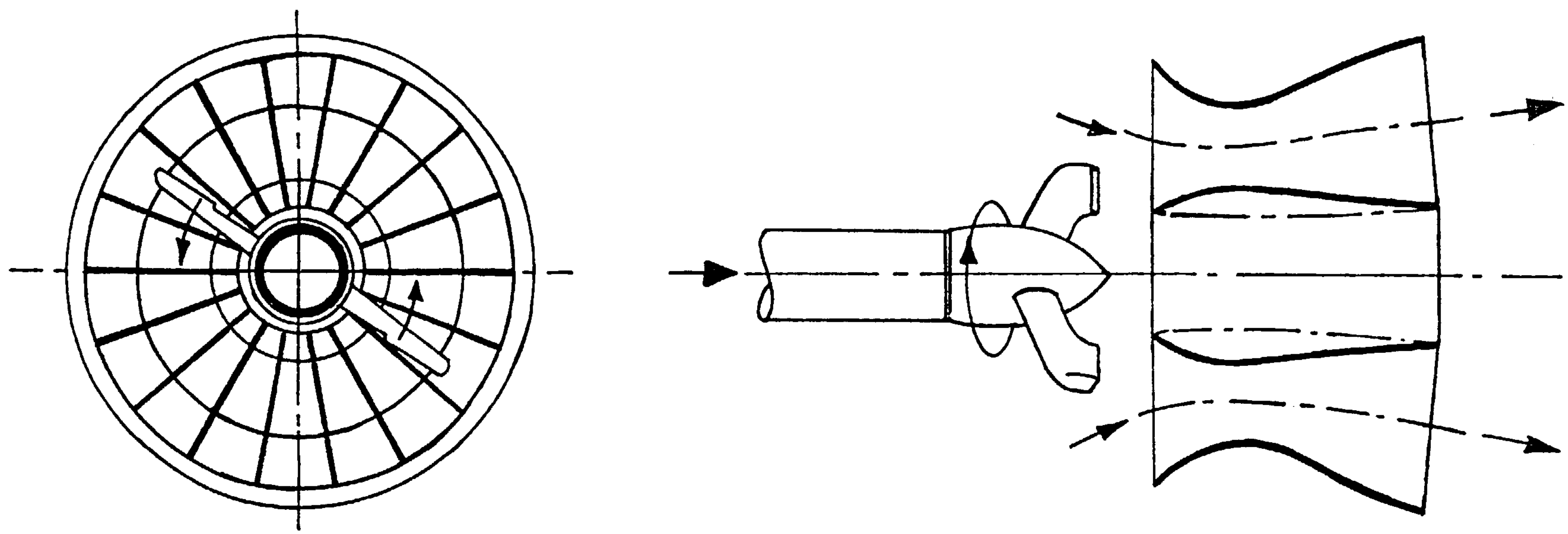


Fig. 2 Clustered One-Dimensional Non-Steady Flow Ejectors Supplied with Primary Fluid Issuing from Nozzles Mounted on a Freely Rotating Hub.

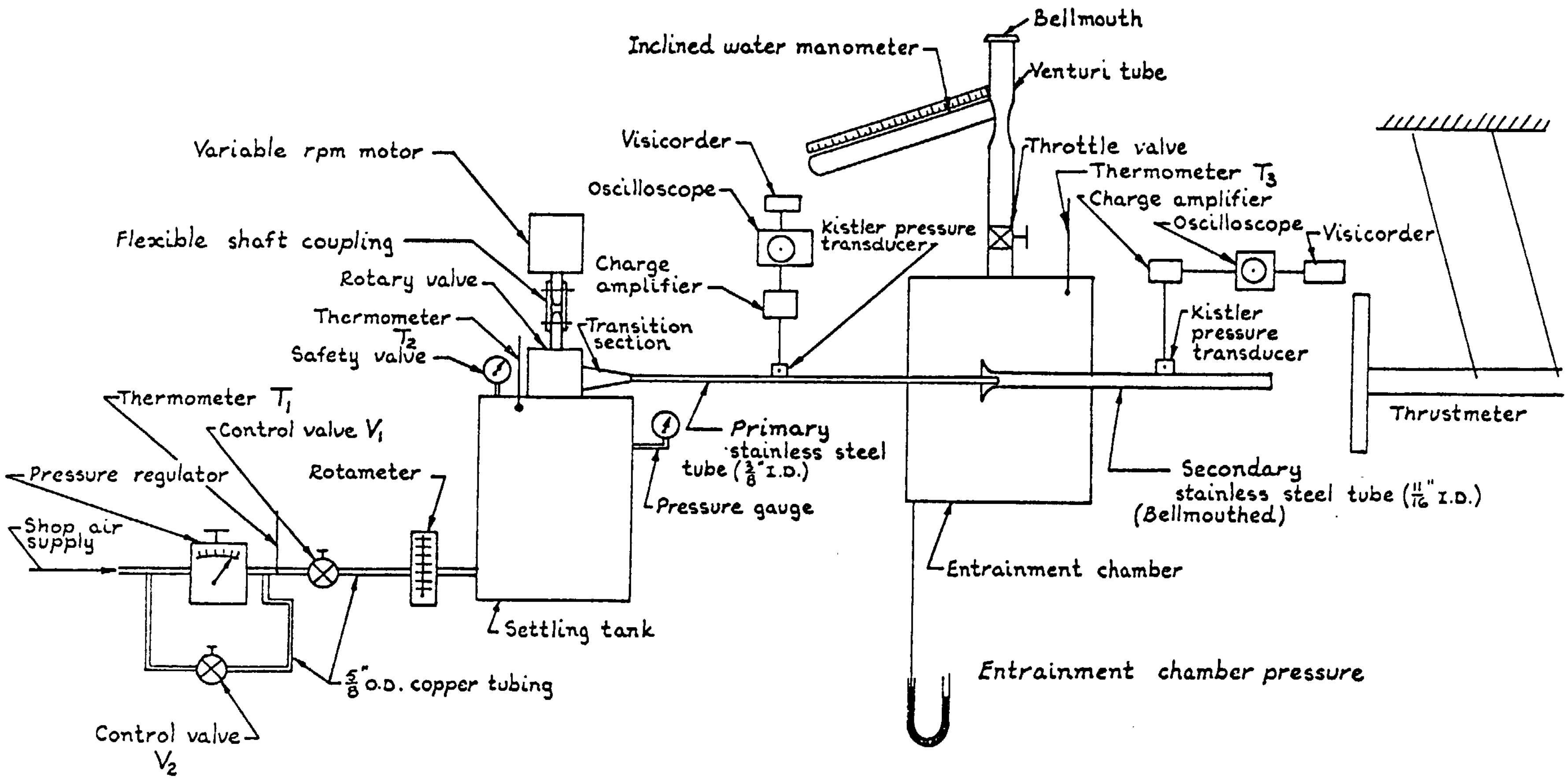


Fig. 3 General Schematic Arrangement of the Experimental Apparatus.

