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GAS REMOVAL SYSTEMS ON A MODEL DREDGE PUMP

by

Rana Partap Gupta

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

Date: March 25, 1971

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ABSTRACT

Dredge pumps encounter mixtures of solids, liquids and gases in varying proportions. These gases may accumulate in considerable quantities at the suction side of the pump and severely reduce its efficiency. This necessitates the installation of gas removal systems on the suction side in order to improve pump performance. Removal systems consist basically of an accumulator and a vacuum source.

The objectives of this experimental research are to study the various factors affecting the pump performance and the efficiency of the gas removal systems. The pump performance was investigated under different conditions of air content, pump speed, and discharge orifice setting. In order to evaluate the efficiency of gas removal systems, experiments were carried out involving numerous combinations of the above variables and the water level in the accumulator. These tests included two gas removal systems, namely, the vacuum pump and the water ejector.

The experimental results are presented in the form of suitable dimensionless parameters. Correlation curves are given to show the relationship among these parameters. These curves could be used for the determination of the amount of water flowrate under different operating conditions. Considerable amounts of gas could be removed by the removal systems before the gas flows to the pump. Higher gas injection ratio and higher water level in the accumulator gave better results. High speed motion pictures of flow in the accumulator and

the impeller showed that the vertical orientation of the discharge pipe helps the pump performance.

1. INTRODUCTION

1.1 Dredging

Dredging may be defined as the process of removing subaqueous materials with the objective of increasing the water depth and/or acquiring subaqueous material for use as fill for its commercial value. This operation can be done by a floating excavating machine called a 'Dredge'. In the past, the dredging operations, performed by manpower and ingenious tools, were limited to small quantities in soft soils. Later on, the steam engine converted dredging into a branch of industry which promoted shipping potentials and industrial developments at large. Since then, the dredging industry has made tremendous progress and many types of dredges with practically all kinds of instrumentation have been developed. Dredging is extensively used for channel and harbor construction, maintenance and improvement, land reclamation, dam and dyke construction, roadway fill, beach replenishment, etc. Besides, it is anticipated that dredging will be an important factor in offshore mining in the future[1].

1.2 Types of Dredges

Basic Types:

Dredges can be classified into two main types, the mechanically operated type and hydraulically operated type.

1.2.1 Mechanical Dredges

Due to their simplicity and analogy with land-based excavating machines, mechanical dredges were the first to be developed. Mechanical dredges[2,3] can be further classified into the grapple dredge, the dipper or scoop dredge, and the bucket-ladder or elevator dredge.

1.2.1.1 Grapple Dredge

The grapple dredge consists of a derrick mounted on a barge and equipped with a "clamshell" or "orange-peel" bucket. The clamshell bucket has two quadri-cylindrical shells forming a portion of a cylinder when closed, whereas the orange-peel bucket has four shells forming a hemispherical bowl when closed. This dredge is best suited to dredging in soft underwater deposits.

1.2.1.2 Dipper Dredge

The dipper or scoop dredge is the floating counterpart of the land-based excavating shovel. Due to its greater leverage and "crowding" action, it works best in hard compact material or rock.

1.2.1.3 Bucket-Ladder Dredge

The bucket-ladder dredge consists essentially of an endless chain of buckets, the top of the chain being thrust into the underwater deposit to be dredged so that each bucket digs its own load and carries it to the surface. Ladder dredges can be classified into three subdivisions:

a) Stationary dredges
b) Self-propelled, barge loading dredges
c) Seagoing hopper dredges

The first is the usual river or calm-water type which is fed laterally or radially by means of anchorages or spuds and hauling cables and discharges either into waiting barges or into deep water or spoil basins remote from the dredge. Both the second and third types have moulded hulls and seagoing capabilities. The second type is confined to the calmer waters of ports and estuary channels because of its accompanying barge, while the third is a seagoing vessel comprising both barge and dredge in one. Since the work cycle is continuous, bucket-ladder dredges are more efficient than either the grapple or dipper dredge. Bucket-ladder dredges are particularly useful to sand and gravel suppliers.

Mechanical dredges are all characterized by their inability to transport dredged materials for long distances, lack of self-propulsion, and relatively low production. Their main advantage is their ability to operate in restricted locations such as docks and jetties.

1.2.2 Hydraulic Dredges

Hydraulic dredges[2], which are the primary concern of this study, are self-contained units and handle both phases of the dredging process, namely, they dig the material and dispose of it either by pumping it through a floating pipeline to a spoil area, or by storing it in hoppers to be subsequently emptied over the spoil area. These dredges are efficient, versatile and economical to operate due to the continuous, self-contained digging and disposal processes.

With a hydraulic dredge, the material to be removed is first loosened and mixed with water by cutterheads or by agitation with water jets and then pumped as a mixture. The three basic units in a hydraulic dredge are the dredge pumps, the agitating machinery, and the hoisting and hauling equipment. The latter is used primarily to raise and lower the cutter and suction dragheads. Hydraulically operated dredges can be classified into three basic types: the dustpan dredge, the hydraulic pipeline cutterhead dredge, and the self-propelled hopper dredge.

1.2.2.1 The Dustpan Dredge

It is a plain-suction, self-propelled dredge. The suction head resembles a large vacuum cleaner or a dustpan and is about as wide as the hull of the dredge. It is fitted with high velocity water jets for agitating and mixing the material. Since it does not have a cutterhead to loosen up hard compact materials, the dustpan dredge is suited mostly for large volume, soft material dredging. A particular use for which this type is well suited is in conjunction with a hopper dredge. The hopper dredge makes its cycle returning to empty its hoppers next to a dustpan dredge. Next, the dustpan dredge sucks up the deposited material and pumps it ashore to the spoil area.

1.2.2.2 The Hydraulic Pipeline Cutter Dredge

This is probably the most well-known, efficient and versatile dredging vessel. It is equipped with a rotating cutter apparatus surrounding the intake end of the suction pipe. These dredges can efficiently dig and pump all types of alluvial material including compacted deposits such as clay and hardpan. The large and more powerful machines are used to dredge rocklike formations such as coral and the softer type of basalt and limestone without blasting. Some of these dredges were used to excavate and transport boulders in sizes up to 30 inches in diameter.

1.2.2.3 The Self-Propelled Hopper Dredge

A hopper dredge of the seagoing type has the molded hull and lines of an ocean vessel and functions in a similar manner to the suction type dredge. The bottom material is raised by dredge pumps through dragarms which are connected to the ship by trunnions. The lower ends of the dragarms have suction dragheads for contact with the bottom material. The dragarms are raised or lowered by hoisting tackles and winches. The pumps lift the mixture through the dragheads to the surface where it is discharged into hoppers. As pumping continues, the solid particles settle in the hoppers while the excess water passes overboard through overflow troughs. After the hoppers have been filled, the dragarms are raised and the dredge proceeds to the spoil area and empties the loaded hoppers through the bottom doors. The doors then close and the dredge returns to the dredging area to start a new cycle.

American dredges operate with dragarms trailing at a ground speed of 2 to 3 miles per hour. Hopper dredges range in size from approximately 180 to 550 feet in length and have hopper capacities between 500 and 8,000 cubic yards. They are equipped with twin propellers and twin rudders for adequate maneuvering. Dredging depths vary from 10 feet to over 70 feet.

Dredges of this type are necessary for maintenance work and improvement of exposed harbors and navigation channels, where traffic and operating conditions rule out the use of stationary dredges. Special equipment could be provided to these dredges to allow for "agitation dredging", where soft or free flowing materials are sucked up and discharged through a suspended discharge pipe directly overboard without storing it in hoppers. It is then carried out of the dredging area by currents and/or stream action.

One of the largest hopper dredges, the Essayons, was built by the U. S. Army Corps of Engineers for dredging along the eastern seaboard. This seagoing dredge has two 36-inch suction pipes, twin dragheads, and a hopper capacity of 8,000 cubic yards. It is 525 feet long. Twin screws and high power give it excellent maneuverability and a 16-knot loaded speed. Twin 1,850 Hp centrifugal pumps dredge up to a depth of 70 feet and can handle a million cubic yards a month. The Essayons has the inherent capability for low cost disposal of the dredged spoil at relatively long distances from excavation site.

2. DESCRIPTION OF THE PROBLEM

2.1 Constituents or Composition of the Dredged Material

Dredged material from coastal areas and estuaries may consist of solids, liquids and gases. The percentages of these constituents may vary considerably, depending on the type of bottom material and the method of dredging. Gases are products of decomposition of organic matter present in the dredged material. They are dissolved in water forming a part of 'in situ' material, and when water is saturated, bubbles form throughout the volume. Since mud usually has high viscosity, such bubbles may be retained in the mixture for many years. Gas samples taken from the dredged material indicate that the most soluble composition of the gas may be 85% methane and 15% carbon dioxide[4,5]. Other gas components may be hydrogen, oxygen and nitrogen in smaller percentages. Methane gas is, of course, inflammable, and the need to remove it from the suction line is important for safety.

2.2 Difficulties in Dredge Pump Operations

Two main difficulties are encountered when solid-liquid mixtures are pumped, namely, the corrosion that may take place especially in the blades due to the presence of solid particles and the choking off of the pump. Both actions increase with the increase of density of the dredged material. Corrosion problems can be overcome by the use of the proper alloys. The choking off problem is generally dealt with by either lifting the draghead out of the mud or by admitting water to the suction line. When a mixture containing a considerable amount of entrapped or dissolved gas is encountered, the gas which enters the suction line of the dredge pump may accumulate in such quantities that the solid-water discharge is drastically reduced or pumping is completely stopped due to loss of priming resulting in what is called "ramming or slugging". In such cases, water needs to be added in the suction system which reduces the output due to dilution of the dredged mixture. It was observed that if the choking off of the pump is due to high gas percentage in the dredged mixture, the suction head gradually drops until the vacuum head is lost. This is different from choking off due to increased density of the mixture, where the pump suction pressure gradually increases. When a dredge pump is operated at or near maximum capacity, it will invariably slug (ram) or choke off under certain conditions. This is in part due to the design characteristics of the pump. The major contributing factors are the dredging conditions, overloading of the suction, a sudden change in material, or the existence of a gas pocket. In recent years, the difference between actual choking and stoppage of a pump due to excessive gas has been recognized.

It was observed[4,6] that gas flows of less than 9% of water flow by volume at pump suction conditions have minor effects on pumping head and flowrate. For higher gas flowrates, unstable flow conditions prevail, and considerable reduction in head and flowrate were observed. Depending on the speed and discharge opening (initial flowrate of the pump), gas percentages (at pump suction conditions) of 12 to 33 were found to cause complete collapse. Dredging is suspended until the pump is reprimed with clear water. A need for a gas removal system on the suction line has become obvious.

Several studies were carried out on gas-liquid and solid-liquid flows in pipes, but very little is known about the quantitative assessment of gas removal and its effect on the performance of dredge pumps. The gas-liquid flow research was supported by the oil industry in connection with the possible transportation of gas-liquid petroleum mixtures and is essentially limited to the mechanics of flow within the pipe itself.

The U. S. Army Corps of Engineers has seventeen hopper dredges in operation[7], with an ever-expanding work to accomplish. It is imperative that work needs to be done to increase and improve the output from each one of them. The gas removal devices installed on existing dredges provide no means of observing the flow of gas into the system. In fact, the only indication of positive results with the prototype system is an occasional odor of gas from the exhaust of the removal system. The unpredictable occurrence of gas in actual dredging operations makes the evaluation of the efficiency of removal systems from prototype output very difficult. The lack of such information leaves great doubt as to whether the existing systems are effective. As a result, the U. S. Army Corps of Engineers entered into a contract with the Hydraulics Division of Lehigh University to carry out research, to study and to develop gas removal systems.

2.3 Existing Gas Removal System

The early suggestions for gas removal systems apparently came from two U. S. Patents granted to Mr. Richard Hoffman[4,8,9]. The idea is to encourage the entrained gas to collect in an enlargement on top of the suction pipe and this gas can then be drawn off through the application of a vacuum pressure. Vacuum could be produced either by a vacuum pump or an ejector system. The removal systems include other auxiliary equipment to prevent solids and water from being drawn through the vacuum pump. Gas removal systems are already installed and are in operation on dredges like Essayons, Goethals, and Comber of the U. S. Army Corps of Engineers. Their salient features[10] are described in the following paragraph.

An accumulator is installed adjacent to and on the suction side of each dredge pump of the Essayons Dredge. An E-S Nash Nytor vacuum pump driven by a 100 Hp variable speed D.C. marine type motor evacuates the gas from this accumulator. The pipeline connecting the accumulator with the pump is raised to avoid or to minimize the passage of solids into the vacuum pump. Vacuum pumps are operated whenever the dredge pumps are in operation and are provided with a water seal. They discharge both gas and sealing water overboard. The pumps are controlled by the setting of a vacuum relief valve blowing air into the vacuum pump suction line. An accumulator is also installed on the suction side of each dredge pump of the Goethals Dredge. The gas removal system is quite similar in construction as well as in operation to that present in the Essayons Dredge. Two gas accumulators are installed for each dredge pump of the Comber Dredge, one adjacent to and on the suction side of the pump, and the other adjacent to and on the inboard side of the trunnion bearing. Two Schutte and Koerting steam ejectors, 4-inch and 3-inch sizes, operating in parallel and supplied with 500 degrees Fahrenheit steam at 225 pounds per square inch minimal pressure evacuate the gas from the accumulator.

2.4 Three-Phase Flow

In actual prototype dredging conditions, solids, liquids and gases are encountered forming the flow media. It was established[2,11] that the model dredge pump performance is not appreciably affected by slight changes in the characteristics of the silt-clay-water mixture being pumped and it was possible under these conditions to pump silt-clay-water mixtures having densities up to 1410 grams per litre. In the present state of knowledge, the effect of gas in silt-clay-water mixture and the performance of dredge pumps, especially gas removal systems, can only be ascertained by experimentation.

3. OBJECTIVES AND DETAILS OF THE EXPERIMENTAL PROGRAM

The main objective of this experimental investigation is to study the various factors affecting the pump performance and the efficiency of the gas removal systems. The study was divided into the following parts.

3.1 Literature Survey

This includes the study of all available information pertinent to the problem. The following aspects will be discussed in the following chapter together with the results of previous experiments carried out at Lehigh University:

a) Mechanics of multi-phase flow in pipes

b) Methods of gas injection

c) Gas removal systems

3.2 Experimental Program

The objective of the experimental program is to identify the various factors affecting pump performance and the efficiency of gas removal systems in operation on dredges of the U. S. Army Corps of Engineers. This program consists of two parts:

a) Dredge pump performance was studied under different conditions of pump speeds, air injection rates, and discharge openings, with gas removal systems kept inactive.

b) Two different systems of gas removal were applied, namely, the vacuum pump and the water ejector.

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

3.2.1 Pump Performance with Air Injection and with Gas Removal System Inactive

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 orifice. The discharge valve was manipulated to get a discharge orifice setting corresponding to a predecided initial flowrate. Air injection rate was varied in various test runs at a constant pump speed and discharge orifice for a specific test until the 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 a 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.

3.2.2 Efficiency of Gas Removal Systems

The necessary vacuum at the top of the accumulator was produced by using either a V.P. 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.

4. THEORETICAL CONSIDERATIONS AND PREVIOUS RESEARCH

4.1 Three-Phase Flow

When the dredge is pumping mixtures composed of solids, liquids and gases, a complex relation exists between the velocity of the mixture and the friction losses encountered. Unfortunately, no attempt was made to study the problem of three-phase flow analytically. However, an extensive amount of information is available on two-phase flow, namely, the gas-liquid and the solid-liquid flow. If the solid-liquid mixture being pumped can be considered as a homogeneous medium, the two-phase flow analysis of liquid and gas flow can be used to determine some essential parameters, such as, friction factor and net positive suction head.

4.2 Two-Phase Flow

The two-phase flow presented herein refers to the simultaneous and concurrent flow of mixtures of gas and liquid. In the literature, several types of this flow were identified, namely, gas-liquid, liquid-solid, gas-solid, liquid-liquid, and solid-solid. In the last two categories, the separate phases were immiscible. Only the two-phase gas-liquid flow is considered in this report. However, discussion of some processes, such as, condensation, evaporation, boiling, aeration, cavitation, foaming, atomization, heat transfer, etc., are not included.

4.2.1 Flow Patterns

The mode of flow for each phase of liquid-gas flow is determined by the slope of the confining conduit, the gravitational forces, the interphase forces, and the intraphase forces. The interactions of these forces lead to a number of possible cross-sectional and longitudinal profiles of flow. The flow orientation is significant.

There is a difference between horizontal flow and vertical flow (upflow and downflow) and flow under the influence of various force fields such as electric, magnetic and gravitational. These factors add to the complexity of the problem. Although the classification of flow patterns (flow regimes) is somewhat arbitrary, the distinctions are of fundamental significance. Gas-liquid flow patterns can be classified as follows[5,12]:

1) <u>Bubble Flow</u> - In which separate bubbles of gas move along the pipe with approximately the same velocity as the liquid. These bubbles may be uniformly distributed in the pipe or move along in the upper region of a horizontal pipe relatively with pure liquid flowing in the lower region.

2) <u>Plug Flow</u> - In which bubbles in the upper part of a horizontal pipe agglomerate to form large bubbles or plugs. Plug flow occurs at low ratios of gas-to-liquid flow.

3) <u>Slug Flow</u> - In which a more or less well-defined interface separates liquid and gas. The level of the interface rises and falls, and slugs pass regularly along the pipe at a much greater velocity than the average liquid velocity.

4) Annular Flow - In which the liquid flows in a film around the pipe wall and the gas flows at high velocity through the central core. The film may contain gas bubbles.

5) Mist Flow - In which liquid droplets are entrained more or less uniformly throughout the gas medium. Spray flow and disperse flow have also been applied to the regime after annular flow breaks down.

6) Separated Flow - In which liquid flows along the bottom of the pipe and gas flows above. This type of flow occurs in a horizontal pipe at smaller liquid flowrates. If low gas-to-liquid flow ratios exist, the flow occurs with a relatively smooth interface (stratified flow) and has characteristics approaching those of open-channel flow. If the ratio is higher, a density wave is produced on the interface.

The main patterns of two-phase flow are[14]: bubble, slug, annular, and mist. Other types are transitions from one to another. It was found[5,15] that for a small gas flowrate, the bubble flow exists, and as the gas flow is increased, the slug flow begins. Galegar[16] presented experimental data on the behavior of kerosene-air and water-air systems in two-phase vertical upward flow using two test sections of different sizes but having the same ratio of diameter to height.

4.2.2 Types of Flow

Flow types are usually designated on the basis of whether laminar or turbulent flow would exist if the phase under consideration were flowing alone in the pipe[5,17]. Turbulent flow exists at Reynolds numbers greater than 1×10^4 while laminar exists at Re values less than 2,000. These Reynolds numbers are based on the diameter of the pipe as the length scale. Four flow types are possible, namely, turbulent-turbulent, turbulent-viscous, viscous-turbulent, and viscous-viscous, describing the gas phase and the liquid phase, respectively.

4.2.3 Flow Models

Several physical models have been used to describe the two-phase flow phenomenon. Two of the most commonly known models are the Martinelli model and the model based on the assumption of homogeneous flow.

4.2.3.1 Martinelli Model

The basic assumptions involved[17,18,19] are:

1) The static pressure drop is equal for both gas and liquid.

2) The volume of gas plus volume of liquid must equal the volume of the pipe.

A method for the prediction of the pressure drop in laminar and turbulent flows was developed. Experimental investigations revealed the following trends[18]:

1) The static pressure drop for two-phase flow is always greater than the pressure drop for each phase flowing alone.

2) When air approaches zero, the pressure drop due to pure liquid is approached.

3) Flow of both air and liquid may be turbulent or laminar.

Equations were given for calculating the pressure drop of two-phase flow[17,18,19].

4.2.3.2 Friction Factor Models

In these models, a single friction factor is used for the mixed flow. One of the widely used methods is that of "homogeneous flow". The basic premise here is the assumption of equal gas and liquid velocity and of thermodynamic equilibrium between the two phases (vapor-liquid equilibrium). The first assumption is seldom fulfilled, however, useful results have been obtained.

The friction factor is usually derived by using the energy balance equation, the momentum equation, and the continuity equation. Complex relationships were developed from these basic equations.

Other types of friction factor models have been attempted. Bergelin and Gazley[20] observed that for both horizontal and vertical flow, an increase in the liquid flow results in an increase in the pressure drop. This was attributed to the "rough wall" effect. Huntington[5] developed an expression for two-phase friction factor which yielded results up to 17% accuracy.

4.2.4 Flow Stability

Two-phase flow may become unstable in the transition zone from one flow pattern to the other. This results in large pressure fluctuations. The instability is usually associated with the transition from bubbly to stratified flow and from wavy to annular flow. A theoretical approach to two-phase flow is presented by Gazley[21] by using energy losses and transfers at fluid-fluid interfaces to evaluate the interfacial shear and stability[21]. It is found that the formation of interfacial waves is dependent essentially on the liquid depth and the relative velocities of each phase. It was found that a relative velocity of 10 to 15 feet per second is needed for the formation of waves.

4.2.5 Gas Injection

Gases present in the suction line of dredges will have to be duplicated in laboratory experimentation. Two methods are available for gas injection into test sections. The first requires the use of an aspirator[23] and gas is injected parallel to and at the middle of the pipe. The basic concept of an aspirator is the occurrence of a sudden pressure rise in the diffuser, at the point where jets of two fluids unite. The expansion is similar to the hydraulic jump in open-channel flow and occurs for the same reason, namely, to overcome a discontinuity in pressure. Aspirators can be with or without a diffuser section, where kinetic energy is converted to pressure energy accompanied by turbulence which entrains the gas bubbles. Other investigators found that injecting air vertically from the top of the pipe resulted in a good distribution of bubbles[18].

Both methods seem to be acceptable, but the latter is probably less expensive. Other methods[18] by which air-water mixtures can be produced in closed conduits are by orifices and effervescence or chemical means.

4.2.6 Gas Removal Systems

Little is known about gas removal systems. Two concepts, however, have been advanced. The first one involves the use of a 90 degree bend in the suction line. Since liquid has a greater specific gravity than gas, it would tend to cling to the outside wall of the bend, leaving an air pocket on the inside. For very high Reynolds numbers, most of the gas will not be able to reach the air pocket due to secondary currents. A proposal was made to install guide vanes inside the elbow, thus producing air pockets on the concave side of all the vanes[24]. The gas could then be drawn off by providing escape routes for the gas through the vanes. Unfortunately, this concept was not properly developed for practical application.

The second concept involves the use of vortex separators[25,26,27,28]. These separators were developed mainly for use in the paper manufacturing process, and are used to remove both gas and grit from the wood pulp. They work on the principle of centrifugal force. The dirty pulp is pumped tangentially into a vertical cylinder. The higher density of the grit forces it to the outside and the gas forms a core in the middle of the cylinder, from where it is drawn off by vacuum pumps.

4.2.7 Gas Bubbles

4.2.7.1 Occurrence and Size of Gas Bubbles

A stable spherical gas bubble respresents a balance between several factors such as surface tension, vapor pressure, partial pressure of the gas within the bubble, relative saturation of the gas, and external pressure[29]. The surface tension becomes increasingly important as the bubble size decreases. It produces high internal pressures, which should lead to the eventual disappearance of all bubbles. However, it was found that for some reason, this does not occur.

The gas bubbles remain very small in a quiescent system, but the introduction of mechanical agitation greatly accelerates gas transfer. Vortex generators, such as propeller tips, tend to promote basic diffusion growth of bubbles as well as growth through the rapid coalescence of many small bubbles into few large bubbles.

