FLOODING VELOCITIES IN BUBBLE PLATE COLUMNS

Thesis for the Degree of M.S.

MICHIGAN STATE COLLEGE

Charles Carleton Sisler

1954

This is to certify that the

thesis entitled

FLOODING VELOCITIES IN BUBBLE PLATE COLUMNS

presented by

Charles Carleton Sisler

has been accepted towards fulfillment of the requirements for

Master's **degree in** Chemical Engineering

Carl Wagner
Major professor

Date May 27, 1954

O-169

FLOODING VELOCITIES IN BUBBLE PLATE COLUMNS

By

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1954

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ACKNOWLEDGEMENT

The author is indebted to Dr. Carl M. Cooper for his invaluable guidance, to Mr. William Clippinger and Mr. Kenneth L. Turbin for their assistance in the installation and modification of the experimental equipment, and to Mr. R. F. Romell, of the Vulcan Copper and Supply Company, and Mr. R. C. Jente, of the Monsanto Chemical Company, for their help in the compilation of the bibliography.

TABLE OF CONTENTS

INDEX TO FIGURES AND TABLES

INTRODUCTION

The capacity of a bubble plate column is usually limited by the quantity of vapor that can rise through the column without causing some undesirable effect. In many cases the maximum allowable vapor velocity is the velocity above which the liquid will no longer flow down from plate to plate in a normal manner, and the column is said to flood. In other cases the specifications for the overhead product from the column may necessitate complete freedom of contaminants that are present in the liquid, and the allowable vapor velocity is one that will result in no appreciable entrainment of liquid in the vapor. Other undesirable effects that sometime arise from excessive vapor velocities are channeling of vapor through only a portion of the bubble caps on a plate and dumping of liquid through inactive caps.

Economic considerations dictate that a column should be designed with as small a diameter as is consistent with satisfactory operation at the design capacity. Also, a column that is grossly oversized in diameter may have unstable plates, and the dumping of liquid through inactive caps may result in a low distillation efficiency. (27) Yet the only methods available for calculating the maximum allowable vapor velocity, and hence the diameter of the column, are empirical, and there is no general agreement as to which of the methods gives the most reliable estimate of allowable velocity.

All the methods in common use today are related to the "F-factor", which is defined as:

$$F = V\,(d_v/d_l)^{0.5}$$

where V is the superficial vapor velocity, based on column cross-section, in feet per second, and d_v and d_l are the vapor and liquid densities, respectively, in pounds per cubic foot.

One design procedure consists of the assumption of a vapor rate, calculation of the pressure drop through the plates, and selection of a plate spacing such that the liquid backup in the downspouts will be high enough to permit liquid downflow against the pressure drop. The F-factor enters this procedure, because the commonly used methods calculate that part of the pressure drop which is due to flow of vapor through the risers and caps as proportional to the square of the vapor velocity. Expressed as head of liquid, this pressure drop is calculated as proportional to $V^2 d_v/d_l$, which is F^2. (12, 15, 17, 20, 29)

Other procedures in common use today are based upon entrainment considerations. Most of the methods are intended to permit calculation of a vapor velocity such that entrainment is negligible, or else a velocity that is typical of commercial practice. (8, 9, 28, 29, 46, 47, 57) Since increased vapor velocity, up to a certain point, results in increased plate efficiency despite the increased

entrainment, one equation has been proposed as a means of estimating the vapor velocity at which distillation efficiency will be at a maximum. (19) None of these methods is purported to permit calculation of the vapor velocity at which the column will flood.

The methods based on entrainment agree in that the calculated vapor velocity is proportional to the minus one-half power of the vapor density, hence F would be constant. In some methods other variables, such as liquid density, interfacial tension, plate spacing, and bubble cap slot area are also introduced.

The objective of this study was to determine the flooding velocity of a pilot-plant sized distillation column at different vapor densities to ascertain whether the flooding took place at a fixed value of F.

Using steam and water in the experimental column, the flooding velocity was determined at three different pressure conditions: atmospheric, 40 psia., and at about 3 or 4 psia. The F-factor at which flooding took place decreased with decreasing vapor density. The pressure drops observed were not proportional to F^2, except at constant vapor density. At constant F the pressure drop increased with decreasing vapor density. These observations suggest a need for improvement of methods for predicting pressure drop through bubble plates.

As the factors that contribute to the flooding of bubble plate columns are numerous and interacting, a brief survey of pertinent literature follows.

SURVEY OF PREVIOUS STUDIES

Allowable Vapor Velocity

Although the present methods for the calculation of allowable vapor velocity leave much to be desired, they are a substantial improvement over the rules-of-thumb developed in the early days of continuous fractionation in bubble plate columns. In 1922 Peters (38) recommended a maximum superficial velocity of 1 to 1.3 feet per second. In 1929 Chillas and Weir (11) advocated the use of higher velocities, and suggested that baffles be installed to decrease entrainment. Commenting on their paper, Peters said, "We found that really the limit is not the velocity at all . . . It's the pressure drop in almost every case." Badger and McCabe (2) state that the vapor velocity, in feet per second, ordinarily should be equal to the distance between plates, in feet.

Souders and Brown (46, 47) stated that the vapor capacity of a column was usually limited by the quantity of entrainment that could be tolerated. They proposed a theoretical equation containing an empirically derived constant for calculation of the maximum allowable vapor velocity:

$$W = C \left[d_v(d_l - d_v) \right]^{0.5}$$

where W is the mass velocity of the vapor, in pounds per hour per square foot, C is a constant, and d_v and d_l are vapor and liquid densities, respectively, in pounds per

cubic foot. Theoretically, with proper evaluation of the constant, this is the equation for the mass velocity of vapor that would just suspend a spherical drop of liquid against the force of gravity, less bouyancy. They evaluated the constant from operating data for a number of commercial columns, and published a graph showing the value of C for various plate spacings. Two curves were presented for two different surface tensions. Later Brown (8) modified the graph by adding more curves for various surface tensions.

Carey (9) published a similar equation,

$$V = K \left[(d_l - d_v)/d_v \right]^{0.5}$$

which is the same as the Souders and Brown equation except that both sides have been divided by the vapor density, to give an expression for allowable linear velocity rather than mass velocity. Tabulated values of the constant K were given for various plate spacings and liquid seals. Carey mentioned some of the complexities other than entrainment that result from high vapor velocities, such as change in the type of vapor-liquid contact, froth buildup, jetting or spouting, and change in weir and downspout performance.

Edmister (18) presented a graph based on the work of Souders and Brown (47) and Peavy and Baker (36) for estimation of allowable vapor velocity as a function of vapor density, liquid density, liquid seal, and the plate spacing less the depth of liquid on the plate. He

recommended it for preliminary design only. Clay, Hutson, and Kleiss (13) compared a capacity curve calculated by the Edmister method with their curve for 90 percent of experimental flooding load. The average agreement was better for the Edmister method than for the Souders and Brown method, but the Edmister curve was the wrong shape, giving an estimated capacity that was too low at high pressures and too high at low pressures.

Kirkbride (29) recommended that the diameter of a column be calculated so that entrainment is nil, and that plate spacing be calculated afterward so that the liquid head in the downspout is adequate. He based the diameter on a maximum allowable vapor velocity calculated by the equation:

$$V = 3.5\ (T/MP)^{0.5}$$

where V is the allowable velocity in feet per second, T is the vapor temperature in degrees Rankine, M is the molecular weight of the vapor, and P is the absolute pressure in pounds per square inch. It is to be noted that the term T/MP is proportional to the reciprocal of the vapor density if the vapor is treated as an ideal gas. Kirkbride says this equation is conservative, and that the calculated velocity can be exceeded by 100 percent without entrainment becoming important, provided the plate spacing is adequate to handle the liquid load.

Eduljee derived an expression for estimation of

the vapor velocity at which distillation efficiency is maximum, in contrast to the velocities calculated by the above methods, at which entrainment is minimum. His equation is:

$$d_v V^2 = 0.375$$

As entrainment is appreciable at the velocity calculated by this method, the method cannot be used in cases where entrainment would affect some quality of the product such as taste, odor, or color.

