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Dredge Pump Research

GAS REMOVAL SYSTEMS
STUDY OF THE TOP HORIZONTAL DISCHARGE PUMP

by

Osman A. El-Ghamry

Rana P. Gupta

Fritz Engineering Laboratory Report No. 310.23

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ABSTRACT

The objective of this investigation is to study the effect of changing the orientation of the discharge pipe on the dredge pump tolerance to an entrained gas content in the flowing fluid. The system performance under various conditions of air content, pump speed, air removal systems, and discharge orifice setting was investigated.

Comparison with previous test results on the model pump with vertical discharge pipe showed that: (a) With the removal system inactive, the system performance was essentially the same in both cases, and (b) for the top horizontal discharge pump, smaller percentages of air removal were obtained and collapse points occurred at lower air percent pump suction.

PREFACE

This final project report summarizes the studies performed between July 1, 1970 and March 1, 1971. The project was conducted in the Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University in accordance with Contract No. DACW61-70-C-0229 for the Marine Design Division, Philadelphia District, U. S. Army Corps of Engineers.

Dr. Osman A. Elghamry is the Project Director and he is assisted by Mr. Rana P. Gupta. The technical staff of Fritz Engineering Laboratory assisted throughout the experimental work. Dr. David A. VanHorn is the Chairman of the Civil Engineering Department and Dr. Lynn S. Beedle is the Director of the Fritz Engineering Laboratory.

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1. INTRODUCTION

1.1 General

Dredging may be defined as the process of removing subaqueous material with the objective of increasing the water depth and/or acquiring subaqueous material for use as fill. Dredging is extensively used for channel and harbor construction, maintenance and improvement, land reclamation, dam and dyke construction, beach replenishment, etc. This operation can be done by a floating machine called a "Dredge".

There are several types of dredges. This study is concerned with the hopper dredges. In the United States, hopper dredges are of the hydraulic-suction type, equipped with special machinery which enables them to dredge material from the ocean bed or channel bottom, to discharge it into hoppers, to transport it, and to dump it at disposal sites.

The most important part of the dredge is the pump. It is of the centrifugal-radial type and must be designed to withstand heavy wear and abrasion. Dredge pumps may encounter mixtures consisting of widely varying proportions of solids, liquids and gases. When liquid-solid mixtures are pumped, the pump may choke if the density of the material in the suction line is too high. A choking condition is alleviated by either lifting the drag-head out of the mud or by admitting water to the suction line. However, if material containing a considerable amount of gas is encountered, the gas drawn into the suction line causes appreciable decrease in both the vacuum and the volume of solids discharged. Thus, the efficiency of the dredging operation is reduced and the pump may lose its prime. In recent years, the difference between actual choking and stoppage of the pump due to excessive gas has been recognized and the need for adequate gas removal from the suction line has become apparent.

1.2 Previous Research at Lehigh

Experimental investigations sponsored by the U. S. Army Corps of Engineers, Philadelphia District, were carried out at Lehigh University since 1962 to evaluate the effectiveness of gas removal systems installed on a model dredge pump. The gas removal system used in the prototype consists of an accumulator installed on the suction line and a vacuum source connected to the top of the accumulator. Experiments were made on a scale model (1:8) of the dredge pump in operation on the dredge Essayons of the U. S. Army Corps of Engineers. These investigations included the following aspects:

a) Location of the accumulator
b) Types of accumulators
c) Vacuum system used
d) Method of injection

Location of Accumulator. - Obviously, the accumulator should be installed at the location of maximum gas concentration. High speed motion pictures demonstrated that air is widely dispersed in small bubbles by turbulence. Under continuous injection of air, a uniform distribution of air throughout the suction pipe was observed. However, in the vicinity of the elbow, the density difference and centrifugal force effects combine to cause most of the air to collect at the inside of the bend. Again, air becomes widely dispersed before it reaches the pump. The best location for the accumulator is where the air collects. Obviously, the accumulator cannot be located at the trunnion elbow for practical reasons. However, on dredges having inboard elbows, this concept deserves consideration. The model accumulator was placed on the top of the suction pipe, with its center at a distance of 12.75 inches from the pump.

Types of Accumulators. - Two types of accumulators, designated as "original accumulator" and "modified accumulator" (Fig. 1, page 42), were tested. Model accumulators were fabricated of Plexiglass to allow visual observations of the flow conditions. The results indicated that the original accumulator was relatively ineffective in removing dispersed gas bubbles[1]*. The use of Level Trol as an automatic control of water level in the accumulator was not effective. The modified accumulator which has a sloping upstream side was tried. The height of the modified accumulator was increased to allow for the study of the influence of the water level in the accumulator.

Air removal was carried out using the modified accumulator and two vacuum sources. The liquid level in the accumulator, the percentage of air injection, the discharge orifice, and the pump speed varied from one run to the other. The modified accumulator proved to be more effective. Up to 40% of the injected gas was removed in the suction line, compared to 10% removed when the original accumulator was used.

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*Superscripts refer to references at the end of the report.

Vacuum Sources. - The vacuum pump and the water ejector were tested as part of the gas removal system to produce the vacuum at the top of the accumulator. With the vacuum pump in operation[1], it was observed that if the vacuum produced was smaller than the dredge pump suction pressure, air was drawn into the suction line through the relief valve on the vacuum line and caused a decrease in the dredge pump efficiency. When the vacuum produced on the top of the accumulator was equal to the dredge pump suction pressure, no significant amount of air was removed. At vacuums larger than the dredge pump suction pressure, air was removed through the accumulator.

A Penberthy Model 190-A, 4-inch ejector was used as a vacuum source. The ejector can be controlled by adjusting the pump speed, a bypass valve, or discharge valve. The most effective removal, using the vacuum pump, occurred when the liquid level in the model was held at about 20 to 24 inches above the centerline of the model suction pipe. The ejector was most effective when the liquid level was held in the upper portion of the accumulator. It is believed that the prototype system behavior is similar. The experimental results revealed that the use of the ejector, as a vacuum source, is superior to the use of the vacuum pump. It should be noted that while operating the two vacuum sources, the water level was kept in the upper portion of the accumulator in the case of the ejector and in the middle portion in the case of the vacuum pump.

Effect of Gas Injection Methods. - The test facility in the early experiments provided for continuous injection of air through a manifold of small openings around the inlet to the drag arm. A continuous stream of very fine air bubbles resulted from this arrangement. Though the air tended to rise in the drag arm, the secondary flow induced by the elbow dispersed the bubbles throughout the flow section at the accumulator. At high flow rates, the travel time in the suction line was not sufficient for the air to concentrate in the pipe, and the air was more uniformally distributed than at lower flow rates. Prototype dredges probably encounter gas in conditions conducive to the entry of occasional slugs or bursts of air into the drag arm. This would be quite different in effect on dredging operations than continuous gas flow, even if several slugs were encountered in close succession. A number of modifications of the gas injection system were tested. The experiments showed that the most successful method of air injection required a valve and a small receiver tank at the injection point. This proved to allow successful generation of a wide range of air flow patterns. Depending on the speed of valve operation, any type of flow, from a very short slug to a continuous stream, can be produced.

2. OBJECTIVES, SCOPE AND DETAILS OF THE EXPERIMENTAL PROGRAM

In the previous experimental investigations[1,5], the piping arrangement was kept the same and allowed for a vertical discharge pipe. The question was raised as to whether a dredge pump could be made self relieving with respect to entrained gas in the flowing mixture by changing the orientation of its discharge pipe to allow for a top horizontal flow at the exit of the pump. It was decided that all tests should be carried out under continuous gas injection.

The main objectives of the present investigation are:

1) To study the effect of changing the orientation of the dredge pump (such that the discharge is horizontal and at the top of the pump) on the pump tolerance to an entrained gas content continuously injected in the flowing fluid.

2) To study the effect of using a gas removal system consisting of the modified accumulator (Fig. 1) and different vacuum sources on the pump performance. Two vacuum sources were used:

   a) A vacuum pump

   b) A water ejector

3) To study the effect of the pump speed upon the pump performance with and without the removal system in operation.

4) To compare the results obtained with previous results.

A summary of the experimental program is given in the following paragraphs.

Pump Performance with Air Injection and with No Gas Removal

In these experiments, the gas removal system was kept inactive. Two types of experiments were performed.

Constant Speed and Variable Discharge Orifice. - In these experiments, the pump speed was kept constant for various settings of the discharge opening[*]. The discharge valve was manipulated to get a discharge orifice setting corresponding to a predecided initial flow rate. Air injection rate was varied in various test runs at a constant pump speed and discharge opening for a specific test until the pump collapse point was reached. Other experiments were performed for different discharge orifices at the same pump speed. Similar sets of experiments were performed at different pump speeds.

Constant Discharge Orifice and Variable Speed. - In this series, the pump speed was allowed to vary, keeping the discharge orifice at a constant setting in each specific test. The discharge orifice was initially adjusted to correspond to some selected flowrate (without air). The experiments were performed by varying the pump speed at a specified air injection rate. The air injection rate was kept constant during each run.

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[*] Discharge opening is used here to indicate the valve setting on the dredge discharge line.

Pump Performance with Air Injection and Gas Removal Systems

The necessary vacuum at the top of the accumulator was produced by using either a vacuum pump system or a water ejector system to affect gas removal. For this investigation, the following factors were considered in the experimental program:

a) Pump speed
b) Discharge orifice
c) Water level in the accumulator

These factors could vary independently, resulting in numerous combinations. Experiments were performed by selecting a few pump speeds, discharge orifice settings, and water levels in the accumulator with the water ejector acting as the vacuum source. For one specific test, two of these three factors were kept constant, and the third factor was allowed to vary with the increased air injection rate until collapse. Similar experiments were performed with the vacuum pump in operation.

3. EXPERIMENTAL SETUP AND PROCEDURE

The laboratory experiments of this investigation were carried out in the Hydraulics Division of the Fritz Engineering Laboratory, Lehigh University. The general arrangement of the experimental equipment is shown in Fig. 2. It consists of a suction tank, suction pipe, discharge pipe, discharge tank, and a return pipe all forming a continuous flow loop. External to the flow system is the pump motor and the air compressor. The details of the test setup are described in the following paragraphs.

3.1 Pump

The pump is a 1:8 scale model of the centrifugal pumps on the U. S. Army Corps of Engineers hopper dredge Essayons. The front of the pump casing is made of Plexiglass so that flow patterns can be visually observed and photographed. The remainder of the pump casing is a bronze casting. The model pump and the prototype pumps were manufactured by the Ellicott Machine Corporation. The pump was oriented to have a top horizontal discharge.

3.2 Impeller

The model pump impeller is 10.5 inches in diameter and has five vanes. The vane layout is in the form of an involute curve with an entrance angle of 45 degrees and an exit angle of 22-1/2 degrees. Earlier studies at Lehigh showed that this impeller design had high efficiency and cavitation performance[2]. The pump impeller is a bronze casting, fitted with a Plexiglass shroud on the suction side. The characteristics of this pump were given in earlier reports[1,5].

3.3 Motor

The pump is driven by a 40 Hp direct current motor manufactured by Westinghouse. It is designed to provide a wide range of speeds and an accurate speed regulation. The motor was calibrated by the manufacturer so that its power output could be calculated from input voltage and amperage data.

3.4 Magnetic Flow Meter

The discharge of the dredge pump was measured by means of a Magnetic Flow Meter manufactured by the Foxboro Company[3]. It is basically an electrical generator[4] which measures the volume flow rate of many liquids and semi-liquids. It operates accurately in any position as long as the line is completely filled. Neither turbulence nor variation in the flow profile seriously affect the transmitter. It is insensitive to line voltage changes of 10%. Hence, it is normally connected directly to the power line. The transmitter is connected directly to the Dynalog Recorder; no separate amplifier is required.

The magnetic flow meter measured volume rate of flow at the flowing temperature, independent of viscosity, density, turbulence and/or suspended material. In measuring air-water mixtures or other liquids containing suspended matter, the only assumptions are that the meter tube is running full and that the mixture is homogeneous.

3.5 Pump Speed

The speed was measured with a Hasler speed indicator. The speed was also monitored frequently with a stroboscopic tachometer.

3.6 Air Compressor

Air was provided by a single stage rotary compressor, model 5ccA, which is rated at 45 cfm at a discharge pressure of 30 psig. It is powered by a 7.5 Hp A.C. motor. The compressed air is fed through an aftercooler, a separator, and a filter before it is injected into the suction pipe.

3.7 Suction Pipe

The 4.5 inch diameter suction pipe is made of Plexiglass so that the air-water flow patterns can be observed and photographed.

3.8 Air Injection

The existing method of air injection includes a ball valve which is operated by means of a pipe extending from the valve stem to an operating lever mounted above the water surface.

3.9 Measuring Equipment

3.9.1 Air Flow Meters

In the preliminary runs of this investigation, the injected air was measured with a rotameter calibrated to read SCFM air at 25 psia and 70 degrees Fahrenheit. The air temperature at the flow meter was measured with a calibrated resistance wire temperature gage. The air pressure at the meter was also measured, and all air volumes were corrected to standard conditions. As the rotameter cannot be used for unsteady flow measurements (slug flow), a system using orifice plates and strain gage type diaphragm transducers was developed to replace the rotameter. A 1/4-inch orifice meter was selected for the 1/2-inch injection line. A Statham 50 psi differential transducer, Model PL 135 Tca-50-350, was installed on the injection line. The output from this differential transducer as well as the output from another transducer measuring the pressure upstream from the meter was fed to a Brush amplifier recorder system. A direct calibration of the transducers, by applying known pressure, gave the following equation for the mass rate of flow of air in the injection line:

$$\dot{m} = \frac{0.00084\, p_1^{0.5}\, (p_1 - p_2)^{0.5}}{\left(T_{ABS}\right)^{0.5}}$$

where: $\dot{m}$ = air flow rate, slugs/sec

p_1 = upstream pressure, psia

p_2 = downstream pressure, psia

T_{ABS} = absolute temperature, degrees Rankine

Computation of standard and local air flow rates was carried out during data reduction.

3.9.2 Suction and Discharge Manometers

The suction and discharge heads were measured by means of differential manometers. The suction head is measured one inch upstream from the outer edge of the pump face. The discharge head was measured 8 inches above the pump centerline and 3 inches from the discharge flange.

3.9.3 Other Measurements

Room temperature was noted in degrees Fahrenheit during experiments. The atmospheric pressure was recorded in inches of mercury using a standard barometer at the beginning and at the end of each test.

3.10 Gas Removal Systems

They consist mainly of an accumulator and a vacuum source. The existing Plexiglass accumulator (shown on Fig. 1b) is 4-1/2 inches square in cross-section. It has an enlarged opening to the suction pipe and is about 48 inches high measured from the centerline of the suction pipe. The vacuum source is either a reciprocating vacuum pump or a water ejector. The details of the two vacuum sources are given in the following.

3.10.1 Vacuum Pump System

It consists of a vacuum pump, a vacuum receiver, a vacuum flow meter, a laminar air flow meter, and an orifice plate equipped with pressure transducers.

3.10.1.1 Vacuum Pump

The vacuum pump is a piston type V244 with a 4 by 4 inch cylinder. It is driven by a 2 Hp A.C. motor. The pump has a maximum vacuum of 29.65 inches of mercury and a piston displacement of 16.0 cf.

3.10.1.2 Vacuum Receiver

This is a 20 by 48 inch cylindrical galvanized tank. It has a capacity of 60 gallons and serves to keep water from entering the vacuum pump.

3.10.1.3 Laminar Air Flow Meter

A laminar air flow meter was used to measure the removed flow rate. This meter is a Model D-23170 manufactured by the Meriam Instrument Company. It has been calibrated to read directly the SCFM at 70 degrees Fahrenheit and 29.92 inches of mercury absolute pressure. As this device is slow responding, it has been replaced by an indirect measuring system using an orifice plate and strain gage diaphragm transducers. However, the laminar air flow meter was used to calibrate the orifice meter. The air flow meter consists of two parts: the laminar flow element and an inclined manometer. The laminar flow element is a flow measuring device indicating volume flow by producing an easily determined differential pressure. The inclined manometer provided good readibility by stretching a vertical differential head along an inclined indicating column. The laminar flow element operates on the principle of Poiseuille flow. The laminar flow meter channels the flow through myriad parallel ducts which keep the velocity about the same as in the pipe while reducing the duct dimension to produce laminar flow. The dimensions of the passages are only a few thousandths of an inch, while the length of the passage is normally a few inches. The pressure drop due to friction is determined by the pressure difference between the inlet and the outlet of the ducts.

3.10.1.4 Orifice Plate and Pressure Transducers

A system using orifice plate and strain gage-diaphragm transducers was developed to measure the air flow rate on the removal side. After several trials, a 3/8-inch orifice was selected for the 1-1/2 inch gas removal line. A 2 psi differential pressure Statham transducer, Model P73-2D-120, was installed on the vacuum line to measure the differential pressure. Another transducer was mounted on the upstream side of the orifice. The output from these transducers was recorded on the Brush recorder. Calibration tests gave the following equation:

$$\dot{m} = 0.002\, p_1^{0.8} \left(\frac{p_1 - p_2}{T_{ABS}}\right)^{0.8}$$

where: $\dot{m}$ = air flow rate, slugs/sec

p_1 = upstream pressure, psia

p_2 = downstream pressure, psia

T_{ABS} = absolute temperature, degrees Rankine

Standard and local air flow rates were computed during the final data reduction. Because of pressure and temperature variations, the volume rate is different at each section of the system, however, the mass flow balance must be maintained.

3.10.2 The Water Ejector System

This system consists of a water ejector, a pipeline carrying the driving water, a venturimeter and a manometer to measure the head differential through the venturimeter, a vacuum gage to measure the general vacuum pressure, and a magnetic flow meter to measure the total flow rate of the air-water mixture.

The ejector used is a Penberthy Model 190A 4-inch ejector capable of handling the following air flow rates with a water supply of 80 gallons per minute at 40 psi: 14.7 SCFM at 5 inches of mercury vacuum, and 8.2 SCFM at 10 inches of mercury vacuum. The water drive for the ejector is supplied from the laboratory sump by a dredge pump similar to the one described previously. It has a rated flow capacity of approximately 10 times the flow required by the ejector. The pipeline is 4 inches in diameter reduced to 2-1/2 inches only at the ejector connection. The discharge from the ejector passes through a magnetic flow meter and a control valve and returns to the sump. The ejector is coupled to the accumulator by means of a rubber hose pipe. The ejector nozzle converts the pressure head into a high velocity stream and thus vacuum is produced.

The water flow rate to the ejector is measured by a venturimeter and indicated on a differential manometer. The rating equation for the venturimeter is:

$$Q = 0.0836\ h^{0.43}$$

where: Q = flow rate, cubic feet/sec

h = manometer head readings, in inches

The total air-water mixture flow rate was measured by a magnetic flow meter mounted on the downstream of the water ejector.

3.11 Tests and Test Procedures

Four test series were performed. The O-Series was designed to study the pump behavior and the flow patterns in the accumulator and the impeller while the vacuum source is kept inactive. The O-N-Series was aimed at investigating the effect of pump speed variation on the pump performance under different air injection rates. The P-Series and the E-Series involved the operation of the gas removal system. In the E-Series, the water ejector provided the vacuum for the gas removal, whereas in the P-Series, the vacuum pump acted as the vacuum source for gas removal. The various test series and the steps involved in actual tests can be described as follows.

3.11.1 O-Series

In this series, the gas removal system was kept inactive. Experiments were conducted for initial flow rates of 400, 600, 800, 1000 and 1200 gpm. The dredge pump speeds used were 1440, 1200 and 1000 rpm. Tests with an initial flow rate of 1200 gpm were performed at speeds of 1440 and 1200 rpm only. It should be noted that the prototype rated pump speed would correspond to a model pump speed of 1440 rpm. The following steps were followed for each run:

a) Switch on the flow recorder and air compressor.

b) Balance Brush recorder amplifiers.

c) Calibrate pressure transducers on recorder channels.

d) Start the pump motor and set the desired pump speed.

e) Select an initial flow rate and adjust the discharge valve until the selected flow rate is obtained.

f) Record the initial readings on the suction and discharge manometers.

g) Record the control parameters, such as, suction and discharge pressure manometer readings, voltage, amperage, flowrate, and pump speed.

h) Inject a controlled amount of air into the suction pipe.

i) Record the injected air on the Brush recorder.

j) Take readings similar to those under item g.

k) Change the injected air flow rate and repeat steps i through k.

l) Note the amount of air injection which causes complete collapse.

m) Note the room temperature and barometric pressure at the start and at the end of the run. Calculate the mean values.

3.11.2 O-N-Series

This series was designed to study the behavior of the pump under variable pump speed and constant discharge orifice. It includes four runs. The gas removal source was kept inactive. No air was injected in the first run, and the discharge opening was adjusted to give an initial flow rate of 800 gpm at a pump speed of 1440 rpm. The pump speed was changed, and the discharge was recorded keeping the discharge opening constant. Readings of the flow rates and suction and discharge pressure manometers were recorded at different pump speeds varying from 886 to 1451 rpm. In the next three runs, the same procedure was followed while air was injected at a constant rate in each run.

3.11.3 P-Series

In this series, the reciprocating vacuum pump was used as a vacuum source to remove the air through the modified accumulator. The test procedure, discharges, pump speeds, and air injection rates were quite similar to that of the O-Series. A few additional observations were taken, namely, the flow rate of the removed air through the accumulator and the vacuum pressure in the receiver tank.

3.11.4 E-Series

In this series, the vacuum pump of the P-Series was replaced by a water ejector to provide vacuum at the top of the accumulator for gas removal. A venturimeter on the ejector line was installed to measure the driving water flow rate. Some additional observations were taken, namely, the magnetic flow meter readings on the ejector line, the head on the venturimeter, and the vacuum pressure created by the ejector. The experiments cover the same initial water discharges, pump speeds, and air injection rates.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results clarified some aspects of the pump performance (as affected by the presence of gas content in the flowing mixture) and the efficiency of the gas removal systems.

4.1 Data Reduction

All the tests were conducted under steady air flow. A sample of input and output quantities in the case of gas removal with the vacuum pump is included here to illustrate the procedure for data reduction and to show the method for calculating values of the variables, which appear in various plots. The basic data reduction was carried out using the CONTROL DATA CORPORATION 6400 COMPUTER of the Computer Center at Lehigh University. A typical computer program is shown in the Appendix.

Steady Flow - Vacuum Pump

Initial Readings: (for entire test)

Test Number, NUM
Number of runs in a test, N
Temperature °F, T
Atmospheric Pressure, inches of mercury, PAT
Suction Manometer, inches of mercury, HSLO, HSRO
Discharge Manometers, inches of mercury, HL10, HR10, HL20, HR20
Revolutions per minute, RPM

Readings: (any run)

Motor Current, amperes, AMP
Motor Voltage, volts, V
Total Flow Rate, gpm, QGPM

Suction Manometer, HSL, HSR
Discharge Manometers, HL1, HR1, HL2, HR2
Injection Air Pressure, psi, gage, API1
Differential Pressure, injection side, psi, DAPI
Vacuum Pressure, removal side, inches of mercury, APR1
Differential Pressure, removal side, inches of mercury, DAPR

Computed Quantities: (any run)

For record purposes, all the input data were reproduced in output except initial suction and discharge manometer readings. The additional computed quantities appearing in the computer output are:

Air Flow Rate Injection, SCFM, SAFI
Air Flow Rate Removal, SCFM, SAFR
Air Flow Rate to Pump, SCFM, SAFP
Air Flow Rate, Pump Suction, cfs, AWS, same as QAP
Air Flow Rate, Pump Discharge, cfs, AQD
Air Percent, Pump Suction, APS, equal to QAP/QW
Velocity Head, Pump Suction, VHS
Velocity Head, Pump Discharge, VHD
Total Flow Rate, gpm, QGPM
Total Flow Rate, cfs, QT
Water Flow Rate, cfs, QW
Water Horsepower, WHP
Pump Discharge Pressure, ft of water, PDW
Pump Suction Pressure, ft of water, PSW
Total Dynamic Head, ft of water, H
Pump Efficiency, EFF
Dimensionless Head, HDIM
Dimensionless Discharge, QDIM
Discharge Pressure, ft of mixture, PDM
Suction Pressure, ft of mixture, PSM
Total Dynamic Head, ft of mixture, HM
Efficiency H Mixture, EFFM
Dimensionless HM, HMDIM
Vacuum Pressure in ft of water, RMOVP1
Air Mass Flow Rate Injected, slugs/sec, AMFI
Air Mass Flow Rate Removed, slugs/sec, AMFR
Air Mass Flow Rate to Pump, slugs/sec, AMFP

The experimental results were presented in terms of relevant dimensionless parameters. Convenient comparisons to previous tests with vertical pump discharge are also included.

4.2 Effect of Gas Content on Pump Performance

In these experiments, no gas removal took place. With the accumulator installed on the suction pipe, the vacuum producing system was kept inactive. Two groups of experiments were carried out.

4.2.1 Variable Pump Speed and Constant Discharge Opening

In these runs, the discharge opening was adjusted to give an initial water flow rate of 800 gpm at a pump speed of 1440 rpm. This speed corresponds to the prototype rated pump speed for no air injection. The pump discharge opening was kept intact throughout the experiment. The pump speed was varied from 1528 to 886 revolutions per minute in short steps and the resultant flow was recorded. Four experiments with continuous air injection rates of 0, 5.35, 5.81 and 6.35 SCFM were performed. A brief discussion of the results is given below.

4.2.1.1 Relationship Between Pump Speed and Flow Rate

Figure 3 shows a plot of the total flow rate (QGPM) against the pump speed. The discharge decreases linearly with the decrease in pump speed in the case of no air injection. For an air injection rate of 5.35 SCFM, the linearity between the flow rate and the pump speed exists for pump speeds higher than 1150 rpm. At this speed, the flow rate decreased abruptly with a slight reduction in pump speed. For pump speeds below 1100 rpm, the flow rate was again a linear function of the pump speed until the collapse point was reached. The behavior of the system was quite similar in the case of air injection rate of 5.81 SCFM, except that the point of sudden change occurred at a higher pump speed (1400 rpm). In the case of air injection rate of 6.35 SCFM, the flow rate dropped sharply from 600 gpm to 450 gpm when pump speed decreased from 1400 to 1310 rpm. It should be noted that the lowest points on the curves represent collapse points.

4.2.1.2 Relationship Between Water Horsepower and Pump Speed

The water horsepower (WHP) was plotted against pump speed in Fig. 4. In the case of air injection of 5.35 and 6.35 SCFM, the water horsepower decreases with the decrease in pump speed, and a sudden change appears at a specific pump speed. This is followed by a gradual decrease of water horsepower with the decreasing pump speed. The curve, showing the result of an air injection rate of 6.35 SCFM, lacks the lower region of gradual change after the sudden change point, due to pump collapse. Pump speeds at which the abrupt changes of both discharge and water horsepower occur (break point) depend upon the percentage of air injection. All runs in these series were conducted at the same conditions of room temperature and atmospheric pressure.

4.2.2 Variable Discharge Opening and Constant Pump Speed

These experiments were carried out at a constant pump speed for various pump discharge openings with the gas removal system inactive. In each run, some preselected discharge opening was maintained, and both the water and total flow rates changed with the variation of air injection rate keeping the pump speed unchanged. The experimental data are presented in terms of four dimensionless parameters, which can be grouped into three sets of relationships. The first parameter is the dimensionless discharge defined by

$$QDIM = QW/(2\pi RPM/60)\ D^3$$

where RPM is the pump speed in revolutions per minute, QW is the water flow rate, and D is the pump diameter. The second parameter is the air percent pump suction, QAP/QW. This is defined as the air flow rate through the pump (and at pump suction conditions of temperature and pressure), QAP, expressed as a percentage of the water flow rate, QW. The third parameter is the air injection ratio, SAFI/QWO, which is the air injection rate in standard cubic feet per minute expressed as a percentage of the initial flow rate, QWO. The fourth parameter is the water discharge ratio, QW/QWO. This is defined as the percentage of the water flow rate to the initial flow rate of the dredge pump.