Donoghue[30] controlled the bubble size in a shear type Air Bubble Generator by forcing a jet of water past an air orifice. As the air flow increased, the size of the bubble increased as long as the water velocity was zero. As the water flow increased, with constant air flow, the size of the bubbles decreased and their number increased. It was observed that the physical properties influence the bubble size. The factors that Donoghue[30] reported, affecting the size of air bubbles formed in water by forcing air through a permeable surface, are:

1) The diameter of the orifice

2) The rate of flow of gas

3) The proximity of other orifices

4) The interfacial forces in the liquid-solid boundaries (electrolytic salt will vary the size of bubbles)

5) The viscosity

6) The induction time, time of adherence to solid

Silberman[23] observed that the bubble size is nearly independent of the jet diameter. By adding detergent to water, the bubble diameters decreased.

4.2.7.2 Effect of Flow Velocity

Measurements[12] showed that the velocity distribution is materially affected by the presence of air bubbles, particularly near the top of a pipe. A non-symmetrical profile was observed which indicates a secondary current with an upward direction in the center of the pipe and a downward direction around the walls. The upper part of the pipe, where the concentration of bubbles is high, is more rough than the bottom.

4.2.7.3 Rise of Gas Bubbles in a Viscous Liquid

The rise of a gas bubble in viscous liquids and at high Reynolds numbers was theoretically analyzed[31]. It was shown that the drag coefficient of a spherical bubble is 32/Re, where Re is the Reynolds number (based on diameter) of the motion of the rising bubble. Equating the drag force to the bouyant force of the bubble, the bubble diameter and velocity can be computed. Similar expressions were derived mathematically for non-spherical bubbles.

4.2.7.4 Effect of Bubbles on Cavitation

Ripken[29] and co-workers found that water velocities as low as 10 feet per second produced vorticity sufficient to grow large gas bubbles. This indicates that prototype propellers, pumps and turbines will normally be supplied with water which may cause cavitation. It was also found that the hysteresis in pressure controlled incipient cavitation is insignificant under stabilized free gas conditions.

4.2.7.5 Measurement of Gas Content in Gaseous Water

An early method of measuring released gas out of a sample of gas-liquid mixtures requires continuous monitoring and actual removal of part of the sample[29].

The United States Navy uses a continuous monitoring device to measure gas content which scrubs the sample of gas in an atmosphere of hydrogen[29]. The gas is then measured for thermal conductivity and compared to pure hydrogen.

Other methods[29] have been attempted to provide an acceptable means of measuring gases. Among those are light scatter, gamma rays, and ultrasonic energy decay.

A device[29] based upon the velocity of propagation of an elastic pulse was developed. Gasified mixtures were found to introduce a delay in time of propagation and this delay was correlated with the gas content. These measurements could be made continuously and instantaneously. The early results did not correlate very well with free gas volume.

4.2.8 Solubility of Gases in Liquids

Air dissolves in various liquids according to their physical characteristics[32]. The solubility in any given liquid is directly proportional to the absolute pressure of the air above it. This important relationship is known as Henry's law. It shows that the concentration of the dissolved gas is directly proportional to the concentration in the free space above the liquid.

In determining air release from liquids, vapor pressure of the liquid must be considered especially in case of low vapor pressure fluids. An increase in temperature causes separation of dissolved air even though the pressure remains the same. The speed of evolution of gas bubbles from a confining container, when opened, depends on the pressure inside and outside the confining vessel, mode of release of pressure whether sudden or gradual, and the mechanical agitation accompanying the pressure release.

4.3 Previous Researches at Lehigh

Experimental investigation were carried out at Lehigh University since 1962 to evaluate the effectiveness of gas removal systems installed on a model dredge pump. The problem of gas removal is not susceptible of an analytical solution due to the complexities involved. 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

A short description of these phases is given below.

4.3.1 Location of Accumulator

Obviously, the accumulator needs to be installed at the location of maximum concentration of gas bubbles. Visual observations and high speed motion picture films demonstrated that air is widely dispersed in small bubbles by the turbulent water flow. The continuous injection of air resulted in a uniform distribution of air throughout the suction pipe in the form of fine bubbles, except in the vicinity of the elbow. Here the density difference and centrifugal force effects combine to cause most of the air to collect at the inside of the bend. Air becomes widely dispersed before it reaches the pump. These observations suggested that the optimum position for the gas removal system appears to be as close to the suction elbow as possible. However, due to the prototype suction line valve, the removal system cannot be located very close to the suction line elbow. Therefore, the accumulator was placed on the top of the suction pipe, with its center at a distance of 12.75 inches from the face of the pump.

4.3.2 Accumulator Types

Two types of accumulators, designated as "original accumulator" and "modified accumulator", are investigated for effectiveness of gas removal system. They are both shown in Fig. 1. Model accumulators were fabricated of Plexiglas to allow visual observations of the flow conditions. The results showed that the original accumulator and the vacuum pump used were not effective in removing dispersed gas bubbles[4]. The use of Level Trol as an automatic control of water in the accumulator permitted a slight improvement. However, the water level was observed to oscillate in the accumulator. The non-effectiveness of the original accumulator in gas removal was evident. This led to use a modified accumulator (Fig. 1) which has a sloping upstream side. The height of the modified accumulator was increased to allow for the study of the influence of the water level in the accumulator on gas removal. The modified model accumulator is 48 inches high above the centerline of the suction pipe.

Air removal was carried out using the modified accumulator. Two vacuum sources were used. 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 effective. Up to 40% of the injected gas was removed in the suction line.

4.3.3 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[4], 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, and the pump operation was not affected. At vacuums larger than the dredge pump suction pressure, both air and water were carried through the vacuum system. To prevent water from entering the vacuum pump, a vacuum receiver was provided. It consists of a 20 x 48 inch cylindrical tank.

Water or steam driven ejectors were used to provide vacuum in some prototype gas removal systems. A water ejector was tested in the experimental study of gas removal systems at Lehigh. The ejector used is a Penberthy Model 190-A, 4-inch ejector. It is capable of handling 14.7 SCFM air at 5 inches of mercury vacuum, and 8.2 SCFM air at 10 inches of mercury vacuum, respectively, with a water supply flow of 80 gallons per minute. The ejector can be controlled by adjusting the pump speed, a bypass valve, or discharge valve. Its performance is not affected by the air. The most effective removal, using the vacuum pump, occurred when the liquid level was held at about 20 to 24 inches above the centerline of the suction pipe. The ejector was most effective when the liquid level was held in the upper portion of the accumulator. This simulates prototype conditions. Some of the results were obtained by varying the vacuum sources, the liquid levels in the accumulator, the pump speeds, and the initial flowrates of the model dredge pump without gas injection. The experimental reresults revealed that the use of the ejector, as a vacuum source, is superior to the use of the vacuum pump. The ejector is mechanically simpler than the vacuum pump, it is not adversely affected by water coming from the accumulator. It should be noted that while operating the two vacuum sources, the water level was kept in the upper portion of the accumulator in case of ejector, and about in the middle portion in the case of vacuum pump. It is possible that the water level variation in the accumulator in the two cases might have made the observed difference in the performance of the two vacuum sources, rather than the functional superiority of the ejector over the vacuum pump, in producing steady vacuum pressures.

4.3.4 Effect of Gas Injection Methods

The failure of the gas removal system in the early experiments to remove any significant amount of air may have been caused by improper simulation of the prototype air flow. The test facility 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 flowrates, 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 flowrates. 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 first experiment was designed to determine the effect of number, size and location of injection ports. The change was from many small ports to fewer larger ports. For continuous air flow, the air stream broke into fine bubbles and dispersed throughout the flow before it could be observed in the clear suction pipe. The pulsed flow was obtained by opening and closing the air flow valves near the air flowmeters.

A simplistic innovation was developed which produced slug flow. Air filled balloons were lowered into the drag arm inlet where they were punctured by a spike. A considerable portion of the air slug rose into the accumulator at a water flowrate of 400 gallons per minute. Unfortunately, this method of producing slug flow was not adapted to yield quantitative results.

The third and 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.

5. 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 connected to 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.

5.1 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 Plexiglas 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.

5.2 Impeller

The 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[33]. The pump impeller is a bronze casting, fitted with a Plexiglas shroud on the suction side. The characteristics of this pump were given in earlier studies at Lehigh[4].

5.3 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 manufacturers so that its power output could be calculated from input voltage and amperage data.

5.4 Magnetic Flowmeter

The discharge of the dredge pump was measured by means of a Magnetic Flowmeter manufactured by Foxboro Company[34]. It is basically an electrical generator[35] which measures the volume flowrate 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 flowmeter measures 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.

5.5 Pump Speed

The speed was measured with a Hasler speed indicator. The speed was also monitored frequently with a stroboscopic tachometer[7].

5.6 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.

5.7 Suction Pipe

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

5.8 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.

5.9 Measuring Equipment

5.9.1 Air Flowmeters

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[7]. The air temperature at the flowmeter was measured with a calibrated resistance wire temperature gauge. 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 gauge 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 on 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 flowrate, slugs/sec

p_1 = upstream pressure, psia

p_2 = downstream pressure, psia

T_{ABS} = absolute temperature, degrees Rankine

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

5.9.2 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.

5.9.3 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.

5.10 Gas Removal Systems

They consist mainly of an accumulator and a vacuum source. The existing accumulator (shown on Fig. 1b) is 4-1/2 inches square in cross-section. It is made of Plexiglas. It has an enlarged opening to the suction pipe and is about 48 inches high above 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.

5.10.1 Vacuum Pump System

It consists of a vacuum pump, a vacuum receiver, and vacuum flowmeters, namely, the laminar air flowmeter and the orifice plate and pressure transducers.

5.10.1.1 Vacuum Pump

The vacuum pump is a piston type V244 with a 4 by 4 inch cylinders. 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 cfm.

5.10.1.2 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.

5.10.1.3 Laminar Air Flowmeter

A laminar air flowmeter was used to measure the removed flowrate. This meter is a Model D-23170 manufactured by the Meriam Instrument Company[36]. 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 gauge diaphragm transducers. However, the laminar air flowmeter was used to calibrate the orifice meter. The air flowmeter consists of two parts[37]: 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 greater 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 flowmeter channels the flow through myriad parallel ducts which keep the velocity about the same as in the pipe while reducing the duct dimension sufficiently to produce laminar flow. The heart of the laminar flow element is called the matrix. 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 matrix. The laminar flow element is not directly affected by temperature changes. However, its flow relationship depends on the viscosity, which depends upon the temperature.

5.10.1.4 Orifice Plate and Pressure Transducers

A system using orifice plate and strain gauge type diaphragm transducers was developed to measure the air flowrate on the removal side. After several trials, a 3/8-inch orifice was selected for the 1-1/4 inch 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 flowrate, slugs/sec

p_1 = upstream pressure, psia

p_2 = downstream pressure, psia

T_{ABS} = absolute temperature, degrees Rankine

Standard and local air flowrates 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.

5.10.2 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 flowrate through the venturimeter, a vacuum gauge to measure the generated vacuum pressure, and a magnetic flowmeter to measure the total flowrate of the air-water mixture.

The ejector used is a Penberthy Model 190A 4-inch ejector capable of handling the following air flowrates with a water supply of 80 gallons per minute at 40 psi[38]: 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 above. 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 flowmeter 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[39] and thus vacuum is produced.

The water flowrate 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 = flowrate, cubic feet/sec

h = manometer head readings, in inches

The total air-water mixture flowrate was measured by a magnetic flowmeter mounted on the downstream of the water ejector.

5.11 Tests and Test Procedures

Four test series were performed. O-Series was designed to study the pump behavior and the flow patterns in the accumulator while the vacuum source is kept inactive. O-N-Series was aimed at investigating the effect of pump speed variation on the pump performance under different air injection rates. P-Series and 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.

5.11.1 O-Series

In this series, the gas removal system was kept inactive. Experiments were conducted for initial flowrates of 400, 600, 800, 1000 and 1200 gpm. The dredge pump speeds used were 1440, 1200 and 1000 rpm. Tests with an initial flowrate of 1200 gpm were performed at speeds of 1440 and 1200 rpm only. 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 flowrate and adjust the discharge valve until the selected flowrate 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 subsection g

k) Change the indicated air flowrate and repeat steps i through k

l) Note the amount of air 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.

5.11.2 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 flowrate 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 flowrates 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.

5.11.3 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 was quite similar to that of the O-Series. A few additional observations were taken, namely, the flowrate of the removed air through the accumulator and the vacuum pressure in the receiver tank.

5.11.4 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 flowrate. Some additional observations were taken, namely, the magnetic flowmeter readings on the ejector line, the head on the venturimeter, and the vacuum pressure created by the ejector.

6. 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.

The results are presented in terms of relevant dimensionless parameters. The problem of the determination of proper similarity parameters was not solved. In general, two sets of parameters are required. One set is needed to describe the pump performance and the other set is required for describing the gas removal system. The interaction between the two processes, namely, the action in the accumulator and the flow in the pump, is not yet fully understood. Discussion of the results will be presented in the following paragraphs.

6.1 Data Reduction

All the tests were conducted under steady air flow. A sample of input and output quantities in 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 Flowrate, gpm, QGPM
Suction Manometer, HSL, HSR
Discharge Manometers, HL1, HR1, HL2, HR2
Injection Air Pressure, psi, gauge, 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 Flowrate Injection, SCFM, SAFI
Air Flowrate Removal, SCFM, SAFR
Air Flowrate to Pump, SCFM, SAFP
Air Flowrate, Pump Suction, cfs, AQS, same as QAP
Air Flowrate, Pump Discharge, cfs, AQD
Air Percent, Pump Suction, APS, equal to QAP/QW
Velocity Head, Pump Suction, VHS
Velocity Head, Pump Discharge, VHD
Total Flowrate, gpm, QGPM
Total Flowrate, cfs, QT
Water Flowrate, 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 Flowrate Injected, slugs/sec, AMFI
Air Mass Flowrate Removed, slugs/sec, AMFR
Air Mass Flowrate to Pump, slugs/sec, AMFP

6.2 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.

6.2.1 Variable Pump Speed and Constant Discharge Opening

In these runs, the discharge opening was adjusted to give an initial water flowrate of 800 gpm at a pump speed of 1440 rpm. This speed corresponds to the prototype pump speed for no air injection. The 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.

6.2.1.1 Relationship Between Pump Speed and Flowrate

Figure 3 shows a plot of the total flowrate (QGPM) against the pump speed. The flowrate decreases linearly with the decrease in pump speed in case of no air injection. For an air injection rate of 5.35 SCFM, the linearity between the flowrate and the pump speed exists for pump speeds higher than 1150 rpm. At this speed, the flowrate decreased abruptly with a slight reduction in pump speed. For pump speeds below 1100 rpm, the flowrate was again a linear function of the pump speed until collapse point was reached. The behavior of the system was quite similar in 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 case of air injection rate of 6.35 SCFM, the flowrate dropped sharply from 600 gpm to 450 gpm when pump speed decreased from 1400 to 1310 rpm.

6.2.1.2 Relationship Between Water Horsepower and Pump Speed

The water horsepower (WHP) was plotted against pump speed in Fig. 4. For no air injection, it shows a normal relationship. In case of air injection of 5.35 and 5.81 SCFM, the water horsepower decreases with the decrease in pump speed, again 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 an early collapse of the pump. Pump speeds at which the abrupt changes of both discharge and water horsepower occur (break point) depend upon the percentage of air injection. It should be noted that these tests were conducted at the same conditions of room temperature and atmospheric pressure.

6.2.2 Variable Discharge Opening and Constant Pump Speed

These experiments were carried out at a constant pump speed for various discharge openings with the gas removal system inactive. In each run, some preselected discharge opening was maintained, and the flowrate 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 flowrate, and D is the pump diameter. The second parameter is the air percent pump suction, QAP/QW. This is defined as the air flowrate through the pump (and at pump suction conditions of temperature and pressure), QAP, expressed as a percentage of the water flowrate, 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 flowrate (QWO). The fourth parameter is the water discharge ratio (QW/QWO). This is defined as the percentage of the water flowrate to the initial flowrate 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, QAP, described as a percentage of water flowrate, QW. Each curve represents the conditions at a specific pump speed and initial flowrate. The second set of curves (Figs. 8, 9 and 10) shows the relationship between the percentage of air flow to water flowrate and the ratio between the volume rates of air injection (at standard air temperature and pressure) (SAFI) to the nominal (initial) water flowrate. 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. The following conclusions could be obtained.

6.2.2.1 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, this 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 flowrates and pump speeds used.

6.2.2.2 Relationship Between QAP/QW and SAFI/QWO

Figures 8, 9 and 10 show plots of QAP/QW against SAFI/QWO. In case of low initial flowrates, 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 case of initial flowrate of 400 gpm. For the same injection ratio, SAFI/QWO, the values of QAP/QW are larger in case of higher flowrates than in the case of lower flowrates. This is partially due to the change in pressures at the pump suction with the initial flowrates. It is obvious that the air injection ratio at the collapse point is much larger in case of lower flowrates than that for higher flowrates. At pump collapse conditions, the QAP/QW is somewhat larger for higher initial flowrates than for lower flowrates, showing that the pump has a higher air tolerance at higher flowrates.

6.2.2.3 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 flowrates 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 flowrates are larger than those for higher flowrates. Again for the same QW/QWO, the value of QAP/QW is larger for lower initial flowrates. This is due to the difference in the suction head.

6.3 Effects of Gas Removal Systems

6.3.1 The Water Ejector Removal System

In these tests, the water ejector provided the necessary vacuum pressure at the top of the accumulator. The 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 air flowrate removed through the accumulator in standard cubic feet per minute. In case of gas removal system, the pump performance can be determined by the use of these curves. Figures 23, 24 and 25 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.

6.3.1.1 Relationship Between QDIM and QAP/QW

Dimensionless discharge is plotted against the air content at pump suction (QAP/QW). This is shown in Figs. 14, 15 and 16.

The shape of the curves is quite similar to those obtained in case of no gas removal. The larger air tolerance of the pump is evident by the delayed collapse, particularly at high flowrates 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, namely, 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 curve has a mild slope at low values of QAP/QW, which is followed by relatively steeper slope 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.

6.3.1.2 Relationship Between QW/QWO and QAP/QW

The air flowrate is a measure of the gas removal system behavior, since the air mass flowing to the pump is the difference between the injected and removed air mass flowrates. The water discharges are needed to evaluate the effect of gas removal system on dredging performance.

Water discharge ratio, QW/QWO, is shown plotted against air percent at pump suction, QAP/QW, in Figs. 17, 18 and 19. 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 flowrate, 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 called a 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.

6.3.1.3 Relationship Between QAP/QW and SAFI/QWO

These curves, presented in Figs. 20, 21 and 22, 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 flowrate at standard conditions.

A relatively large percentage of air has to be injected at low flowrates to get the measurable values of QAP. For the same QAP/QW, values of the injection ratio, SAFI/QWO, are larger for lower flowrates than those for higher flowrates. Again for the same SAFI/QWO, higher values of QAP/QW occur for higher flowrates. At collapse, SAFI/QWO is larger for lower flowrates with a few exceptions which may be due to experimental error in determining the exact collapse point.

6.3.1.4 Relationship Between SAFR/SAFI and SAFI/QWO

Percent gas removal, SAFR/SAFI, is plotted against SAFI/QWO for various initial flowrates and pump speeds. These curves illustrate the efficiency of the gas removal system and are shown in Figs. 23, 24 and 25. 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 a strong dependence of SAFR/SAFI upon the gas injection ratio, SAFI/QWO. This is indicated by the steep slopes of the curves.

6.3.2 The Vacuum Pump Removal System

The reciprocating vacuum pump acted as a source of vacuum pressure for gas removal. 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. 26, 27 and 28. 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 of 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 flowrate, pump speed, and water level in the accumulator.

Generally, the higher the initial flowrate, the higher is the value of QAP/QW at collapse.

Figures 29, 30 and 31 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 case of the water ejector removal system. The behavior of the system depends mainly upon the pump speed, the initial flowrate, 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. The discussion of the experimental results is also the same as that done for the water ejector removal system.

Figures 32, 33 and 34 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 35, 36 and 37 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 flowrate, 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.

6.4 General Remarks

The gas removal system removes only a portion of the gas injected and the remaining gas flow to the suction side of the pump. Thus, the percentage of the injected gas reaching the pump suction is reduced and not completely eliminated. The amount of gas removal depends upon many factors, such as, initial flowrate, water flowrate, gas injection rate, pump speed, water level in the accumulator, etc. High gas injection rates are possible by using an active gas removal system. The results show some scatter which is natural for this type of phenomenon.

The comparison of air percent pump suction, QAP/QW, at collapse for a specific initial flowrate (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 two things. One is a considerable increase of the QAP/QW at collapse in 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 a specific discharge valve setting and pump speed 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 accumulator water level is kept at its highest as is the case in actual prototype practice.

6.5 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 case of gas removal system inactive.

High speed movies of the accumulator and its sloping portion joining the suction pipe were used to study the flow pattern in 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. The visual study of these movies also clarifies the effect of pump speeds on the pump performance. In case of a horizontally oriented discharge pipe, the air does not get a chance to escape towards the discharge side of the pump, but keeps on circulating in the pump. This action is further aggravated in case of operation of higher pump speeds because more air will just pass by without entering the discharge pipe than the one in case of lower pump speeds. The vertical alignment of the discharge pipe is considered to be better than the horizontal orientation because it is apparent from the movies that it allows a better chance for the air to escape towards the discharge side.

6.6 Practical Application

A serious consideration throughout this investigation has been the lack of information about the quantities of gas encountered in actual dredging practice. The designed gas removal capacity and water discharge of the Essayons dredge are 1000 SCFM and 64,000 gpm, respectively. Scaling and equivalent prototype behavior can aid in the interpretation of the model results. The use of pump scale techniques leads to the model values of water discharge equal to 1000 gpm and a gas removal capacity of 15.6 standard cubic feet per minute (SCFM). This is a gas injection ratio of 11.8 percent. The Froude number scaling, which is based on the assumption that bouyant force on the gas bubble is the primary cause of motion of gas relative to the water in the suction line, would indicate a model flowrate of 0.78 cfs or 350 gpm.

7. 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 efficiency of 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 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 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 air content beyond

which a rapid decrease of the water discharge takes place with a relatively small increase in the air content.

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 discharge opening, pump speed, water level in the accumulator, and the gas content.

(2) The water ejector is more efficient than the vacuum pump as a vacuum device on a gas removal system. It provides more manageability and is not affected by liquid-gas mixture. Larger amounts of gas removal were possible in case of 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 dredged 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.