Some designers estimate the maximum allowable vapor velocity in terms of a modification of the factor F and define the factor as $V(d_v)^{0.5}$, with no mention of the liquid density. (28) Since the range of liquid densities normally encountered in distillation columns is quite narrow compared to the range of vapor densities, a design procedure that consistently neglects the liquid density (tantamount to considering it to be constant) would not differ a great deal from a procedure that takes liquid density into consideration.

Zenz (57) advocates calculation of the vapor capacity per bubble cap rather than the superficial velocity based on column cross-section. He offers the equation:

$$V_c = \frac{S_o^{1.5} W(d_l/d_v)^{0.5}}{2.43}$$

where V_c is vapor capacity in CFM per cap, S_o is the slot opening in inches, W is the total slot width per cap, and

d_l and d_v are the liquid and vapor densities, respectively, in pounds per cubic foot. In order to use this equation a designer must assume a slot opening. Zenz mentions that slots should be blown open no less than 0.3 inches and no greater than 1.25 inches. It seems that a designer would require specific experience upon which to base a choice of slot openings, as the above limits represent an eightfold variation in cap vapor capacity.

Pressure Drop

Pressure drop is important in a study of column flooding since it affects the height of liquid backup in the downspouts, and hence affects the flooding velocity at any given plate spacing.

Cicalese, *et al.*, (12) present equations for calculating the pressure drop for vapor flow through the cap riser, reversal of flow, flow through the dry slots, and flow through the liquid on the plate. Dauphine (15), Edmister (17), and Eld (20) also give methods for calculating the pressure drop. All these methods indicate that the items contributing to pressure drop can be grouped into two categories, one of which is proportional to F^2, the other of which is a function of the slot submergence and the effective density of the fluid.

Rogers and Thiele (42) discuss the effect of the relative height of the weir and the cap slots and the effect of foam height on pressure drop.

Souders, Huntington, Corneil and Emert (48) concluded that the pressure drop is influenced greatly by the head of fluid (usually a mixture of liquid and vapor) required to pass the liquid into the downspout.

Entrainment

Entrainment can be classified into several basic types: small droplets entrained from the liquid surface at moderate vapor velocities, large drops splashed by a jetting action at higher velocities, and froth resulting from the foaming characteristics of the material. (1, 30, 33) Strang (50) also reported considerable re-entrainment of drops that had collected on the bottom of the plate and flowed to the edge of the vapor risers.

Small droplets have no effect on flooding, and little effect on column operation except in those cases where some quality of the product, such as taste, odor, or color, is concerned. Large drops have an appreciable effect on plate efficiency, and can contribute slightly to a tendency to flood by increasing the amount of liquid downflow. Large quantities of froth can cause flooding either by interfering with the flow in the downspouts or by filling the space between plates, since the hydraulic gradient to cause flow across the plate is much higher for froth than for liquid. If appreciable froth is entrained in the vapor flow to the next plate, a decrease in plate efficiency and a slight increase in the liquid load result. (13, 42, 48)

The type and quantity of entrainment depend upon many factors. Much has been written about the effects of superficial velocity, slot velocity, vapor density, and plate spacing. (1, 10, 25, 35, 43, 45, 50, 53, 54)

The effects of foaming tendency and interfacial tension are discussed by Kirschbaum (30, 33), White (56), and Souders and Brown (47). These effects sometimes vary in an unpredictable manner. Pyott, Jackson, and Huntington (39), working with air and kerosene, got different curves of entrainment vs. either mass velocity or linear velocity, for different temperatures. They explained this difference as due to a change in foaming characteristics. Rhodes and Slachman (41), distilling a benzene-toluene mixture, observed that entrainment went through a minimum at 60-70 mole percent benzene, without apparent change in foam or manner of boiling. The variation seemed to be in drop size. Distilling an ethanol-water mixture, they observed that foaming varied with composition. They noted entrainment due to foam rising to the next plate at ethanol concentrations higher than 30 percent. Thompson (52), working with the system ethanol-water-calcium chloride, reported that the critical vapor velocity, beyond which entrainment increased rapidly, was lower for higher ethanol concentrations. Stabnikov (49) blew air through water, solutions of sodium hydroxide, and solutions of sodium hydroxide with soap, and found that for superficial velocities below 0.25 meters per

second, entrainment was greater for foaming liquids than for non-foaming liquids; at higher velocities the converse was true.

Several equations have been derived for calculating the effect of entrainment on plate efficiency or the required number of plates. (3, 4, 14, 19, 40, 43, 47, 53) Peavy and Baker (36) found the optimum vapor velocity calculated by the method of Colburn (14) to be beyond flooding velocity in many cases. Brown and Lockhart (7) studied data from both laboratory and commercial columns, and concluded that plate efficiency levelled off at a maximum, extending in most cases over a range of vapor velocities of from 0.8 to 1.2 times those calculated by the method of Souders and Brown (47).

Weir and Downspout Design

A bubble plate column floods if the discharge weirs and downspouts fail to carry liquid away from each plate at a rate adequate to maintain steady-state conditions. If steady-state conditions at the required liquid rate can be maintained only with a very high liquid level on the plates, the column will not necessarily flood, but the pressure drop may be objectionably high (12, 48), and entrainment may be increased due to the decreased distance between the liquid surface and the plate above (39).

Methods for estimating the liquid level in the downspouts are presented by Kirkbride (29) and White (56),

both of whom itemize and discuss the various items that constitute this total backup head. As these methods do not take into consideration the possible interference of froth with downspout operation, both Kirkbride and White recommend that the plate spacing be at least twice the calculated height of liquid in the downspouts.

Kallam (27) pointed out the importance of the configuration of the discharge weir and downspout on liquid capacity. He found that a downspout bounded by a weir on one side and by the column wall on the other side had a higher capacity than a downspout with the same cross-sectional area bounded on all sides by a weir. In the latter case, liquid falling from one portion of the weir interfered with that falling from another part. He obtained curves of flooding velocity of an absorber at various oil-to-gas ratios, with several different downspout arrangements.

Souders, Huntington, Corneil, and Emert showed that a downspout can operate under three distinct conditions of fluid head: 1) at low heads, as a weir; 2) at intermediate heads, as a free-running orifice, accepting a mixture of liquid and vapor, but having sufficient vortex to allow separation; and 3) at high heads, as an orifice running full, with its capacity diminished by disengagement within the orifice.

Carey (9) mentioned the need for froth disengagement space between the bubble caps and the discharge weir. Peavy and Baker (36) suggested placing a top baffle in front of the weir so that the liquid must flow under it, as an aid to disengagement.

White (56) recommends that downspouts be deliberately over-designed, as they constitute a relatively unimportant cost item but are an important factor in flooding.

Plate Stability

A bubble plate is said to be stable if vapor issues from all the slots on the plate. A plate that is unstable, due to poor design, is characterized by a high hydraulic gradient, with the liquid at the liquid inlet end of the plate so deep that vapor preferentially flows through the shallower part of the plate. Liquid may dump through the risers of the inactive caps. As the vapor passes through a fewer number of caps than the designer intended, it flows at a higher velocity, resulting in increased entrainment. The higher velocity also causes a greater pressure drop, which further aggravates the unstable condition by increasing the liquid level in the downspouts and on the deep side of the plate. (28)

Plate instability can cause a column to flood, especially if it is a large column with a high liquid rate, when the excessive hydraulic gradient causes liquid to back up to the top of the downspout. Harrington, Bragg,

and Rhys (24) describe the difficulties encountered with several extremely large columns installed by the Standard Oil Company of New Jersey around the beginning of World War II. In addition to an excessively high liquid gradient caused by the large quantity of liquid flowing over a conventional arrangement of caps and hold-down bars, some of these columns exhibited a unique problem due to vapor cross flow. As vapor passed through caps at the liquid discharge side of the plates only, it had to cross to the opposite side of the column after it passed each plate. One column had large I-beams to support the plates, and the clearance beneath the beams was such that the velocity of the vapor cross flow was more than ten times the calculated superficial velocity. The cross flow entrained liquid from the shallow side of the plate and deposited it on the deep side. The buildup would continue for about two minutes, after which the differential pressure would become great enough to blow vapor up through the deep side of the plate, after which the cycle would repeat. Another column had a similar difficulty with vapor cross flow, but flooded due to full downspouts instead of surging.