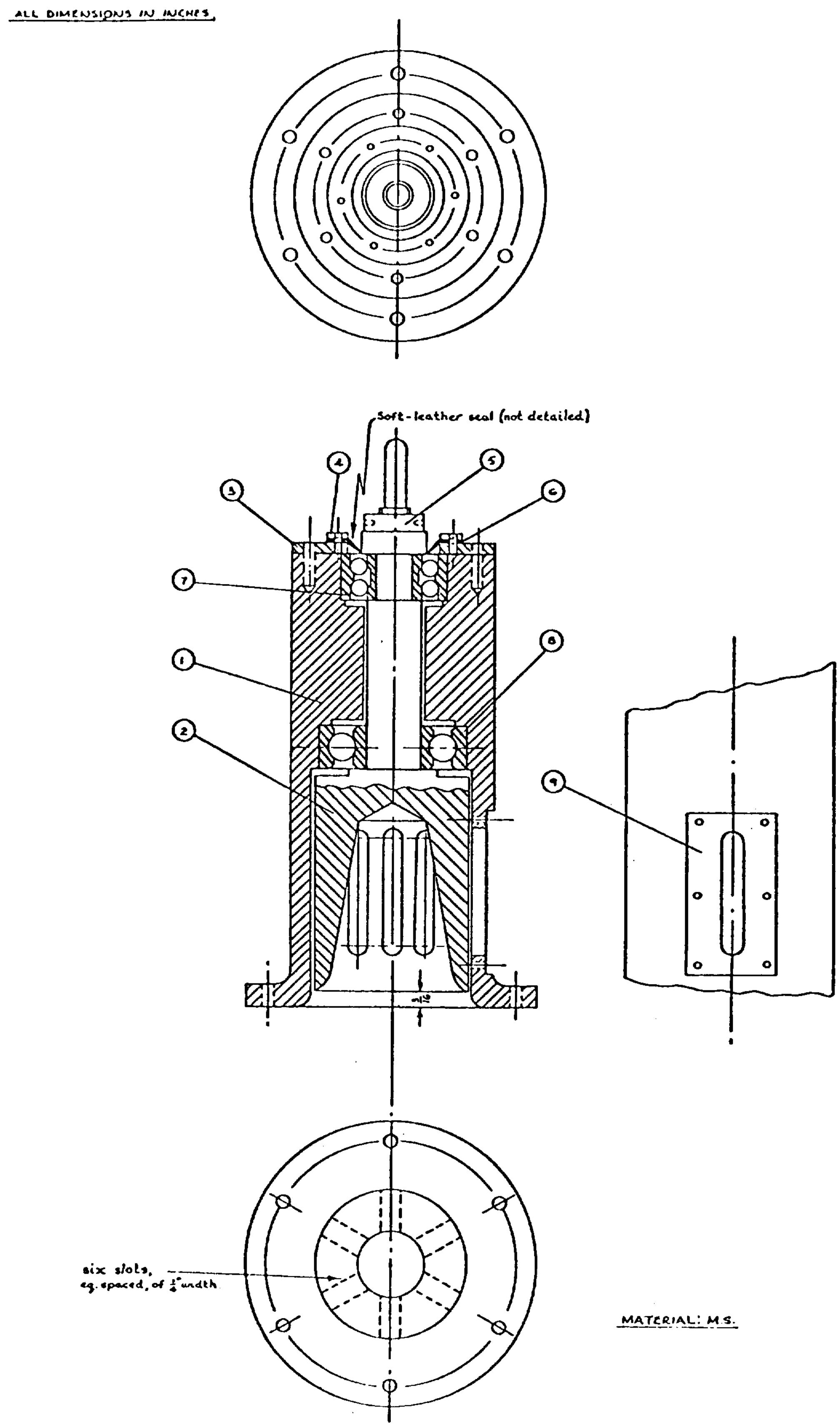
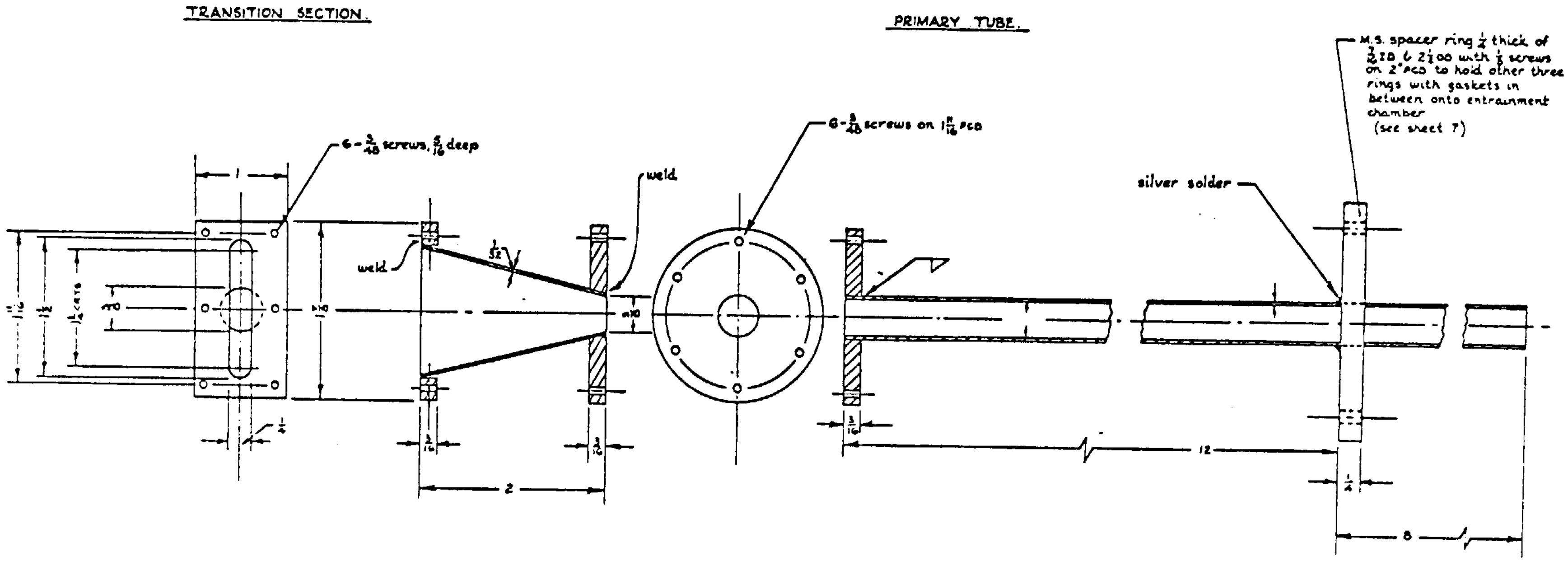


