Purdue University
Purdue e-Pubs

International Compressor Engineering Conference | School of Mechanical Engineering

1972

Some Practical Applications of Modern Compressor Valve Technology

D. Woollatt
Worthington CEI

SOME PRACTICAL APPLICATIONS OF MODERN COMPRESSOR VALVE TECHNOLOGY

D. Woollatt

INTRODUCTION

This paper is intended to show how modern compressor valve technology can be applied in the practical context of compressor design, development and application engineering. Few, if any, of the techniques presented here are new, most being fully described in the literature, but we feel that combined into an overall valve design procedure as they are at Worthington CEI, they form an extremely useful advance over earlier methods. It is, of course, still necessary to base many decisions on experience, but the improved understanding of the parameters affecting valve operation provided by the experimental and theoretical techniques described here, allow the experience to be used effectively. Many of the compressors we build are for non-standard applications in that the gas composition, pressure levels, flow requirements, etc. are different for each case. Our improved understanding of valve operation allows us to choose the most efficient reliable valves for each application and to calculate the compressor's performance more accurately.

EXPERIMENTAL TECHNIQUES

Static Tests

Static tests are performed on the rig shown in Fig. 1 in order to determine the effective flow area of the valve under any conditions. In the initial tests a large number of factors such as the drag coefficient (Fig 2), effects of Reynolds number, change of effective flow area with lift (Fig 3) were considered, but for routine testing of valves we now just obtain results as shown in Fig 4 except that data without the springs are not obtained. This provides all the essential information and can be obtained quickly. The approximately constant effective flow area once the valve is fully open and the approximately straight line relationship between effective flow area and pressure drop when the valve is only partly open should be noted. To simplify slightly, the latter is a result of a constant drag coefficient, a constant spring constant and a linear relationship between lift and effective flow area. The data represented by this curve are basic to all the theoretical work described here. Curves have been obtained experimentally for a large number of valves and predicted for all other types and sizes that we make.

Dynamic Tests

The purpose of the dynamic tests is to measure the instantaneous valve element position and pressure drop across the valve. The instrumentation used is shown in Fig 5. The valve motion is measured using a fibre optics probe (MTI fotonic sensor) that measures the light reflected from the strip. This can be related to the distance of the strip from the sensor. Pressure drop across the valve is measured with a piezo-electric transducer and a pneumatically operated valve that can rapidly switch the transducer to the valve passage or the cylinder. The assembly is mounted in a valve as shown. By switching the transducer from passage to cylinder in less than 1 sec., errors that might otherwise be introduced by drift due to temperature change or charge leakage are eliminated and accurate valve pressure drops can be obtained.

To reduce the time and effort required for obtaining, analyzing and plotting indicator cards, an analogue to digital recording system is used. This automatically samples the pressure at one point in each cycle, digitizes it and punches it on paper tape. By arranging for the crank angle at which the pressure is sampled to progress by a given small increment for each cycle, a complete indicator card in digital form is punched on paper tape in a form suitable for computer analysis.

ANALYTICAL TECHNIQUES

The analytical techniques used range from a full dynamic analysis that is used occasionally for special purposes to a fast, but approximate, prediction of valve losses that is used for day to day sizing of compressors.

Full Dynamic Analysis

For a detailed analysis of valve performance it is necessary to consider the movement of each valve element as calculated from the equation of motion for the element, the correct change of cylinder conditions and the unsteady flow effects in the cylinder passage and piping. Our program uses conventional methods (3) for the valve element motion and cylinder conditions and homentropic mesh method (5) for the unsteady flow calculations. Data on drag coefficients, equivalent flow area against lift etc. are fed into the program in the form of curve fits. If the valve has elements of different sizes, or spring forces, these must be considered separately as each will have its own different motion.

This program has been in use at Worthington for over 5 years and has proved extremely valuable for investigation of typical applications of new compressors in the design stage and investigation of trouble jobs. The results are considered in two ways. First, the capacity and power loss due to the valves can be obtained. If these are excessive e.g. due to the valve not fully opening for the majority of the valve event, due to the valve remaining open after the dead centre or due to high pulsations, then the valve or piping can be redesigned, perhaps by changing the spring force or pipe lengths, to improve the performance. Second, the valve motion is studied for clues that the valve will not operate reliably. We require that the impact velocity of the valve element on the seat or guard not be too high and that the valve not oscillate unduely. Examples of calculated valve motion are shown in Figs. 6 and 7 along with corresponding measured traces.