Several methods for the calculation of hydraulic gradient and the design of stable plates have been published. (16, 21, 22, 23, 28, 51)

Eld (20) and Kallam (27) caution against designing columns larger than necessary. At relatively low vapor

rates not all the caps will be active, and liquid will dump through the risers of the inactive caps.

Flooding Velocity

Very little has been published about the experimental determination of flooding velocity.

Since this study was completed, Clay, Hutson, and Kleiss (13) have reported an investigation of the effect of load and pressure on performance of a commercial bubble plate column separating isobutane from normal butane. Flooding in their column was due to the rising of the froth level to the next plate. The downspouts worked satisfactorily, and the downflow rate had no appreciable effect on the flooding velocity. They recommend the use of the Souders and Brown method in lieu of better capacity data, and suggest multiplication of the constant by 1.33 for light hydrocarbons. This will give a curve equivalent to about 90 percent of the experimentally-determined flooding velocity.

Peavy and Baker (36) were unable to determine accurately at what velocity flooding began in laboratory investigations, as the flooding velocity varied with the rate of increase in vapor velocity. Accordingly, they recommend that columns be operated well below the flooding velocity range.

EXPERIMENTAL EQUIPMENT

A modified Model A-2 Experimental Laboratory Distillation Unit, manufactured by the Vulcan Copper and Supply Company, of Cincinnati, Ohio, was used for this study. The column of this unit is made from 8-inch seamless copper pipe, and contains 24 bubble plates spaced on 6-inch centers. Each plate has two 3-inch Vulcan pressed bubble cap assemblies.

Total slot area is 5.54 square inches. The cross-sectional area of the downpipes is 3.3 square inches, and the effective length of both the distributing weir and the overflow weir is about 6.5 inches. The effective cross-sectional area of the column, allowing for the downpipe, is about 0.323 square feet.

Certain modifications of auxiliary equipment were required for this study. The experimental objective was the determination at three different pressures of the vapor velocity that would cause the column to flood, as evidenced by the differential pressure across the column. A steam and water system was used to avoid the complications of composition changes.

Accordingly, the calandria was blanked off and steam was introduced directly into the bottom of the column. The perforated sparger was removed. Water from the bottom of the column was pumped through a rotameter to the top

plate of the column to provide a metered liquid downflow. Figure 1 is a schematic diagram of the equipment and piping.

The valving arrangement was necessarily different for operation under the three pressure conditions: atmospheric, pressure, and vacuum. For the atmospheric runs the atmospheric vent valve V-6 (referring to Figure 1) and needle valve V-5 were open to keep the condenser at atmospheric pressure. Valve V-2 was open so that condensate from the condenser would flow to a barrel on a scale, to be weighed. Valve V-4 was open, so that any water accumulating in the bottom of the column, due to heat losses, would be bled off to another barrel on a scale. The liquid level controller in the bottom of the column and control valve V-9 controlled this flow. All other valves were closed, except V-10, by which the downflow rate was controlled manually.

For the runs under pressure, valve V-7, connecting with a compressed air supply, was open. Condensate from the condenser was routed through valve V-3 and relief valve RV-1. A pressure of 25 psig., as indicated by pressure gauge PG-1 at the bottom of the column, was maintained by careful adjustment of needle valve V-5 and relief valve RV-1. The relief valve handled a mixture of air and water. Bottom accumulation was again discharged through valves V-4 and V-9. All other valves were closed except V-10, by which the

downflow rate was controlled manually.

For the vacuum runs, valve V-8, connecting with a vacuum pump, and atmospheric vent valve V-6 were open. Needle valve V-5 was just cracked, to permit a small amount of air to be drawn into the piping to result in a stable pressure at the vacuum pump. Condensate from the condenser was brought through valve V-1 to combine with water from the bottom of the column on the suction side of the pump. All the condensate was discharged through valves V-4 and V-9. All other valves were closed except V-10, by which the downflow rate was controlled manually.

A larger condenser was installed in place of the one that came with the equipment. As the unit installed was a two-pass baffled heat exchanger, not designed as a condenser, it was connected so as to condense inside the tubes, and cooling water was piped to the shell. It was installed in a horizontal position, with the vapor line from the top of the column connected to the upper half of the tube bundle. A portion of the vapor line was raised to prevent condensate from running back into the column.

The separator, where non-condensibles disengaged from the condensate, consisted of a vertical section of 3-inch pipe, fed at a 3-inch tee in the middle.

A length of Saran tubing was installed vertically, as shown in Figure 1, connecting the top of the separator with the water piping below the bottom of the column. This

tubing and the gauge glass in the bottom of the column served as the two legs of a manometer to indicate the pressure drop through the column in inches of water. This arrangement gave greater sensitivity than did the mercury manometer originally provided with the distillation equipment. Also, trouble with the mercury manometer was experienced in early exploratory runs, as vapor condensed in the connecting tubing unless the air purge rates were increased to a point that they resulted in an appreciable pressure drop in the tubing.

Steam was supplied by the College power plant at a nominal pressure of 100 psig. Unfortunately, the piping between the power plant and the Chemical Engineering Building, where the experimental equipment was located, was so small that the pressure dropped considerably at the flow rates used in this study.

A Foxboro Model 40 recording flow controller was installed to control the steam input to the column. The flow was measured by the differential pressure across a 1.481-inch diameter orifice installed in a 3-inch schedule 40 pipe. The pressure in the orifice run was regulated by a Fisher Model 92-A pilot-operated reducing valve.

The condensate streams from the condenser and the bottom of the column were collected in open steel barrels on platform scales.

Figure 2 is a photograph of the equipment.

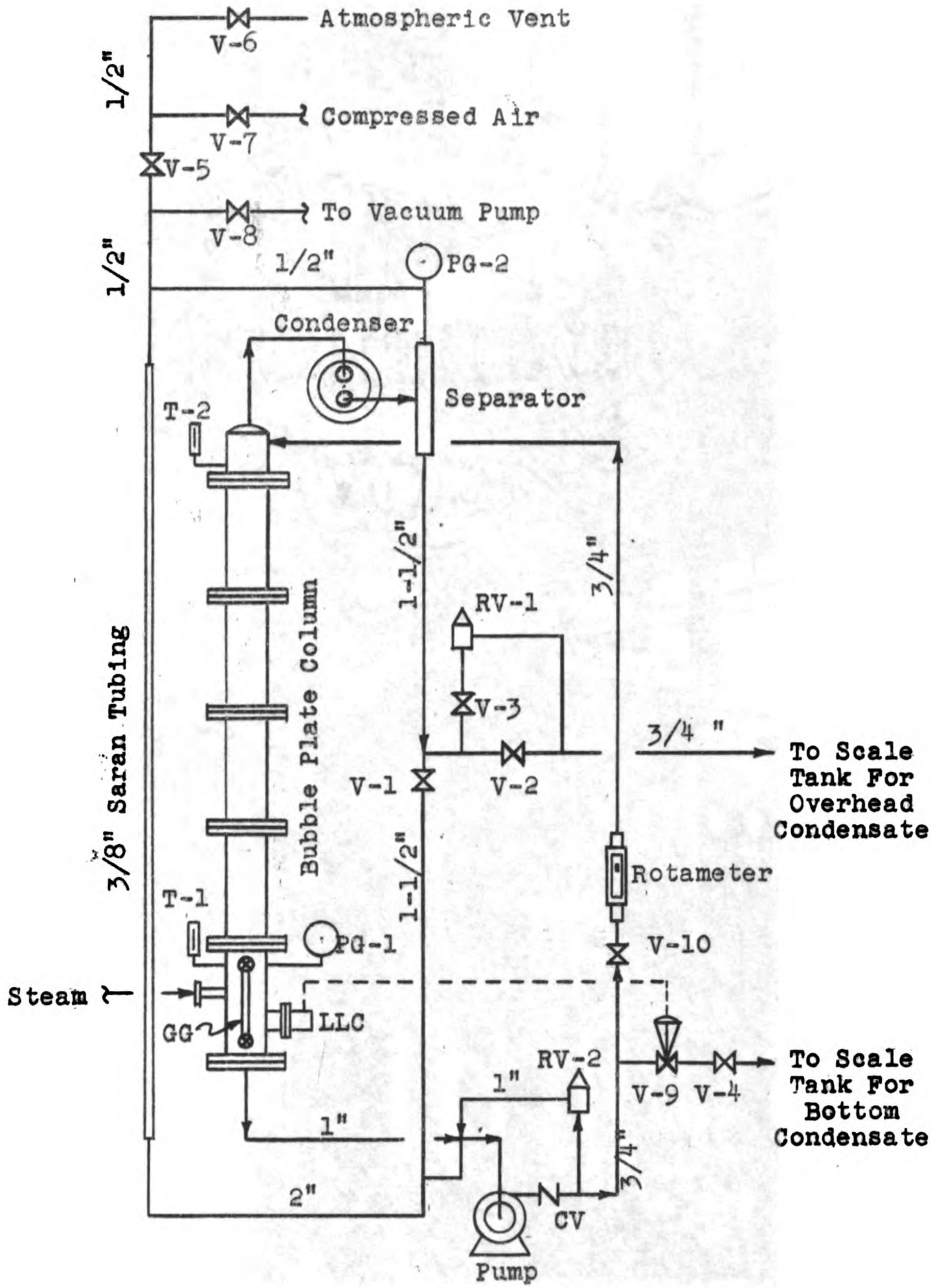

Figure 1. Schematic Diagram of Equipment and Piping.

