JACKET HEAT TRANSFER COEFFICIENTS IN AN AGITATED VESSEL, THE PADDLE AGITATOR

by

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THESIS:

Four papers have been published which correlate variables affecting heat transfer through a jacket in a kettle agitated by a paddle type agitator. There are differences in the equations resulting from each of these papers. In none of these papers was variation of the stirrer diameter or stirrer width considered.

It is the purpose of this paper to show that all published data in such a system can be correlated by a single equation which differs from those previously presented. Preliminary recalculation of published data indicated that a relationship exists which involves the stirrer width and diameter. Experimental work was undertaken to provide data for determining this relationship.

As a result of this work, the following equation is proposed to correlate heat transfer coefficients on the wall of a jacketed kettle agitated by a paddle type agitator with the fluid and geometric variables:

$$\frac{hT}{k} = 0.112 \left(\frac{c\,\mu}{k}\right)^{.44} \left(\frac{D^2 N \rho}{\mu}\right)^{.75} \left(\frac{\mu}{\mu_w}\right)^{.25} \left(\frac{T}{D}\right)^{.40} \left(\frac{D_w}{D}\right)^{.13}$$

It is believed that this best expresses the data observed by the author. It is further believed to express adequately all previously published data. Without the two groups (T/D) and (D_w/D), equations having coefficients ranging from 0.097 to 0.176 were derived. These varying coefficients result from the use of different agitators having different ratios of T/D and D_w/D. Without these correlating groups, the limiting equations vary in coefficient by a factor of two. For a given system at any Reynolds number, heat transfer coefficients derived from the limiting equations also would vary by a factor of two.

This is the first paper on this subject to include the terms (T/D) and (D_w/D) in such a correlation. This is the first paper to suggest an exponent other than 2/3 for the Reynolds number. This is the first paper to suggest the 0.44 power of the Prandtl number. Brown, Scott and Toyne (22) suggested that this exponent should be 1/4. Uhl (151), however, suggested that it might be greater than 1/3. The -1/4 exponent chosen for the ratio (μ_w/μ) is essentially the same as that (-0.24) proposed by Uhl (151).

INTRODUCTION:

Agitation or stirring has been defined in many ways although it is almost self evident. Brown (21) defines it in process industries as "...the production of irregular disturbances or turbulent motion within a fluid by means of mechanical devices acting on that fluid." A more broad definition might be the production motion within a fluid by means of controlled physical operations on that fluid.

Obviously, the field covered is extremely broad. Taken in their broadest terms, these definitions could include pumps, power turbines, aeroplane propellers and the like. Indeed these are in fact agitators and subject to the same laws but by their special applications they are not generally considered in the same studies. A fluid can be a gas, or a liquid, or a divided solid, or mixtures of these. By more or less common usage, this extremely broad field has been narrowed somewhat by considering that agitation deals primarily with fluids enclosed within a vessel and which remain enclosed for a significant length of time. This still leaves the field a broad one and makes further subdivision necessary.

Again by common usage several types of subdivision of the general field of agitation are accepted. One way is to consider the nature of the fluid, as to liquid or solid, or liquid-gas, liquid-liquid, liquid-solid or gas-solid. Also the objective of agitation may be considered, heat transfer, mass transfer, mixing or blending or chemical reaction. Even these subdivisions cover wide ranges of unique situations. In the development of the art, the solution of individual problems has been for the most part empirical. As a result, an enormous variety of equipment of all sizes, shapes and types has been evolved and is in use.

The development of a science of agitation has been handicapped seriously by the lack of a satisfactory criterion or "unit of measure." This stems both from the wideness of the field and from the complex nature of any individual problem. A wide range of variables, both in the physical nature of the fluid and in the geometry of the system, present an extremely difficult problem in establishing a basis for quantitative comparison of one agitated system with another. As the fields of hydrodynamics and fluid mechanics, of development of measuring instruments, and of techniques of investigation are developed, the valid criteria for studying agitation are also developing.

The lack of an adequate criterion is simultaneous with the lack of a satisfactory general theory. The two are practically inseparable. For this reason the difficulty in evolving one applies directly to the other.

At the present stage of the art, sufficient science has been introduced to do some mathematical correlation of data. It is possible to measure and correlate most or all of the variables in a specific system for a specific operation with reasonable accuracy. The difficulty now lies in using this information in scaling the data from one size of equipment to another. Here geometric and dynamic similitude are the immediate problems requiring solution.

It is the purpose of this paper to evaluate as completely as possible all the variables in a single type of equipment in regard to a single objective. More specifically, it is to evaluate the heat transfer coefficients at the jacket wall when various single phase liquid fluids are agitated by a simple paddle. The purpose is to carry the existing correlations further taking into consideration the geometry of the system so that the resulting equation can be used for measuring and scaling up data in any geometric system.

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I. Review of Literature

Before entering directly into discussion of heat transfer coefficients in agitated vessels, it seems appropriate to review briefly the development to date of the entire field of agitation. It is only in the last few years that any real scientific investigation has been done. Almost all of the work published to date is of an empirical nature and it remains for a sound theory and criterion to be developed.

A. Early Developments

Prior to 1920 very little was published on experimental work in the field of agitation. In 1855 Thompson (149) reported that for a disc rotating in a fluid, the power consumed was a function of N^3D^5. In 1880, Unwin (152) extended this study with a discussion of viscosity, chamber and disc size and roughness. Odell (106) in 1904 found that the exponent of D was between 5 and 6 and that, for low speeds, the exponent of N was 2 while at high speeds the exponent of N was between 3.1 and 3.8. It should be noted that the power measurements in these works were made by measurements of currents and voltages in the motor circuits.

B. Developments since 1920

Practically all of the work done in the field of agitation has been during the last 33 years. Of this work the major portion has been in the last 15 years, the latter contributing most of the current design data. A number of papers (155,156,157,119,140,123,124,125,10,126,127,130,105, 134,34,136) have been published which survey the literature and comment on them individually and collectively. There are, of course, references to the literature in all of the papers, but these appear to be the most extensive bibliographies.

1. General

a. Criteria for Defining Agitation

It has been long recognized that an accurate quantitative criterion to define an agitated system is necessary to any study. A number of papers have been published wherein the determination of such criteria is the prime purpose. So far, however, no completely general criterion has been found. The modified Reynolds number for stirring has been generally accepted as the best substitute, but Dunlap and Rushton (33) point out the limitation of this in a heat transfer correlation.

Wood, Whittemore and Badger (171) proposed an electrical conductivity method to describe mixing by a paddle stirrer in 1922. White and Sumerford and their coworkers (164,165, 166) published works in 1932-34 on studies of efficiencies of suspending sand. They suggested a criterion of intensity of agitation based on the speed at which the maximum concentration is reached. Hixson and Wilkens (59) in 1933 studied liquid-solid systems and gave general relations for rates of solution. In 1934-35, Hixson and Tenney (58) stated, "If the total quantities in a two-component mixture are of the ratio A/B and every small sample withdrawn from the batch shows the same ratio, we have 100% mixing. Based on this definition a qualitative mixing index is defined." Gunness and Baker (40) describe standards and test method for evaluating and judging performance of mixing equipment. They show the application of these to proper selection of agitators and efficient operation. Yates and Watson (172) define a mixing coefficient on transfer of mass from one phase to another and a stirring efficiency on power per unit volume. Beaudry (2) describes statistical methods for determination of quantitative criteria for blending. He suggests a similar treatment to develop a criterion for agitation.

b. General Theory

Concurrent with attempts to find a criterion for agitation, numerous investigators have attempted to define a general theory. The need for such is obvious. The difficulties of working without it were adequately described by Killeffer (71) in 1923.

In 1938 Valentine (153) proposed a three-fold program for the study of agitation. He proposed; first, planned research to discover the laws of mixing; second, development of a relatively small number of "standard" mixers; and third, standardization of the methods of measuring and describing the variables. Brothman and Kaplan (15) attempted to define mixing and present a broad mathematical analysis. In 1944, Hixson (46) discussed the wide variety of variables and applications and suggested that "the formulation of general, unified and practical expression for agitation does not appear possible."

In 1944 Miller and Rushton (94) appraised the operation of agitation from the standpoint of the interrelated actions of the impeller with its flow discharge and the nature of the flow required to produce the desired result.

Rushton, Mack and Everett (138) approached the problem in 1946 by determining displacement capacities of propellers and turbines. Lyons (78) discussed the existing theory in 1948. In 1950 Serner (146) proposed a theoretical "radius of agitation" depending on the fluid dynamics of the system. He presented a relationship among this radius, viscosity and power input. Rushton (135) and Rushton and Oldshue (137) in 1952 and 1953 discuss the application of the principles of fluid dynamics.

c. Design of Equipment

Many papers have been published which discuss means of designing equipment and scaling-up data in rather general terms. MacLean and Lyons (83) and Gunness (40) in 1938 and Harcourt (42) in 1941 discussed design of equipment from a qualitative standpoint. Greene (39) described in 1942 a variety of effects on mixing in glass-lined steel equipment by varying type and speed of agitator and arrangement of baffles. Serner (145) in 1943 classified mixing operations based on correlations of previously published data. He then discusses each major type of agitator with its application to the classes of mixing.

In 1944, Bissell (5) gave a brief account of the methods used by Mixing Equipment Company. Rushton (122) in

1945 discussed the evaluation and use of pilot plant data. Bissell, Miller and Everett (9) discussed this further and Bissell (6) discussed the major factors in design. Chaddock (29) discussed the work of other authors in view of experience in 1946. In 1946, Bissell, Everett and Rushton (7) discussed the special design problems in shallow tanks. Brumagin (23) and Rushton (140) discussed in 1946 the general applications of various types of agitators to various problems.

In 1947 Bissell, Hesse, Everett and Rushton (8) described the methods of designing and using internal fittings such as thermowells, coils, baffles, etc. In the same year, Mack and Uhl (87,88) analyzed four aspects of agitation in developing methods of predicting agitator performance. Morton and Redman (98) in 1948 discussed design of propeller stirrers and Serner (144) described a simple qualitative approach to design problems. In 1951, Reavell (117) discussed design generally according to types of problems and agitators. Shinji Nagata et al. (102) described proper design of baffles in detail.

The all important question of scaling-up pilot plant data is treated at length by Rushton (131,132,133) in 1951-2. In this he discussed geometric and dynamic similitude and showed how the existing empirical design equations may be used. Oldshue (107) described in 1952 means of testing the performance of agitators in the pilot plant.

d. Viscous Materials

This paper is primarily designed to deal with relatively fluid systems. Handling of particularly viscous materials, pastes, powders and the like in agitated systems stands in a field by itself. Vollrath (159) in 1923 described equipment for this use and discusses proper design and application. Levey (76) and Bullock (25) described very well the special problems encountered in this field.

e. Economics

Because of the wide variety of sizes, types and applications of fluid mixers, the costs of equipment, installation, operation and maintenance have been difficult to determine. Lewis (77) presented data in the form of charts for estimating the cost of mixing equipment of all types. Boutros (12) described proper installation, operation and maintenance of fluid mixes.

f. Special Equipment

A number of papers have been published in addition to those already mentioned which describe specific types of agitators. Tyler (150) in 1923 described a number of types used at that time. Bissell (4) in 1938 described propeller type agitators. Kiebler (70) in 1945 described a high speed agitator for pressure vessels and in 1948, Hoffman, Montgomery and Moore (60) described a method of agitating high pressure vessels by rocking. Serner (143) in 1949 described the advantages and uses of disc impellers. Fossett (35) in 1951 described the action of free jets in mixing of fluids in the petroleum industry.

2. Continuous Processing

The use of continuous processes instead of batch often has considerable economic advantage. This is first discussed in 1918 by Ham and Coe (41), and amplified by MacMullin and Weber (80) in 1935. In 1943, Brothman, Weber and Barish (16,17,18) developed methods of predicting equipment performance and illustrated their application. In 1945 MacMullin and Weber (81) and Olsen and Lyons (111) reviewed the current status of knowledge and Brothman, Wollan and Feldman (19,20) derived theoretical relationships for design. In 1949, Bogachov and Devyatov (11) developed further equations for designing equipment. In 1951, Jones (67) presented a general graphical analysis for a series of agitated vessels and McDonald and Piret (82) described in some detail the agitation requirements for such a system. In 1953, Weber (161) discussed the problems of scaling-up pilot plant data on continuous processes.

3. Power Requirements

In the design of an agitated system, one of the most important items is prediction of the power requirements. More work has been done on this than on any other phase of agitation. A major source of difficulty is in measuring the actual power consumed. Early measurements were by electrical means and were generally unsatisfactory as explained by Wood, et al, (171). Relatively good data have been obtained in more recent works using dynamometer measurements.

In 1933-34, White, Brenner, Philips and Morrison (162) described tests using a dynamometer and White and Brenner (162 A) correlated these data into an equation based on dimensional analysis. White and Sumerford (163) presented graphical data on suspending sand in 1936. In 1937, Hixson and Luedeke (56) presented an equation for the friction drag and Buche (24) discussed power requirement calculations for several types of agitators. In 1940, Vishnevskii (156) presented a detailed procedure for determining power requirements of propellers. Hixson and Baum (50) concluded that power requirements of a turbine should not be used to evaluate mixing efficiency but that the two should be treated as separate problems. In 1943 Steeps and Lovell (148) presented an equation for the power required by a propeller type agitator.

In 1944, Miller and Mann (93) presented a paper on power data and degree of mixing data for seven designs of agitators. This was presented in the form of power number versus Reynolds number graphs, and the mixing index of Hixson and Tenney (58). A method of scale-up is also presented. Martin (92) in 1946 presented data graphically for thirteen different agitators and discusses applications to non-geometrically similar systems. In 1947, Ollney and Carlson (110) presented power number-Reynolds number data for a number of systems and correlated it with work reported by other investigators. In the same year, Romankov and Pavlushenko (121) presented an equation for power required by a propeller derived from hydromechanics.

Mack and Kroll (84) in 1948 presented data on the effect of baffles on power consumption of a flat paddle. Hooker (61) that year correlated published data in terms of dimensionless groups in a graphical representation. Magnusson (89) in 1949 reviewed the requirements of various agitators for castor oil, linseed oil and water. In 1950 Mack and O'Connell (86) investigated the power required by various turbine agitators. Equations for viscous and turbulent regions were presented which are included in the number and width of blades as well as the usual power number and Reynolds number.

Rushton, Costich and Everett (128,129) presented in 1950 correlations of data for the common forms of agitators covering a wide range of sizes and arrangements. Wingard, Vinyard and Craine (170) presented data for paddles and propellers in 1952 and Ryder (141) determined the power number-Reynolds number curve for a paddle. In 1953, Magnusson (90) discussed calculations of power requirements for a number of stirrers in a test apparatus. Uhl (151) presented power number-Reynolds number curves for the paddle, turbine and anchor agitators used in his study of heat transfer coefficients in the viscous range. Shinji Nagata *et al*. (101) verified the data of Buche (24) mentioned earlier.

4. Mass Transfer

A considerable amount of information has been published in the field of mass transfer in agitated systems. This has been both for the purpose of predicting reaction velocities and dissolution rates and also of finding a suitable standard for describing an agitated system. This was discussed both by Murphree (99) and by Milligan and Reed (95) in 1923.

In 1926, Huber and Ried (63) reported that in studies of a number of organic reactions, three classes of reactions were found based on the variation of reaction rates with agitator speed. In the same year Bekier and Rodziewicz (3) presented an equation correlating the rate of dissolution of copper in iron-alum solutions with agitator speed. In 1927, Klein (72) confirmed their work.

Hixson and Crowell (53,52,54) published three papers in 1931 dealing with the dependence of reaction velocity on surface and agitation. Heterogeneous reaction kinetics in liquid-liquid, liquid-solid and liquid-gas systems were studied. Relationships between velocity of solution, agitation, surface and concentration are derived and experimentally verified on a semiplant scale. In 1941, Hixson and Baum (47,48) presented two papers in which mass transfer is correlated with agitation by turbines in terms of dimensionless groups. A critical Reynolds number was found at 6700. In 1942, Hixson and Baum (49,50) extended this work to develop an equation for propeller agitators.

In 1942, Callaham (27) discussed the similarity between dissolution in an agitated vessel and simple liquid-solid mixing. Cooper, Fernstrom and Miller (31) determined in 1944 the variation of absorption coefficients with agitator power and gas velocity. Foust, Mack and Rushton (36) also presented an equation in 1944 for gas-liquid contacting in an agitated vessel. Agitated gas absorbers were further discussed by Valentine(154).

Hixson and Baum (51) discussed the rate of mass transfer and chemical reaction between benzoic acid pellets and dilute aqueous sodium hydroxide in an agitated vessel. The same system was studied by Mack and Marriner (85) in 1949, and by Shinji Nagata _et_ _al_. (103) in 1953. Hixson and Smith (57) in 1949 also studied mass transfer in an agitated liquid-liquid extraction system and determined a relationship.

Wingard and Crain (169) studied dissolution of crystals of definite size with various types and speeds of agitation. Mohle (97) introduced the concept of the "Thompson Unit" or turnover of a charge. Shinji Nagata _et_ _al_. (104) determined the critical speed for agitation of two immiscible liquids below which separate layers existed. Garner and Skelland (37) studied in 1951 the effect of internal circulation of droplets in liquid-liquid agitation. Shinji Nagata _et_ _al_. (100) described the optimum construction of a gas-liquid mixer.

In 1951 Hixson and Knox (55) reported mass transfer coefficients for copper sulfate and magnesium sulfate for the growth of single crystals in an agitated system. Oldshue and Rushton (108) reported in 1952 performance data for a continuous countercurrent extraction column having internal agitation.

5. Heat Transfer

The earlier papers dealing with heat transfer in an agitated system dealt primarily with over-all coefficients. Many of these were for special applications. Little, if any, attempt was made to correlate the coefficients with any of the agitation variables. The results of a number of these papers are summarized in Table I. Other work of the same type was reported by Olin, Southwick and Prince (109) and by Heatsie (43,44,45). Huggins (64) discussed the effect of scrapers where thick liquids are encountered. Houlton (62) discussed the special advantages of a Votator. In 1924, Pierce and Terry (113) presented graphical data showing the effect of agitator speed on over-all coefficients. Rhodes (118) presented further data in 1934.

The first attempt on record to correlate film coefficients of heat transfer with the variables of an agitated system was by Gordon (38) in 1941. He used a 23 1/2" diameter dished bottom copper kettle and a 12" diameter, 9" wide flat paddle agitator. Water and three hydrocarbon oils were tested by batch heating. Wall temperatures were measured directly by thermocouples imbedded in the walls and film coefficients were calculated directly. A correlation in the form of dimensionless groups was presented. However, the units chosen were not such that the groups were entirely dimensionless. Since the tests were made on heating only, no correlation between heating and cooling by the viscosity ratio method of Sieder and Tate (147) was attempted. The utmost care was taken to measure temperatures and the properties of the fluids. Because of the high conductivity of the copper walls, high wall temperatures resulted. For oils, the wall temperatures were between 207° and 221°F and for water from 144° to 212°F.

In 1944, Chilton, Drew and Jebens (30) published their paper which has become the standard work on the subject. They

TABLE I
OVERALL HEAT TRANSFER COEFFICIENTS
JACKETED VESSELS

FLUID IN JACKET	FLUID IN VESSEL	WALL MAT'L	AGIT. RPM	U	REF.	YEAR
Steam	Water	Enameled C. I.	0-400	96-120	114,112,79	1924
Steam	Milk	Enameled C. I.	200	86	114,112,79	1924
Steam	Fruit Slurry	Enameled C. I.	None	33-90	114,112,79	1924
Steam	Fruit Slurry	Enameled C. I.	Some	154	144,112,79	1924
Steam	Water	Lead lined C. I.	Some	4-9	116,112,79	1925
Steam	Water	Lead lined C. I.	None	3	116,112,79	1925
Steam	Boiling SO_2	Steel	--	60	116,112,79	1925
Steam	Boiling Water	Steel	--	187	116,112,79	1925
Steam	Milk	Enameled C. I.	None	200	13,112,79	1930
Steam	Milk	Enameled C. I.	Some	300	13,112,79	1930
Steam	Boiling Milk	Enameled C. I.	None	500	13,112,79	1930
Steam	Water	Copper	None	148	13,112,79	1931
Steam	Water	Copper	Some	244	112,79	1931
Steam	Boiling Water	Copper	None	250	112,79	1931
Steam	Wax	Copper	None	27	112,79	1931
Steam	Wax	Cast iron	Scraper	107	64,112,79	1931
Steam	Water	Copper	None	24	64,112,79	1931
Steam	Water	Cast iron	Scraper	72	64,112,79	1931
Steam	Evaporat. Water	Copper	--	381	126,112,79	1936
Steam	Evaporat. Water	Enamel	--	37	126,112,79	1936
Steam	Solution	Cast iron	Double Scraper	175-210	75,112	1940
Steam	Slurry	Cast iron	Double Scraper	160-175	75,112	1940
Steam	Paste	Cast iron	Double Scraper	125-140	75,112	1940
Steam	Lumpy Mass	Cast iron	Double Scraper	75-96	75,112	1940

TABLE I (cont.)

FLUID IN JACKET	FLUID IN VESSEL	WALL MAT'L	AGIT. RPM	U	REF.	YEAR
Steam	Powder 5% water	Cast iron	Double Scraper	41-51	75,112	1940
Hot water	Warm water	Enameled C.I.	--	70	114,112,79	1924
Cold water	Cold water	Enameled C.I.	--	43	114,112,79	1924
Ice water	Cold water	Stoneware	Some	7	116,112,79	1925
Ice water	Cold water	Stoneware	None	5	116,112,79	1925
Water	$NaOC_2H_5$	Frederking	Some	80	116,112,79	1925
Brine	Nitration	Stoneware	35-38	32-60	112,79	1933

used a 12" diameter dished bottom steel kettle and a 7.2" diameter, 1.2" wide flat paddle agitator for testing. Three confirmatory tests were made in a geometrically similar system five times larger. Water 92% glycerol and two hydrocarbon oils were tested both batchwise and under steady state conditions. The steady state was achieved by the use of an internal coil. A constant liquid temperature resulted when heat was applied to the jacket and removed by the coil and vice versa.

For jacket film coefficients, they derived the equation:

$$(1) \quad N_{Nu} = 0.36\, N_{Pr}^{1/3}\, N_{Re}^{2/3}\, (\mu_w/\mu)^{-0.14}$$

In the same manner, the equation derived for the coil film coefficients was:

$$(2) \quad N_{Nu} = 0.87\, N_{Pr}^{1/3}\, N_{Re}^{.62}\, (\mu_w/\mu)^{-.14}$$

In 1947 Brown, Scott and Toyne (22) made a study of jacket film coefficients in cooling plant scale sulfonations and nitrations. The vessels used were cast iron kettles five feet in diameter with hemispherical bottoms. Both anchor and marine propeller agitators were used. The film coefficients on the batch side were calculated from the over-all coefficient by first determining the combined resistances of metal wall, dirt films and cooling water films. These combined resistances were based on tests run on water using the method of Wilson (168) to determine the individual resistances. Batch temperatures were measured while cooling and the density and viscosity variation with temperature was determined experimentally. The dimensionless form of the equation as given by Chilton _et al_. (30) was accepted for correlating the data.

Since all tests were made at constant agitator speed on the same material, it was postulated that h should vary as . Plotting log h versus log gave for each case a slope of -0.425. In the Chilton equation (not considering the viscosity ratio) h varies as $^{-0.333}$. Brown *et al* (22) then suggested that the exponent for either the Reynolds or Prandtl number should be changed accordingly. This suggested the equation:

(3) $N_{Nu} = 0.55\, N_{Pr}^{1/4}\, N_{Re}^{2/3}\, (\mu_w/\mu)^{-.14}$

Also in 1947, Pratt (115) made a study of the film coefficients on internal cooling and heating coils. Tanks both square and circular in cross section were used. The largest was 2' in diameter or length of side. Twenty-five different shapes and combinations of paddle type stirrers were used. Five different arrangements of lead or stainless steel coils were used. Film coefficients were deduced by a complex resolution of the over-all coefficient into its component parts. Water and isopropyl alcohol were tested. Correlation was in terms of dimensionless groups by the cross-plotting method already described. For square tanks, the correlation equation was:

(4) $h\, l/K = 39(N_{Re})^{0.5}(N_{Pr})^{0.3}(s/r)^{0.8}(D_w/m)^{0.25}(D^2 l/e^3)^{0.1}$

and for cylindrical tanks,

(5) $N_{Nu} = 34(N_{Re})^{0.5}(N_{Pr})^{0.3}(s/r)^{0.8}(D_w/m)^{0.25}(D^2 T/e^3)^{0.1}$

Rushton, Lichtman and Mahoney (139) in 1948 investigated heat transfer to vertical tubes in a mixing vessel. A four-foot diameter cylindrical iron tank having a flat bottom was used. Four banks of vertical tubes of 1" pipe were used for heating and cooling and served also as baffles. Two flat blade turbine agitators were tested, one of four 12" diameter blades, the other of six 16" diameter blades. Location of the agitator was varied. Power was recorded by dynamometer. Over-all coefficients were obtained and the film coefficients were calculated from determinations of the remaining resistances. Film coefficients were correlated with Reynolds number giving the equations: For 16", 6 blade turbine

(6) $h_{heat} = 0.00285\ (D^2N\rho/\mu)$

(7) $h_{cool} = 0.00265\ (N_{Re})$ and for 12", 4 blade turbine

(8) $h_{heat} = 0.00235\ N_{Re}^{0.7}$

(9) $h_{cool} = 0.00220\ N_{Re}^{0.7}$

A plot of heat transfer coefficient versus power is also given.

Cummings and West (32) made a study of both coil and jacket coefficients in 1950. The arrangement for steady state operation was similar to that used by Chilton _et_ _al_. (30). The vessel used was a jacketed Type 347 stainless steel kettle with a dished bottom and internal coil. Most runs were made using a pair of 12" diameter, 6 retreating blade turbine impellers 10" apart. In a few runs a single turbine was used and in a few, a 45° pitched blade turbine impeller of 6-12" blades was used. These latter were only for runs involving the coil alone. Film coefficients were obtained from the over-all coefficients by a modification of the method of Wilson (168). The equations proposed by Chilton _et_ _al_. (30) were used except for the coefficient in the correlation and in addition the recalculated data of Gordon (38), the data of Chilton et al. (30) and the data of Rushton, Lichtman and Mahoney (139) were plotted jointly. The equations correlating all data were for the jacket:

$$(10)\quad N_{Nu} = 0.40\ N_{Re}^{2/3}\ N_{Pr}^{1/3}\ (\mu_w/\mu)^{-0.14}$$

and for the coil

$$(11)\quad N_{Nu} = 1.01\ N_{Re}^{0.62}\ N_{Pr}^{1/3}(\mu_w/\mu)^{-0.14}$$

Kraussold (73) reported in 1951 on tests made in a 1,000 mm steel autoclave using a paddle type stirrer. Their data plus that of Chilton et al. (30), Cummings and West (32), Rushton et al. (139) and Rhodes (118) results,by similar procedures, in the same equations offered by Chilton et al. (30).

Carroll (28) made a series of tests in 1952 whichw as similar to the work of Chilton et al. (30). A jacketed steel kettle 12" in diameter with a flat bottom was used. It was fitted with a helical copper cooling coil. The agitator was a flat paddle 4 1/2" in diameter, 3 1/2" wide run at a constant speed of 106 r.p.m. Water and glycerol solutions were used as a test medium. The over-all coefficients were measured and the film coefficients isolated by calculating the other resistances from formulas in the literature. The form of correlation of Chilton et al. (30) was used calculating new coefficients for the system. The resulting equations were for jacket heating:

$$(12)\quad N_{Nu} = 0.6\ N_{Pr}^{1/3}\ N_{Re}^{2/3}\ (\mu_w/\mu)^{-0.14}$$

and for cooling coil

$$(13)\quad N_{Nu} = 1.5\ N_{Pr}^{1/3}\ N_{Re}^{0.62}\ (\mu_w/\mu)^{-0.14}$$

The most extensive work reported to date was done by Uhl (151) in 1952. A jacketed kettle 23 1/2" in diameter, Monel lined with a dished bottom was used. It was fitted with removable baffles. Three types of stirrers were used; a 14" diameter, 2 3/8" wide flat paddle, a 12" diameter, 6 pitched blade turbine and a 22 5/8" diameter anchor. Tests at various speeds were made on a bodied linseed oil and a heavy cylinder oil. Over-all coefficients were calculated and the film coefficients determined by a modification of the method of Wilson (168). The Nusselt, Prandtl and Reynolds numbers and the viscosity ratio were calculated as in previous papers and correlated by cross plotting. The equations resulting were:

(14) For the paddle $N_{Nu} = 0.415\ N_{Pr}{}^{1/3} N_{Re}{}^{2/3} (\mu_w/\mu)^{-0.24}$

(15) For the turbine $N_{Nu} = 0.535\ N_{Pr}{}^{1/3} N_{Re}{}^{2/3} (\mu_w/\mu)^{-0.24}$

(16) For the anchor $N_{Nu} = 0.43\ N_{Pr}{}^{1/3} N_{Re}{}^{2/3} (\mu_w/\mu)^{-0.18}$

Dunlap and Rushton (53) reported heat transfer coefficients in vessels where vertical heat transfer tubes were used as baffles. Two dimensionally similar systems were tested both by heating and cooling. Flat-bottomed cylindrical steel tanks, two and four feet in diameter, were used. Vertical pipe heat transfer tubes were arranged in the form of baffles and provided steady state transfer conditions. Four bladed turbine type impeller agitators were used. Water and two oils were tested. Film coefficients were calculated from over-all coefficients. The data were assembled as the usual dimensionless groups and these were correlated graphically. The resulting equation was:

$$(17)\quad N_{Nu} = 0.09\ N_{Pr}^{0.3} N_{Re}^{0.65} (\mu_w/\mu)^{0.4} \frac{2}{B}^{0.2} \frac{D}{T}^{0.33}$$

In addition, the authors discuss the dimensional similarity of the test systems and the limits of use of the data. Also, they discuss the effect of natural convection on the data and show that Reynolds number cannot be used as a criterion for relative liquid agitation. A comparison is made with the work of previous investigators.

Rushton (137) also reports on tentative data of the Mixing Equipment Company. Heat transfer coefficients on a helical coil were determined in a four-foot diameter baffled tank stirred by a flat blade turbine. An equation was developed:

$$(18)\quad N_{Nu} = .037\ N_{Pr}^{.30}\ N_{Re}^{.67}\ (\mu_w/\mu)^{.90}$$

C. Mathematics

1. Dimensional Analysis

It has been shown in numerous papers that heat transfer coefficients may be correlated with the variables of a system by means of a dimensional analysis as described by Bridgeman (14). The variables in the system include the heat transfer coefficient h, the physical properties of the fluid μ, ρ, c, k and μ_w, and the geometry of the system, D, T, D_w, N, Z, C, J, B and Y. This may be postulated as a general equation:

$$(19)\quad h = f(T^A D^B D_w^C k^D \mu^E \rho^F c^G \mu_w^H N^I Z^J C^K J^L gc^M j^N)$$

This may also be expressed as an infinite series.

$$(20)\quad h = \gamma\, T^A D^B D_w^C k^D \mu^E \rho^F c^G \mu_w^H N^I Z^J C^K J^L gc^M j^N + \gamma' T^{A'} D^{B'} \text{ etc...}$$

Substituting for this the net dimensions of force F, mass M, length L, time Θ, temperature T, and heat H,

$$(21)\quad \frac{H}{\Theta L^2 T} = \gamma\,(L)^A(L)^B(L)^C\left(\frac{H}{\Theta LT}\right)^D\left(\frac{M}{L\Theta}\right)^E\left(\frac{M}{L^3}\right)^F\left(\frac{H}{MT}\right)^G\left(\frac{M}{L\Theta}\right)^H\left(\frac{1}{\Theta}\right)^I$$

$$(L)^J(L)^K(L)^L\left(\frac{ML}{F\Theta^2}\right)^M\left(\frac{LF}{H}\right)^N \quad + \quad \gamma' \text{ etc.}$$

For each dimension, equating the exponents gives 6 equations

(22) ΣH: $1 = D-N+G$

(23) $\Sigma \Theta$: $-1 = D-E-H-I-2M$

(24) ΣL: $-2 = A+B+C+J+K+L+M+N-D-E-3F-H$

(25) ΣT: $-1 = -D-G$

(26) ΣM: $0 = E+F+H+M-G$

(27) ΣF: $0 = N-M$

Since there are six equations and fourteen unknowns, it is necessary to solve in terms of eight of the unknowns. Those chosen are B, C, G, H, I, J, K and L. This results in:

(28) $A = -1+2I-B-C-J-K-L$

(29) $D = 1-G$

(30) $E = G-H-I$

(31) $F = I$

(32) $N = M = 0$

Substituting these for the exponents in equation (20)

$$(33)\quad h = \gamma\,\frac{T^{2I}{}_{D}{}^{B}{}_{D_W}{}^{C}{}_{k\,\mu}{}^{G}{}_{\rho}{}^{I}{}_{c}{}^{G}{}_{\mu_W}{}^{H}{}_{N}{}^{I}{}_{Z}{}^{J}{}_{C}{}^{K}{}_{J}{}^{L}}{T\,T^{B}{}_{T}{}^{C}{}_{T}{}^{J}{}_{T}{}^{K}{}_{T}{}^{L}{}_{k}{}^{G}{}_{\mu}{}^{H}{}_{\mu}{}^{I}} + \gamma' \text{ etc.}$$

$$(34)\quad h = \gamma\left(\frac{k}{T}\right)\left(\frac{D}{T}\right)^{B}\left(\frac{D_w}{T}\right)^{C}\left(\frac{c\mu}{k}\right)^{G}\left(\frac{\mu_w}{\mu}\right)^{H}\left(\frac{NT^2\rho}{\mu}\right)^{I}\left(\frac{Z}{T}\right)^{J}\left(\frac{C}{T}\right)^{K}\left(\frac{J}{T}\right)^{L}+\gamma' \text{ etc.}$$

This may also be expressed:

$$(35)\quad \frac{hT}{k} = F\left[\left(\frac{c\mu}{k}\right),\left(\frac{T^2N\rho}{\mu}\right),\left(\frac{\mu_w}{\mu}\right),\left(\frac{D}{T}\right),\left(\frac{D_w}{T}\right),\left(\frac{Z}{T}\right),\left(\frac{C}{T}\right),\left(\frac{J}{T}\right),\left(\frac{B}{x}\right),\left(\frac{Y}{y}\right)\right]$$

Since both L and D are linear, the equation may be expressed in the more familiar form:

$$(36)\quad \frac{hT}{k} = F'\left[\left(\frac{c\mu}{k}\right),\left(\frac{D^2N\rho}{\mu}\right),\left(\frac{\mu_w}{\mu}\right),\left(\frac{T}{D}\right),\left(\frac{D_w}{D}\right),\left(\frac{Z}{D}\right),\left(\frac{C}{D}\right),\left(\frac{J}{D}\right),\left(\frac{B}{x}\right),\left(\frac{Y}{y}\right)\right]$$

2. Heat Transfer Equations

a. General

The three fundamental equations of conductive and convective heat transfer have been developed and described so fully and generally (68,79,112) that there is no purpose in doing so here. These equations are:

$$(37)\quad q = UA\Delta t_m$$

$$(38)\quad q = wc(t_{b2} - t_{b1})/\Delta\theta$$

$$(39)\quad 1/U = 1/h + (1/h_o + r_d + r_m)$$

Equating equations (37) and (38) and solving for U

$$(40)\quad U = \frac{wc\ (t_{b2} - t_{b1})}{\Delta\theta A\Delta t_m}$$

By the use of equation (40) the overall coefficient U can be calculated directly from the change in temperature over a definite time interval for a specific quantity of fluid. All factors in equation (40) except U can be evaluated directly and U calculated therefrom.