This program is by far the most powerful method we have for investigation of valve performance. It does, however, have two drawbacks. It is expensive in computer time and manpower requirements and it requires considerable experience in the person using it, expecially in the area of choosing the model used to simulate the usually complex piping system.

Dynamic Valve Analysis Without Piping Pulsations

Much of the information available from the full dynamic analysis can also be obtained from the much faster and easier to use analysis obtained by retaining the dynamic valve element motion and cylinder condition analysis, but assuming that the pressure in the cylinder passages is constant. This is especially useful at the design stage when the piping with which the compressor will be used may be unknown.

Theta Ratio Analysis

The theta ratio analysis (1) is used to ensure that the valve design is reasonable with respect to valve dynamics for each application and therefore that neither performance nor valve reliability problems should be encountered. The analysis is quick and easy to use and can therefore be applied to all applications. The method is based on comparing the time in crank angle degrees of the following three events. (see Fig 8)

1. The closing time of the valve element in the absence of all gas forces, θ_1

2. The interval between the time when the gas force becomes insufficient to hold the valve fully open and the top dead centre, θ_2

3. The total duration of the suction or discharge process, θ_3

To ensure satisfactory operation we require that $\theta_2/\theta_1 > 2$ and $\theta_2/\theta_3 < 0.7$

to allow the valve adequate time to close and to ensure that it is at full lift for a sufficient time. Experience has shown that in the absence of other factors such as large amounts of dirt or excessive pulsations, valves designed within these limits will perform well.

Prediction of Equivalent Valve Areas

The equivalent flow areas of a large number of valves have been measured as described above. It is, however, impractical to test all types and size of valves required for our range of applications. For this reason and also for use in designing improved valves, it is necessary to have ways of predicting the equivalent flow area of a valve from its geometry. The following describes our present simple approach to this. Although we feel that this can be improved eventually, it has given extremely useful results.

We assume that two flow areas, [1] the lift area and the area between elements (Fig 9) are the important flow restricting areas and consider these to act as orifices in series. It is further assumed that constant discharge coefficients can be applied to each of these areas and then by examination of steady flow results from valves with different geometries, the two coefficients can be evaluated.

Valve Loss Aspects of Compressor Sizing

The basic approach of most compressor sizing methods is to start with the ideal volumetric efficiency and horsepower equations and to modify these as required to account for the various losses occuring in an actual machine. Many of these losses are influenced by the valve design (Fig 10). The pressure drop across the valve increases the horsepower directly and decreases the capacity by reducing the pressure and increasing the temperature in the cylinder at suction valve closing. The temperature effect arises because on its way from the suction flange to the cylinder at valve closing, the gas is first throttled through the valve and then recompressed in the cylinder.

The methods used for compressor sizing must be fast as they will typically be used many times per day and yet, for obvious reasons, they must be accurate. The approach used to predict the average pressure drop across the valve is described in references (1), (2). The instantaneous pressure drop, assuming that the gas is incompressible and the valve equivalent flow area constant, is calculated as a function of piston velocity and the average pressure drop to give the same valve loss can then be obtained. The integration necessary for this can be done analytically. If there is doubt that the valve is fully open for the majority of the suction or discharge process, this should be checked and, if necessary, the equivalent area reduced accordingly.

Two other valve factors that affect the compressor performance are the spring preload and the crank angle at which the valve closes. The first of these can easily be incorporated into the calculation procedure (Fig 10), but as yet we have no quick way of accounting for closing time errors.

Prediction of Gas Properties

Our equipment is used for compressing a wide variety of mixtures of gases at a large range of pressures. The calculation of compressor valve operation depends critically on knowledge of the gas properties, expecially the density and to some extent the isentropic volume exponent. We have found the Redlich-Kwong equation of state [4] to be the most suitable for our purposes. It gives accurate results, but requires knowledge only of the critical pressure and temperature of the gas mixture and if the low pressure specific heats are known, the equation is simple enough to allow all the other gas properties e.g. enthalpy, entropy, isentropic exponents, fugacity, to be calculated easily.

EXAMPLES OF USE OF THE ABOVE TECHNIQUES

Valve Reliability - Theta Ratio Analysis

The limits for the theta ratios given above were determined from a large number of successful and unsuccessful valve applications. They were chosen so that no valves that experienced unexplained failures would satisfy the criteria. However, we do have some valves that do not satify the criteria and yet operate satisfactorily. In cases where valves operating outside the criteria have had failures, the problem has been corrected by changing the valve geometry to change the theta ratios and make them satisfy the criteria established.