The first set of curves is a plot of QDIM against QAP/QW (Figs. 5, 6 and 7) and is meant to define the pump characteristics under different conditions of air content in the mixture at pump suction conditions. Each curve represents the conditions at a specific pump speed and initial flow rate. The second set of curves (Figs. 8, 9 and 10) shows the relationship between the percentage of air flow to water flow rate through the pump and the ratio between the volume rates of air injection (at standard air temperature and pressure) (SAFI) to the nominal (initial) water discharge. The initial discharge QWO could be obtained from the pump characteristic curves. The third set of curves (Figs. 11, 12 and 13) shows how the ratio of the actual water discharge to the initial water discharge and QAP/QW are related.

4.2.2.1 Relationship Between QDIM and QAP/QW

Figures 5, 6 and 7 show the variation of QDIM with QAP/QW. Starting from QAP equal to zero, the water discharge stayed substantially the same with the increase of QAP/QW up to a certain value. For QAP/QW above 5% in most cases, a sharp decrease took place in the water discharge with the increase of QAP/QW. This stage of the flow can be termed the "Break Point". It indicates a zone of unstable flow. Afterwards, the flow stabilizes again with a small rate of change of the dimensionless discharge with the increase in QAP/QW until pump collapse is reached.

It is difficult to define exactly the so-called "break point", but the trend of all curves is quite similar for all initial flow rates and pump speeds used.

4.2.2.2 Relationship Between QAP/QW and SAFI/QWO

Figures 8, 9 and 10 show plots of QAP/QW against SAFI/QWO. In the case of low initial flow rates, it was difficult to obtain accurate results for small values of air injection ratio. Therefore, no points were given on the plots up to an injection ratio of about 5 percent in the case of an initial flow rate of 400 gpm. For the same injection ratio, SAFI/QWO, the values of QAP/QW are larger in the case of higher flow rates than in the case of lower flow rates. This is partially due to the change in pressures at the pump suction with the initial flow rates. It is obvious that the air injection ratio at the collapse point is much larger in the case of lower flow rates than that for higher flow rates. At pump collapse conditions, QAP/QW is somewhat larger for higher initial flow rates than for lower flow rates, showing that the pump has a higher air tolerance at higher flow rates.

4.2.2.3 Relationship Between QW/QWO and QAP/QW

For the direct estimation of the water discharge, plots of QW/QWO against QAP/QW for different values of initial flow rates and pump speeds are given in Figs. 11, 12 and 13. These figures show that the rate of decrease of QW/QWO with the increase of QAP/QW is small for low values of QAP/QW. At some critical value of QAP/QW, QW/QWO experiences a sudden fall with the increase of QAP/QW. This critical value is followed by a gradual slow change of QW/QWO until pump collapse is reached. These results indicate that for a certain QAP/QW, the values of QW/QWO at low initial flow rates are larger than those for higher flow rates. Again for the same QW/QWO, the value of QAP/QW is larger for lower initial flow rates. This is due to the difference in the suction head.

4.2.2.4 General Conclusions

It is clear from Figs. 5, 6, 7, 11, 12 and 13 that the break point for most cases was at an air percent pump suction between 6 and 10. In an earlier report[1] on similar tests performed on the vertical discharging pump, it was shown that for air percent pump suction up to 9%, only minor effects on the water flow rate or the pumping head were observed. A sample of this data is given on Fig. 14. Although break points cannot be precisely defined yet, it seems that the change of orientation of the discharge pipe does not affect the pump performance.

4.3 Effects of Gas Removal Systems

4.3.1 The Water Ejector Removal System

In these tests, the water ejector provided the necessary vacuum pressure at the top of the accumulator. Tests were conducted at pump speeds of 1000, 1200, and 1440 rpm, discharge valve settings corresponding to initial discharges of 400, 600, 800, 1000, and 1200 gpm, and at various water levels in the accumulator.

The experimental results are presented by four sets of plots including the three sets previously described. The fourth set of curves shows the relationship between the percent of gas removal, SAFR/SAFI, and the gas injection ratio, SAFI/QWO, where SAFR is the air flow rate removed through the accumulator in standard cubic feet per minute. Figures 26, 28 and 29 show plots of SAFR/SAFI against SAFI/QWO. These plots demonstrate the efficiency of the gas removal system. Three independent factors, namely, the pump speed, the discharge orifice setting, and the water level in the accumulator, can lead to numerous combinations. Tests were run by selecting a few pump speeds, discharge orifice settings, and water levels in the accumulator. Only one of these three factors was allowed to vary with the increased air injection rate until collapse occurred.

4.3.1.1 Relationship Between QDIM and QAP/QW

Dimensionless discharge is plotted against the air content at pump suction, QAP/QW. This is shown in Figs. 15, 17 and 18. The shape of the curves is quite similar to those obtained in the case of no gas removal. The larger air tolerance of the pump is evident by the delayed collapse, particularly at high flow rates of 1000 and 1200 gpm. This is due to the additional suction in the vicinity of the pump entrance produced by the removal system. In other words, the vacuum produced by the removal system will have two effects: It reduces the amount of injected air flow to the pump by removing part of it, and it helps maintain the pump suction (priming) at high percentages of air flow to the pump. The curves have mild slopes at low values of QAP/QW, which are followed by relatively steeper slopes until collapse is reached. The break points and collapse points in various tests occur at different values of QAP/QW, depending upon the pump speed, the initial discharge valve setting, and the water level in the accumulator. Figure 16 is a reproduction of previous results obtained with vertical discharging pipes which are comparable to those shown on Fig. 15. It seems that no improvement was obtained by changing the orientation of the discharge pipe from vertical to horizontal. However, the collapse points for the horizontal orientation occurred at lower QAP/QW in cases of low initial discharges.

4.3.1.2 Relationship Between QW/QWO and QAP/QW

The air percent pump suction demonstrates the effects of gas removal and air injection ratio, since the air mass flowing to the pump is the difference between the injected and removed air mass flow rates. The water discharges are needed to evaluate the effect of the gas removal systemson the dredging performance.

Water discharge ratio, QW/QWO, is plotted against air percent at pump suction, QAP/QW, on Figs. 19, 20 and 21. QW/QWO decreases very little with an increase of QAP/QW at low values of QAP/QW. At some specific QAP/QW, depending upon the initial flow rate, pump speed, and water level in the accumulator, QW/QWO experiences an abrupt and unsteady drop even with a small increase in QAP/QW. This is the break point and is followed by stable flow conditions until collapse occurs. The trend of curves is quite similar to that obtained for no gas removal.

4.3.1.3 Relationship Between QAP/QW and SAFI/QWO

These curves, presented in Figs. 22, 24 and 25, show the relationship between air percent at pump suction, QAP/QW, and air injection rate in SCFM divided by initial water discharge, SAFI/QWO. The initial water discharge is used as a reference for the injected air flow rate at standard conditions.

A relatively large percentage of air has to be injected at low flow rates to get the measurable values of QAP. For the same QAP/QW, values of the injection ratio, SAFI/QWO, are larger for lower flow rates than those for higher flow rates. Again for the same SAFI/QWO, higher values of QAP/QW occur for higher flow rates. At collapse, SAFI/QWO is larger for lower flow rates with a few exceptions which may be due to experimental error in determining the exact collapse point. A comparison between Figs. 22 and 23 would show that no improvement is achieved by changing the orientation of the discharge pipe.

4.3.1.4 Relationship Between SAFR/SAFI and SAFI/QWO

Percent gas removal, SAFR/SAFI, is plotted against SAFI/QWO for various initial flow rates and pump speeds. These curves illustrate the efficiency of the gas removal system and are shown in Figs. 26, 28 and 29. It is clear from the curves that a significant percentage of injected gas is removed before it reaches the suction side of the pump. The percentage of gas removal depends mainly on initial water discharge, pump speed, water level in the accumulator, and the injection ratio, SAFI/QWO. Curves also show that maximum percentage of gas removal varies between 15 and 35. There is strong dependence of SAFR/SAFI upon the gas injection ratio, SAFI/QWO. This is indicated by the steep slopes of the curves. A comparison between these results and those obtained with the vertical discharging pump, Figs. 26 and 27, shows that smaller air removal was achieved in the case of a horizontally discharging pump.

4.3.2 The Vacuum Pump Removal System

The reciprocating vacuum pump acted as a source of vacuum pressure for gas removal. The tests performed are quite similar to those described for the water ejector system. The vacuum pump can be easily controlled by the use of air admission valves, but must be protected from any water discharge. To meet this requirement, experiments were conducted with the liquid level held in the central portion of the accumulator. The method of presentation of results is similar to the one adopted for the water ejector removal system.

The dimensionless discharge is plotted against air percent pump suction, QAP/QW, and is shown in Figs. 30, 32 and 33. The curves display a resemblance with those plotted for the water ejector removal system. A small steady flow zone at low values of QAP/QW leads to a break point, characterized by an abrupt change in QDIM with QAP/QW and unsteady flow. This unstable flow zone is followed by stabilized conditions leading to a collapse. The break point and the collapse point occur at different values of QAP/QW, depending mainly upon the initial flow rate, pump speed, and water level in the accumulator. Generally, the higher the initial flow rate, the higher is the value of QAP/QW at collapse.

Figures 34, 35 and 36 illustrate the relationship between the water discharge ratio, QW/QWO, and the air percent pump suction, QAP/QW. These curves are very useful for evaluating the dredging performance. The curves show similar trends to those observed in the case of the water ejector removal system. The behavior of the system depends mainly upon the pump speed, the initial flow rate, and the water level in the accumulator. Accordingly, the break points, the collapse points, the values of QAP/QW, and the corresponding discharge ratios may vary, but the shapes of the curves essentially remain the same.

Figures 37, 39 and 40 show the relationship between the air percent suction, QAP/QW, and the air injection ratio, SAFI/QWO. The curves are similar to those obtained for the water ejector removal system. Conclusions are essentially the same as derived in the case of the water ejector removal system.

Figures 41, 43 and 44 present the relationship between the percentage of gas removal, SAFR/SAFI, and the air injection ratio, SAFI/QWO. Though there is considerable scatter, a good amount of injected gas can be removed by this system. The percentage of gas removal varies with initial flow rate, pump speed, water level in the accumulator, and air injection ratio, SAFI/QWO. The performance of the vacuum pump as a vacuum source proved to be inferior to that of the water ejector. When the latter was used, better manageability, control of the water level in the ejector, and steadiness of the flow pattern were obtained. The use of the vacuum pump put some restrictions on the maximum water level in the accumulator.

To study the influence of the discharge pipe orientation, Figs. 30, 37 and 41 are compared with Figs. 31, 38 and 42, respectively. The following conclusions could be reached:

(a) Similar trends are observed in both cases of the discharge pipe orientation.

(b) The vacuum pump gas removal system is more efficient in the case of a vertical discharge pipe.

(c) Collapse points occurred, in general, at higher values of QAP/QW in the case of vertical discharge pipe. In this case, the pump would be more tolerant to entrained gas in the flowing mixture.

4.4 General Remarks

The gas removal system removes only a portion of the gas injected and the remaining gas flows to the suction side of the pump. Thus, the percentage of gas reaching the pump suction is reduced but cannot be eliminated. The amount of gas removal depends upon many factors, such as, initial flow rate, water flow rate, gas injection rate, pump speed, water level in the accumulator, etc. The model test results show some scatter which is natural for this type of phenomenon. However, the results indicate clearly the beneficial effect of a gas removal system when pumping a fluid with high gas content. It is apparent that the use of an active gas removal system permits the pumping of fluids with higher gas contents than could otherwise be tolerated.

The comparison of air percent pump suction, QAP/QW, at collapse for a specific initial flow rate (corresponding to some specific discharge valve setting) for no gas removal and for gas removal with the vacuum pump or the water ejector at different pump speeds shows that there is a considerable increase of QAP/QW at collapse in the case of gas removal systems in operation. This indicates an increase in the pump tolerance to air flow. It should be noted that an exact determination of the collapse point is rather impossible due to the instability of the flow conditions in the accumulator. The comparative examination of the QAP/QW against SAFI/QWO plots at comparable discharge valve settings and pump speeds for the two cases of no gas removal and a gas removal system in operation shows that a considerable amount of gas is being removed.

The vacuum pump can be easily controlled by an air admission valve but must be protected from water. The most effective use of the vacuum pump resulted with the liquid level held in the central portion of the accumulator. The ejector can be controlled using pump speed, a bypass valve, or the discharge valve and is not affected by liquid-gas mixtures. The water ejector gave the best performance when the water in the accumulator is kept at its highest level, as is believed to be the case in actual prototype practice.

4.5 Visual Observations

High speed movies were taken at a speed of 1500 frames per second to study the flow pattern in the accumulator under constant gas injection. Another set of high speed motion pictures were taken for the study of the flow characteristic inside the pump casing. These movies were for several combinations of pump speeds, discharge valve settings, vacuum sources, and air injection and air removal rates. A few were also taken in the case of the gas removal system inactive.

High speed movies of the accumulator were used to study the flow pattern in the case of constant injection of air in the accumulator. A vortex is created by the air accumulated in the space underneath the sloping portion of the modified accumulator at its junction to the suction pipe. Out of the total gas injected, a certain percentage enters the accumulator, whereas the remaining gas travels straight to the suction side of the pump. A portion of gas in the accumulator rises towards its top where it flows to the vacuum pump or the water ejector. The high speed movie clearly shows the distribution of the air bubbles in the accumulator.

High speed movies of the air flow in the pump casing has enabled a comparative study of horizontal and vertical alignments of the discharge pipe. These pictures clarify the effect of pump speed on the pump performance. In the case of a horizontally oriented discharge pipe, the air does not have a good chance to flow in the discharge side of the pump, but keeps on circulating in the pump. This action is further aggravated in the case of operation at higher pump speeds because more air will just pass by without entering the discharge pipe. The vertical alignment of the discharge pipe is considered to be better than the horizontal orientation. It seems that the vertical discharge pipe offers a better chance for the air to escape towards the discharge side.

5. SUMMARY AND CONCLUSIONS

This experimental investigation is concerned with the study of the effect of gas content in flowing mixtures on a dredge pump performance. The experimental program includes the study of the comparitive effectiveness of two gas removal systems. The gas removal systems used consist of an accumulator, installed on the suction line, with its top connected to a vacuum generating source. The pump in these tests had a horizontal top discharging pipe. The results were compared with previous observations with vertical (upward) discharge pipe.

The following conclusions could be drawn from the experimental results:

Pump Performance with the Removal System Inactive

(1) The discharge-speed and water horsepower-speed curves of the pump with gas content in the flow mixture were lower than those with no gas content.

(2) Break points in the discharge-speed (and the water horsepower-speed) curves took place at certain speeds which depend upon the gas content of the flowing mixture and the discharge opening.

(3) For the same pump discharge opening, the pump speed at which collapse occurred increased with the increase of air injection.

(4) For small values of air injection, the water discharge is slightly affected up to a certain percentage of air in the suction (see Nomenclature, pages 86-89), between 6 and 10. Beyond these values, a rapid decrease of the water discharge takes place with a relatively small increase in the air content.

(5) Previous observations, obtained with a top vertical discharge pipe, showed tendencies similar to (1), (2), (3) and (4) above. Figure 14 shows that for pump suction air percentage up to 9%, only minor effects on the water flow rate or the pumping head were observed.

Effect of Gas Removal Systems

A vacuum was produced using two different devices, namely, the water ejector and the vacuum pump.

(1) A good percentage of the injected mass of gas could be removed by the removal systems used. Maximum values of gas removal ranged from 15% to 35% of the injected gas, depending upon the dredge pump discharge opening, pump speed, water level in the accumulator, and the gas content.

(2) The water ejector appears to be preferable to the vacuum pump as a vacuum device on a gas removal system. It provides easier control of the water level

in the accumulator and is not affected by liquid-gas mixture. Larger amounts of gas removal were possible in the case of the water ejector due to these reasons.

(3) The pump performance improved with the operation of either of the gas removal systems used. This was due to two reasons, namely, the removal of a certain percentage of the gas content in the fluid mixture, and the additional suction created by the gas removal system. It was observed that the air content at which collapse took place with the vacuum system in operation was higher than the corresponding air content for the case when the vacuum source was kept inactive.

(4) Comparisons with previous tests on the vertical discharge pipe showed that:

  (a) No substantial improvements were obtained by changing the orientation of the discharge pipe from vertical to horizontal. The collapse points for the case of the horizontal top discharge pipe occurred with lower air percentages in the pump suction.

  (b) Smaller percentages of air removal were obtained in the case of the top horizontal discharge pipe.

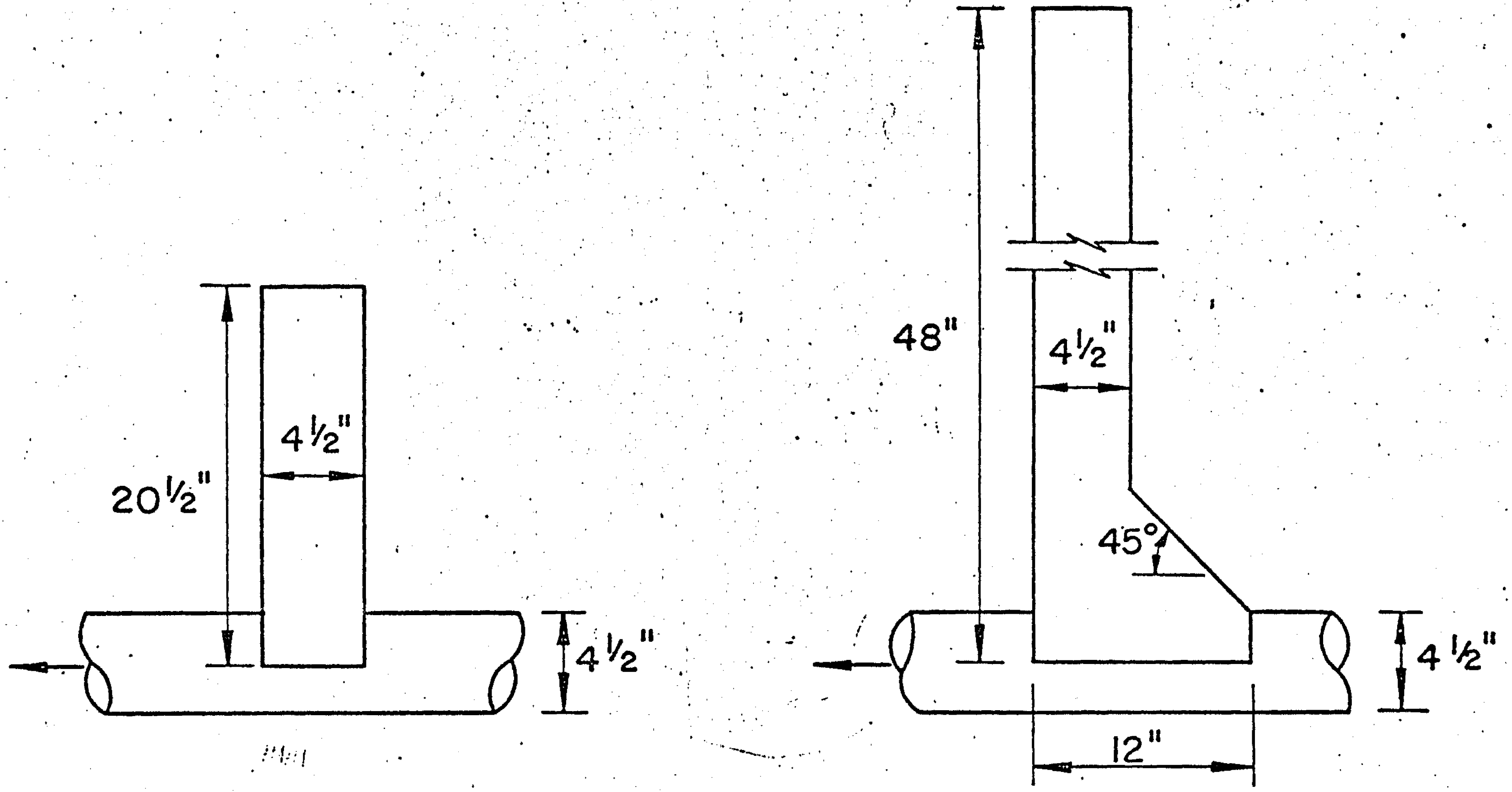
6. FUTURE STUDIES

The test facilities have been improved substantially. Accurate data were obtained in the case of top horizontal discharge pipe. The terms of the present contract do not provide for further analysis of the data.

In order to apply the results obtained to prototype conditions, the similarity parameters relevant to the problem should be determined. There is a lack of accurate information about the quantities of gas encountered in actual dredging practice. No prototype observations are available to check the validity of the model results. However, considerable analysis of the data would yield the similarity parameters. It seems that two sets of parameters are needed. One set is required to describe the pump performance, and the other is required to describe the gas removal system. In the present investigation, model scaling was based upon the pump performance parameters.

Further modifications of the accumulator geometry and addition of streamlined dividers are possible. Additional testing would be appropriate.

FIGURES



(a) Original (b) Modified

Fig. 1 Side Views of Accumulators

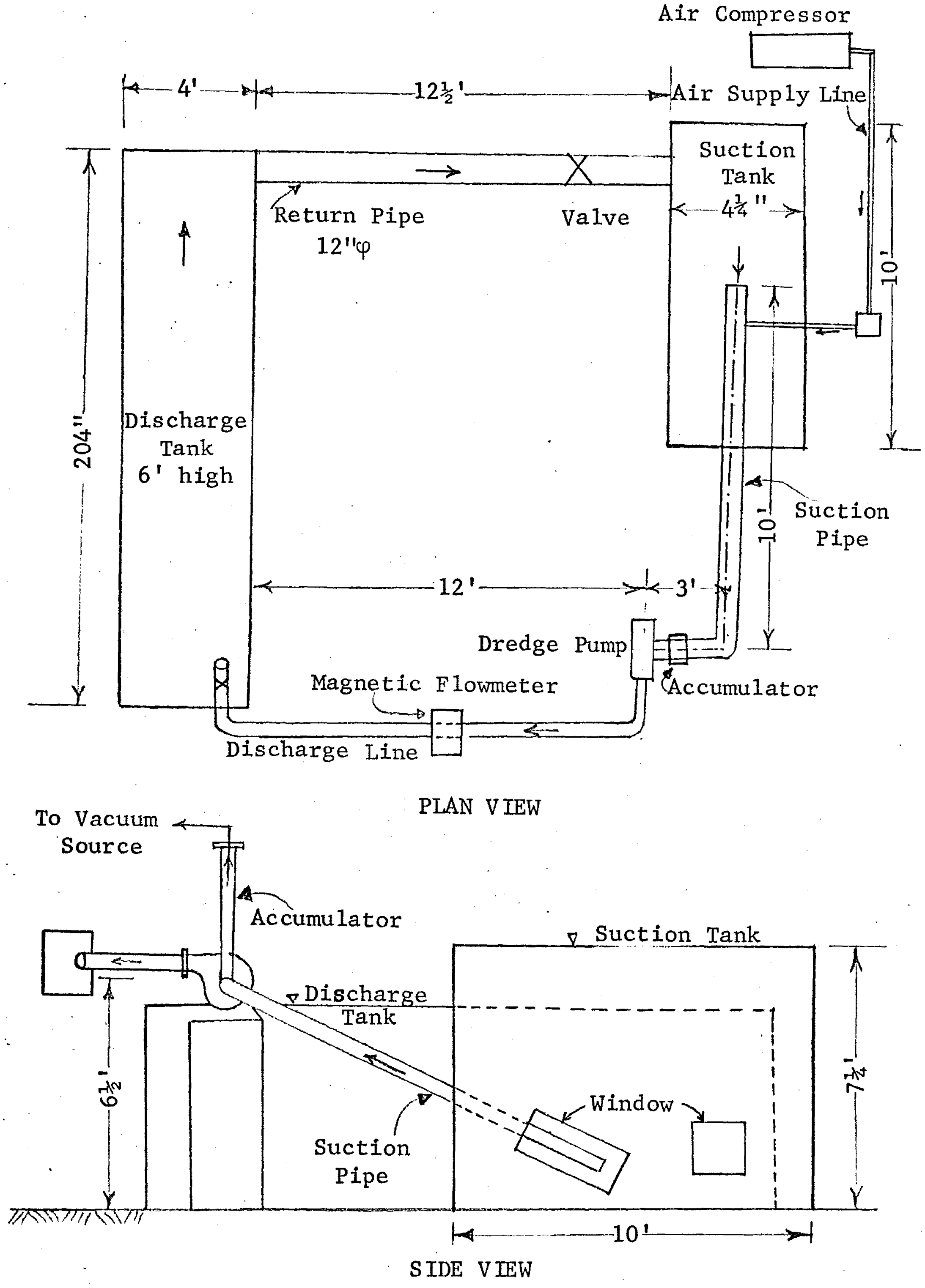


Fig. 2 Experimental Setup

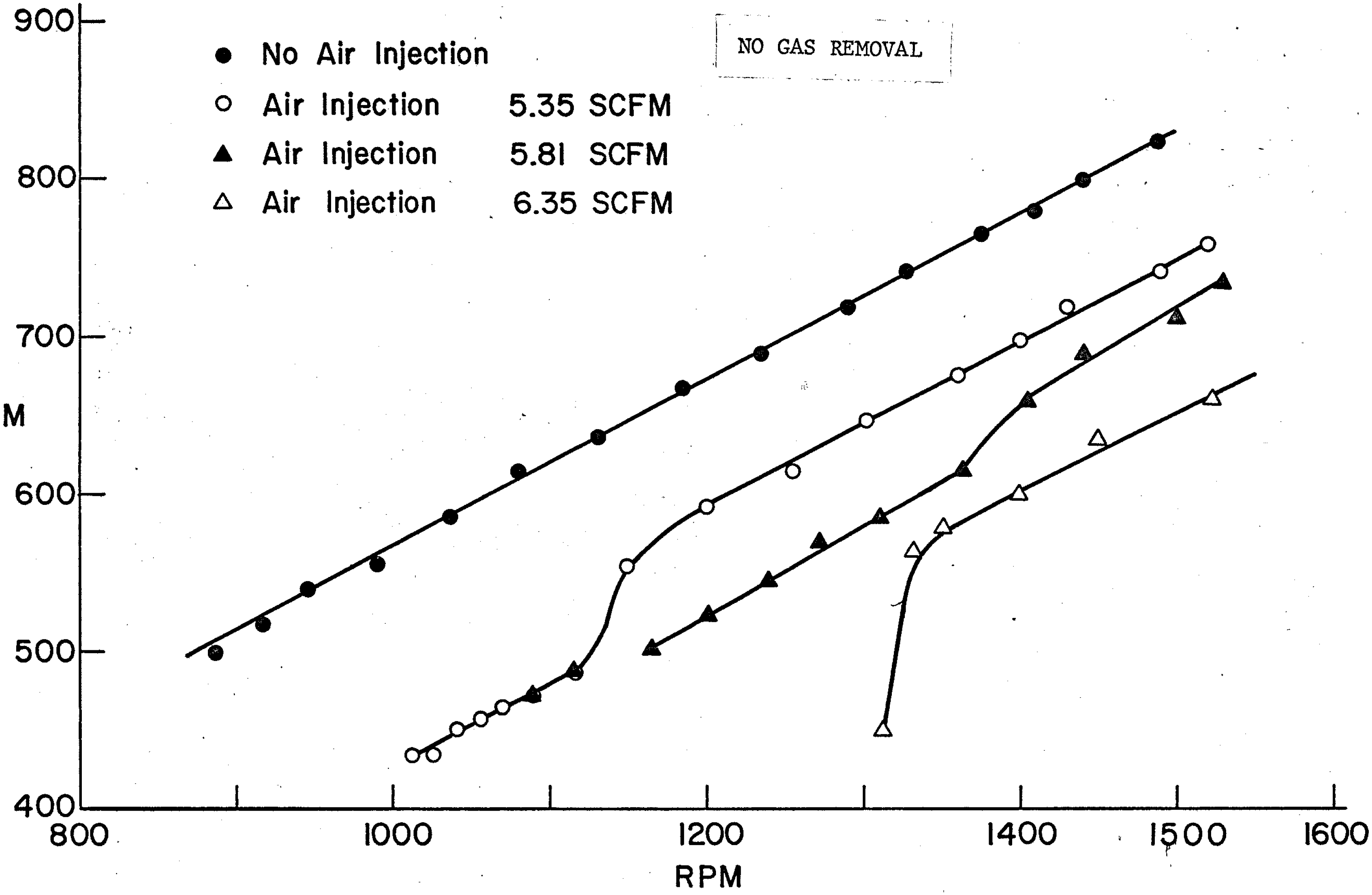


Fig. 3: Relationship Between Total Flow Rate and Pump Speed at Constant Discharge Orifice