The more difficult problem is the measurement or evaluation of the batch film coefficient. Two methods are available. One is to measure the temperature drop across the film and to calculate h from equations (37) and (38) directly. The second is to calculate the overall coefficient U and resolve it into its component parts. The latter can be done in two ways: one by calculation of individual film coefficients, the other by use of the method of Wilson (168).

Chilton, Drew and Jebens (30) and Gordon (38) both measured wall temperatures by means of thermocouples imbedded in the vessel walls so that they measured the temperature of the surface. This involved a great deal of precise machine and thermocouple work and considerable calibration of the instruments. Both Carroll (28) and Uhl (151) resolved the film coefficients from the overall coefficients. Carroll who used only steam condensing in the jacket, calculated the condensing steam film coefficients, the wall resistance and by observation assumed the dirt film to be negligible. Uhl used both water and steam in the jacket. Since there are no adequate equations for the film coefficients for water flowing in jackets, he evaluated h from the graphical method of Wilson.

In each of these three methods of determining the film coefficients, there are inherent inaccuracies. Measurement of wall temperatures involves considerable physical work done on the thermocouple junctions which may lead to inaccuracies. Also, there is no way to be absolutely certain exactly what the thermocouple is measuring. Where condensing steam is used in the jacket, it is probable that the equations for individual resistances are as good as any method except that a dirt film must be assumed. Also, this method allows no means for determining coefficients for water circulating in the jacket. The Wilson plot method is admittedly an approximate method. It is probable, however, that the results are very nearly as accurate as the other methods and it has the virtue of simplicity.

It was therefore decided that in this paper film coefficients would be evaluated from the overall coefficient U by the method of Wilson (168). The basic equation for this is equation (39) above. This equation states that the overall resistance is the sum of the jacket film, dirt film, metal wall, and batch film resistances. In a given set of equipment the metal wall resistance is essentially constant. Care in cleaning and operation will make the dirt film resistances small and relatively constant. If the fluid in the jacket is kept at constant velocity, the jacket film resistance will be essentially constant. If the sum of these nearly constant resistances is called R_c, equation (39) becomes:

$$(41)\quad 1/U = R_c + 1/h$$

Wilson postulated that the batch film coefficient h is a function of the velocity of the fluid passing the surface, Holding all other variables constant and varying only the velocity of the fluid he found h to be a function of the eight-tenths power of the velocity in turbulent flow in pipe lines. By analogy, the same fundamental relationship should hold in a jacketed agitated vessel. While the velocity of the fluid past the wall is not easily measurable it may be assumed to be directly proportional to the ~~relational~~ rotational speed of the agitator, N. In this case, equation (41) becomes:

(42) $1/U = R_c + 1/f(N)$

Returning to the dimensional analysis, it was assumed in equation (36) that, when all variables other than N were constant,

(43) $h = KN^I$ and equation (42) becomes

(44) $1/U = R_c + 1/KN^I$

Equation (44) is of the form $y = mx + k$ or the simple linear equation. Plotting $1/U$ versus $1/N^{I}$ $3/4$ on coordinate paper should result in a straight line having a slope and y-intercept R_c. Thus R_c can be obtained graphically and h can be calculated from U using equation (41).

In order to use this method for determining the film coefficient, it is necessary to know the exponent I in equation (44). Chilton et al (30) determined this exponent as 2/3 in equation (1). This value has been used by all subsequent investigators~~. However,~~ recalculation of the data of Chilton et al (30) indicated to the author that a better correlation of data can be made using the 3/4 power of the Reynolds number. For this reason, therefore, the exponent I is given the value 3/4 in this paper, and equation (44) becomes:

(45) $1/U = R_c + 1/KN^{3/4}$

The recalculation and critique of previous data is described in the two sections following.

b. Results of Previous Investigators

Because of the subject matter of this paper, this is limited to work done on the jacket film coefficients in vessels stirred by paddle type agitators.

Referring to the dimensional analysis in Section I. C. 1., there are eleven dimensionless groups involved in a complete correlation. These involve the Nusselt, Prandtl and Reynolds numbers, the ratio of wall viscosity to bulk viscosity and several groups describing the geometry of the system. Thus far the work done has been only to attempt to correlate the first four groups mentioned. The variations in results between the various investigators undoubtedly involve differences in some or all of these geometric groups as well as differences in experimental techniques. Prior to actual experimental work to define some of these geometric variables, some investigation of published data was made to see if any correlation is indicated.

The published work of Chilton, Drew and Jebens (30) was the first paper on the subject. As an authoritative paper presented by recognized experts in the field, it has found wide acceptance in the field. The equations presented have become the standard and are reprinted as such in references such as Perry (112) and Kern (68). The heat transfer coefficients were determined by means of direct wall temperature measurements. As described previously, the Nusselt, Prandtl, and Reynolds numbers were correlated by a method of cross plotting. In a plot of log N_{Nu} versus log N_{Re} the points fall into various groups according to the Prandtl numbers through which parallel lines having a 2/3 slope are drawn. There is sufficient scatter of data that other slopes could also be drawn without too much impunity. In the second plot, log $(N_{Nu}/N_{Re}{}^{2/3})$ was plotted against log N_{Pr}. Here a line having a slope of 1/3 was drawn through scattered data. The third plot, log $(N_{Nu}N_{Pr}{}^{-1/3})$ versus log N_{Re}, was shown with a line drawn through scattered data having a slope of 2/3 to confirm the first plot. The spread of points grouped the heating and cooling data rather logically into two separate parallel lines. Following the method of Sieder and Tate (147), a plot of log $(N_{Nu}N_{Pr}{}^{-1/3}N_{Re}{}^{-2/3})$ versus log $(\mu w/\mu)$ was made. A line having a slope of-0.14 was arbitrarily drawn through the points. This value was the value found by Sieder and Tate (147) for flow inside pipes. A final plot (Fig. 1) of log $N_{Nu}(\mu w/\mu)^{-.14}(N_{Pr})^{-1/3}$ versus log N_{Re} gave a good correlation in the form equation (1).

In each of these four correlations, a certain amount of choice can be made in the slope of the correlating line. This is particularly true in establishing the exponent of the viscosity ratio. It would appear to the eye that a slope of about -1/5 would better describe the data of the viscosity ratio plot than the -0.14 selected. In the figures where the exponent of the Reynolds Number is in question, it is also possible to obtain slopes of 0.7 to 0.75 instead of the 2/3 selected which also describes the data. In the plot determining the Prandtl number exponent, it is likewise possible

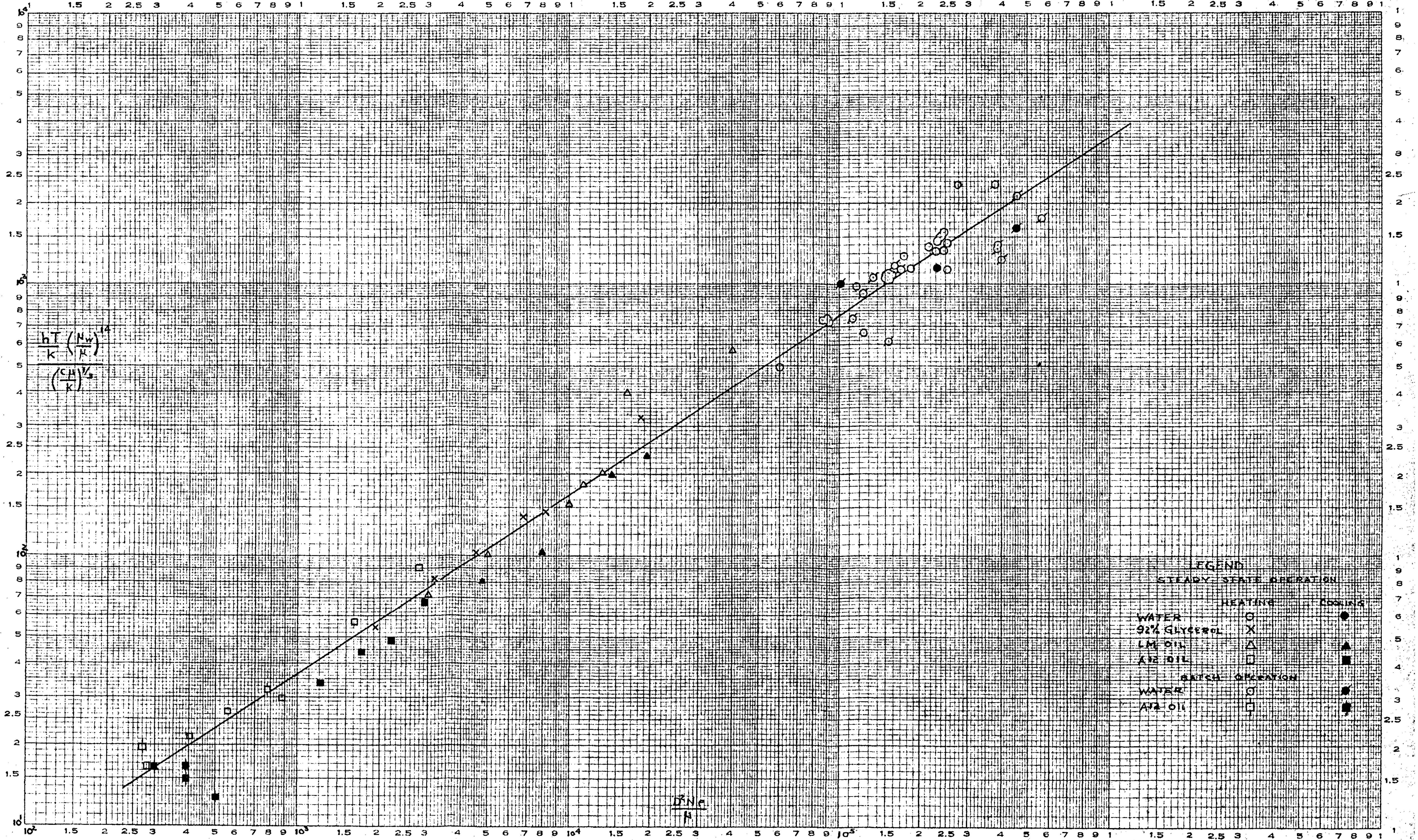

FIG.I PUBLISHED CORRELATION, DATA OF CHILTON ET AL. (30)

to draw a line having a slope of 2/5 instead of 1/3 selected.

Gordon (38) presented a correlation in terms of Nusselt, Prandtl and Reynolds numbers in which the groups were not truly dimensionless. Also, since his data were for heating only, no use was made of the viscosity ratio. Therefore, it is not possible to compare his work directly with that of Chilton et al. (30). Like Chilton et al (30), Gordon measured wall temperatures directly and obtained film coefficients therefrom. Thus, and also considering the pains taken to achieve accurate measurements, there can be no argument with the coefficients. In order to compare Gordon's data with those of Chilton et al (30),a plot of log $N_{Nu}N_{Pr}^{-1/3}(\mu_w/\mu)^{0.14}$ versus log N_{Re} was made using recalculated dimensionless groups. Over all, the data appear as a curve concave up made up of a series of nearly parallel straight lines corresponding to the groups by constant Prandtl number. A line corresponding to the equation

$$N_{Nu} = 0.47\, N_{Pr}^{1/3} N_{Re}^{2/3} (\mu_w/\mu)^{-0.14} \qquad (46)$$

can be drawn through these data to give a comparison to the equation of Chilton. A line having a slope of 3/4 would better describe the data although the correlation is obviously not the best. This is evident from the grouping of certain data and leads to the assumption that the physical properties are not accurately correlated by this form of the equation. This indicates that another exponent for the Prandtl number should be chosen. Cummings and West (32) recalculated Gordon's data and it is shown in their final correlation. Their results confirm the author's recalculation.

It should be noted that the agitator was quite wide in relation to its diameter (D_W/D) = 0.75 versus 0.167 for Chilton) and had a curved bottom. This may have some effect on the correlation. Also, the wall temperatures were relatively high in Gordon's work. In the case of the oils, they were still low with respect to the boiling point. In the case of water, however, nine of the twelve points had water temperatures 175°F or higher and five of these are in excess of 200°F. The conductivity of the copper walls is relatively high and in the case of the high wall temperatures, the apparent film coefficients may be high because of localized vaporization. It is, therefore necessary to place more weight on the oil than on the water data.

In Carroll's (28) work, the film coefficients were deduced from over-all coefficients measured in a system at steady state. The resistance of dirt films was assumed negligible since the surfaces, clean to start with, remained clean to the eye. The metal resistance was calculated from the conductivity, relative areas and thickness. The heating steam film coefficient was calculated as that of condensing steam (160). The batch film coefficient was computed by the difference of the over-all resistance and the remaining resistances. Steam film coefficients ranging from 1750 to 2200 B.t.u. per hour - sq. ft. - °F were obtained which correspond roughly to those used by other investigators.

Since only one speed was used in steady temperature operation, no check by the method of Wilson (168) was possible and wall temperatures were not measured directly. Adequate precautions in the accuracy of measurements of temperature and physical properties were taken.

Carroll's (28) work covers only a range of Reynolds numbers from 16,000 to 75,000 and Prandtl numbers from 1.9 to 11.5. He, therefore, did not attempt to correlate by the method of cross plotting. He rather accepted the Chilton (30) equation and determined a new coefficient for this equipment. Carroll's equation was

$$(47) \qquad N_{Nu} = 0.6\ N_{Pr}^{1/3} N_{Re}^{2/3} (\mu_w/\mu)^{-0.14}$$

There is sufficient scattering of data points to draw lines with slopes from 0.6 to 0.8. There is a possibility that some vortexing occurred which made some of the apparent coefficients excessively high.

Uhl's (151) extensive work was done in the lower Reynolds number range between 17 and 4000. The film heat transfer coefficients were deduced from the over-all coefficients by a modification of the method of Wilson (168). In Uhl's paper, the equation of Chilton et al (30) was assumed to be correct insofar as $h = f\ (N)^{2/3}$.

From the data, a plot of $1/U$ versus $1/N^{2/3}$ was made. The combined resistances thus obtained were, for heating $0.0033, [1/2(0.004 + 0.0026)]$ and for cooling $0.010, [1/4(0.010 + 0.014 + 0.018 + 0.014)]$. Individual batch film coefficients were calculated from this and the dimensionless groups, N_{Re}, N_{Pr}, N_{Nu} and (μ_w/μ) evaluated.

Correlation of the dimensionless groups was by the cross plotting method. A plot of log N_{Nu} versus log N_{Re} gave a slope of 2/3. A plot of log $N_{Nu}N_{Re}^{-2/3}$ versus log N_{Pr} gave a slope of 0.320 for heating and 0.337 for cooling. A plot of log $N_{Nu}N_{Pr}^{-1/3}N_{Re}^{-2/3}$ versus log (μ_w/μ) gave a slope of -0.24. The final correlation was a plot of $N_{Nu}N_{Pr}^{-1/3}(\mu_w/\mu)^{-0.24}$ versus N_{Re} and resulted in the equation $N_{Nu} = 0.415\ N_{Pr}^{1/3}N_{Re}^{2/3}(\mu_w/\mu)^{-0.24}$.

In the first place, assuming h a function of $N^{2/3}$ established h as a function of $N_{Re}^{2/3}$. On the basis of previous work, this is a valid assumption. It leaves, however, no opportunity to correlate at any other function of the Reynolds number as has already been suggested.

In the second place in the plot where the exponent of the Prandtl number is determined, secondary correlations of smaller groups of data are obvious. The slopes of these are about 0.45. This indicates the possibility that a better correlation exists at a higher exponent than 1/3 of the Prandtl number.

For the first time on record, Uhl (151) has shown that the exponent of the viscosity ratio should be greater than -0.14. This was a particularly significant development and was at least indicated by the paper of Chilton <u>et al</u> (30).

c. Recalculation of the Data of Other Investigators

Before investigating the correlation of the geometric ratios in the dimensional analysis (eq. 36), it was decided to investigate further the exponents of the Prandtl and Reynolds numbers and the viscosity ratio. There is considerable evidence as discussed in the previous section that the exponents now in general use are not the best.

As a first step, the data of Chilton, Drew and Jebens (30) were recorrelated by the method they used. First, log N_{Nu} was plotted against log N_{Re}. Parallel lines of slope 3/4 were drawn through groups of data having essentially the same Prandtl numbers (Fig.2). This seemed to describe the data adequately. Log $N_{Nu}N_{Re}^{-3/4}$ was then plotted against log N_{Pr} (Fig.3). A line having a slope of 0.44 seemed best to describe the data. Then log $N_{Nu}N_{Re}^{-3/4}N_{Pr}^{-0.44}$ was plotted against log (μ_w/μ) (Fig.4). A line having a slope of -1/4 seemed best to describe the data. Finally, log $N_{Nu}(N_{Pr})^{-1/3}(\mu_w/\mu)$ was plotted against log N_{Re} (Fig.5). The line best describing the data appeared to be described by

$$(48) \quad N_{Nu} = 0.0765\, N_{Re}^{0.786} N_{Pr}^{0.44} \, (\mu_w/\mu)^{-1/4}$$

This corresponds to the final correlation of Chilton *et al* (30). To the author, at least, the correlation of Figure 5 appears better than that of Figure 1.

In the same manner, the data of Gordon (38) were recalculated. The Nusselt number was plotted against Reynolds number on log paper. For essentially the same Prandtl numbers, slopes of 3/4 were drawn. Log $N_{Nu}N_{Re}^{-3/4}$ was plotted against log N_{Pr}, the correlating line having a slope of 0.44. Log $N_{Nu}N_{Re}^{-3/4}N_{Pr}^{-0.44}$ plotted against log (μ_w/μ) gave a line having a slope about -1/4. Log $N_{Nu}(\mu_w/\mu)^{1/4}N_{Pr}^{-0.44}$ plotted

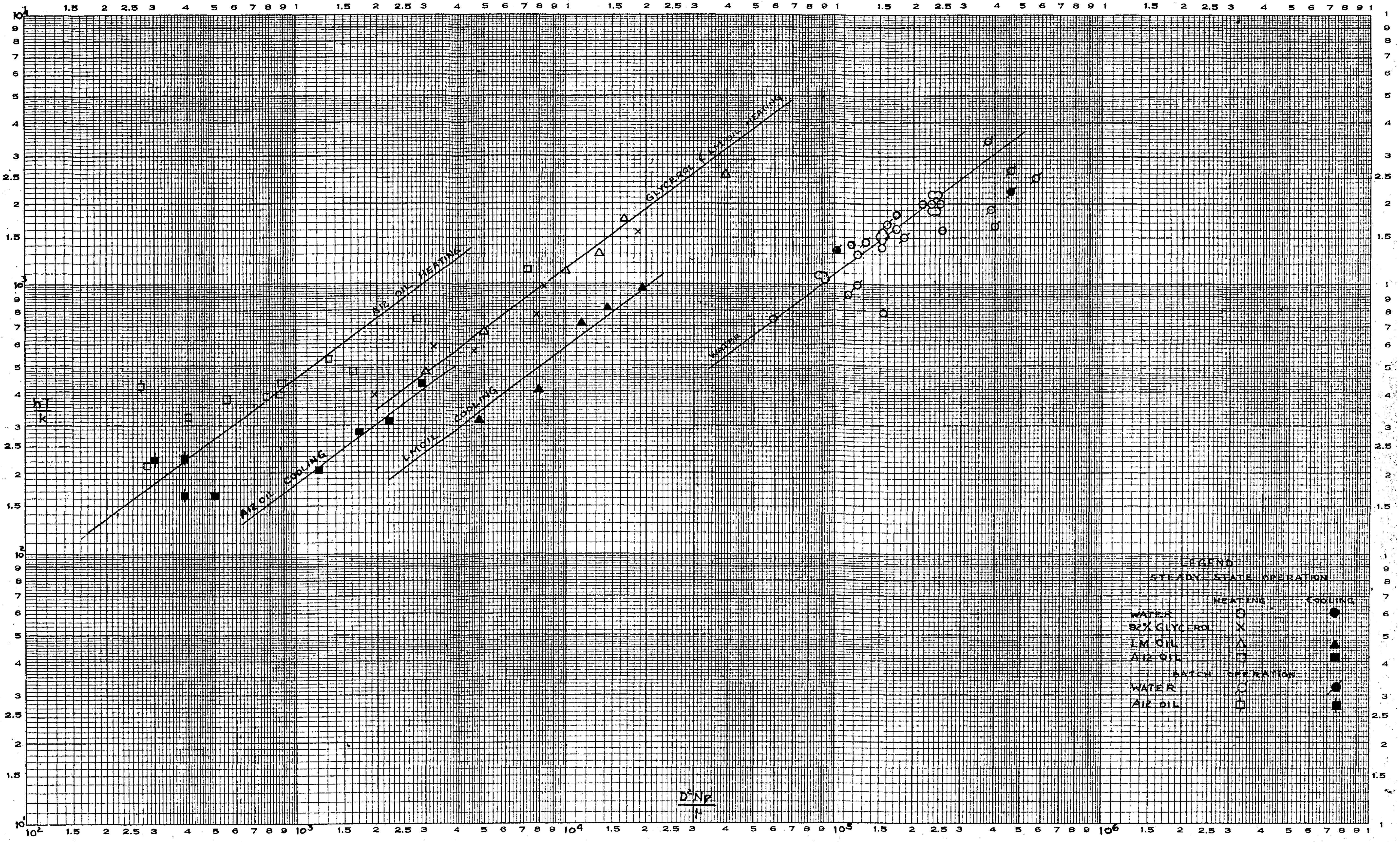

FIG. 2 DETERMINATION OF REYNOLDS No. EXPONENT
DATA OF CHILTON ET AL. (30)

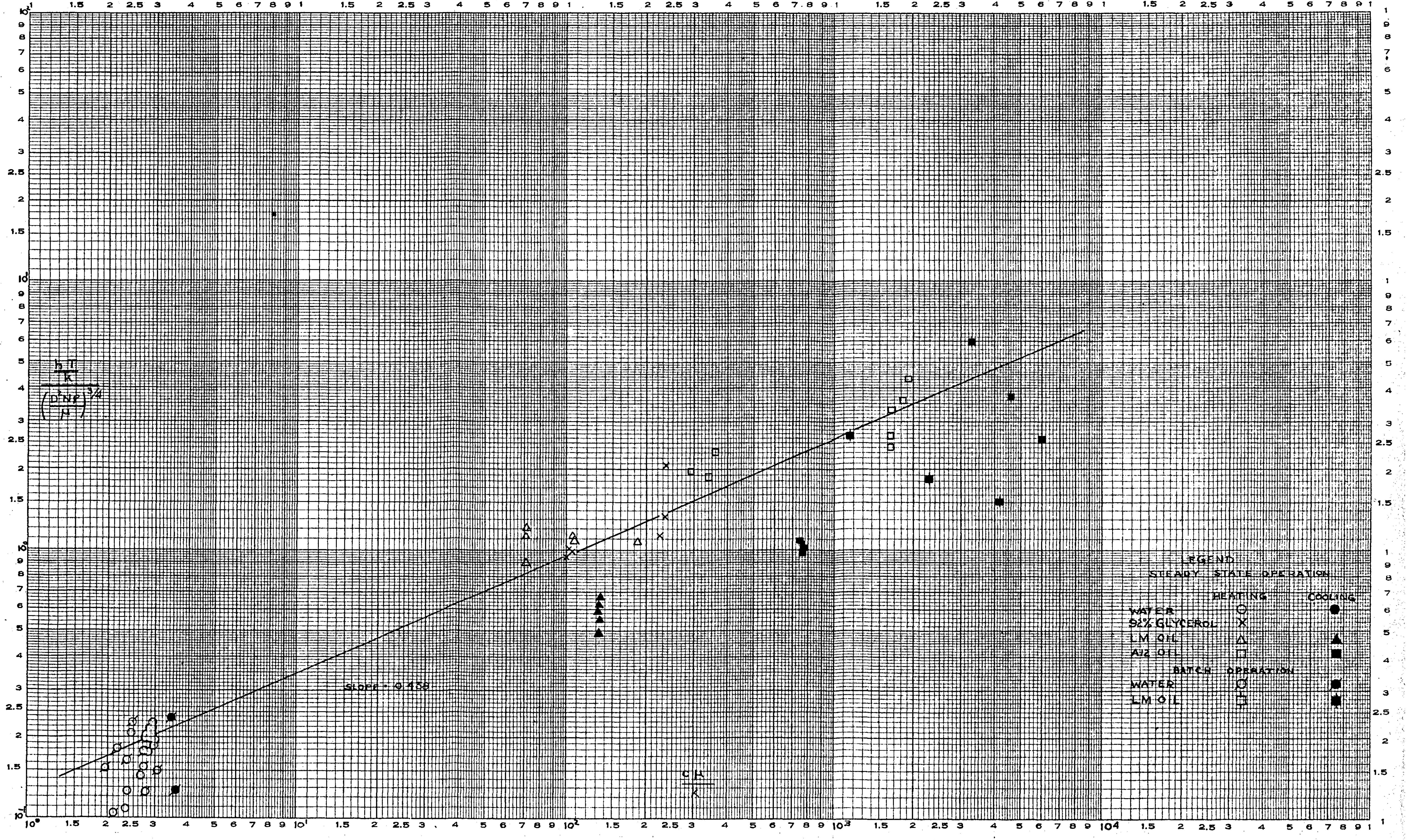

FIG. 3 DETERMINATION OF PRANDTL No. EXPONENT
DATA OF CHILTON ET AL. (30)

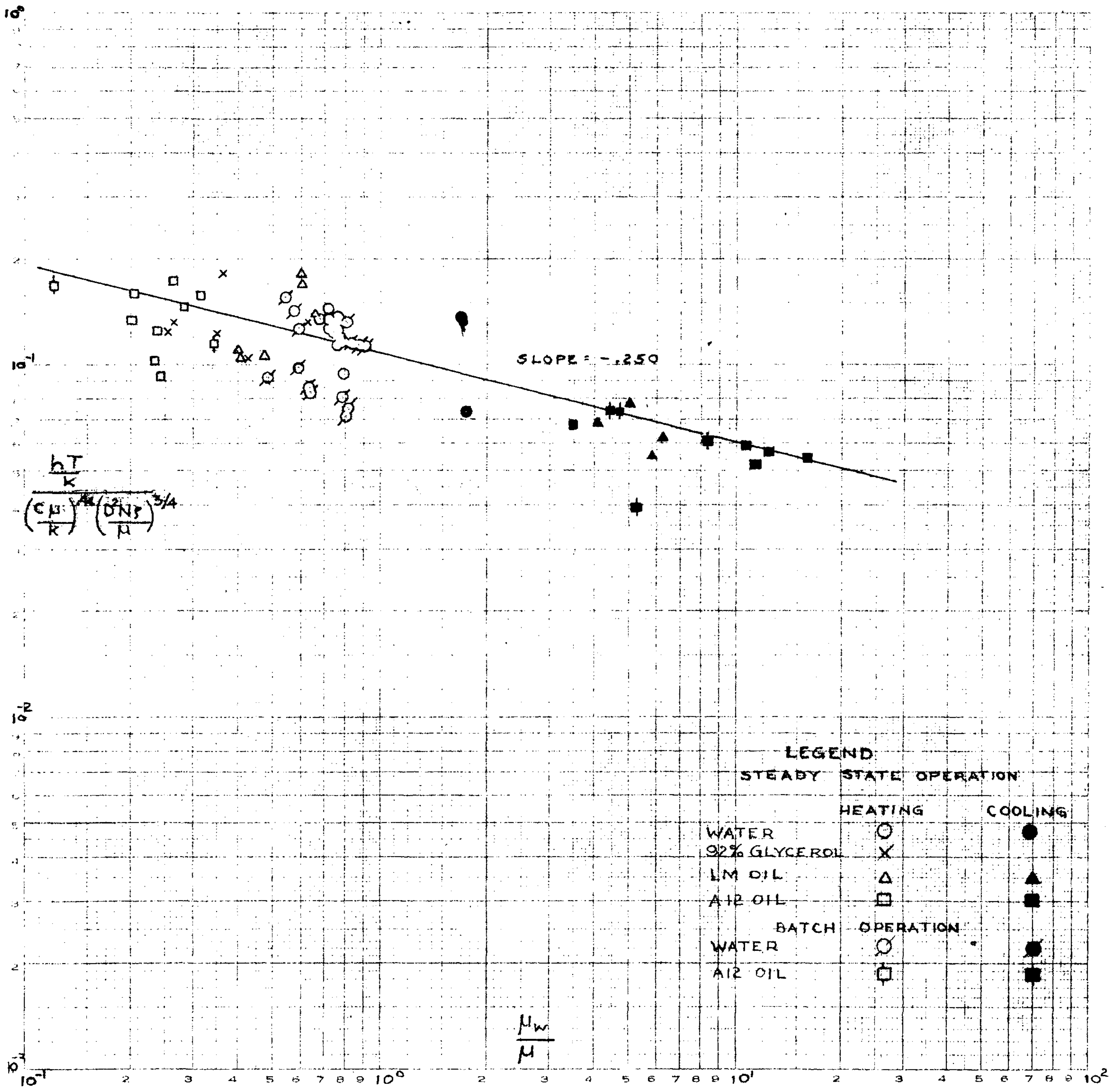

FIG. 4. DETERMINATION OF VISCOSITY RATIO EXPONENT
DATA OF CHILTON ET. AL. (30)

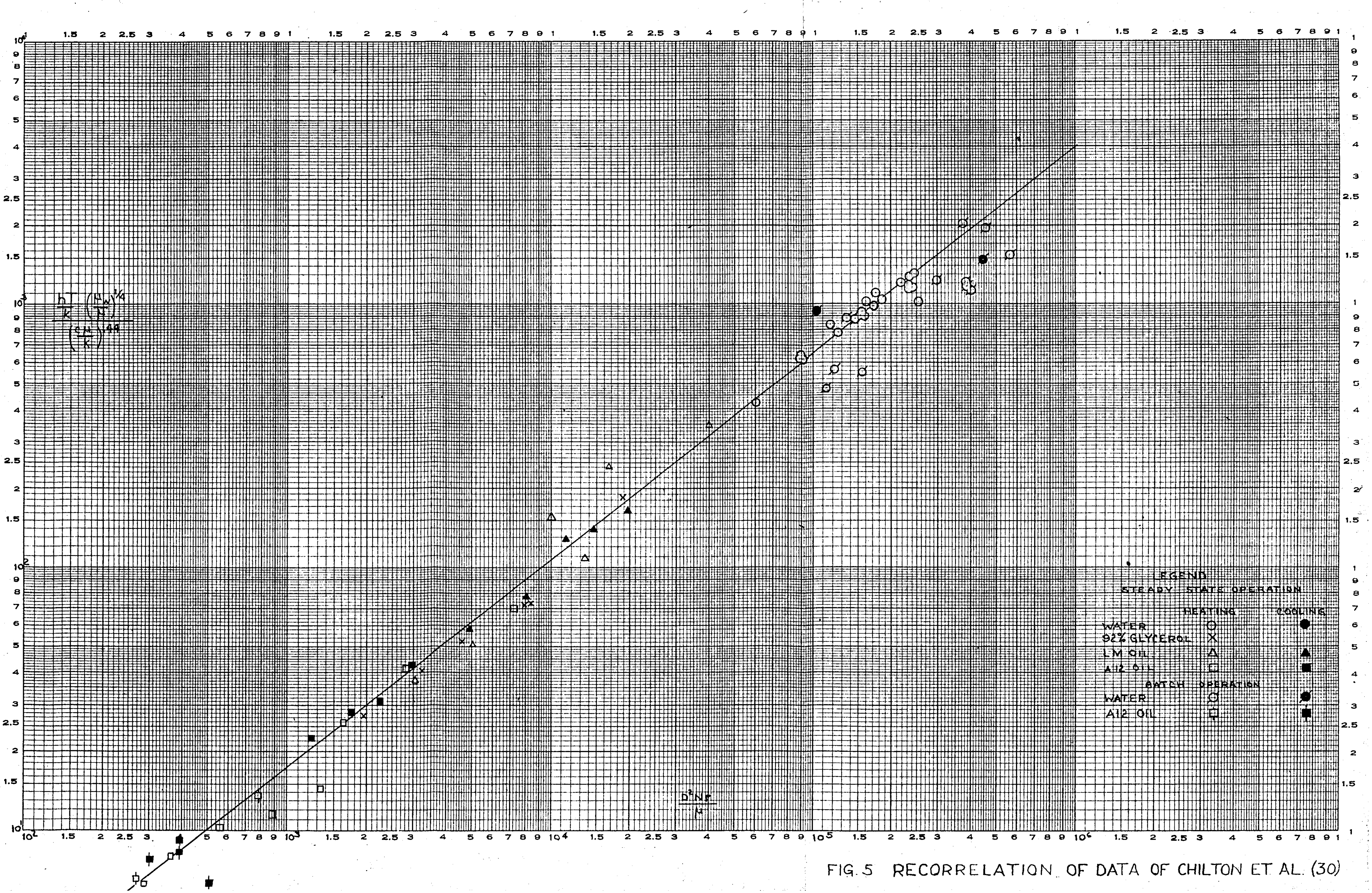

FIG. 5 RECORRELATION OF DATA OF CHILTON ET AL. (30)

against log N_{Re} gave a line having the equation

$$(49) \quad N_{Nu}(\mu_w/\mu)^{1/4} = 0.110\ N_{Pr}^{0.44}\ N_{Re}^{0.781}$$

This corresponds to Figure 5 for Chilton's data and appears a better correlation than the previous one.