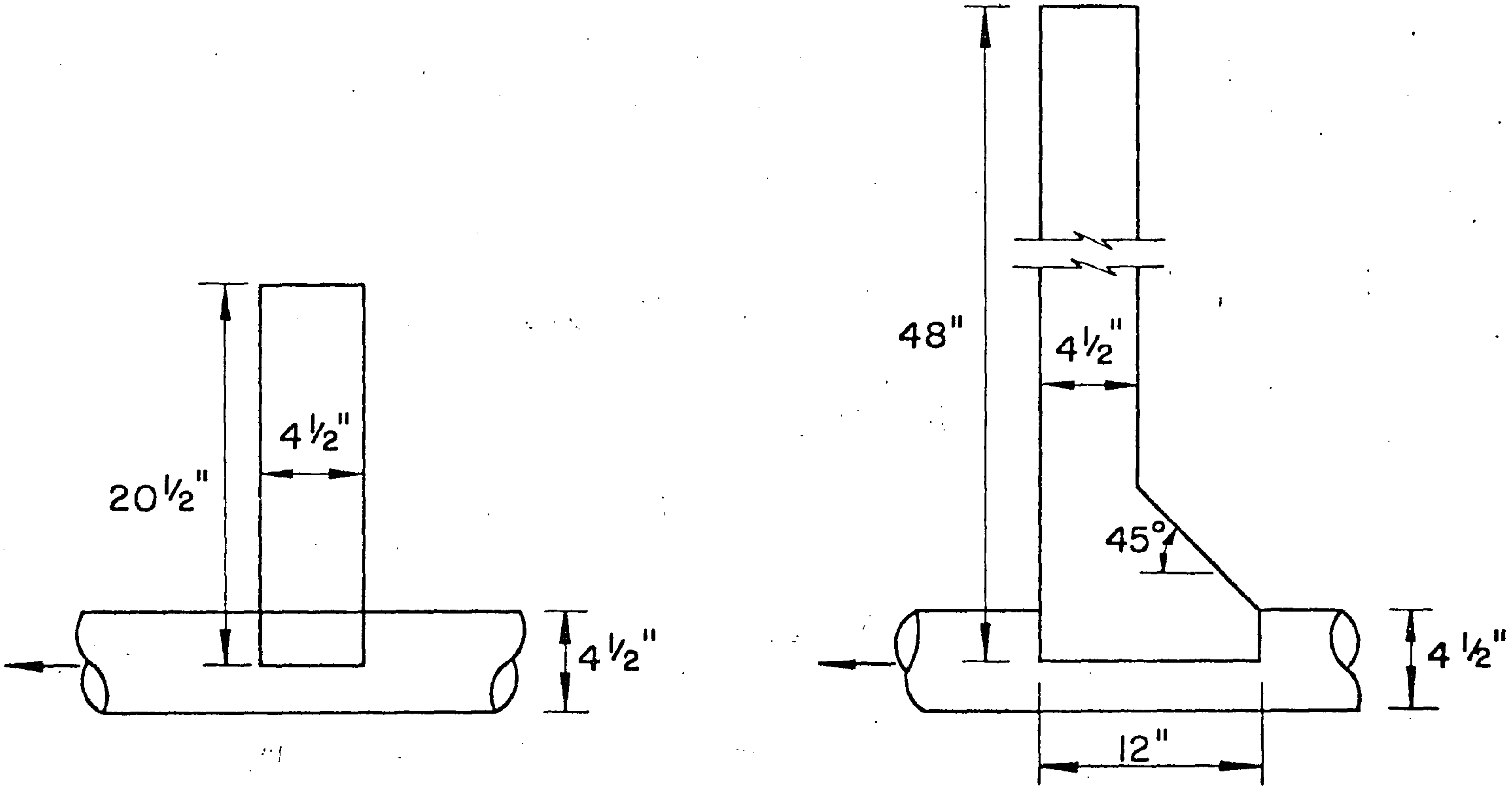
APPENDIX

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(5,607)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
```

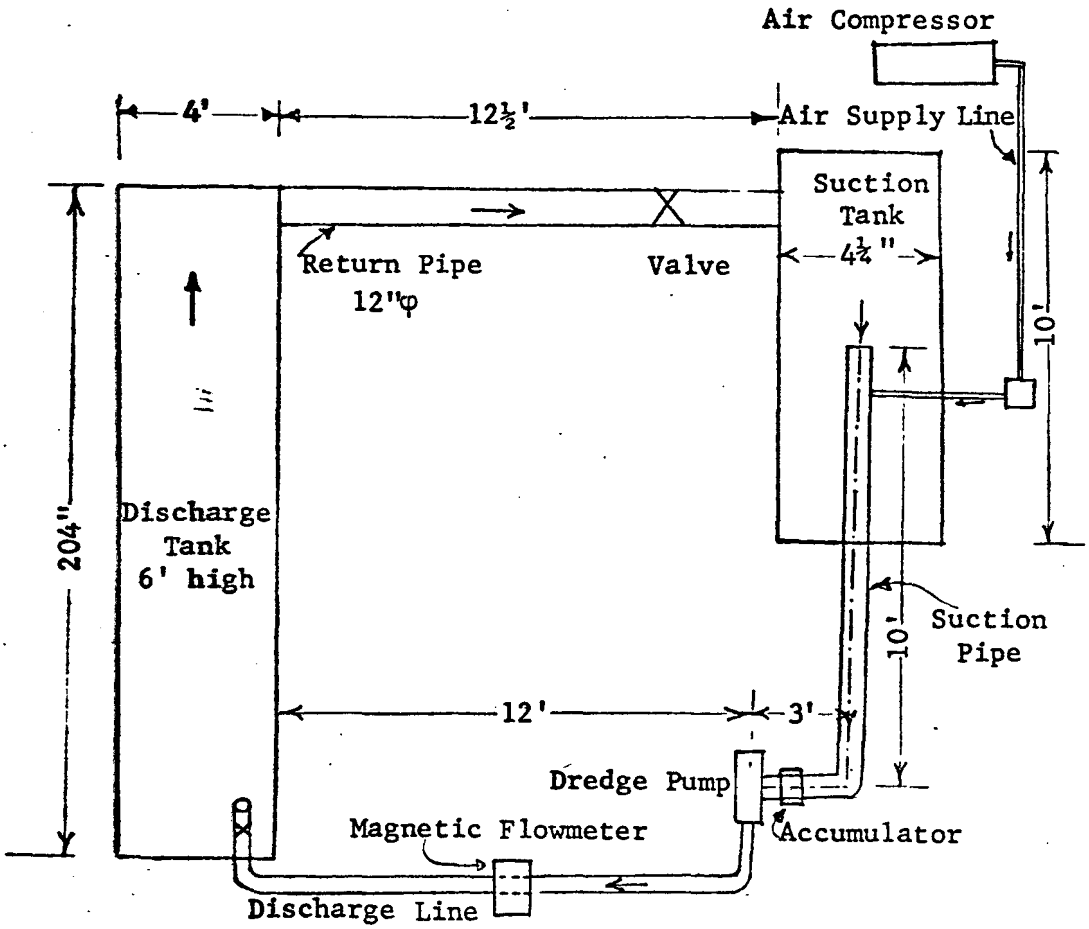
FIGURES



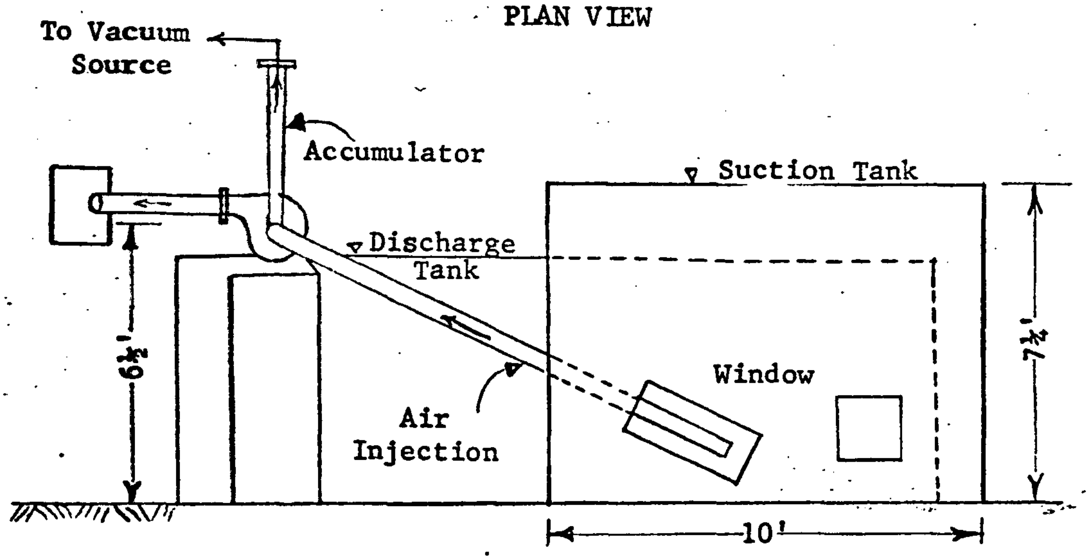
(a) Original

(b) Modified

Fig. 1 Side Views of Accumulators



PLAN VIEW



SIDE VIEW

Fig. 2 Experimental Setup

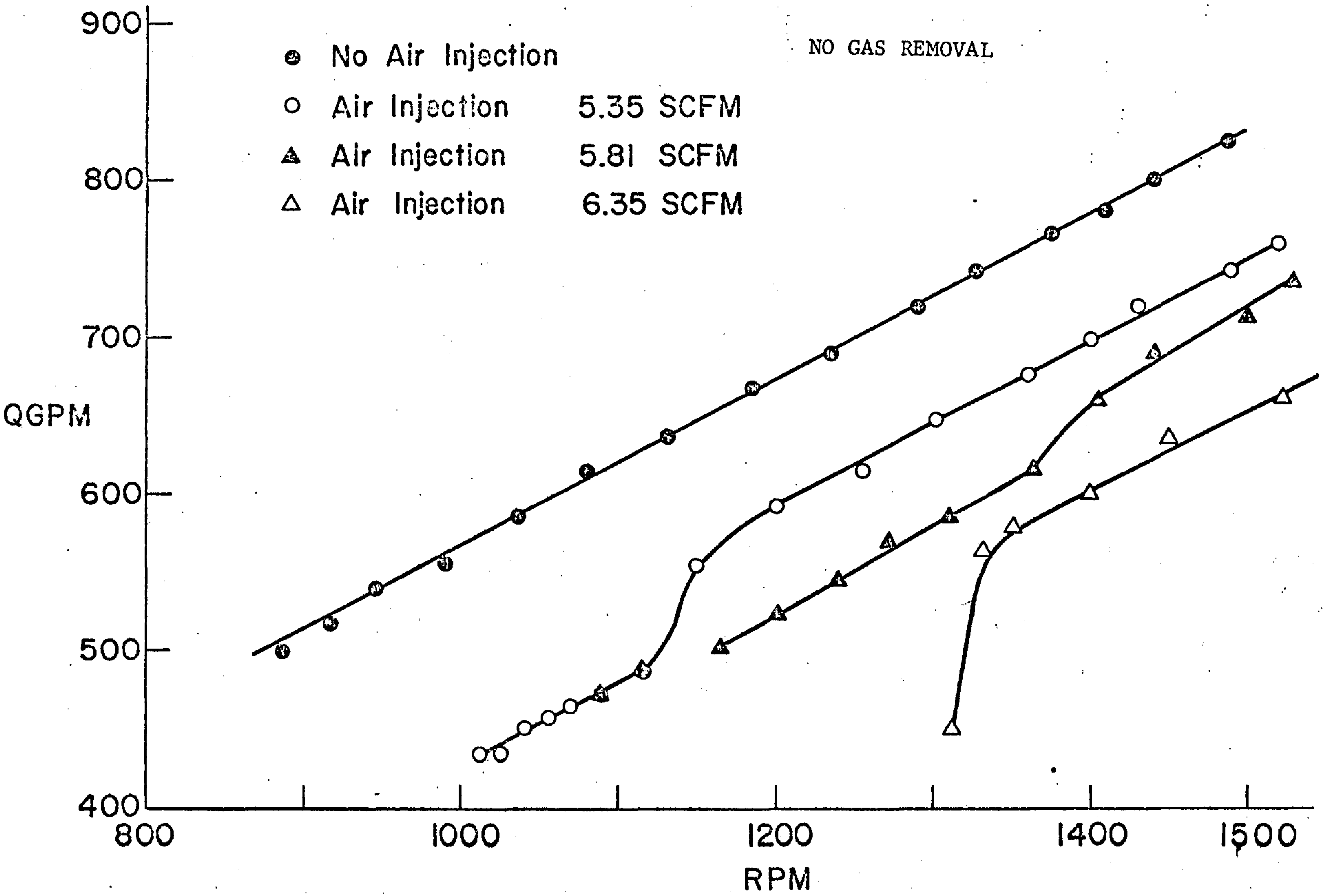


Fig. 3 Relationship Between Total Flowrate and Pump Speed at Constant Discharge Orifice

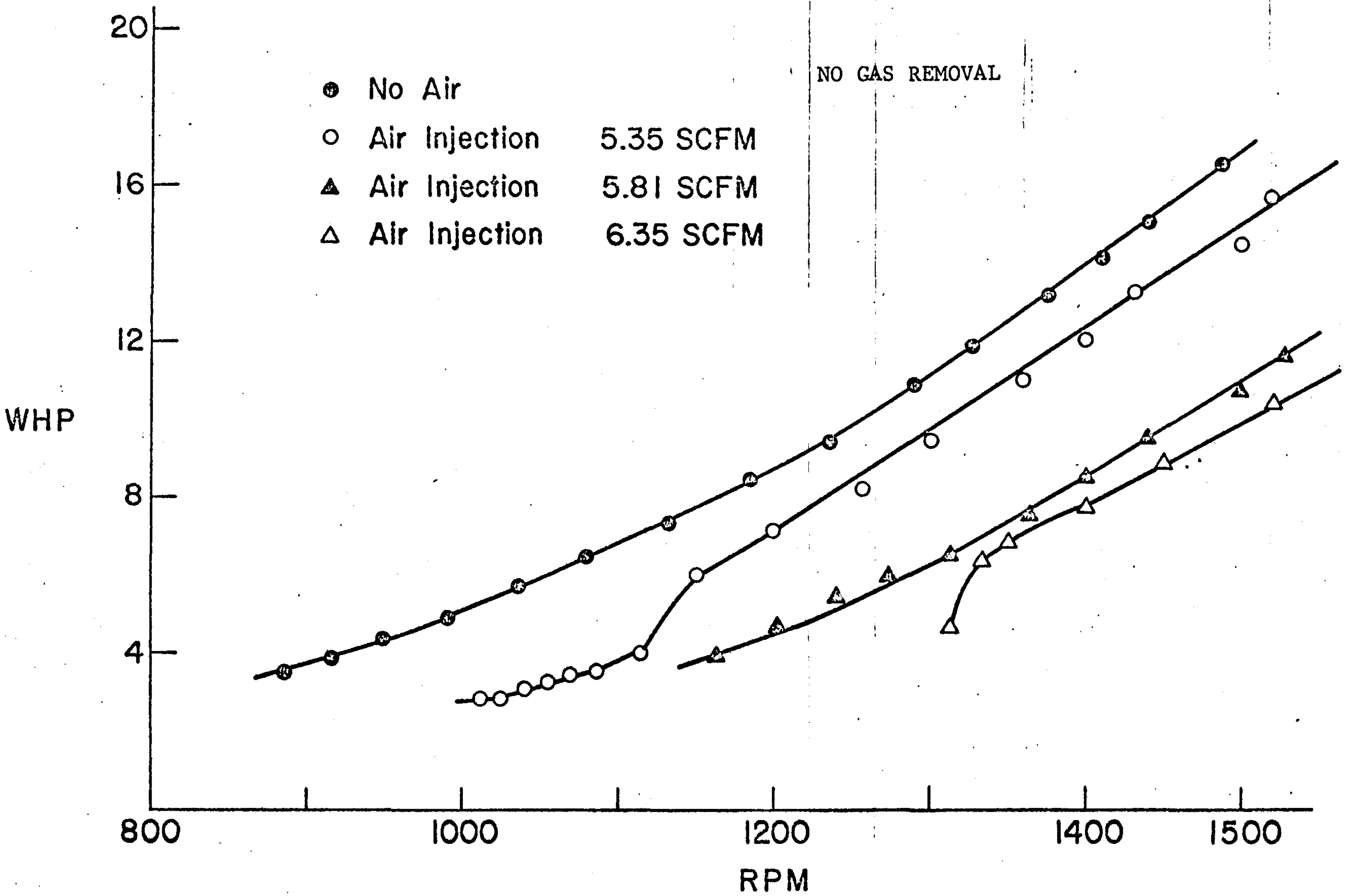


Fig. 4 Relationship Between Water Horsepower and Pump Speed at Constant Discharge Orifice

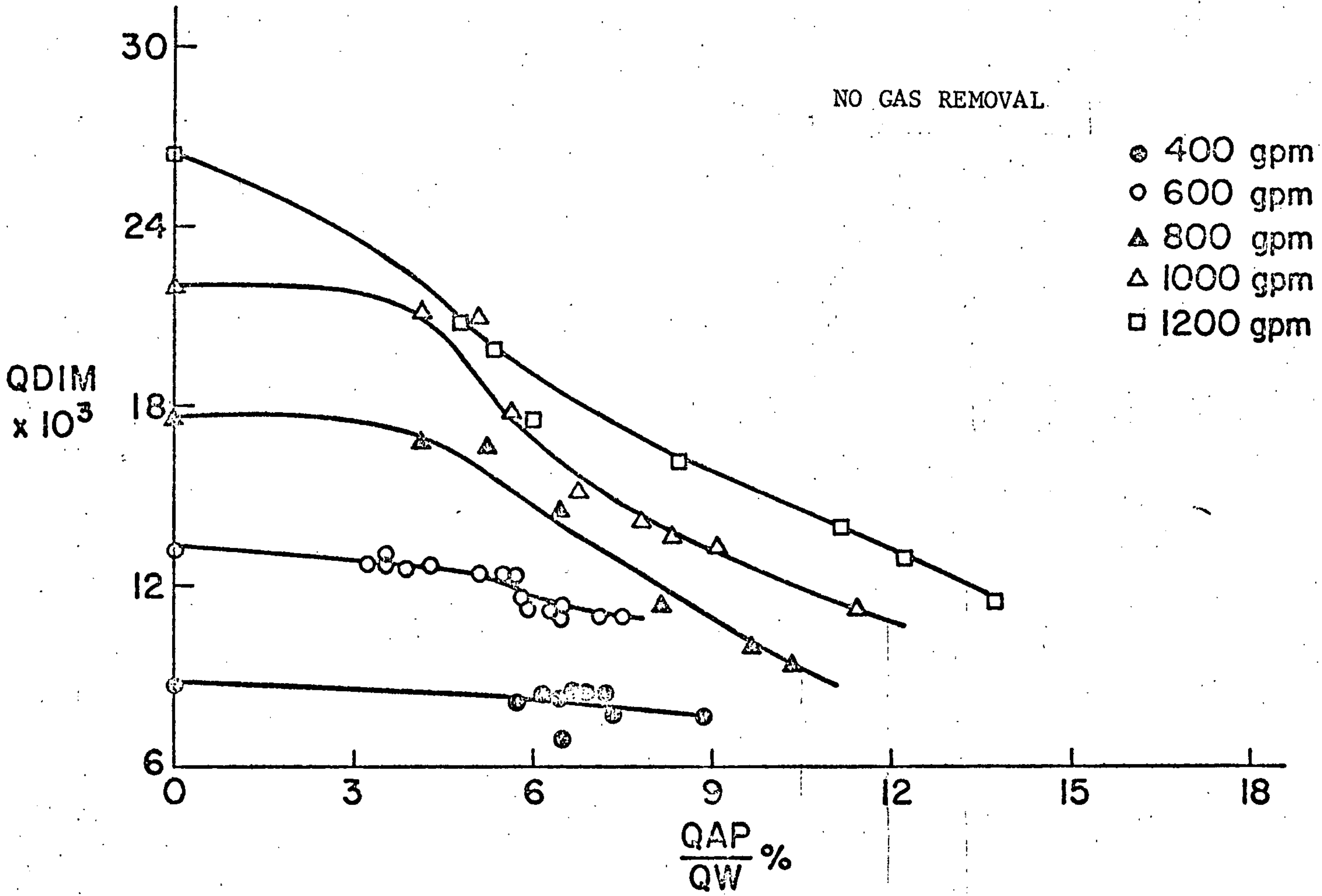


Fig. 5 Relationship Between Dimensionless Discharge and QAP/QW at 1440 RPM

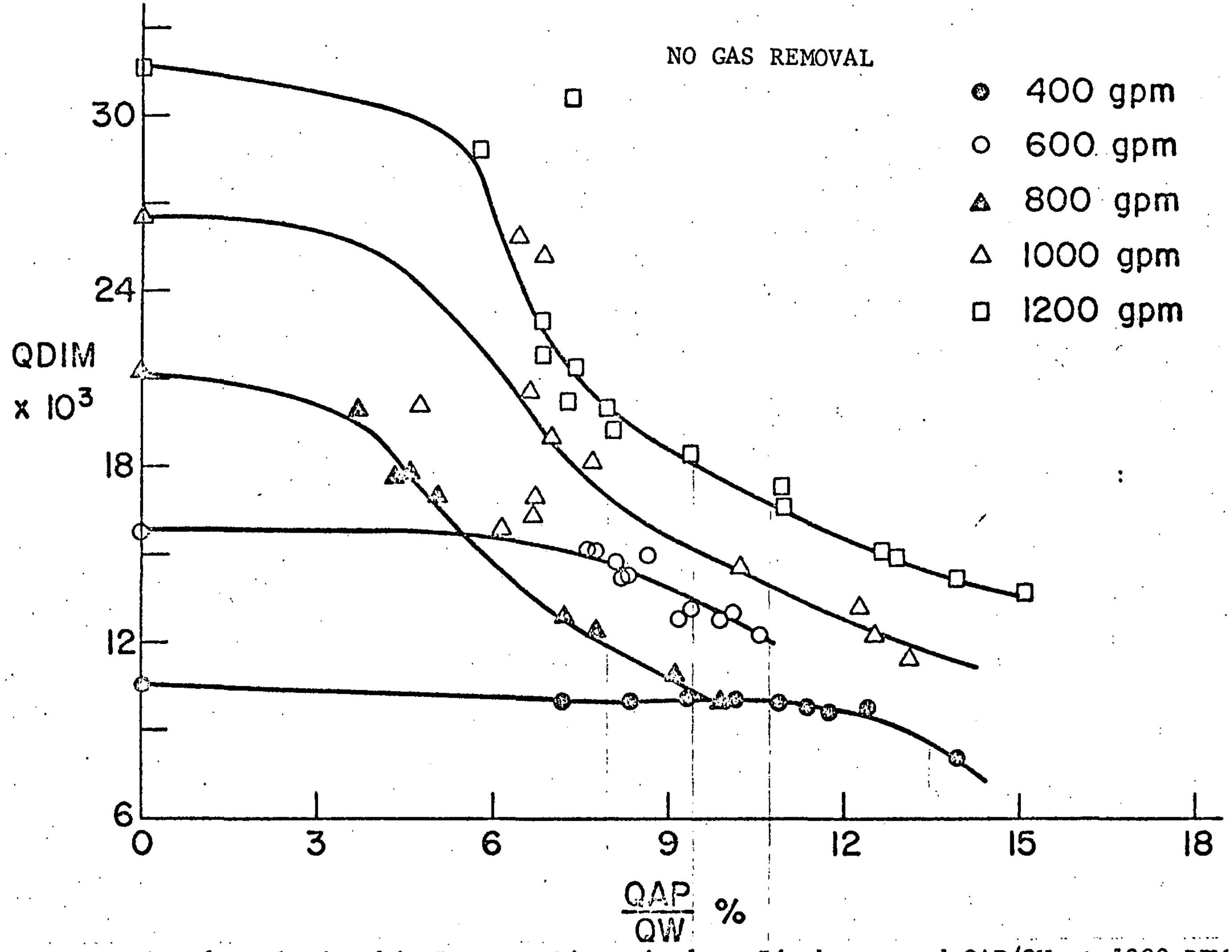


Fig. 6 Relationship Between Dimensionless Discharge and QAP/QW at 1200 RPM

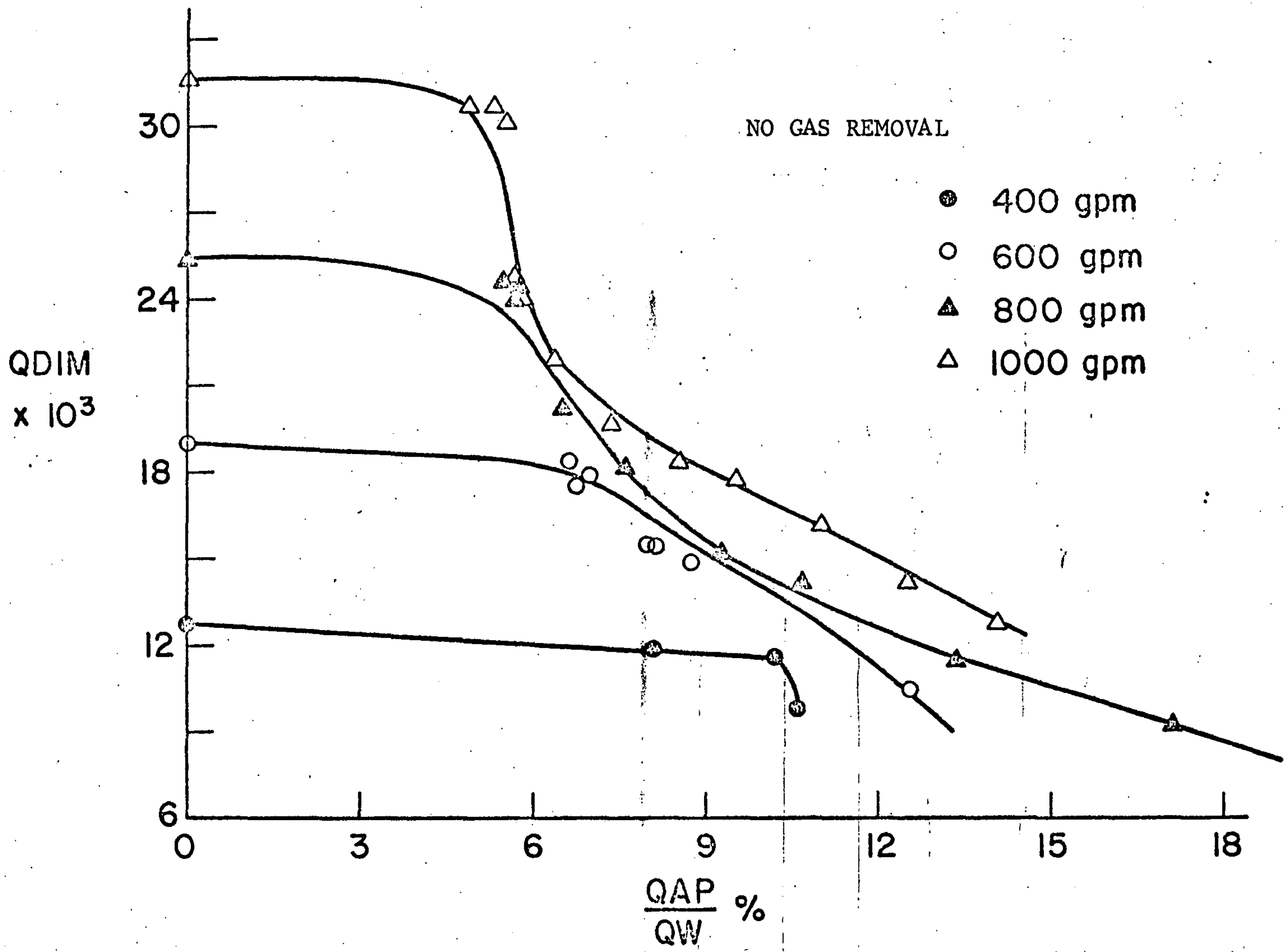