Fig. 4 Rotary Valve Details.

ALL DIMENSIONS IN INCHES



NOTE:

1. Transition section is to be fastened to rotary valve stator.
2. The other (R hand end) of transition section is to be coupled to the primary tube.

MATERIAL: STAINLESS STEEL.

Fig. 5 Details of the Transition Section and the Primary Tube.

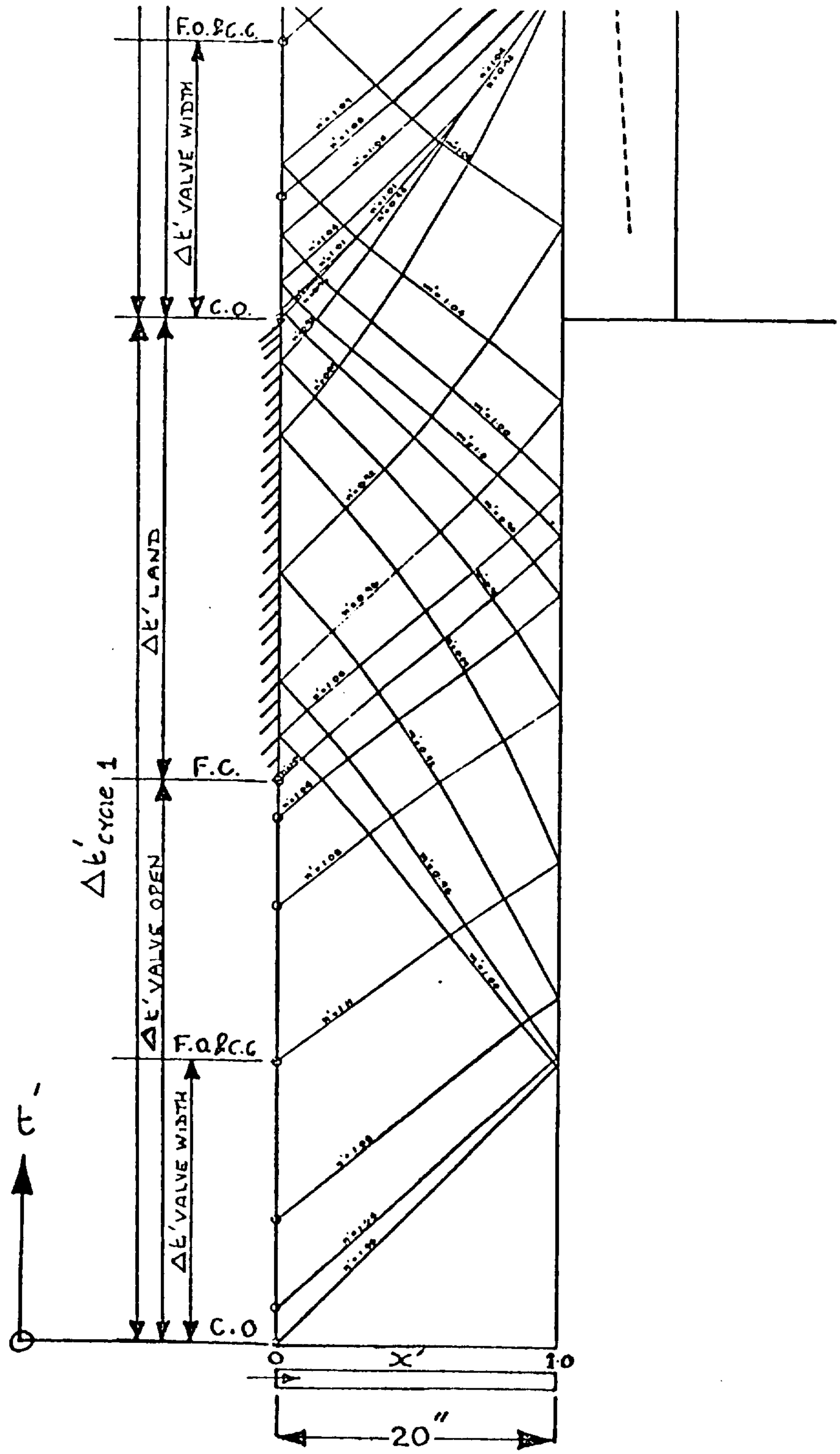


Fig. 6 Predicted Flow Field, for the First (Start-Up) Cycle of Operation, in Primary Tube on $x' \sim t'$ Plane. Rotary Valve at Left Hand End of Primary Tube.

a_{ref} = 1120 ft/s (340 m/s)