It has been found that due to the non symmetry of piston motion caused by the crank mechanism, the theta ratios are significantly different for head and crank end valves. This has provided the explanation for why we sometimes encountered failures only of head end discharge valves.

Improved Valve Design

As described above, the analysis of the steady flow tests results led to an assessment of the coefficients of discharge for each flow restricting area in the valve. This information allowed the geometry of the valve to be optimized. A new series of valves was designed using these results and tested in two of our standard types of compressor. The improvement in performance as measured by BHP/100 cfm relative to the best of our previous standard valve designs varied from 1 to 10%.

Performance Improvement by Dynamic Analysis

The simplified dynamic analysis neglecting pulsations and not considering suction heating or any losses other than those caused by the valves was used to investigate the possible performance improvement by changing the strip thickness in the suction valve of a gas gathering type compressor. The valves considered were feather valves in which changes to strip thickness vary the spring constant for the valve. The valve had two different strip lengths. Typical cylinder pressure and valve lift diagrams are shown in Fig 11. The measured and calculated flows for different strip thicknesses are shown in Fig 12. As would be expected with this analysis which ignores all losses other than valve losses, the calculated flow is higher than the measured. However, the prediction of the effect of strip thickness on flow and of the optimum strip thickness are excellent.

CONCLUSIONS

The range of experimental and analytical techniques now used at Worthington CEI for compressor valve problems has been described. We hope that we have shown how modern technology can be used by a compressor manufacturer to improve the efficiency of his compressor development and applications engineering.

ACKNOWLEDGEMENTS

The author wants to thank Worthington CEI for permission to publish this paper and all those individuals especially H. Davis and R. W. Beyer involved with the development of the techniques described.

REFERENCES

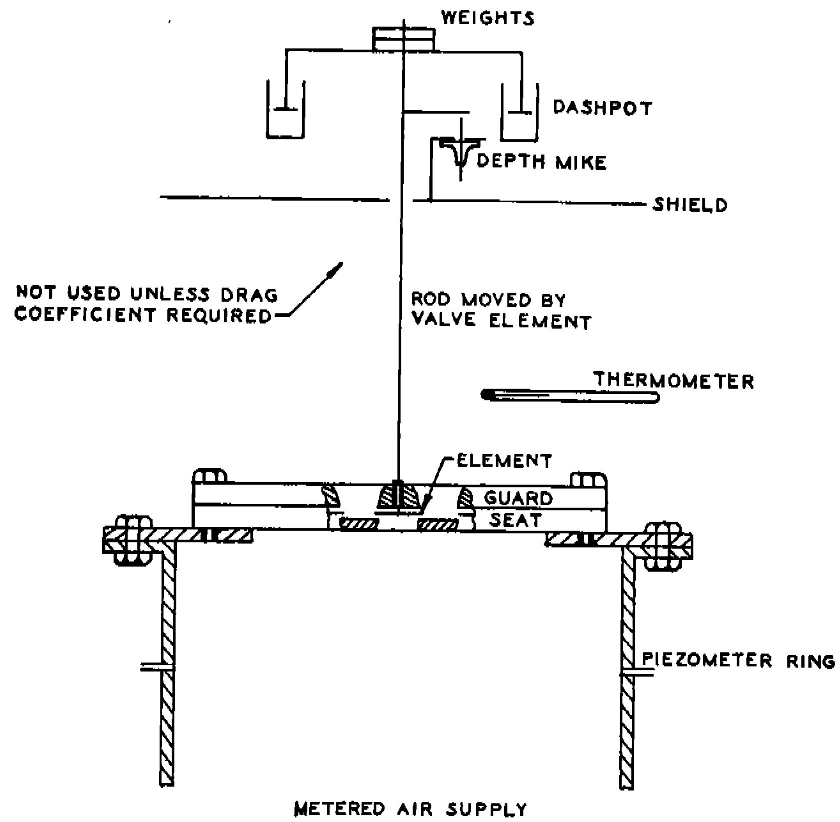
1. H. Davis 'Effects of Reciprocating Compressor Valve Design on Performance and Reliability' I. Mech. E. (1970)

2. W. Hartwick 'Efficiency Characteristics of Reciprocating Compressors' ASME paper 68-WA/DGP-3

3. J. F. T. MacLaren and S. V. Kerr 'An Analytical and Experimental Study of Self-Acting Valves in a Reciprocating Air Compressor' I. Mech. E. (1970)