Fig. 7 Relationship Between Dimensionless Discharge and QAP/QW at 1000 RPM

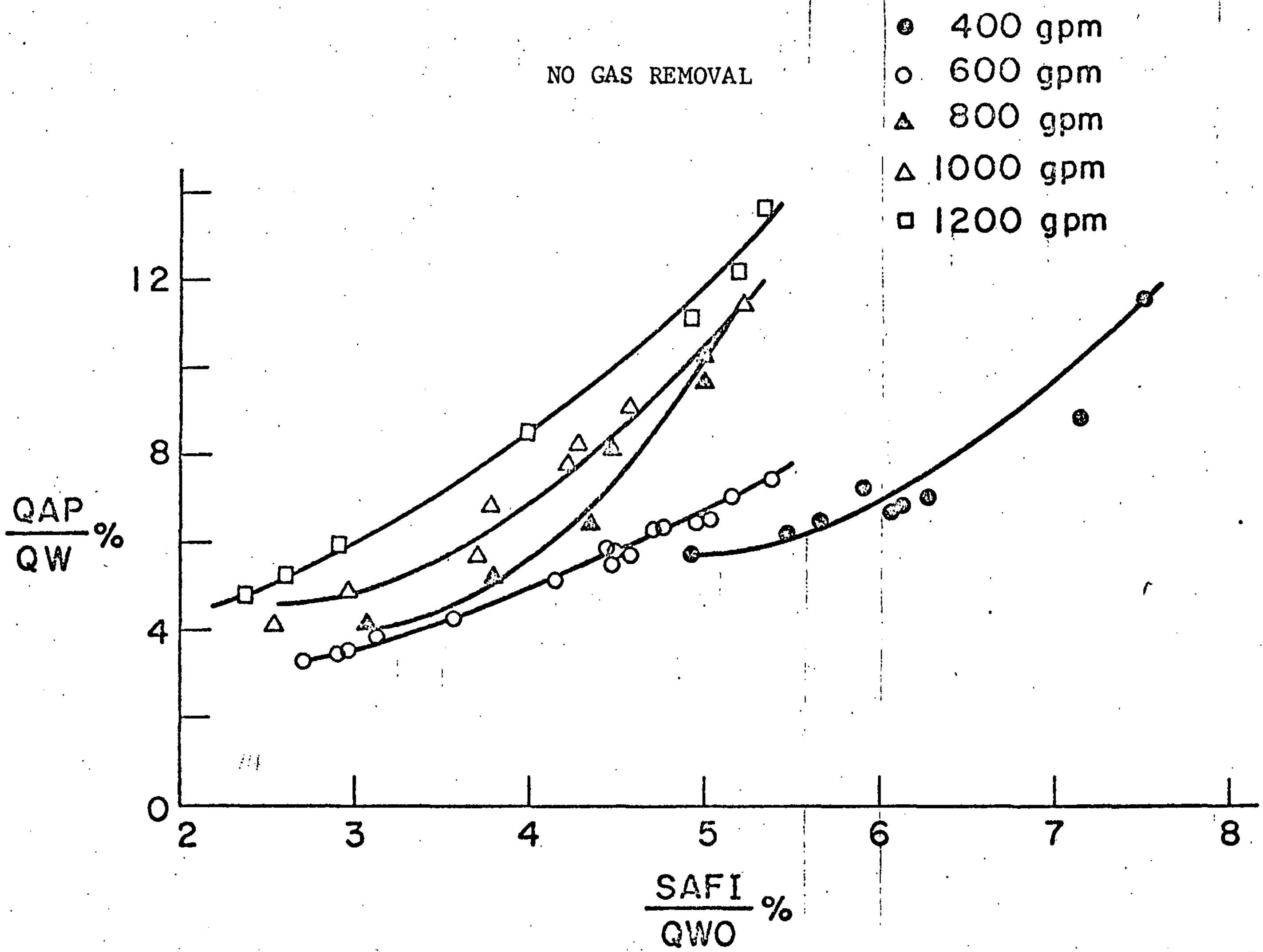


Fig. 8 Relationship Between QAP/QW and Air Injection Ratio at 1440 RPM

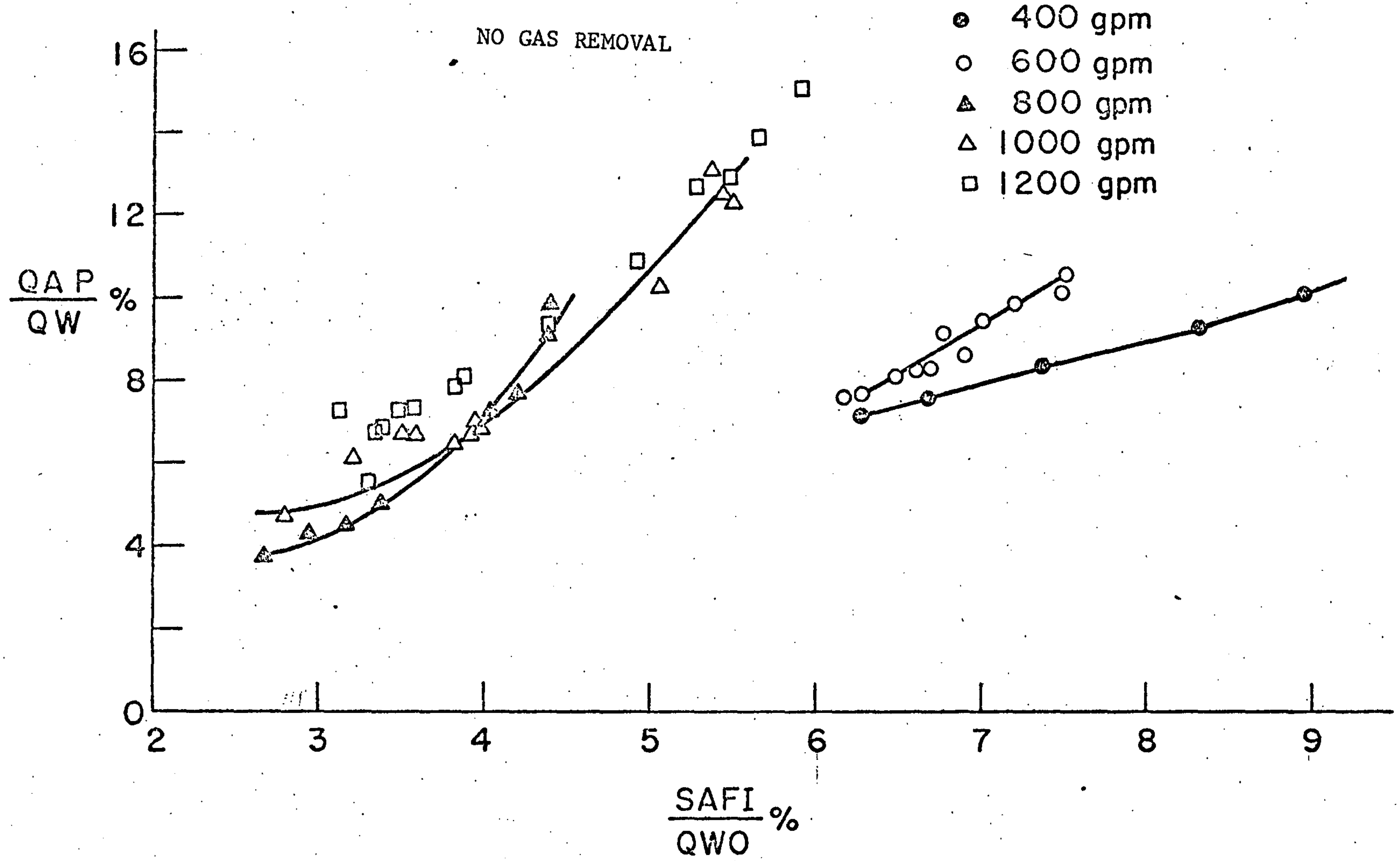


Fig. 9 Relationship Between QAP/QW and Air Injection Ratio at 1200 RPM

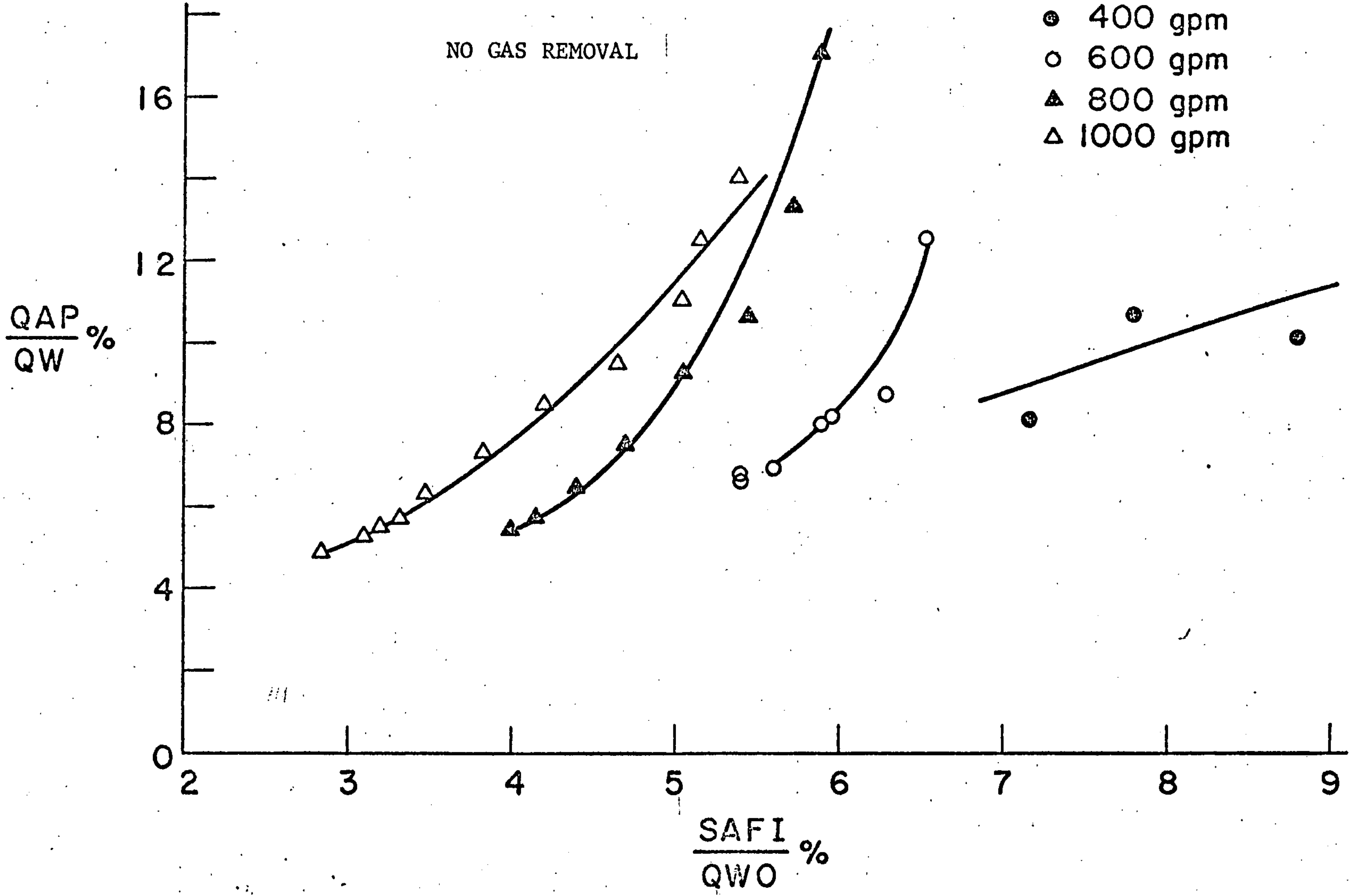


Fig. 10 Relationship Between QAP/QW and Air Injection Ratio at 1000 RPM

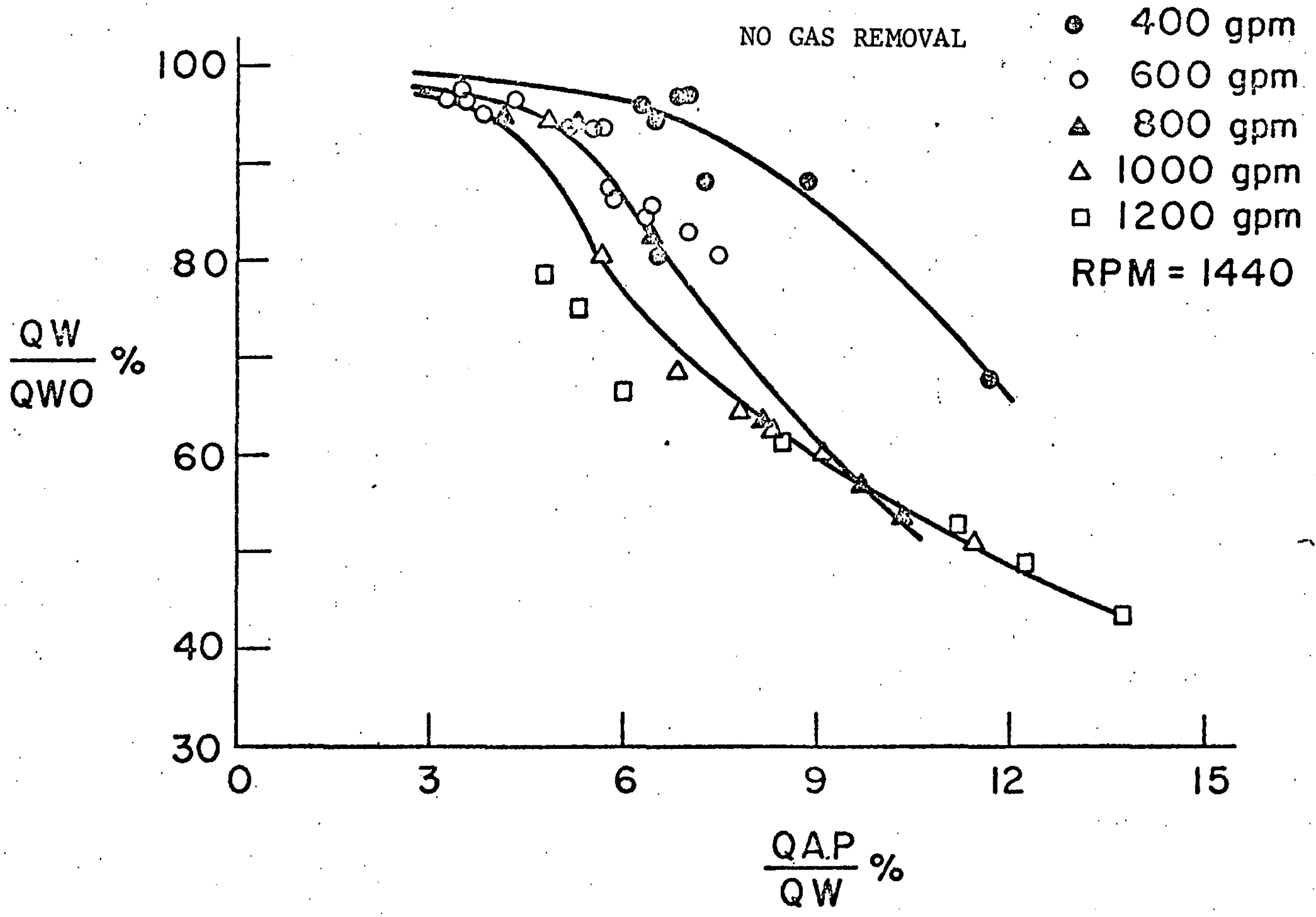


Fig. 11 Relationship Between Water Discharge Ratio and QAP/QW at 1440 RPM

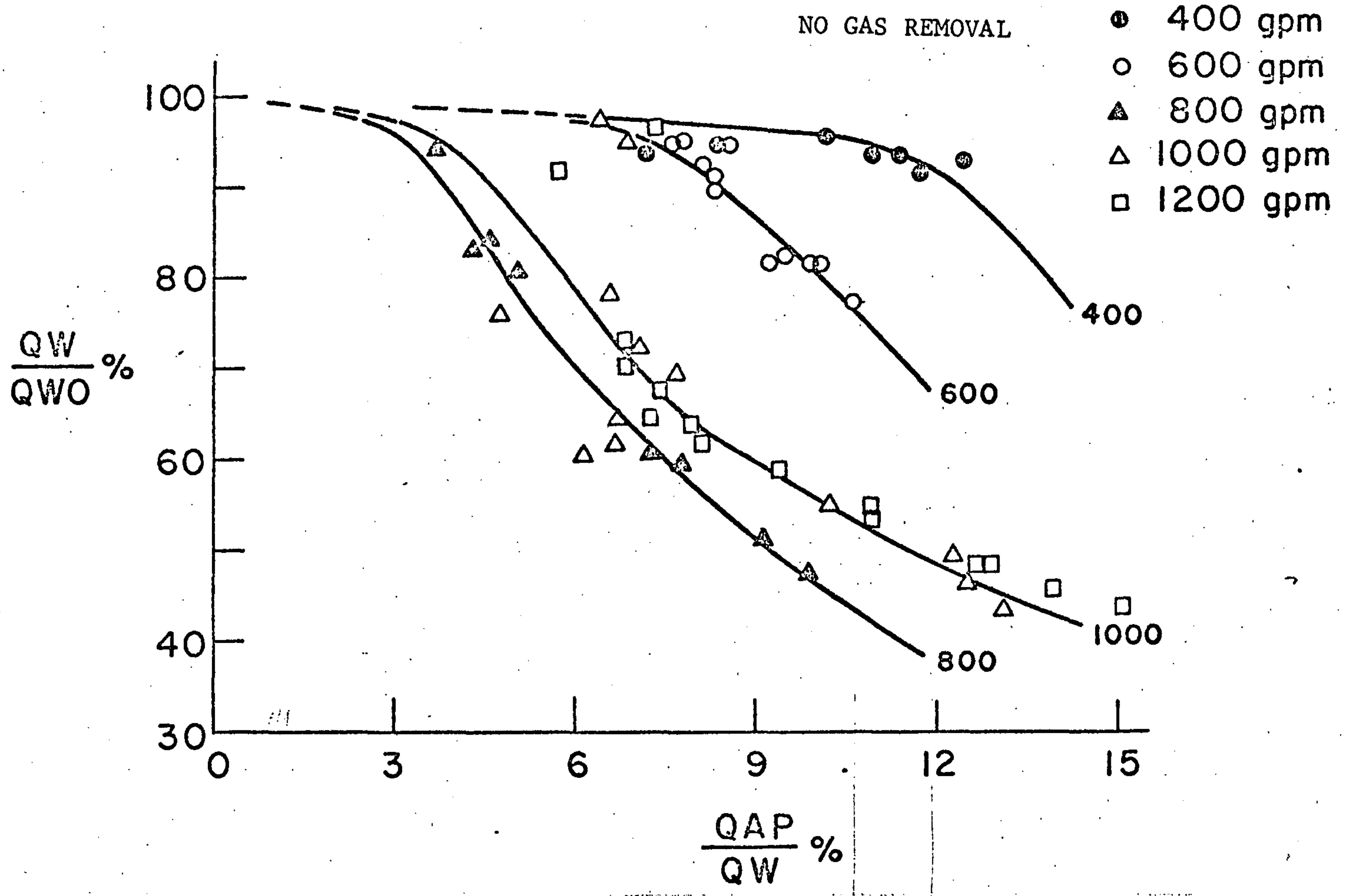


Fig. 12 Relationship Between Water Discharge Ratio and QAP/QW at 1200 RPM

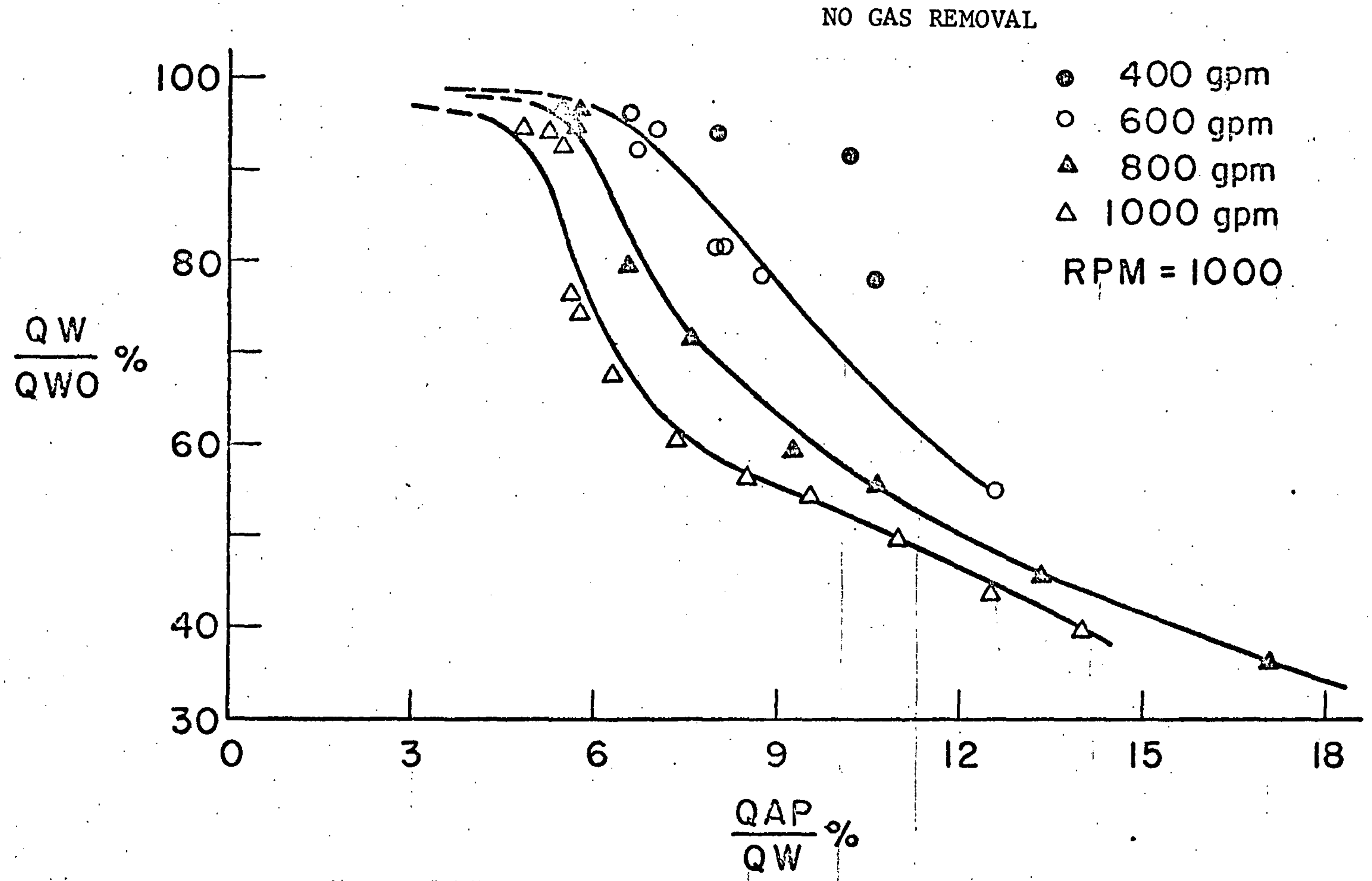


Fig. 13 Relationship Between Water Discharge Ratio and QAP/QW at 1000 RPM

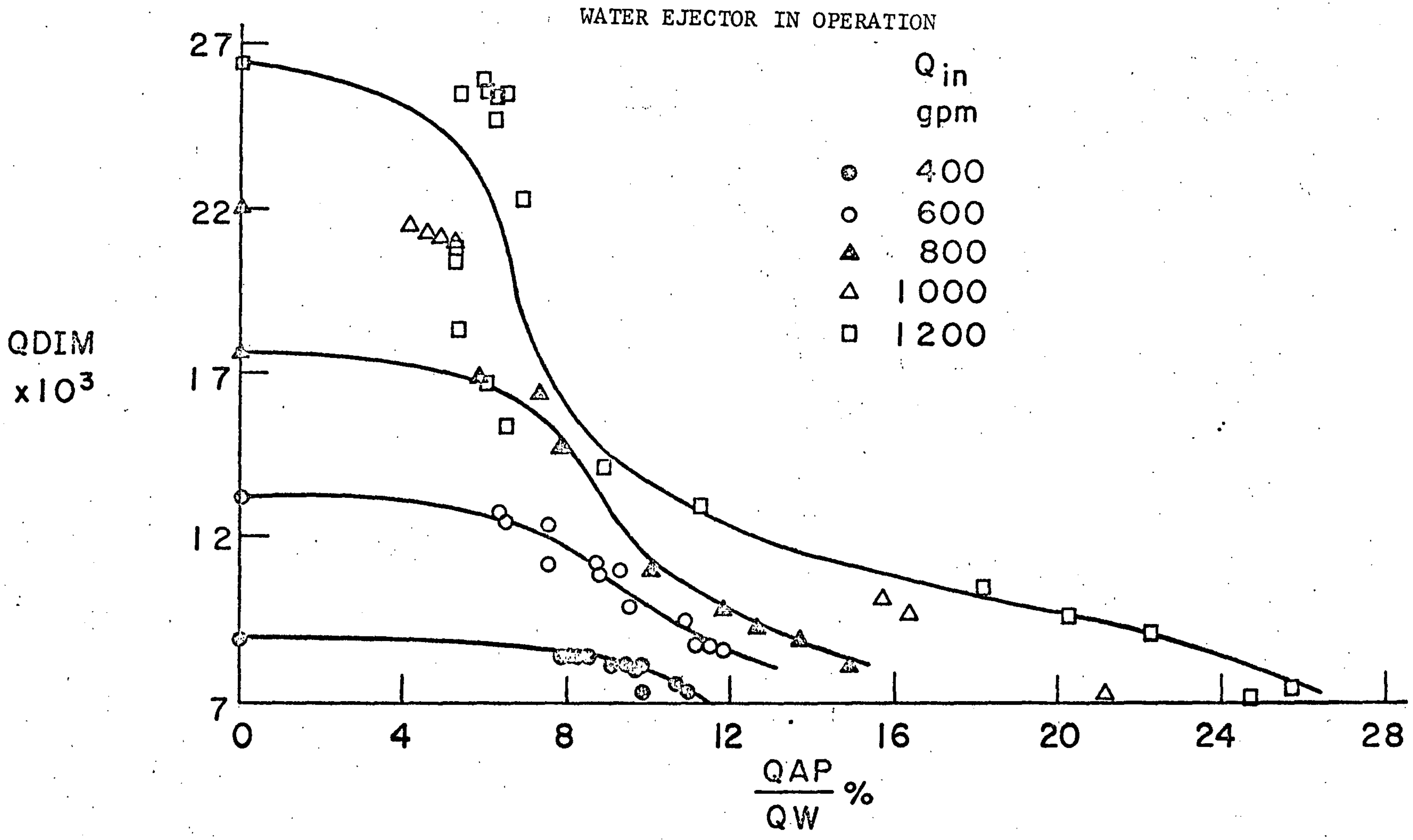


Fig. 14 Relationship Between Dimensionless Discharge and QAP/QW at 1440 RPM

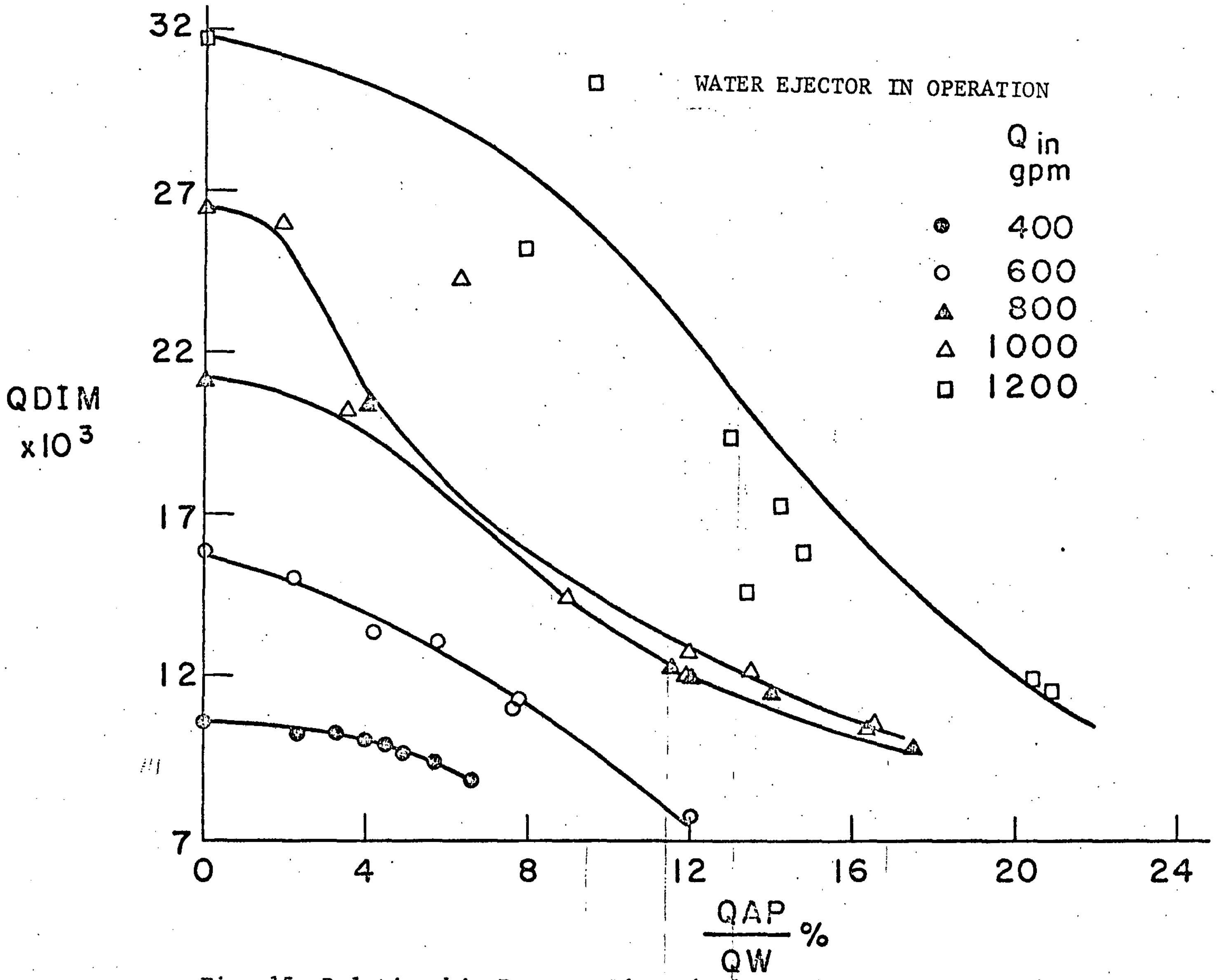


Fig. 15 Relationship Between Dimensionless Discharge and QAP/QW at 1200 RPM