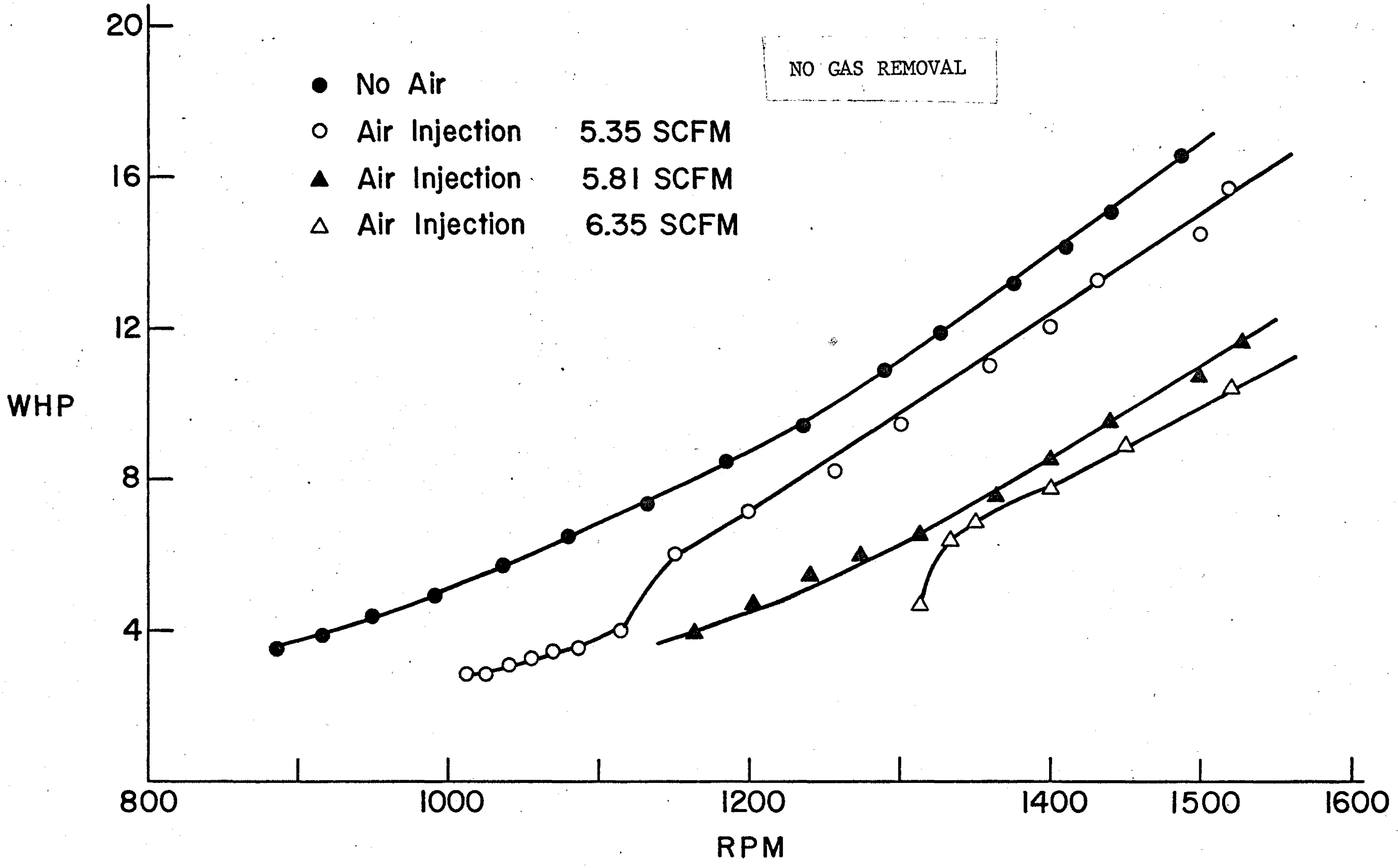


Fig. 4: Relationship Between Water Horsepower and Pump Speed at Constant Discharge Orifice