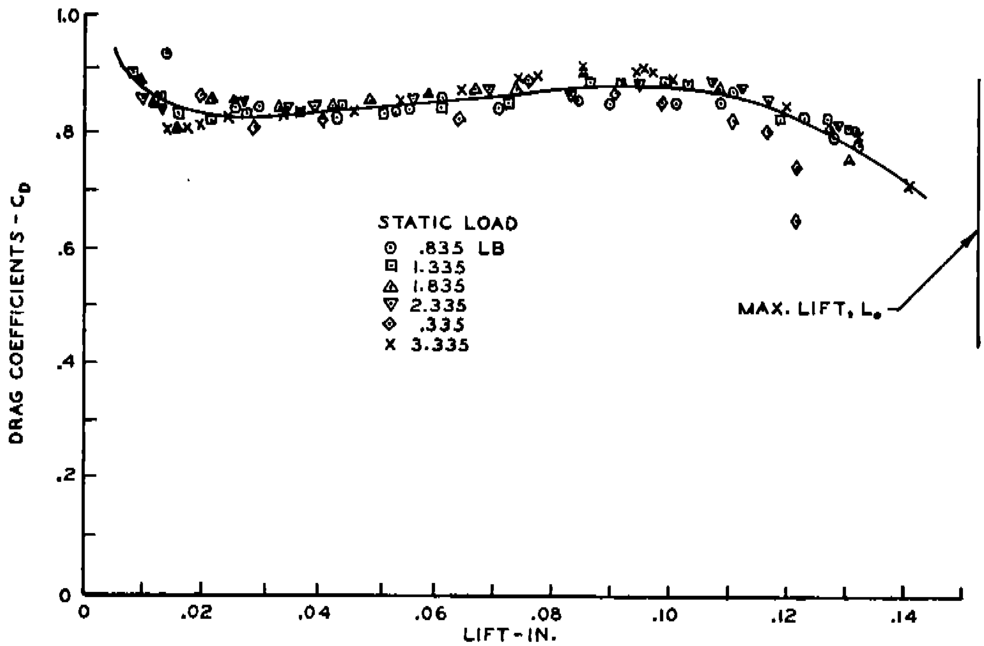
4. O. Redlich and J. N. S. Kwong Chemical Reviews, 44, 233 (1949)

5. D. Woollatt 'The Application of Unsteady Gas-Dynamic Theories to the Exhaust System of Turbo-charged Two-Stroke Engines ASME paper 65-WA/DGEP-1