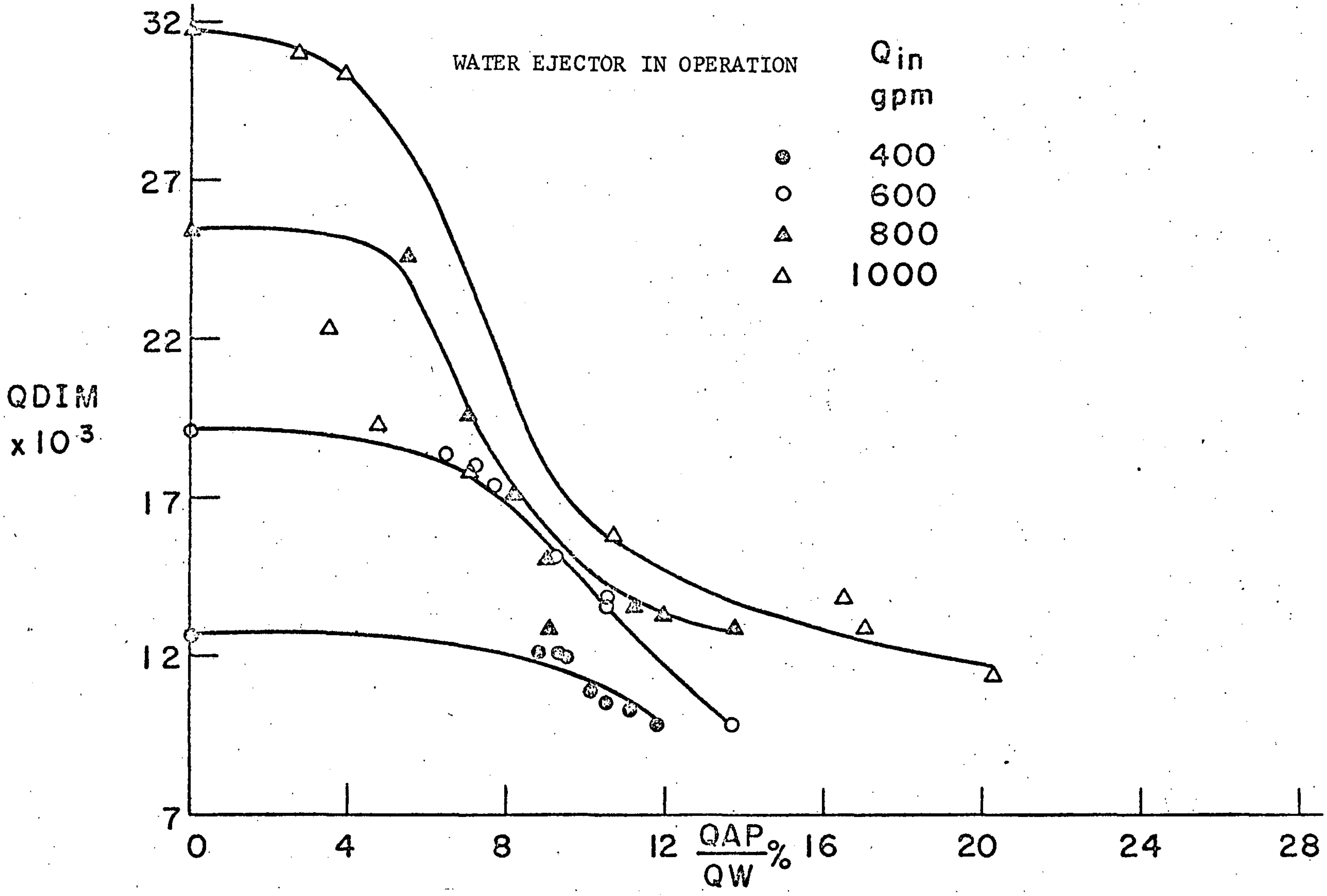


Fig. 16 Relationship Between Dimensionless Discharge and QAP/QW at 1000 RPM

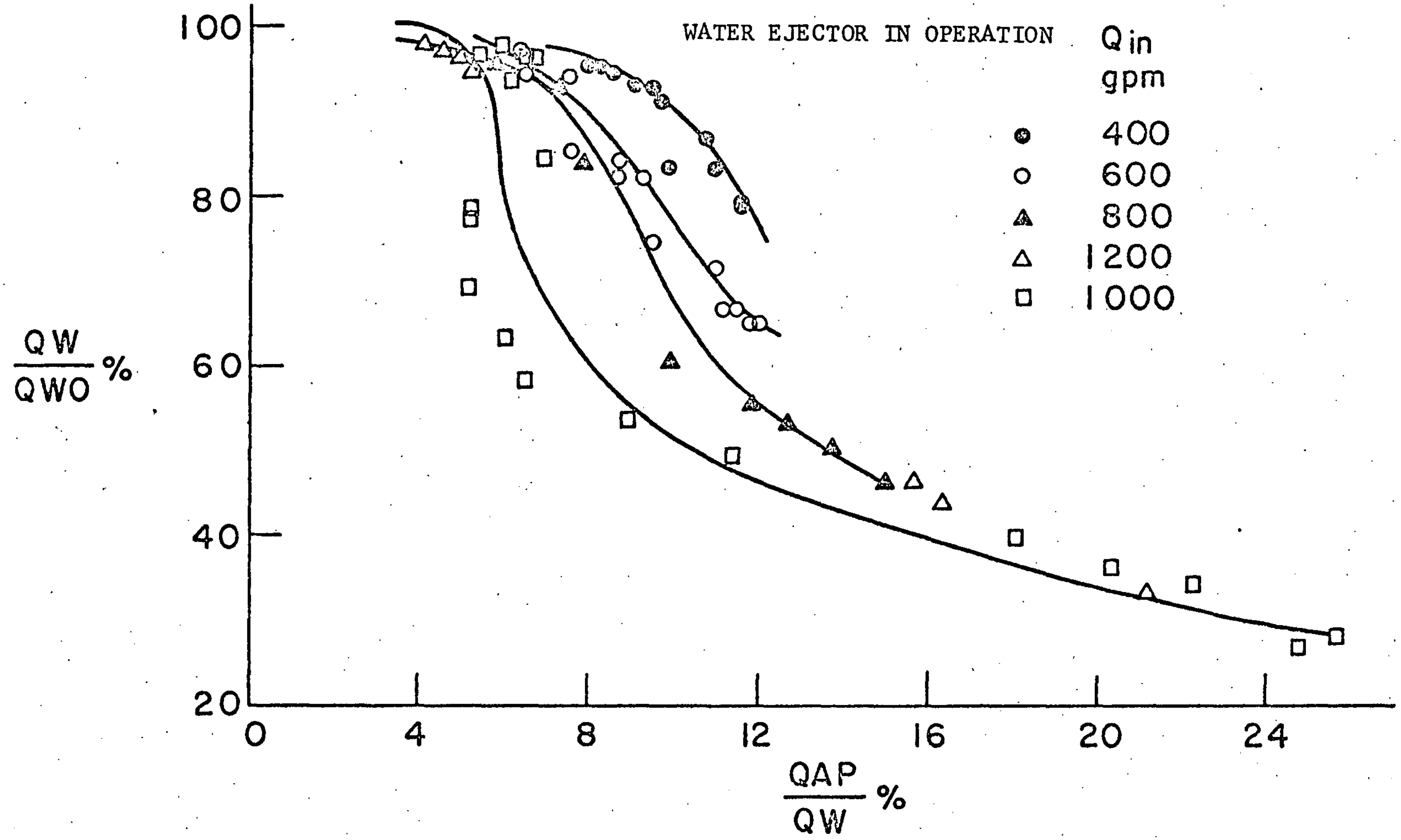


Fig. 17 Relationship Between Water Discharge Ratio and QAP/QW at 1440 RPM

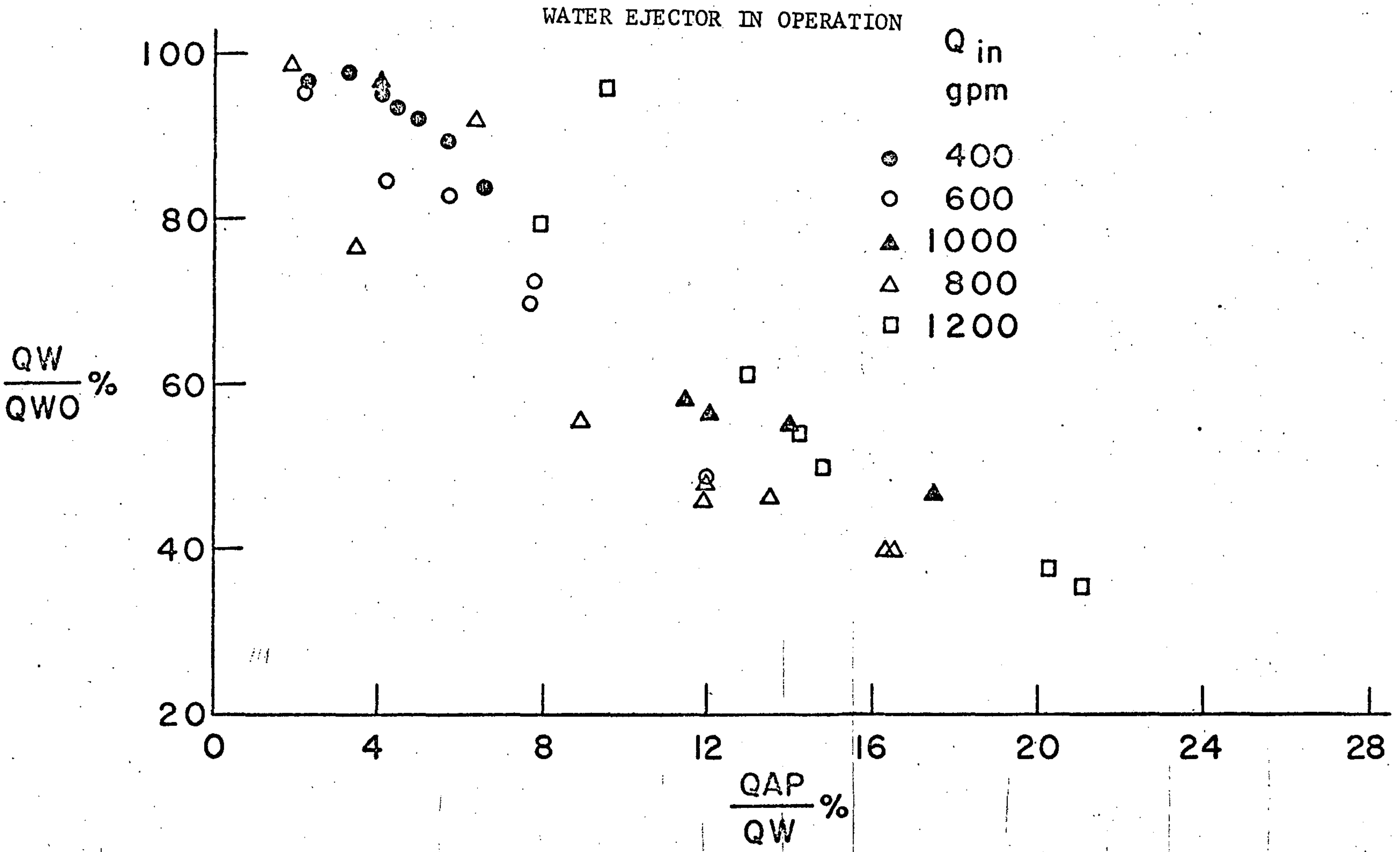


Fig. 18 Relationship Between Water Discharge Ratio and QAP/QW at 1200 RPM

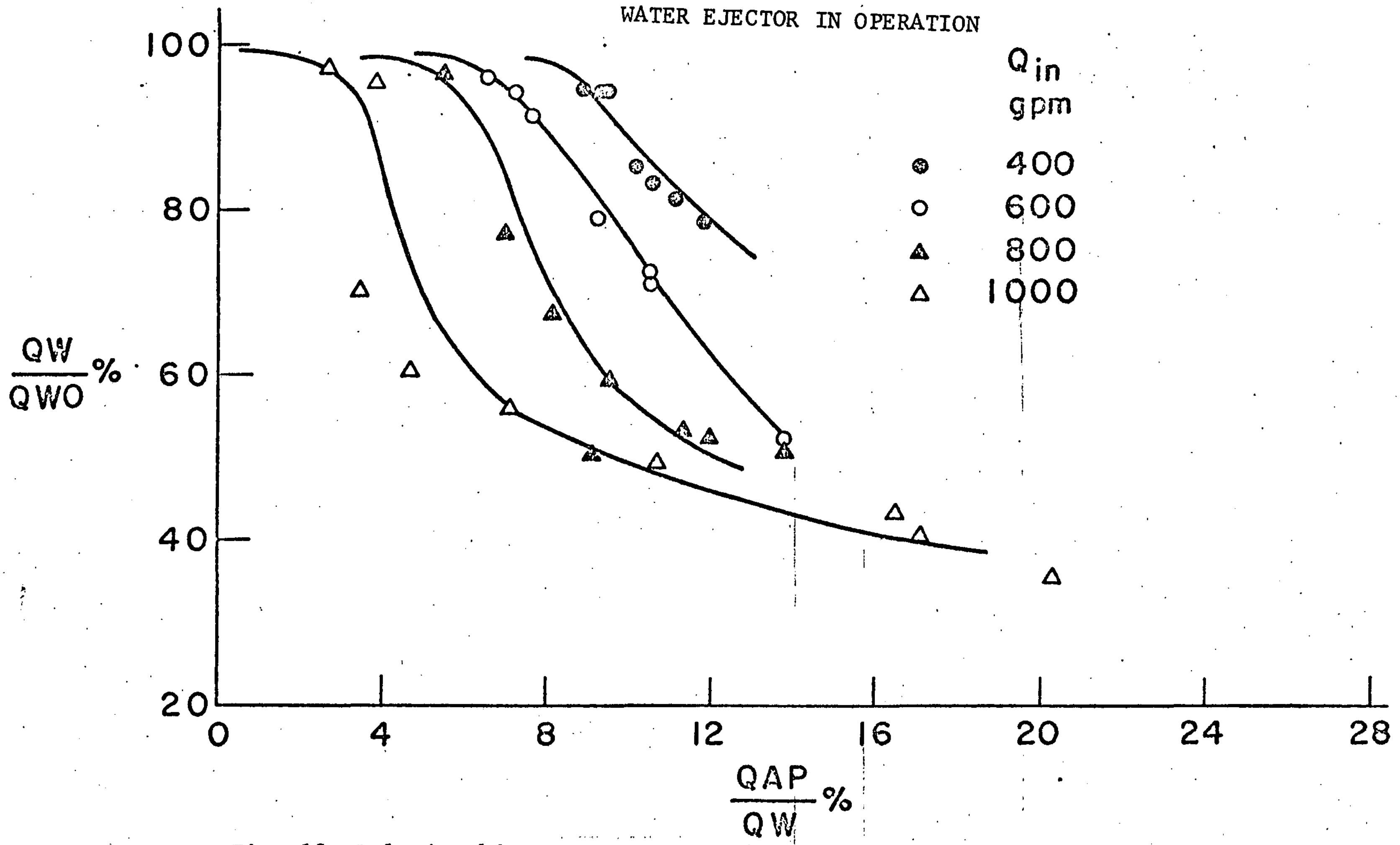


Fig. 19 Relationship Between Water Discharge Ratio and QAP/QW at 1000 RPM

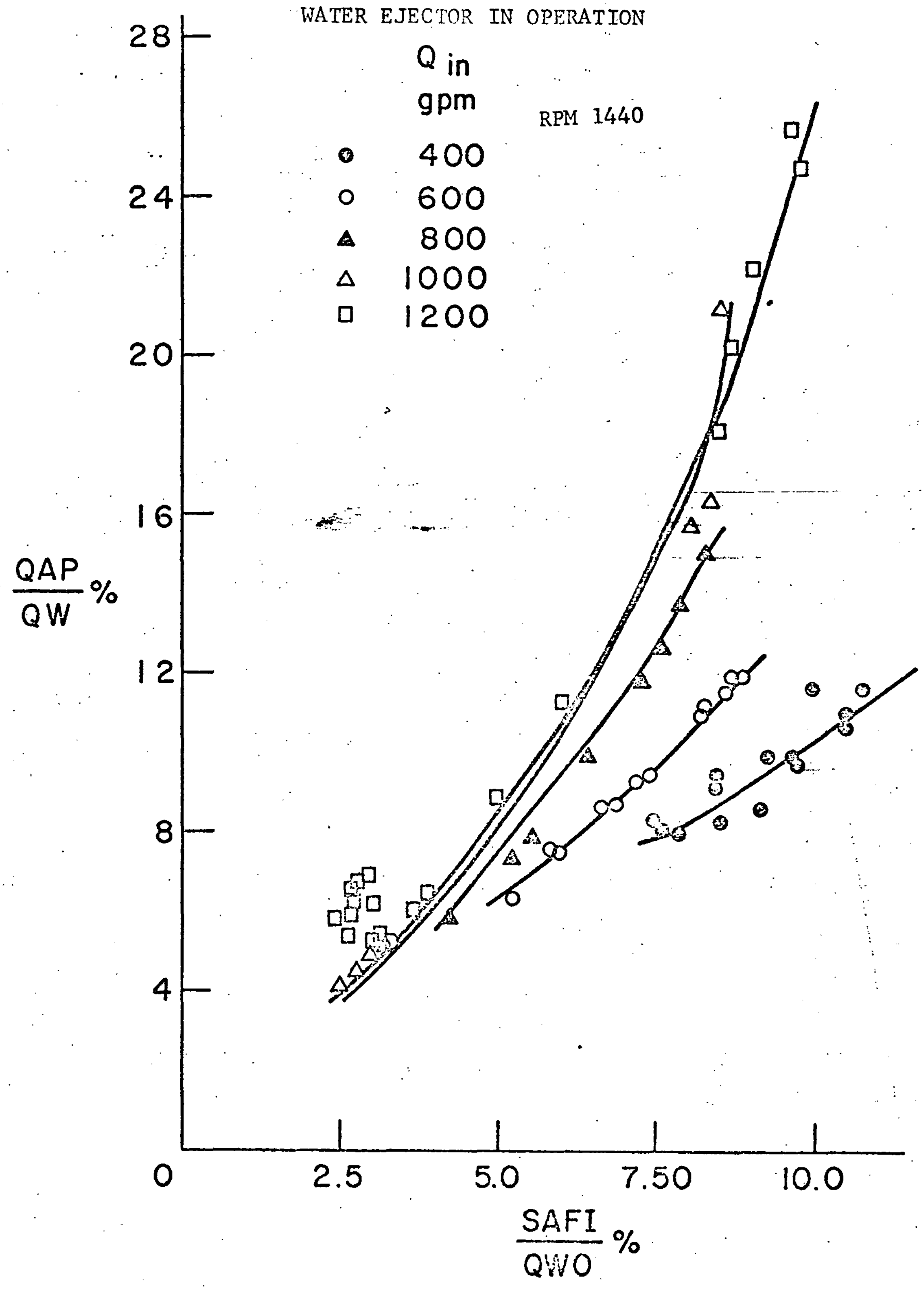


Fig. 20 Relationship Between QAP/QW and Air Injection Ratio

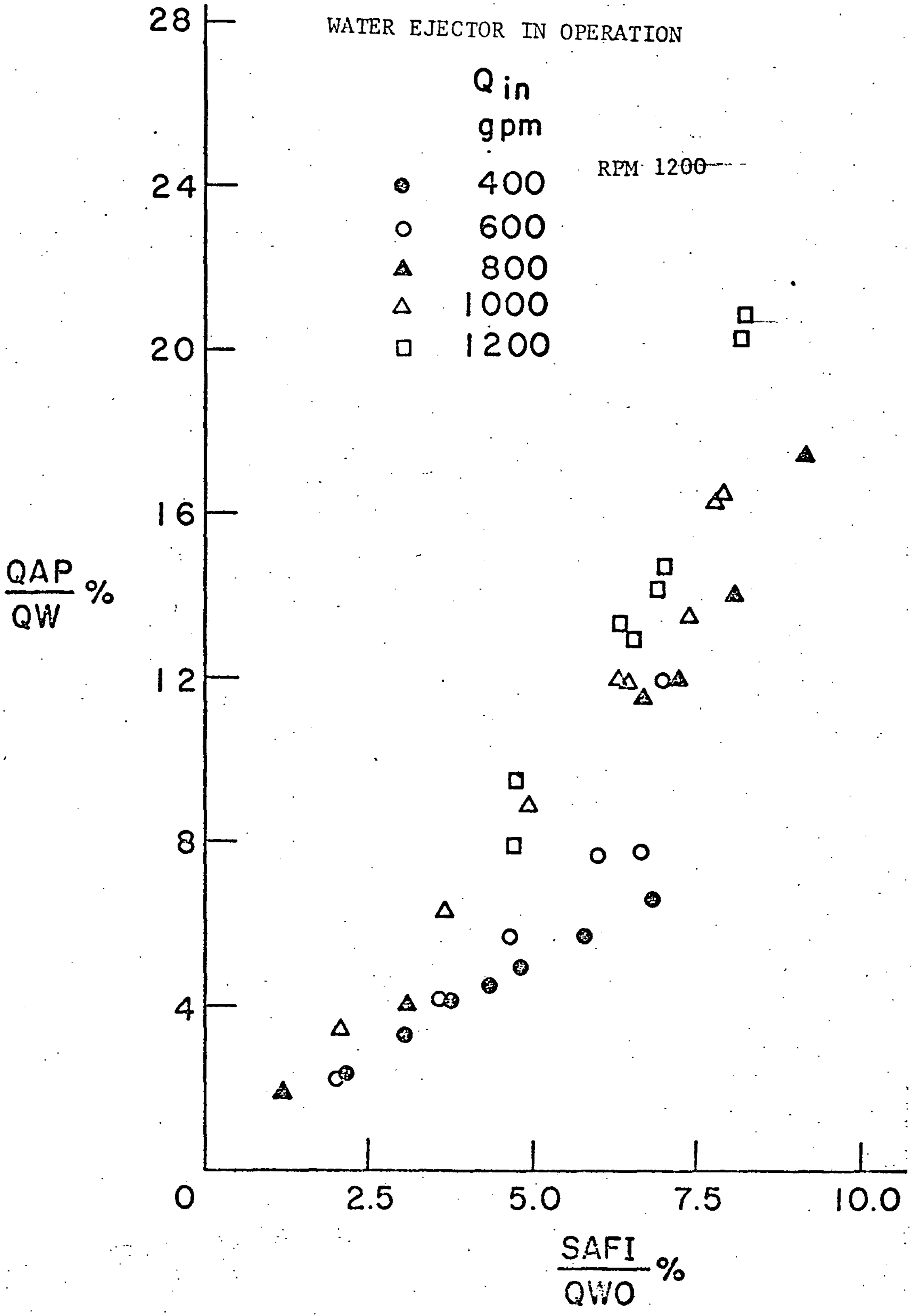


Fig. 21 Relationship Between QAP/QW and Air Injection Ratio

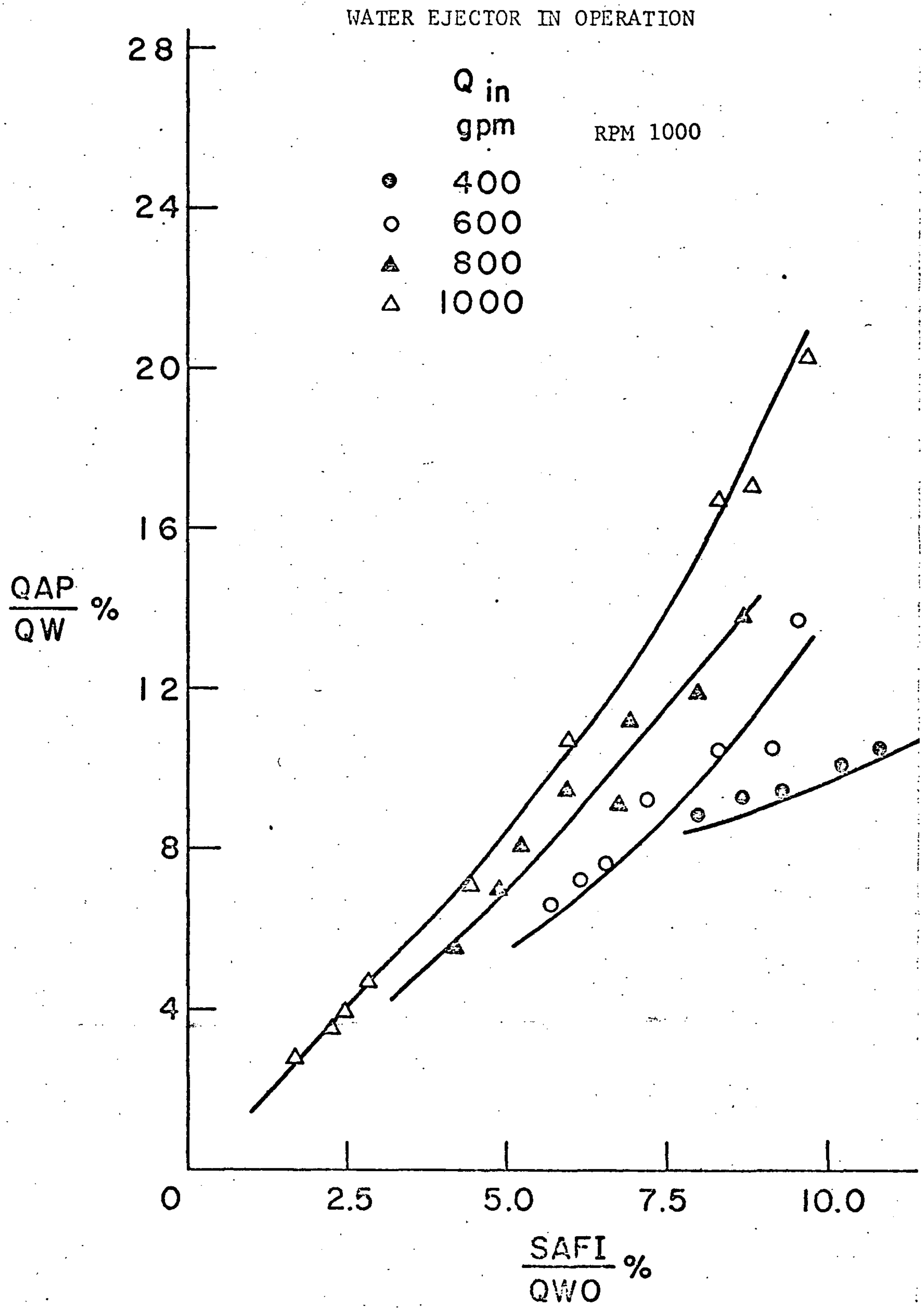


Fig. 22 Relationship Between QAP/QW and Air Injection Ratio

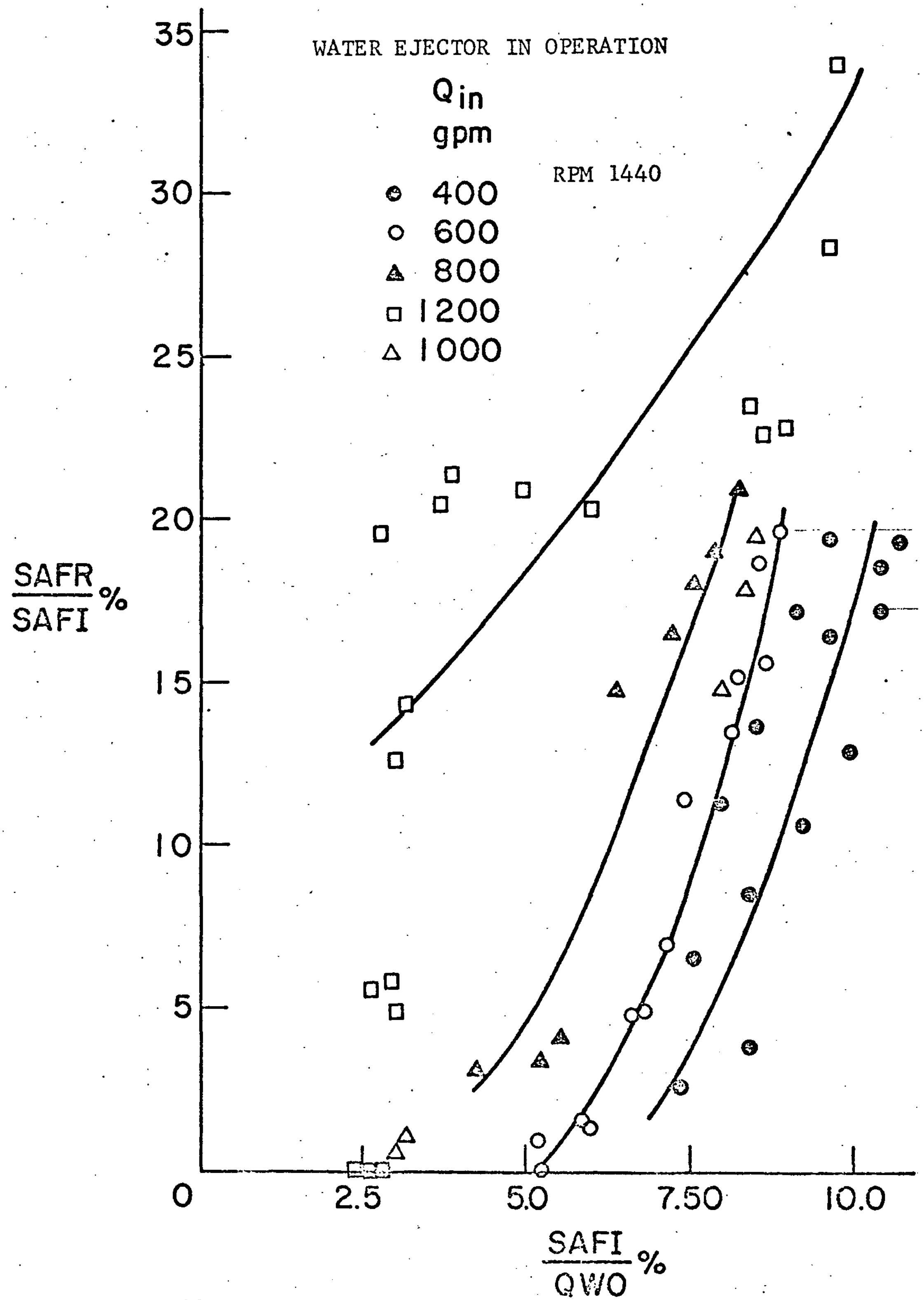


Fig. 23 Relationship Between Percent Gas Removal and SAFI/QWO

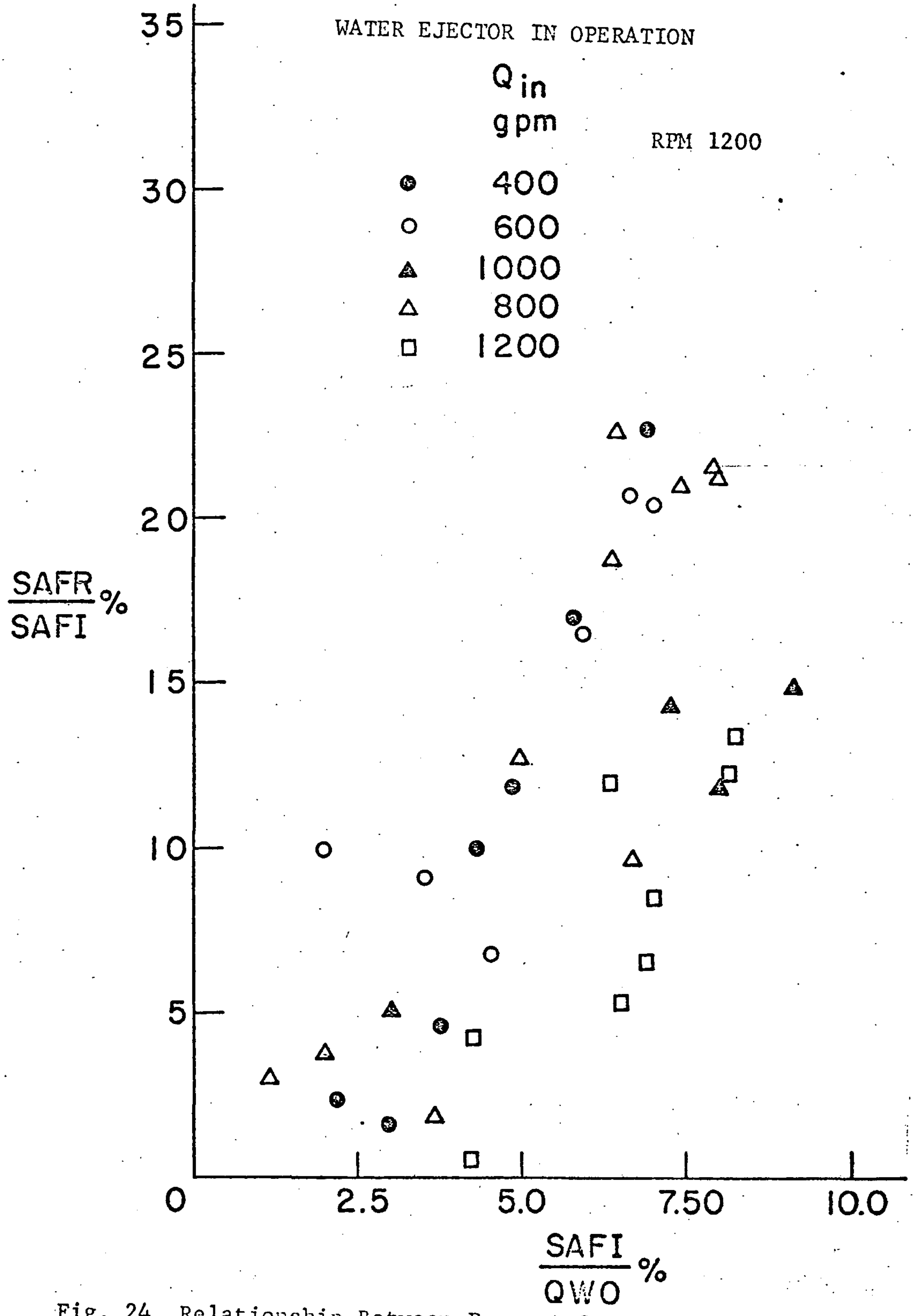