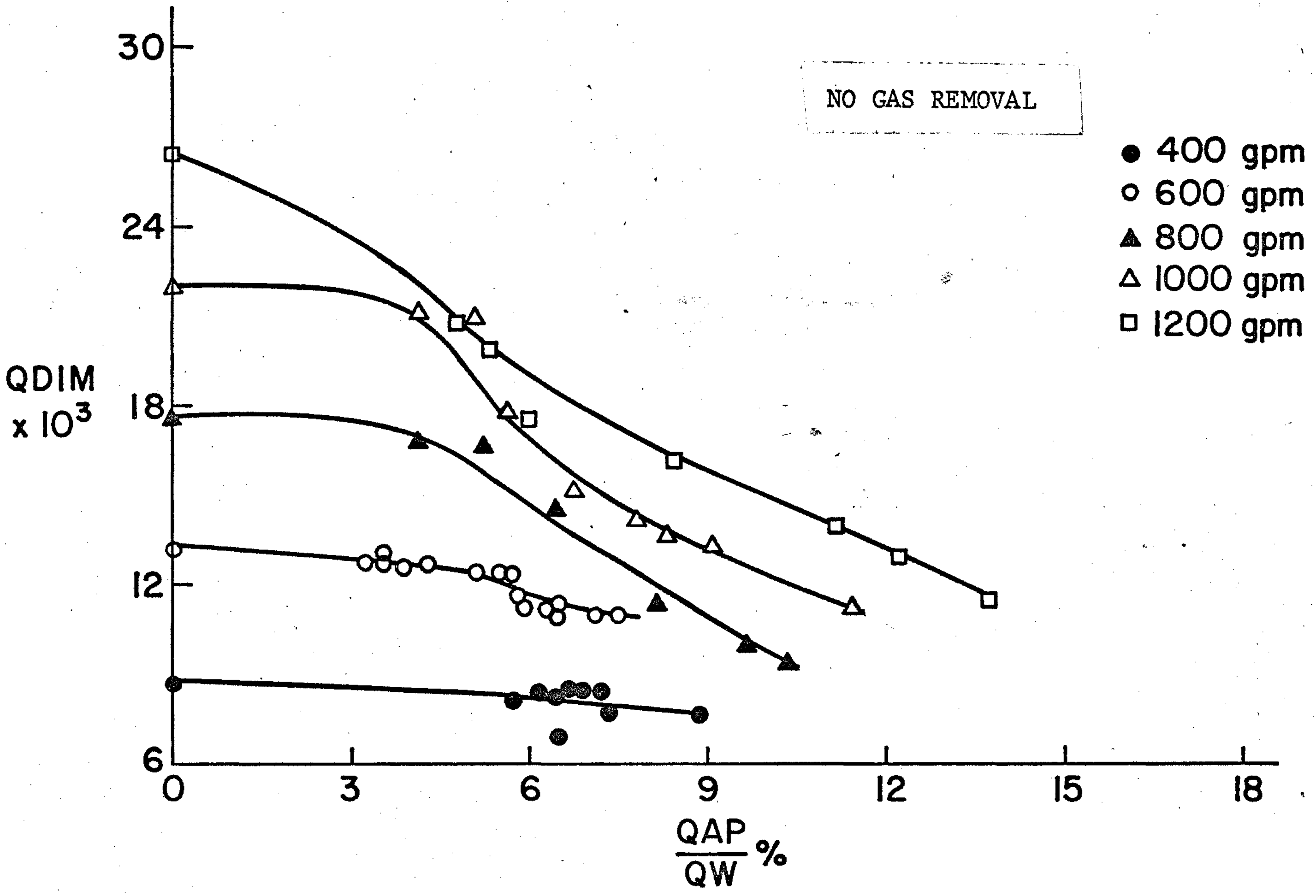


Fig. 5: Relationship Between Dimensionless Discharge and QAP/QW at 1440 RPM

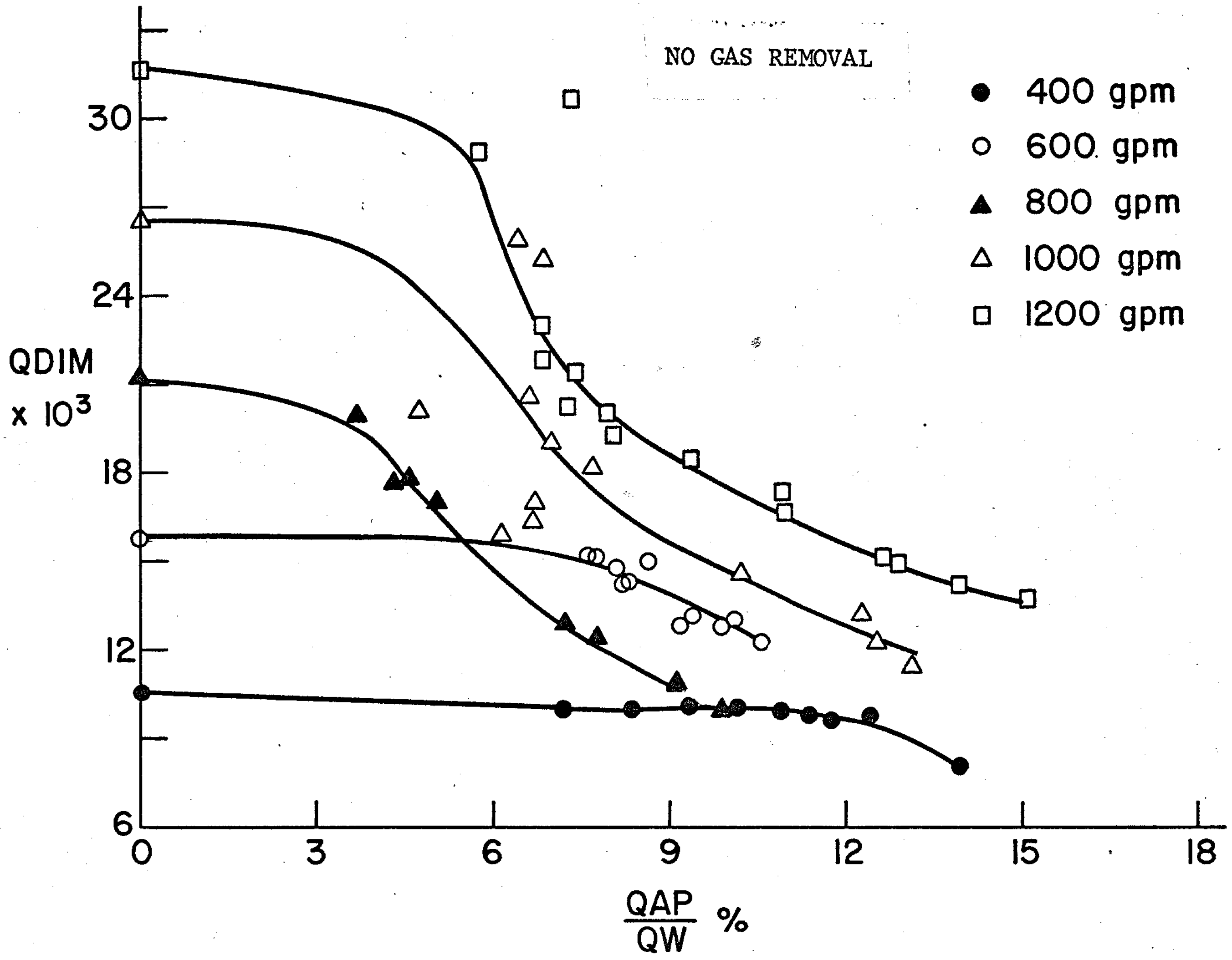


Fig. 6: Relationship Between Dimensionless Discharge and QAP/QW at 1200 RPM

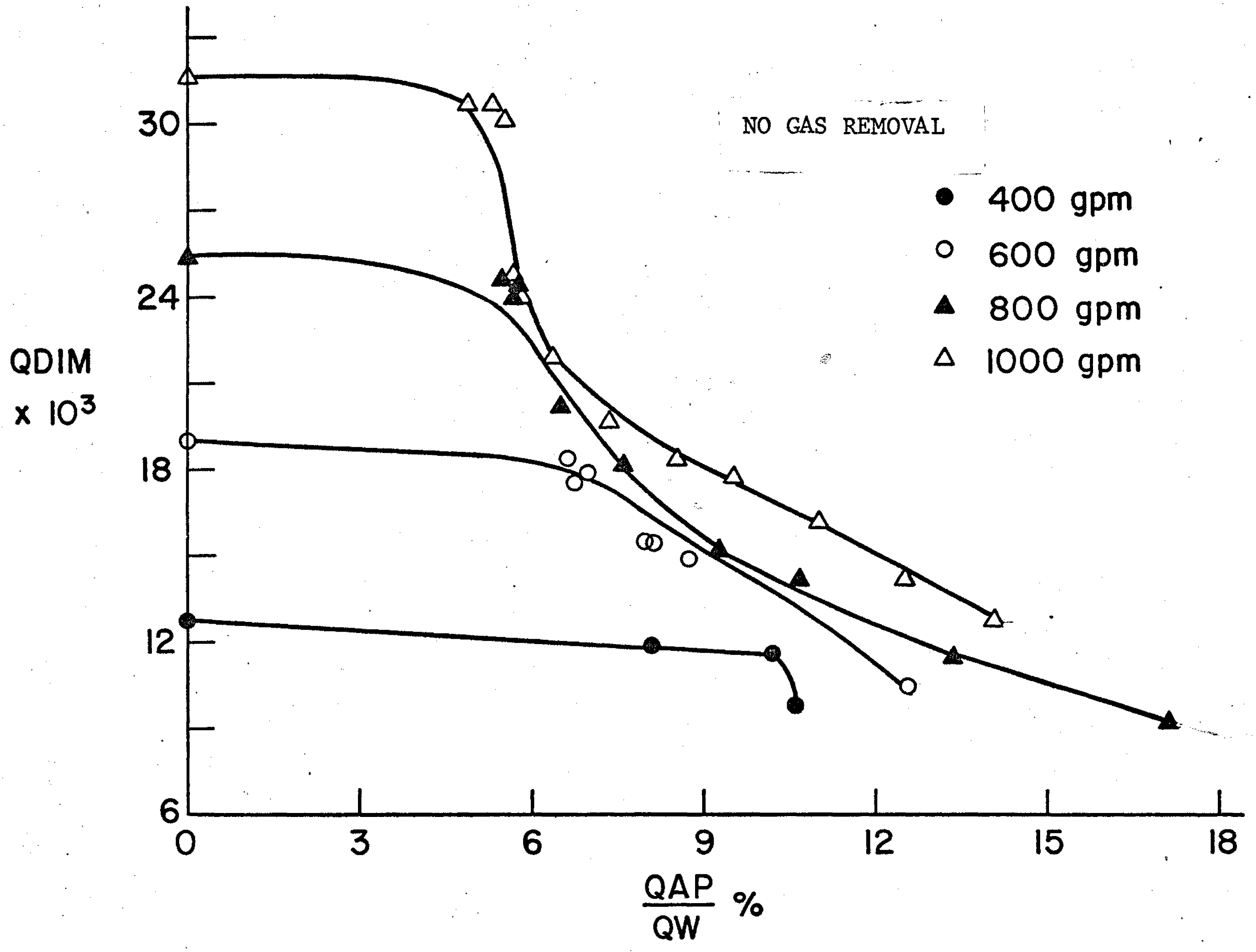


Fig. 7: Relationship Between Dimensionless Discharge and QAP/QW at 1000 RPM

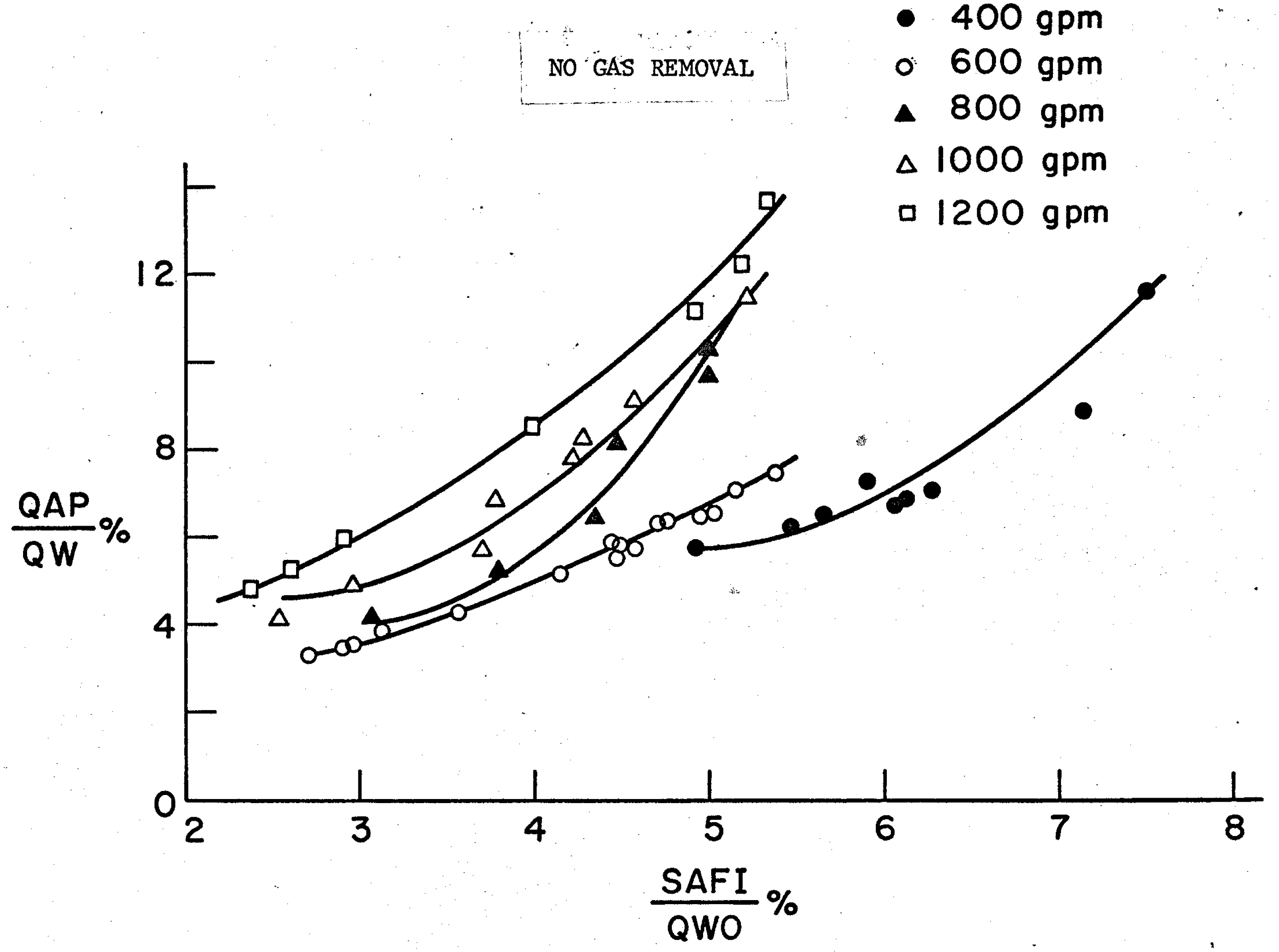


Fig. 8: Relationship Between QAP/QW and Air Injection Ratio at 1440 RPM

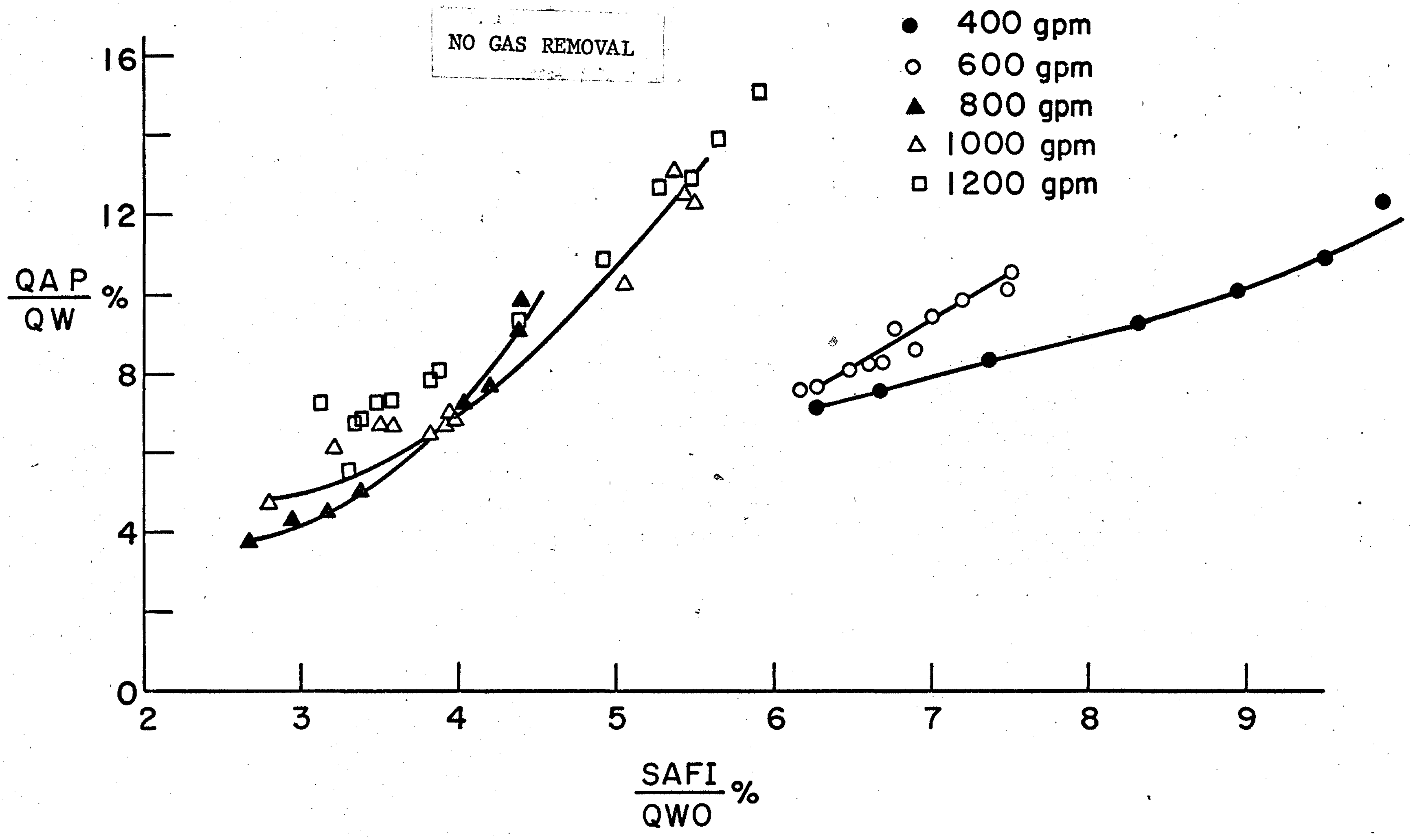


Fig. 9: Relationship Between QAP/QW and Air Injection Ratio at 1200 RPM

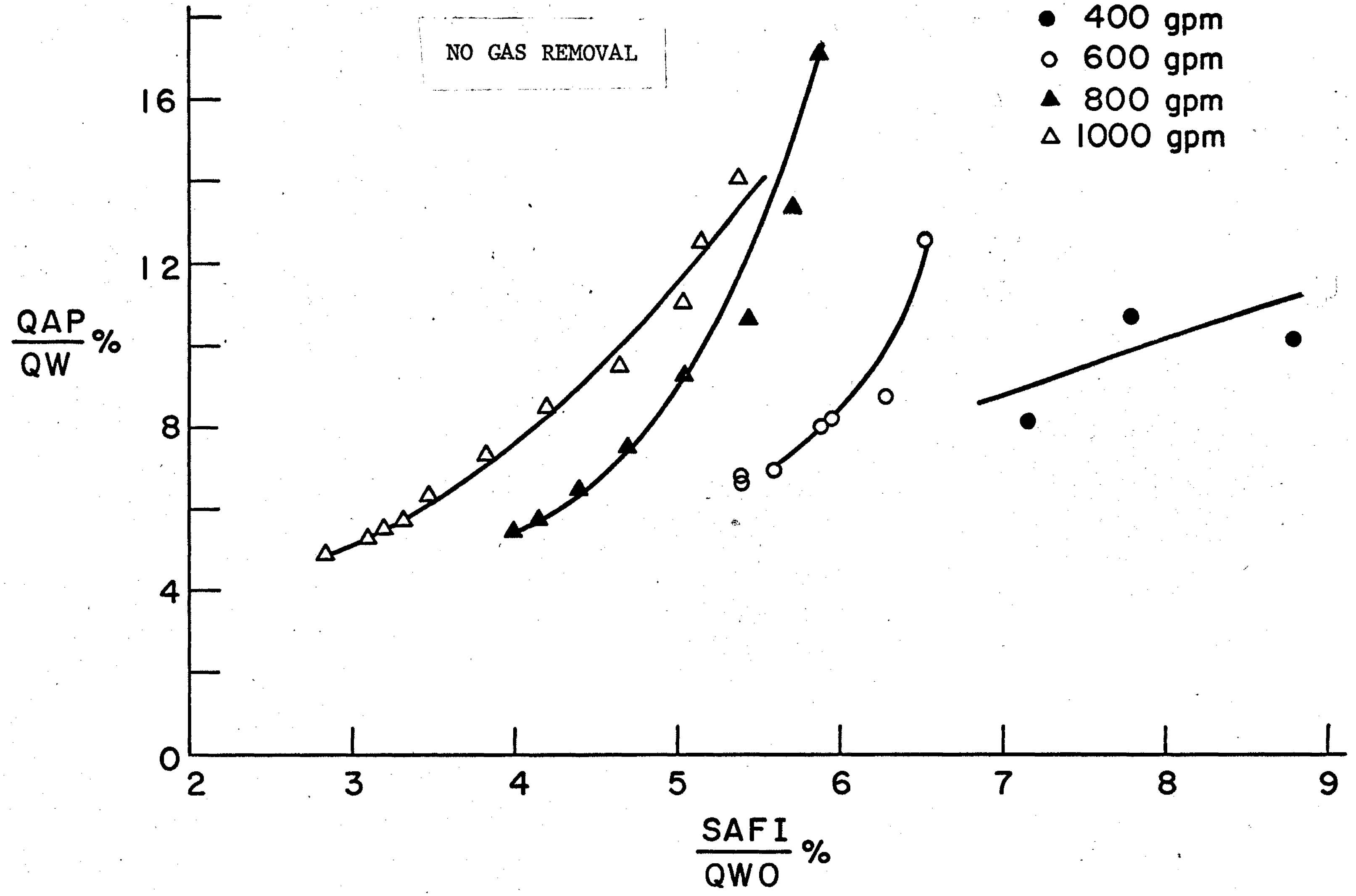


Fig. 10: Relationship Between QAP/QW and Air Injection Ratio at 1000 RPM

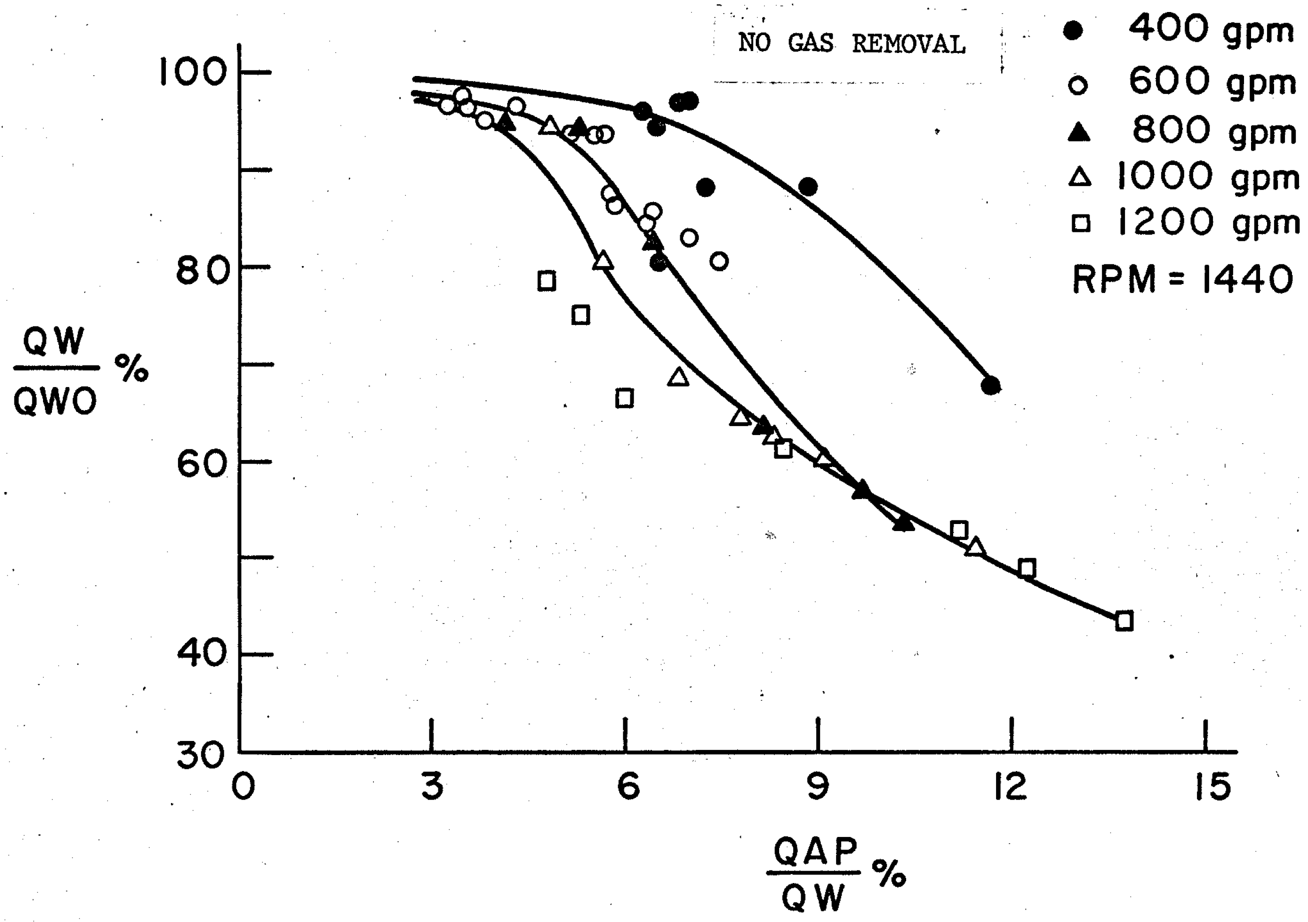


Fig. 11: Relationship Between Water Discharge Ratio and QAP/QW at 1440 RPM

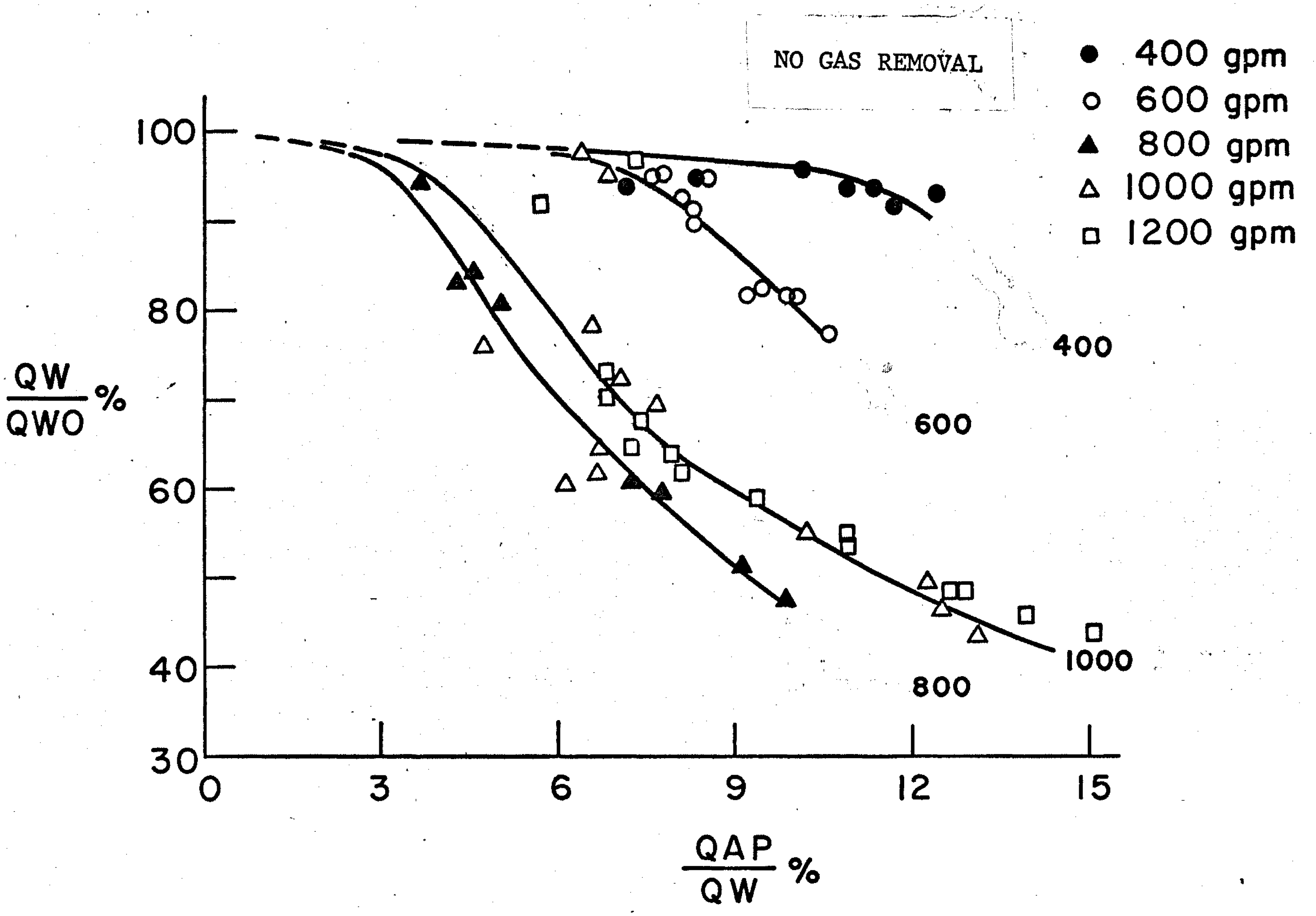


Fig. 12: Relationship Between Water Discharge Ratio and QAP/QW at 1200 RPM

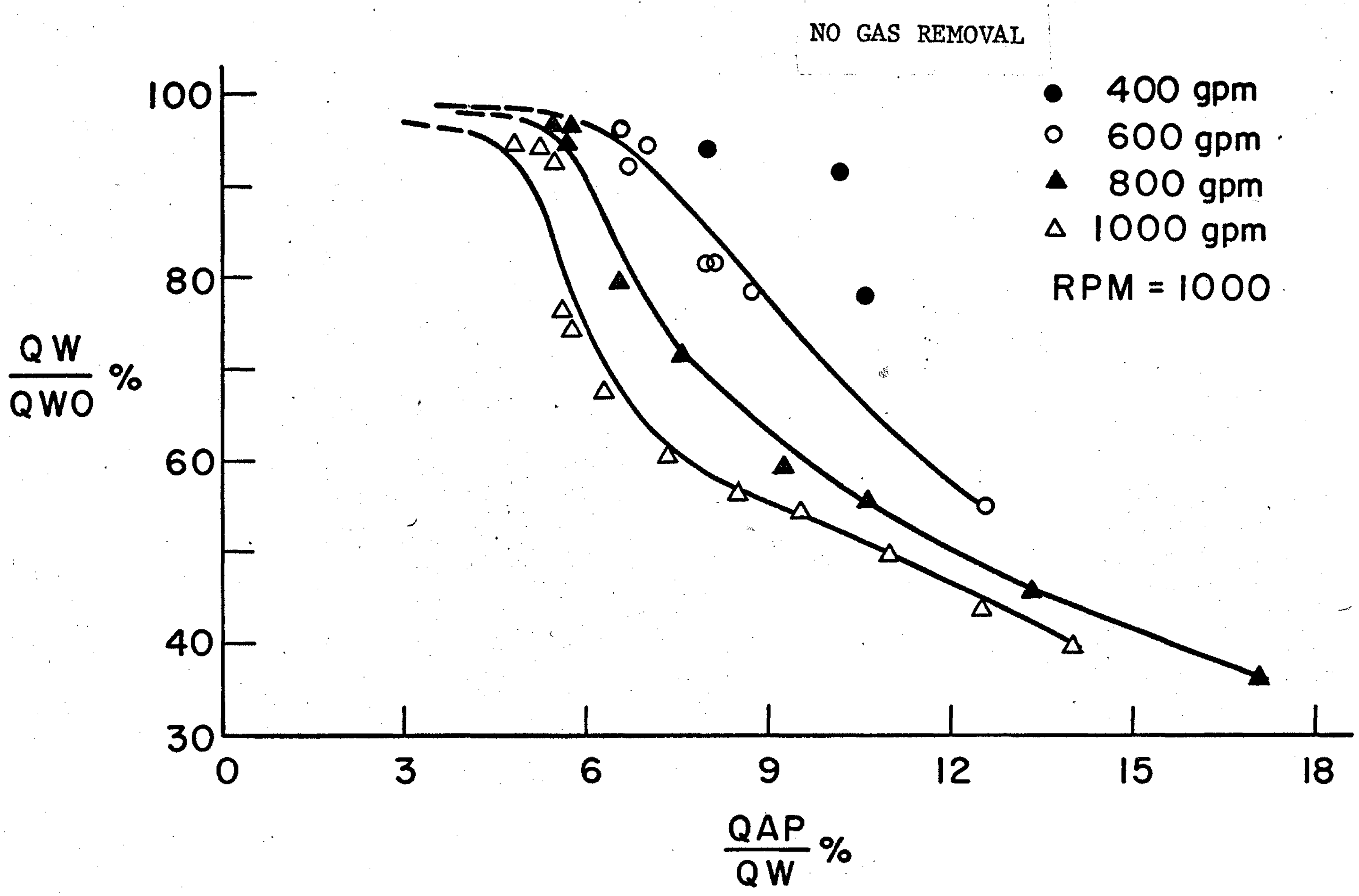


Fig. 13: Relationship Between Water Discharge Ratio and QAP/QW at 1000 RPM

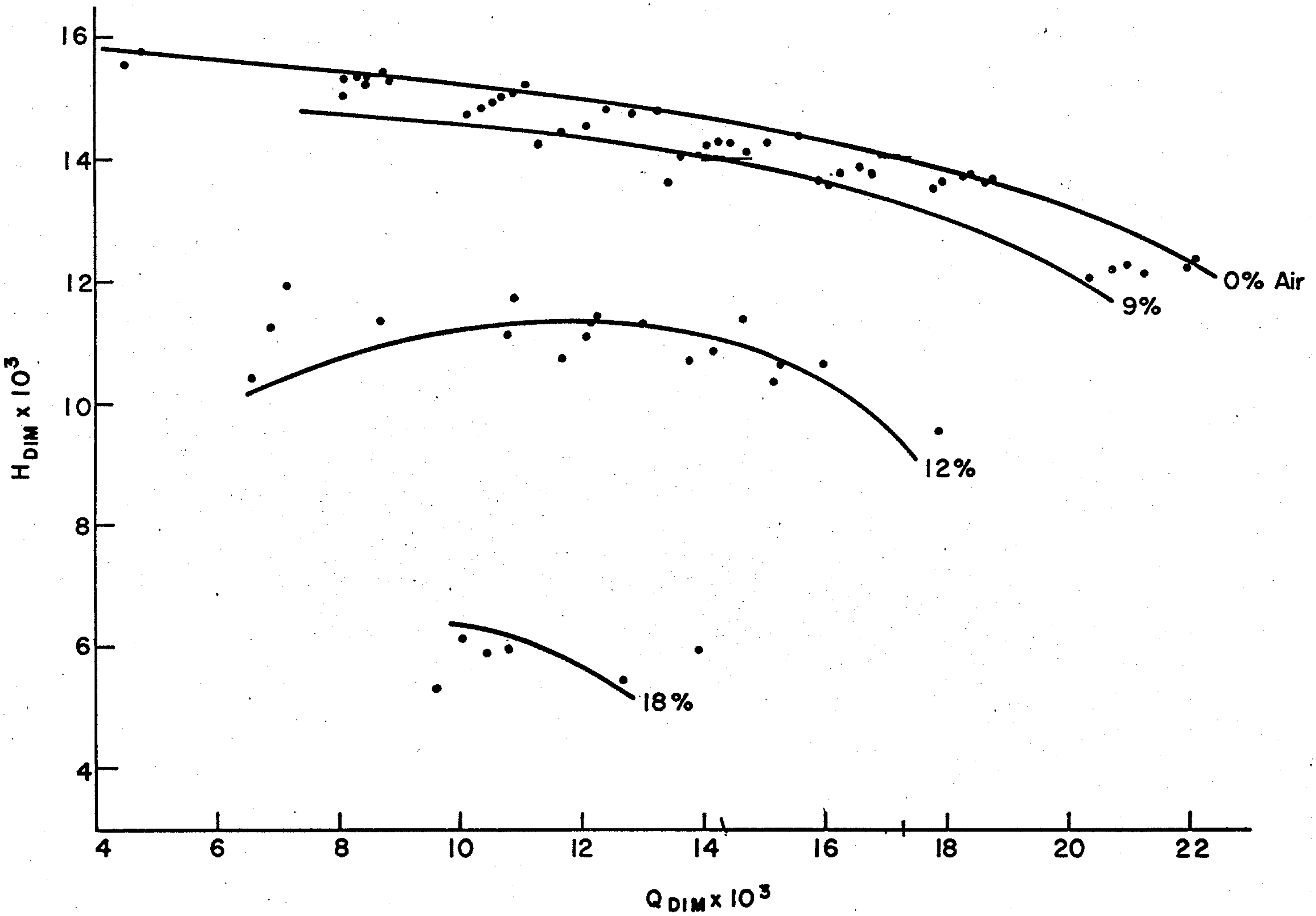


Fig. 14: Results of Tests on Vertical Discharge Pipe [Ref. 1]