To recalculate the data of Uhl (151) it was necessary first to recalculate the heat transfer coefficients. Uhl had started with the assumption that h was a function of $N^{2/3}$. The previous paragraphs of this section indicate that h is a function of about the 3/4 power of N. Therefore, h was recalculated by a Wilson plot of 1/U versus $1/N^{3/4}$. For heating the average of the combined resistances was 0.0040 versus Uhl's 0.0033 and for cooling it was 0.020 versus Uhl's 0.010. New values of h and μ_w and the Nusselt numbers and viscosity ratios were recalculated from this. Since h was now assumed to be a function of $N^{3/4}$, it was assumed to apply also to these data. A plot of log $N_{Nu}N_{Re}^{-3/4}\ N_{Pr}^{-0.44}$ versus log (μ_w/μ) was made which had a slope of -0.247. A plot of log $N_{Nu}(\mu_w/\mu)^{1/4}\ N_{Pr}^{-0.44}$ versus log N_{Re} gave a line having an equation

$$(50) \quad N_{Nu}(\mu_w/\mu)^{1/4} = 0.1042\ N_{Pr}^{0.44}\ N_{Re}^{0.746}$$

This corresponds to Figure 5 for the data of Chilton *et al*.

In the case of Carroll's data (28), there was insufficient data to evaluate the exponents of each group independently. Therefore, log $N_{Nu}(\mu_w/\mu)^{1/4}\ N_{Pr}^{-0.44}$ plotted against log N_{Re} gave a line having the equation

$$(51) \quad N_{Nu}(\mu_w/\mu)^{1/4} = 0.195\ N_{Pr}^{0.44}\ N_{Re}^{0.745}$$

This corresponds to Figure 5.

Up to this point, the method of correlating groups corresponds to the method used by previous investigators. Two points, however, are evident. First, the data in the graphs were spread because other significant data had not yet been introduced. This meant more approximating of the true slopes of correlating lines. Second, the viscosity which varies over a wide range appears in three of the four groups correlated. It is entirely possible and probable that in chosing exponents for the various groups, operations on one group containing μ may influence the exponent in another group. If the basic assumption in the dimensional analysis is valid, that is, if h varies as μ to a specific power, then that power must be the sum of the exponents of μ in each group in which it appears. This was shown by Brown et al (22) who determined $h = F\ (\mu)^{-0.425}$. These various exponents for the dimensionless groups, however, must also determine the exponents for the other variables such as c, k, ρ, D, N, etc., and the values must be properly chosen to do so. For this reason, the correlation was carried further in order to determine more exactly the proper exponent for each group.

It was decided first to check the exponent of the Prandtl number. An average value of the 3/4 power of the Reynolds number was assumed from the above data. Plots were made of log $N_{Nu}(\mu_w/\mu)^{1/4}\ N_{Re}^{-3/4}$ versus log N_{Pr}. For the data of Chilton et al (Figure 6) the slope was 0.44; for the data of Gordon the slope was 0.44; for the data of Uhl the slope was 0.402. This lead fairly conclusively to the assump-

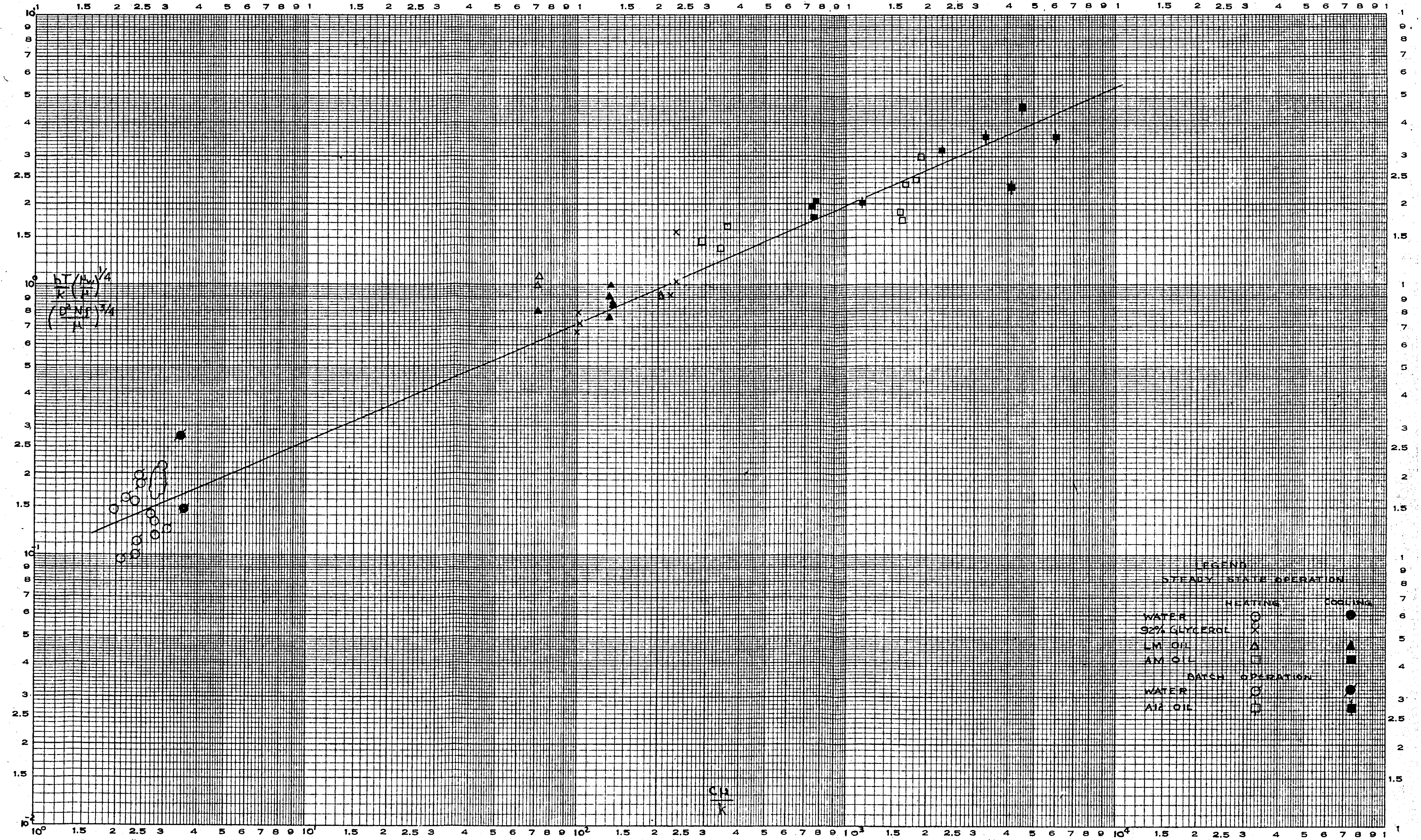

FIG. 6 RECHECK OF PRANDTL No. EXPONENT
DATA OF CHILTON ET. AL. (30)

tion of the .44 power of the Prandtl number. Also, it indicated that the previous calculations of the 3/4 power of the Reynolds number and the -1/4 power of the ratio μ_w/μ were correct.

3. Calibration of Instruments

For the runs made on water, a General Electric thermocouple potentiometer was used. Copper copnic thermocouples were used and connected through a selector switch to the potentiometer. A cold-junction thermocouple was kept in a thermos bottle of ice at zero degrees. This instrument was calibrated on the dial to read directly in degrees centigrade and also in millivolts. The thermocouples actually used including the selector switch were calibrated against ice and boiling water. It was found that at 100°C, the selector switch in the circuit lowered the reading slightly. Therefore, it was necessary to make a calibration curve of millivolts versus temperature. The instrument and selector switch circuit was thus calibrated against itself without the selector switch. This was done for ten degree intervals between 0 and 100°C. The data was plotted in Figure 7 as emf in millivolts versus temperature in degrees Fahrenheit. As an added precaution, the potentiometer was checked by simultaneous readings against the L & N galvanometer. It was found to check exactly.

The L & N galvanometer was used for the glycerol and glycerine-water runs.

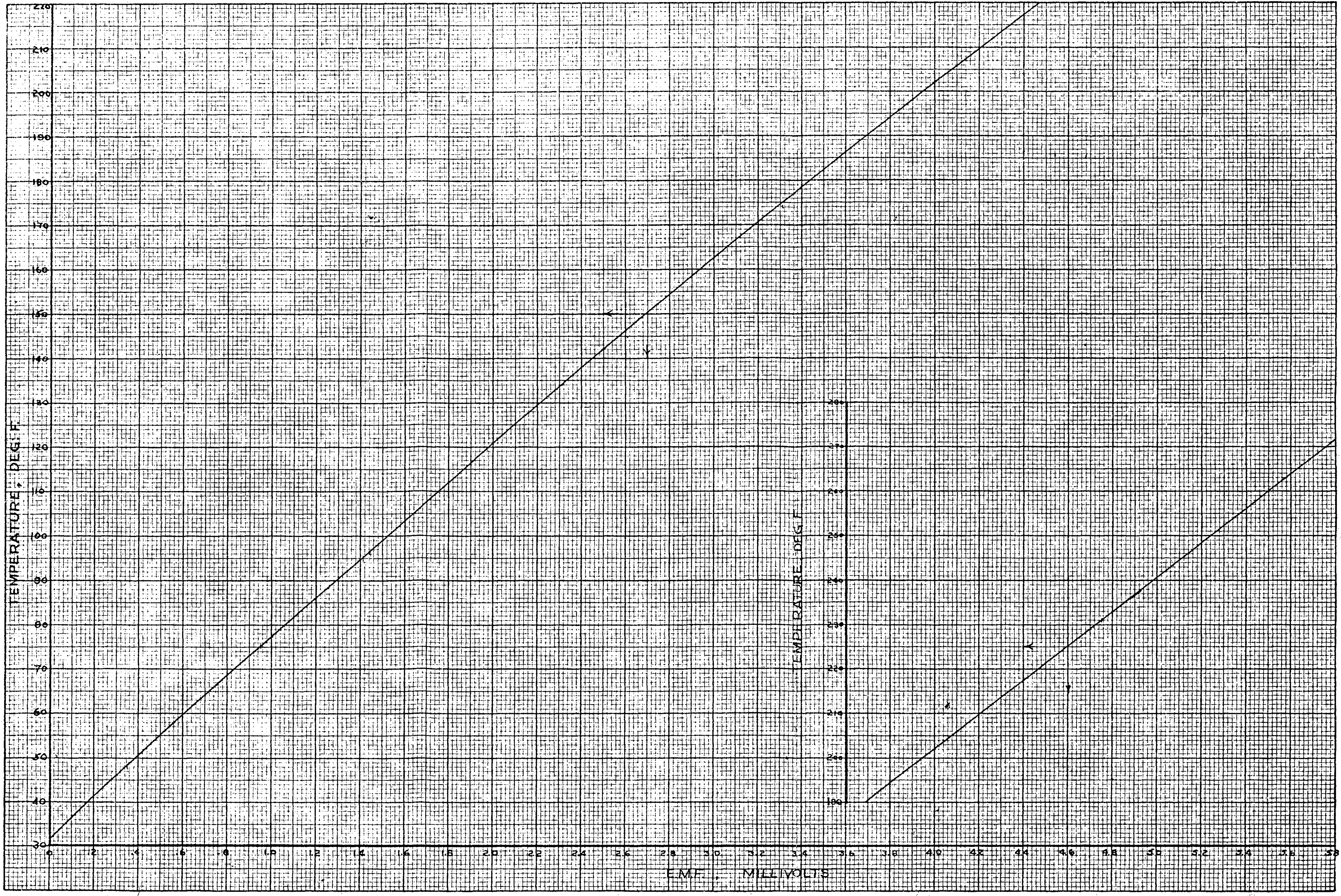

FIG. 7 CALIBRATION OF INSTRUMENTS

II. EQUIPMENT

Specifications

Kettle (Fig. 8)

Inside diameter (T)	23 1/2 in.,1.96 ft.
Wall thickness	1/4 in., .0208 ft.
Material	Steel
Head thickness	1/4 in., .0208 ft.
Length of straight side (TO KR)	24 in., 2.00 ft.
Overall depth	28 11/16 in.
Type head APPROX VOL = 7.83 GALLONS	Standard flange and dish
Heating surface, head, inside	3.17 sq. ft.
Heating surface, head, outside	3.37 sq. ft.
Heating surface, shell inside, per inch above KR	0.512 sq.ft./in.
Heating surface, shell outside, per inch above KR	0.523 sq.ft./in.

Jacket

Inside diameter	29 1/2 in., 2.46 ft.
Wall thickness	1/4 in., .0208 ft.
Material	Steel
Head thickness	1/4 in., .0208 ft.
Length of straight side (TO KR)	27 in., 2.50 ft.
Overall depth	28 15/16 in.
Type head	Standard flange and dish

Motor

Make	Scott
Rated voltage	110
Rated horsepower	1/2
Full load speed	1750 rpm

Reduction Unit.

Make	Worthington
Model	A, All Speed selector
Serial No.	1A220
Reduction ratio	1:1 -- 15:1

Potentiometer

Maker	General Electric
Type	PJ - LB4
No.	2052346

Thermocouples	
Copper-Copnic	H-821233
Galvanometer	
Maker	Leeds & Northrop
Cat. No.	6667
Serial	702727
Tachometer	
Maker	James G. Biddle Co., Philadelphia,Pa.
No.	K 504147
Ranges	25-100 rpm by units 100-300 rpm by twos

Five different agitators were tested. These were all of the same type made from 1/8" thick bar 3 inches wide and welded to a 1 1/2" diameter hub 4" long. A 5/8" diameter shaft was used and the agitators fastened to the shaft by set screws. Overall diameters ranged from 5 7/8 in. to 19 1/8 in. These are shown in Fig. 9.

The equipment was arranged as shown in Figure 10. The motor at 1750 rpm drove the input of the All-Speed Selector through a 2:1 reduction gear and sprocket. The Selector allowed variation in speed reduction from 16:1 to 1:1 or 54.7 rpm to 875 rpm. The agitator shaft was driven from this through bevel gears having a reduction ratio of 1.7 to 1. This allowed variation of agitator speeds from 32 to 515 rpm.

Thermocouples were mounted in copper thermowells swedged and brazed closed. The wells in the pipe line were 1/8 in dia. tubing. The well used in the kettle was 1/4 in. heavy wall tubing with the tip turned down before swedging. After installing the thermocouples in the wells, copper powder was poured in and tamped down to insure rapid response.

1.625
.75
.875

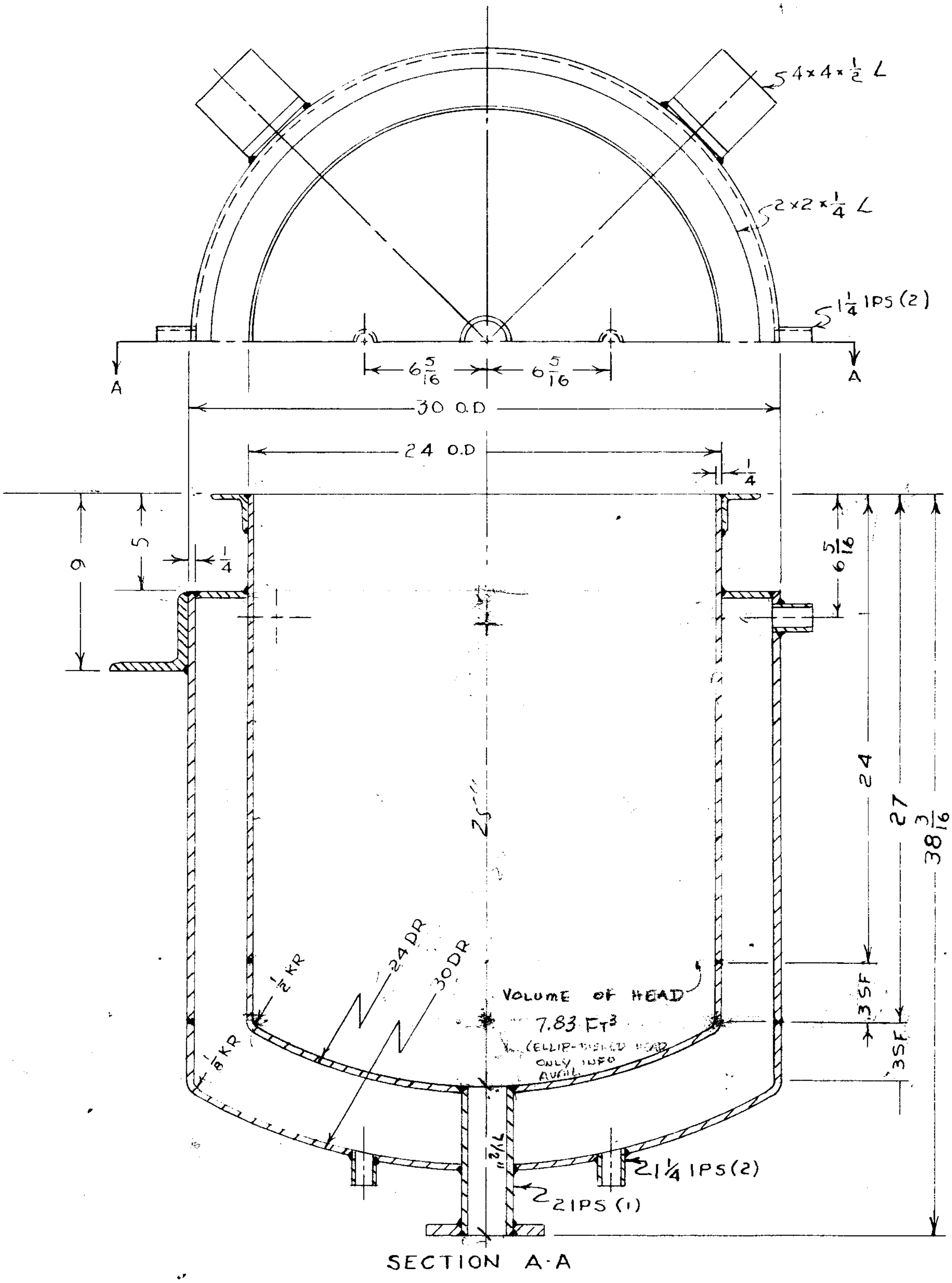

FIG. 8 KETTLE DETAILS

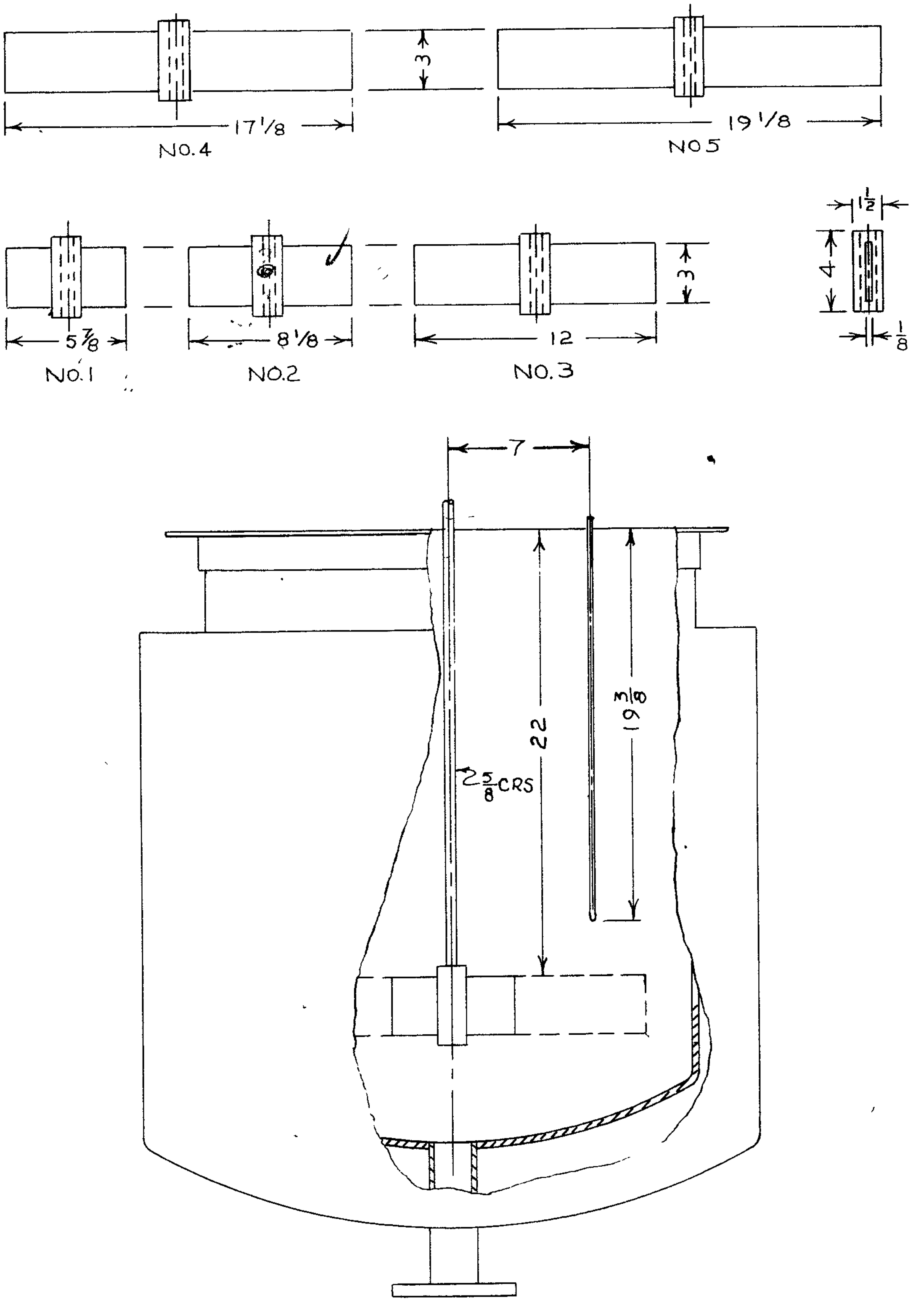

FIG. 9 AGITATOR DETAILS

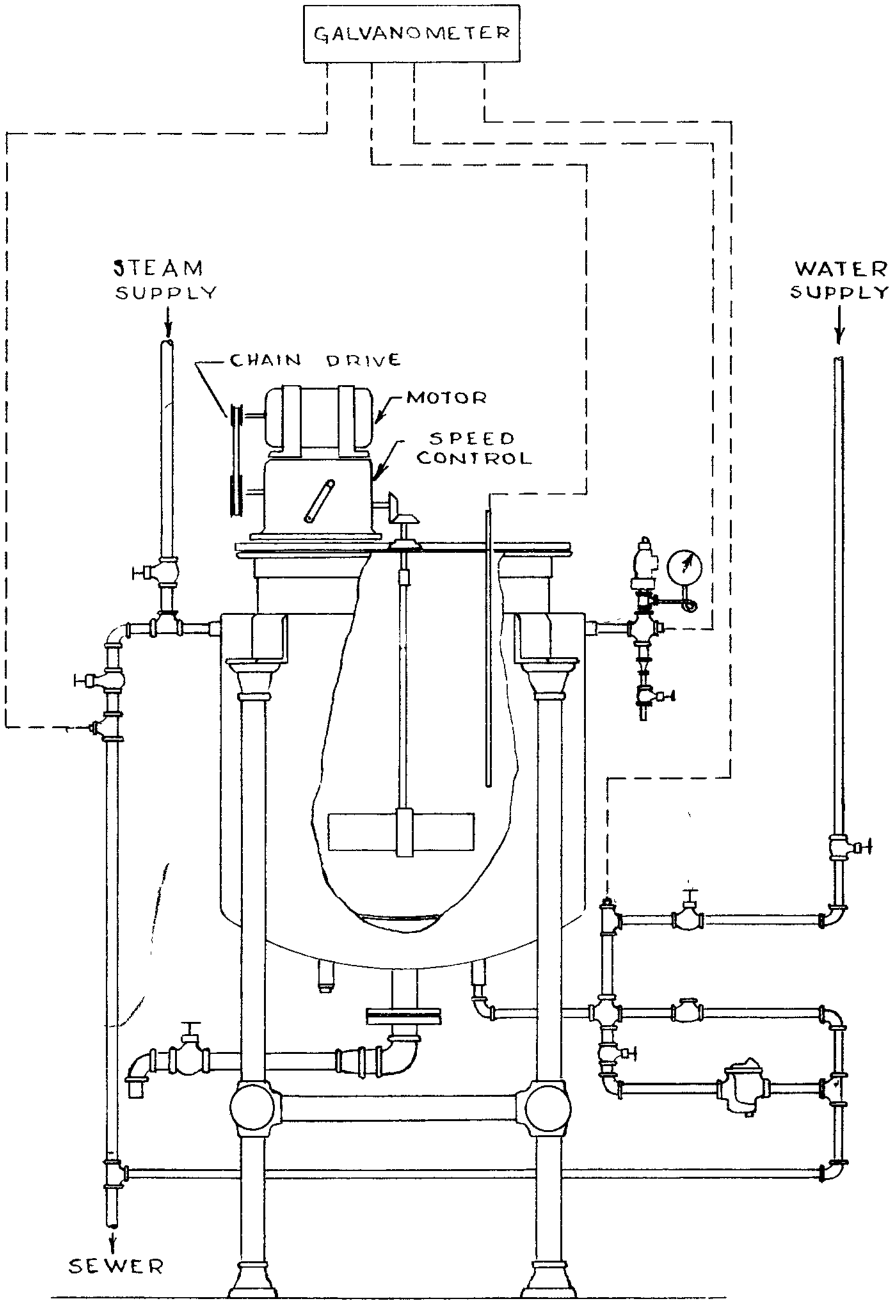

FIG. 10 ARRANGEMENT OF EQUIPMENT

III. PHYSICAL PROPERTIES OF FLUIDS

Water:

Water from the Newark city water supply was used. Viscosity data (74A) for water is shown in Fig. 11. Density, thermal conductivity, and specific heat data are shown in Table II.

Glycerol:

CP - USP grade glycerol made by Colgate Palmolive Peet Co. was used. One group of runs was made using this undiluted. Another set of runs was made wherein the CP glycerol was diluted to 72.4% with water. Samples of these two glycerin charges were analyzed for percent water by a Karl Fischer test. Viscosities (96 D) of these are shown in Fig. 12. Other properties are given in Table II.

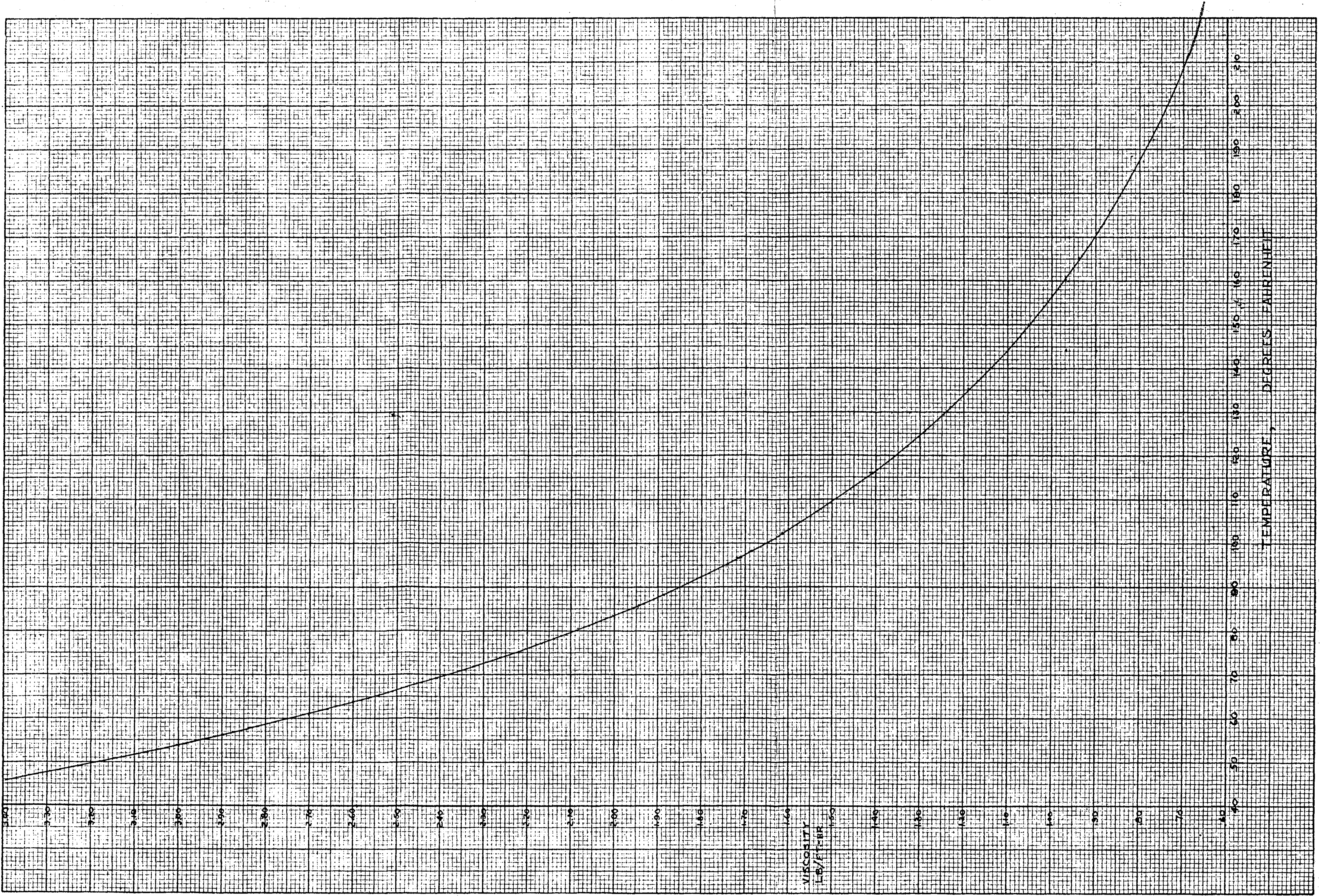

FIG.11 VISCOSITY OF WATER

TABLE II

PHYSICAL PROPERTIES OF FLUIDS

FLUID	TEMP. °F	ρ lb/Ft.^{3}	REF.	μ lb/Ft.Hr.	REF.
Water	120	61.70	69	1.354	74A
	130	61.54	69	1.238	74A
	140	61.38	69	1.136	74A
	150	61.19	69	1.050	74A
95.8% Glycerol	120	77.1	65A, 96B	191	96D
	130	76.9	65A, 96B	140	96D
	140	76.6	65A, 96B	106	96D
72.4% Glycerol	120	73.2	65A, 96B	19.2	96D
	125	73.1	65A, 96B	17.6	96D
	130	72.9	65A, 96B	16.1	96D
	140	72.7	65A, 96B	13.7	96D
	150	72.5	65A, 96B	11.7	96D

FLUID	TEMP. °F	c BTU/°F lb	REF.	k BTU/Hr.Ft.°F	REF.
Water	120	.9982	74B	.367	69,112,96F,74C
	130	.9987	74B	.372	69,112,96F,74C
	140	.9994	74B	.377	69,112,96F,74C
	150	1.0001	74B	.382	69,112,96F,74C
95.8% Glycerol	120	.6150	65B,96E	.1683	69,112,96F
	130	.6220	65B,96E	.1683	69,112,96F
	140	.6300	65B,96E	.1683	69,112,96F
72.4% Glycerol	120	.7080	65B,96E	.202	69,112,96F
	125	.7110	65B,96E	.202	69,112,96F
	130	.7140	65B,96E	.202	69,112,96F
	140	.4200	65B,96E	.203	69,112,96F
	150	.7260	65B,96E	.204	69,112,96F

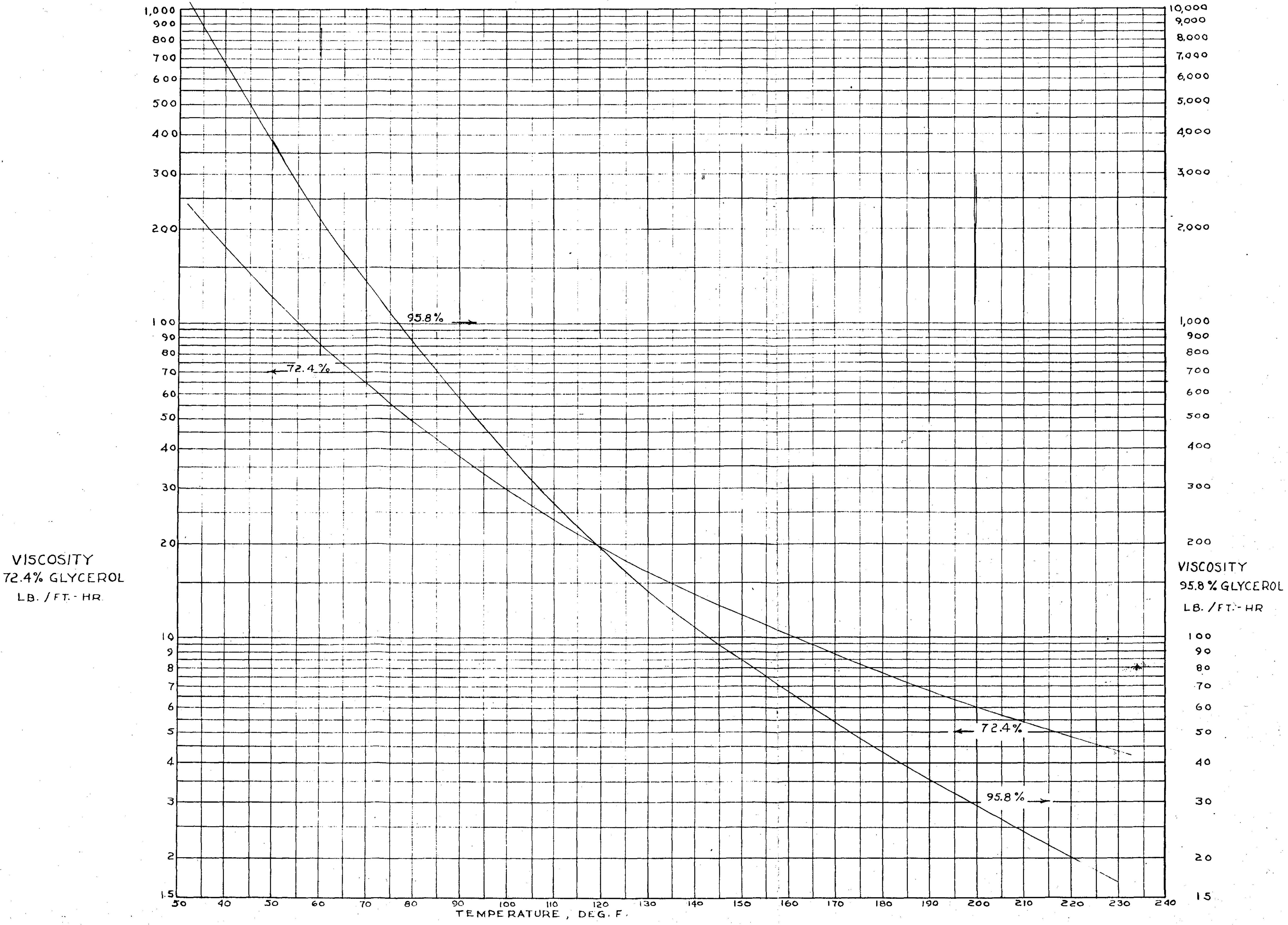

FIG.12 VISCOSITY OF GLYCEROL SOLUTIONS (96D)

IV. EXPERIMENTAL PROCEDURE

The material to be tested was charged into the kettle on a weight basis. The agitator was turned on and the speed changer was adjusted to give the desired speed as measured by the tachometer. The initial batch temperature was measured before turning on the steam.