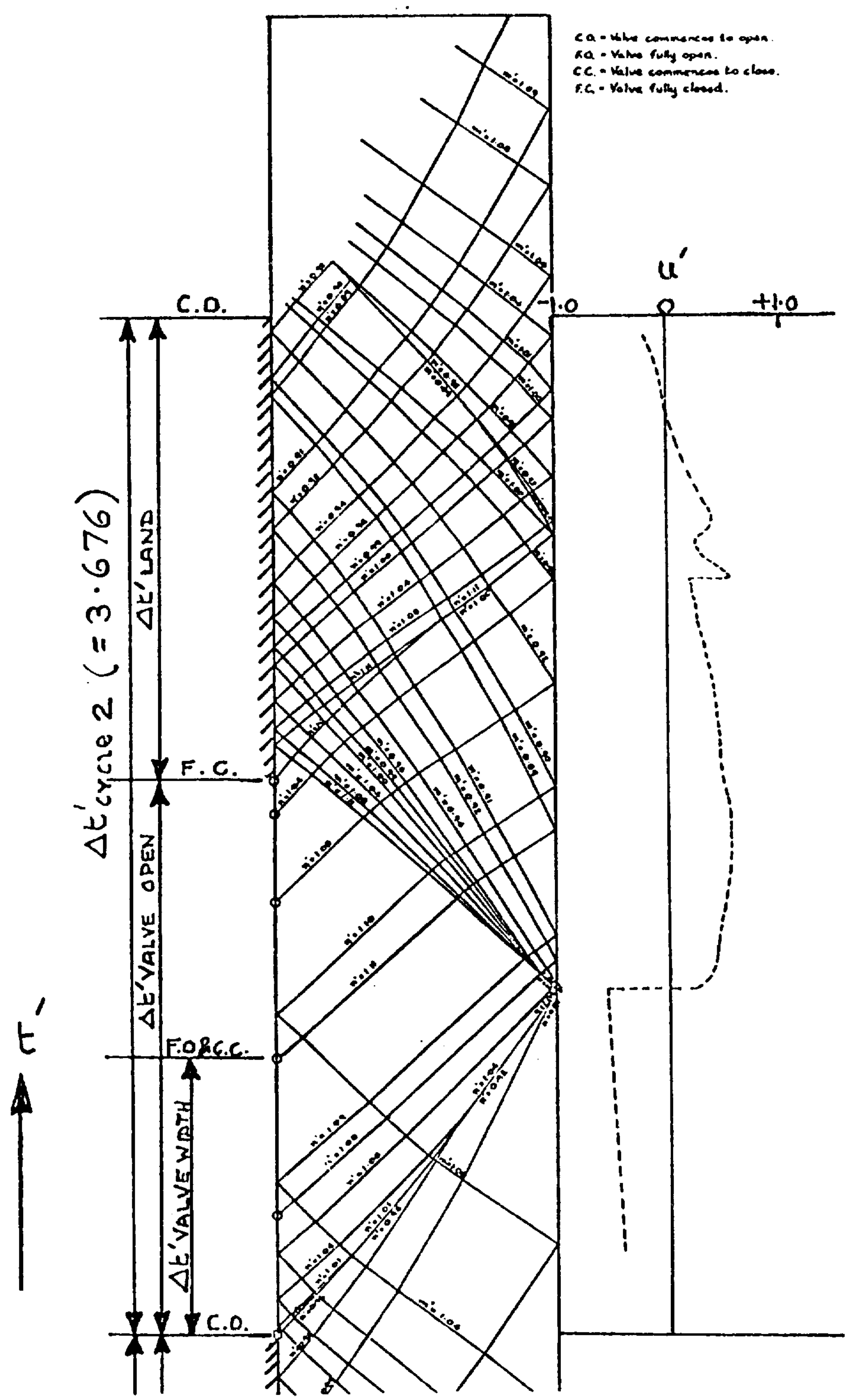


Fig. 6 (continued) x' ∿ t' Diagram for the Second Cycle of Operation. The Normalised Velocity Profile at the Outlet End of the Primary Tube is also Shown.