Fig. 24 Relationship Between Percent Gas Removal and SAFI/QWO

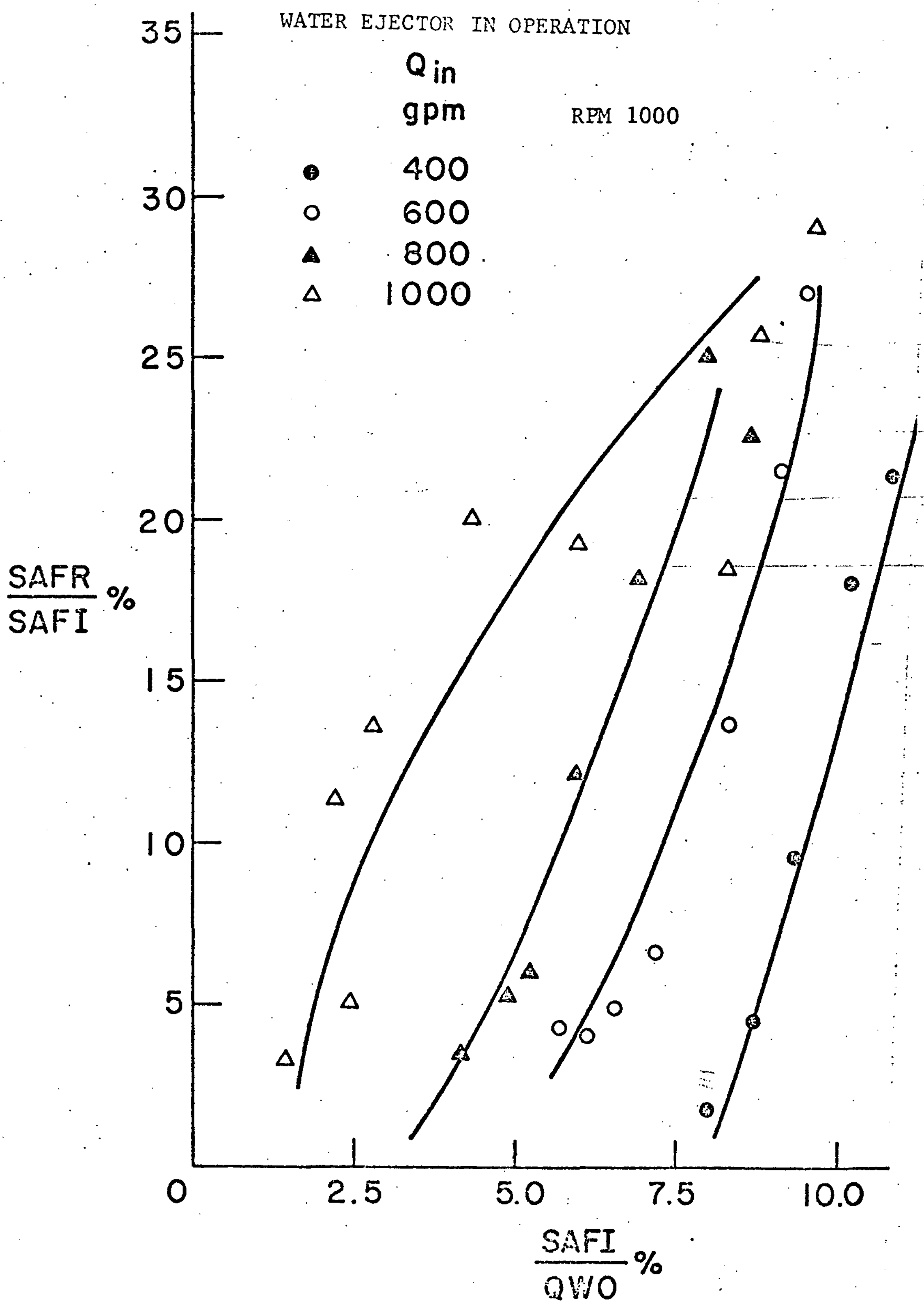


Fig. 25 Relationship Between Percent Gas Removal and SAFI/QWO

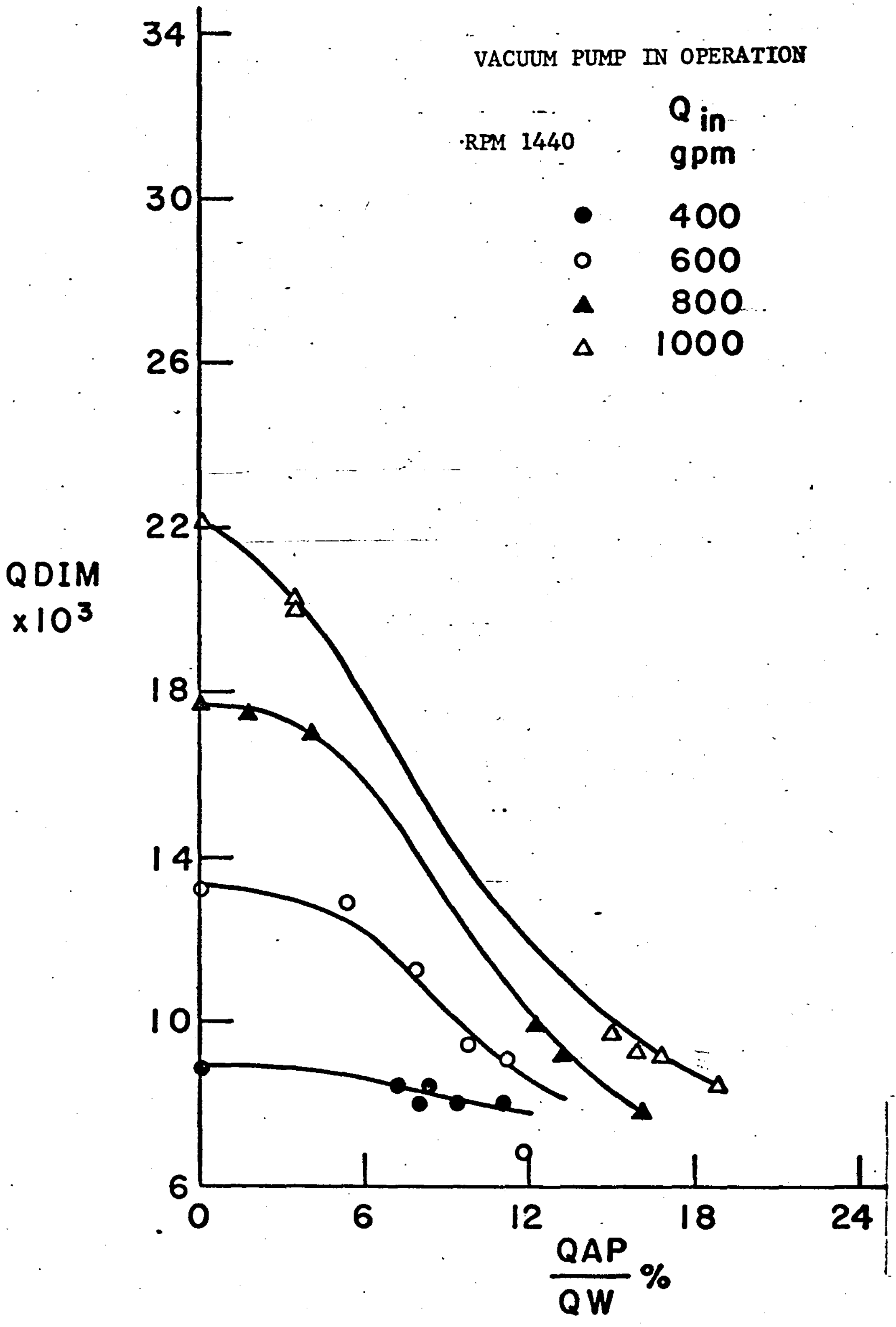


Fig. 26 Relationship Between Dimensionless Discharge and QAP/QW

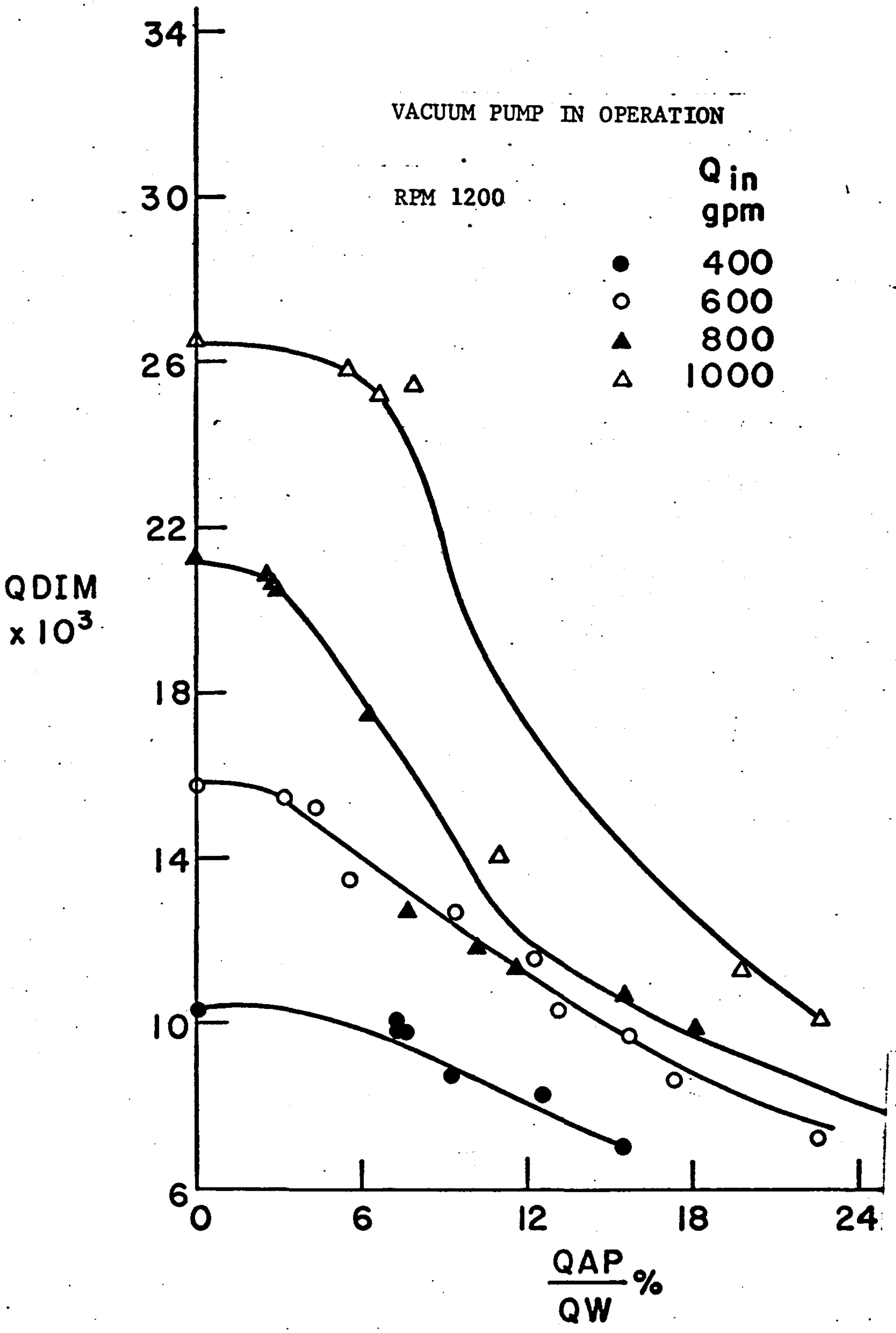


Fig. 27 Relationship Between Dimensionless Discharge and QAP/QW

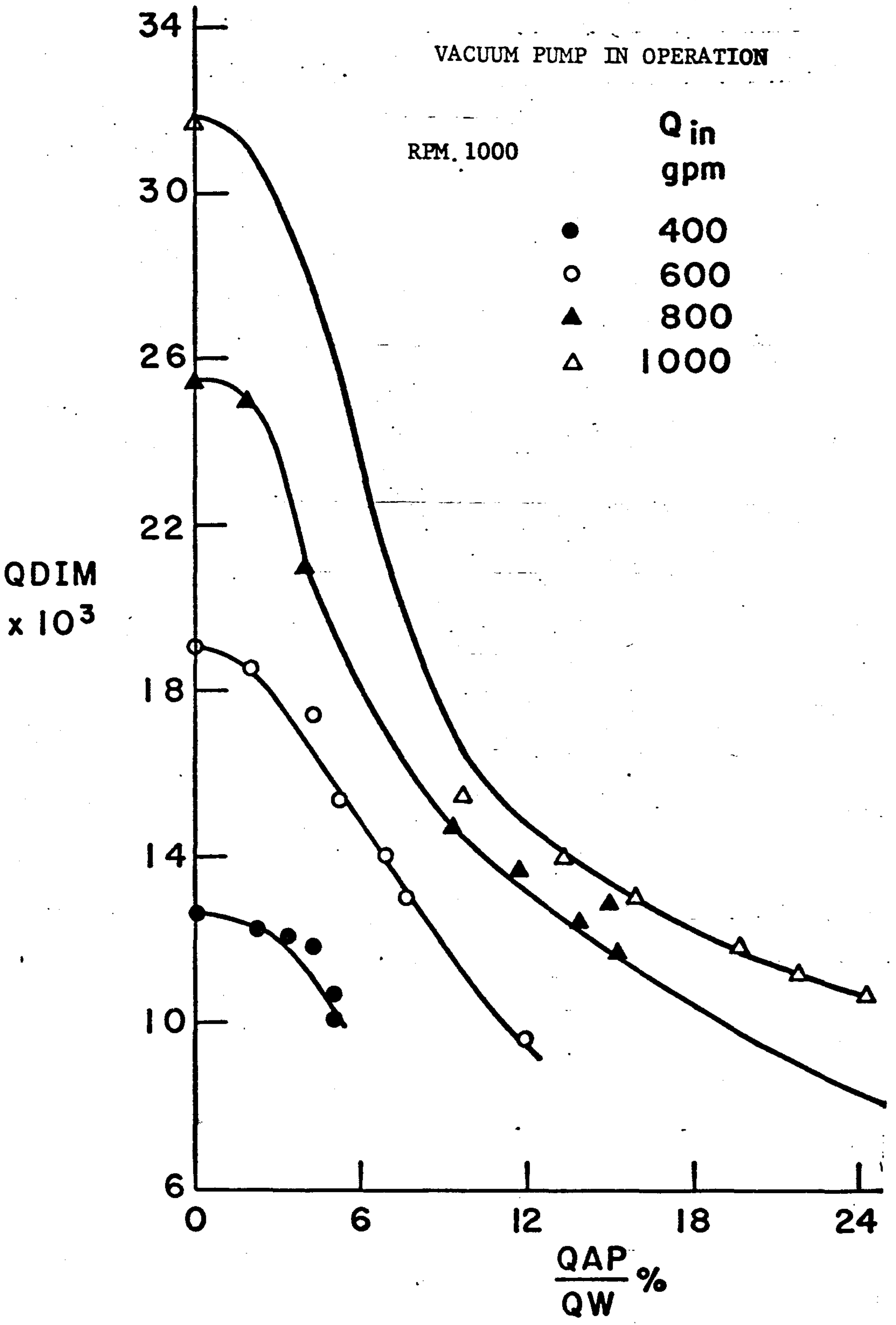


Fig. 28 Relationship Between Dimensionless Discharge and QAP/QW

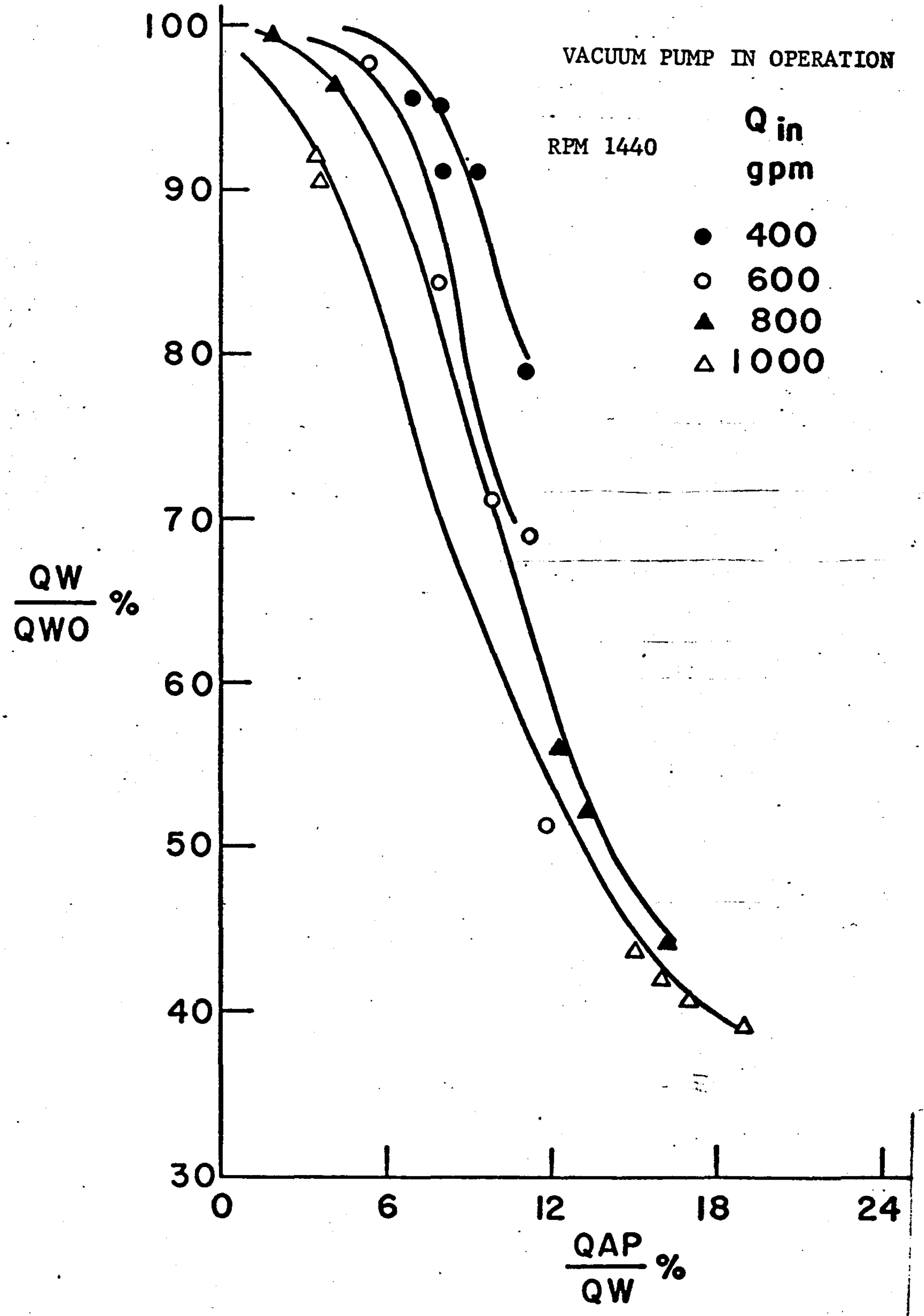


Fig. 29 Relationship Between Water Discharge Ratio and QAP/QW

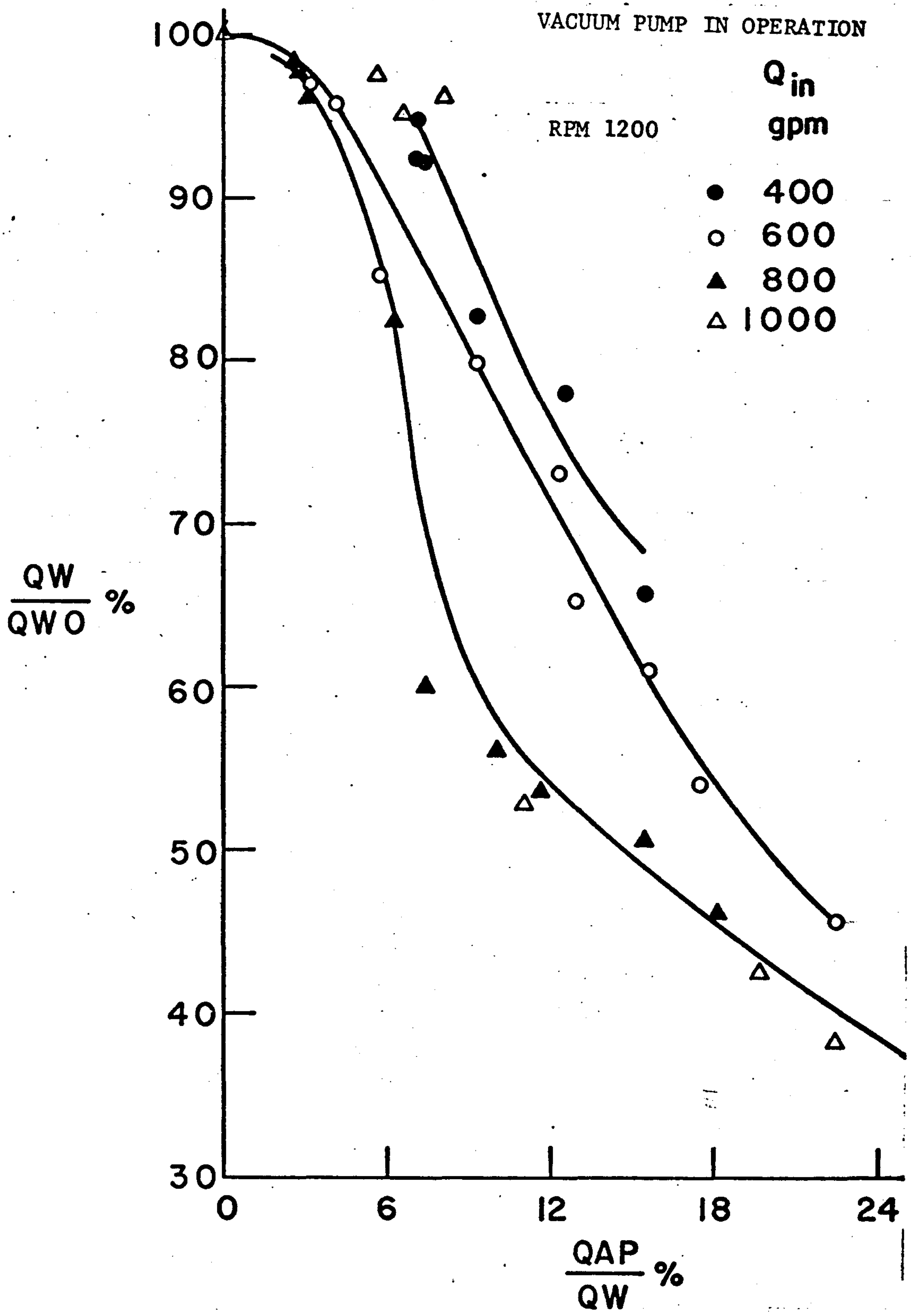


Fig. 30 Relationship Between Water Discharge Ratio and QAP/QW

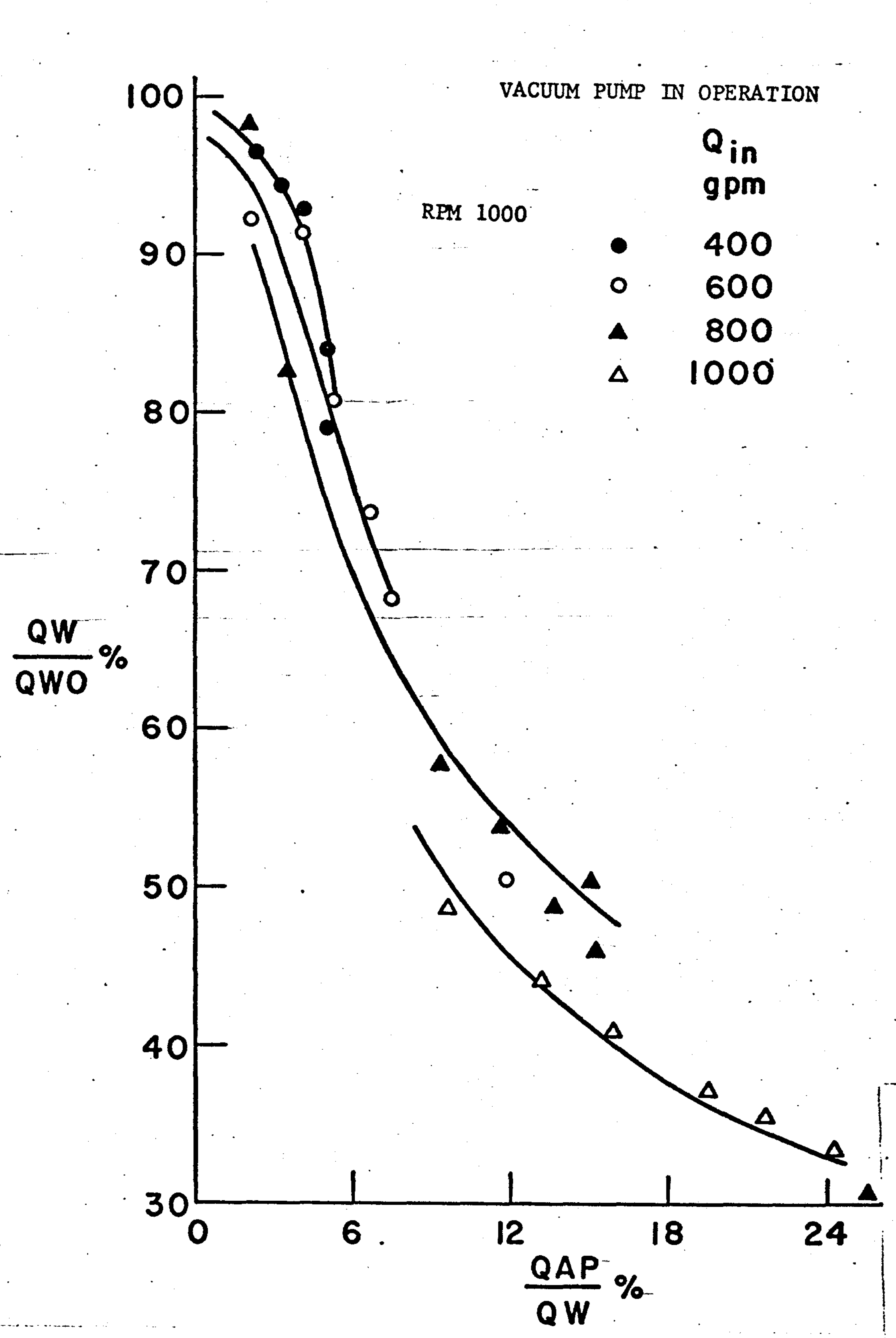


Fig. 31 Relationship Between Water Discharge Ratio and QAP/QW

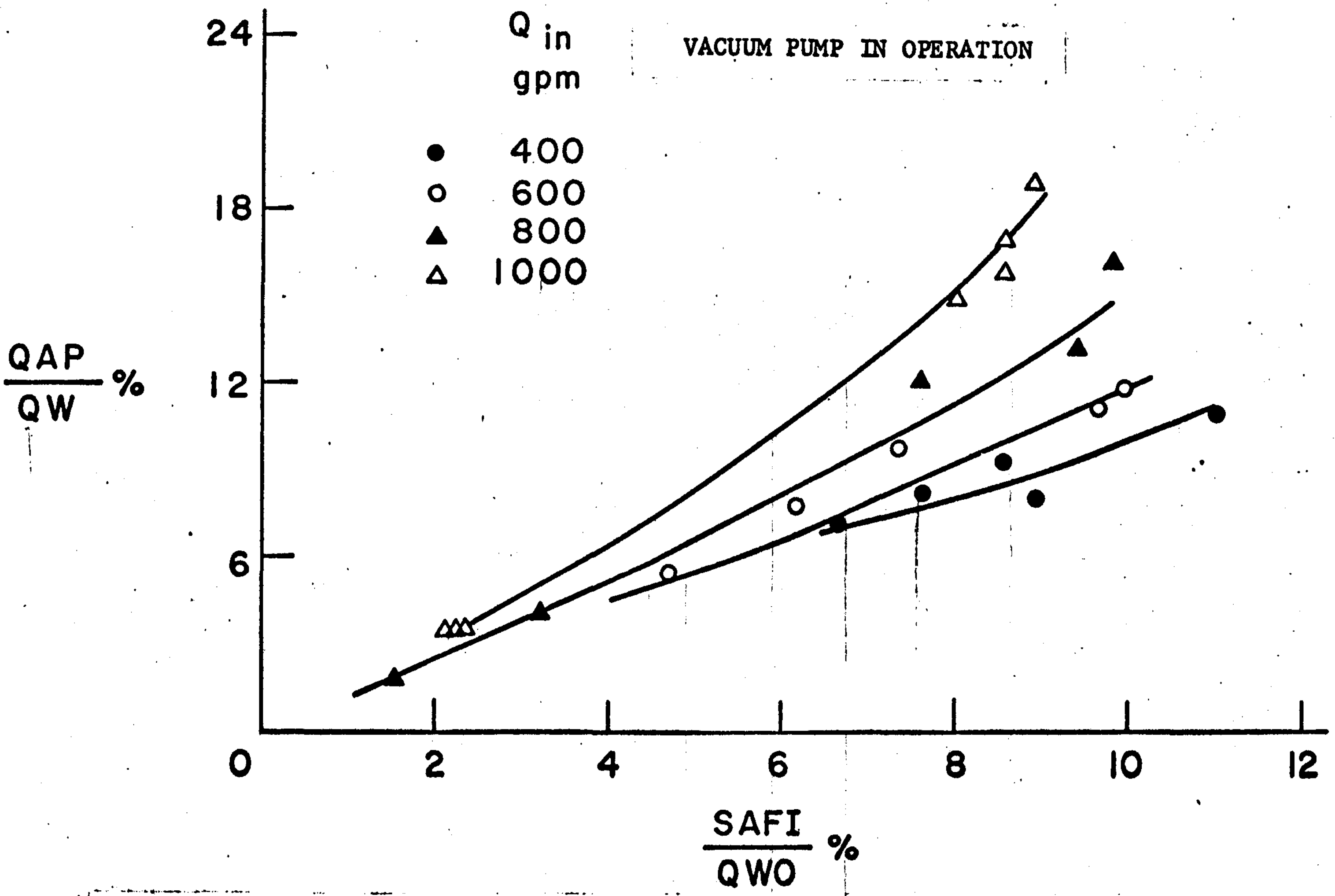


Fig. 32 Relationship Between QAP/QW and Air Injection Ratio at 1440 RPM

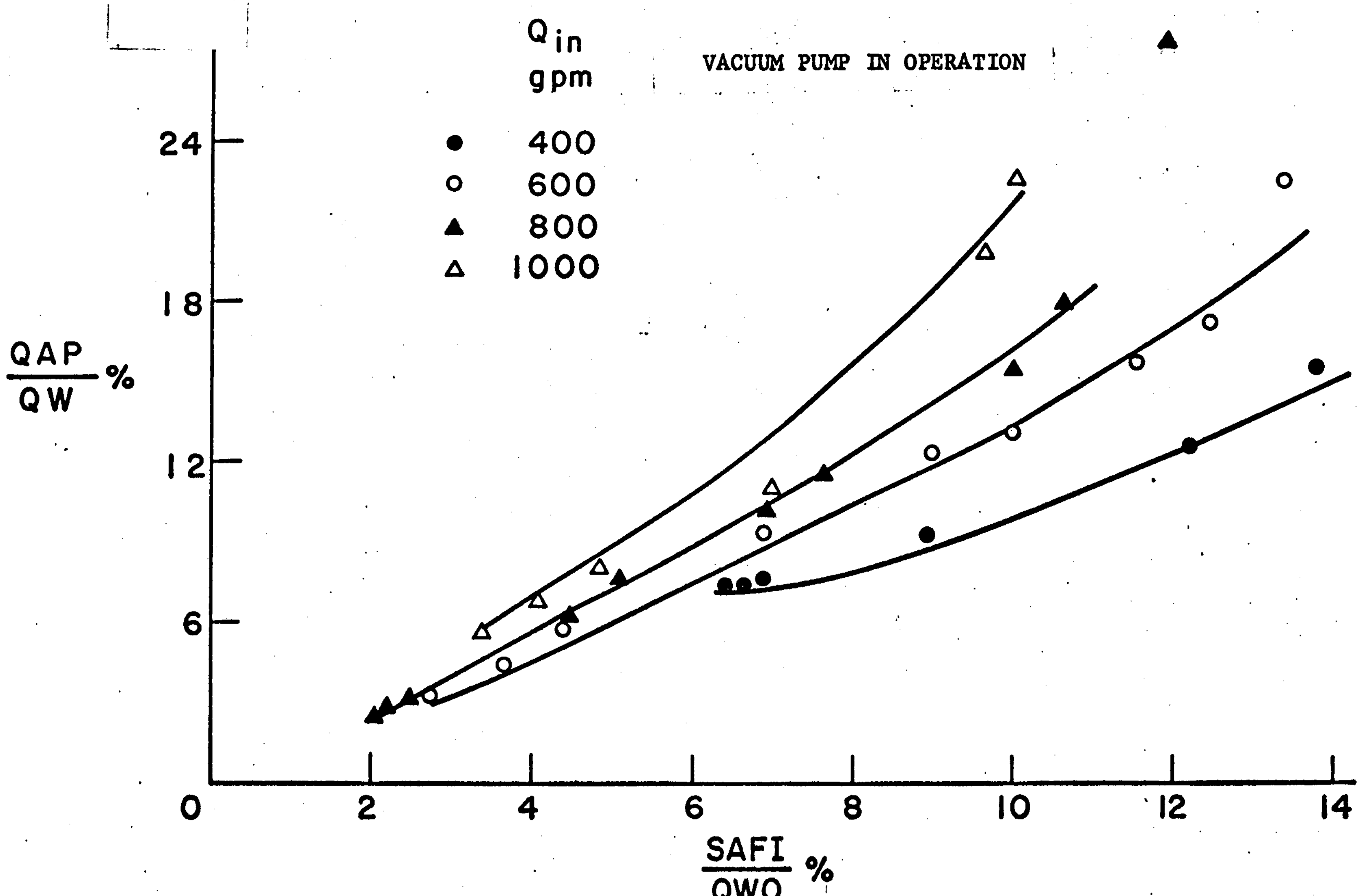