A heating run was begun by turning on the steam. The stop watch was started at the time the steam valve was opened. The jacket vent valve was kept cracked open throughout each heating run to keep the jacket filled with steam. The condensate trap bypass valve was wide open at the start of a run. As soon as the excess condensate was blown out (one to two minutes), the bypass was closed not quite tight to permit a small blow down of steam. This assured constant temperature throughout the jacket. The initial steam setting was done by pressure and it was found that the setting would hold quite well throughout a run with only very minor valve adjustments. Readings were taken every 30 seconds alternating steam condensate, steam inlet, and batch temperatures. These were recorded as EMF's. It was found to be more satisfactory to read EMF at a given time on the stopwatch than to note the time for a particular EMF reading.

When the batch temperature reached 80 to 85°C, the steam was shut off and pressure drained from the jacket. These maximum temperatures were chosen to minimize evaporation losses. As soon as the jacket pressure was relieved, cooling water was turned on. About three minutes were required to fill the jacket with water. The stopwatch was started and the initial batch temperature for the cooling run measured at the time that water first began to overflow from the jacket. Alternate readings of EMF's corresponding to water inlet, water outlet, and batch temperatures were taken at frequent intervals depending upon the rate of change of readings.

In order to approximate the effects of natural convection a heating and cooling run was made without stirring for each of the three fluids. In general the procedure was the same as for the agitated runs. The initial temperature was measured with one of the larger agitators running. The agitator was stopped and motion allowed to subside. The run was started and continued as in the normal agitated runs. At a preestimated time, steam was shut off and drained, the time recorded and the agitator started. An equilibrium temperature reached in one to one and a half minutes was assumed to be that reached in the heating period. A like procedure was followed in a cooling run.

Agitator speeds were checked by tachometer at convenient intervals throughout each run. The volume of the material in the kettle was measured from a zero point at the end of each run. After completing tests on each fluid, the kettle charge was weighed as it was drained off.

V. DATA TABULATION

TABLE III: EXPERIMENTAL DATA (p.54-95)

RUN NO. 1
MATERIAL: WATER
AGITATOR: 5
FREEBOARD 5"
RPM: 0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.87			
.5			3.06	
1.0		4.57		5
1.5	.88			
2.0			4.65	
2.5		4.67		5
3.0	.93			
3.5			4.64	
4.0		4.66		5
4.5	1.06			
5.0			4.65	
5.5		4.67		6
6.0	1.31		4.67	
6.5				
7.0		4.66		5
7.5	1.81			
8.0	2.02			
8.5	2.33	steam off,agt.on		
9.0	2.81			
9.5	2.89			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	2.57	.42	
.5			.61
1.0	2.57		
1.5			.56
2.0	2.56		
3.0			.54
4.0	2.54		
5.0			.51
5.5		.42	
6.0	2.51		
7.0			.49
8.0	2.47		
9.0			.48
10.0		.42	
11.0	2.42		
12.0			.48
14.0	2.35		
15.0			.47
15.5		.42	
16.0	2.25	water off,agt.on	
16.5	1.68		
17.0	1.35		
17.5	1.30		
18.0	1.29		

RUN NO. 2
MATERIAL: WATER
AGITATOR: 5
FREEBOARD 5"
RPM: 56.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.90			13
0.5		4.46		13
1.0			2.94	
1.5	1.32			6
2.0			4.57	
2.5		4.68		5
3.0	1.84			
3.5			4.68	
4.0		4.69		5
4.5	2.33			
5.0			4.67	
5.5		4.68		5
6.0	2.87			
6.5			4.69	
7.0		4.69		5
7.5	3.27			
8.5	3.47			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.69	.42	
0.5			1.11
1.0	3.62		
1.5			1.05
2.0	3.48		
2.5			.93
3.0	3.31		
3.5			.90
4.0		.42	
4.5	3.00		
5.0			.84
6.0	2.64		
6.5			.79
8.0	2.25		
8.5			.74
9.0		.42	
10.0	1.96		
10.5			.69
12.0	1.78		
12.5			.65
13.0		.42	
15.0	1.55		
15.5			.62
16.0		.42	

RUN NO. 3
MATERIAL: WATER
AGITATOR: 5
FREEBOARD 5"
RPM: 33.5

HEATING					COOLING			
TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG	TIME MIN.	TEMPERATURE, EMF		
	BATCH	STEAM	COND.			BATCH	WATER IN	WATER OUT
0	.83				0	3.30	.38	
0.5		4.72		8	0.5			1.23
1.0			2.94	9	1.0	3.11		
1.5	.94				1.5			1.08
2.0		4.82		8	2.0	2.93		
2.5			4.74		2.5			.98
3.0	1.28				3.0	2.80		
3.5		4.81		8	3.5			.88
4.0			4.80		4.0	2.58		
4.5	1.59				4.5			.81
5.0		4.77		7	5.0		.38	
6.0	2.35				5.5	2.35		
6.5		4.74		7	6.0			.75
7.0			4.74		7.0	2.15		
7.5	2.92				8.0			.69
8.0		4.73		7	9.0	1.92		
8.5			4.74		10.0			.63
9.0	3.25			7	11.0	1.73		
10.0	3.44			8	12.0			.61
					13.0	1.56		
					14.0			.57
					14.5		.38	
					15.0	1.45		

RUN NO. 4
MATERIAL: WATER
AGITATOR: 4
FREEBOARD 5"
RPM: 33.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.39			
0.5		4.58		6
1.0			4.41	6
1.5	1.62			
2.0		4.67		5
2.5			4.64	
3.0	2.03			
3.5		4.67		5
4.0			4.64	
5.0	3.17			
5.5	3.36			
6.0		4.70		6
6.5			4.65	6
7.0	4.01			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.53	.38	
0.5			1.30
1.0	3.27		
1.5			1.14
2.0	3.31		
2.5			1.02
3.0		.38	
3.5	2.81		
4.0			.90
4.5	2.69		
5.0			.83
6.0	2.48		
7.0			.75
8.0	2.25		
8.5			.71
9.0		.38	
10.0	2.03		
10.5			.68
12.0	1.84		
12.5			.63
14.0	1.66		
14.5			.60
16.0	1.47		
16.5			.55
17.0		.38	

RUN NO. 5
MATERIAL: WATER
AGITATOR: 4
FREEBOARD 5"
RPM: 75.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.39			
0.5		4.75		7
1.0			4.67	
1.5	1.78			
2.0		4.81		8
2.5			4.80	8
3.0	2.45			
3.5		4.78		8
4.0			4.77	7
4.5	3.36			
5.0		4.74		7
5.5			4.72	6
6.0	4.02			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.43	.38	
0.5			1.51
1.0	3.19		
1.5			1.25
2.0	2.97		
2.5			1.06
3.0	2.82		
3.5			.98
4.0	2.62		
4.5			.90
5.0	2.45		
5.5			.85
6.0		.38	
7.0	2.12		
7.5			.71
10.0	1.78		
10.5			.64
12.0	1.52		
12.5			.62
13.0		.38	

RUN NO. 6
MATERIAL: WATER
AGITATOR: 3
FREEBOARD 5"
RPM: 102.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS.
	BATCH	STEAM	COND.	
0	1.36			
0.5		4.64		7
1.0			2.64	
1.5	1.54			
2.0		4.74		7
2.5			4.70	
3.0	1.91			
3.5		4.77		7
4.0			4.74	7
4.5	2.28			
5.0		4.72		7
5.5			4.72	
6.0	2.74			
6.5		4.71		6
7.0			4.72	
7.5	3.18			
8.0		4.72		7
8.5			4.72	7
9.0	3.56			
9.5		4.73		7
10.0	3.83			
10.5				
11.0				

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.34	.38	
0.5			1.52
1.0	3.09		
1.5			1.21
2.0	2.89		
2.5			1.01
3.0	2.70		
3.5			.74
4.0	2.57		
4.5			.86
5.0	2.40		
5.5			.80
6.0		.38	
7.0	2.12		
7.5			.74
9.0	1.87		
9.5			.68
11.0	1.62		
11.5			.66
12.0		.38	

RUN NO. 7
MATERIAL: WATER
AGITATOR: 3
FREEBOARD 5"
RPM: 44.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.04			
0.5		4.54		5
1.0			4.39	
1.5	1.47			
2.0		4.65		5
2.5			4.64	
3.0	2.04			
3.5		4.67		6
4.0			4.67	5
4.5	2.57			
5.0		4.64		5
5.5			4.64	
6.0	3.04			
6.5		4.64		5
7.0			4.65	5
7.5	3.44			
8.0		4.67		6
8.5	3.68			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.61	.38	
0.5			1.37
1.0	3.38		
1.5			1.19
2.0	3.18		
2.5			1.01
3.0	2.96		
3.5			.90
4.0	2.84		
4.5			.82
5.0	2.67		
5.5			.77
7.0	2.34		
7.5			.71
8.0		.38	
10.0	1.96		
10.5			.67
14.0	1.59		
14.5			.62
15.0		.38	

RUN NO. 8
MATERIAL: WATER
AGITATOR: 2
FREEBOARD: 5"
RPM: 46.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.47			
1.0		4.46		4
1.5			1.29	
2.0	.64			
2.5		4.63		5
3.0			4.41	5
3.5	1.08			
4.0		4.67		5
4.5			4.65	5
5.0	1.64			
5.5		4.70		6
6.0			4.67	6
6.5	2.19			
7.0		4.70		6
7.5			4.70	6
8.0	2.63			
8.5		4.72		6
9.0			4.73	6
9.5	3.01			
10.0		4.75		7
10.5	3.20			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.32	.38	
1.0	3.18		
1.5			1.31
2.0	3.03		
2.5			1.10
3.0	2.87		
3.5			.92
4.0	2.77		
4.5			.83
5.0	2.64		
5.5			.76
6.0		.36	
7.0	2.38		
7.5			.69
10.0	2.12		
10.5			.64
14.0	1.77		
14.5			.54
18.0	1.52		
18.5			.54
21.5		.34	.52
22.0	1.34		

RUN NO. 9
MATERIAL: WATER
AGITATOR: 2
FREEBOARD 5"
RPM: 159.0

HEATING				
TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.07			
0.5		4.72		6
1.0			4.64	
1.5	1.31			
2.0		4.85		8
2.5			4.82	8
3.0	1.84			
3.5		4.85		8
4.0			4.82	8
4.5	2.45			
5.0		4.82		8
5.5			4.82	8
6.0	3.14			
6.5		4.83		8
7.0	3.48			

COOLING			
TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.30	.37	
0.5			1.29
1.0	3.04		
1.5			1.13
2.0	2.80		
2.5			1.06
3.0	2.64		
3.5			.99
4.0	2.50		
4.5			.93
5.0	2.35		
5.5			.90
6.0		.37	
7.0	2.10		
7.5			.82
10.0	1.75		
10.5			.71
12.0	1.55		
12.5			.64
15.0	1.37		
15.5			.60
16.0		.37	

RUN NO. 10
MATERIAL: WATER
AGITATOR: 1
FREEBOARD 5"
RPM: 160.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.11			
0.5		5.10		12
1.0			3,94	
1.5	1.31			
2.0		5.05		11
2.5			4.98	
3.0	1.79			
3.5		5.05		11
4.0			5.02	
4.5	2.33			
5.0		5.02		11
5.5			5.03	
6.0	2.87			
6.5		5.05		11
7.0			5.06	
7.5	3.31			
8.0	3.42			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.31	.35	
0.5			1.41
1.0	3.16		
1.5			1.13
2.0	3.02		
2.5			1.04
3.0	2.84		
3.5			.92
4.0	2.67		
4.5			.85
5.0	2.45		
5.5			.79
6.0		.35	
7.0	2.19		
7.5			.72
10.0	1.87		
10.5			.65
14.0	1.56		
14.5			.58
17.0	1.39		
17.5			.54
18.0		.35	

RUN NO. 11
MATERIAL: WATER
AGITATOR: 1
FREEBOARD 5"
RPM: 215

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.18			
0.5		4.89		8
1.0			4.56	8
1.5	1.75			
2.0		4.85		8
2.5			4.85	
3.0	1.99			
3.5		4.85		8
4.0			4.85	
4.5	2.59			
5.0		4.82		8
5.5			4.82	
6.0	3.06			
6.5		4.80		7
7.0			4.77	
7.5	3.39			
8.0	3.46			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.34	.37	
0.5			1.43
1.0	3.15		
1.5			1.08
2.0	2.95		
2.5			.99
3.0	2.75		
3.5			.91
4.0	2.61		
4.5			.84
5.0	2.40		
5.5			.78
6.0		.37	
7.0	2.11		
7.5			.71
10.0	1.75		
10.5			.64
13.0	1.54		
13.5			.59
15.0	1.43		
15.5			.55
16.0		.37	

RUN NO. 12
MATERIAL: WATER
AGITATOR: 1
FREEBOARD 5"
RPM: 127.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.19			
0.5			3.82	9
1.0		4.85		9
1.5	1.37			
2.0			4.91	9
2.5		4.98		10
3.0	1.71			
3.5			4.97	10
4.0		4.95		10
4.5	2.15			
5.0			4.93	10
5.5		4.93		9
6.0	2.65			
6.5			4.93	9
7.0		4.93		9
7.5	3.06			
8.0		4.94		9
8.5			4.95	9
9.0	3.40			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.32	.37	
0.5			1.51
1.0	3.15		
1.5			1.18
2.0	2.97		
2.5			.99
3.0	2.87		
3.5			.86
4.0	2.67		
4.5			.79
5.0	2.52		
5.5			.74
6.0		.37	
7.0	2.26		
7.5			.69
10.0	1.96		
10.5			.61
14.0	1.63		
14.5			.55
18.0	1.40		
18.5			.50
20.0	1.29		
20.5			.48
21.0		.37	

RUN NO. 13
MATERIAL: WATER
AGITATOR: 1
FREEBOARD 5"
RPM: 93.2

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.16			
0.5		4.81		8
1.0			4.34	8
1.5	1.25			
2.0		4.95		10
2.5			4.94	10
3.0	1.59			
3.5		4.95		10
4.0			4.95	10
4.5	2.05			
5.0		4.96		10
5.5			4.98	11
6.0	2.50			
6.5		4.99		11
7.0			4.98	11
7.5	2.94			
8.0		4.98		11
8.5			4.95	11
9.0	3.34			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.40	.32	
0.5			1.51
1.0	3.24		
1.5			1.13
2.0	3.06		
2.5			.93
3.0	2.93		
3.5			.80
4.0	2.77		
4.5			.75
5.0	2.64		
5.5			.70
6.0		.32	
7.0	2.38		
7.5			.67
10.0	2.03		
10.5			.61
14.0	1.78		
14.5			.55
18.0	1.51		
18.5			.52
19.0		.32	

RUN NO. 14
MATERIAL: WATER
AGITATOR: 1
FREEBOARD 5"
RPM: 66.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.84			
1.0		4.97		10
1.5			4.48	
2.0	1.10			
2.5		5.15		14
3.0			5.13	14
3.5	1.54			
4.0		5.15		14
4.5			5.14	14
5.0	2.08			
5.5		5.15		14
6.0			5.15	
6.5	2.55			
7.0		5.17		14
7.5			5.18	14
8.0	2.96			
8.5		5.19		14
9.0			5.20	15
9.5	3.26			
10.0	3.34			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.51	.51	
0.5			1.45
1.0	3.31		
1.5			1.18
2.0	3.16		
2.5			1.02
3.0	2.99		
3.5			.92
4.0	2.89		
4.5			.85
5.0	2.77		
5.5			.79
6.0		.39	
7.0	2.52		
7.5			.71
10.0	2.22		
10.5			.64
14.0	1.91		
14.5			.59
20.0	1.56		
20.5			.54
21.0		.39	

RUN NO. 15
MATERIAL: C.P. GLYCEROL
AGITATOR: 1
CHARGE 449 lbs.
RPM: 230.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.66			
1.0		4.84		9
2.0	.76			
2.5		4.88		9
3.0			4.34	
3.5	1.04			
4.0		4.90		9
4.5			4.81	
5.0	1.34			
5.5		4.93		10
6.0			4.89	10
6.5	1.63			
7.0		4.94		10
7.5			4.94	10
8.0	1.89			
8.5		4.95		10
9.0			4.93	10
9.5	2.12			
10.0		4.98		11
10.5			4.94	10
11.0	2.35			
11.5		4.96		10
12.0			4.95	10
12.5				
13.0	2.63			
13.5		4.94		10
14.0			4.94	
14.5	2.88			
15.0		4.94		10
15.5			4.91	
16.0	3.06			
16.5		4.94		10
17.0			4.95	
17.5	3.24			
18.0		4.96		10
18.5			4.98	
19.0	3.36			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.39	.29	
0.5			.99
1.0	3.31		
1.5			.70
2.0	3.31		
2.5		.29	
3.0			.58
4.0	3.21		
5.0			.52
6.0	3.10		
7.0			.48
8.0		.29	
10.0	2.78		
10.5			.45
14.0	2.47		
14.5			.44
20.0	2.26		
20.5			.42
21.0		.30	
25.0	2.08		
25.5			.42
30.0	1.89		
30.5			.42
36.0	1.71		
36.5			.41
45.0	1.54		
45.5			.40
46.0		.32	

RUN NO. 16
MATERIAL: C.P. GLYCEROL
AGITATOR: 1
CHARGE 449 lbs.
RPM: 113.3

HEATING

TIME MIN.	TEMPERATURE, EMF BATCH	TEMPERATURE, EMF STEAM	TEMPERATURE, EMF COND.	STEAM PRESS. PSIG
0	1.11			
1.0		5.09		13
2.0	1.18			
2.5		5.11		13
3.0			4.77	
3.5	1.26			
4.0		5.10		13
4.5			5.05	13
5.0	1.43			
5.5		5.11		13
6.0			5.11	13
6.5	1.62			
7.0		5.14		14
7.5			5.13	14
8.0	1.83			
8.5		5.12		13
9.0			5.11	13
9.5	2.07			
10.0		5.14		13
10.5			5.14	13
11.0	2.27			
11.5				
12.0		5.18		14
12.5			5.15	14
13.0	2.55			
13.5		5.17		14
14.0			5.16	14
14.5	2.72			
15.0		5.15		14
15.5			5.16	14
16.0	2.89			
16.5		5.17		14
17.0			5.16	14
17.5	3.04			
18.0		5.18		14
18.5			5.17	
19.0	3.18			

COOLING

TIME MIN.	TEMPERATURE, EMF BATCH	TEMPERATURE, EMF WATER IN	TEMPERATURE, EMF WATER OUT
0	3.28	.35	
0.5			1.41
1.0	3.24		
1.5			.76
2.0	3.19		
2.5			.58
3.0	3.15		
3.5			.56
4.0	3.11		
5.0			.49
6.0	3.03		
7.0			.46
10.0	2.84		
10.5			.44
11.0		.33	
15.0	2.61		
15.5			.42
20.0	2.42		
20.5			.41
25.0	2.27		
25.5			.41
30.0	2.14		
30.5			.40
31.0		.33	
40.0	1.91		
40.5			.40
41.0		.33	
50.0	1.71		
50.5			.39
51.0		.34	

RUN NO. 17
MATERIAL: C.P. GLYCEROL
AGITATOR: 5
CHARGE 449 lbs.
RPM: 49.7

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS.
	BATCH	STEAM	COND.	PSIG
0	.56			
0.5		4.93		9
1.0	.58			
2.0		5.02		11
2.5			1.06	
3.0	.74			
3.5		5.04		11
4.0			4.85	
4.5	1.05			
5.0		5.07		12
5.5			5.06	
6.0	1.41			
6.5		5.09		12
7.0			5.07	12
7.5	1.76			
8.0		5.09		13
8.5			5.05	12
9.0	2.10			
9.5		5.09		13
10.0			5.05	13
10.5	2.39			
11.0		5.05		12
11.5			5.05	12
12.0	2.65			
12.5		5.08		12
13.0			5.04	12
13.5	2.90			
14.0		5.07		12
14.5			5.08	12
15.0	3.14			
15.5		5.08		12
16.0	3.29			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.39	.32	
0.5			1.31
1.5	3.26		
2.0			.73
2.5			.64
3.0	3.13		
3.5			.58
4.0	3.04		
5.0	2.96		
5.5			.51
6.0		.32	
7.0	2.77		
7.5			.49
9.0	2.64		
9.5			.48
11.0	2.51		
11.5			.45
13.0	2.40		
13.5			.42
14.0		.32	
15.0	2.28		
15.5			.42
20.0	2.05		
20.5			.39
25.0	1.87		
25.5			.38
26.0		.31	
30.0	1.70		
30.5			.38
31.0		.31	
40.0	1.43		
40.5			.35
41.0		.29	
45.0	1.34		
45.5			.34

RUN NO. 18
MATERIAL: C.P.GLYCEROL
AGITATOR: 5
CHARGE 449 lbs
RPM: 0

HEATING

TIME MIN.	TEMPERATURE, EMF BATCH	TEMPERATURE, EMF STEAM	TEMPERATURE, EMF COND.	STEAM PRESS. PSIG
0	1.20			
0.5		4.85		9
1.0	1.22			
1.5		4.99		11
2.0			1.14	
2.5	1.22			
3.0		5.06		12
3.5			5.07	12
4.0				
5.0	1.24			
5.5		5.13		13
6.0			5.08	
6.5	1.15			
7.0		5.10		13
7.5			5.10	
8.0	1.15			13
8.5		5.10		13
9.0			5.12	13
9.5	1.36			
10.0		5.14		13
10.5			5.14	13
11.0	1.43			
11.5		5.14		13
12.0			5.15	13
12.5	1.56			
13.0		5.16		14
13.5			5.16	
14.0	1.70	off-agit.on		
15.0	2.35			
15.5	2.45			
16.0	2.47			

COOLING

TIME MIN.	TEMPERATURE, EMF BATCH	TEMPERATURE, EMF WATER IN	TEMPERATURE, EMF WATER OUT
0	2.47	.29	
0.25			1.36
1.25			.67
2.0	2.46		
2.5			.49
3.0	2.46		
3.5			.42
4.0	2.46		
4.5			.38
5.0	2.46		
5.5			.36
10.0	2.44		
10.5			.35
18.0	2.40		
18.5			.33
19.0		.29	
29.0			.32
29.5		.29	
30.0	2.20	off - agit. on	
30.5	2.05		
31.0	1.98		
31.5	1.91		
32.0	1.90		

RUN NO. 19
MATERIAL: C.P. GLYCEROL
AGITATOR: 5
CHARGE 449 lbs.
RPM: 75.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.91			
1.0		5.03		11
1.5			1.18	
2.0	1.05			
2.5		5.09		13
3.0			5.00	
3.25	1.21			
3.5		5.08		12
4.0			5.08	12
4.5	1.41			
5.0		5.09		12
5.5			5.09	
6.0	1.78			
6.5		5.13		13
7.0			5.10	
7.5	2.17			
8.0		5.13		13
8.5			5.13	13
9.0	2.51			
9.5		5.14		13
10.0			5.14	14
10.5	2.82			
11.0		5.15		14
11.5			5.15	14
12.0	3.14			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.26	.30	
0.25			1.57
0.5			1.32
1.0			1.01
1.5			.64
2.0	3.04		
3.0	3.05		
3.5			.58
4.0	2.84		
4.5			.56
5.0	2.74		
5.5			.53
7.0	2.57		
7.5			.49
8.0		.30	
10.0	2.33		
10.5			.46
15.0	2.07		
15.5			.43
22.0	1.64		
22.5			.38
30.0	1.47		
30.5			.37
44.0	1.15		
44.5			.36
45.0		.30	

RUN NO. 20
MATERIAL: C.P. GLYCEROL
AGITATOR: 4
CHARGE 449 lbs.
RPM: 87.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.05			
1.0		5.10		13
1.5			1.45	
2.0	1.20			
2.5		5.13		13
3.0			4.93	
3.5	1.52			
4.0		5.13		13
4.5			5.13	
5.0	1.95			
5.5		5.15		14
6.0			5.13	
6.5	2.27			
7.0		5.13		14
7.5			5.14	14
8.0	2.63			
8.5		5.14		14
9.0			5.15	14
9.5	2.98			
10.0		5.23		15
10.5			5.23	15
11.0	3.26			
11.5		5.24		15
12.0	3.41			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.40	.32	
0.25			1.70
0.5			1.45
0.75			1.22
1.0			1.15
1.5			.91
2.0	3.18		
2.5			.77
3.5	2.99		
4.0			.69
5.0	2.88		
5.5			.62
7.0	2.66		
7.5			.55
10.0	2.42		
10.5			.53
11.0		.32	
15.0	2.11		
15.5			.48
22.0			.44
22.5	1.74		
30.0	1.50		
30.5			.38
40.0	1.24		
40.5			.35
41.0		.29	

RUN NO. 21
MATERIAL: C.P. GLYCEROL
AGITATOR: 4
CHARGE 449 lbs.
RPM: 39.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.11			
1.0		5.00		11
1.5			4.34	
2.0	1.26			
2.5		5.08		12
3.0			4.95	
3.5	1.56			
4.0		5.08		12
4.5			5.03	12
5.0	1.87			
5.5		5.08		12
6.0			5.08	
6.5	2.10			
7.0		5.09		12
7.5			5.08	12
8.0	2.32			
8.5		5.08		12
9.0			5.08	
9.5	2.55			
10.0		5.09		12
10.5			5.06	
11.0	2.75			
11.5		5.06		12
12.0			5.07	
12.5	2.96			
13.0		5.08		12
13.5			5.07	
14.0	3.15			
14.5		5.09		12
15.0	3.27			12

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.35	.29	
0.25			1.61
0.5			1.38
0.75			1.16
1.00			1.02
1.25			.87
1.75			.70
2.00	3.20		
2.5			.61
3.0	3.14		
3.5			.54
4.0	3.06		
4.5			.49
5.0	2.99		
5.5			.47
7.0			.42
7.5		.29	
8.0	2.82		
10.0	2.69		
10.5			.40
15.0	2.44		
15.5			.38
22.0	2.14		
22.5			.37
23.0		.29	
32.0	1.82		
32.5			.36
33.0		.29	
45.0	1.62		
45.5			.35
46.0		.29	
55.0	1.34		
55.5			.34
56.0		.29	

RUN NO. 22
MATERIAL: C.P. GLYCEROL
AGITATOR: 3
CHARGE 449 lbs.
RPM: 127.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.91			
1.0		5.03		11
1.5			1.22	
2.0	1.06			
2.5		5.14		14
3.0			5.05	
3.5	1.46			
4.0		5.11		13
4.5			5.10	13
5.0	1.82			
5.5		5.12		13
6.0			5.11	13
6.5	2.19			
7.0		5.15		14
7.5			5.11	13
8.0	2.51			
8.5		5.12		13
9.0			5.10	13
9.5	2.81			
10.0		5.15		14
10.5			5.14	14
11.0	3.11			
11.5		5.14		14
12.0	3.29			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.33	.34	
0.25			1.88
0.5			1.56
1.0			1.20
1.5			1.01
2.0	3.14		
2.5			.88
3.0	3.05		
3.5			.78
4.0	2.94		
4.5			.59
5.0	2.85		
5.5			.57
6.0		.34	
7.0	2.68		
7.5			.53
10.0	2.47		
10.5			.49
15.0	2.14		
15.5			.42
16.0		.31	
21.5	1.84		
22.0			.38
30.5	1.54		
31.0			.37
32.0		.30	
40.0	1.29		
40.5			.35
41.0		.30	

RUN NO. 23
MATERIAL: C.P. GLYCEROL
AGITATOR: 3
CHARGE 449 lbs.
RPM: 105.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.06			
1.0		4.73		7
1.5			1.13	
2.0	1.13			
2.5		4.82		8
3.0			4.72	
3.5	1.31			
4.0		4.87		9
4.5			4.85	9
5.0	1.55			
5.5		4.89		9
6.0			4.87	9
6.5	1.83			
7.0		4.89		9
7.5			4.89	9
8.0	2.10			
8.5		4.89		9
9.0			4.89	
9.5	2.38			
10.0		4.85		9
10.5			4.85	
11.0	2.67			
11.5		4.88		9
12.0			4.88	
12.5	2.92			
13.0		4.88		9
13.5	3.11			
14.25	3.23			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.38	.25	
0.25			1.31
0.5			1.10
0.75			.97
1.0			.91
1.5	3.24		
2.0			.78
2.5	3.11		
3.0			.54
3.5	3.00		
4.0			.49
4.5	2.92		
5.0			.47
7.0			.42
7.5	2.64		
8.0		.24	
10.0			.39
10.5	2.42		
15.0			.36
15.5	2.14		
21.0	1.89		
21.5			.34
22.0		.24	
30.0	1.57		
30.5			.31
31.0		.23	
40.0	1.34		
40.5			.28
41.0		.22	

RUN NO. 24
MATERIAL: C.P. GLYCEROL
AGITATOR: 3
CHARGE 449 lbs.
RPM: 80.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.19			
1.0		4.80		8
1.5			4.34	
2.0	1.27			
2.5		4.89		9
3.0			4.72	
3.5	1.54			
4.0		4.89		9
4.5			4.85	
5.0	1.83			
5.5		4.90		9
6.0			4.91	
6.5	2.11			
7.0		4.90		9
7.5			4.89	
8.0	2.36			
8.5		4.92		9
9.0			4.90	
9.5	2.63			
10.0		4.93		10
10.5			4.90	
11.0	2.82			
11.5		4.90		9
12.0			4.91	
12.5	3.02			
13.0		4.94		10
13.5			4.91	
14.0	3.20			
14.5		4.92		10
15.0			4.93	
15.5	3.37			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.31	.23	
0.5			1.31
1.0			1.07
1.5			.88
2.0	3.16		
2.5			.55
3.0	3.07		
3.5			.52
4.0	2.99		
4.5			.46
5.0	2.92		
5.5			.42
7.0	2.75		
7.5			.40
8.0		.23	
10.0	2.55		
10.5			.38
15.0	2.27		
15.5			.34
21.0	2.01		
21.5			.32
30.0	1.75		
30.5			.30
31.0		.23	
40.0	1.45		
40.5			.29
47.5			.27
48.0	1.24		
48.5		.23	

RUN NO. 25
MATERIAL: C.P. GLYCEROL
AGITATOR: 3
CHARGE 449 lbs.
RPM: 55.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.13			
1.0		4.86		9
1.5			4.40	
2.0	1.18			
2.5		4.93		9
3.0			4.86	
3.5	1.45			
4.0		4.94		10
4.5			4.94	
5.0	1.73			
5.5		4.96		10
6.0			4.95	
6.5	1.98			
7.0		4.96		10
7.5			4.95	
8.0	2.18			
8.5		4.98		10
9.0			4.98	
9.5	2.41			
10.0		4.95		10
10.5			4.93	
11.0	2.59			
11.5		4.95		10
12.0			4.95	
12.5	2.74			
13.0		4.94		10
13.5			4.95	
14.0	2.93			
14.5		4.95		10
15.0			4.95	
15.5	3.10			
16.0		4.96		10
16.5			4.97	
17.0	3.24			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.21	.22	
0.5			1.24
1.0			.86
2.0	3.18		
2.5			.53
3.0	3.11		
3.5			.44
4.0	3.00		
4.5			.38
5.0	2.95		
5.5			.37
7.0	2.83		
7.5			.34
8.0		.22	
10.0	2.67		
10.5			.33
15.0	2.42		
15.5			.31
22.0	2.14		
22.5			.30
23.0		.22	
30.5	1.88		
31.0			.29
43.0	1.57		
43.5			.27
44.0		.22	
60.0	1.25		
60.5			.26
61.0		.22	

RUN NO. 26
MATERIAL: C.P. GLYCEROL
AGITATOR: 3
CHARGE 449 lbs.
RPM: 34.2

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS.
	BATCH	STEAM	COND.	PSIG
0	1.15			
1.0		4.72		6
1.5			4.52	
2.0	1.16			
2.5		4.83		8
3.0			4.73	
3.5	1.34			
4.0		4.89		9
4.5			4.85	
5.0	1.51			
5.5		4.89		9
6.0			4.89	
6.5	1.74			
7.0		4.91		9
7.5			4.89	
8.0	1.98			
8.5		4.88		9
9.0			4.88	
9.5	2.19			
10.0		4.90		9
10.5			4.88	
11.0	2.36			
11.5		4.89		9
12.0			4.88	
12.5	2.56			
13.0		4.90		9
13.5			4.88	
14.0	2.71			
14.5		4.90		9
15.0			4.89	
15.5	2.81			
16.0		4.90		9
16.5			4.90	
17.0	2.95			
17.5		4.92		9
18.0			4.90	
18.5	3.09			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.24	.22	
0.5			.83
1.0	3.17		
2.0			.52
2.5	3.07		
3.0			.40
4.0			.37
5.0	2.95		
5.5			.36
7.0	2.87		
7.5			.34
10.0	2.72		
10.5			.32
11.0		.22	
15.0	2.54		
15.5			.30
22.0	2.26		
22.5			.29
30.0	2.05		
30.5			.28
31.0		.22	
42.0	1.78		
42.5			.26
43.0		.22	
55.0	1.56		
55.5			.25
56.0		.22	
70.0	1.35		
70.5			.24
71.0		.22	

RUN NO. 27
MATERIAL: C.P. GLYCEROL
AGITATOR: 2
CHARGE 449 lbs.
RPM: 175.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.20			
1.0		4.98		11
1.5			1.86	
2.0	1.34			
2.5		4.94		10
3.0			4.67	
3.5	1.59			
4.0		4.89		9
4.5			4.81	
5.0	1.89			
5.5		4.85		9
6.0			4.85	
6.5	2.14			
7.0		4.83		9
7.5			4.83	
8.0	2.39			
8.5		4.83		9
9.0			4.82	
9.5	2.59			
10.0		4.82		8
10.5			4.82	
11.0	2.81			
11.5		4.83		8
12.0			4.82	
12.5	2.99			
13.0		4.82		8
13.5			4.82	
14.0	3.14			
14.5		4.85		9
15.0	3.28			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.31	.26	
0.5			1.37
1.0			.98
1.5			.76
2.0	3.16		
2.5			.58
3.0	3.06		
3.5			.52
4.0	2.99		
4.5			.45
5.0	2.89		
7.0	2.72		
7.5			.38
10.0			.37
10.5	2.51		
11.0		.26	
15.0			.36
15.5	2.24		
23.0	1.91		
23.5			.32
24.0		.26	
33.0	1.57		
33.5			.30
34.0		.26	
44.5			.29
45.0	1.29		
45.5		.26	