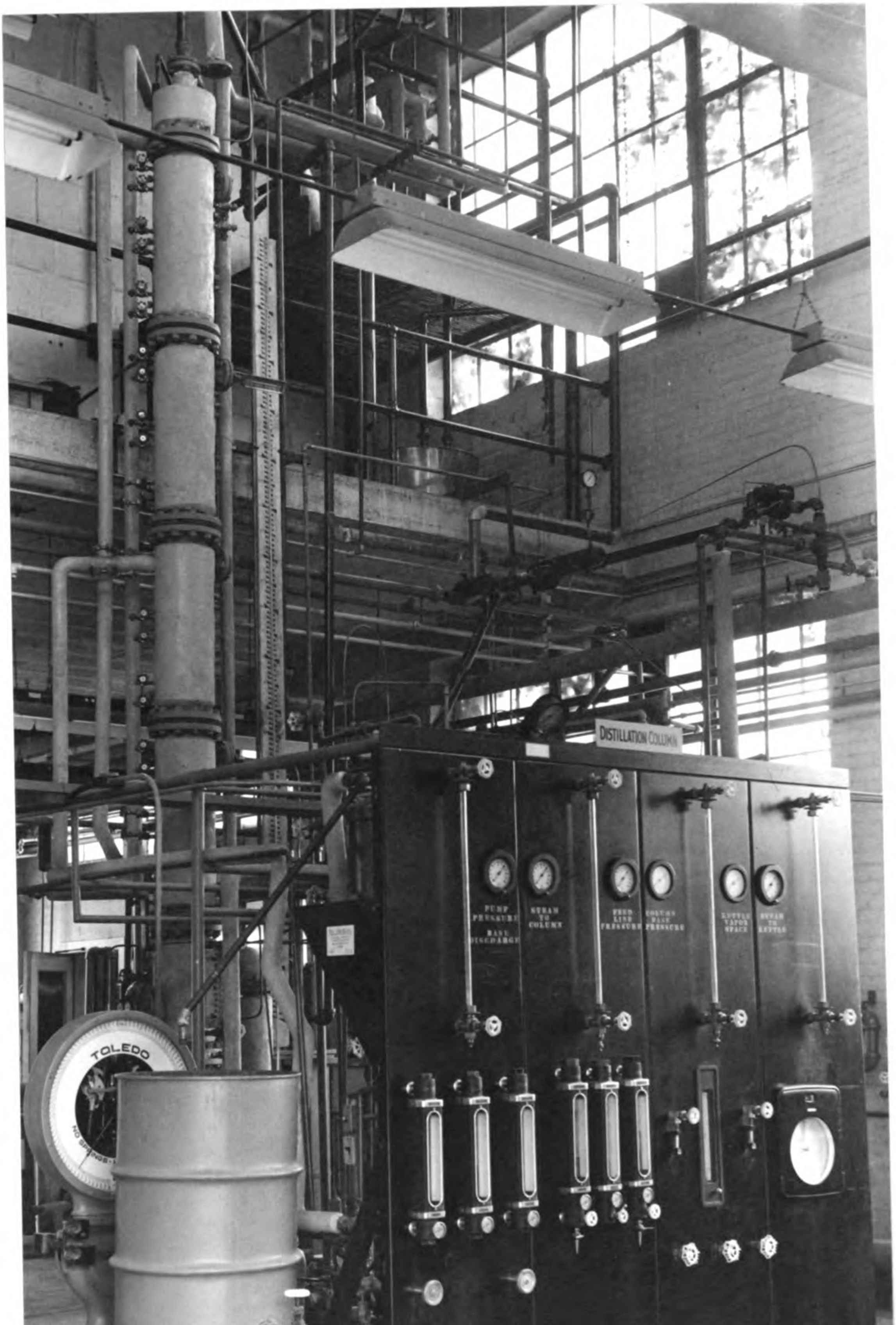

Figure 2. Photograph of Equipment

PROCEDURE AND CALCULATIONS

Preliminary runs indicated the need for increasing the steam rate in small increments, as the column would flood after a large increase, even at relatively low steam rates.

Preliminary runs also indicated that the column could not be flooded at a pressure much higher than 25 psig. due to the pressure drop in the steam line from the power plant. The series of pressure runs, originally planned for 60 or 70 psig., was accordingly run at only 25 psig.

Data were entered in the operating log at frequent intervals. The timing varied, but generally entries were made at 1, 3, 5, 10, 15, 20, 25 and 30 minutes after the steam control point was changed. Some runs were observed for longer periods if erratic behavior justified doing so. Some of the runs, in which the column flooded, lasted only a minute or two.

The following data were recorded at these frequent intervals: time since controller setting, weight of overhead condensate collection drum, weight of bottoms condensate collection drum, height of water in both sides of the manometer (the Saran tubing and the gauge glass on the column), temperatures at bottom and top of column, downflow rotameter reading, pressure reading at the base of the column and at the separator. Once during each run the

following data were also noted: time run started, steam controller setting, pressure of main steam line and of steam at orifice. Thermometers were read to the nearest half degree C., pressure gauges to the nearest pound, and manometer legs to the nearest tenth of an inch.

The data that were obtainable at the main floor level were usually all obtained within a period of one minute. The temperature at the top of the column and the pressure at the separator were read less frequently, and usually about a minute before the other items.

The bottoms condensate collection drum was on a dial-type scale, which was read at exact time intervals, usually of 5 or 10 minutes, timed by a stop watch. The collection drum for overhead condensate (in the atmospheric and pressure runs only) was on a beam-type scale. The flow rate to this drum was determined by timing the interval between the rising of the beam at two settings, usually 10 pounds apart. Several time and weight readings were always taken and the increments were checked for uniformity. This precluded gross errors in scale or watch readings, and also ascertained that steady state conditions had been reached before the weight data were taken.

As the original log contained over a hundred pages, it is not reproduced here in detail. Tables IV, V, and VI, in the Appendix, are a consolidation of the log, with the data used in the calculations on one line for each

steam setting. In transferring the data from the log to the consolidated tables, the condensate collection rate for each drum was converted to pounds per hour by straightforward arithmetic that requires no explanation. A pressure drop figure that was typical for the period during which the rates were determined was selected for each run. In the few cases where the pressure drop surged more than one or two inches of water, two figures were entered in the table, representing the extremes.

Tables I, II, and III in the Appendix develop the F-factor for each run, for conditions at the bottom of the column. The bottom of the column was chosen because both the vapor rate and the liquid downflow rate are highest at the bottom, due to heat losses. Hence, in this study, flooding conditions were probably first reached at the bottom plates.

The runs have been designated by two letters and a number. The first letters (A, P, or V) signify atmospheric, pressure, or vacuum. The second letters (L or H) signify a low or high liquid downflow rate. The numbers indicate sequence.

In all the runs at the "low" downflow rate, the downflow reading of the rotameter was 12 (arbitrary units). At the high downflow rate, the rotameter read 24. These rates were determined to be 304 and 671 pounds per hour, respectively. For the atmospheric and pressure runs, wherein

any condensate that accumulated at the bottom was withdrawn and weighed separately, this accumulation was added to the metered downflow rate. For the vacuum runs no such correction was possible.