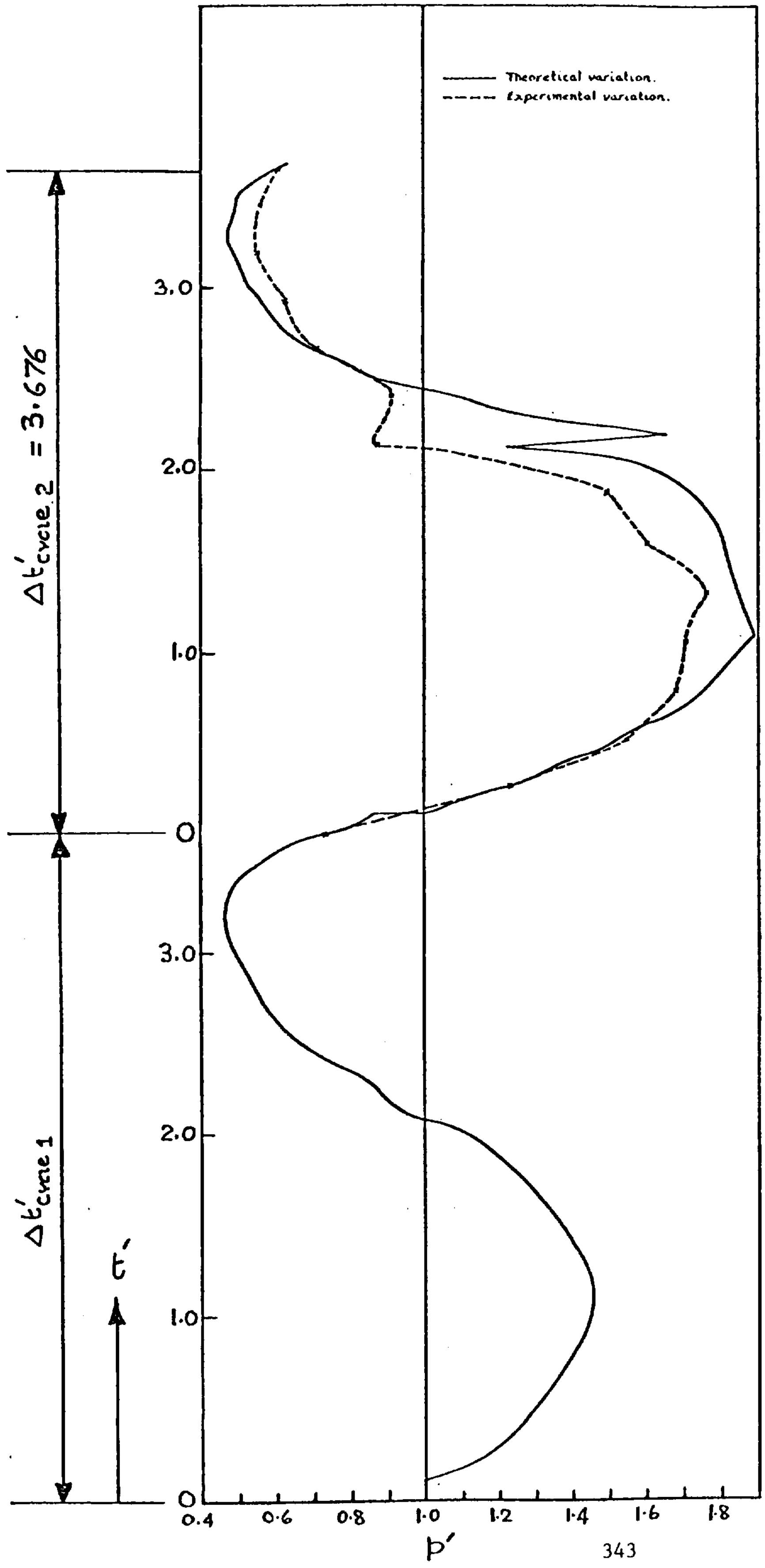


Fig. 7 Experimental and Theoretical Pressure-Time Plot (p' ~ t') at the 2 inch Location in the Primary Tube; Optimum Valve Speed

(p_{ref} = Surroundings pressure
= Static pressure at exit of primary tube.)

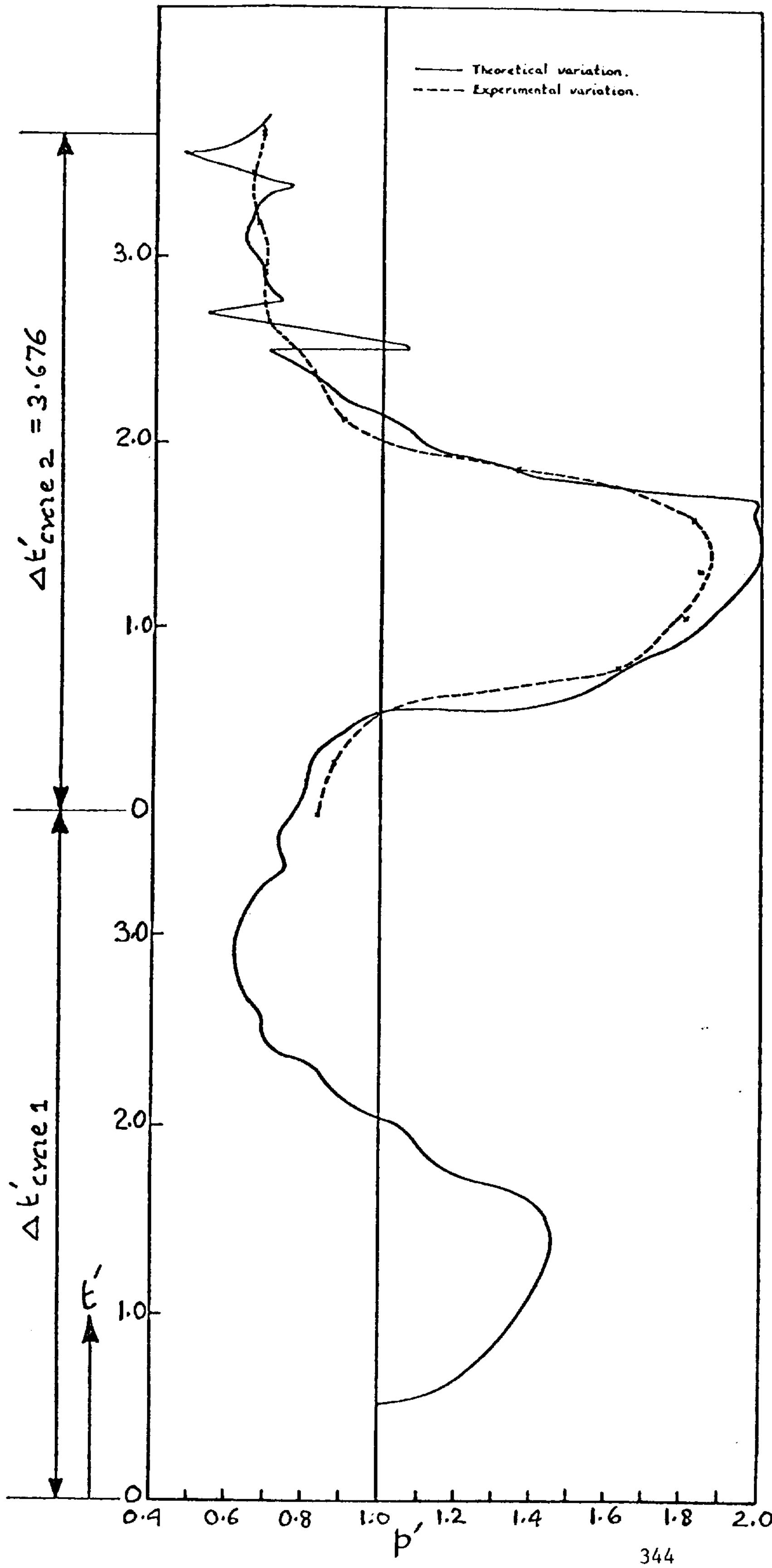


Fig. 8 Experimental and Theoretical Pressure-Time Plot ($p' \sim t'$) at the 10 inch Location in the Primary Tube; Optimum Valve Speed

(p_{ref} = Surroundings pressure
= Static pressure at exit of primary tube.)