RUN NO. 28
MATERIAL: C.P. GLYCEROL
AGITATOR: 2
CHARGE 449 lbs.
RPM: 96.1

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.22			
1.0		5.06		12
1.5			2.00	
2.0	1.26			
2.5		5.07		12
3.0			4.02	
3.5	1.49			
4.0		5.07		
4.5			5.07	12
5.0	1.73			
5.5		5.09		13
6.0			5.07	
6.5	1.97			
7.0		5.10		13
7.5			5.09	
8.0	2.16			
8.5		5.11		13
9.0			5.11	
9.5	2.35			
10.0		5.12		13
10.5			5.08	
11.0	2.56			
11.5		5.09		12
12.0			5.09	
12.5	2.73			
13.0		5.08		12
13.5			5.08	
14.0	2.90			
14.5		5.08		12
15.0			5.06	
15.5	3.05			
16.0		5.05		11
16.5			5.03	
17.0	3.21			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.28	.28	
0.5			1.41
1.0			1.10
1.5	3.22		
2.0			.65
2.5	3.12		
3.0			.54
3.5	3.07		
4.0			.48
4.5			
5.0	2.99		
5.5			.45
7.0	2.89		
7.5			.43
8.0		.28	
10.0	2.73		
10.5			.40
15.0	2.50		
15.5			.36
16.0		.28	
28.0	2.05		
28.5			.36
29.0		.28	
40.0	1.73		
40.5			.33
41.0		.28	
55.0	1.45		
55.5			.32
56.0		.28	
65.0	1.31		
65.5			.32
66.0		.28	

RUN NO. 29
MATERIAL: GLYCEROL-WATER
AGITATOR: 2
CHARGE 390 lbs
RPM: 180.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.85			
1.5		5.13		14
2.0			1.59	
2.5	1.27			
3.0		4.93		10
3.5			4.85	10
4.0	1.66			
4.5		4.99		11
5.0			4.96	
5.5	2.18			
6.0		4.98		11
6.5			4.98	11
7.0	2.56			
7.5		5.00		11
8.0			5.01	12
8.5	2.95			
9.0		5.05		12
9.5			5.08	13
10.0	3.28			
10.5	3.39			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.44		
0.5			1.66
0.75		.29	
1.0			1.13
1.5	3.10		
2.0			.89
2.5	2.92		
3.0			.79
3.5	2.76		
4.0			.74
4.5	2.63		
5.0			.69
5.5	2.51		
7.0			.60
7.5	2.28		
10.0	2.07		
10.5			.53
11.0		.28	
15.0	1.70		
15.5			.47
21.5	1.45		
22.0			.36
22.5		.26	

RUN NO. 30
MATERIAL: GLYCEROL-WATER
AGITATOR: 2
CHARGE 390 lbs.
RPM: 45.0

HEATING				
TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.20			
1.5		5.19		14
2.0	1.26			
2.25		4.98		
2.5			2.70	9
3.0	1.50			
4.0		5.18		14
4.5			5.14	14
5.25	1.73			
6.0		5.17		14
6.5			5.15	14
7.0	2.09			
7.5		5.17		14
8.0	2.27			
8.5		5.17		14
9.0			5.13	
9.5	2.57			
10.0		5.21		15
10.5			5.15	15
11.0	2.81			
11.5		5.20		15
12.0			5.15	14
12.5	3.10			
13.0		5.18		14
13.5			5.18	14
14.0	3.25			
15.0	3.38			

COOLING			
TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.47	.34	
0.25			1.18
0.75			1.00
1.25			.80
1.5	3.31		
2.0			.73
2.5	3.22		
3.0			.65
3.5	3.11		
4.5			.58
5.0	2.98	.32	
7.0	2.83		
7.5			.51
10.0	2.62		
10.5		.32	.49
14.0	2.37		
14.5			.47
20.0			.44
20.5	2.02		
30.0	1.61		.40
30.5			.39
40.0		.32	
40.5	1.33		

RUN NO. 31
MATERIAL: GLYCEROL-WATER
AGITATOR: 2
CHARGE 390 lbs.
RPM: 145.5

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.18			
1		4.98		10
1.5			1.37	12
2.0	1.40			
2.5		5.25		15
3.0			5.13	14
3.5	1.88			
4.0		5.13		14
4.5			5.12	14
5.0	2.32			
5.5		5.14		14
6.0			4.95	13
6.5	2.71			
7.0		5.13		12
7.5			5.12	13
8.0	3.04			
8.5		5.17		13
9.0			5.06	13
9.5	3.34			
10.0	3.41			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.44		
0.5			1.55
0.75			1.33
1.00			1.16
1.25			1.03
1.5	3.23		
2.0		.33	.91
2.5			.84
3.0	2.97		
3.5			.80
4.0	2.86		
5.0			.70
5.5	2.66		
7.0			.61
7.5	2.44	.32	
10.0			.55
10.5	2.15		
15.0	1.82		
15.5		.32	.49
20.0	1.52		
20.5			.45
26.0	1.26		
26.5		.32	.41

RUN NO. 32
MATERIAL: GLYCEROL-WATER
AGITATOR: 2
CHARGE 390 lbs.
RPM: 110.2

HEATING					COOLING			
TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG	TIME MIN.	TEMPERATURE, EMF		
	BATCH	STEAM	COND.			BATCH	WATER IN	WATER OUT
0	1.10				0	3.46		
1.5		5.30		16	0.25			1.75
2.0	1.29				0.45			1.32
2.5		4.87		8	1.0			1.12
3.0			4.65	8	1.5			.96
3.5	1.67				2.0	3.25		
4.0		5.05		12	2.5		.32	.78
4.5			5.05	12	3.0	3.02		
5.0	2.05				3.5			.71
5.5		5.07		11	4.0	2.89		
6.0			5.07		4.5			.66
6.5	2.40				5.0	2.79		
7.0		5.04		11	5.5			.60
7.5			5.02	12	7.0	2.56		
8.0	2.70				7.5		.32	.63
8.5		5.10		13	10.0	2.31		
9.0			5.10	13	10.5			.52
9.5	2.95				15.0	1.97		
10.0		5.10		13	15.5			.47
10.5			4.98	13	22.0	1.57		
11.0	3.26				22.5		.32	.45
11.5		5.11		13	30.0	1.23		
12.0	3.46				30.5		.32	.38

RUN NO. 33
MATERIAL: GLYCEROL-WATER
AGITATOR: 2
CHARGE 390 lbs.
RPM: 79.1

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.10			
1.5		4.98		13
2.0			2.20	
2.5	1.35			
3.0		5.24		15
3.5			5.16	15
4.0	1.76			
4.5		5.23		15
5.0			5.20	16
5.5	2.09			
6.0		5.19		14
6.5			5.07	14
7.0	2.42			
7.5		5.24		16
8.0			5.08	15
8.5	2.72			
9.0		5.19		15
9.5			5.17	15
10.0	2.97			
10.5		5.25		16
11.0			5.12	14
11.5	3.28			
12.0		5.23		16
12.5			5.22	16
13.0	3.50			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.51		
0.5			1.54
1.0	3.44	.32	
1.5			.83
2.0	3.29		
2.5			.74
3.0	3.14		
3.5			.68
4.0	3.06		
4.5			.62
5.0	2.91		
5.5			.57
7.0	2.75		
7.5			.53
10.0	2.47		
10.5			.50
15.0	2.10		
15.5		.32	.48
22.0	1.74		
22.5			.43
30.0	1.42		
34.0	1.27		
34.5		.32	.38

RUN NO. 34
MATERIAL: GLYCEROL-WATER
AGITATOR: 5
CHARGE 390 lbs.
RPM: 41.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS.
	BATCH	STEAM	COND.	
0	1.13			
1.0		5.12		
1.5			1.82	12
2.0	1.44			
2.5		4.82		9
3.0			5.02	12
3.5	1.87			
4.0		5.13		13
4.5			5.03	12
5.0	2.42			
5.5		5.06		13
6.0			5.03	13
6.5	2.87			
7.0		5.12		14
7.5			5.12	14
8.0	3.22			
8.5		5.13		14
9.0	3.41			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.49		
0.5		.35	1.56
1.0	3.32		
1.5			1.08
2.0	3.18		
2.5			.90
3.0	3.01		
3.5		.32	.80
4.0	2.88		
4.5			.71
5.0	2.65		
5.5			.62
7.0	2.48		
7.5		.32	.56
10.0	2.17		
10.5		.32	.54
15.0	1.81		
15.5		.32	.50
24.5			.42
25.0	1.28		

RUN NO. 35
MATERIAL: GLYCEROL-WATER
AGITATOR: 5
CHARGE 390 lbs.
RPM: 75.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.12			
1.0		4.55		7
1.5			.92	12
2.0	1.41			
2.25		4.72		
2.50			4.44	9
4.0	2.18			
4.5		4.87		9
5.0			4.87	9
5.5	2.73			
6.0		4.87		9
6.5			4.84	9
7.0	3.12			9
8.0	3.46			9

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.45		
0.5			1.50
1.0	3.23		
1.5		.32	1.08
2.0	2.98		
2.5			.94
3.0	2.87		
3.5			.77
4.0	2.62		
4.5			.73
5.0	2.48		
5.5			.70
7.0	2.24		
9.5			.67
10.0	1.93		
10.5			.55
14.5			.52
15.0	1.46		
15.5			
20.0	1.22		
20.5		.32	.43

RUN NO. 36
MATERIAL: GLYCEROL-WATER
AGITATOR: 4
CHARGE 390 lbs
RPM: 41.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.98			
1.0		4.85		9
1.5			3.80	13
2.0	1.30			
2.5		5.16		14
3.0			5.12	14
3.5	1.75			
4.0		5.05		13
4.5			5.04	13
5.0	2.19			
5.5		5.15		14
6.0			5.09	14
6.5	2.64			
7.0		5.11		13
7.5			5.10	13
8.0	2.98			
8.5		5.14		13
9.0			5.08	13
9.5	3.32			12
10.0	3.41			13

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.49		
0.5			1.63
1.0	3.30		
1.5		.35	1.17
2.0	3.13		
2.5			.97
3.0	3.02		
3.5			.83
4.0	2.87		
4.5			.78
5.0	2.72		
5.5			.72
7.0	2.53		
7.5		.35	.66
10.0	2.24		
10.5			.61
14.0			
14.5			.56
15.0	1.87		
22.0	1.45		
22.5		.35	.48
30.0			.42
30.5	1.14		

RUN NO. 37
MATERIAL: GLYCEROL-WATER
AGITATOR: 4
CHARGE 390 lbs.
RPM: 80.4

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.02			
1.0		4.80		7
1.5			2.36	10
2.0	1.45			
2.5		4.84		8
3.0			4,84	10
3.5	2.15			
4.0		5.12		13
4.5			5.15	13
5.0	2.60			
5.5		5.24		14
6.0			5.20	14
6.5	3.16			
7.0		5.18		13
7.5	3.48			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.49		
0.5			1.43
1.0	3.13		
1.5		.35	1.01
2.0	2.93		
2.5			.92
3.0	2.80		
3.5			.77
4.0	2.64		
4.5			.74
5.0	2.49		
5.5		.35	.71
7.0	2.26		
7.5			.68
10.0	1.96		
10.5			.62
14.0	1.57		
14.5			.52
21.0		.35	.47
21.5	1.18		

RUN NO. 38
MATERIAL: GLYCEROL-WATER
AGITATOR: 1
CHARGE 390 lbs.
RPM: 89.2

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.08			
1.0		4.62		7
1.5			3.30	14
2.0	1.22			
2.5		5.24		15
3.0			5.03	13
3.5	1.46			
4.0		5.10		12
4.5			5.00	
5.0	1.83			
5.5		5.12		14
6.0			5.12	14
6.5	2.12			
7.0		5.07		12
7.5			5.02	12
8.0	2.47			
8.5		5.08		13
9.0			5.08	13
9.5	2.68			
10.0		5.15		14
10.5			5.09	14
11.0	2.92			
11.5		5.09		13
12.0			5.07	13
12.5	3.17			
13.0		5.10		13
13.5			5.09	13
14.0	3.28			
14.5		5.18		15
15.0			5.16	15
15.5	3.46			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.50		
0.5		.35	1.16
1.0	3.37		
1.5			.80
2.0	3.32		
2.5			.70
3.0	3.19		
3.5			.60
4.0	3.08		
4.5			.57
5.0	3.00		
5.5			.55
7.0	2.83		
7.5			.52
10.0	2.62		
10.5			.50
14.0	2.35		
14.5			.48
20.0			.47
20.5	2.00		
30.0	1.61		
30.5			.42
40.0		.35	
41.5			.39
42.0	1.27		

RUN NO. 39
MATERIAL: GLYCEROL-WATER
AGITATOR: 1
CHARGE 390 lbs.
RPM: 205

HEATING

TIME MIN.	TEMPERATURE, EMF BATCH	TEMPERATURE, EMF STEAM	TEMPERATURE, EMF COND.	STEAM PRESS. PSIG
0	1.10			
1.0		4.75		10
1.5			2.10	14
2.0	1.35			
2.5		5.00		11
3.0			5.02	11
3.5	1.70			
4.0		5.02		12
4.5			5.02	13
5.0	2.10			
5.5		5.16		14
6.0			5.14	14
6.5	2.44			
7.0		5.22		14
7.5			5.10	14
8.0	2.77			
8.5		5.14		14
9.0			5.12	
9.5	3.13			
10.0		5.15		14
10.5			5.13	
11.0	3.33			
11.5	3.43			

COOLING

TIME MIN.	TEMPERATURE, EMF BATCH	TEMPERATURE, EMF WATER IN	TEMPERATURE, EMF WATER OUT
0	3.46		
0.5			1.52
1.0	3.29		
1.5			.99
2.0	3.15		
2.5		.35	.84
3.0	3.02		
3.5			.72
4.0	2.89		
4.5			.67
5.0	2.79		
5.5			.63
7.0	2.58		
7.5		.35	.59
10.0	2.32		
10.5			.55
15.0	1.93		
15.5		.50	
21.0	1.58		
21.5		.35	.46
30.0	1.24		
30.5		.34	.42

RUN NO. 40
MATERIAL: GLYCEROL-WATER
AGITATOR: 3
CHARGE 390 lbs.
RPM: 111.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.11			
1.0		4.65		9
1.5			1.60	14
2.0	1.33			
2.5		5.25		14
3.0			5.06	12
3.5	1.88			
4.0		4.80		11
4.5			4.80	12
5.0	2.30			
5.5		5.08		13
6.0			5.10	14
6.5	2.77			
7.0		5.20		16
7.5			5.13	15
8.0	3.19			
8.5		5.12		14
9.0	3.43			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.49	.35	
0.5			1.57
1.0	3.29		
1.5		.35	1.07
2.0	3.09		
2.5			.86
3.0	2.93		
3.5			.81
4.0	2.79		
4.5			.75
5.0	2.57		
5.5			.70
7.0	2.37		
7.5		.35	.66
10.0	2.07		
10.5			.60
14.0	1.72		
14.5			.53
20.5	1.34		
21.0			.46
24.0		.35	
24.5			.44
25.0	1.14		

RUN NO. 41
MATERIAL: GLYCEROL-WATER
AGITATOR: 3
CHARGE 390 lbs.
RPM: 0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	.88			
1.0		4.60		7
1.5			4.10	9
2.0	.89			
2.5		5.22		15
3.0			5.20	14
3.5	1.00			
4.0		5.08		13
4.5			5.08	13
5.0	1.20			
5.5		5.12		13
6.0			5.16	13
6.5	1.47			
7.0		5.09		
7.5			5.12	13
8.0	1.87			
8.5		5.08		13
9.0			5.08	13
9.5	2.21			
10.0		5.04		12
10.5			5.04	12
11.0	2.54			
11.5		5.10		13
11.75			5.10	13
12.0	2.70	steam off agit.on		
13.0	2.88			
14.0	2.95			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	2.95	.38	
0.5			1.40
1.0			1.04
1.25		.37	
1.50	2.93		
2.0			.75
2.5	2.89		
3.0			.63
4.0	2.84		
5.0			.55
6.0	2.75		
7.0			.49
7.5		.37	
10.0	2.62		
10.5			.47
15.0	2.43		
15.5			.45
22.0	2.22		
22.5			.42
23.0		.36	
30.0	2.00		
30.5		.36	.41
40.0	1.75	water off,agit.on	
40.5			.40
41.0	1.55		
41.5	1.52		
42.0	1.50		
42.5	1.50		

RUN NO. 42
MATERIAL: GLYCEROL-WATER
AGITATOR: 3
CHARGE 390 lbs.
RPM: 44.0

HEATING

TIME MIN.	TEMPERATURE, EMF			STEAM PRESS. PSIG
	BATCH	STEAM	COND.	
0	1.00			
1.0		5.24		16
1.5			2.00	13
2.0	1.26			
2.5		5.03		11
3.0			5.20	13
3.5	1.65			
4.0		5.15		12
4.5			5.12	12
5.0	2.03			
5.5		5.13		12
6.0			5.13	12
6.5	2.36			
7.0		5.15		13
7.5			5.15	13
8.0	2.64			
8.5		5.16		14
9.0			5.13	13
9.5	2.92			
10.0		5.13		12
10.5			5.15	13
11.0	3.18			
11.5		5.15		12
12.0			5.15	12
12.5	3.43			

COOLING

TIME MIN.	TEMPERATURE, EMF		
	BATCH	WATER IN	WATER OUT
0	3.46		
0.5			1.50
1.0	3.34		
1.5		.34	1.02
2.0	3.27		
2.5			.79
3.0	3.09		
3.5			.61
4.0	2.94		
4.5			.65
5.0	2.83		
5.5		.35	.64
7.0	2.64		
7.5			.58
10.0	2.41		
10.5			.53
15.0	2.04		
15.5			.50
22.0	1.66		
22.5			.45
30.0	1.38		
30.5		.35	.43
35.0	1.22	.35	.41

VI. CALCULATIONS:

The first step in calculating the film coefficient of heat transfer was to plot the experimental data graphically. The experimental data of Table III $\overset{\text{were}}{\text{was}}$ plotted as temperature in degrees Fahhrenheit versus time, converting EMF to degrees Fahrenheit by Figure 7. Typical curves for heating and cooling water agitated with the 5 7/8 in. diameter agitator are shown in Figures 13 to 22 inclusive.

In order to reduce the number of calculations these curves were studied to find suitable intervals which had common average batch temperatures. In the case of heating water, this temperature was $140^\circ\overset{F}{C}$, and for cooling, two temperatures $130^\circ\overset{F}{C}$ and $150^\circ\overset{F}{C}$ were chosen. Intervals were taken from ten degrees above to ten degrees below the average temperature.

The average batch temperature t_b, the initial batch temperature t_{b1} taken 10° earlier, and the final batch temperature t_{b2} taken 10° later than t_b were recorded. The initial time θ_1 at t_{b1} and the final time θ_2 at t_{b2} were recorded. The initial jacket inlet temperature t_{ji1} was taken at t_{b1}. The final jacket inlet temperature t_{ji2} was taken at t_{b2}. The initial jacket outlet temperature t_{jo1} was taken at t_{b1} and the final jacket outlet temperature t_{jo2} was taken at $t_{b\overset{2}{1}}$. The physical properties of the fluid from Table III, density ρ, viscosity μ, specific heat c, and thermal conductivity k were recorded corresponding to t_b.