The steam input, in pounds per hour, is the total condensate rate, since at steady state conditions, the steam input and the condensate discharge must be equal. A graph comparing condensate rates with the steam controller setting, included in the Appendix, shows some scatter. The controller setting and this graph were used to estimate the steam input rate in those cases where the column flooded rapidly and no condensate rates were obtained.

The quality of the steam supply was not determined experimentally. A drain leg and trap were located just ahead of the regulating valve for the orifice run. As steam normally leaves the power plant with not more than 5 degrees of superheat (according to power plant personnel) and passes through several hundred feet of pipe between buildings, it seems safe to assume that the stream was saturated just before it was throttled by the regulator, at whatever pressure existed at that point during any given run. The steam was also assumed to be dry, although it is quite possible that some water was entrained at high rates.

If the steam was saturated at line pressure before throttling by the regulator and the automatic control valve, it was superheated when it entered the column. It any condensate that accumulated at the bottom was withdrawn and weighed separately, this accumulation was added to the metered downflow rate. For the vacuum runs no such correction was possible.

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If the steam was saturated at line pressure before throttling by the regulator and the automatic control valve, it was superheated when it entered the column. It

would accordingly vaporize a slight amount of water from either the bottom of the column or the bottom plate, and become saturated at the conditions prevailing there. Thus for every pound of steam input, slightly over a pound would rise through the lower part of the column.

Run A-L-1 is cited as an example of a typical calculation:

Steam line pressure gauge reading: 101 psig.

Corrected pressure, from gauge calibration in Appendix: 92 psig.

Absolute pressure: 92 + 15 = 107 psia.

Bottom temperature, to nearest half degree C: 102.0

Bottom temperature, to nearest degree F: 216

As throttling is isenthalpic, it was possible to calculate the quantity of saturated steam rising in the bottom part of the column from enthalpy data, taken from steam tables (Keenan, J. H., and Keyes, F. G., Thermodynamic Properties of Steam, John Wiley and Sons, New York, 1936).

$$h_g \text{ at } 107 \text{ psia.} = 1{,}188.4 \text{ Btu./lb.}$$

In its final condition, the steam was saturated at the bottom temperature of 216 degrees F.

$$h_g \text{ at } 216^{\circ}\text{F.} = 1{,}151.9 \text{ Btu/lb.}$$

The decrease in enthalpy of the steam, 36.5 Btu/lb., was used to vaporize water at 216°F. to saturated steam at 216°F. This heat of vaporization is

$$h_{fg} \text{ at } 216^{o}F. = 967.8 \text{ Btu/lb.}$$

For every pound of steam input, the amount of water vaporized in the bottom of the column is

$$36.5/967.8 = 0.038 \text{ lb.}$$

and the steam rising in the column is

$$1 + 0.038 = 1.038 \text{ lb.}$$

The steam rate rising in the column is then

$$(1.038)(251) = 261 \text{ lbs./hr.}$$

The specific volume of the saturated steam is also taken from the steam tables:

$$v_g \text{ at } 216^{o}F. = 24.90 \text{ cu. ft./lb.}$$

The superficial velocity, based on a cross-sectional area of 0.323 sq. ft., is calculated

$$V = (261)(24.90)/(0.323)(3600) = 5.59 \text{ ft./sec.}$$

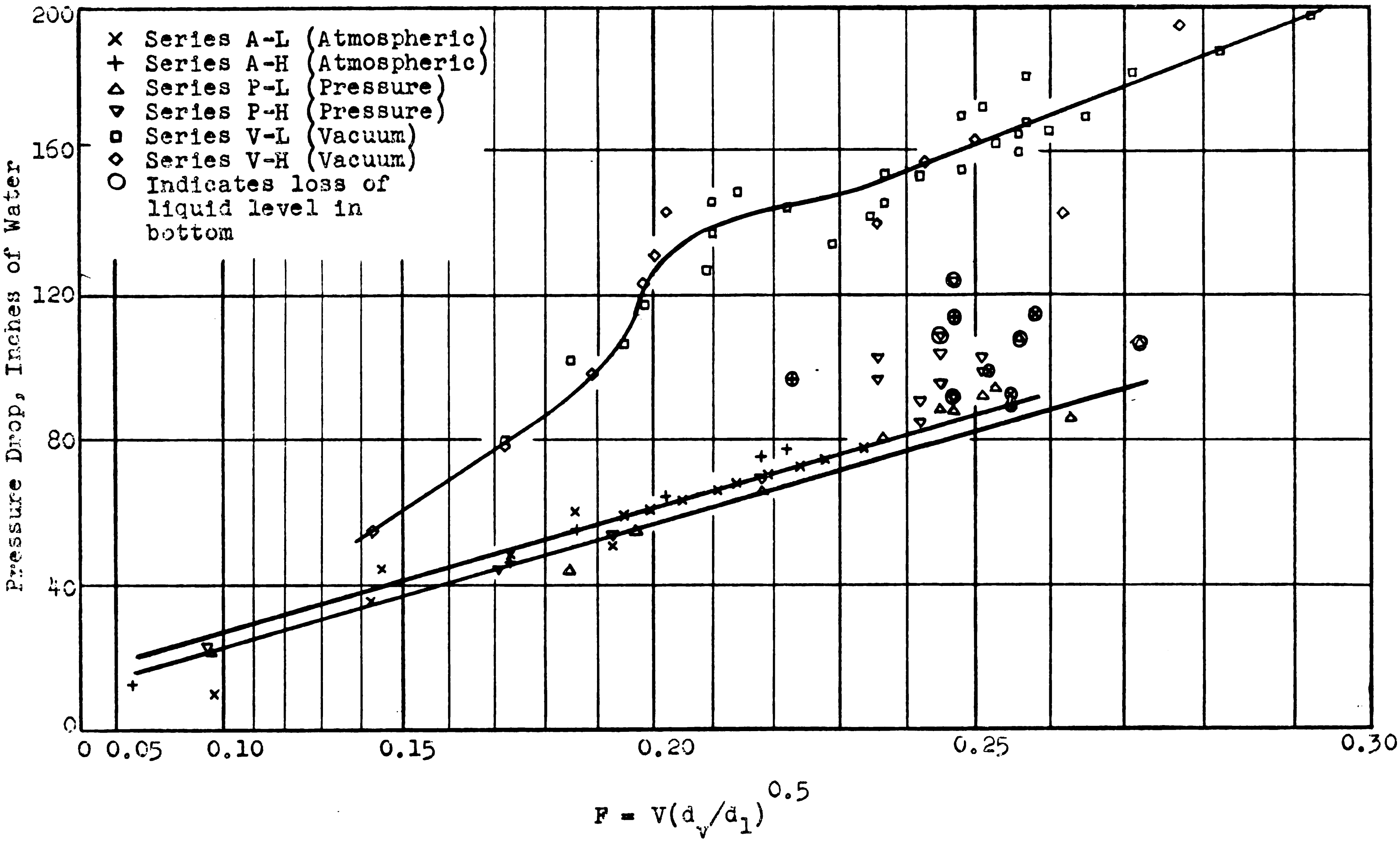
The factor F is calculated

$$F = V(d_v/d_l)^{0.5} = V(v_l/v_v)^{0.5}$$
$$= (5.59)(0.01674/24.90)^{0.5} = 0.142$$

The above calculations were repeated for each run.

Immediately following is Figure 3, which shows column pressure drop vs. the factor F for the atmospheric, pressure, and vacuum runs.

Figure 3. Pressure Drop vs. F-Factor



DISCUSSION OF RESULTS

In Figure 3 the abscissas were plotted on a scale proportional to F^2 rather than F, as the literature indicates that pressure drop should be linear with respect to F^2. (12, 17, 20) The data for runs at any one of the three pressures exhibit this linearity below the flooding point, but the data for the three series do not coincide. At any given value of F the pressure drop for the atmospheric series is slightly higher than for the pressure series, and the pressure drop for the vacuum series is considerably higher.

During several of the atmospheric and pressure runs, flooding was evidenced by the loss of the liquid level in the bottom of the column. Data points for those runs have been encircled on Figure 3, to denote definite flooding. Some other runs, especially in the pressure series, showed erratic pressure drops but gave no visible indication of flooding.