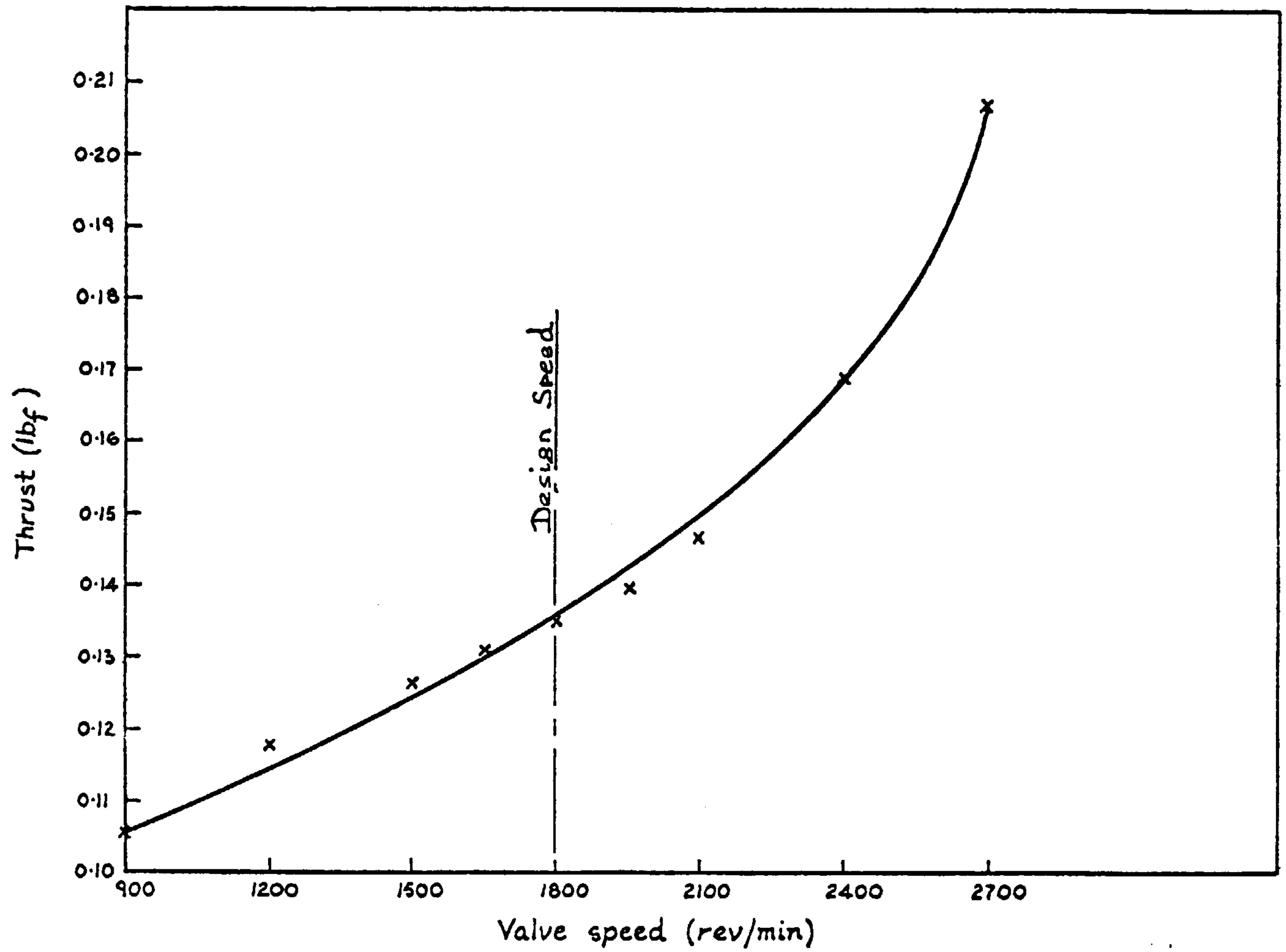


Fig. 9 Average Thrust - Valve Speed Plot for Augmenter Duct #1.

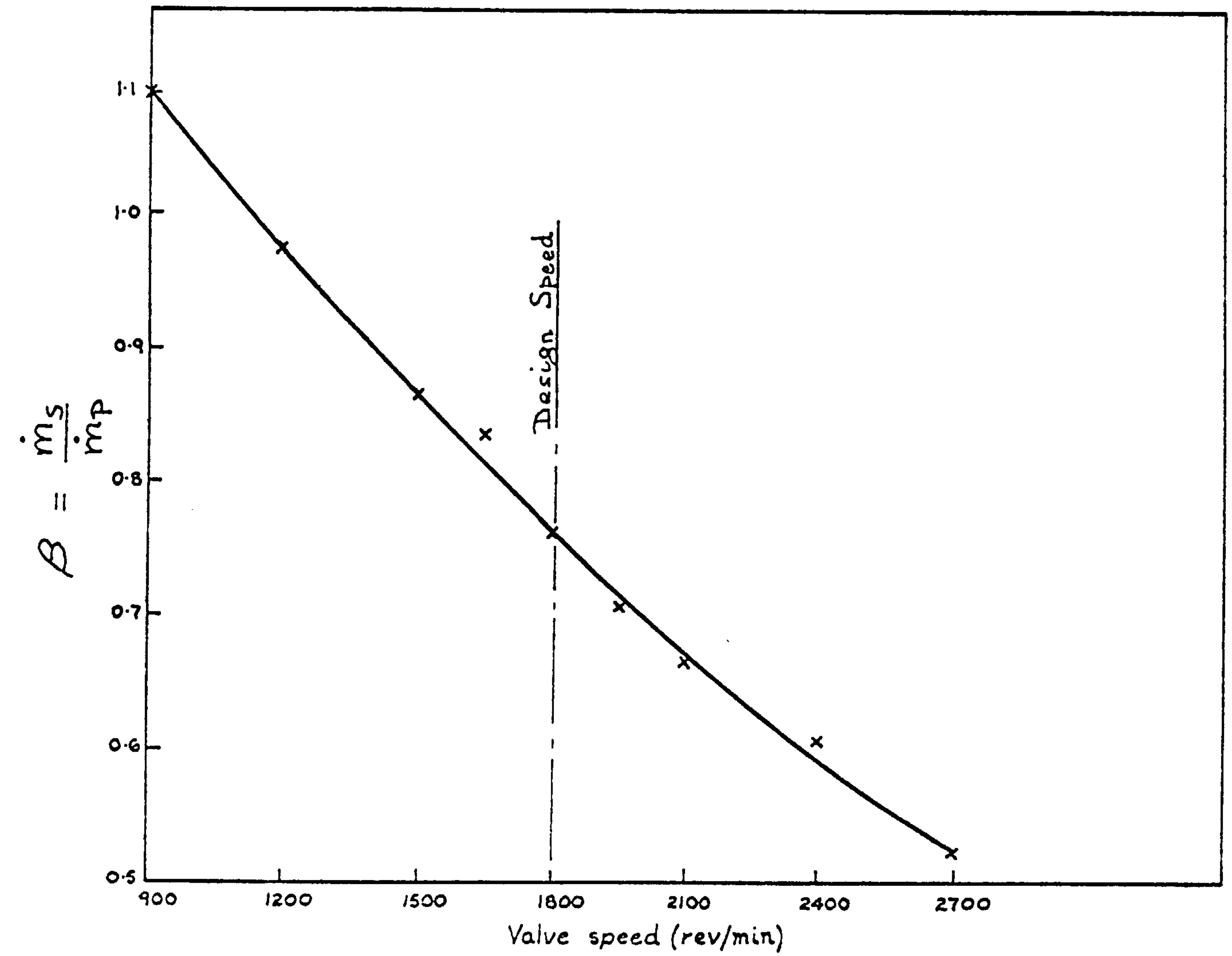


Fig. 10 Mass Flow Ratio - Valve Speed Plot for Augmenter Duct #1.