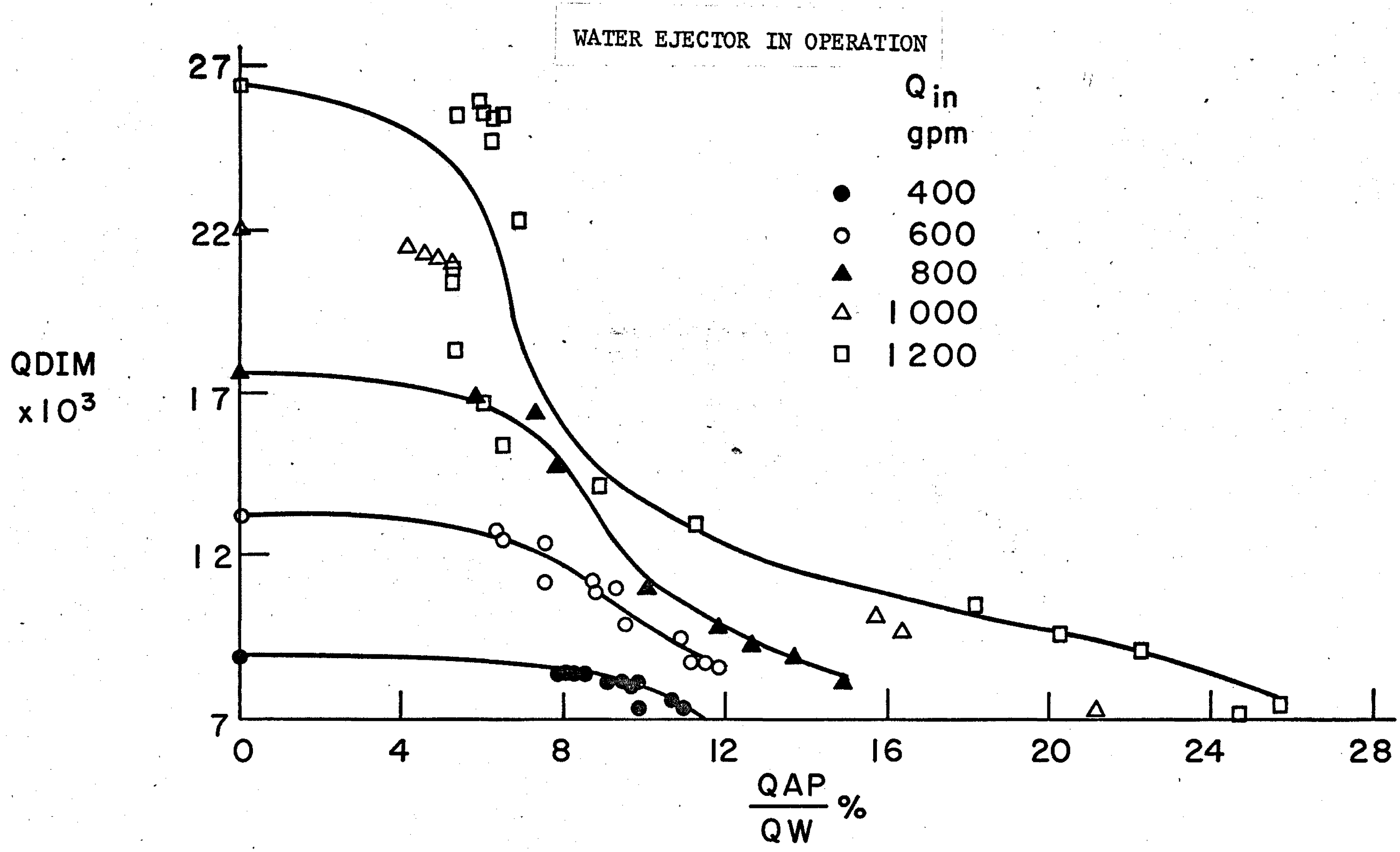


Fig. 15: Relationship Between Dimensionless Discharge and QAP/QW at 1440 RPM

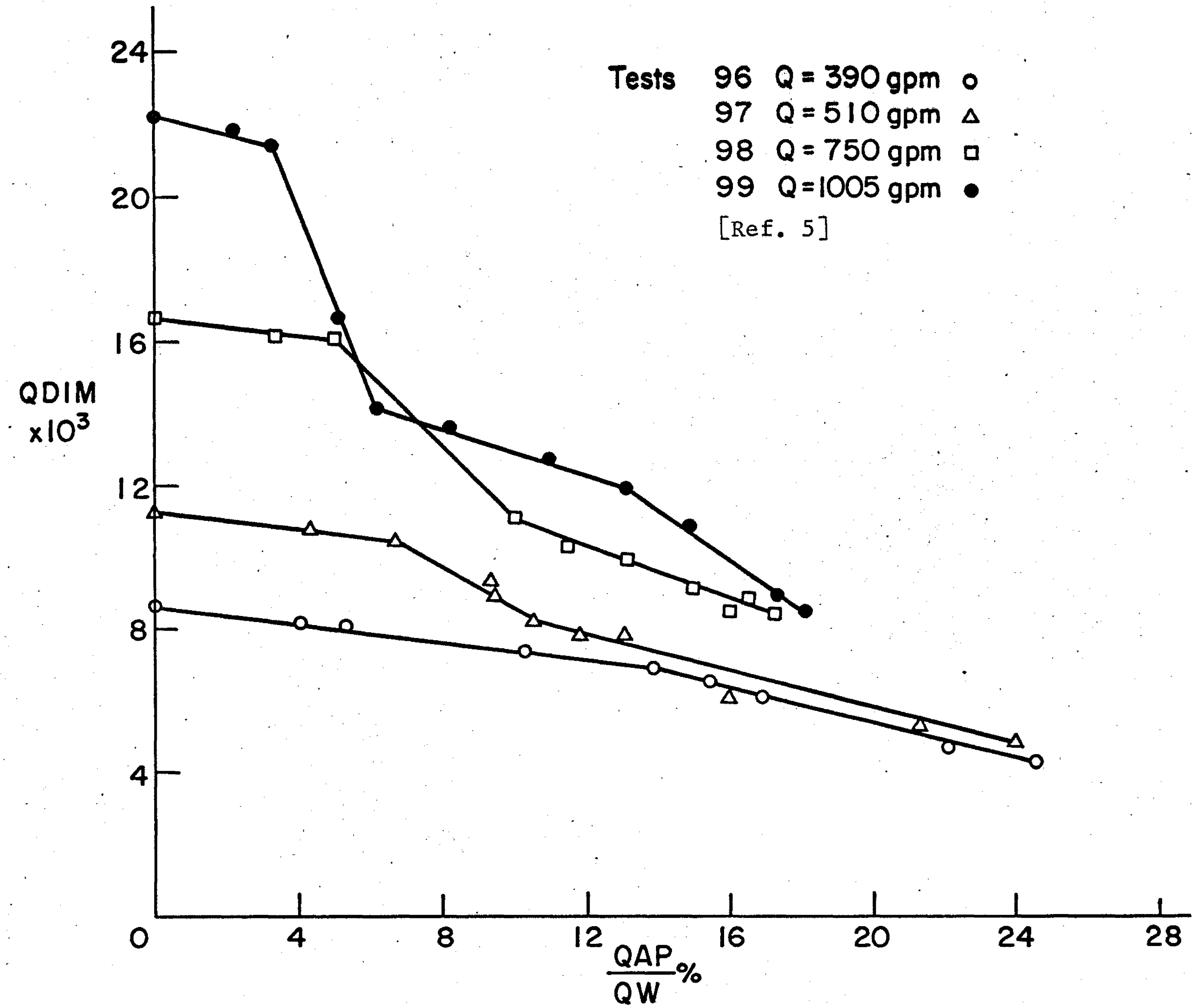


Fig. 16: Dimensionless Water Discharge versus Air at Pump Suction: Ejector

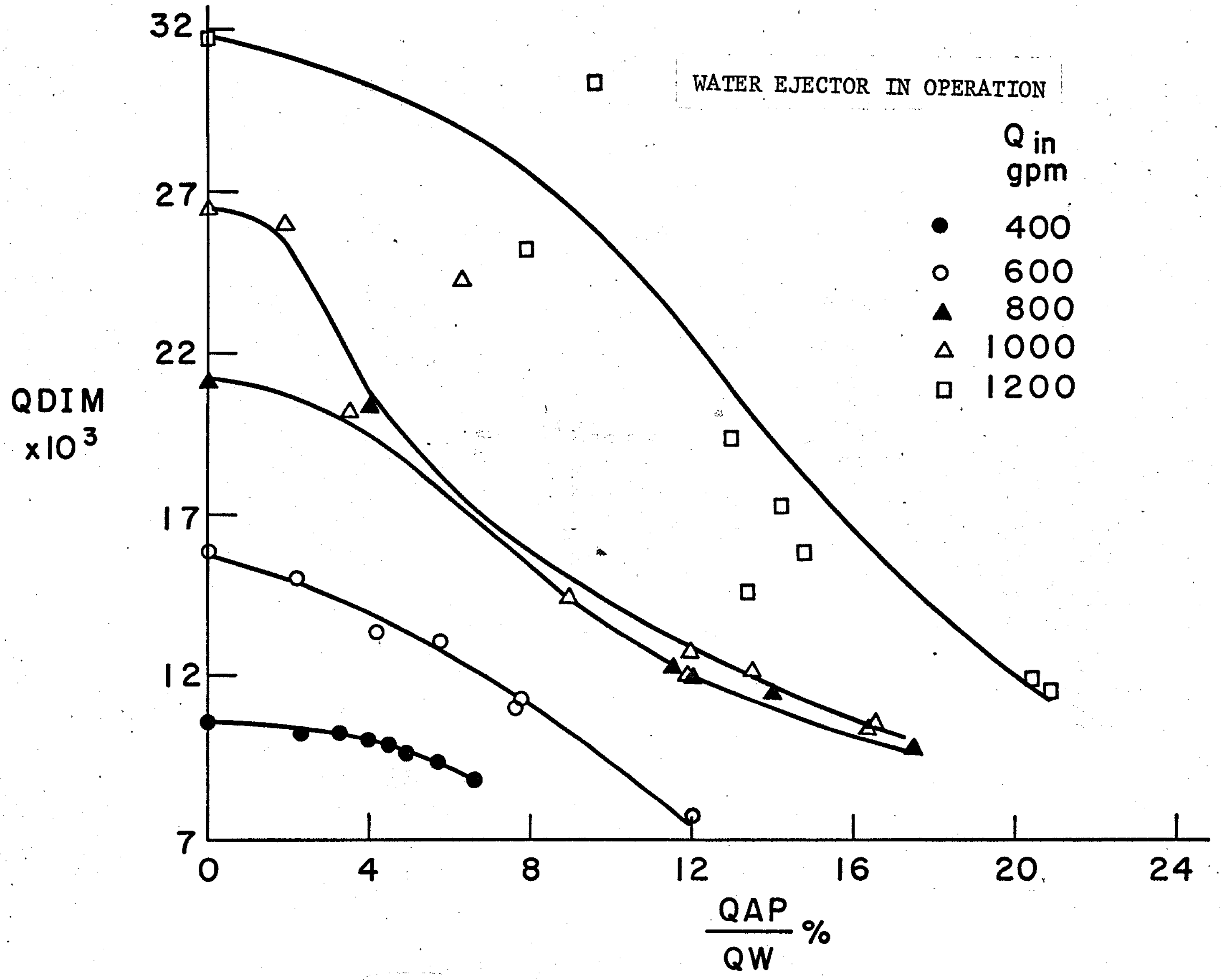


Fig. 17: Relationship Between Dimensionless Discharge and QAP/QW at 1200 RPM

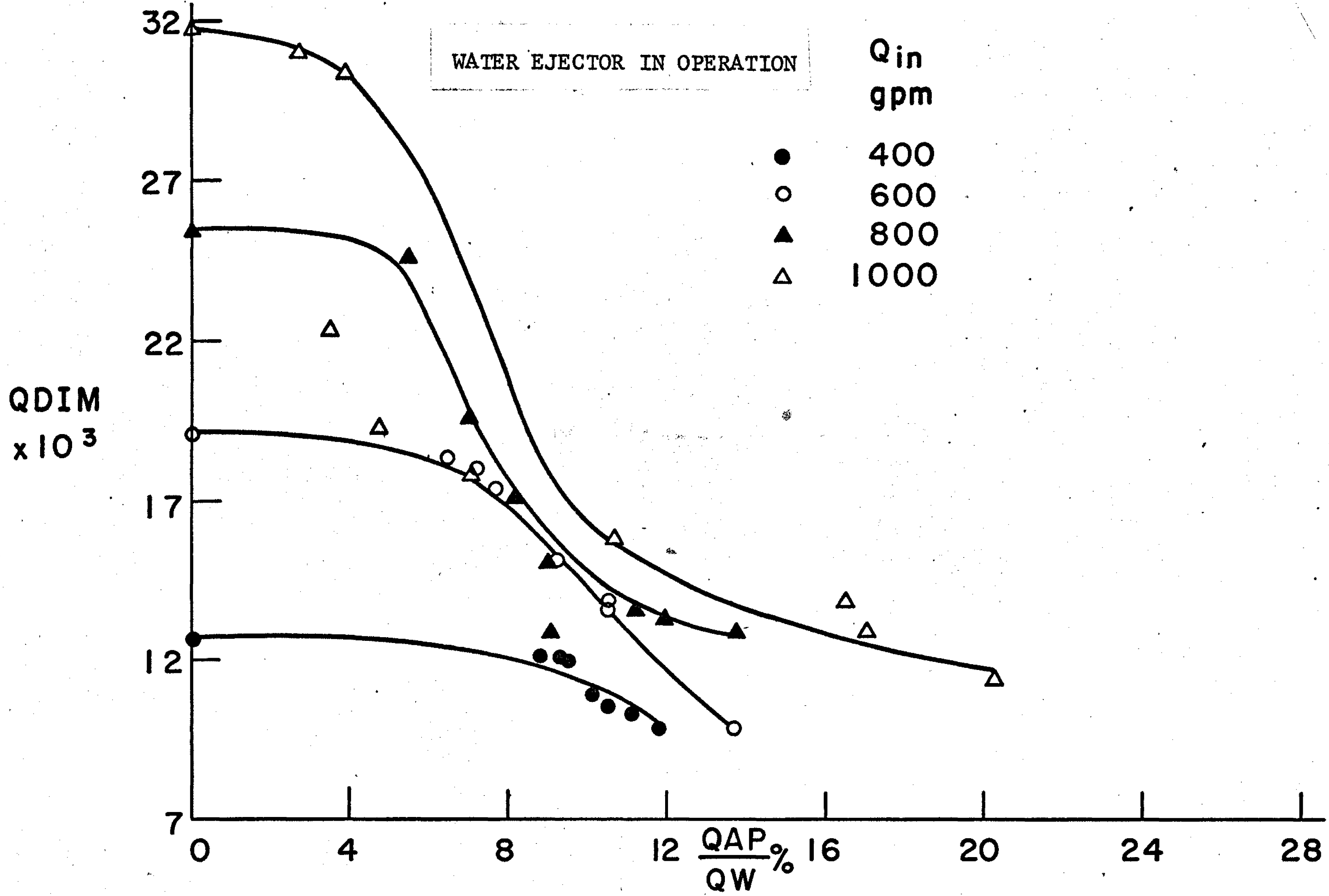


Fig. 18: Relationship Between Dimensionless Discharge and QAP/QW at 1000 RPM

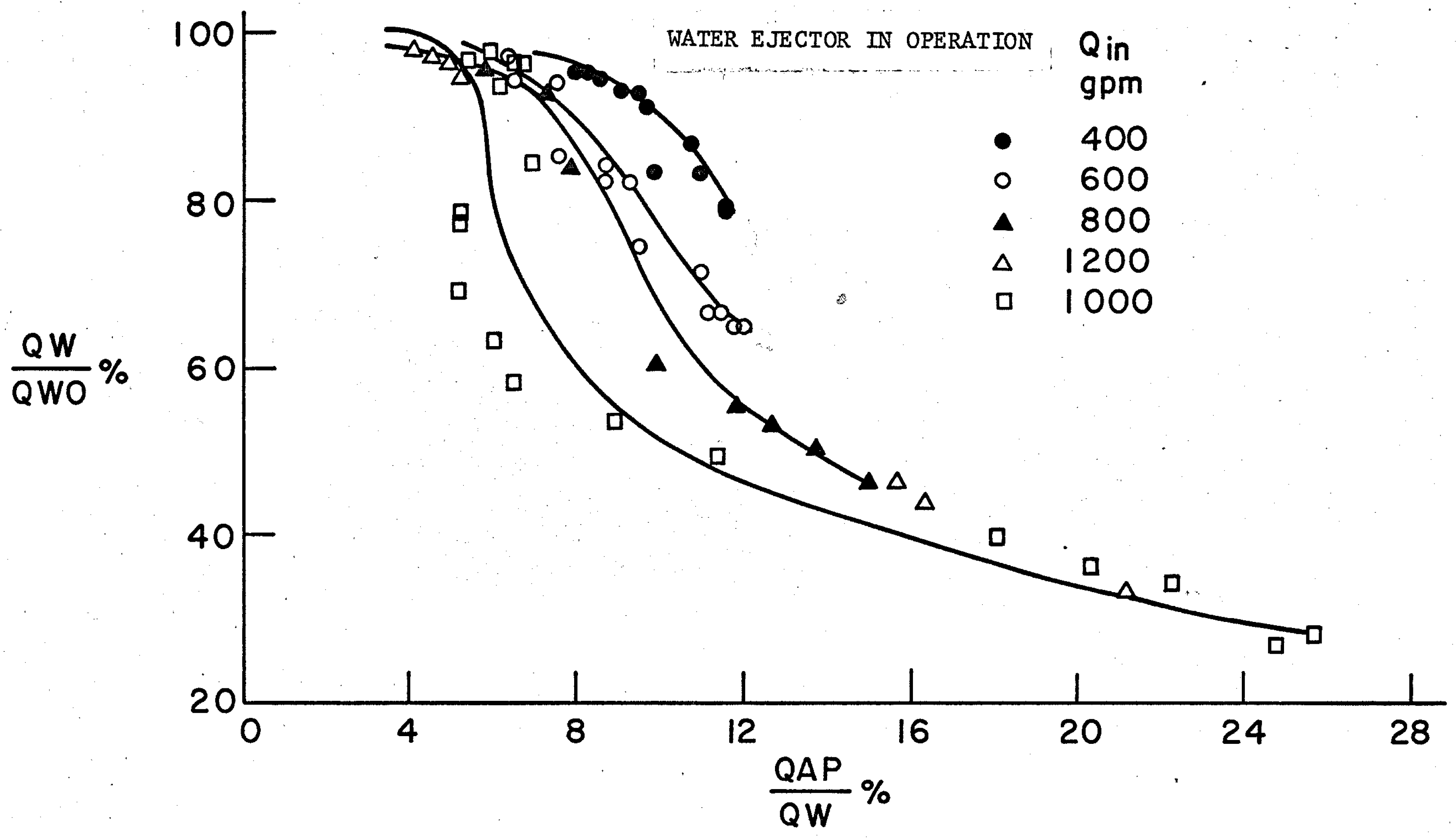


Fig. 19: Relationship Between Water Discharge Ratio and QAP/QW at 1440 RPM

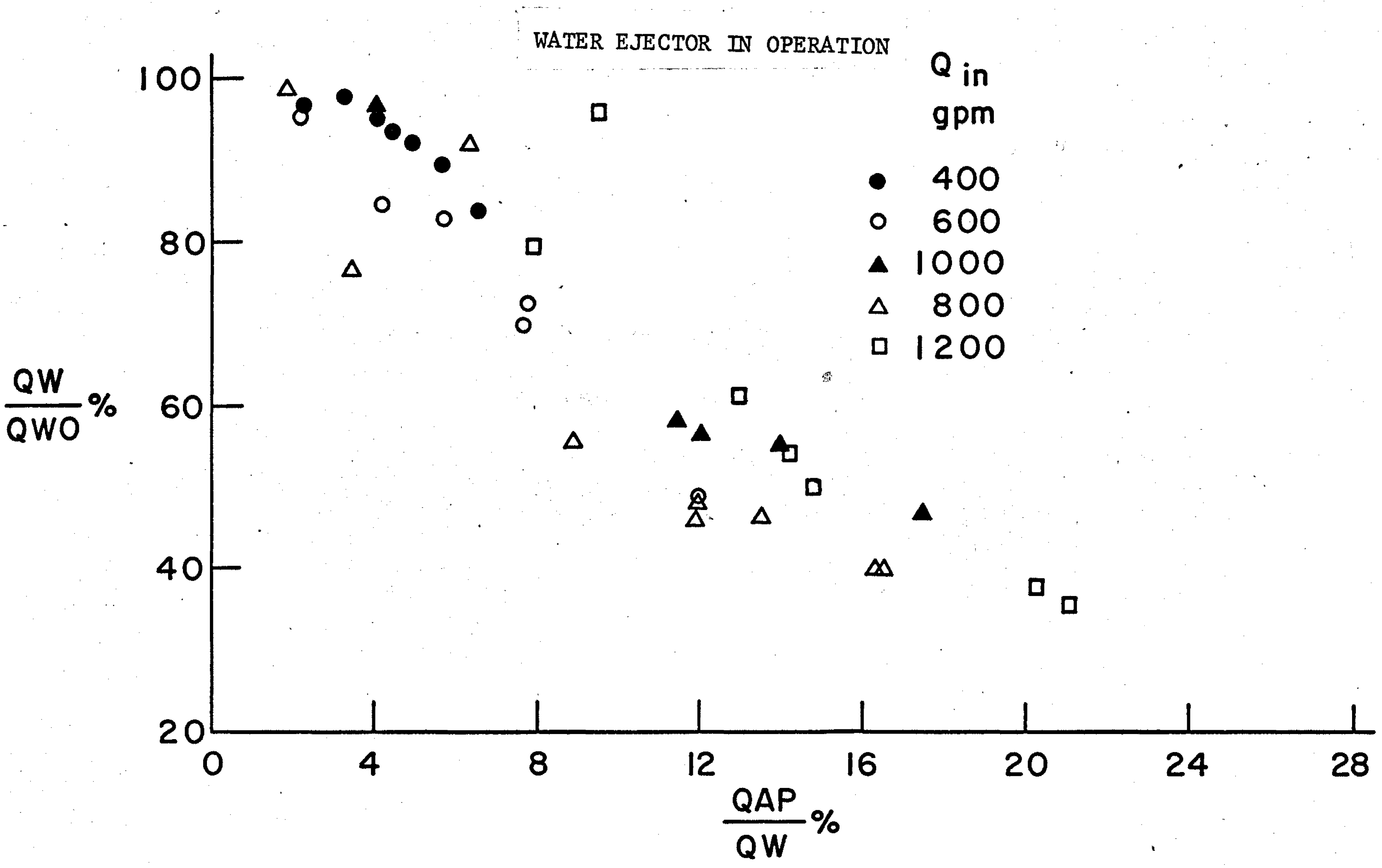


Fig. 20: Relationship Between Water Discharge Ratio and QAP/QW at 1200 RPM

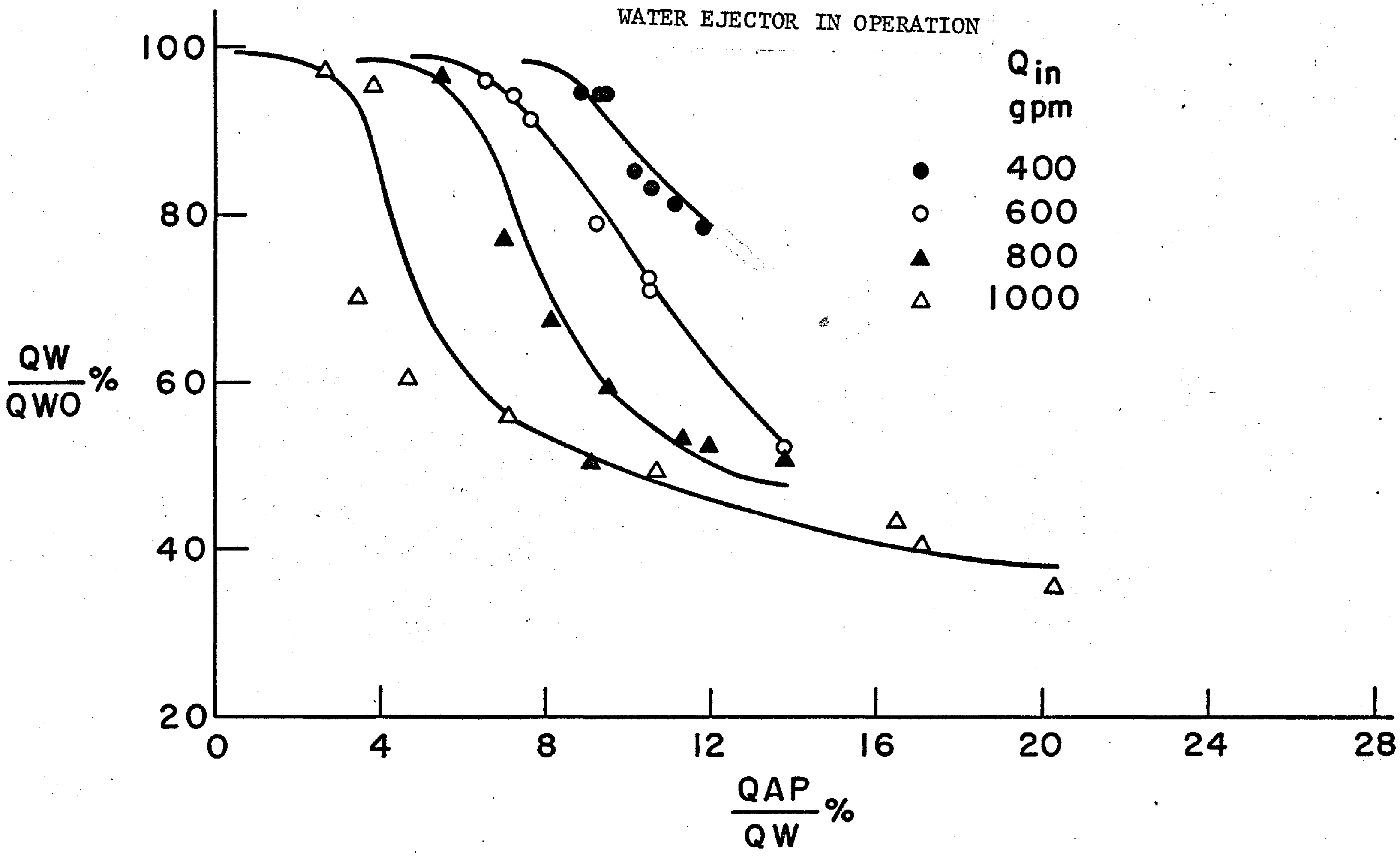


Fig. 21: Relationship Between Water Discharge Ratio and QAP/QW at 1000 RPM

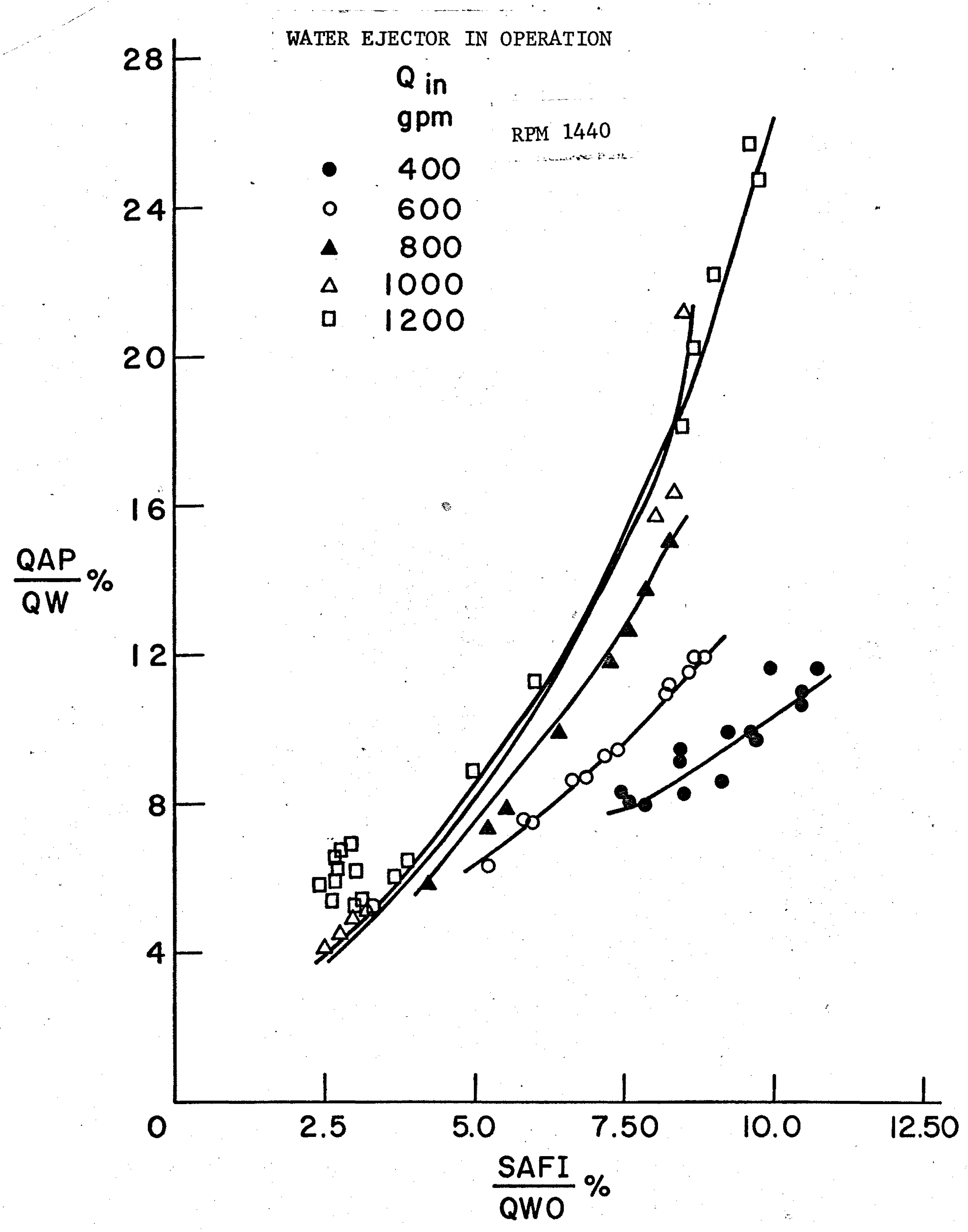


Fig. 22: Relationship Between QAP/QW and Air Injection Ratio

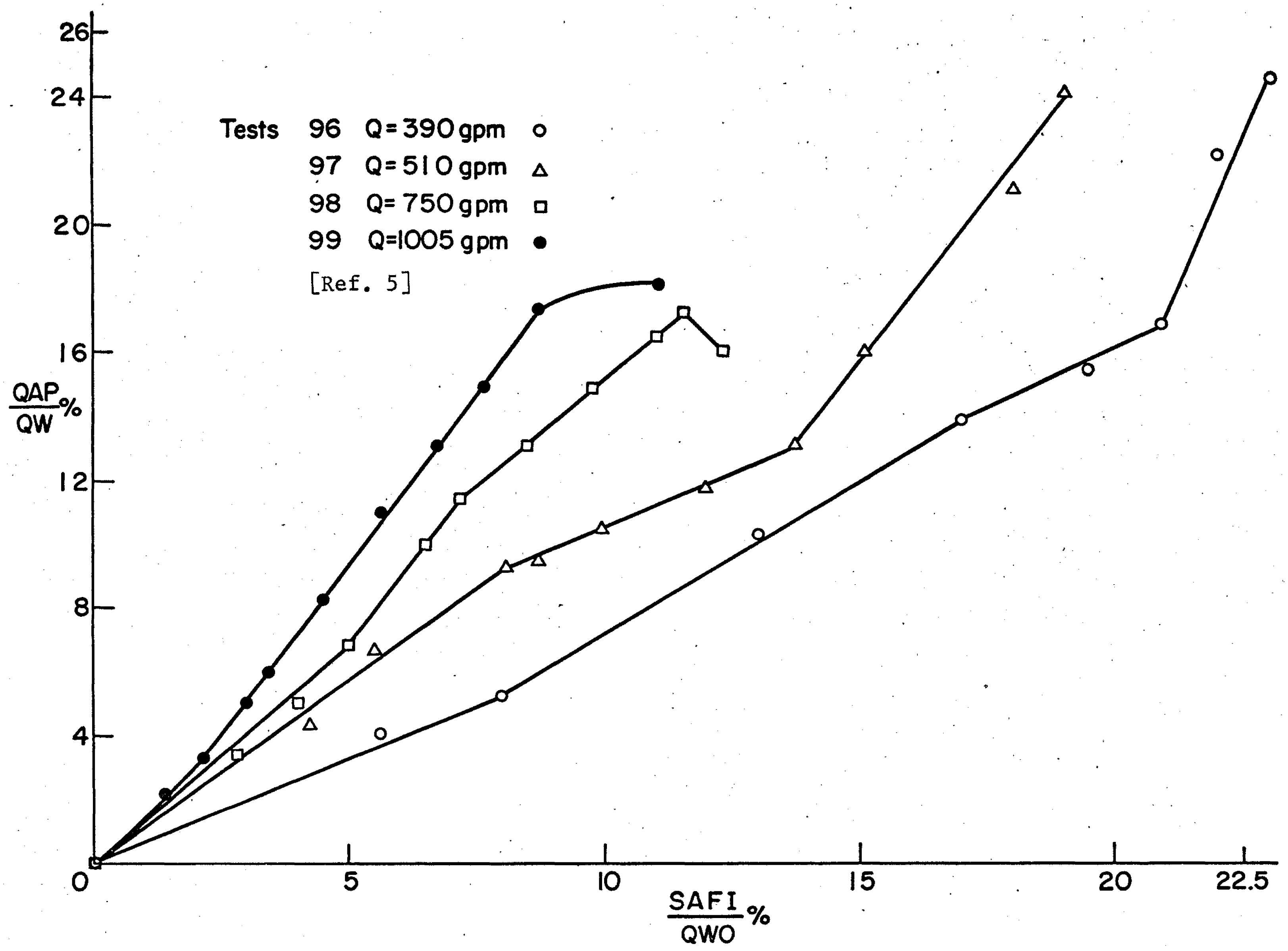


Fig. 23: Air Percent at Pump Suction versus Air Injected: Ejector

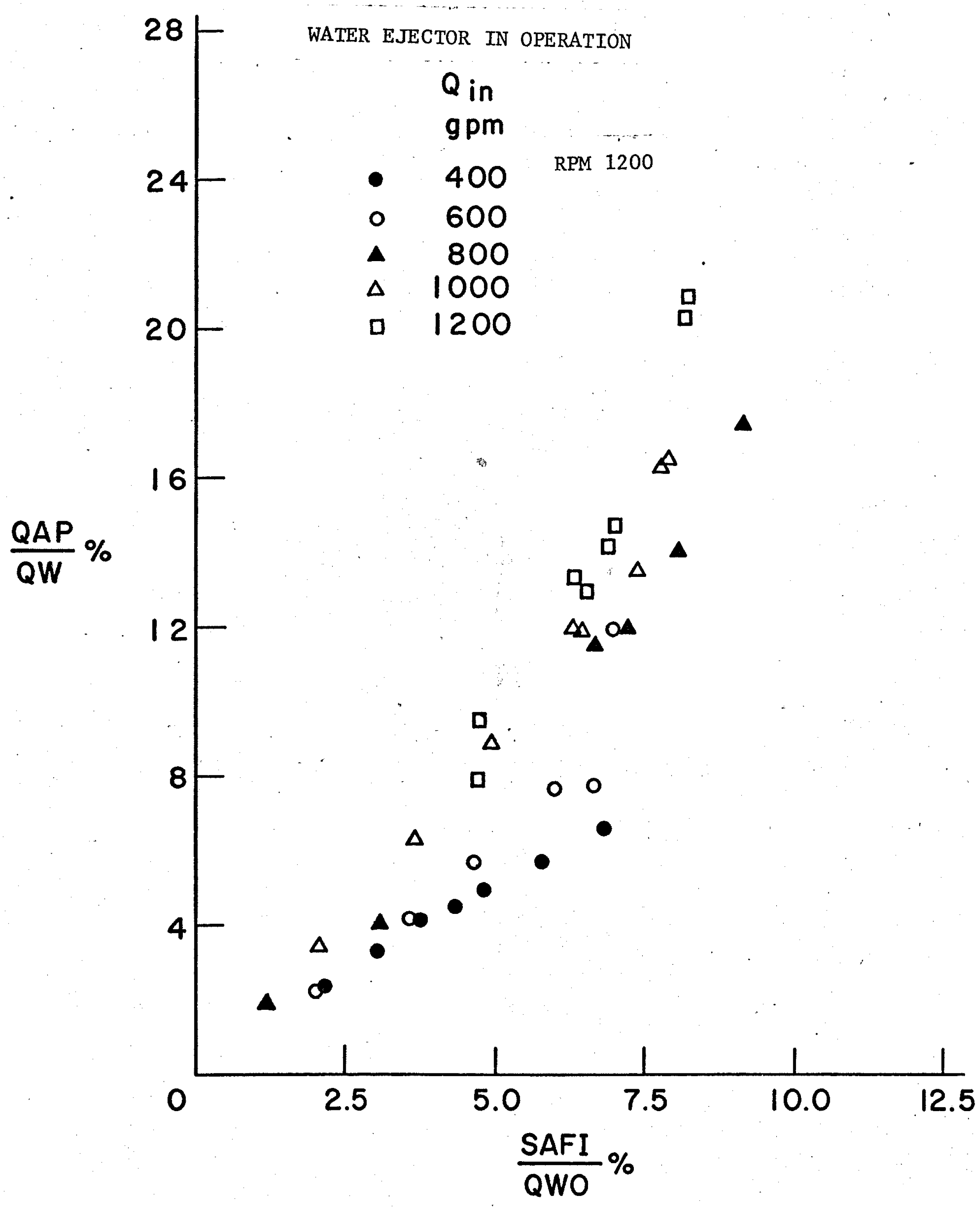


Fig. 24: Relationship Between QAP/QW and Air Injection Ratio

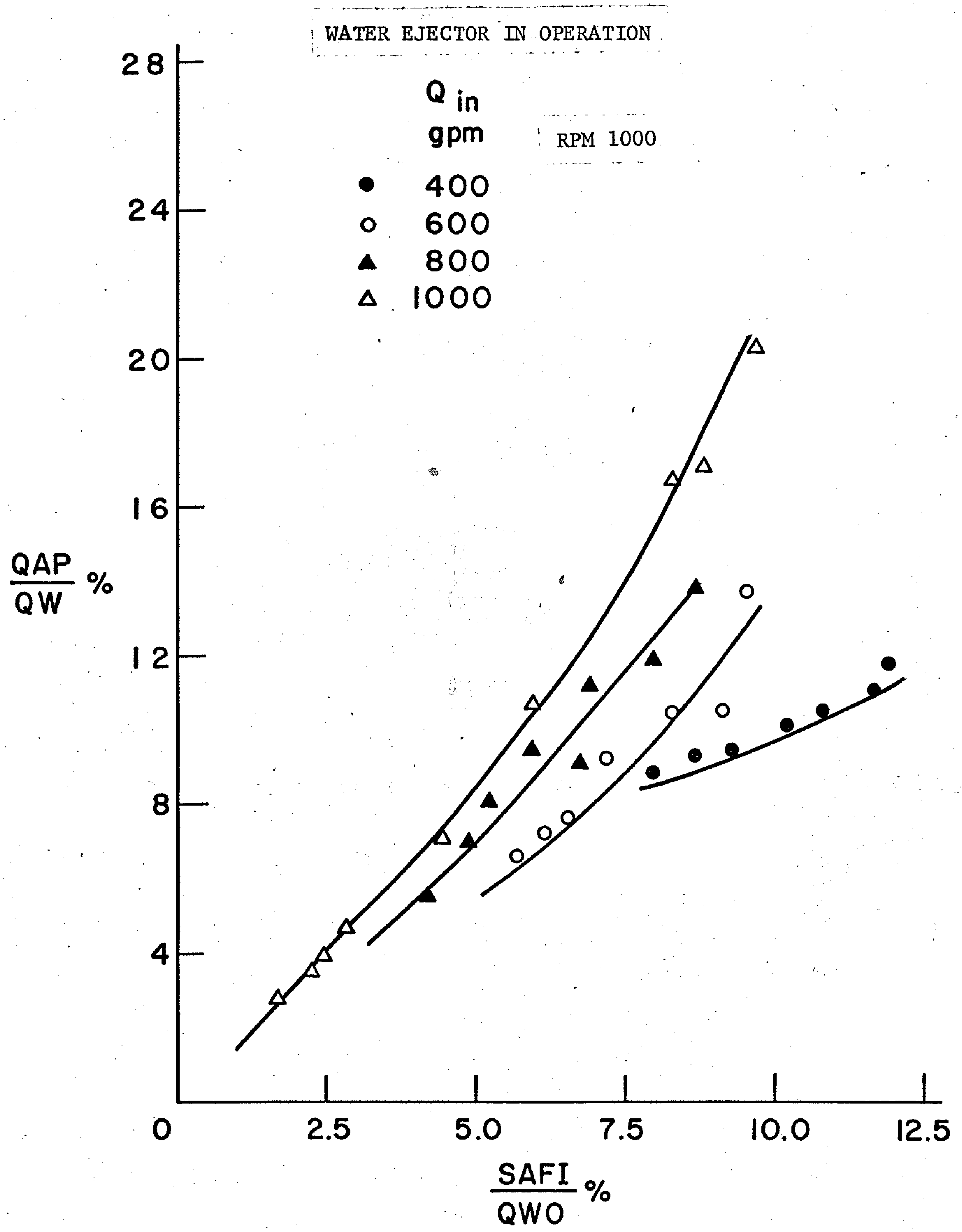


Fig. 25: Relationship Between QAP/QW and Air Injection Ratio

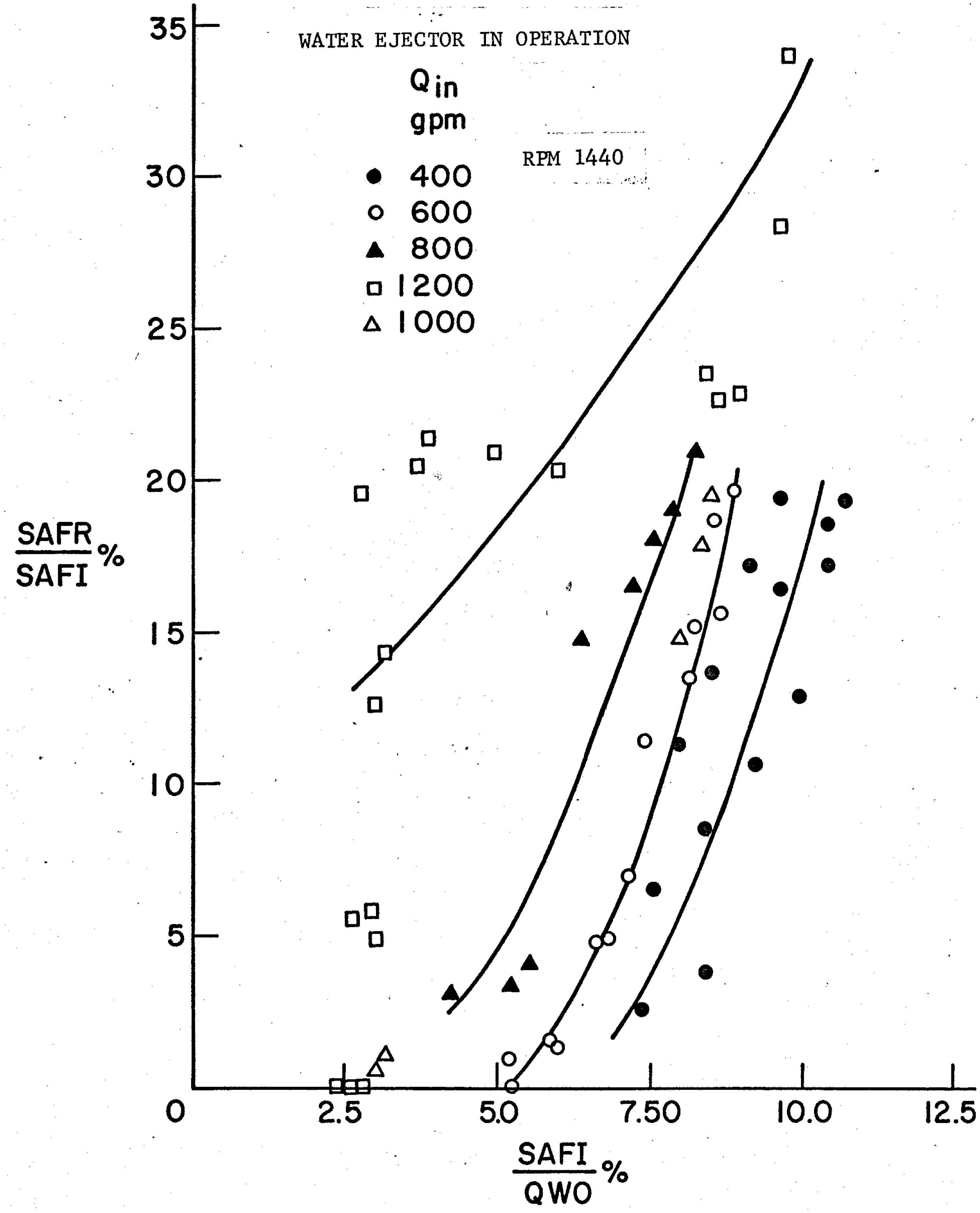


Fig. 26: Relationship Between Percent Gas Removal and SAFI/QWO

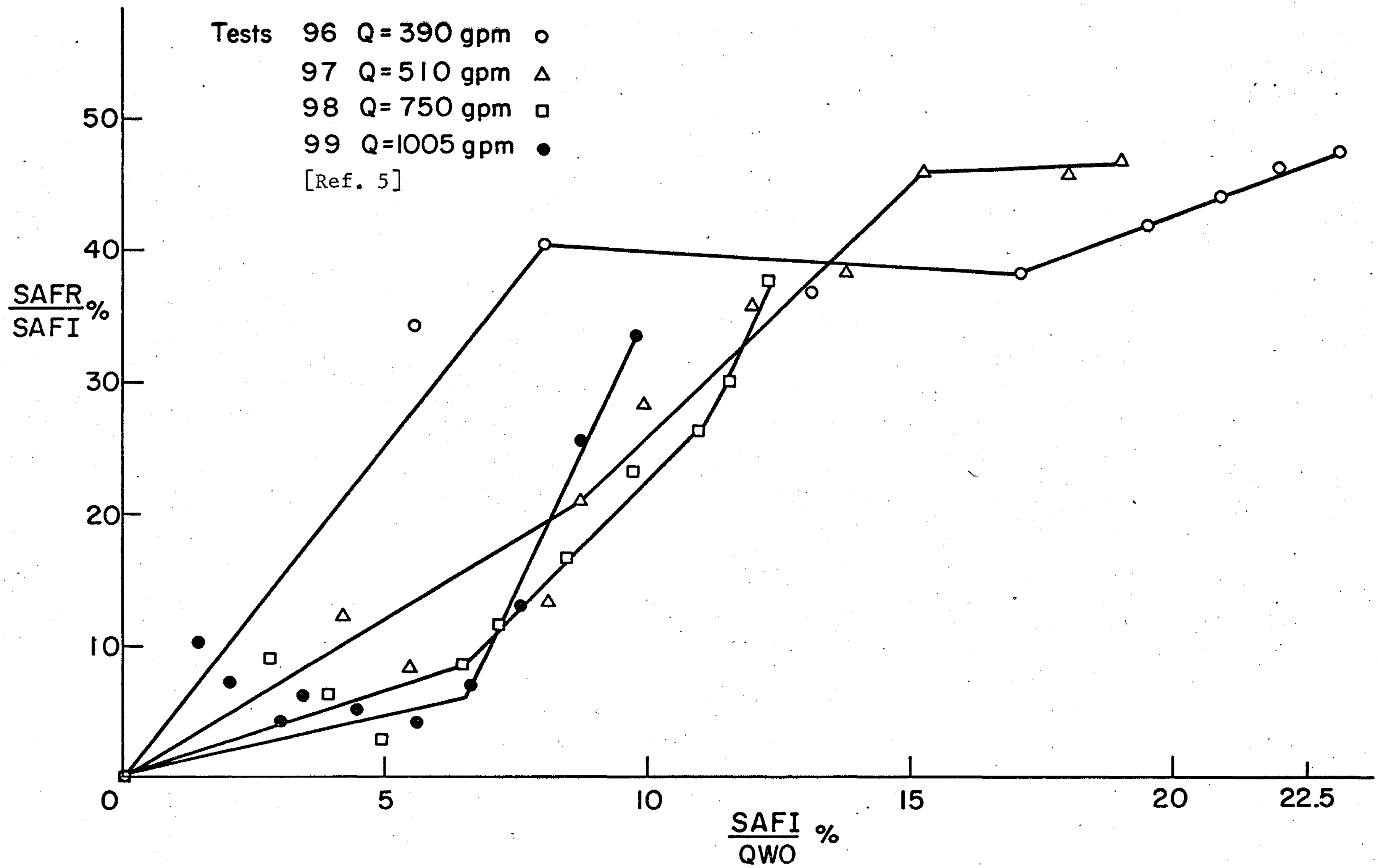


Fig. 27: Air Removed versus Air Injected: Ejector

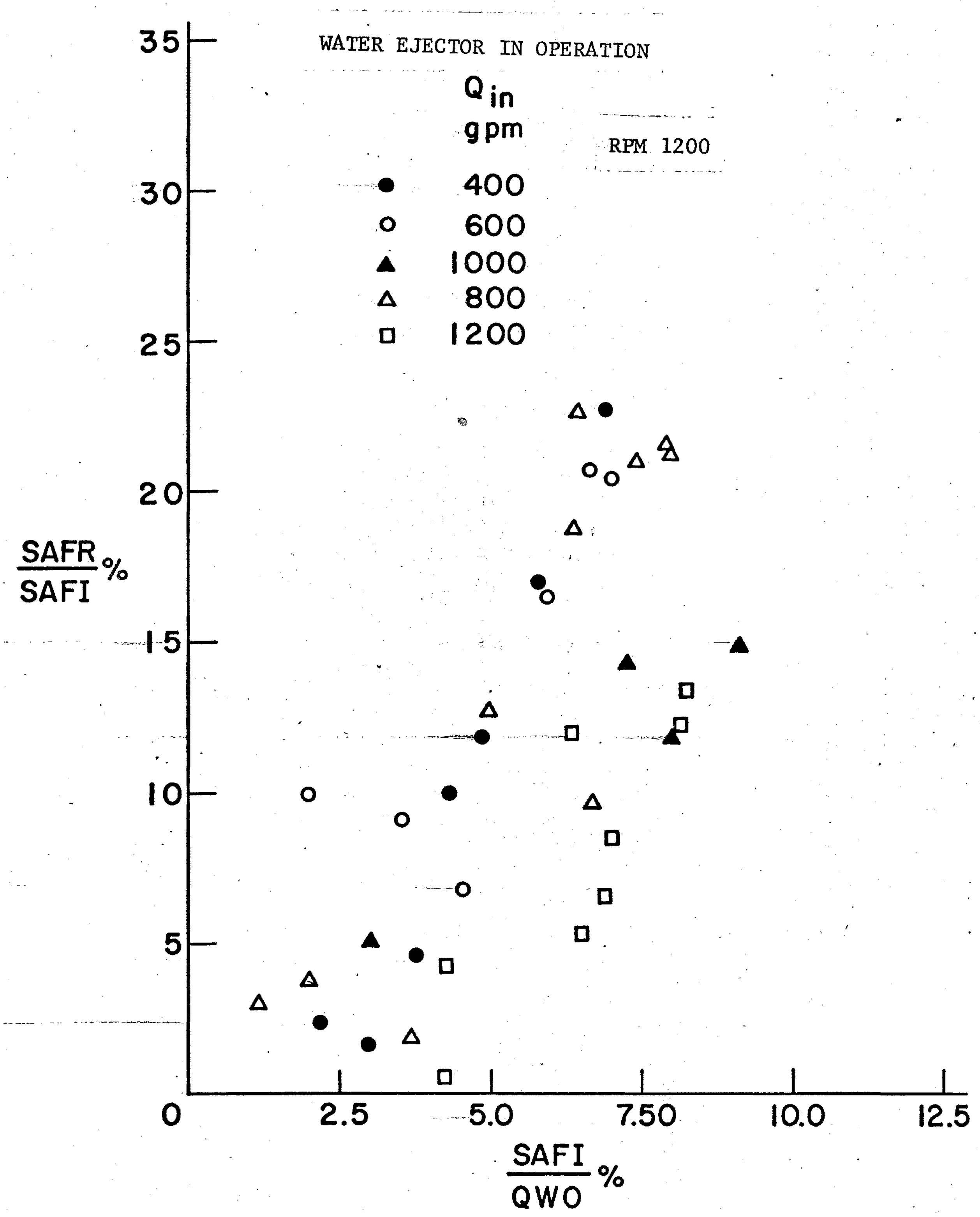


Fig. 28: Relationship Between Percent Gas Removal and SAFI/QWO

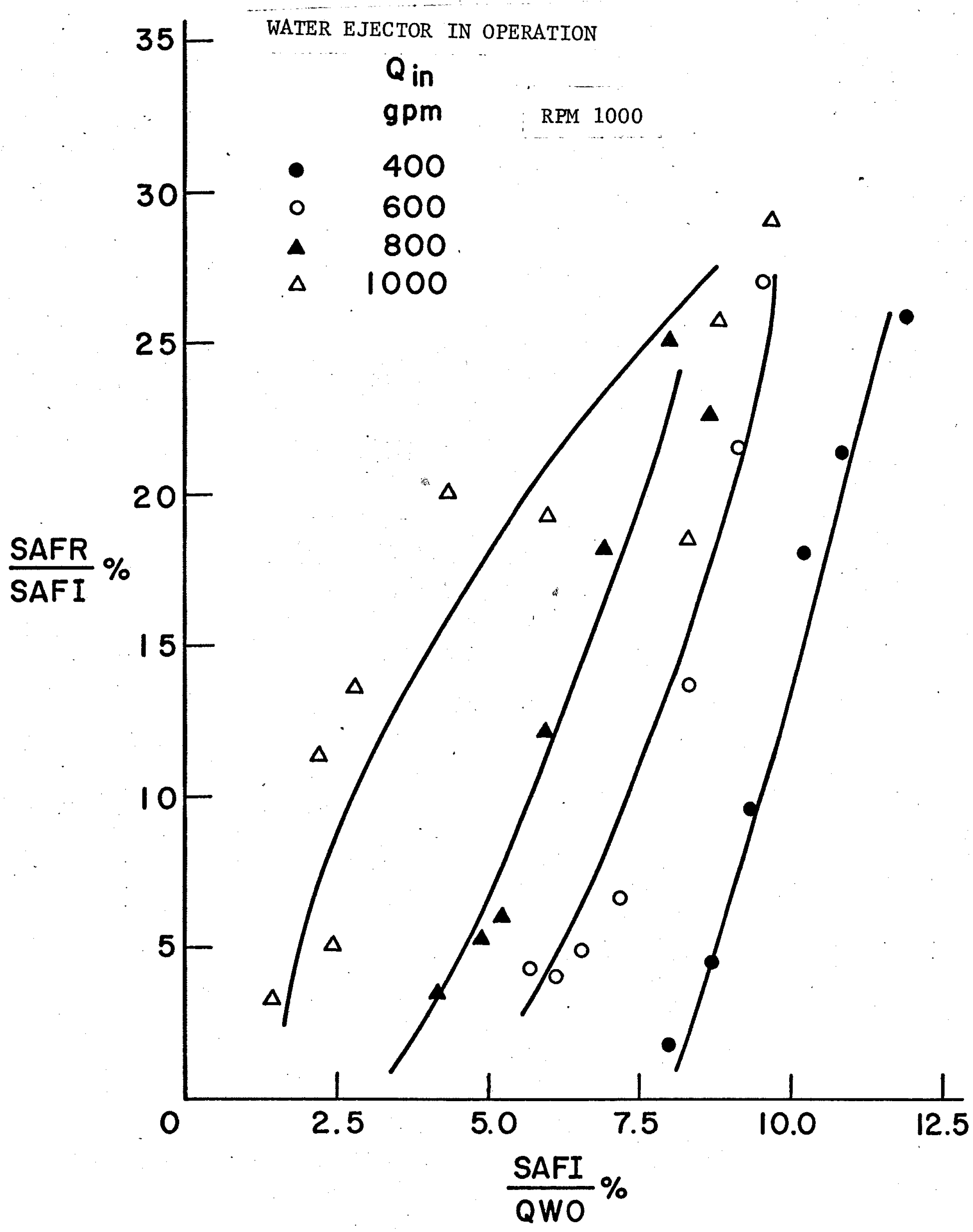


Fig. 29: Relationship Between Percent Gas Removal and SAFI/QWO

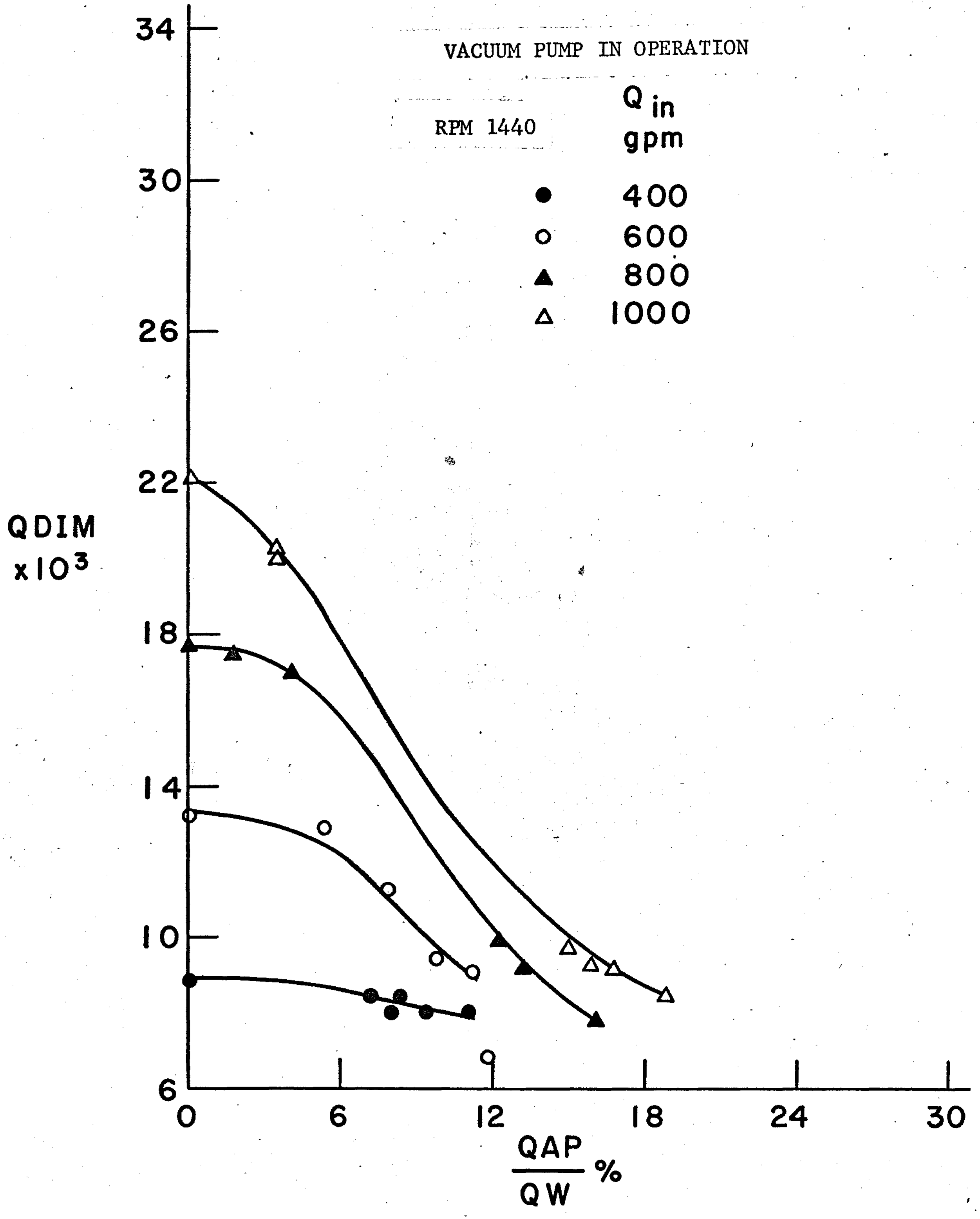


Fig. 30: Relationship Between Dimensionless Discharge and QAP/QW

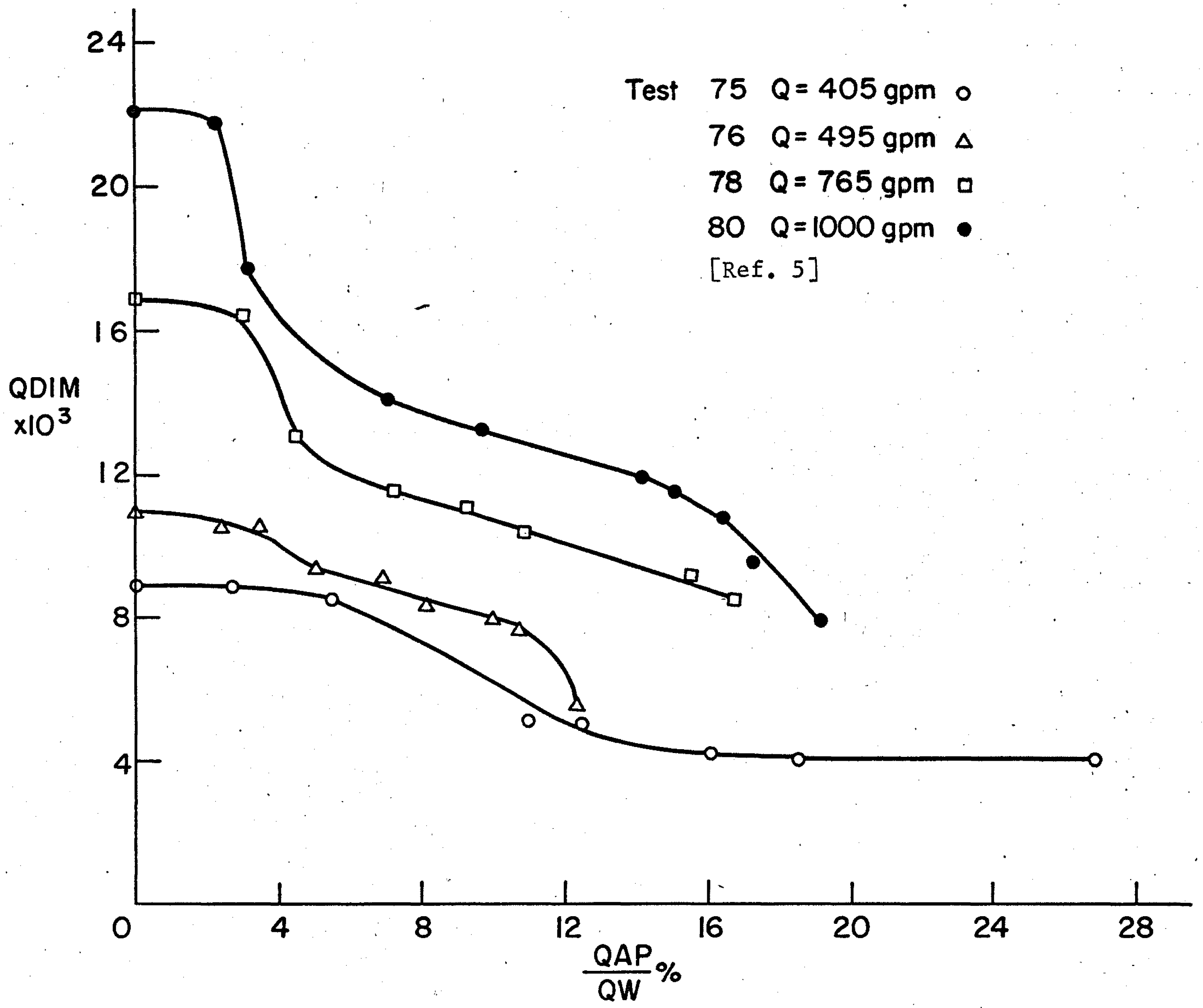


Fig. 31: Dimensionless Water Discharge versus Air at Pump Suction: Vacuum Pump

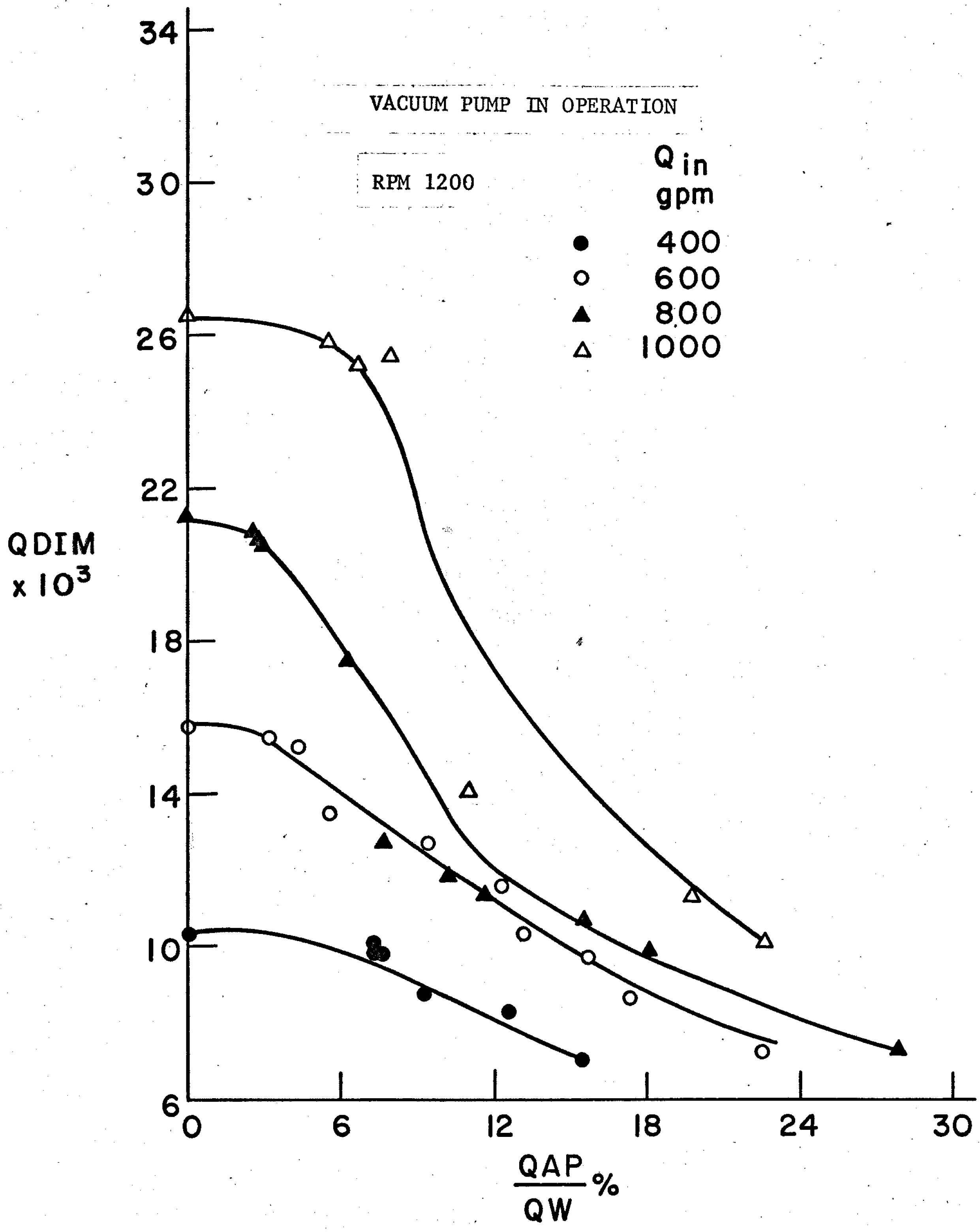


Fig. 32: Relationship Between Dimensionless Discharge and QAP/QW

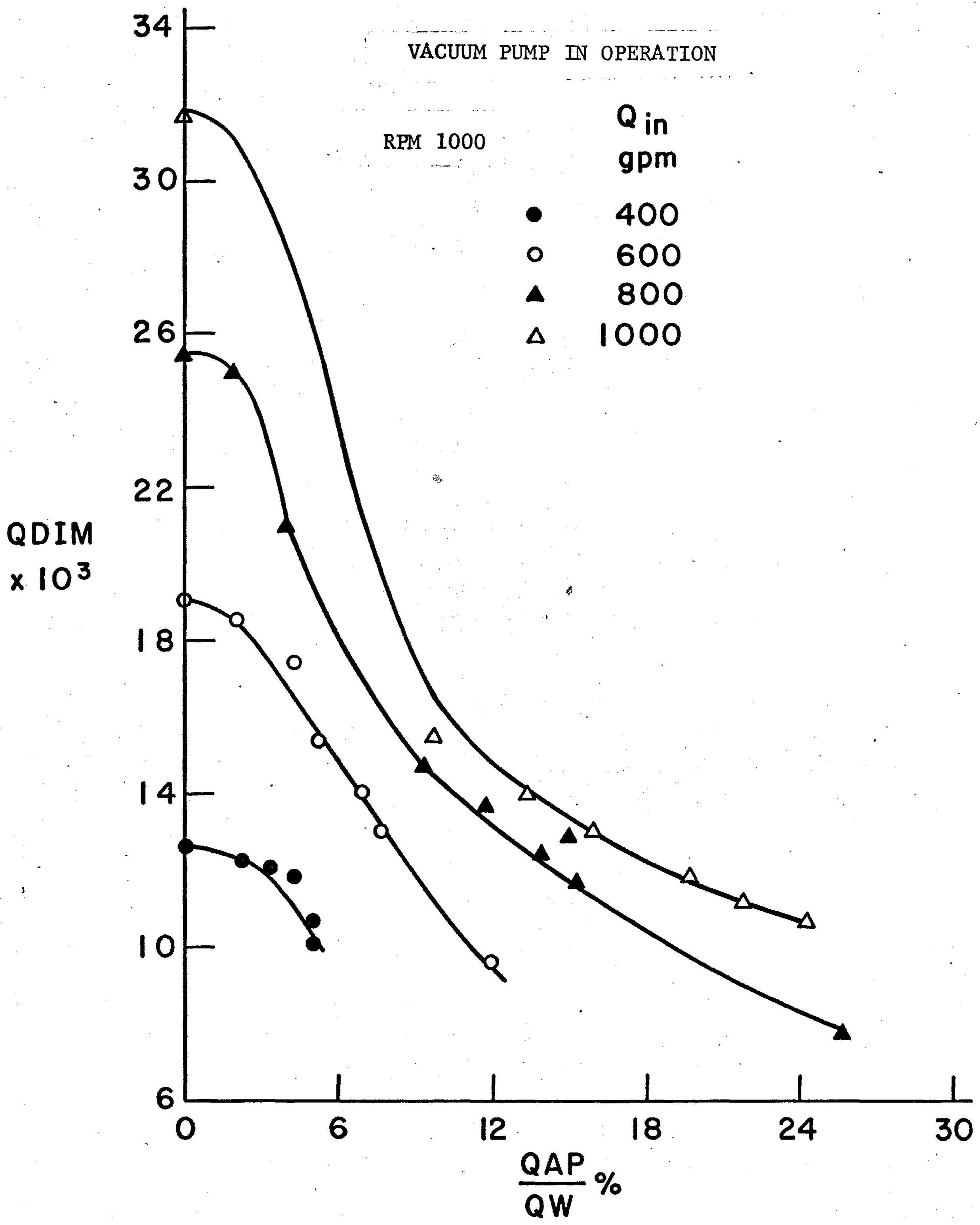


Fig. 33: Relationship Between Dimensionless Discharge and QAP/QW

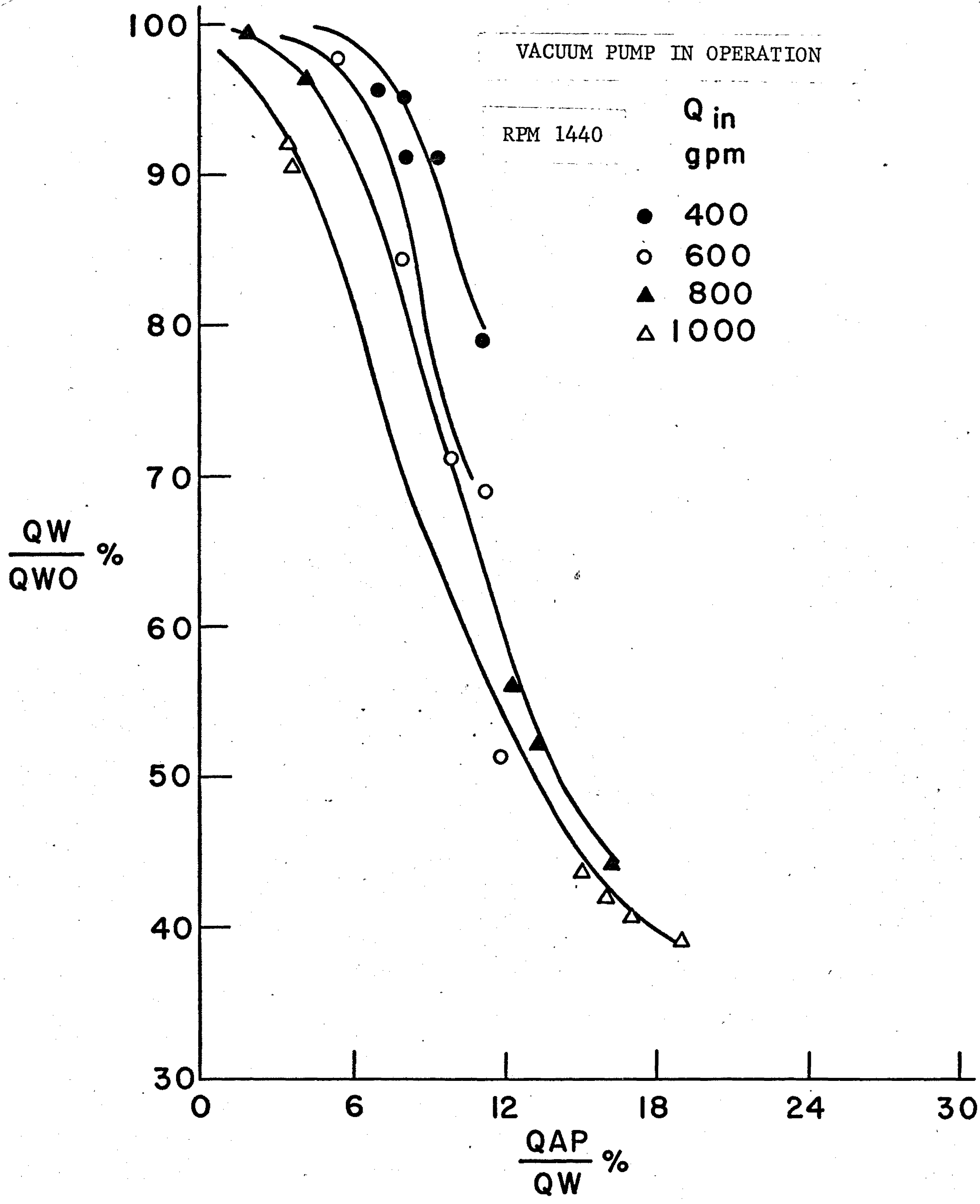


Fig. 34: Relationship Between Water Discharge Ratio and QAP/QW

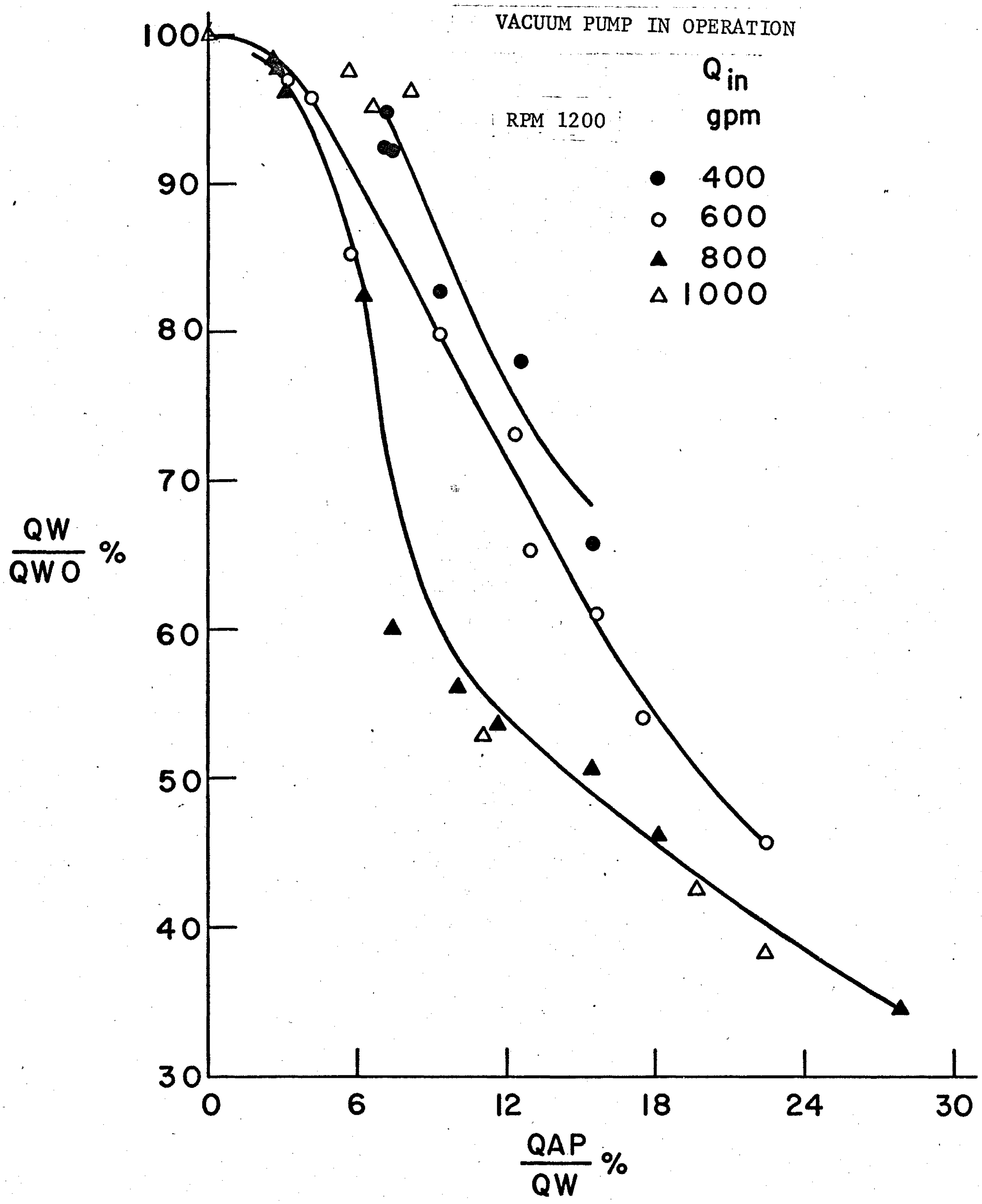


Fig. 35: Relationship Between Water Discharge Ratio and QAP/QW

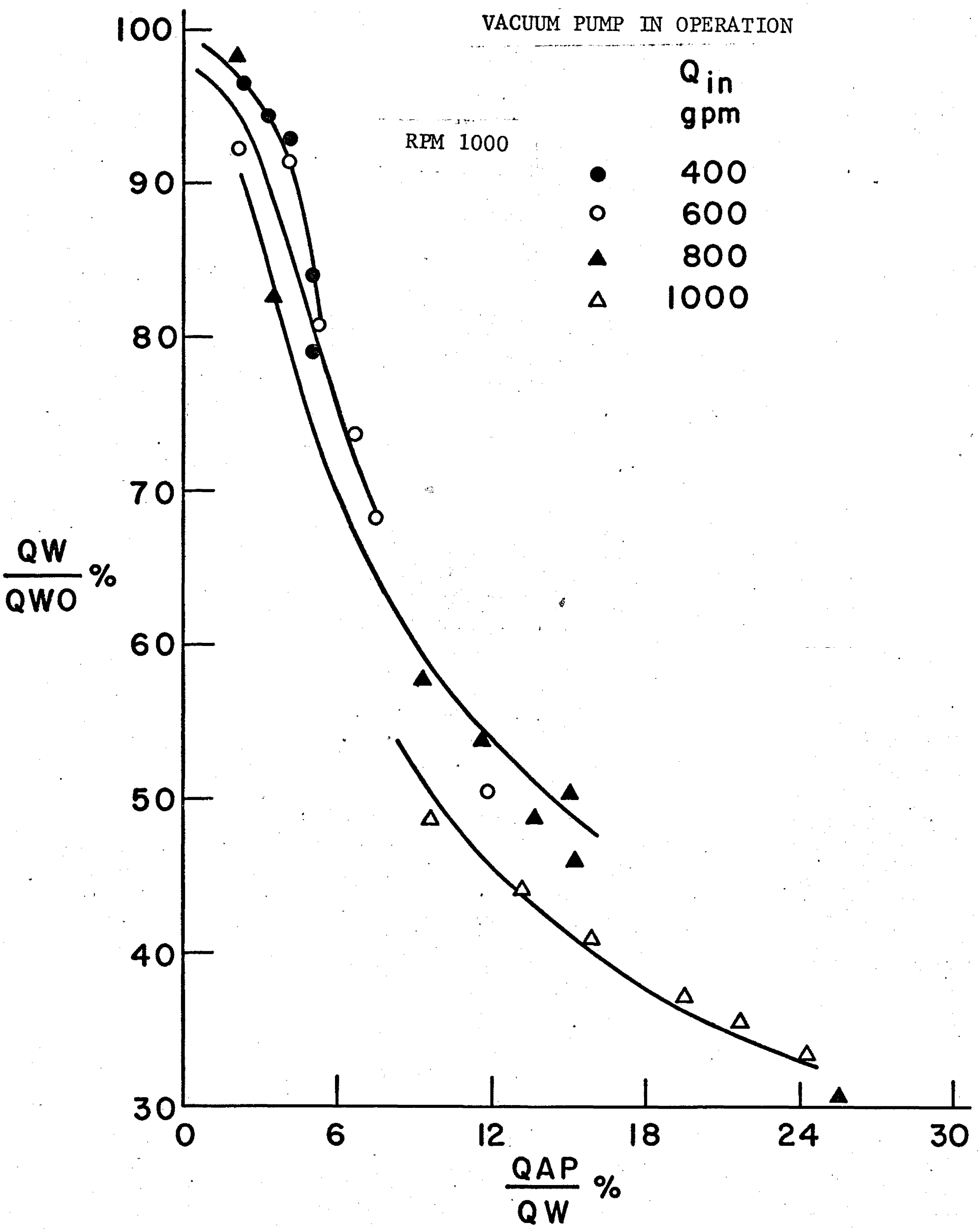


Fig. 36: Relationship Between Water Discharge Ratio and QAP/QW

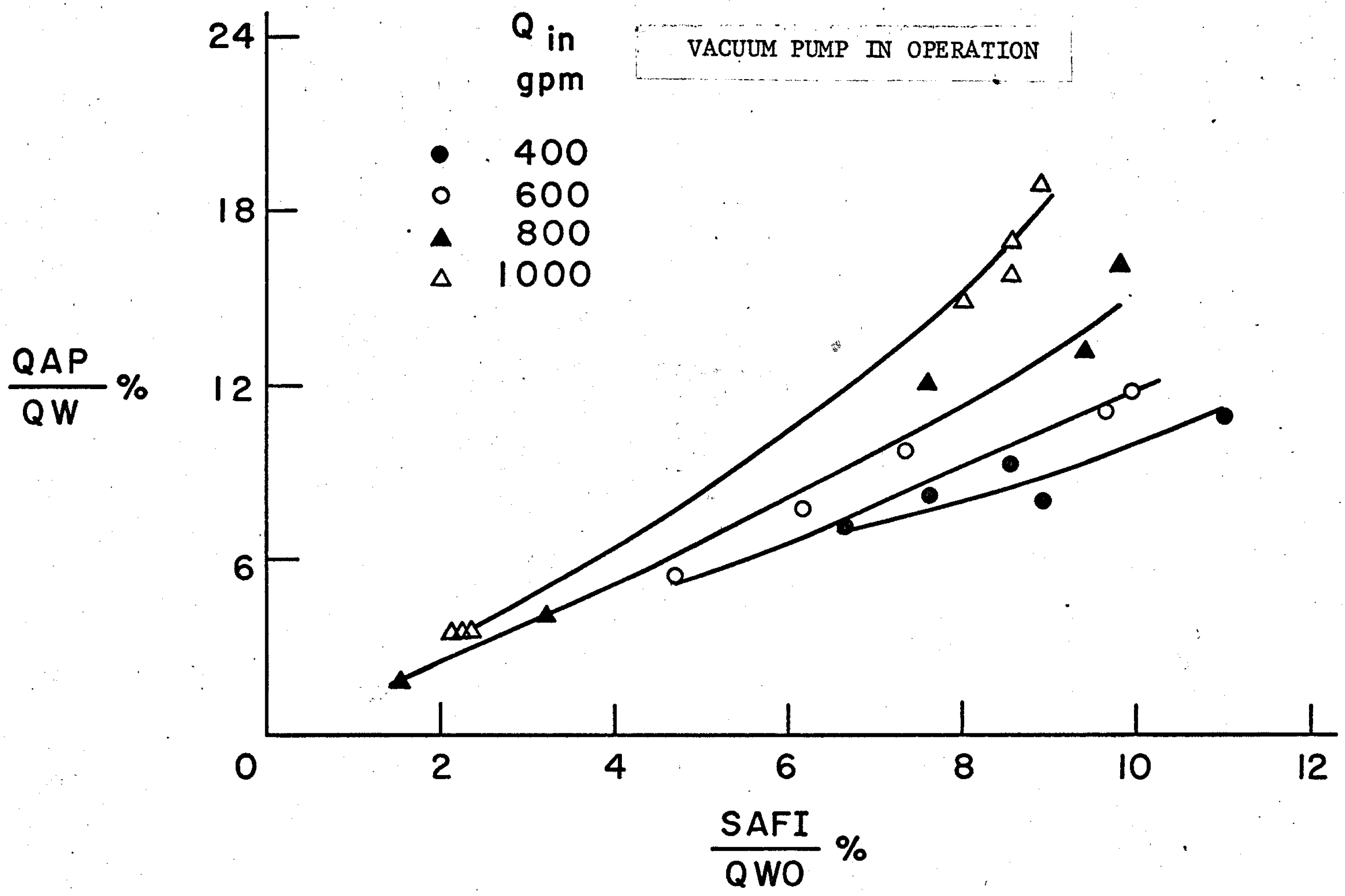


Fig. 37: Relationship Between QAP/QW and Air Injection Ratio at 1440 RPM