Apparently the column was flooded during most of the vacuum runs, although the author was unaware of the flooded condition at the time. There was no visible indication of improper operation. The pressure drop was high, but steady and reproducible. The condenser discharge piping was connected with the bottom of the column during the vacuum runs, so that overhead condensate and any bottom

accumulation could be pumped out of the system, hence a normal level was maintained in the gauge glass at the bottom of the column.

A closer inspection of the pressure drop data indicates that the column must have been flooded during many of the vacuum runs. Differential pressures as high as 198 inches of water were recorded. Since the total distance between the top plate and the bottom plate was only 138 inches, water pumped onto the top plate could not have come down the column, and must have gone up the vapor line and through the condenser. The manometer was connected so as to give the total pressure drop through the column, the vapor line, and the condenser, but the pressure drop through the vapor line and the condenser would be negligible unless they were partially flooded.

In Figure 3 the pressure drop data for the vacuum runs show a hump in the F-factor range of 0.19 to 0.21, with pressure drops ranging from 100 to 150 inches of water. During the runs in this range the water level probably rose in the top section of the column above the top plate, and into the vapor line. At higher F-factors the data lie along a straight line, but with considerable scatter.

Under vacuum, the column apparently started to flood at an F-factor of about 0.19 or 0.20, compared to 0.22 for operation at atmospheric pressure or 0.24 for operation at 25 psig.

The maximum pressure drop at which the column could be operated without flooding appears to be 80 or 90 inches of liquid, or perhaps 100 inches under vacuum conditions.

In the atmospheric and pressure runs, slightly higher F-factors were permissible at low liquid rates than at high liquid rates. In the vacuum runs, the flooding point was not determined with sufficient accuracy to detect the effect of liquid rate. This relationship should prevail under any conditions, however, as a higher liquid rate causes a higher head over the discharge weirs, a higher friction head in the downspouts, and a higher head over the distributing weirs.

SUMMARY

The effect of vapor density on flooding velocity in a pilot-plant sized bubble plate column was investigated by flooding the column at three different pressures, using a steam and water system.

Design methods in common use today predict that the column should flood at a constant value of the F-factor, and also predict that the pressure drop through the column (not flooded) should be a linear function of F^2.

Experimentally, the linear relationship between pressure drop and F^2 was observed only at constant vapor density. At constant values of F, a decrease in vapor density resulted in an appreciable increase in pressure drop. A decrease in vapor density accordingly lowered the value of F at which flooding took place, since comparable pressure drops were obtained at lower values of F.

RECOMMENDATIONS FOR FUTURE WORK

The results of this study indicate a need for an improved method of predicting the pressure drop through bubble plates. Since the equipment and procedure in this study were not devised for the purpose of obtaining exact information on the relationship between pressure drop and vapor density, future work should begin with a preliminary investigation designed to confirm or refute the observations of this study.

This preliminary investigation could utilize the same bubble plate column, with the addition of certain accessories. The use of air and water at room temperature is recommended, rather than steam and water. This change will reduce the amount of mass transfer in the column, hence should make the data more reliable.

The pressure drop data should be taken across one plate, or across a section of the column short enough that the change in absolute pressure is of negligible magnitude. The test plate (or section) should be located midway in the column, so that the air will be saturated and in approximate thermal equilibrium with the water. It should be equipped with:

1) A sloping manometer, filled with a light liquid such as water or Meriam red oil, connected with short sections of air-purged tubing, to read differential pressure;

2) An accurate pressure gauge or a large mercury manometer, to indicate gauge pressure;
3) A thermometer; and
4) A gauge glass to show liquid level on the plate.

Water could be pumped onto the top plate through the reflux rotameter. A suitable rotameter, a thermometer, and a pressure gauge should be installed in the air piping. Barometer readings should be taken, to permit accurate calculation of the air density in the test section.

If the preliminary pressure drop study confirms the observations made in this study, further investigation will be needed to develop an accurate correlation between pressure drop, vapor rate, vapor density, and liquid density. This would probably involve an extensive study of pressure drop through dry bubble caps and through wet caps with various liquids, submergences, and cap layouts.

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APPENDIX

TABLE I. SUMMARY OF DATA AND CALCULATIONS, ATMOSPHERIC RUNS

Run No.	Downflow Lbs./Hr.	Steam Input Lbs./Hr.	Calculated Steam Rate at Bottom Lbs./Hr.	Specific Volume at Bottom Cu. Ft./Lb.	Superficial Velocity Ft./Sec.	$F = V(d_v/d_1)^{0.5}$	Differential Pressure In. of Water
A-L-1	323	251	261	24.90	5.59	0.142	35.6
A-L-2	322	258	268	24.90	5.73	0.145	44.5
A-L-3	317	313	324	24.45	6.80	0.173	48.5
A-L-4	317	345	358	24.45	7.51	0.193	51.4
A-L-5	307	353	366	24.01	7.55	0.195	59.5
A-L-6	306	340	352	23.56	7.11	0.186	60.2
A-L-7	304	362	375	23.56	7.59	0.199	61.0
A-L-8	304	375	389	23.56	7.88	0.205	63.5
A-L-9	304	384	398	23.56	8.07	0.211	66.5
A-L-10	304	400	414	23.56	8.37	0.219	70.5
A-L-11	304	414	428	23.15	8.51	0.224	72.7
A-L-12	304	425	440	22.74	8.60	0.228	74.5
A-L-13	304	396	410	23.15	8.15	0.214	68.4
A-L-14	304	440	456	22.74	8.92	0.234	78.5
A-L-15	304	472	489	22.74	9.58	0.255	92.3
A-L-16	304	489	507	21.94	9.56	0.258	115.5
A-L-17	304	478	496	25.83	10.1	0.252	99.5
A-L-18	304	170	177	25.83	3.94	0.097	9.8
A-H-1	688	310	321	24.45	6.75	0.173	46.8
A-H-2	687	337	349	24.01	7.20	0.186	55.4
A-H-3	678	367	380	23.56	7.70	0.202	64.3
A-H-4	671	408	426	22.74	8.32	0.222	77.8
A-H-5	671	472	490	22.74	9.59	0.255	89.8
A-H-6	671	437	454	24.90	9.71	0.247	114.0
A-H-7	701	108	112	25.83	2.49	0.061	12.5
A-H-8	671	405	420	22.74	8.21	0.218	75.5
A-H-9	671	414	429	22.74	8.40	0.223	97.0

TABLE II. SUMMARY OF DATA AND CALCULATIONS, PRESSURE RUNS

Run No.	Downflow Lbs./Hr.	Steam Input Lbs./Hr.	Calculated Steam Rate at Bottom Lbs./Hr.	Specific Volume at Bottom Cu. Ft./Lb.	Superficial Velocity Ft./Sec.	$F=V(d_v/d_l)^{0.5}$	Differential Pressure In. of Water
P-L-1	339	491	499	10.540	4.51	0.185	44.1
P-L-2	336	545	554	10.704	5.11	0.197	55.6
P-L-3	328	600	611	10.704	5.63	0.218	66.0
P-L-4	314	653	664	10.704	6.11	0.237	81.2
P-L-5	304	750	762	10.704	7.02	0.272	107.0+
P-L-6	312	679	691	10.704	6.37	0.261	86.4
P-L-7	304	677	688	10.704	6.33	0.245	89.0
P-L-8	304	707	718	10.704	6.61	0.256	108.5
P-L-9	304	683	694	10.704	6.40	0.247	88.6
P-L-10	304	693	704	10.704	6.49	0.251	92.7
P-L-11	304	699	710	10.704	6.54	0.253	94.5
P-L-12	347	273	279	10.540	2.48	0.096	21.6
P-H-1	706	483	492	10.540	4.38	0.171	44.4
P-H-2	703	532	542	10.704	4.99	0.193	54.1
P-H-3	698	599	610	10.704	5.62	0.218	69.6
P-H-4	714	670	681	10.704	6.28	0.242	85-91
P-H-5	671	685	697	10.704	6.41	0.247	92-124
P-H-6	671	650	661	10.704	6.09	0.236	97-103
P-H-7	671	673	685	10.704	6.31	0.245	96-104
P-H-8	671	693	705	10.704	6.50	0.251	99-103
P-H-9	671	675	686	10.704	6.31	0.245	109.0+
P-H-10	714	270	275	10.540	2.45	0.095	22.5