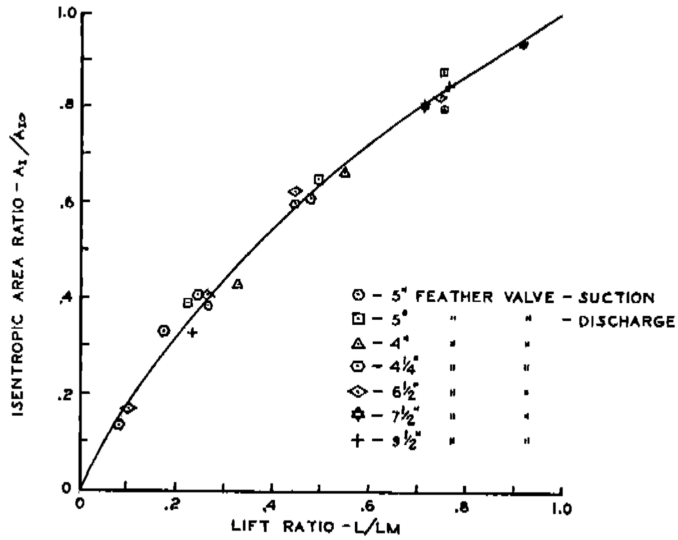
STEADY FLOW RIG

FIG. I



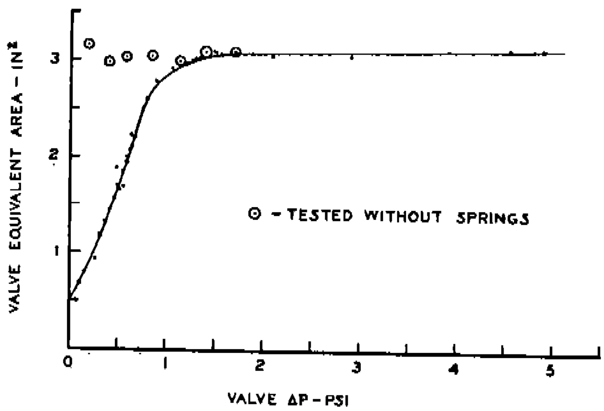
DRAG COEFFICIENT TEST DATA

FIG. 2



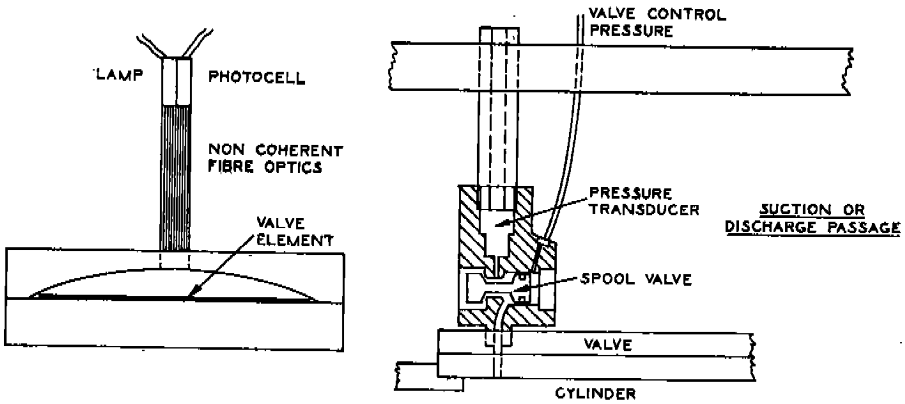
CORRELATION OF ISENTROPIC FLOW AREAS

FIG. 3