Fig. 33 Relationship Between QAP/QW and Air Injection Ratio at 1200 RPM

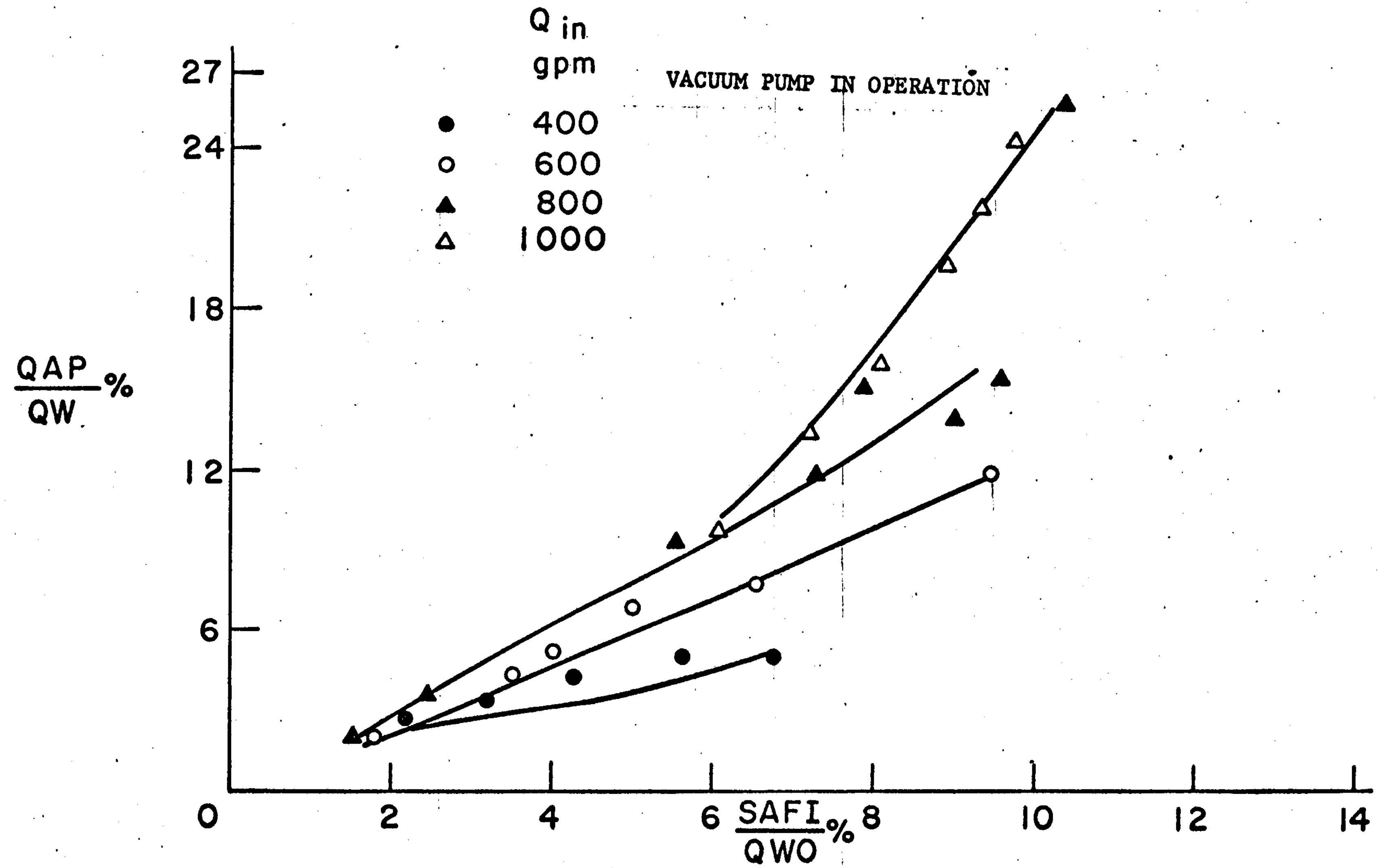


Fig. 34 Relationship Between QAP/QW and Air Injection Ratio at 1000 RPM

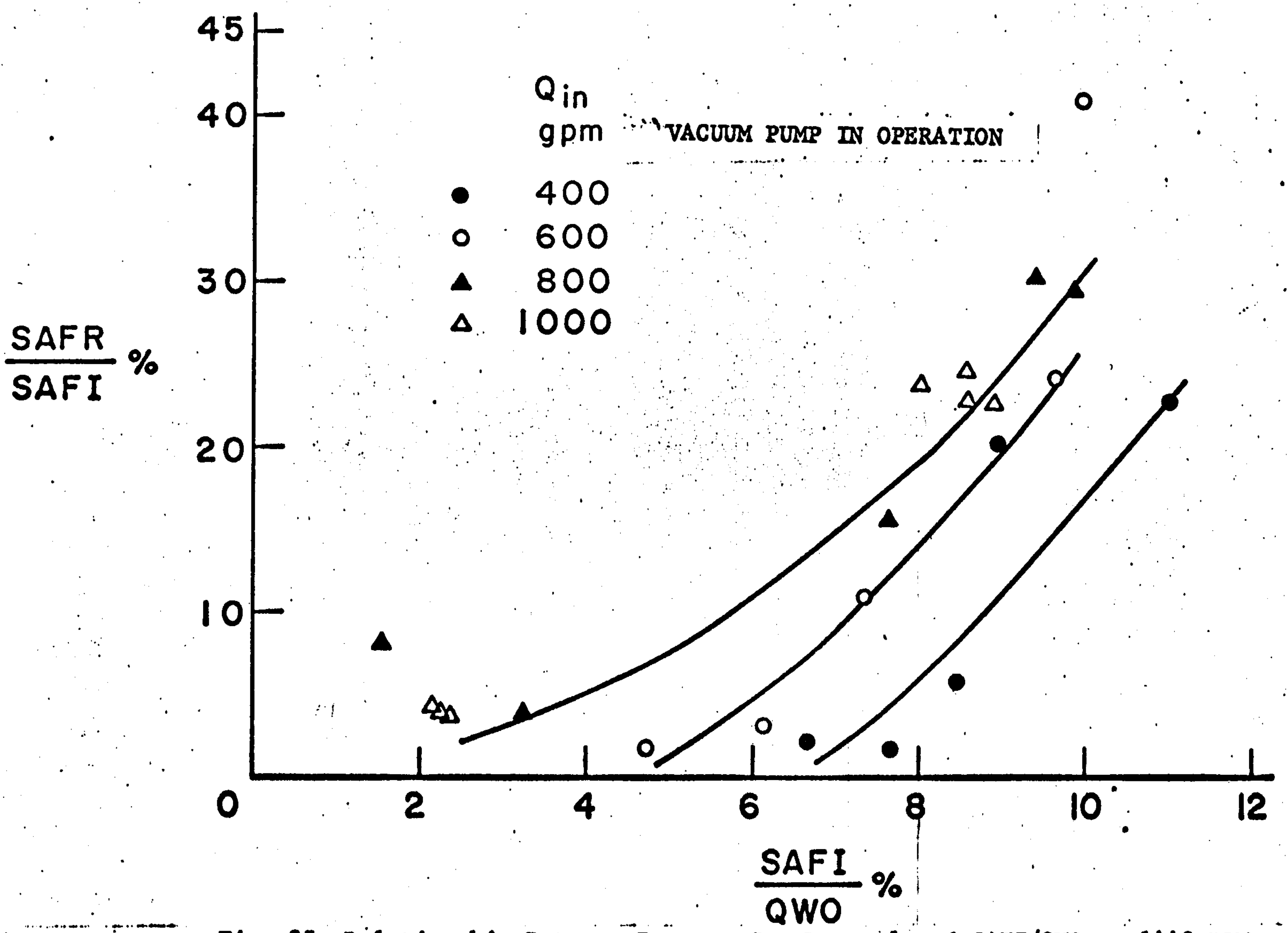


Fig. 35 Relationship Between Percent Gas Removal and SAFI/QWO at 1440 RPM

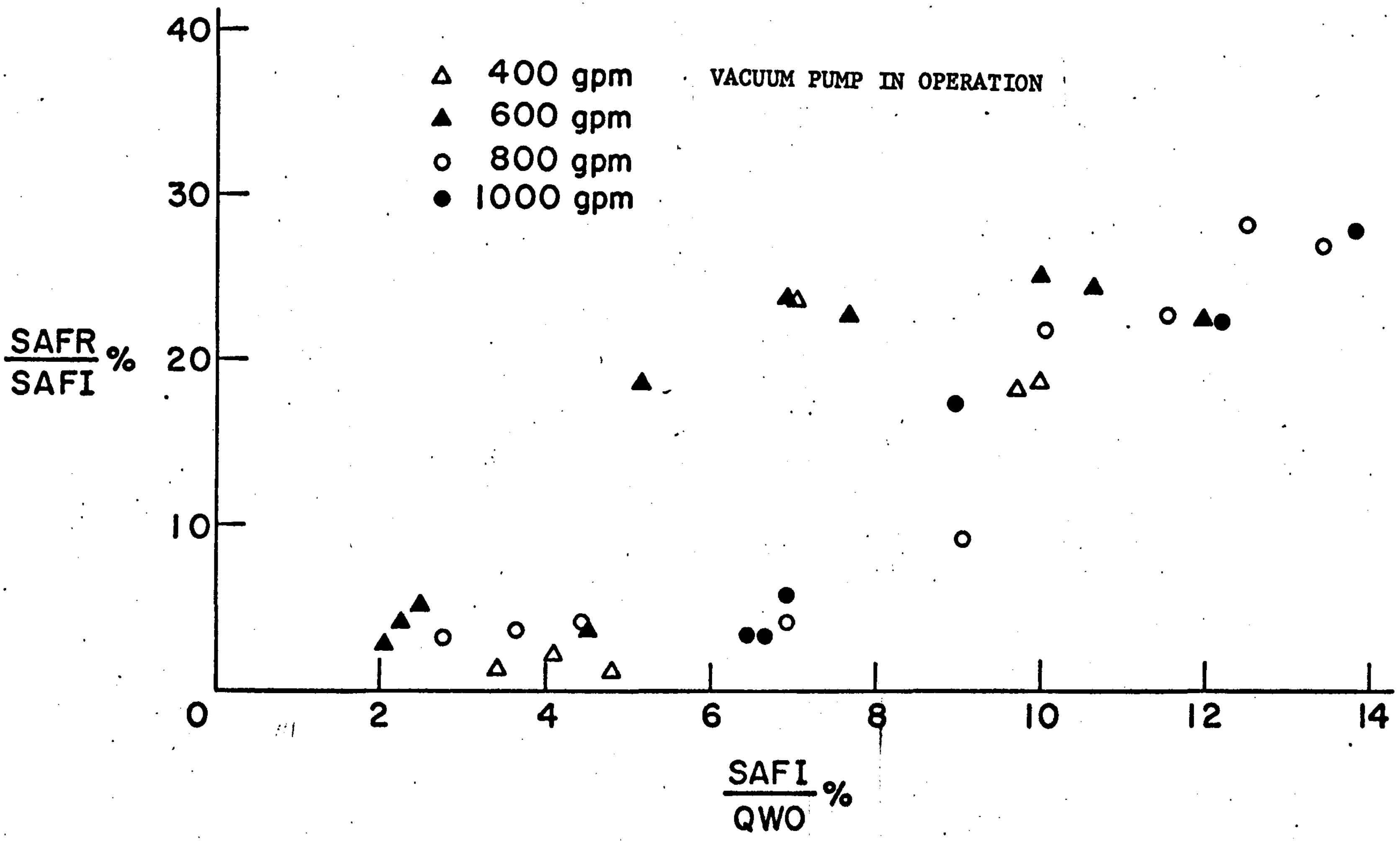


Fig. 36 Relationship Between Percent Gas Removal and SAFI/QWO at 1200 RPM

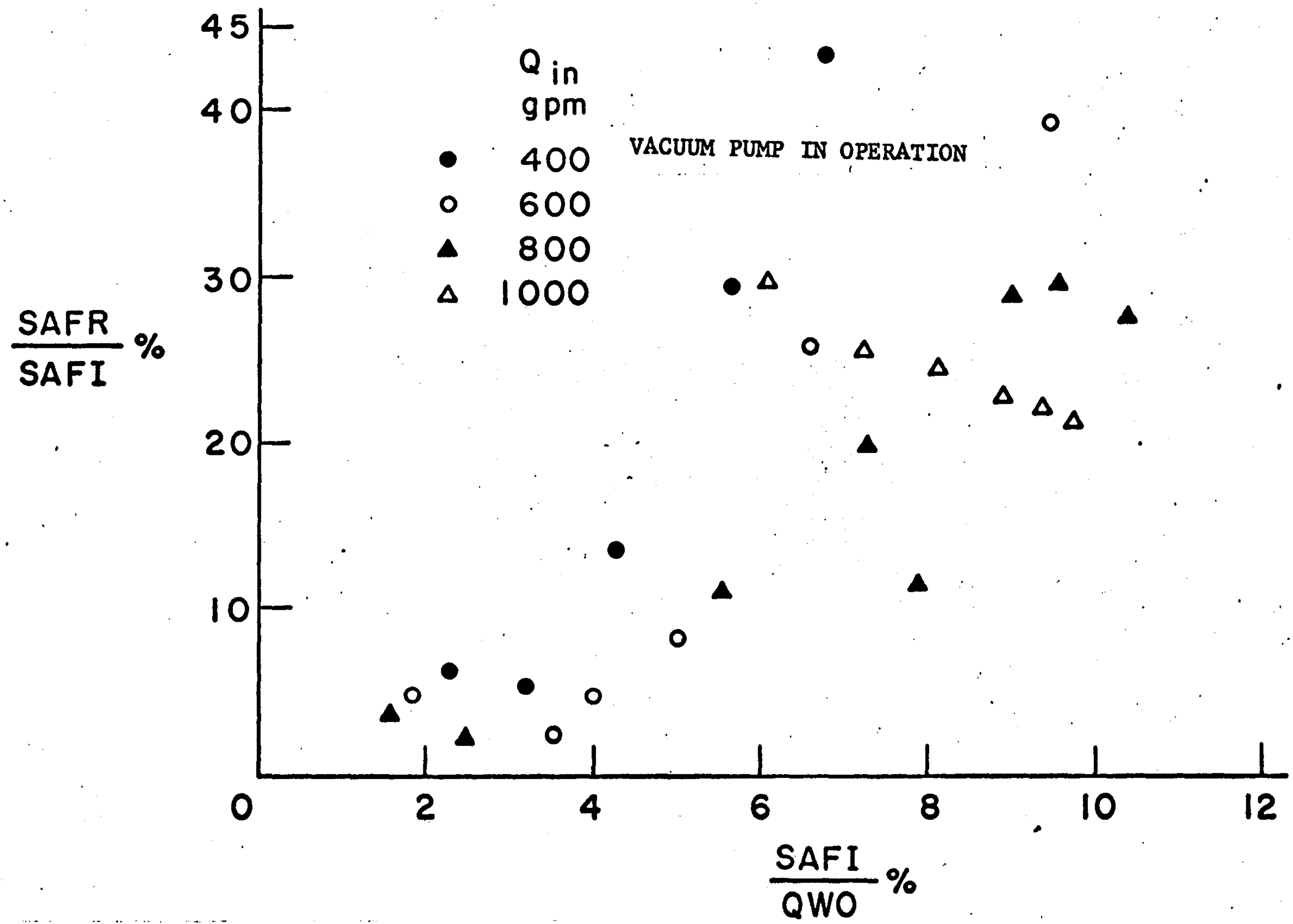


Fig. 37 Relationship Between Percent Gas Removal and SAFI/QWO at 1000 RPM

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
°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, $gH/(2\pi RPM/60)^2 D^2$
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

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VITA

Rana P. Gupta was born in District Sialkot (now in West Pakistan) on October 1, 1937. On partition of India in July 1947, Mr. Gupta migrated to Amritsar, Punjab State, India, where he had his early education at the D.A.V. High School and the Hindu Sabha College. Mr. Gupta got his Bachelor's degree in Civil Engineering from the Punjab Engineering College, Chandigarh, in April 1960.

After working for about five months in the Cost Control Directorate of the Central Water & Power Commission, Government of India, New Delhi, he joined the Punjab Public Works Department, Irrigation Branch, where he worked for about 8-1/2 years in planning, design, construction and operation of various civil engineering structures connected with water resources, drainage, river protection works, and hydroelectric power plants. Mr. Gupta completed his Post Graduate Diploma in Civil Engineering from the Punjab University in May 1969 and joined Lehigh University as a Graduate Research Assistant in September 1969 in the Fritz Engineering Laboratory, Department of Civil Engineering.

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