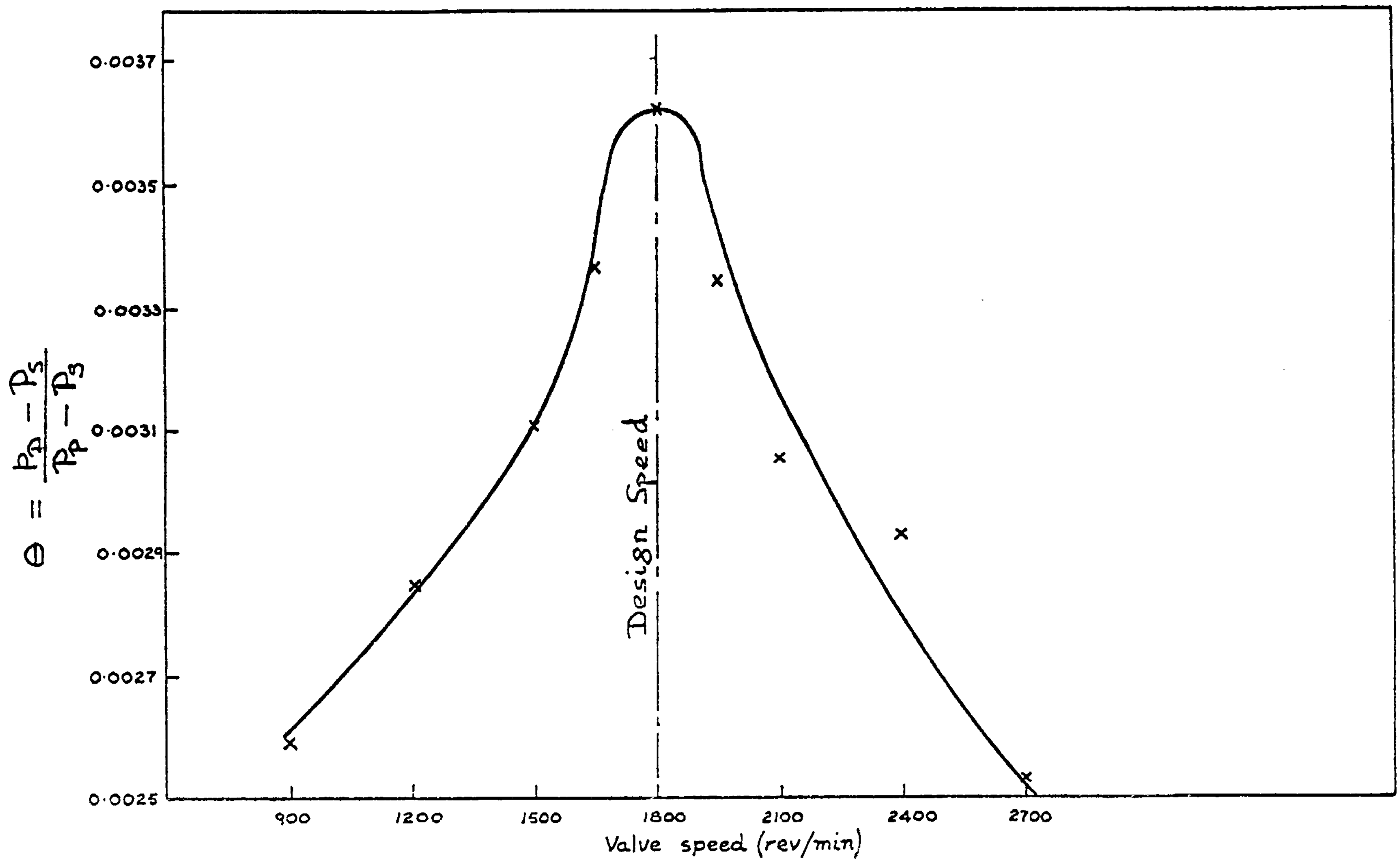


Fig. 11 Pressure Parameter - Valve Speed Plot for Augmenter Duct #1.