VALVE EQUIVALENT AREA

FIG. 4

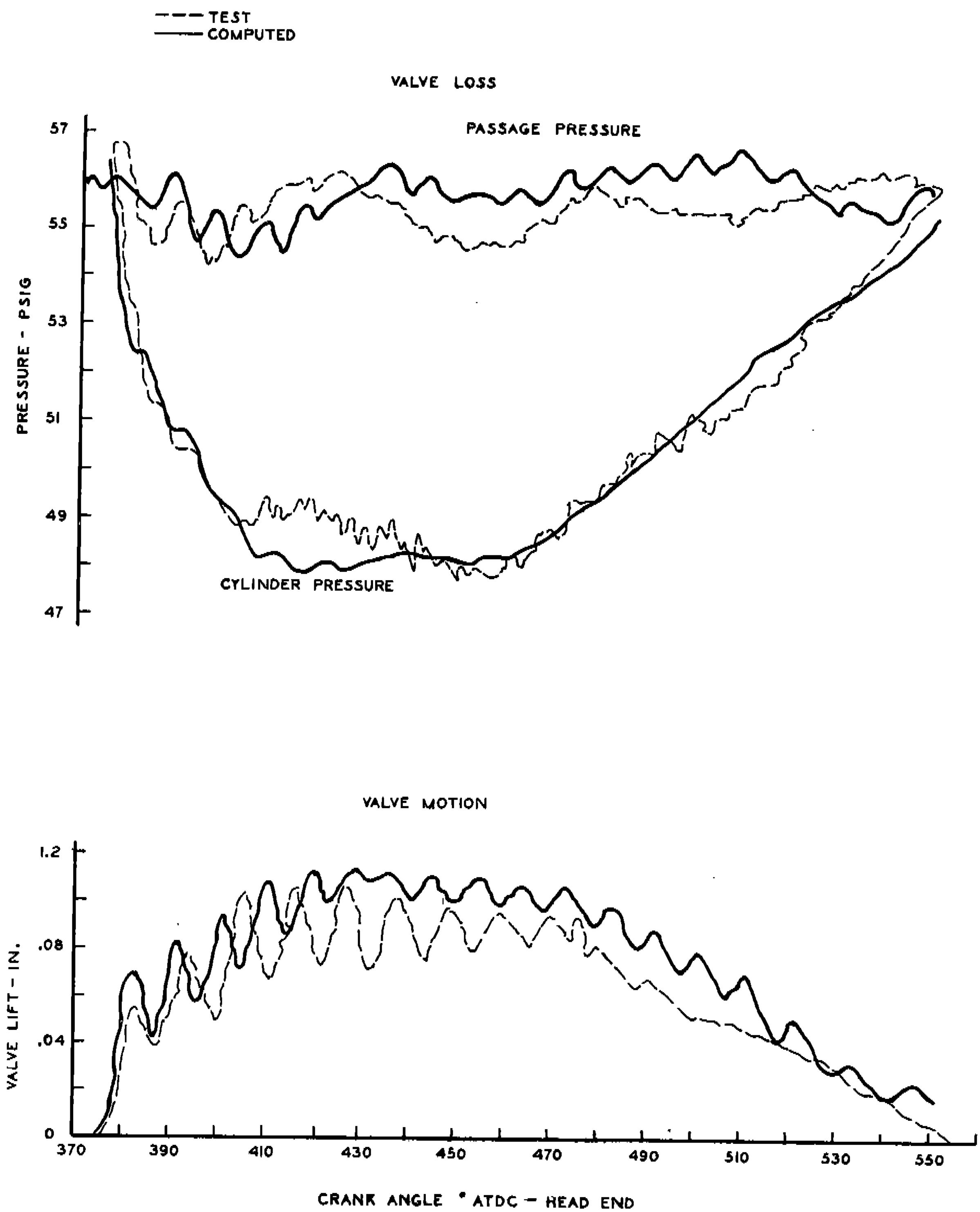


A. VALVE MOTION

B. VALVE PRESSURE DROP

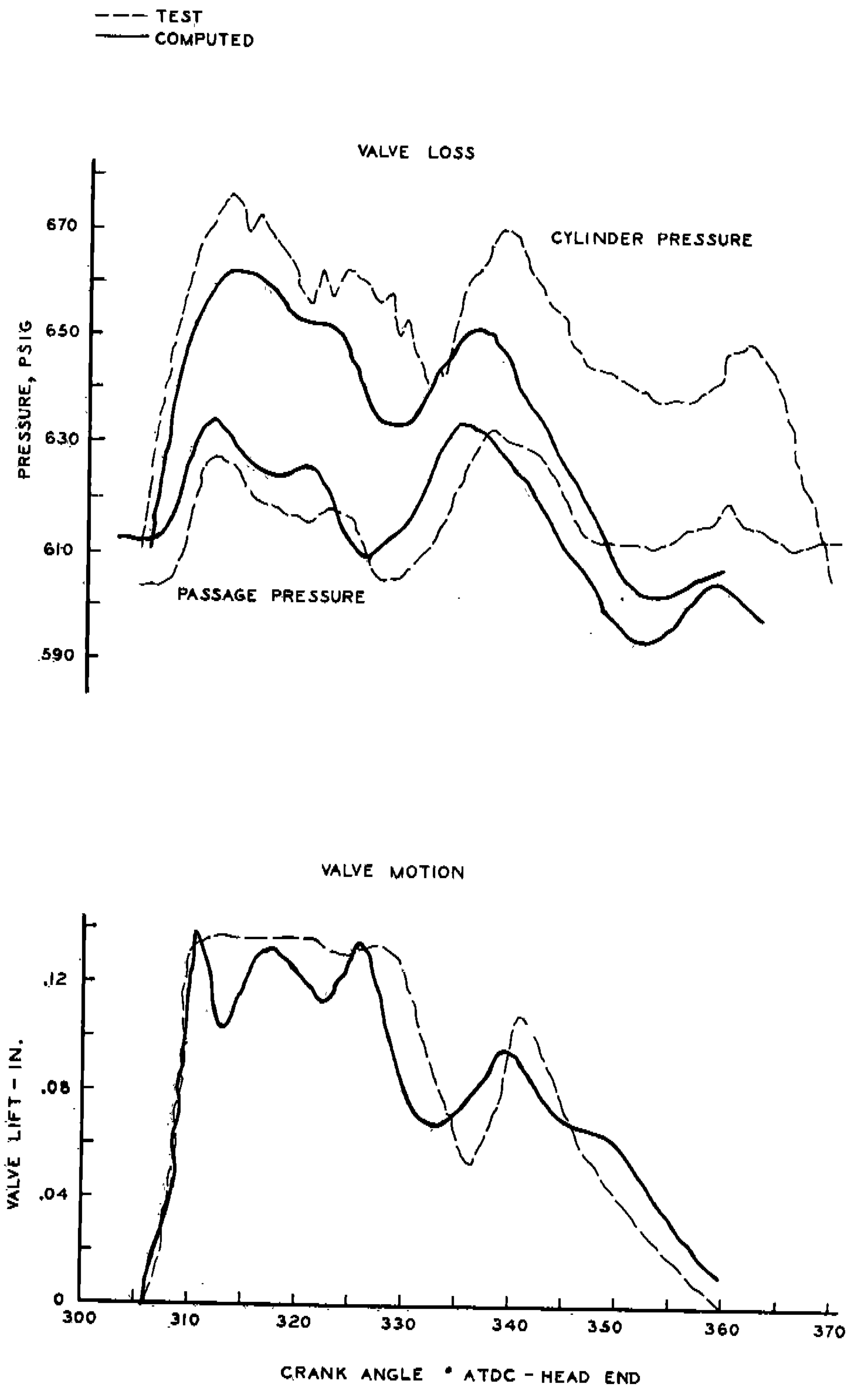
DYNAMIC INSTRUMENTATION

FIG. 5



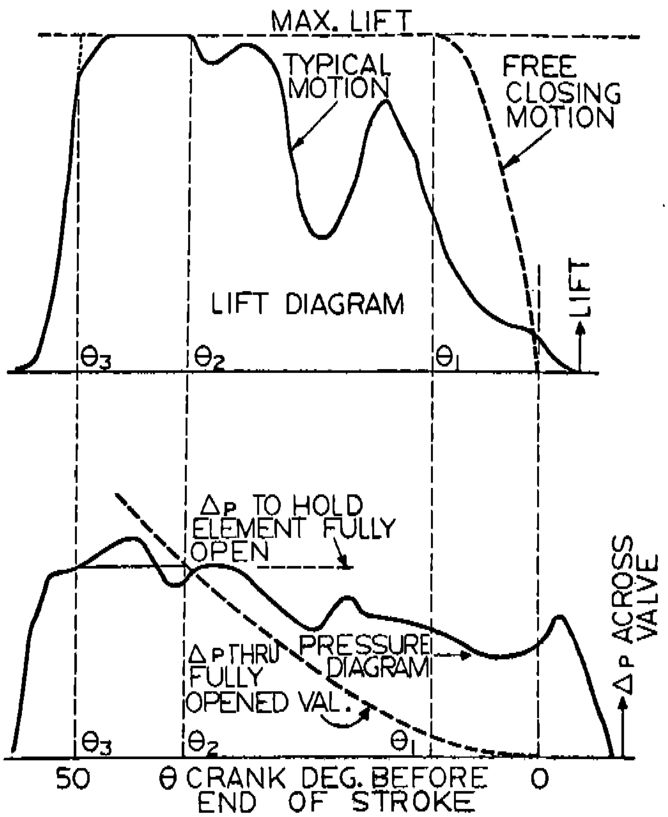