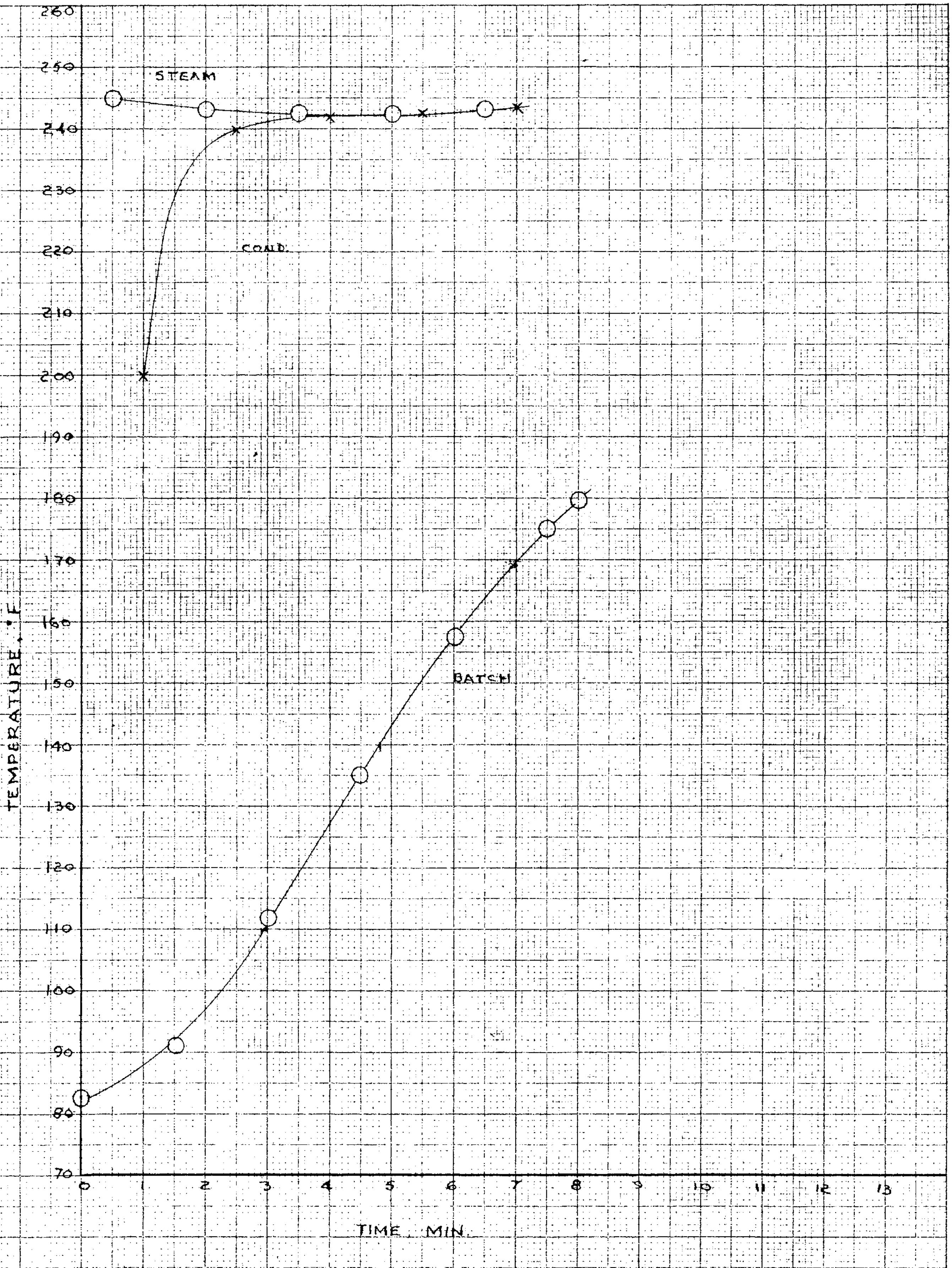

FIG.13 HEATING CURVE, WATER, No.1 AGITATOR, 160 RPM

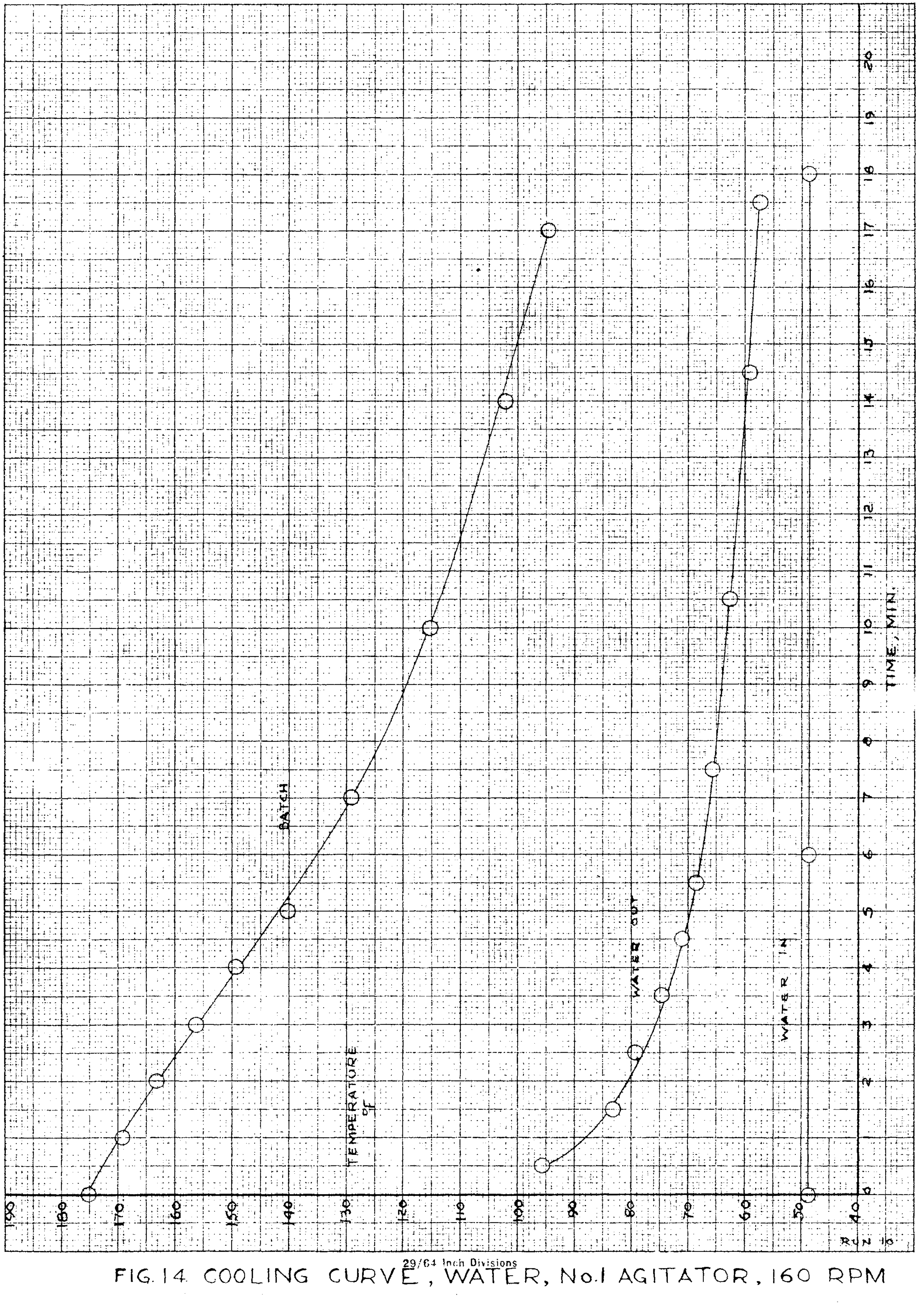

FIG. 14 COOLING CURVE, WATER, No.1 AGITATOR, 160 RPM

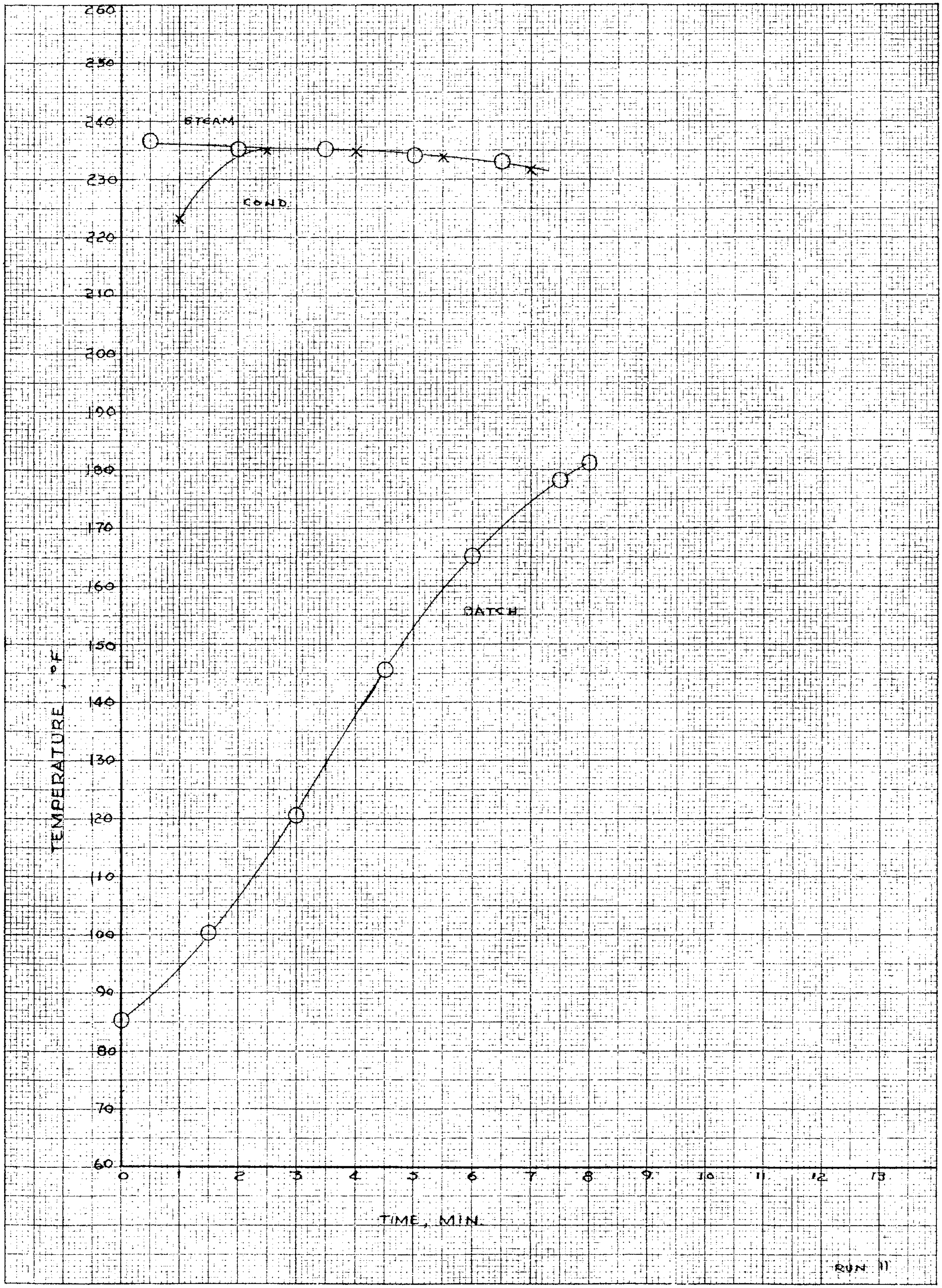

FIG.15 HEATING CURVE, WATER, No.1 AGITATOR, 215 RPM

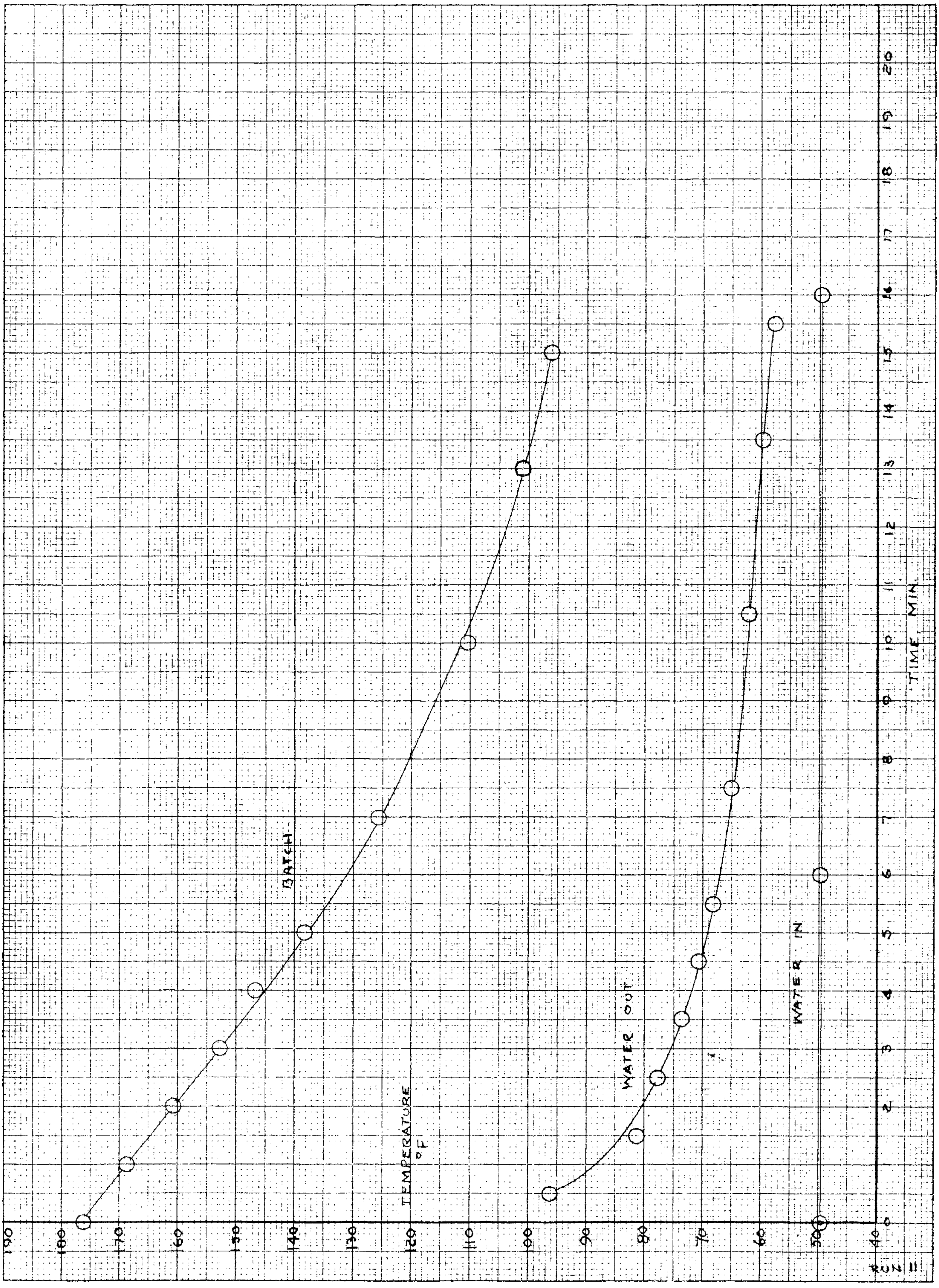

FIG.16 COOLING CURVE, WATER, No.1 AGITATOR, 215 RPM

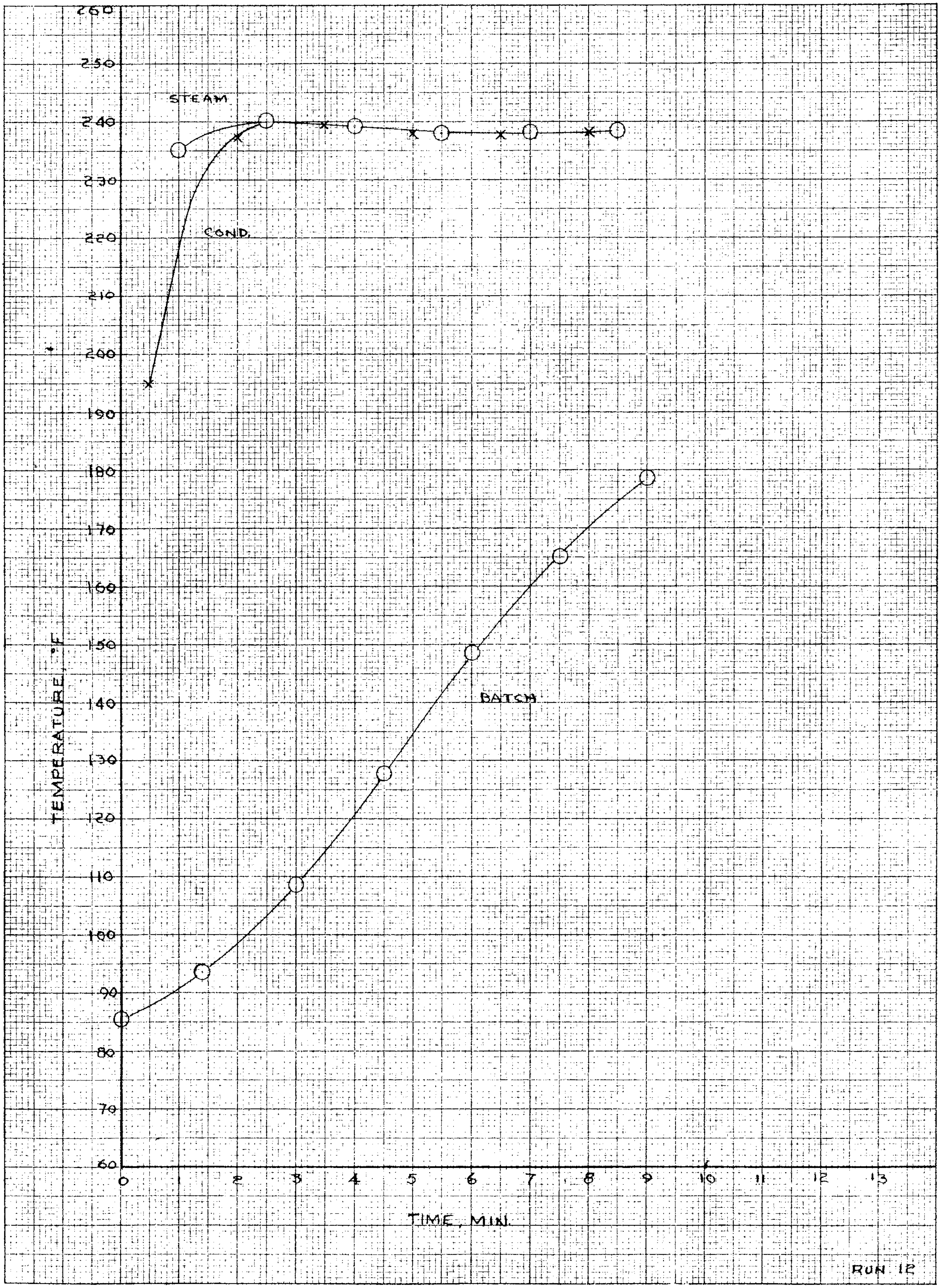

FIG. 17 HEATING CURVE, WATER, No. 1, AGITATOR, 127 RPM

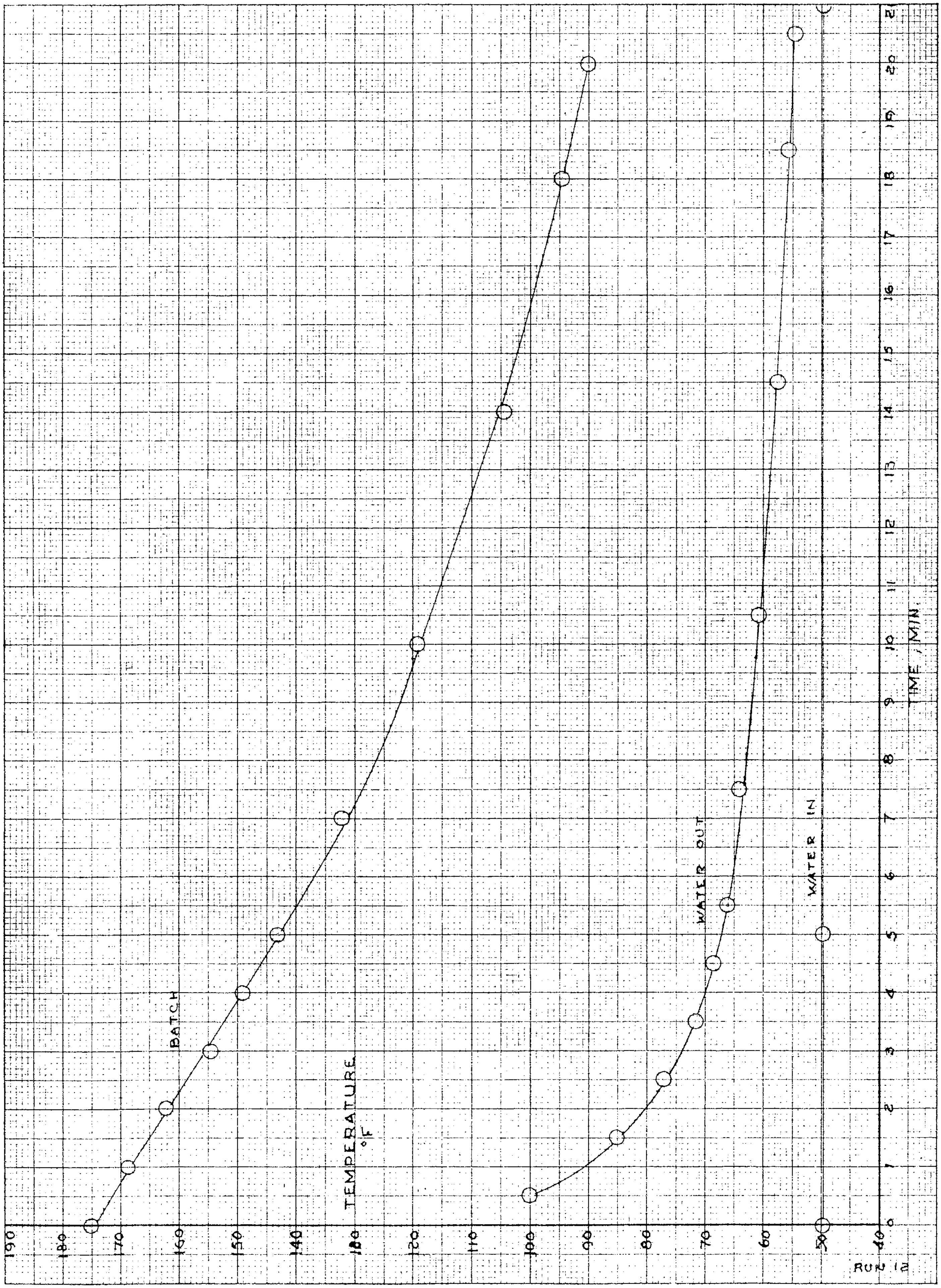

FIG. 18 COOLING CURVE, WATER, No.1 AGITATOR, 127 RPM

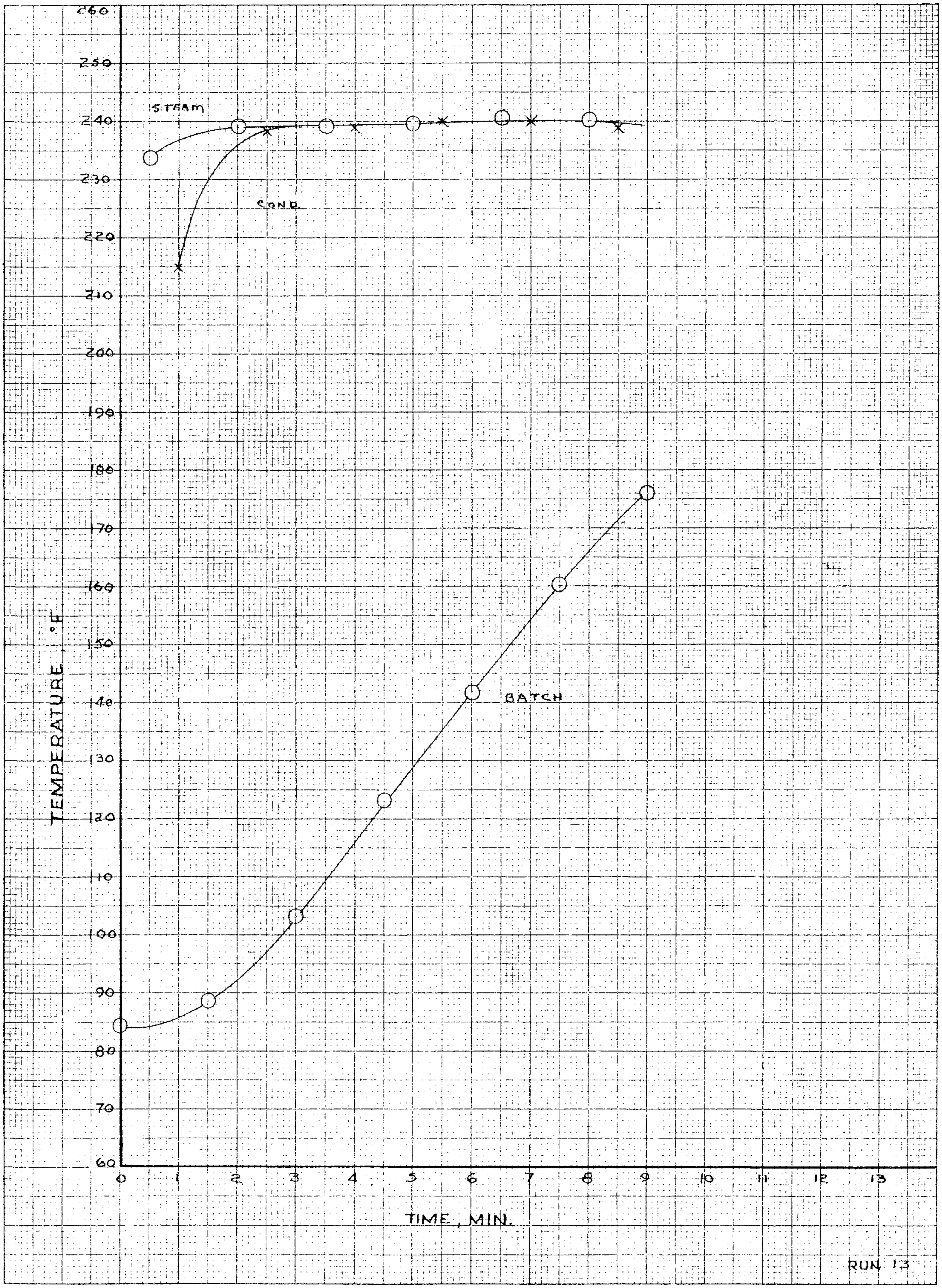

FIG.19 HEATING CURVE, WATER, No.1 AGITATOR, 93 RPM

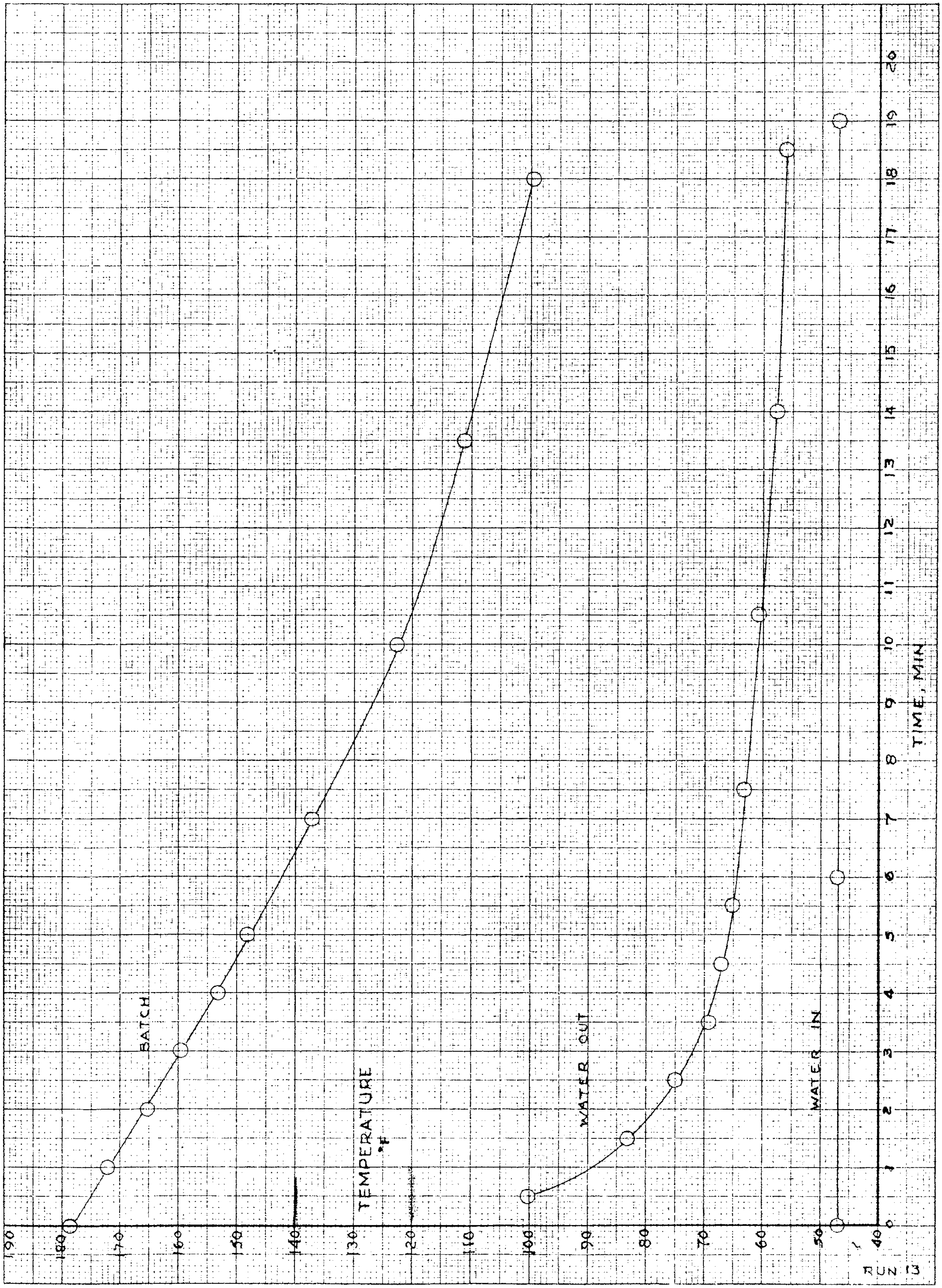

FIG.20 COOLING CURVE, WATER, No.1 AGITATOR, 93 RPM

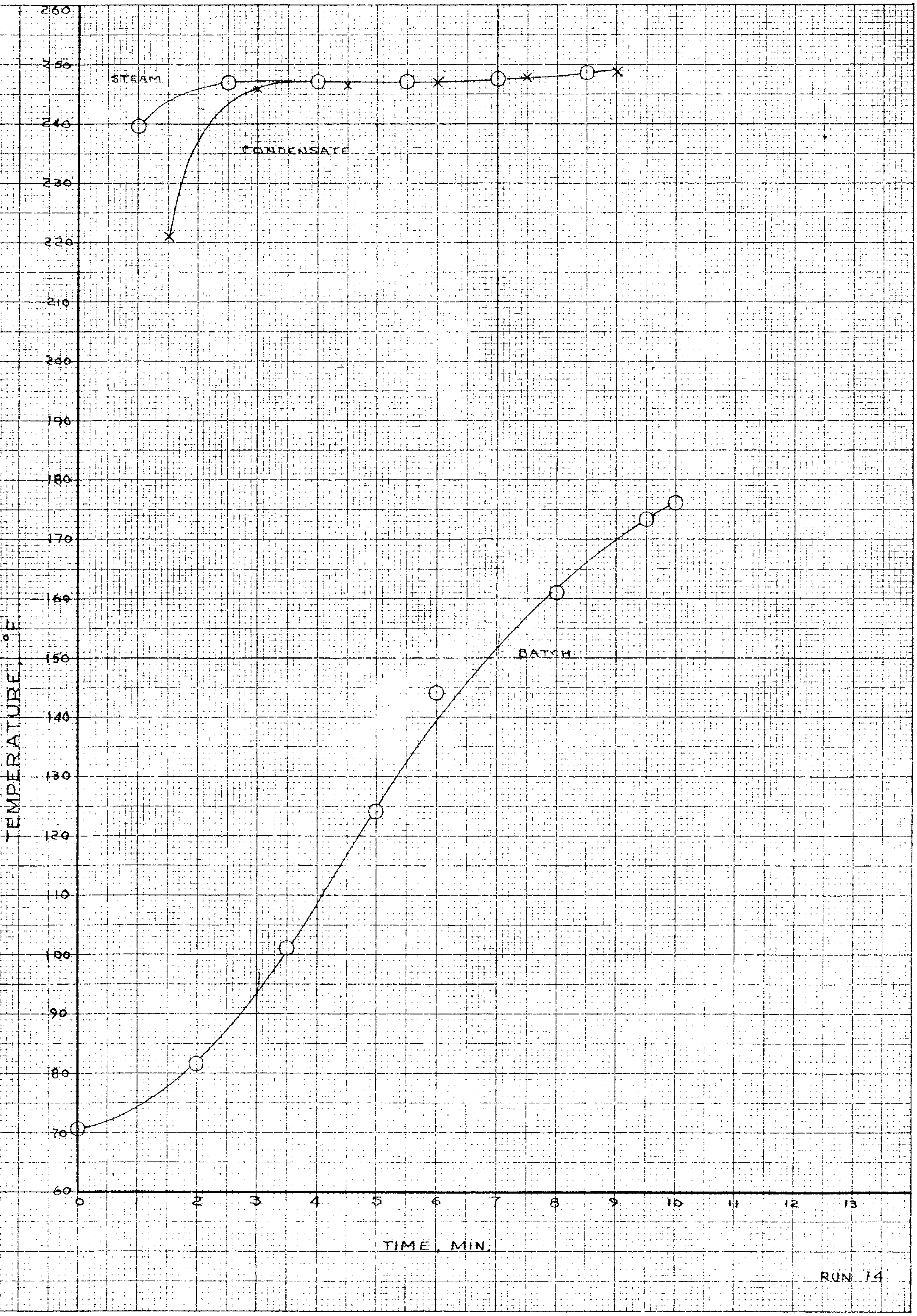

FIG. 21 HEATING CURVE, WATER, No.1 AGITATOR, 66.5 RPM

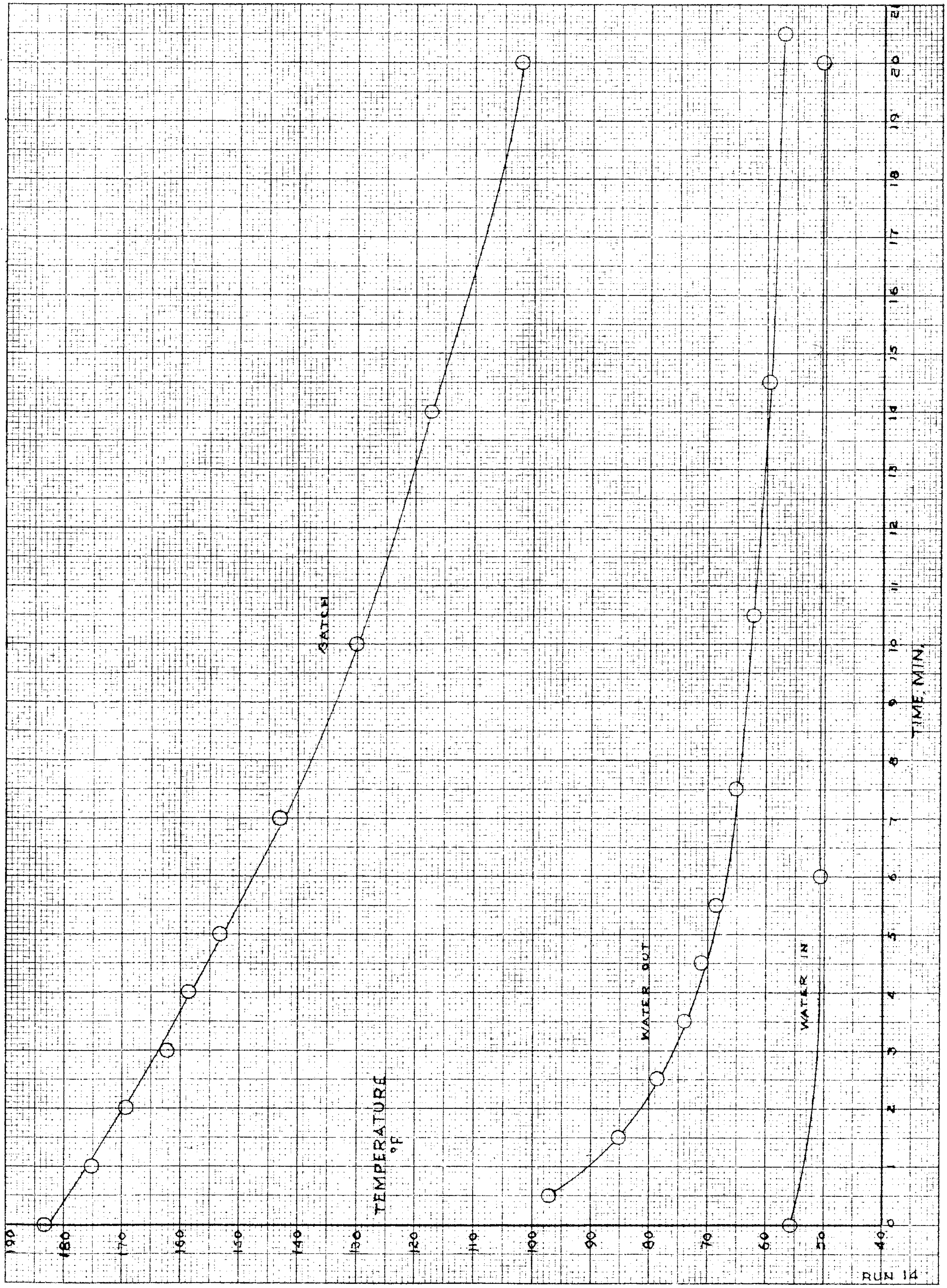

FIG. 22 COOLING CURVE, WATER, No. 1 AGITATOR, 66.5 RPM

Rates of heat transfer through the wall, q BTU per hr. were calculated from equation (38) where w is batch weight

$$(38)\qquad q = \frac{wc_p(t_{b2} - t_{b1})}{\theta_2 - \theta_1}$$

The initial temperature difference between batch and jacket was taken as

$$(52)\qquad \Delta t_1 = \tfrac{1}{2}(t_{ji1} + t_{jo1}) - t_{b1}$$

for heating and the reverse signs for cooling. The final temperature difference was taken as

$$(53)\qquad \Delta t_2 = \tfrac{1}{2}(t_{ji2} + t_{jo2}) - t_{b2}$$

for heating and the reverse signs for cooling. The mean temperature difference Δt_m between batch and jacket fluid was taken as

$$(54)\qquad \Delta t_m = \frac{\Delta t_2 - \Delta t_1}{2.3 \log \dfrac{\Delta t_2}{\Delta t_1}}$$

The inside heating surface, A, of the kettle was calculated from the volume of the batch. From this, the overall coefficient U was determined from equation (40)

$$(40)\qquad U = \frac{q}{A\ \Delta t_m}$$

These data and calculations are summarized in Table IV through VIII inclusive.

Runs were made at five different speeds for water with the No. 1 agitator, for 95.8% glycerine with the No. 3 agitator and for 72.4% glycerine with the No. 2 agitator. For the heating data for these runs values of U and the speeds, N

TABLE IV

SUMMARY OF CALCULATIONS OF FILM COEFFICIENTS
NO. 1 AGITATOR

RUN No	t_1 °F	t_2 °F	Θ_1 MIN	Θ_2 MIN	t_{ji1} °F	t_{ji2} °F	t_{jo1} °F	t_{jo2} °F	Δt_1 °F	Δt_2 °F	Δt_m °F	t_b °F	C BTU/LB °F	q BTU/HR	U BTU/HR. FT² °F	$\bar{h}$ BTU/HR. FT² °F	Δt_{fW} °F	t_w °F	μ_w LB/FT. HR.	ρ LB/CU. FT	k BTU/HR-FT-°F	μ LB/FT. HR
HEATING WATER, 347.1 LBS., 14.63 SQ. FT.																						
10H1	110.0	170.0	2.90	7.02	242.6	241.0	243.2	243.2	132.9	72.1	99.4	140.0	.9994	03,000	208	469	44.2	184.2	.816	61.38	.377	1.136
11H1	110.0	170.0	2.32	6.45	235.0	235.0	233.2	233.2	124.1	64.1	90.9	140.0	.9994	03,000	227	578	35.8	175.8	.865	61.38	.377	1.136
12H1	110.0	170.0	3.11	8.00	239.5	239.5	238.4	238.4	128.9	68.9	95.8	140.0	.9994	55,000	181.6	353	49.4	189.4	.790	61.38	.377	1.136
13H1	110.0	170.0	2.52	8.40	239.0	239.0	240.0	240.0	129.5	69.5	96.2	140.0	.9994	12,000	150.6	252	57.6	197.6	.750	61.38	.377	1.136
14H1	110.0	170.0	4.09	9.03	247.1	249.0	246.5	249.0	136.8	79.0	105.4	140.0	.9994	53,000	164.0	293	59.0	199.0	.743	61.38	.377	1.136
HEATING 95.8 % GLYCEROL, 449.0 LBS. 14.63 SQ. FT.																						
15H1	100.0	160.0	5.9	15.0	238.0	238.6	236.5	238.6	137.2	76.5	103.9	130.0	.6220	0,500	72.6	91.5	82.5	212.5	23.1	76.9	.1683	140.0
16H1	100.0	160.0	5.8	16.5	245.5	247.5	245.5	247.5	145.5	87.5	114.0	130.0	.6220	4,000	56.3	66.4	96.7	226.7	17.9	76.9	.1683	140.0
HEATING 72.4 % GLYCEROL, 390.0 LBS. 14.63 SQ. FT.																						
38H1	110.0	170.0	4.60	12.64	243.0	245.0	243.0	245.0	133.0	75.0	101.2	140.0	.7200	5,800	84.9	110.0	78.1	218.1	4.95	72.7	.203	13.7
39H1	110.0	170.0	3.70	9.80	244.0	247.0	244.0	247.0	134.0	77.0	102.9	140.0	.7200	5,600	109.9	155.9	75.2	215.2	5.10	72.7	.203	13.7
COOLING WATER, 347.1 LBS., 14.12 SQ. FT.																						
10C1	140.0	120.0	5.20	8.91	48.5	48.5	69.1	64.2	81.2	63.7	71.8	130.0	.9987	2,200	110.5	233	34.1	95.9	1.730	61.54	.372	1.238
10C2	160.0	140.0	2.40	5.20	48.5	48.5	79.2	69.1	96.2	81.2	88.1	150.0	1.0001	8,500	119.1	274	38.3	111.7	1.465	61.19	.382	1.050
11C1	140.0	120.0	4.65	8.10	49.5	49.5	70.0	64.2	80.3	63.2	71.4	130.0	.9987	0,600	119.5	276	30.9	99.1	1.666	61.54	.372	1.238
11C2	160.0	140.0	2.10	4.65	49.5	49.5	80.0	70.0	95.3	80.3	86.9	150.0	1.0001	3,200	133.1	339	34.1	115.9	1.409	61.19	.382	1.050
12C1	140.0	120.0	5.50	9.75	49.5	49.5	66.0	61.2	82.3	64.7	73.6	130.0	.9987	7,900	94.1	170.5	40.7	89.3	1.857	61.54	.372	1.238
12C2	160.0	140.0	2.30	5.50	49.5	49.5	78.1	66.0	96.2	87.3	92.5	150.0	1.0001	0,000	99.3	188.5	48.8	101.2	1.628	61.19	.382	1.050
13C1	140.0	120.0	6.42	10.68	47.0	47.0	64.0	60.0	84.5	66.5	75.2	130.0	.9987	7,800	92.1	163.8	42.3	87.7	1.896	61.54	.372	1.238
13C2	160.0	140.0	2.92	6.42	47.0	47.0	72.0	64.0	100.5	84.5	91.5	150.0	1.0001	8,900	92.0	163.3	51.5	98.5	1.678	61.19	.382	1.050
14C1	140.0	120.0	7.60	13.00	50.5	50.5	64.8	60.0	82.4	64.8	73.6	130.0	.9987	7,000	74.1	114.2	47.7	82.3	2.023	61.54	.372	1.238
14C2	160.0	140.0	3.63	7.60	50.5	50.5	73.8	64.8	102.4	82.4	91.6	150.0	1.0001	4,800	80.9	131.4	56.4	93.6	1.774	61.19	.382	1.050
COOLING 95.8% GLYCEROL, 449.0 LBS. 14.12 SQ. FT.																						
15C1	130.0	110.0	21.5	33.8	46.1	46.8	52.3	51.8	90.8	60.7	74.8	120.0	.6150	7,000	25.6	29.1	65.7	54.3	2840	77.1	.1683	191
15C2	150.0	130.0	11.0	21.5	45.9	46.1	53.0	52.3	100.6	80.8	89.7	140.0	.6300	2,400	26.6	29.5	77.8	62.2	1900	76.6	.1683	106
16C1	130.0	110.0	27.0	48.2	47.5	48.0	51.4	50.8	80.6	60.6	70.1	120.0	.6150	5,660	15.80	17.1	64.8	55.2	2760	77.1	.1683	191
16C2	150.0	130.0	13.0	27.0	47.5	47.5	52.0	51.4	100.3	80.6	90.1	140.0	.6300	4,300	19.10	21.05	81.8	58.2	2320	76.6	.1683	106
COOLING 72.4% GLYCEROL, 390.0 LBS., 14.12 SQ. FT.																						
38C1	137.5	112.5	12.6	24.6	48.5	48.5	54.6	53.0	86.0	61.8	73.1	125.0	.7110	4,700	33.6	39.9	61.6	63.4	77.5	73.1	.202	17.6
38C2	162.5	137.5	5.0	12.6	48.5	48.5	58.0	54.6	109.3	86.0	96.5	150.0	.7260	,800	41.7	52.0	78.4	71.6	61.0	72.5	.204	11.7
39C1	137.5	112.5	9.0	16.7	48.4	48.2	58.3	56.0	83.2	60.4	70.8	125.0	.7110	4,000	54.0	72.7	52.5	72.5	60.0	73.1	.202	17.6
39C2	162.5	137.5	3.1	9.0	48.6	48.4	66.6	58.3	104.9	83.2	93.4	150.0	.7260	1,800	54.4	72.3	50.8	99.2	30.2	72.5	.204	11.7