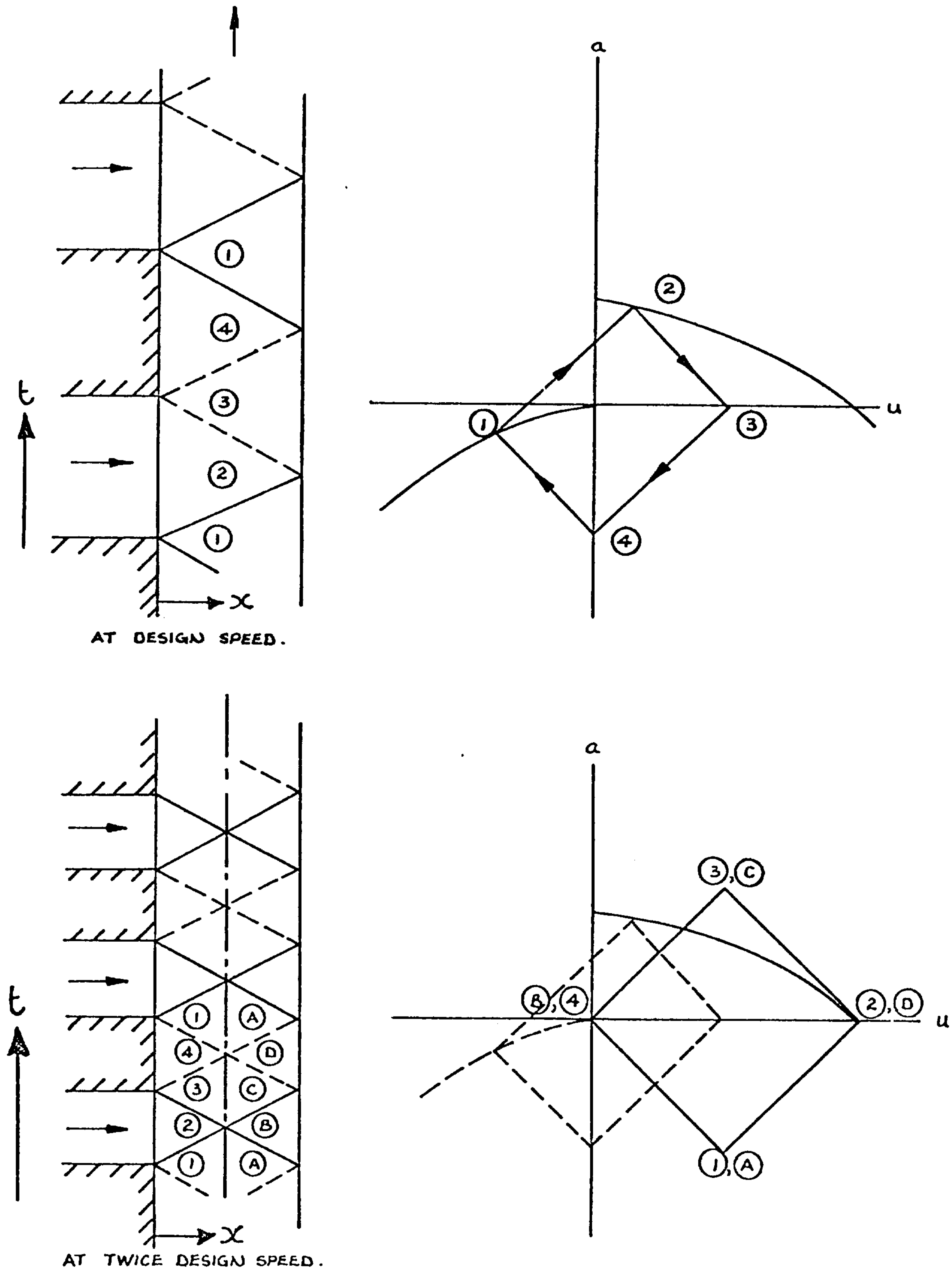


Fig. 13 Increase of Primary Tube Flow Velocity With Increase of Valve Speed.

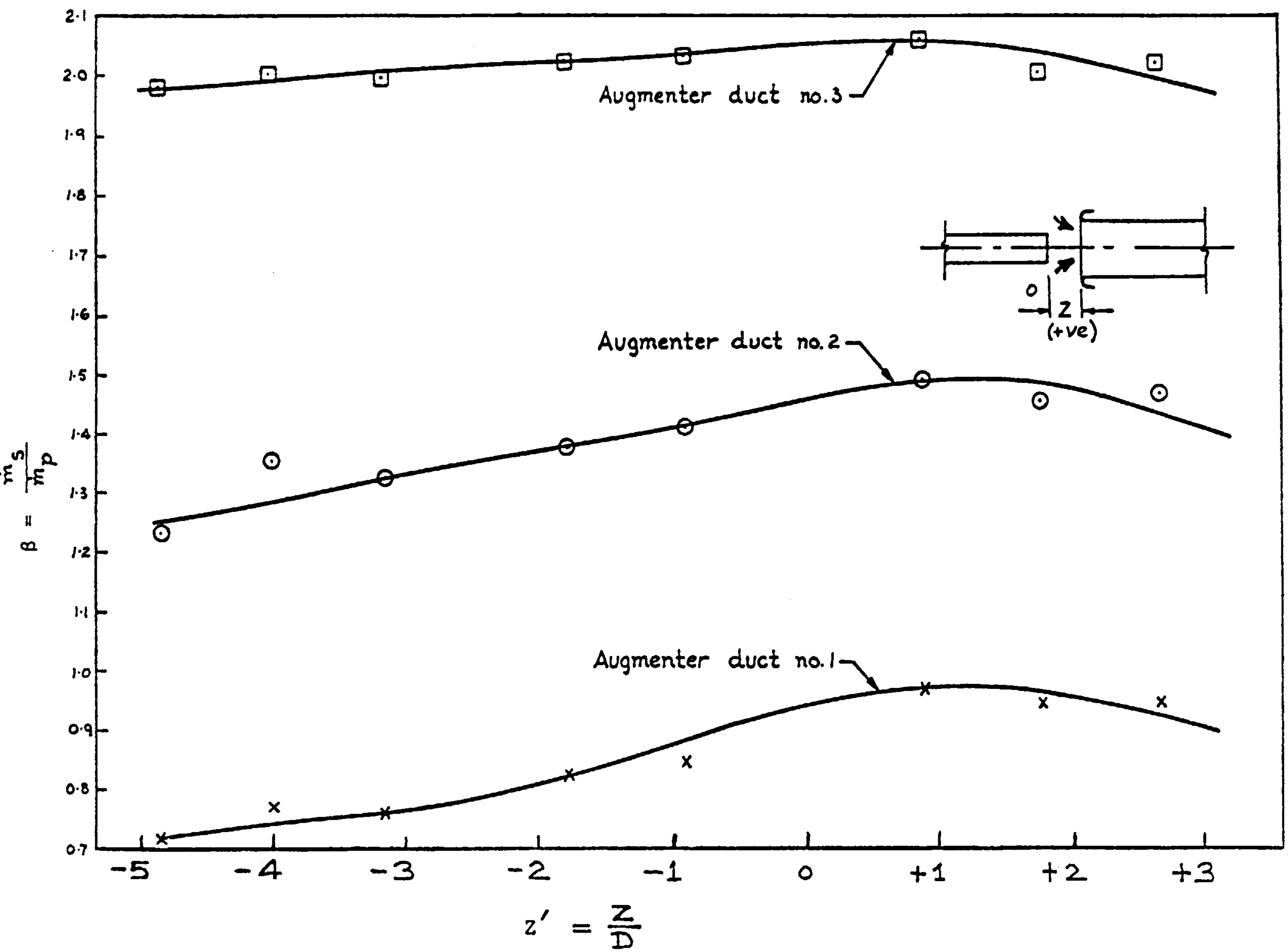


Fig. 12 Mass Ratio β versus Z′ for Augmenter Ducts #1, 2 and 3: Optimum Valve Speed.