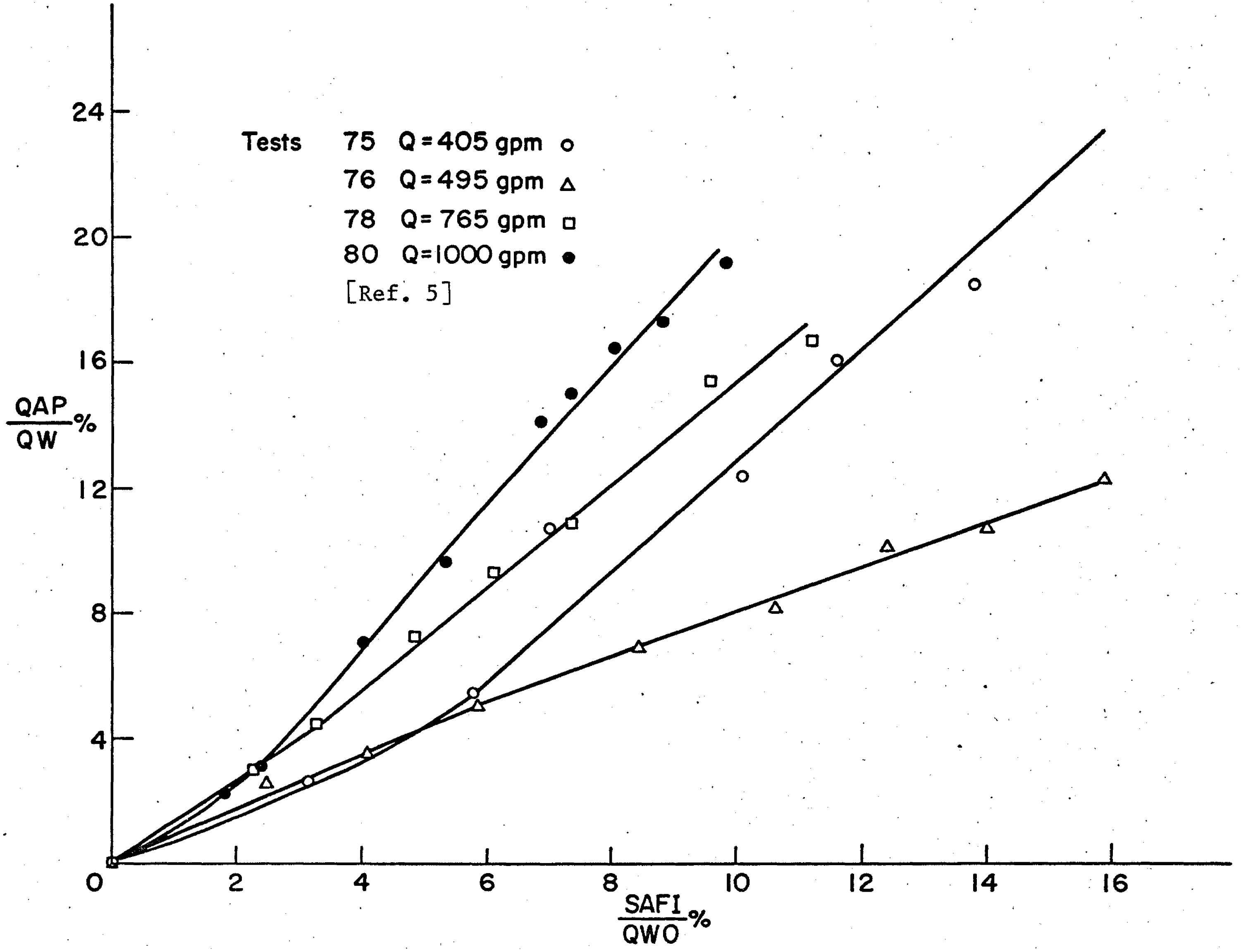


Fig. 38: Air Percent at Pump Suction versus Air Injected: Vacuum Pump

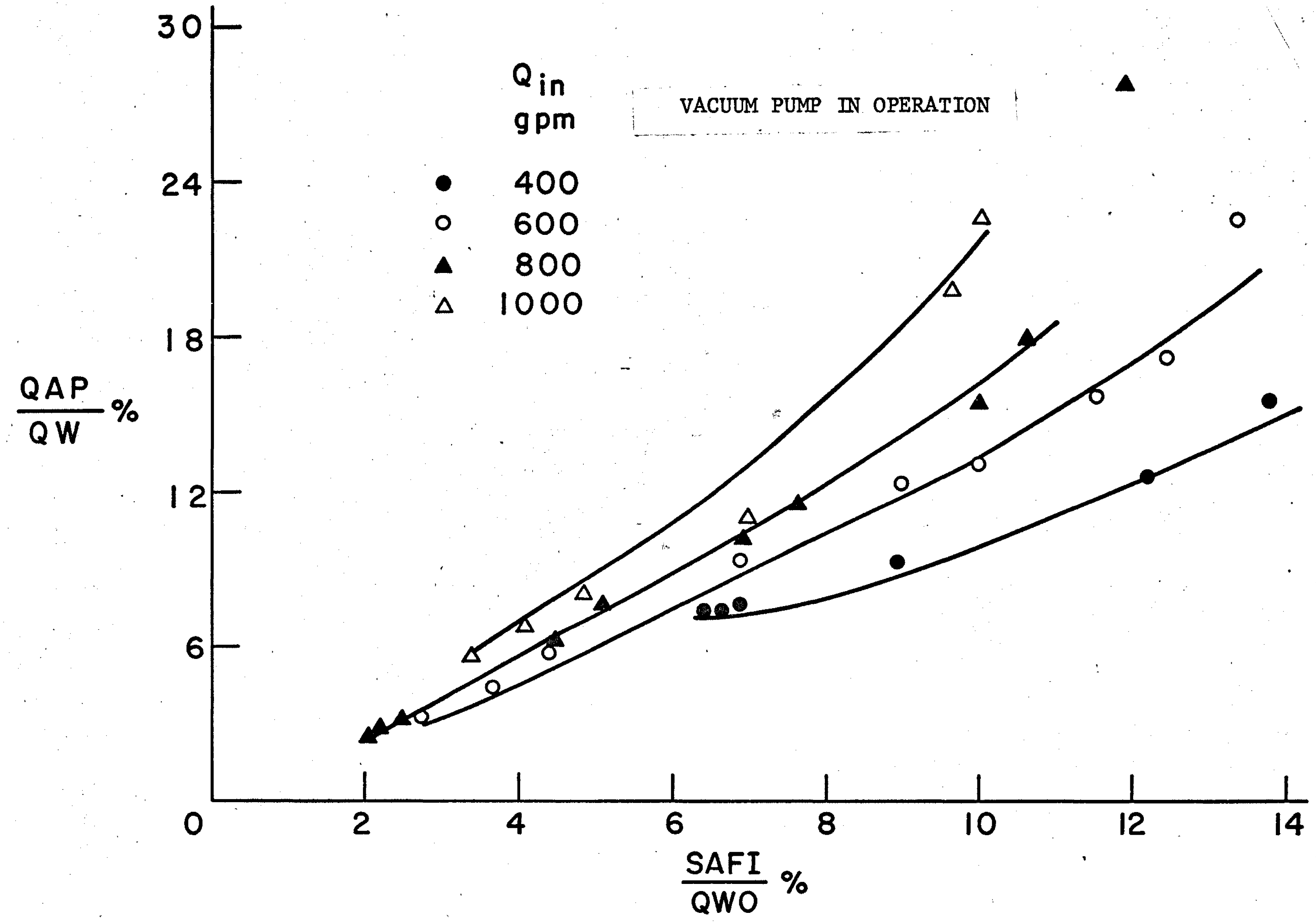


Fig. 39: Relationship Between QAP/QW and Air Injection Ratio at 1200 RPM

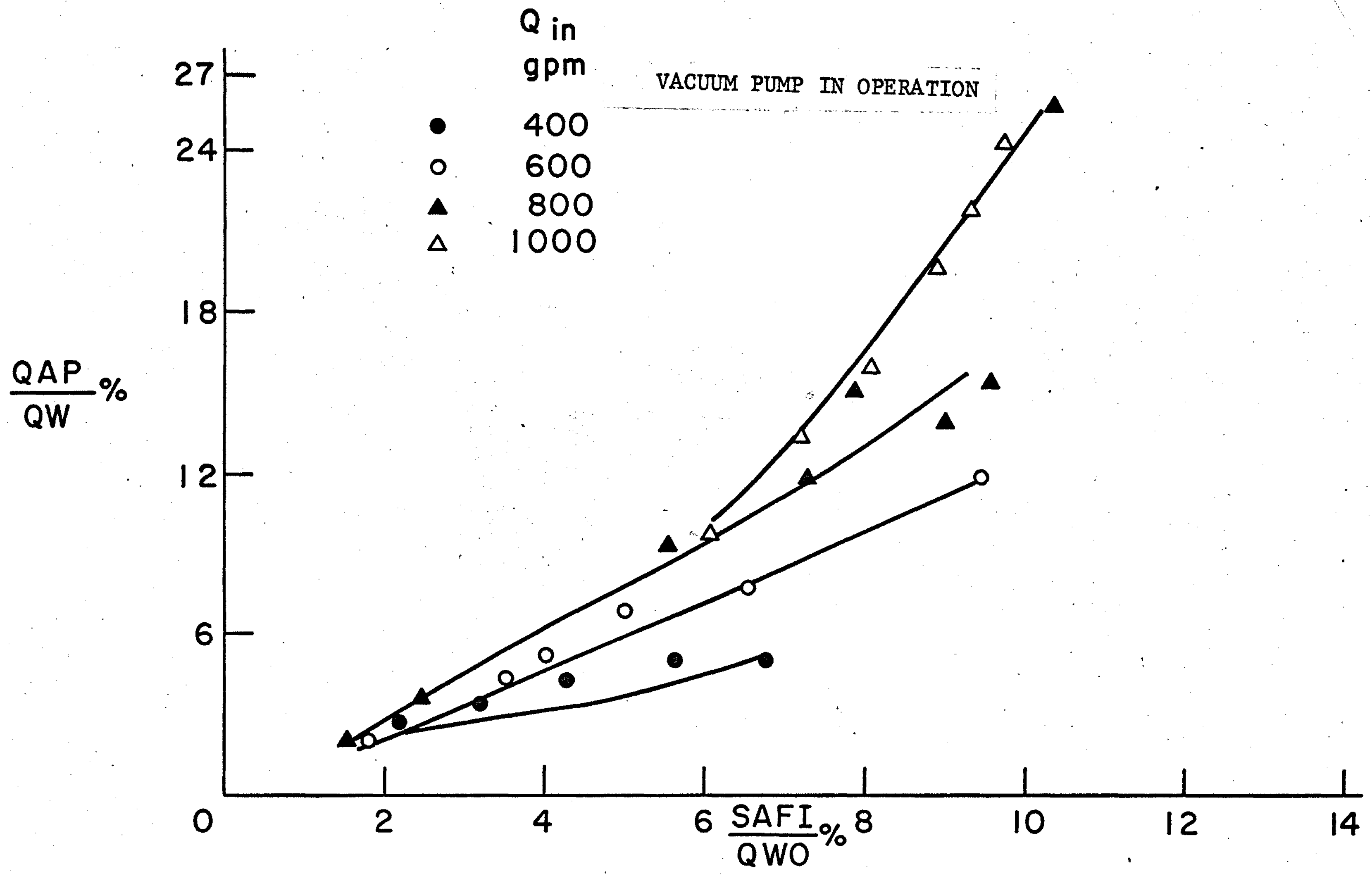


Fig. 40: Relationship Between QAP/QW and Air Injection Ratio at 1000 RPM

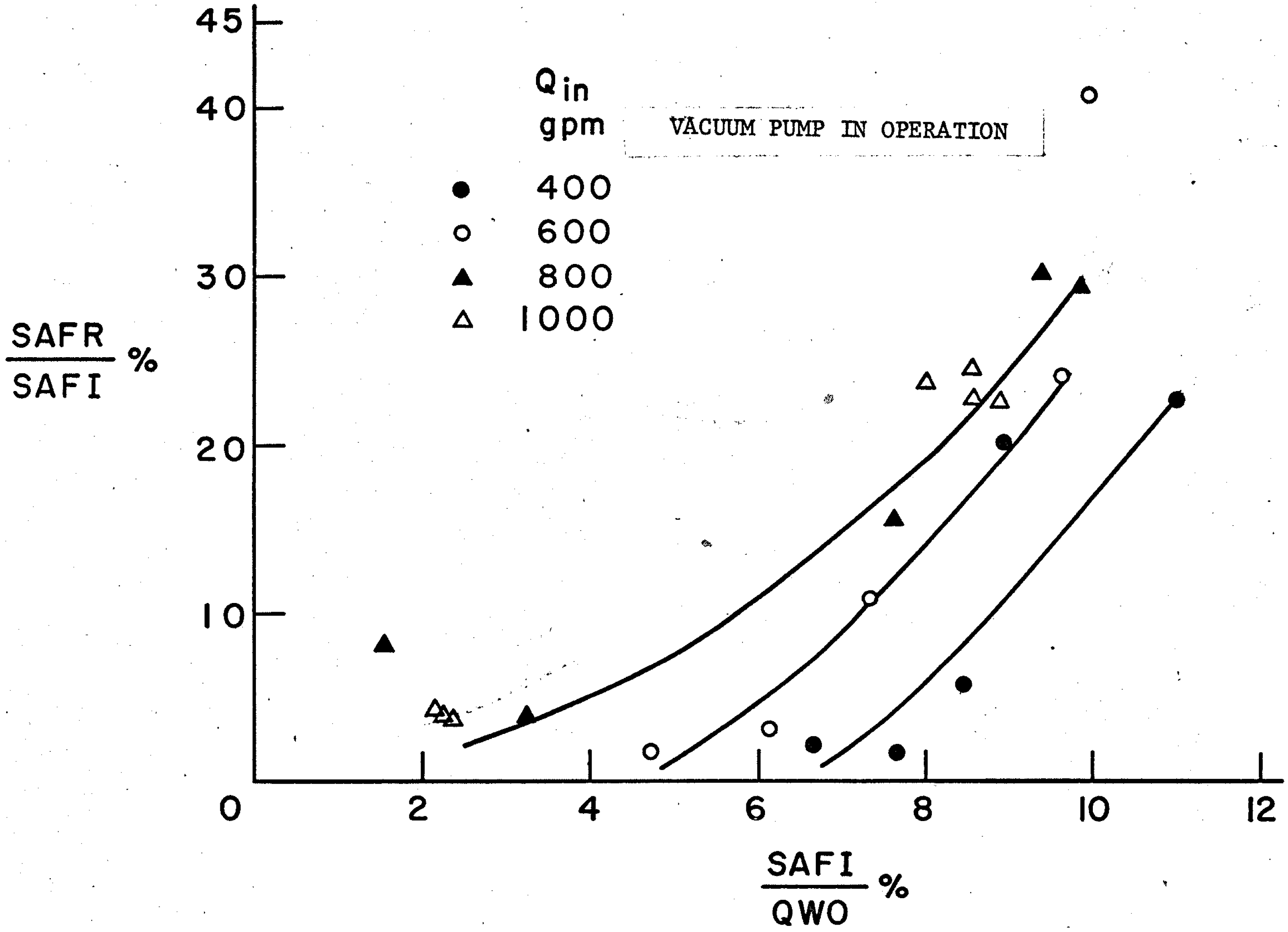


Fig. 41: Relationship Between Percent Gas Removal and SAFI/QWO at 1440 RPM

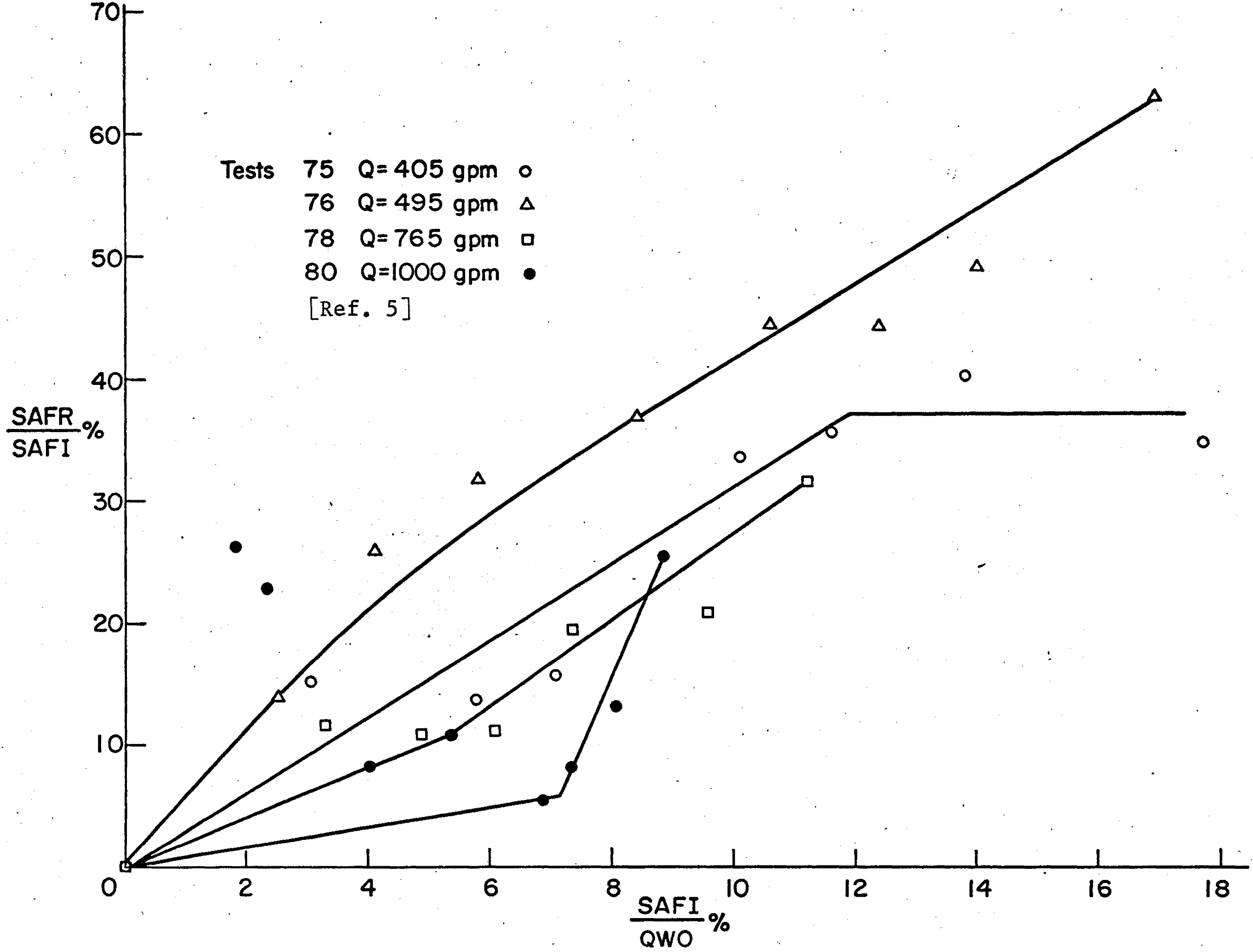


Fig. 42: Air Removed versus Air Injected: Vacuum Pump

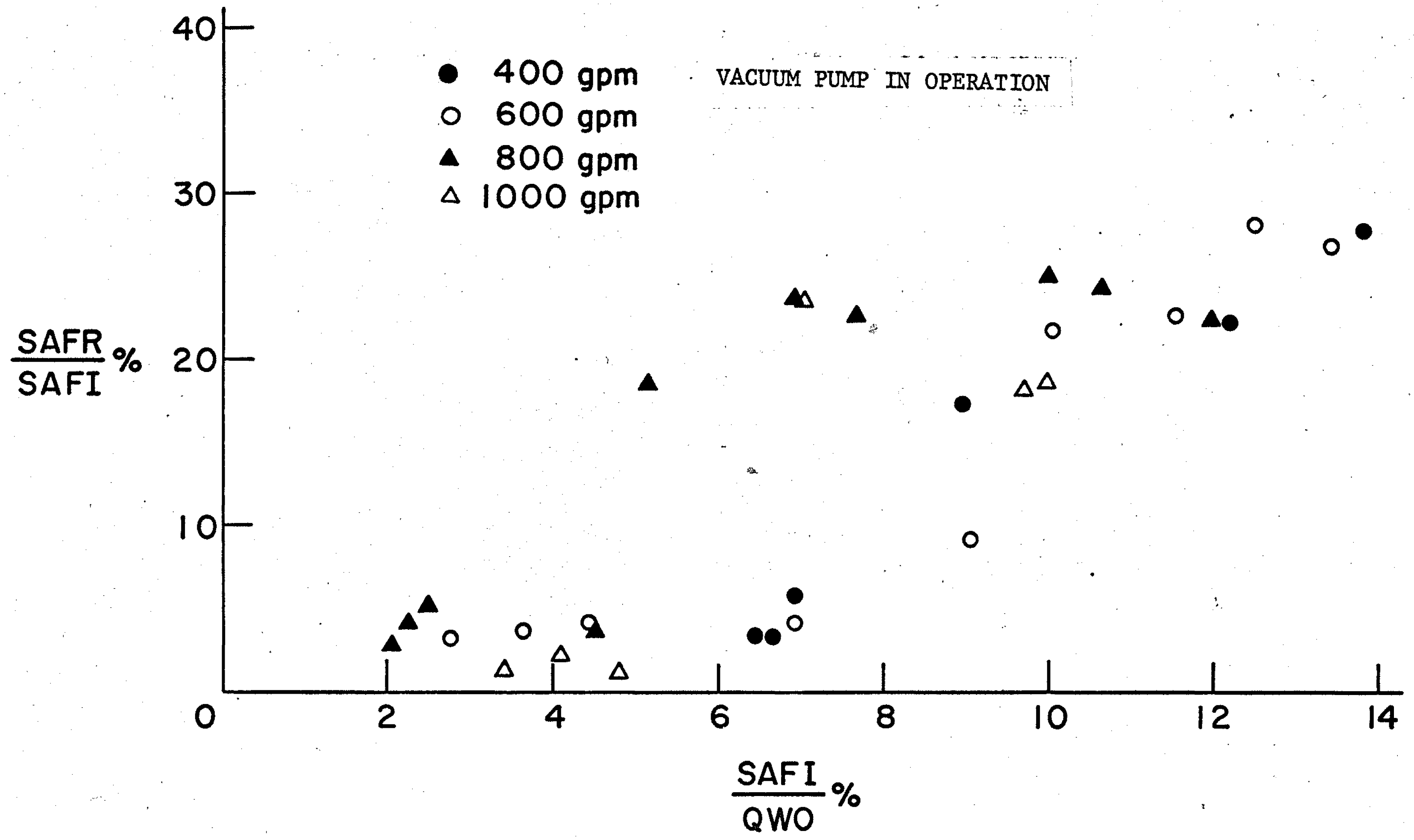


Fig. 43: Relationship Between Percent Gas Removal and SAFI/QWO at 1200 RPM

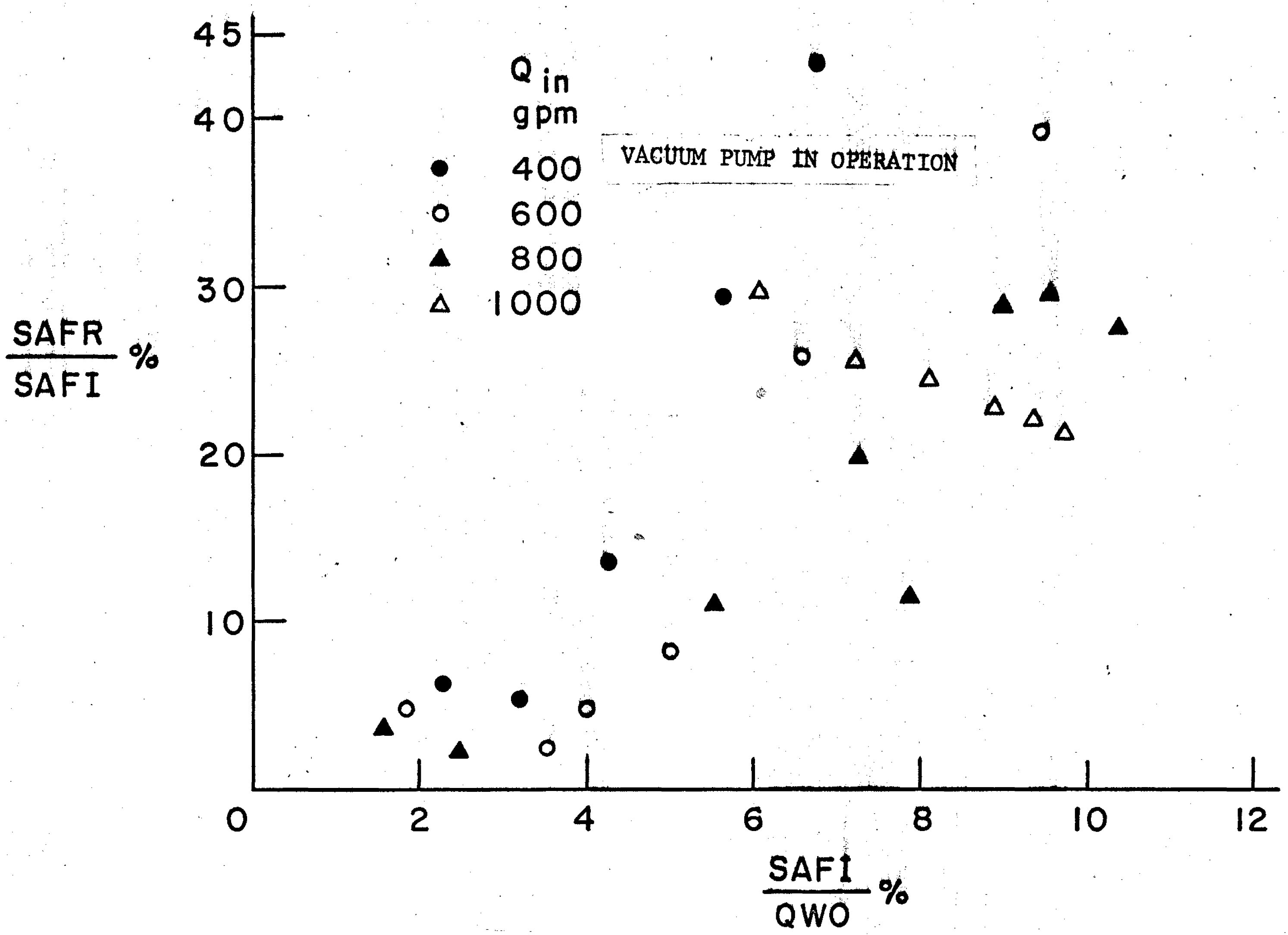


Fig. 44: Relationship Between Percent Gas Removal and SAFI/QWO at 1000 RPM

NOMENCLATURE

AMFP	air mass flowrate to pump, slugs/sec
AMFI	air mass flowrate injected, slugs/sec
AMFR	air mass flowrate removed, slugs/sec
AMP	electric current, amperes
API1	injection pressure p_1, pounds per square inch gauge
APR1	vacuum pressure removal, inches of mercury
APS	air percent pump suction, AQS/QW or QAP/QW
AQD	air flow pump discharge, cubic feet/sec
AQS	air flow pump suction, cubic feet/sec, same as QAP
BHP	horsepower to pump
cfm	cubic feet per minute
cfs	cubic feet per second
D	impeller diameter, ft
DAPI	differential pressure, injection side, pounds per square inch
DAPR	differential pressure, removal side, inches of mercury
EFF	pump efficiency, WHP/BHP
EFFM	efficiency, H mixture
$^\circ$F	degrees Fahrenheit
g	acceleration due to gravity, ft/sec^2
gpm	gallons per minute
h	venturi head reading, same as HV

H	total dynamic head, feet of water
HDIM	dimensionless head, $gH/(2\pi RPM/60)^2D^2$
Hg	mercury
HM	total dynamic head, feet of mixture
HMDIM	dimensionless HM
HV	venturi head, inches of manometer fluid of specific gravity, 1.75, same as h
HSLO	suction manometer, initial reading left, inches of Hg
HL10	discharge manometer 1, initial reading left, inches of Hg
HR10	discharge manometer 1, initial reading right, inches of Hg
HL20	discharge manometer 2, initial reading left, inches of Hg
HR20	discharge manometer 2, initial reading right, inches of Hg
HSL	suction manometer reading left, inches of Hg
HSR	suction manometer reading right, inches of Hg
HL1	discharge manometer 1, reading left, inches of Hg
HR1	discharge manometer 1, reading right, inches of Hg
HL2	discharge manometer 2, reading left, inches of Hg
HR2	discharge manometer 2, reading right, inches of Hg