MEASURED AND COMPUTED PRESSURES AND VALVE MOTION

FIG. 6



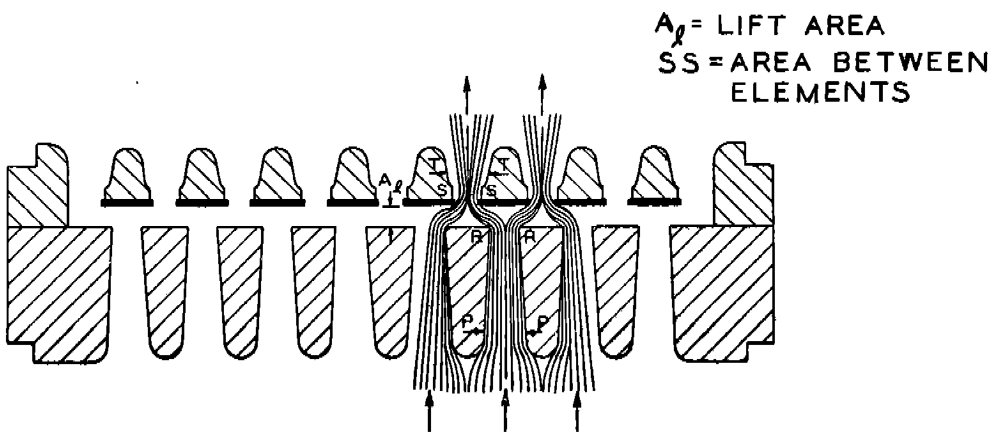
MEASURED AND COMPUTED PRESSURES AND VALVE MOTION

FIG. 7



Δp AND MOTION TRACES ILLUSTRATING DEFINITIONS OF θ_1, θ_2, AND θ_3

FIG. 8



FLOW CHARACTERISTICS THROUGH VALVE ELEMENTS