TABLE III. SUMMARY OF DATA AND CALCULATIONS, VACUUM RUNS

Run No.	Downflow* Lbs./Hr.	Steam Input Lbs./Hr.	Calculated Steam Rate at Bottom Lbs./Hr.	Specific Volume at Bottom Cu. Ft./Lb.	Superficial Velocity Ft./Sec.	$F=V(d_v/d_l)^{0.5}$	Differential Pressure In. of Water
V-L-1	304	146	155	104.12	13.9	0.172	80.2
V-L-2	304	177	189	84.58	13.7	0.185	102.2
V-L-3	304	187	199	80.84	13.8	0.195	106.9
V-L-4	304	199	210	73.92	13.3	0.196	117.9
V-L-5	304	217	229	70.73	13.9	0.209	127.3
V-L-6	304	226	238	66.23	13.5	0.210	137.3
V-L-7	304	244	258	62.06	13.8	0.222	144.6
V-L-8	304	237	250	70.73	15.2	0.229	134.5
V-L-9	304	250	264	66.23	15.0	0.235	142.2
V-L-10	304	258	272	63.41	14.8	0.210	146.7
V-L-11	304	264	278	63.41	15.1	0.214	149.0
V-L-12	304	270	285	60.74	14.9	0.242	153.7
V-L-13	304	280	295	59.45	15.1	0.248	155-170
V-L-14	304	288	304	59.45	15.5	0.256	160-165
V-L-15	304	293	308	56.97	15.1	0.253	161.6
V-L-16	304	308	324	56.97	15.8	0.265	169.7
V-L-17	304	266	280	60.74	14.6	0.237	154.0
V-L-18	304	306	322	53.48	14.8	0.257	168-181
V-L-19	304	296	311	54.61	14.6	0.251	172.5
V-L-20	304	261	275	62.06	14.7	0.237	145.7
V-L-21	304	303	319	55.78	15.3	0.260	166.0
V-L-22	304	329	346	52.37	15.5	0.271	182.0
V-L-23	304	348	365	50.23	15.7	0.282	188.0
V-L-24	304	369	387	49.20	16.3	0.293	198.0

(Continued on Next Page)

TABLE III. SUMMARY OF DATA AND CALCULATIONS, VACUUM RUNS (Continued)

Run No.	Downflow* Lbs./Hr.	Steam Input Lbs./Hr.	Calculated Steam Rate at Bottom Lbs./Hr.	Specific Volume at Bottom Cu. Ft./Lb.	Superficial Velocity Ft./Sec.	$F=V(d_v/d_l)^{0.5}$	Differential Pressure In. of Water
V-H-1	671	102	109	142.42	13.4	0.143	54.8
V-H-2	671	143	152	109.15	14.2	0.172	79.7
V-H-3	671	164	174	99.36	14.8	0.189	98.9
V-H-4	671	199	211	73.92	13.4	0.198	123.8
V-H-5	671	206	218	70.73	13.3	0.200	131.3
V-H-6	671	216	228	66.23	15.1	0.236	140.0
V-H-7	671	218	230	64.80	12.8	0.202	143.5
V-H-8	671	275	290	59.45	14.8	0.243	157.4
V-H-9	671	284	299	58.20	15.0	0.250	163.7
V-H-10	671	280	295	66.23	16.8	0.262	142.9
V-H-11	671	345	362	49.20	15.3	0.277	195.2

* Downflow rates for vacuum runs are not corrected for increases due to heat losses, as water accumulating at the bottom of the column was not withdrawn separately.

TABLE IV. CONSOLIDATED DATA FOR ATMOSPHERIC RUNS

Run No.	Date	Starting Time	Steam Setting	Condensate Rate, Lbs./Hr. Overhead	Bottom	Total	Diff. Pr., In. of Water	Bottom Temp., °C.	Psig., Line	Psig. at Orifice
A-L-1	6/23/50	1550	17.0	232	19	251	35.6	102.0	101	68
A-L-2	6/23/50	1623	18.0	240	18	258	44.5	102.5	100	68
A-L-3	6/23/50	1702	18.9	300	13	313	48.5	103.0	98	68
A-L-4	6/23/50	1756	19.3	332	13	345	51.4	103.0	98	68
A-L-5	6/23/50	1834	19.8	350	3	353	59.5	103.5	98	68
A-L-6	6/23/50	2006	20.1	338	2	340	60.2	104.0	98	68
A-L-7	6/23/50	2105	20.2	362	0	362	61.0	104.0	97	68
A-L-8	6/23/50	2135	20.5	375	0	375	63.5	104.0	97	68
A-L-9	6/23/50	2214	20.7	384	0	384	66.5	104.0	97	68
A-L-10	6/23/50	2248	21.0	400	0	400	70.5	104.0	96	68
A-L-11	6/23/50	2345	21.1	414	0	414	72.7	104.5	96	68
A-L-12	6/24/50	0005	21.5	425	0	425	74.5	105.0	96	68
A-L-13	6/24/50	0106	20.7	396	0	396	68.4	104.5	94	68
A-L-14	6/24/50	0130	21.6	440	0	440	78.5	100.0	105	68
A-L-15	6/24/50	0151	22.0	472	0	472	86.6	100.0	105	68
A-L-16	6/24/50	0247	22.25	-	0	-	105.0	106.0	105	68
A-L-17	6/24/50	0338	22.1	-	0	-	99.5	101.0	105	68
A-L-18	6/26/50	1835	13.8	137	33	170	9.8	101.0	102	68
A-H-1	6/24/50	0415	18.0	293	17	310	46.8	103.0	100	68
A-H-2	6/24/50	0448	19.0	321	16	337	55.4	103.5	99	68
A-H-3	6/24/50	0512	20.0	360	7	367	64.3	104.0	98	68
A-H-4	6/24/50	0533	21.0	408	0	408	77.8	105.0	96	68
A-H-5	6/24/50	0552	22.0	-	0	-	89.8	105.0	105	68
A-H-6	6/24/50	0610	21.5	-	0	-	114.0	102.0	105	68
A-H-7	6/26/50	1735	13.6	78	30	108	12.5	101.0	107	68
A-H-8	6/26/50	2041	21.0	405	0	405	75.5	105.0	107	68
A-H-9	6/26/50	2128	21.1	-	0	-	97.0	105.0	102	68

TABLE V. CONSOLIDATED DATA FOR PRESSURE RUNS

Run No.	Date	Starting Time	Steam Setting	Condensate Rate, Lbs./Hr. Overhead	Bottom	Total	Diff. Pr., In. of Water	Bottom Temp., °C.	Psig., Line	Psig. at Orifice
P-L-1	6/30/50	1200	28.0	456	35	491	44.1	130.5	92	55
P-L-2	6/30/50	1230	30.1	513	32	545	55.6	130.0	90	55
P-L-3	6/30/50	1300	32.5	576	24	600	66.0	130.0	87	55
P-L-4	6/30/50	1336	35.0	643	10	653	81.2	130.0	84	55
P-L-5	6/30/50	1409	37.5	-	0	-	> 107.0	130.0	81	55
P-L-6	6/30/50	1604	36.1	671	8	679	86.4	130.0	84	55
P-L-7	6/30/50	1637	36.5	677	0	677	89.0	130.0	83	55
P-L-8	6/30/50	1700	37.0	707	0	707	108.5	130.0	82	55
P-L-9	6/30/50	1858	36.2	683	0	683	88.6	130.0	83	55
P-L-10	6/30/50	1927	36.6	693	0	693	92.7	130.0	82	55
P-L-11	6/30/50	1958	36.7	699	0	699	94.5	130.0	82	55
P-L-12	7/1/50	0404	20.0	230	43	273	21.6	130.5	101	55
P-H-1	6/30/50	2147	28.0	448	35	483	44.4	130.5	93	55
P-H-2	6/30/50	2218	30.0	500	32	532	54.1	130.0	90	55
P-H-3	6/30/50	2246	32.5	572	27	599	69.6	130.0	88	55
P-H-4	6/30/50	2319	35.0	627	43	670	85-91	130.0	84	55
P-H-5	7/1/50	0010	36.0	-	-	-	92-124	130.0	83	55
P-H-6	7/1/50	0115	35.1	650	0	650	97-103	130.0	84	55
P-H-7	7/1/50	0157	35.2	673	0	673	96-104	130.0	83	55
P-H-8	7/1/50	0223	35.25	693	0	693	99-103	130.0	83	55
P-H-9	7/1/50	0303	35.6	785	-	-	> 109	130.0	82	55
P-H-10	7/1/50	0343	20.0	227	43	270	22.5	130.5	101	55