$\dot{m}$	air flowrate, slugs/sec
N	number of runs in a steady flow test

NUM	test number in case of a steady flow test
P_1	upstream pressure, pounds per square inch absolute
PAT	atmospheric pressure, inches of mercury
P_2	downstream pressure, pounds per square inch absolute
PDM	pump discharge pressure, feet of mixture
PDW	pump discharge pressure, feet of water
psi	pounds per square inch
PSM	pump suction pressure, feet of mixture
PSW	pump suction pressure, feet of water
Q	flowrate, cfs
Q_{in}	initial water flowrate, gpm
QAP	air flowrate, pump suction, cfs, same as AQS
QAP/QW%	air percent, pump suction, same as APS
QAR	air flowrate removal, cfs
QDIM	dimensionless discharge, $QW/(2\pi RPM/60)D^3$
QGPM	total flowrate in gallons per minute
QTOTLE	total flowrate (magnetic flowmeter on ejector), cfs
QT	total flowrate, cfs
QTS	total flowrate, pump suction, cfs
QW	a) water flowrate in cfm (when used in QW/QWO and SAFI/QWO) b) water flowrate in cfs
QWO	initial water flowrate (= Q/7.48), cfm
QW/QWO%	water discharge ratio
QWATRV	water flowrate (venturimeter), cfs

Re	Reynolds number based on diameter
RMOVP1	pressure removal, feet of water
RPM	revolutions per minute
SAFI	air flowrate injection, standard cubic feet/minute
SAFP	air flowrate to pump, standard cubic feet/minute
SAFR	air flowrate removal, standard cubic feet/minute
SAFI/QWO%	air injection ratio
SAFR/SAFI%	percent gas removal
SCFM	standard cubic feet per minute
T	temperature °F
TABS	absolute temperature (°F + 459.0)
V	electric voltage, volts
VHD	velocity head, pump discharge
VHS	velocity head, pump suction
WHP	water horsepower
WHPM	water horsepower, H mixture
WLAC	accumulator water level in inches above centerline of suction pipe to the pump
WMD	unit weight of mixture, discharge
WMS	unit weight of mixture, suction

APPENDIX

SOURCE PROGRAM
FOR STEADY FLOW AIR INJECTION
VACUUM PUMP IN OPERATION

PROGRAM STEADY(OUTPUT,TAPE6=OUTPUT,INPUT,TAPE5=INPUT)

```
      WRITE(6,600)
 2    READ(5,510)NUM
      IF(NUM.LT.0)GO TO 1
      READ(5,500)N,RPM,T,PAT,HSLO,HSRO,HL10,HR10,HL20,HR20
 600  FORMAT(1H1,20X,*PROJECT 310*,10X,*GAS REMOVAL FOR DREDGE PUMPS*
     2/,20X,*STEADY GAS FLOW*,//)
 500  FORMAT(I2,F8.0,8F5.2)
      WRITE(6,601)NUM,RPM,T,PAT
 601  FORMAT(5X,*TEST NO*,2X,I2,4X,*INPUT  DATA*,4X,*PUMP SPEED*,2X,F8.0
     2,4X,*TEMPERATURE*,2X,F5.2,4X,*ATMOSPHERIC PRESSURE*,2X,F5.2,//)
      DO 200 I=1,N
      READ(5,501)AMP,V,QGPM,HSL,HSR,HL1,HR1,HL2,HR2,API1,DAPI,APR1,DAPR
 501  FORMAT(3F6.0,10F5.2)
 510  FORMAT(I4)
      WRITE(6,499)I
 499  FORMAT(4X,*RUN NUMBER*,2X,I2)