FIG. 9

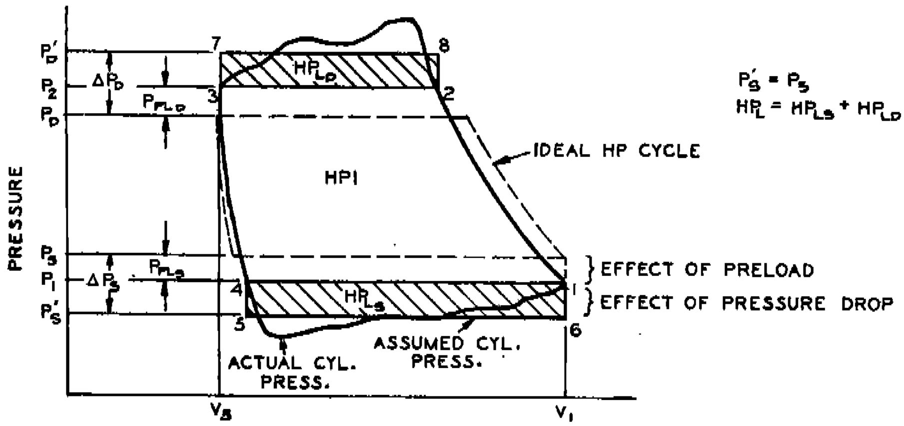
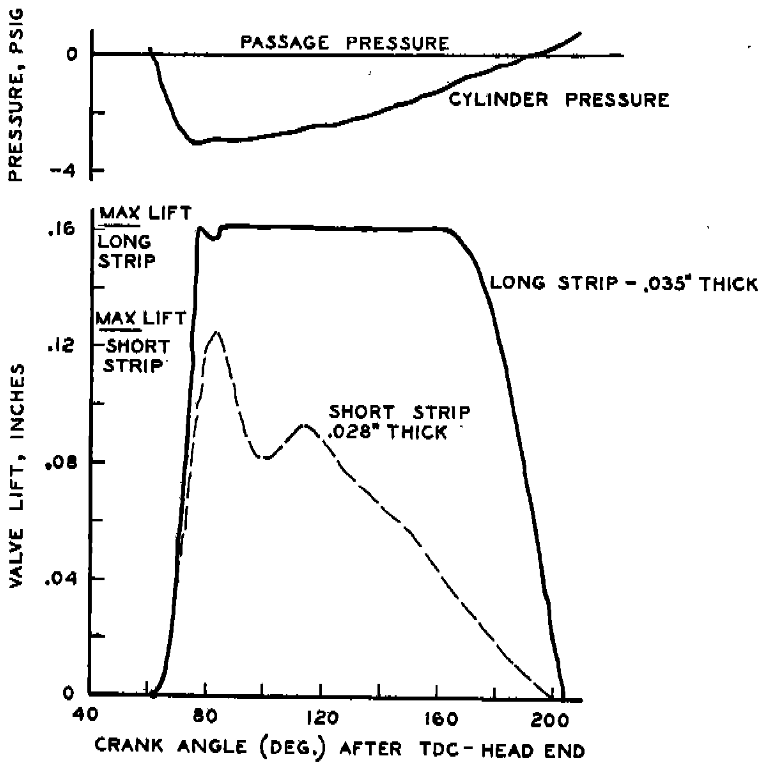
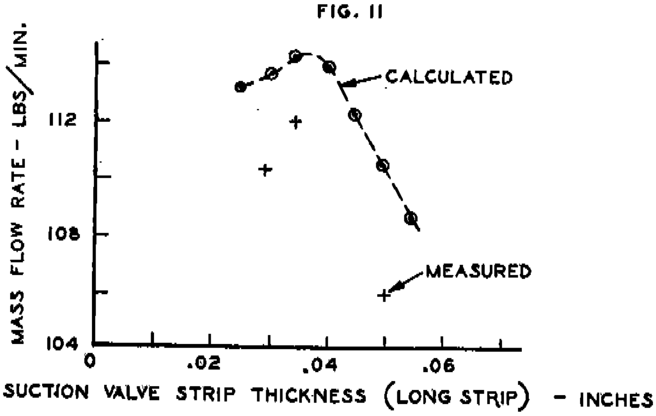


FIG. 10



SUCTION VALVE PERFORMANCE

FIG. 11



EFFECT OF SUCTION VALVE STRIP THICKNESS

FIG. 12