TABLE VI. CONSOLIDATED DATA FOR VACUUM RUNS

Run No.	Date	Starting Time	Steam Setting	Condensate Rate, Lbs./Hr. Overhead	Condensate Rate, Lbs./Hr. Bottom	Condensate Rate, Lbs./Hr. Total	Diff. Pr., In. Water	Bottom Temp., °C.	Psig., Line	Psig. at Orifice
V-L-1	7/4/50	1807	16.0			146	80.2	64.0	105	55
V-L-2	7/4/50	1845	17.0			177	102.2	69.0	105	55
V-L-3	7/4/50	1918	17.3			187	106.9	70.0	105	55
V-L-4	7/4/50	2015	17.7			199	117.9	72.0	104	55
V-L-5	7/4/50	2055	18.0			217	127.8	73.5	104	55
V-L-6	7/4/50	2134	18.4			226	137.3	75.0	104	55
V-L-7	7/4/50	2210	18.7			244	144.6	76.5	102	55
V-L-8	7/6/50	1248	19.3			237	134.5	73.5	101	55
V-L-9	7/6/50	1315	19.7			250	142.2	75.0	101	55
V-L-10	7/6/50	1354	20.1			258	146.7	76.0	101	55
V-L-11	7/6/50	1436	20.2			264	149.0	76.0	101	55
V-L-12	7/6/50	1516	20.4			270	153.7	77.0	100	55
V-L-13	7/6/50	1557	20.7			280	155-170	77.5	101	55
V-L-14	7/6/50	1640	21.0			288	160-165	78.0	101	55
V-L-15	7/6/50	2231	21.2			293	161.6	79.0	101	55
V-L-16	7/6/50	2303	21.5			308	169.7	79.0	100	55
V-L-17	7/9/50	2307	21.7			266	154.0	77.0	100	55
V-L-18	7/9/50	2349	21.9			306	168-181	80.5	100	55
V-L-19	7/10/50	0129	21.1			296	172.5	80.0	99	55
V-L-20	7/10/50	0322	19.6			261	145.7	76.5	100	55
V-L-21	7/10/50	0355	20.9			303	166.0	79.5	100	55
V-L-22	7/10/50	0429	21.9			329	182.0	81.0	99	55
V-L-23	7/10/50	0506	22.4			348	188.8	82.0	97	55
V-L-24	7/10/50	0541	23.0			369	198.0	83.0	97	55

(Continued on Next Page)

TABLE VI. CONSOLIDATED DATA FOR VACUUM RUNS (Continued)

Run No.	Date	Starting Time	Steam Setting	Condensate Rate, Lbs./Hr. Overhead	Bottom	Total	Diff. Pr., In. Water	Bottom Temp., °C.	Psig., Line	Psig. at Orifice
V-H-1	7/5/50	1507	15.0			102	54.8	56.5	104	55
V-H-2	7/5/50	1555	16.1			143	79.7	63.0	104	55
V-H-3	7/5/50	1627	17.0			164	78.9	67.0	104	55
V-H-4	7/5/50	1658	18.0			199	123.8	72.0	104	55
V-H-5	7/5/50	1735	18.25			206	131.3	73.5	102	55
V-H-6	7/5/50	1811	18.5			216	140.0	75.0	102	55
V-H-7	7/5/50	1843	18.6			218	143.5	75.5	102	55
V-H-8	7/7/50	0014	20.0			275	157.4	77.5	101	55
V-H-9	7/7/50	0051	20.25			284	163.7	78.5	100	55
V-H-10	7/7/50	0124	19.2			280	142.9	75.0	100	55
V-H-11	7/10/50	0645	22.25			345	195.2	82.5	99	55

TABLE VII. PRESSURE GAUGE CALIBRATION

July 7, 1950

Actual Psig., Dead Weight Tester	Indicated Psig.	
	Gauge on Main Steam Line	Gauge at Orifice Run
0	5.0	0.0
25	33.0	25.0
50	59.0	50.0
75	84.5	75.0
100	109.0	99.0
125	133.5	124.5

CORRECTION CURVE FOR STEAM LINE PRESSURE GAUGE

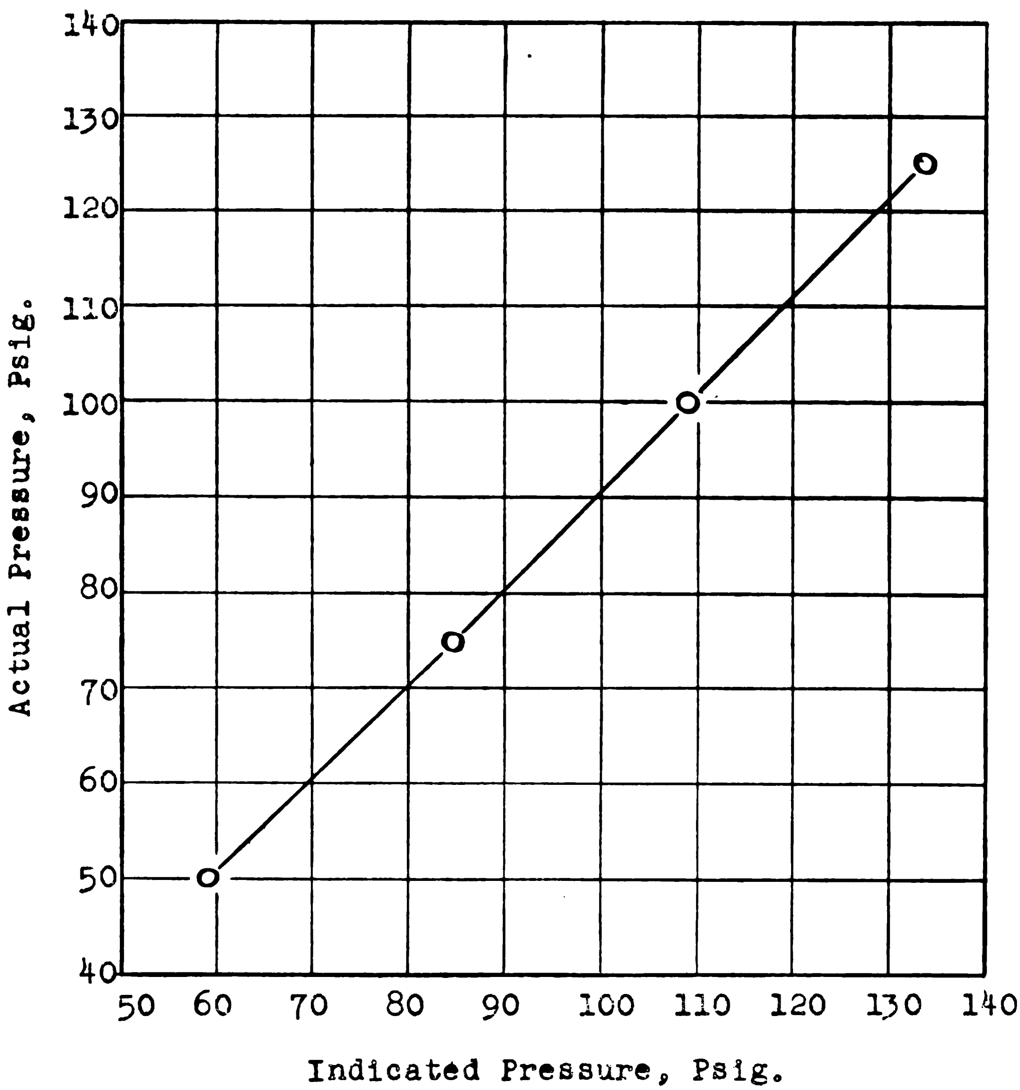

Figure 4. Steam Flow Rate *vs.* Controller Setting