TABLE V
SUMMARY OF CALCULATIONS OF FILM COEFFICIENTS
NO. 2 AGITATOR

RUN No.	t_1 °F	t_2 °F	Θ_1 MIN.	Θ_2 MIN.	t_{ji1} °F	t_{ji2} °F	t_{jo1} °F	t_{jo2} °F	Δt_1 °F	Δt_2 °F	Δt_m °F	t_b °F	c BTU/LB °F	q BTU/HR	U BTU/HR. FT.² °F	h BTU/HR-FT.² °F	Δt_{f_W} °F	t_w °F	μ_w LB/FT. HR	ρ LB/CU. FT	k BTU/HR-FT-°F	μ LB/FT-HR
HEATING WATER, 347.1 LBS. 14.63 SQ FT																						
8H1	110.0	170.0	5.32	10.40	229.0	232.5	228.0	232.5	118.5	62.5	87.6	140.0	.9994	246,000	191.5	394	42.7	182.7	.826	61.38	.377	1.136
9H1	110.0	170.0	2.80	6.87	234.5	234.5	234.0	234.5	124.2	64.5	91.1	140.0	.9994	307,000	230	565	37.2	177.2	.857	61.38	.377	1.136
HEATING 95.8% GLYCEROL, 449.0 LBS. 14.63 SQ.FT																						
27H1	100.0	160.0	3.20	12.00	237.5	234.0	229.5	234.0	133.5	74.0	100.6	130.0	.6220	114,200	77.6	98.0	79.9	209.9	24.4	76.9	.1683	140.0
28H1	100.0	160.0	3.70	14.40	244.0	243.0	242.5	243.0	143.2	83.0	110.2	130.0	.6220	94,000	58.3	69.2	92.8	222.8	19.2	76.9	.1683	140.0
HEATING 72.4% GLYCEROL, 390.0 LBS. 14.63 SQ.FT.																						
29H1	110.0	170.0	4.40	9.60	239.0	244.0	239.0	244.0	129.0	74.0	98.9	140.0	.7200	194,500	134.5	210	63.2	203.2	5.80	72.7	.203	13.7
30H1	110.0	170.0	5.33	13.60	246.5	248.0	245.5	248.0	135.0	78.0	103.8	140.0	.7200	122,100	80.4	102.4	80.8	220.8	4.80	72.7	.203	13.7
31H1	110.0	170.0	3.11	8.64	246.2	247.0	245.2	246.0	135.7	76.5	103.2	140.0	.7200	182,900	120.9	180.1	69.4	209.4	5.40	72.7	.203	13.7
32H1	110.0	170.0	3.80	10.59	243.0	243.0	243.0	243.0	133.0	73.0	100.0	140.0	.7200	148,900	101.7	139.5	73.0	213.0	5.20	72.7	.203	13.7
33H1	110.0	170.0	4.04	10.92	247.6	247.6	247.6	247.6	137.6	77.6	104.8	140.0	.7200	146,800	95.8	129.0	77.8	217.8	5.00	72.7	.203	13.7
COOLING WATER, 347.1 LBS. 14.12 SQ.FT.																						
8C1	140.0	120.0	6.72	11.50	49.0	48.8	65.0	61.1	83.0	65.1	73.4	130.0	.9987	87,000	84.0	139.6	44.1	85.9	1.942	61.54	.372	1.238
8C2	160.0	140.0	2.62	6.72	49.4	49.0	81.0	65.0	94.8	83.0	88.5	150.0	1.0001	102,400	82.0	134.2	54.1	95.9	1.730	61.19	.382	1.050
9C1	140.0	120.0	4.29	7.94	49.6	49.6	75.0	68.9	77.7	60.8	68.6	1300	.9987	114,000	117.6	267	30.3	99.7	1.658	61.54	.372	1.238
9C2	160.0	140.0	1.46	4.29	49.6	49.6	84.4	75.0	97.7	77.7	87.0	150.0	1.0001	147,000	119.6	276	37.7	112.3	1.453	61.19	.382	1.050
COOLING 95.8% GLYCEROL, 449.0 LBS. 14.12 SQ.FT.																						
27C1	130.0	110.0	15.9	27.0	43.0	43.0	48.8	46.8	84.1	65.1	74.5	120.0	.6150	29,900	28.4	32.9	64.3	55.7	2,700	77.1	.1683	191
27C2	150.0	130.0	7.7	15.9	43.0	43.0	49.9	48.8	93.6	84.1	88.0	140.0	.6300	41,400	33.3	39.7	73.8	66.2	1,590	76.6	.1683	106
28C1	130.0	110.0	22.8	39.2	45.0	45.0	49.3	47.9	82.9	63.6	72.3	120.0	.6150	20,200	19.75	21.8	65.8	54.5	2,800	77.1	.1683	191
28C2	150.0	130.0	10.8	22.8	45.0	45.0	50.0	49.3	102.5	82.9	92.7	140.0	.6300	28,300	21.6	24.05	83.3	56.7	2,550	76.6	.1683	106
COOLING 72.4% GLYCEROL, 390.0 LBS. 14.12 SQ.FT.																						
29C1	137.5	112.5	6.6	13.3	45.0	44.8	61.0	54.1	84.5	63.1	73.3	125.0	.7110	62,100	59.6	82.1	53.6	71.4	61.5	73.1	.202	17.6
29C2	162.5	137.5	2.0	6.6	45.5	45.0	72.5	61.0	103.5	84.5	92.8	150.0	.7260	92,200	70.2	105.2	61.9	88.1	39.1	72.5	.204	11.7
30C1	137.5	112.5	13.6	25.8	47.0	47.0	54.2	51.1	86.9	63.5	74.2	125.0	.7110	34,100	32.4	38.2	63.2	61.8	72.0	73.1	.202	17.6
30C2	162.5	137.5	4.9	13.6	47.0	47.0	58.8	54.2	109.6	86.9	97.7	150.0	.7260	48,800	35.4	42.6	81.2	68.8	66.0	72.5	.204	11.7
31C1	137.5	112.5	7.9	14.8	47.0	47.0	60.0	55.3	84.0	61.4	71.7	125.0	.7110	60,300	59.6	82.1	52.0	73.0	58.5	73.1	.202	17.6
31C2	162.5	137.5	3.0	7.9	47.2	47.0	69.0	60.0	104.4	84.0	93.4	150.0	.7260	86,600	65.7	95.6	64.2	85.8	42.0	72.5	.204	11.7
32C1	137.5	112.5	9.1	17.8	47.0	47.0	57.4	54.0	85.3	62.0	72.8	125.0	.7110	47,800	46.5	59.7	56.8	68.2	66.5	73.1	.202	17.6
32C2	162.5	137.5	3.3	9.1	47.0	47.0	64.0	57.4	107.0	85.3	95.2	150.0	.7260	73,200	54.5	73.5	70.6	79.4	49.0	72.5	.204	11.7
33C1	137.5	112.5	11.1	20.5	47.0	47.0	55.0	53.0	86.5	61.5	71.5	125.0	.7110	44,300	42.9	53.9	58.2	66.8	69.5	73.1	.202	17.6
33C2	162.5	137.5	4.1	11.1	47.0	47.0	61.1	55.0	112.5	86.5	98.3	150.0	.7260	60,600	43.6	55.1	77.9	72.1	60.2	72.5	.204	11.7

TABLE VI
SUMMARY OF CALCULATIONS OF FILM COEFFICIENTS
NO. 3 AGITATOR

RUN No	t_1 °F	t_2 °F	Θ_1 MIN.	Θ_2 MIN.	t_{ji_1} °F	t_{ji_2} °F	t_{jo_1} °F	t_{jo_2} °F	Δt_1 °F	Δt_2 °F	Δt_m °F	t_b °F	c $\frac{BTU}{LB.\ °F}$	q $\frac{BTU}{HR}$	U $\frac{BTU}{HR-FT^2-°F}$	h $\frac{BTU}{HR-FT^2-°F}$	Δt_f °F	t_w °F	μ_w $\frac{LB}{FT.\ HR.}$	ρ $\frac{LB.}{CU\ FT}$	k $\frac{BTU}{HR-FT-°F}$	μ $\frac{LB}{FT.\ HR}$
HEATNG WATER 347.1 LBS. 14.63 SQ.FT.																						
6H1	110.0	170.0	2.30	7.70	231.2	229.8	228.2	229.8	119.7	59.8	86.5	140.0	.9994	231,000	182.5	357	44.2	184.2	.816	61.38	.377	1.136
7H1	110.0	170.0	2.24	6.59	227.5	227.5	226.6	227.5	117.0	57.5	83.7	140.0	.9994	287,000	234	667	29.4	169.4	.904	61.38	.377	1.136
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ.FT.																						
22H1	100.0	160.0	3.75	10.00	246.0	246.0	244.3	246.0	145.1	86.0	112.5	130.0	.6220	160,900	97.6	132.2	83.0	213.0	23.0	76.9	.1683	140.0
23H1	100.0	160.0	4.80	12.62	235.6	236.0	235.0	236.0	135.3	75.5	102.2	130.0	.6220	128,700	85.9	111.6	78.8	208.8	25.8	76.9	.1683	140.0
24H1	100.0	160.0	3.4	11.9	236.6	237.2	232.2	237.2	134.4	77.2	103.1	130.0	.6220	118,200	78.4	99.2	58.3	188.3	36.5	76.9	.1683	140.0
25H1	100.0	160.0	3.8	14.0	238.1	239.0	238.1	239.0	138.1	79.0	105.8	130.0	.6220	98,600	63.7	76.7	87.9	217.9	21.0	76.9	.1683	140.0
26H1	100.0	160.0	5.1	16.4	236.5	236.9	235.8	236.9	136.1	76.9	103.6	130.0	.6220	89,000	58.6	69.5	87.5	217.5	21.2	76.9	.1683	140.0
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63 SQ.FT.																						
40H1	110.0	170.0	3.02	7.98	243.5	245.8	243.5	245.8	133.5	75.8	101.9	140.0	.7200	204,000	136.9	221	63.2	203.2	5.80	72.7	.203	13.7
41H1	90.0	150.0	2.00	12.00	243.0	244.2	240.0	244.2	151.5	94.2	120.2	120.0	.7080	99,400	56.5	66.5	102.1	222.1	4.75	73.2	.202	19.2
42H1	110.0	170.0	3.91	11.00	247.0	246.0	247.0	246.0	137.0	76.0	103.5	140.0	.7200	142,600	94.0	125.6	77.6	217.6	5.05	72.7	.203	13.7
COOLING WATER 347.1 LBS. 14.12 SQ.FT.																						
6C1	140.0	120.0	4.65	8.10	50.0	50.0	71.2	64.9	79.4	62.6	70.2	130.0	.9987	120,500	121.3	287	29.7	100.3	1.644	61.54	.372	1.238
6C2	160.0	140.0	1.75	4.65	50.0	50.0	84.0	71.2	93.0	79.4	85.7	150.0	1.0001	143,500	118.6	271	37.5	112.5	1.451	61.19	.382	1.050
7C1	140.0	120.0	6.30	9.80	50.0	50.0	66.0	63.2	81.0	63.4	71.5	130.0	.9987	118,900	117.5	265	31.7	98.3	1.680	61.54	.372	1.238
7C2	160.0	140.0	3.41	6.30	50.0	50.0	73.2	66.0	98.4	81.0	89.0	150.0	1.0001	144,000	114.6	251	40.6	109.4	1.498	61.19	.382	1.050
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ.FT.																						
22C1	130.0	110.0	13.8	24.2	46.5	46.2	52.3	50.0	80.6	61.9	70.7	120.0	.6150	31,900	31.9	37.7	59.8	60.2	2,110	77.1	.1683	191
22C2	150.0	130.0	7.0	13.8	46.8	46.5	56.8	52.3	98.2	80.6	89.0	140.0	.6300	50,000	39.8	49.2	72.0	68.0	1,460	76.6	.1683	106
2 C1	130.0	110.0	14.3	24.6	43.0	42.5	49.2	47.4	83.9	65.1	73.6	120.0	.6150	32,200	31.0	36.3	62.8	57.2	2,500	77.1	.1683	191
23C2	150.0	130.0	7.0	14.3	43.2	43.0	51.9	49.2	102.5	83.9	91.9	140.0	.6300	46,600	36.9	44.7	73.8	66.2	1,590	76.6	.1683	106
24C1	130.0	110.0	16.2	29.2	42.5	42.5	47.8	46.2	84.9	65.7	74.5	120.0	.6150	25,500	24.2	27.4	65.9	54.1	2,920	77.1	.1683	191
24C2	150.0	130.0	7.8	16.2	42.5	42.5	50.5	47.8	103.5	84.9	93.4	140.0	.6300	40,500	30.7	36.0	79.5	60.5	2,080	76.6	.1683	106
25C1	130.0	110.0	20.0	35.2	42.0	42.0	46.0	45.2	86.0	66.4	75.4	120.0	.6150	21,800	20.4	22.1	69.8	50.2	3,650	77.1	.1683	191
25C2	150.0	130.0	9.7	20.0	42.0	42.0	47.5	46.0	105.3	86.0	94.2	140.0	.6300	33,000	24.8	28.1	83.2	56.8	2,530	76.6	.1683	106
26C1	130.0	110.0	24.4	43.3	42.0	42.0	45.2	43.9	86.4	67.1	76.3	120.0	.6150	17,560	16.26	19.27	64.5	55.5	2,730	77.1	.1683	191
26C2	150.0	130.0	9.1	24.4	42.0	42.0	47.0	45.2	105.5	86.4	95.4	140.0	.6300	22,200	16.50	19.65	80.0	60.0	2,140	76.6	.1663	106
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ.FT.																						
40C1	137.5	112.5	6.9	12.8	48.5	48.5	63.0	58.2	81.8	59.2	69.7	125.0	.7110	70,500	71.6	108.5	46.0	79.0	50.0	73.1	.202	17.6
40C2	162.5	137.5	2.7	6.9	48.5	48.5	71.5	63.0	102.5	81.8	91.8	150.0	.7260	132,500	102.1	198.0	47.4	102.6	27.8	72.5	.204	11.7
41C1	150.0	110.0	8.9	40.0	49.0	49.0	54.5	51.0	98.3	60.0	77.5	130.0	.7140	13,660	12.45	13.23	73.0	57.0	95.0	72.9	.202	16.1
42C1	137.5	112.5	9.8	19.5	47.5	47.5	56.2	54.0	85.7	61.8	73.3	125.0	.7110	42,800	41.3	51.4	59.0	66.0	71.5	73.1	.202	17.6
42C2	162.5	137.5	3.7	9.8	47.5	47.5	64.0	56.2	106.8	85.7	95.6	150.0	.7260	69,500	51.5	68.2	72.2	77.8	52.0	72.5	.204	11.7

TABLE VII

SUMMARY OF CALCULATIONS OF FILM COEFFICIENTS
No. 4 AGITATOR

RUN No	t_1 °F	t_2 °F	Θ_1 MIN.	Θ_2 MIN.	t_{ji1} °F	t_{ji2} °F	t_{jo1} °F	t_{jo2} °F	Δt_1 °F	Δt_2 °F	Δt_m °F	t_b °F	c BTU/LB °F	q BTU/HR	U BTU/HR-FT²-°F	h BTU/HR-FT²-°F	Δt_f °F	t_w °F	μ_w LB./FT.-HR.	ρ LB/CU. FT	k BTU/HR-FT-°F	μ LB/FT-HR
HEATING WATER 347.1 LBS. 14.63 SQ. FT.																						
4H1	110.0	170.0	2.08	5.15	228.0	228.2	226.2	228.2	117.1	58.2	84.3	140.0	.9994	407,000	330	2,860	9.7	149.7	1.050	61.38	.377	1.136
5H1	110.0	170.0	1.45	4.20	233.0	231.6	231.0	231.6	122.0	61.6	88.4	140.0	.9994	454,000	351	5,890	5.3	145.3	1.089	61.38	.377	1.136
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ. FT.																						
20H1	100.0	160.0	3.5	9.3	246.0	247.7	244.5	247.7	145.2	87.7	114.0	130.0	.6220	173,300	103.9	144.0	82.3	212.3	23.7	76.9	.1683	140.0
21H1	100.0	160.0	3.2	12.4	243.5	243.8	239.5	243.8	141.5	83.8	110.0	130.0	.6220	109,300	67.9	83.0	51.1	181.1	42.0	76.9	.1683	140.0
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63 SQ. FT.																						
36H1	110.0	170.0	3.52	8.74	245.0	244.6	245.0	244.6	135.0	74.6	101.8	140.0	.7200	193,600	129.6	198.5	66.7	206.7	5.60	72.7	.203	13.7
37H1	110.0	170.0	2.70	6.40	236.6	238.5	236.6	238.5	126.6	66.6	93.5	140.0	.7200	273,000	199.5	428	43.6	183.6	7.35	72.7	.203	13.7
COOLING WATER 347.1 LBS. 14.12 SQ. FT.																						
4C1	140.0	120.0	6.28	10.60	50.0	50.0	67.6	63.1	81.2	63.5	71.8	130.0	.9987	96,400	95.0	173.5	39.3	90.7	1.833	61.54	.372	1.238
4C2	160.0	140.0	2.70	6.28	50.0	50.0	77.5	67.6	97.3	81.2	88.6	150.0	1.0001	116,100	92.9	166.4	49.4	100.6	1.640	61.19	.382	1.050
5C1	140.0	120.0	5.00	8.33	50.0	50.0	71.0	64.4	79.5	62.8	71.2	130.0	.9987	124,900	124.1	303	29.1	100.9	1.637	61.54	.372	1.238
5C2	160.0	140.0	2.22	5.00	50.0	50.0	83.3	71.0	93.4	79.5	86.2	150.0	1.0001	149,600	122.8	294	36.0	114.0	1.434	61.19	.382	1.050
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ. FT.																						
20C1	130.0	110.0	13.2	22.0	47.0	46.5	54.5	51.3	79.3	61.1	70.0	120.0	.6150	37,600	38.0	44.9	59.2	62.8	1,850	77.1	.1683	191.
20C2	150.0	130.0	6.8	13.2	47.0	47.0	59.0	54.5	97.0	79.3	87.4	140.0	.6300	53,200	43.0	53.9	69.8	70.2	1320	76.6	.1683	106.
21C1	130.0	110.0	20.3	36.9	45.5	45.5	49.6	48.8	82.5	62.9	72.2	120.0	.6150	20,000	19.60	21.6	65.5	54.5	2,800	77.1	.1683	191.
21C2	150.0	130.0	10.2	20.3	45.5	45.5	51.0	49.6	101.8	82.5	92.2	140.0	.6300	33,700	25.9	29.6	80.7	59.3	2,180	76.6	.1683	106.
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ. FT.																						
36C1	137.5	112.5	8.2	16.3	48.5	48.5	62.0	57.4	82.2	59.6	70.3	125.0	.7110	51,300	51.7	68.4	53.1	71.9	60.5	73.1	.202	17.6
36C2	162.5	137.5	3.0	8.2	48.5	48.5	73.0	62.0	101.8	82.2	91.6	150.0	.7260	81,700	63.2	90.2	64.2	85.8	42.0	72.5	.204	11.7
37C1	137.5	112.5	5.9	11.9	47.0	47.0	64.5	60.2	81.8	58.9	69.7	125.0	.7110	69,300	70.5	106.0	46.2	78.8	50.4	73.1	.202	17.6
37C2	162.5	137.5	1.7	5.9	47.0	47.0	75.6	64.5	106.8	81.8	93.8	150.0	.7260	101,100	76.5	120.1	59.6	90.4	37.0	72.5	.204	11.7

TABLE VIII
SUMMARY OF CALCULATIONS OF FILM COEFFICIENTS
No. 5 AGITATOR

RUN No	t_1 °F	t_2 °F	Θ_1 MIN	Θ_2 MIN	t_{ji1} °F	t_{ji2} °F	t_{jo1} °F	t_{jo2} °F	Δt_1 °F	Δt_2 °F	Δt_m °F	t_b °F	c $\frac{BTU}{LB-°F}$	q $\frac{BTU}{HR}$	U $\frac{BTU}{HR-FT^2-°F}$	h $\frac{BTU}{HR-FT^2-°F}$	Δt_f °F	t_w °F	μ_w $\frac{LB}{FT.HR}$	ρ $\frac{LB}{CU.FT.}$	k $\frac{BTU}{HR-FT-°F}$	μ $\frac{LB}{FT-HR}$
HEATING WATER 347.1 LBS. 14.63 SQ. FT.																						
1H1	90.0	150.0	1.80	7.80	227.4	227.4	227.4	227.4	137.4	77.4	104.2	130.0	.9987	208,000	136.2	214	66.4	196.4	.754	61.54	.372	1.238
2H1	110.0	170.0	2.72	7.22	228.6	228.6	227.5	228.6	118.0	58.6	85.0	140.0	.9994	278,000	223	562	33.8	173.8	.879	61.38	.377	1.136
3H1	110.0	170.0	4.30	8.71	232.5	230.7	232.5	230.7	122.5	60.7	88.3	140.0	.9994	284,000	219	553	35.1	175.1	.871	61.38	.377	1.136
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ. FT.																						
17H1	100.0	160.0	6.4	13.8	243.7	243.7	243.7	243.7	143.7	83.7	110.0	130.0	.6220	135,900	83.5	119.8	77.5	207.5	25.2	76.9	.1683	140.0
18H1	100.0	140.0	4.0	15.0	245.0	248.0	245.0	248.0	145.0	88.0	114.1	120.0	.6150	60,300	36.1	40.0	103.2	223.2	16.1	77.1	.1683	191.0
19H1	100.0	160.0	5.0	10.9	244.8	247.0	244.8	247.0	144.8	84.8	112.5	130.0	.6220	170,300	103.6	143.5	81.2	211.2	23.7	76.9	.1683	140.0
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63 SQ. FT.																						
34H1	110.0	170.0	3.10	7.85	243.7	245.8	242.8	245.8	133.2	75.8	101.8	140.0	.7200	213,000	143.0	232	62.8	202.8	5.65	72.7	.203	13.7
35H1	110.0	170.0	2.90	7.10	234.0	235.8	233.0	235.8	123.5	65.8	91.7	140.0	.7200	240,000	178.9	344	47.7	187.7	6.95	72.7	.203	13.7
COOLING WATER 347.1 LBS. 14.12 SQ. FT.																						
1C1	140.0	100.0	1.50	14.00	52.0	52.0	58.2	54.4	84.9	46.8	63.9	120.0	.9982	66,600	73.8	115.0	41.0	79.0	2.113	61.70	.367	1.354
2C1	140.0	120.0	6.90	9.78	52.0	52.0	68.0	64.7	80.0	61.7	70.4	130.0	.9987	144,400	145.1	468	21.8	108.2	1.517	61.54	.372	1.238
2C2	160.0	140.0	4.80	6.90	52.0	52.0	70.8	68.0	98.6	80.0	88.8	150.0	1.0001	198,100	158.0	633	22.2	127.8	1.261	61.19	.382	1.050
3C1	140.0	120.0	4.83	8.42	50.0	50.0	68.6	63.4	80.7	63.3	71.8	130.0	.9987	116,000	114.4	252	33.5	96.5	1.717	61.54	.372	1.238
3C2	160.0	140.0	1.91	4.83	50.0	50.0	79.0	68.6	95.5	80.7	88.0	150.0	1.0001	142,500	114.4	252	40.0	110.0	1.488	61.19	.382	1.050
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ. FT.																						
17C1	130.0	110.0	16.4	28.1	46.7	46.0	51.5	49.8	80.9	62.1	71.1	120.0	.6150	28,300	28.2	32.5	61.6	58.4	2,250	77.1	.1683	191.0
17C2	150.0	130.0	8.4	16.4	47.0	46.7	54.1	51.5	99.5	80.9	89.8	140.0	.6300	42,500	33.5	39.9	75.4	64.6	1,700	76.6	.1683	106.0
18C1	140.0	120.0	1.0	25.6	45.5	45.5	65.7	47.2	84.4	78.7	81.6	130.0	.6220	13,650	11.82	12.51	77.2	52.8	3,170	76.9	.1683	140.0
19C1	130.0	110.0	12.2	21.4	46.0	46.0	53.1	51.0	80.5	61.5	70.6	120.0	.6150	36,100	36.2	43.8	58.2	61.8	1,970	77.1	.1683	191.0
19C2	150.0	130.0	5.6	12.2	46.0	46.0	57.2	53.1	98.4	80.5	88.4	140.0	.6300	51,500	41.2	51.2	71.3	68.7	1,390	76.0	.1683	106.0
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ. FT																						
34C1	137.5	112.5	7.8	15.0	47.0	47.0	57.7	55.0	85.2	61.5	72.6	125.0	.7110	57,800	56.4	77.0	53.1	71.9	60.5	73.1	.202	17.6
34C2	162.5	137.5	3.2	7.8	47.0	47.0	69.0	57.7	104.5	85.2	94.3	150.0	.7260	92,300	69.4	103.5	63.1	86.9	40.5	72.5	.204	11.7
35C1	137.5	112.5	5.7	11.4	47.0	47.0	63.0	57.2	82.5	60.4	70.6	125.0	.7110	73,000	73.3	112.6	45.9	79.1	48.0	73.1	.202	17.6
35C2	162.5	137.5	2.0	5.7	47.0	47.0	76.5	63.0	100.8	82.5	91.4	150.0	.7260	114,600	88.8	153.4	52.8	97.2	31.6	72.5	.204	11.7

214 x 14.6

3,120

r.p.h. were tabulated in Table IX. Values of 1/U and $1/N^{3/4}$ were calculated. Likewise, values of 1/U and $1/N^{3/4}$ for cooling were calculated in Table X. In Figure 23, 1/U was plotted against $1/N^{3/4}$ for the heating data. For water, R_c was .00211, for 72.4% glycerol R_c was .00281, and for 95.8% glycerol, R_c was .00312. These gave an average combined resistance for heating of .00268. Film coefficients for heating were then calculated using equation (39):

(39a) $1/U = .00268 + 1/h$.

In Fig. 24, 1/U was plotted against $1/N^{3/4}$ for the cooling data. Values of R_c are shown in Table X for each of the groups of data. The average value of R_c for cooling was .00475. Film coefficients for cooling were then calculated using equation (39):

(39b) $1/U = .00475 + 1/h$

For each point of data the temperature drop across the film, Δt_w, was calculated from

(55) $\Delta t_w = \dfrac{q}{hA}$

For heating data, the wall temperature t_w was calculated as

(56) $t_w = t_b + \Delta t_w$ and for cooling,

(57) $t_w = t_b - \Delta t_w$

From the temperatures of the wall, t_w, the corresponding viscosities, μ_w, were taken from figures 11 and 12. These data are all summarized in Tables VI to X inclusive.

From the data tabulated in Tables VI to X, the dimen-

TABLE IX

DETERMINATION OF COMBINED RESISTANCES

HEATING

RUN NO.	n RPM	N RPH	$N^{3/4}$	$\frac{1}{N^{3/4}}$	U	$\frac{1}{U}$	R	
WATER, HEATING, NO. 1 AGITATOR 140°F								
10 H 1	160.0	9,600	968	.001024	208	.00481		
11 H 1	215.0	12,900	1,210	.000826	227	.00440		
12 H 1	127.0	7,620	815	.001227	181.6	.00552	.00210	
13 H 1	93.2	5,592	647	.001546	150.6	.00664		
14 H 1	66.5	3,990	502	.001993	164.0	.00610		
72.4% GLYCEROL, HEATING, NO. 2 AGITATOR 130°F								
29 H 1	180.0	10,800	1,059	.000945	134.5	.00744		
30 H 1	45.0	2,700	375	.00267	80.4	.01243		
31 H 1	145.5	8,730	904	.001107	120.9	.00827	.00281	.00268
32 H 1	110.2	6,612	732	.001367	101.7	.00985		
33 H 1	79.1	4,746	572	.001750	95.8	.01043		
95.8% GLYCEROL, HEATING, NO. 3 AGITATOR 140°F								
22 H 1	127.0	7,620	815	.001227	97.6	.01024		
23 H 1	105.0	6,300	716	.001398	85.9	.01164		
24 H 1	80.0	4,800	572	.001750	78.4	.01276	.00312	
25 H 1	55.5	3,330	438	.002285	63.7	.01570		
26 H 1	34.2	2,052	303	.00330	58.6	.01708		

TABLE X

DETERMINATION OF COMBINED RESISTANCES

COOLING

RUN NO.	n RPM	N RPH	$N^{3/4}$	$\frac{1}{N^{3/4}}$	U	$\frac{1}{U}$	R
WATER, COOLING, NO. 1 AGITATOR 130°F							
10 C 1	160.0	9,600	968	.001024	110.5	.00905	
11 C 1	215.0	12,900	1,210	.000826	119.5	.00836	
12 C 1	127.0	7,620	815	.001227	94.1	.01062	.0048 ✓
13 C 1	93.2	5,592	647	.001546	92.1	.01086	
14 C 1	66.5	3,990	502	.001993	74.1	.01350	
WATER, 150°F							
10 C 2	160.0	9,600	968	.001024	119.1	.00840	
11 C 2	215.0	12,900	1,210	.000826	133.1	.00751	
12 C 2	127.0	7,620	815	.001227	99.3	.01007	.0047
13 C 2	93.2	5,592	647	.001546	92.0	.01087	
14 C 2	66.5	3,990	502	.001993	80.9	.01236	
72.4% GLYCEROL, COOLING, NO. 2 AGITATOR 125°F							
29 C 1	180.0	10,800	1,059	.000945	59.6	.01679	
30 C 1	45.0	2,700	375	.00267	32.4	.0309	
31 C 1	145.5	8,730	904	.001107	59.6	.01679	.0044
32 C 1	110.2	6,610	732	.001367	46.5	.0215	
33 C 1	79.1	4,746	572	.001750	42.9	.0233	
72.4% GLYCEROL 150°F							
29 C 2	180.0	10,800	1,059	.000945	70.2	.01425	
30 C 2	45.0	2,700	375	.00207	35.4	.0283	
31 C 2	145.5	8,730	904	.001107	65.7	.01521	.0049
32 C 2	110.2	6,612	732	.001367	54.5	.01836	
33 C 2	79.1	4,746	572	.001750	43.6	.0229	
95.8% GLYCEROL, COOLING, NO. 3 AGITATOR 120°F							
22 C 1	127.0	7,620	815	.001227	31.9	.0313	
23 C 1	105.0	6,300	716	.001398	31.0	.0323	
24 C 1	80.0	4,800	572	.001750	24.2	.0413	.0052
25 C 1	55.5	3,330	438	.002285	20.4	.0490	
26 C 1	34.2	2,052	303	.00330	16.26	.0616	

TABLE X (cont.)

RUN NO.	n RPM	N RPH	$N^{3/4}$	$\frac{1}{N^{3/4}}$	U	$\frac{1}{U}$	R
95.8% GLYCEROL			140°F				
22 C 2	127.0	7,620	815	.001227	39.8	.0251	
23 C 2	105.0	6,300	716	.001398	36.9	.0271	
24 C 2	80.0	4,800	572	.001750	30.7	.0326	.0044
25 C 2	55.5	3,330	438	.002285	24.8	.0403	
26 C 2	34.2	2,052	303	.00330	16.50	.0607	
							AVE. .00475

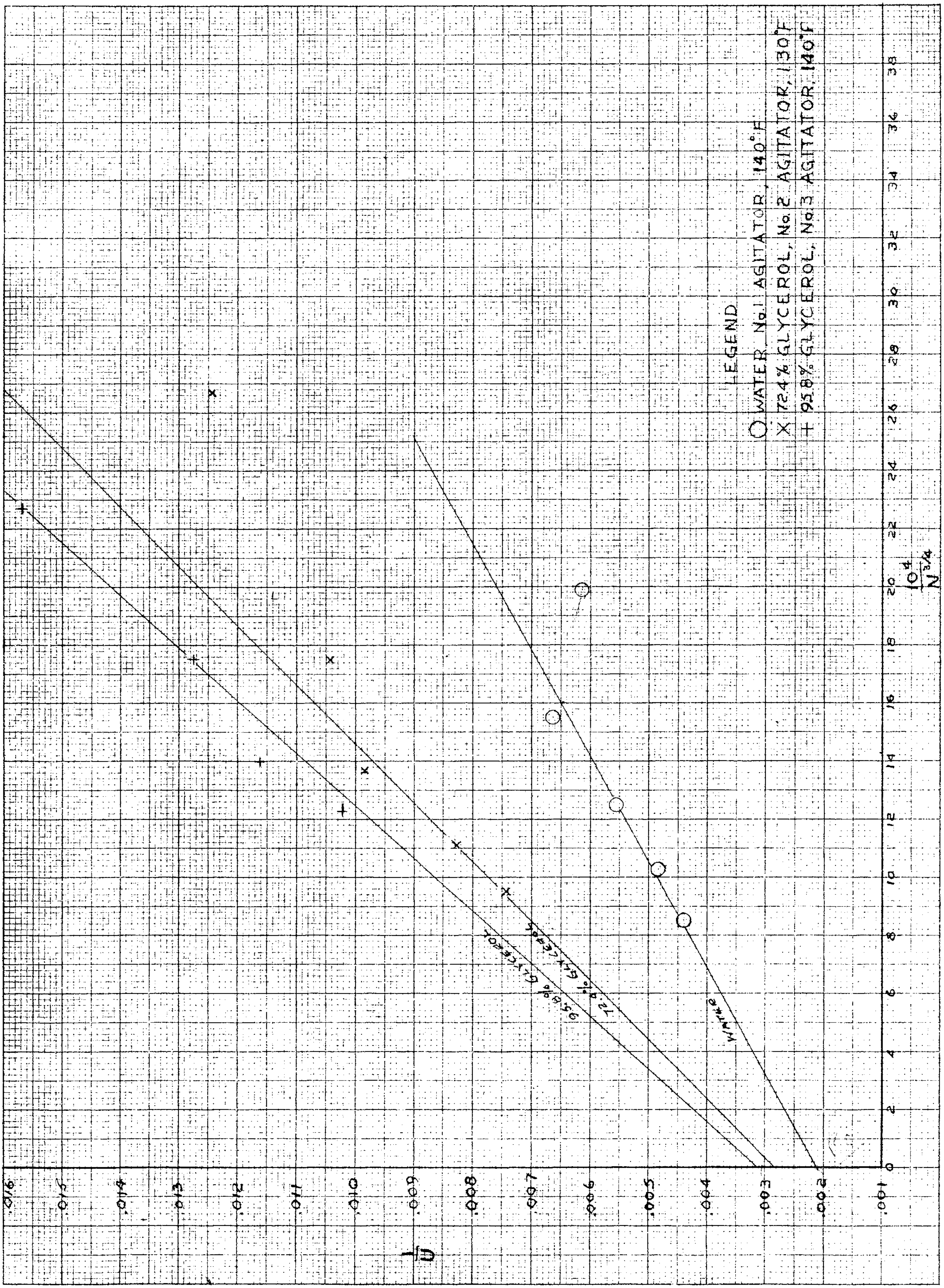

FIG. 23 DETERMINATION OF COMBINED RESISTANCES, HEATING

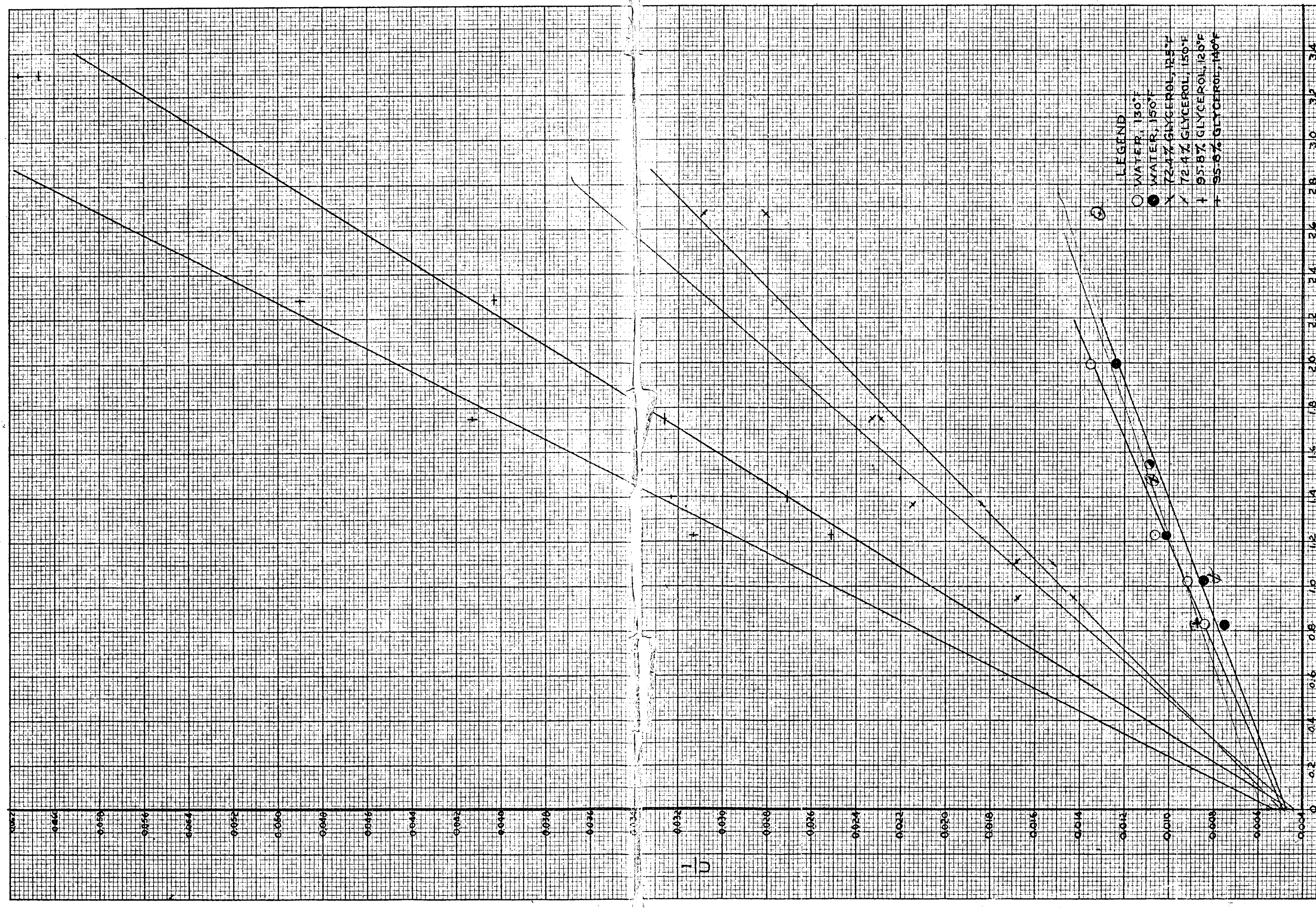

FIG. 2-4 DETERMINATION OF COMBINED RESISTANCES, COOLING

sionless groups (hT/K), $(c\mu/K)$, $(D^2N\rho/\mu)$, and (μ_w/μ) were calculated. These are tabulated in Tables XI to XV inclusive.