      WRITE(6,610)AMP,V ,QGPM,HSL,HSR,HL1,HR1,HL2,HR2,API1,DAPI,APR1,DAP
     2R
 610  FORMAT(10X,*AMP*,4X,*V*,4X,*QGPM*,4X,*HSL*,4X,*HSR*,4X,*HL1*,4X,*H
     2R1*,4X,*HL2*,4X,*HR2*,4X,*API1*,4X,*DAPI*,4X,*APR1*,4X,*DAPR*,//,9
     3X,F4.1,2X,F5.1,2X,F6.1,1X,F4.1,5(3X,F4.1),4(4X,F4.1))
      QT=QGPM*2.228E-3
      BHP=AMP*V*1.17E-3
      PSW=-13.55*(HSL+HSR-HSLO-HSRO)*8.333E-2
      PDW=(13.55*((HL1+HR1+HL2+HR2)-(HL10+HR10+HL20+HR20))+(HL10+HR10+HL
     220)-(HL1+HR1+HL2))*8.333E-2
C     STEADY  AIR  FLOW  COMPUTATION
      AMFI=.00084*((PAT*14.7/29.92+API1)*DAPI/(459.+T))**0.5
      AMFR=.002*((PAT-APR1)*14.7/29.92*DAPR*14.7/29.92*1.0/(459.+T))**.8
      AMFP=AMFI-AMFR
      SAFI=60.0*AMFI/0.00237
      SAFR=60.*AMFR/0.00237
      SAFP=60.*AMFP/0.00237
C     STEADY  AIR  FLOW
      AQS=AMFP*1720.*(459.+T)/(PAT*2116./29.92+PSW*62.3)
      AQD=AMFP*1720.*(459.+T)/(PAT*2116./29.92+PDW*62.3)
      QW=QT-AQD
      QTS=QW+AQS
      APS=AQS/QW
      VHS=1.277*QTS*QTS
      VHD=2.042*QT*QT
      H=PDW-PSW+VHD-VHS+1.07
      WHP=62.3*QW*H/550.
      EFF=WHP/BHP
      HDIM=32.2*H/(RPM*.09163)**2.
      QDIM=QW/((RPM*.1047)*.875**3.)
      WMS=62.3*QW/QTS
      WMD=62.3*QW/QT
      PSM=PSW*62.3/WMS
      PDM=PDW*62.3/WMD
      HM=PDM-PSM+VHD-VHS+1.07
      HMDIM=HDIM*HM/H
      WHPM=62.3*QW*HM/550.
      EFFM=WHPM/BHP
      RMOVP1=-APR1*34.0/29.92

      WRITE(6,602)
 602  FORMAT(//,20X,*AIR FLOW*,/,20X,*INJECTION*,20X,*REMOVAL*,20X,*PUMP
     2*)
      WRITE(5,603)SAFI,SAFR,SAFP
 603  FORMAT(/,16X,*SCFM*,3X,F6.3,21X,F6.3,19X,F6.3)
      WRITE(6,604)AMFI,AMFR,AMFP
 604  FORMAT(/,10X,*SLUGS/SEC*,2X,E13.6,19X,E13.6,18X,E13.6)
      WRITE(5,605)AQS,QTS,APS
 605  FORMAT(///,20X,*AIR FLOW,PUMP SUCTION,CFS*,3X,E13.6,/,16X,*TOTAL
     2DISCHARGE,PUMP SUCTION,CFS*,2X,E13.6,/,25X,*AIR PERCENT,PUMP
     3SUCTION*,2X,E13.6)
      WRITE(6,606)VHS,VHD,QGPM,QT,QW,WHP
 606  FORMAT(///,20X,*PUMP DATA*,/,10X,*VHS=*,E13.6,2X,*VHD=*,E13.5,2X,*
     2QGPM=*,F6.0,2X,*QT=*,F7.3,2X,*QW=*,F7.3,2X,*WHP=*,F6.3)
      WRITE(6,607)PDW,PSW,H,EFF,HDIM,QDIM
 607  FORMAT(/,10X,*PDW=*,F7.3,2X,*PSW=*,F7.3,3X,*H=*,F7.3,3X,*EFF=*,F7.
     24,3X,*HDIM=*,E13.6,3X,*QDIM=*,E13.6)
      WRITE(6,608)PDM,PSM,HM,EFFM,HMDIM
 608  FORMAT(/,10X,*PDM=*,F7.3,2X,*PSM=*,F7.3,2X,*HM=*,F7.3,2X,*EFFM=*,F
     27.4,2X,*HMDIM=*,E13.6)
      WRITE(6,609)RMOVP1
 609  FORMAT(/,20X,*REMOVAL PRESSURE P1 IN FEET OF WATER*,2X,F8.3,//)
 200  CONTINUE
      GO TO 2
 1    CALL  EXIT
      END
```

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