In order to determine the function of the Reynolds Number, N_{Nu} was plotted against N_{Re} on log paper (Fig. 25). Only those data where 5 runs per fluid were made with the same agitator were used. By eye, it appeared that lines having slopes of 3/4 appeared to express this data.

To determine the exponent of the Prandtl number, $\log N_{Nu}/N_{Re}{}^{3/4}$ was plotted against $\log N_{Pr}$. The data for the No. 1 agitator is shown in Figure 26, for No. 2 agitator in Figure 27, for No. 3 agitator in Figure 28, for No. 4 agitator in Figure 29, and for the No. 5 agitator in Figure 30. By eye, the line which appeared to express these data best had a slope of 0.44.

Log $N_{Nu}/N_{Re}{}^{3/4}N_{Pr}{}^{.44}$ was then plotted against log (μ_w/μ) for each of the five stirrers. These plots are shown in Figures 31 through 35 inclusive. The line which appeared by eye to express these data best had a slope of -1/4.

In order to check the exponents already determined, $\log N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Re}{}^{3/4}$ was plotted against $\log N_{Pr}$ for each stirrer. These are shown in Figures 36 to 40 inclusive. It appeared by eye that a line having a slope of 0.44 best expressed all the data. This confirmed the determination in Figures 26 to 30.

A final check of the exponent of the Reynolds Number

TABLE XI

CORRELATION OF DIMENSIONLESS GROUPS
NO. 1 AGITATOR

	RUN No	N RPH	$\frac{hT}{K}$	$\frac{c\mu}{K}$	$\frac{\mu_w}{\mu}$	$\frac{D^2N\rho}{\mu}$	$\frac{\frac{hT}{K}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{K}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}\left(\frac{c\mu}{K}\right)^{.44}}$	$\frac{\frac{hT}{K}(\mu_w/\mu)^{1/4}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{K}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{K}\right)^{.44}}$	$\frac{\frac{hT}{K}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{K}\right)^{.44}\left(\frac{T}{D}\right)^{4/5}\left(\frac{D_w}{D}\right)^{.13}}$
HEATING WATER 347.1 LBS. 14.63 SQ. FT.	10H1	9,600	2,490	3.01	.718	124,500	.375	.231	.345	1,412	881
	11H1	12,900	3,070	3.01	.762	167,200	.370	.228	.345	1,758	1,096
	12H1	7,620	1,874	3.01	.695	98,800	.337	.207	.308	1,053	658
	13H1	5,592	1,338	3.01	.660	72,400	.303	.1865	.273	742	463
	14H1	3,990	1,555	3.01	.654	51,700	.453	.279	.408	862	538
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ. FT.	15H1	13,830	1,086	518	.1650	1,821	6.13	.390	3.91	44.2	27.5
	16H1	6,798	790	518	.1280	895	4.82	.307	2.89	30.1	18.75
HEATING 72.4% GLYCEROL 390.0 LBS 14.63 SQ. FT.	38H1	5,352	1,082	48.6	.361	6,800	1.448	.262	1.122	152.0	94.8
	39H1	12,300	1,533	48.6	.372	15,640	1.095	.1985	.857	217	135.5
COOLING WATER 347.1 LBS. 14.12 SQ. FT.	10C1	9,600	1,256	3.32	1.398	114,200	.201	.1185	.218	804	501
	10C2	9,600	1,437	2.75	1.395	134,000	.204	.1306	.222	999	622
	11C1	12,900	1,489	3.32	1.345	153,600	.1914	.1130	.206	945	588
	11C2	12,900	1,729	2.75	1.341	180,100	.1963	.1259	.211	1,190	742
	12C1	7,620	918	3.32	1.500	90,700	.1763	.1040	.1944	596	372
	12C2	7,620	987	2.75	1.550	106,200	.1676	.1172	.1852	699	435
	13C1	5,592	881	3.32	1.530	66,600	.214	.1262	.236	574	358
	13C2	5,592	856	2.75	1.596	78,100	.1830	.1172	.206	616	384
	14C1	3,990	615	3.32	1.635	47,500	.1910	.1126	.216	411	256
	14C2	3,990	688	2.75	1.689	55,700	.1900	.1217	.217	502	313
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ. FT.	15C1	13,830	346	698	15.40	1,335	1.565	.0879	3.11	38.5	24.0
	15C2	13,830	351	397	17.93	2,390	1.025	.0755	2.11	53.2	33.2
	16C1	6,798	203	698	14.46	656	1.481	.0832	2.89	22.3	13.90
	16C2	6,798	250	397	21.9	1,176	1.238	.0911	2.68	39.8	24.8
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ. FT.	38C1	5,352	395	61.9	4.41	5,320	.634	.1038	.918	93.5	58.2
	38C2	5,352	492	41.7	5.22	7,950	.586	.1138	.888	144.2	90.0
	39C1	12,300	720	61.9	3.41	12,220	.616	.1007	.837	159.5	99.5
	39C2	12,300	708	41.7	2.58	18,290	.451	.0875	.571	173.6	108.3

TABLE XII
CORRELATION OF DIMENSIONLESS GROUPS
NO. 2 AGITATOR

	RUN No.	N RPH	$\frac{hT}{K}$	$\frac{c\mu}{k}$	$\frac{\mu_w}{\mu}$	$\frac{D^2N\rho}{\mu}$	$\frac{\frac{hT}{K}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{K}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{K}(\mu_w/\mu)^{1/4}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{K}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{K}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}\left(\frac{T}{D}\right)^{.44}\left(\frac{D_w}{D}\right)^{.13}}$
HEATING WATER 347.1 LBS. 14.62 SQ.FT.	8H1	2,760	2,090	3.01	.729	68,400	.495	.304	.361	1,190	880
	9H1	9,540	3,000	3.01	.754	237,000	.298	.1835	.225	1,722	1,272
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ.FT.	27H1	10,530	1,162	518	.1745	2,650	3.14	.200	2.03	47.8	35.3
	28H1	5,766	822	518	.1372	1,451	3.49	.222	2.08	31.3	23.1
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63 SQ.FT.	29H1	10,800	1,971	48.6	.423	26,300	.948	.1719	.765	288.	213.
	30H1	2,700	1,010	48.6	.351	6,570	1.392	.252	1.074	140.9	104.0
	31H1	8,730	1,776	48.6	.394	21,250	1.001	.1811	.793	255	188.3
	32H1	6,612	1,374	48.6	.380	16,100	.961	.1740	.755	195.7	144.5
	33H1	4,746	1,271	48.6	.365	11,550	1.136	.206	.882	178.9	132.0
COOLING WATER 347.1 LBS. 14.12 SQ.FT.	8C1	2,760	751	3.32	1.568	62,800	.1896	.1118	.212	496.	366.
	8C2	2,760	703	2.75	1.648	71,200	.1610	.1030	.1830	512	378
	9C1	9,540	1,440	3.32	1.339	217,000	.1411	.0835	.1520	915	675
	9C2	9,540	1,449	2.75	1.384	275,000	.1202	.0770	.1326	1,005	742
COOLING 95.8% GLYCEROL 449.0 LBS 14.12 SQ.FT.	27C1	10,530	391	698	14.14	1,949	1.340	.0755	2.60	44.7	34.0
	27C2	10,530	472	397	15.00	3,490	1.041	.0767	2.05	68.2	50.3
	28C1	5,766	259	698	14.66	1,066	1.386	.0778	2.71	28.4	21.0
	28C2	5,766	286	397	24.1	1,908	.996	.0733	2.21	46.7	34.5
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ.FT.	29C1	10,800	812	61.9	3.49	20,500	.472	.0780	.645	181.1	134.0
	29C2	10,800	1,032	41.7	3.34	30,700	.445	.0863	.603	271	200
	30C1	2,700	378	61.9	4.09	5,130	.622	.1015	.875	87.9	64.9
	30C2	2,700	417	41.7	5.64	7,670	.498	.0965	.767	124.7	92.2
	31C1	8,730	812	61.9	3.33	16,600	.582	.0902	.746	179.4	132.6
	31C2	8,730	937	41.7	3.59	24,800	.472	.0914	.650	250	184.6
	32C1	6,612	592	61.9	3.78	12,560	.500	.0817	.697	134.8	99.6
	32C2	6,612	722	41.7	4.18	18,800	.448	.0869	.640	200	147.9
	33C1	4,746	534	61.9	3.95	9,020	.580	.0948	.817	122.9	90.8
	33C2	4,746	540	41.7	5.20	13,500	.417	.0807	.630	158.0	106.6

TABLE XIII
CORRELATION OF DIMENSIONLESS GROUPS
NO. 3 AGITATOR

	RUN No	N RPH	$\frac{hT}{k}$	$\frac{c\mu}{k}$	$\frac{\mu_w}{\mu}$	$\frac{D^2N\rho}{\mu}$	$\frac{\frac{hT}{k}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{k}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}\left(\frac{T}{D}\right)^{2/3}\left(\frac{D_w}{D}\right)^{.13}}$
HEATING WATER 347.1 LBS. 14.63 SQ.FT.	6H1	6,120	1,894	3.01	.718	331,000	.1371	.0846	.1262	1,075	978
	7H1	2,640	3,540	3.01	.795	142,700	.484	.298	.457	2,060	1,873
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ.FT.	22H1	7,620	1,571	518	.1645	4,180	3.02	.1938	1.925	63.8	58.0
	23H1	6,300	1,326	518	.1845	3,460	2.94	.1875	1.927	55.3	50.3
	24H1	4,800	1,178	518	.261	2,630	3.21	.205	2.29	53.7	48.8
	25H1	3,330	912	518	.150	1,830	3.25	.207	2.02	36.2	32.9
	26H1	2,052	826		.1515	1,126	4.25	.271	2.65	32.8	29.8
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63 SQ.FT.	40H1	6,660	2,180	48.6	.423	35,300	.845	.1530	.681	318	289
	41H1	0	658	67.3	.247	0	-	-	-	72.8	72.8
	42H1	2,640	1,239	48.6	.369	14,010	.963	.1744	.752	175.0	159.1
COOLING WATER 347.1 LBS. 14.12 SQ.FT.	6C1	6,120	1,548	3.32	1.328	304,000	.1185	.0700	.1273	981	892
	6C2	6,120	1,422	2.75	1.382	357,000	.0975	.0623	.1068	988	898
	7C1	2,640	1,429	3.32	1.357	131,100	.207	.1222	.1382	910	827
	7C2	2,640	1,317	2.75	1.427	154,000	.1691	.1083	.1237	922	838
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ.FT.	22C1	7,620	448	698	11.05	3,070	1.082	.0608	1.975	45.8	41.7
	22C2	7,620	585	397	13.77	5,500	.907	.0667	1.749	84.2	76.6
	23C1	6,300	432	698	13.10	2,540	1.205	.0667	2.30	46.2	42.1
	23C2	6,300	591	397	15.00	4,550	1.068	.0785	2.10	85.5	77.7
	24C1	4,800	326	698	15.30	1,935	1.116	.0626	2.21	36.2	32.9
	24C2	4,800	428	397	19.62	3,470	.950	.0698	2.00	66.2	60.2
	25C1	3,330	363	698	19.10	1,340	1.626	.0913	2.63	42.6	38.7
	25C2	3,330	334	397	23.9	2,410	.972	.0715	2.15	54.3	49.4
	26C1	2,052	229	698	14.30	827	1.478	.0830	2.87	25.0	22.7
	26C2	2,052	234	397	20.2	1,480	.976	.0718	2.07	36.5	33.2
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ.FT.	40C1	6,660	1,075	61.9	2.84	27,600	.514	.0840	.668	228	207
	40C2	6,660	1,940	41.7	2.38	41,300	.667	.1394	.828	467	424
	41C1	0	131.1	56.9	5.90	0	-	-	-	34.5	34.5
	42C1	2,640	509	61.9	4.07	10,960	.481	.0785	.684	118.1	107.4
	42C2	2,640	667	41.7	4.44	16,370	.461	.0893	.670	188.0	171.0

TABLE XIV
CORRELATION OF DIMENSIONLESS GROUPS
NO.4 AGITATOR

	RUN No.	N RPH	$\frac{hT}{k}$	$\frac{c\mu}{k}$	$\frac{\mu_w}{\mu}$	$\frac{D^2N\rho}{\mu}$	$\frac{\frac{hT}{k}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{k}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}\left(\frac{T}{D}\right)^{2/3}\left(\frac{D_w}{D}\right)^{.13}}$
HEATING WATER 347.1 LBS. 14.63 SQ.FT.	4H1	2,010	15,190	3.01	.923	221,000	1.472	.907	1.442	916	1,005
	5H1	4,530	31,300	3.01	.957	498,000	1.675	1.032	1.655	1,909	2,090
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ.FT.	20H1	5,220	1,711	518	.1669	5,830	2.57	.1638	1.635	69.8	76.5
	21H1	2,340	987	518	.300	2,610	2.71	.1726	2.01	46.5	51.1
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63. SQ.FT.	36H1	2,460	1,958	48.6	.409	26,600	.937	.1700	.750	283	311
	37H1	4,824	4,230	48.6	.536	52,200	1.226	.222	1.050	656	720
COOLING WATER 347.1 LBS. 14.12 SQ.FT.	1C1	2,010	933	3.32	1.481	203,000	.0973	.0573	.1075	608	658
	1C2	2,010	871	2.75	1.562	239,000	.0807	.0517	.0903	623	684
	5C1	4,530	1,633	3.32	1.321	458,000	.0929	.0548	.0998	1,032	1,134
	5C2	4,530	1,541	2.75	1.366	538,000	.0779	.0499	.0843	1,068	1,172
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ.FT.	20C1	5,220	534	698	9.67	4,280	1.011	.0568	1.785	52.9	58.0
	20C2	5,220	641	397	12.45	7,670	.787	.0579	1.450	86.7	95.2
	21C1	2,340	257	698	14.66	1,918	.893	.0502	1.750	28.3	31.0
	21C2	2,340	352	397	20.6	3,440	.783	.0579	1.660	54.8	60.2
COOLING 72.4% GLYCEROL 390.0 LBS. 14.12 SQ.FT	36C1	2,460	678	61.9	3.44	20,800	.392	.0640	.534	151.0	165.8
	36C2	2,460	885	41.7	3.59	31,000	.377	.0730	.518	236	259
	37C1	4,824	1,050	61.9	2.87	40,800	.366	.0597	.477	224	246
	37C2	4,824	1,178	41.7	3.26	60,800	.305	.0591	.411	307	337

TABLE XV
CORRELATION OF DIMENSIONLESS GROUPS
NO.5 AGITATOR

	RUN No.	N RPH	$\frac{hT}{k}$	$\frac{c\mu}{k}$	$\frac{\mu_w}{\mu}$	$\frac{D^2N\rho}{\mu}$	$\frac{\frac{hT}{k}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{k}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{D^2N\rho}{\mu}\right)^{3/4}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}}$	$\frac{\frac{hT}{k}(\mu_w/\mu)^{1/4}}{\left(\frac{c\mu}{k}\right)^{.44}\left(\frac{T}{D}\right)^{2/3}\left(\frac{D_w}{D}\right)^{.13}}$
HEATING WATER 347.1 LBS. 14.63 SQ. FT.	1H1	0	1,153	3.32	.609	0	-	-	-	602	602
	2H1	3,360	2,980	3.01	.774	462,000	.1686	.1037	.1580	1,722	2,000
	3H1	2,010	2,930	3.01	.767	276,000	.240	.1479	.221	1,689	1,960
HEATING 95.8% GLYCEROL 449.0 LBS. 14.63 SQ. FT.	17H1	2,982	1,423	518	.1802	4,170	2.74	.1746	1.784	59.0	68.5
	18H1	0	475	698	.0843	0	-	-	-	14.40	14.40
	19H1	4,500	1,706	518	.1695	6,280	2.43	.1549	1.560	68.7	79.8
HEATING 72.4% GLYCEROL 390.0 LBS. 14.63 SQ.FT	34H1	2,460	2,290	48.6	.413	33,200	.925	.1675	.742	333	387
	35H1	2,460	3,390	48.6	.508	60,700	.879	.1580	.741	518	602
COOLING WATER 347.1 LBS. 14.12 SQ. FT.	1C1	0	625	3.68	1.563	0	-	-	-	394	394
	2C1	3,360	3,060	3.32	1.225	424,000	.1833	.1082	.1930	1,900	2,210
	2C2	3,360	3,320	2.75	1.202	498,000	.1774	.1135	.1855	2,220	2,560
	3C1	2,010	1,357	3.32	1.386	254,000	.1200	.0708	.1304	869	1,100
	3C2	2,010	1,320	2.75	1.416	298,000	.1031	.0654	.1132	930	1,081
COOLING 95.8% GLYCEROL 449.0 LBS. 14.12 SQ. FT.	17C1	2,982	386	698	11.79	3,060	.941	.0528	1.745	40.2	46.7
	17C2	2,982	474	397	16.04	5,470	.745	.0548	1.490	69.8	81.0
	18C1	0	148.9	518	22.7	0	-	-	-	20.7	20.7
	19C1	4,500	522	698	10.32	4,610	.932	.0523	1.673	52.6	61.1
	19C2	4,500	608	397	13.11	8,250	.706	.0519	1.420	85.1	99.0
COOLING 72.4% GLYCEROL 390.0 LBS 14.12 SQ.FT.	34C1	2,460	762	61.9	3.44	25,900	.372	.0608	.507	169.6	197.0
	34C2	2,460	1,012	41.7	3.46	38,700	.367	.0711	.501	268	311
	35C1	4,500	1,112	61.9	2.73	47,400	.345	.0563	.443	234	272
	35C2	4,500	1,505	41.7	2.70	70,800	.347	.0672	.445	375	436

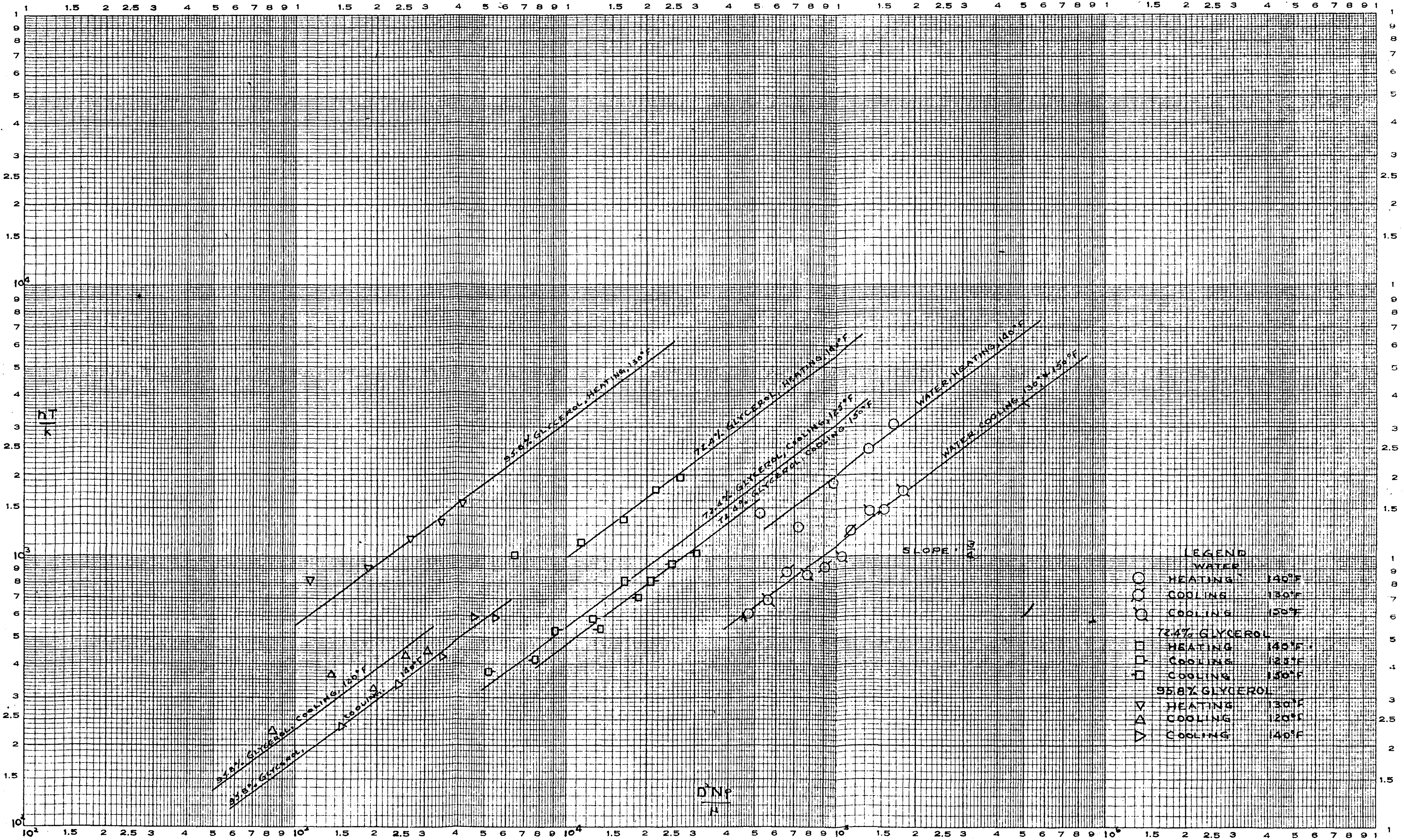

FIG. 25 DETERMINATION OF EXPONENT OF REYNOLDS No.

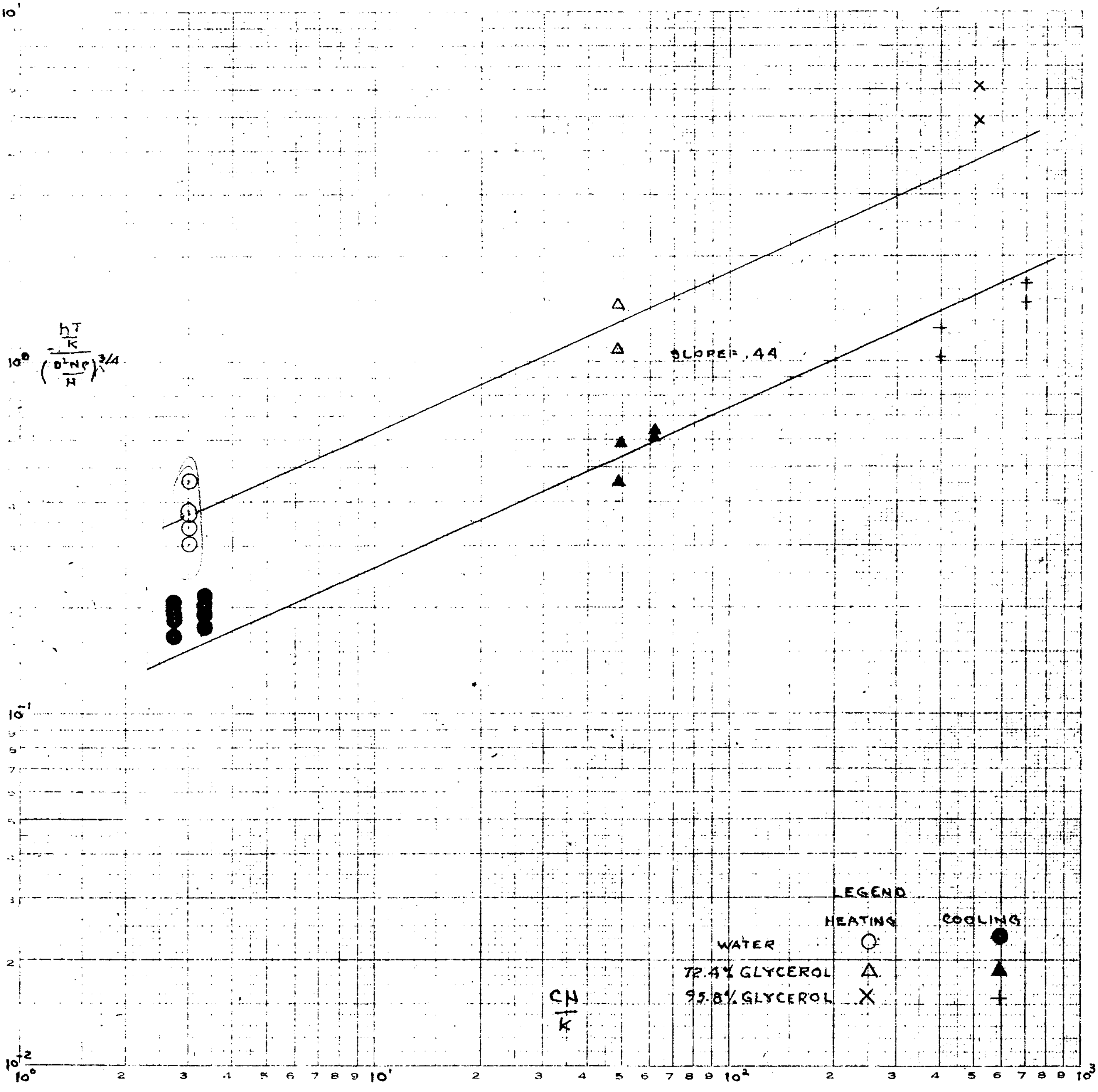

FIG. 26 DETERMINATION OF EXPONENT OF PRANDTL No.
No. 1 AGITATOR

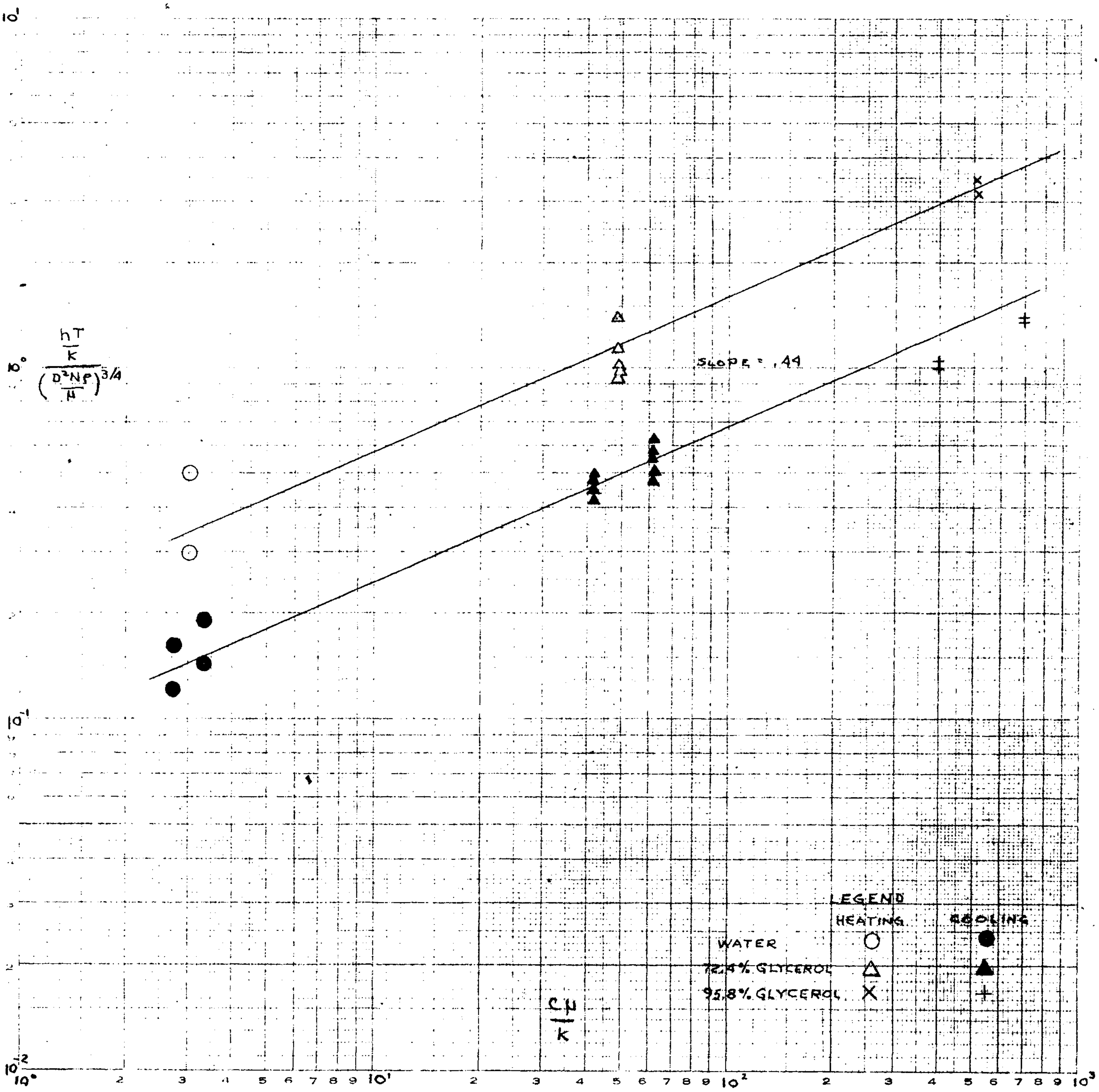

FIG. 27 DETERMINATION OF EXPONENT OF PRANDTL No.
No. 2 AGITATOR

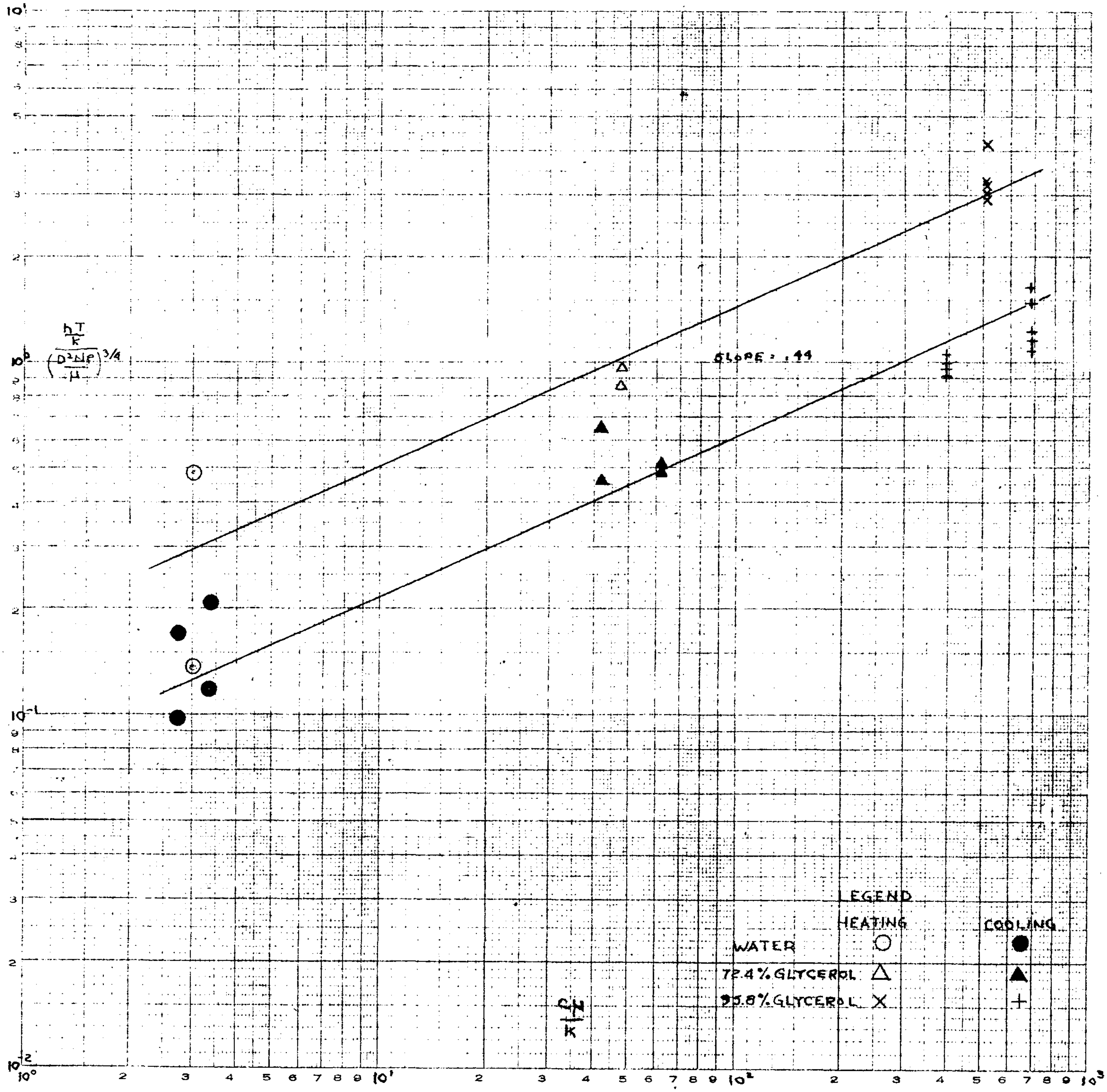

FIG. 28 DETERMINATION OF EXPONENT OF PRANDTL No.
No. 3 AGITATOR

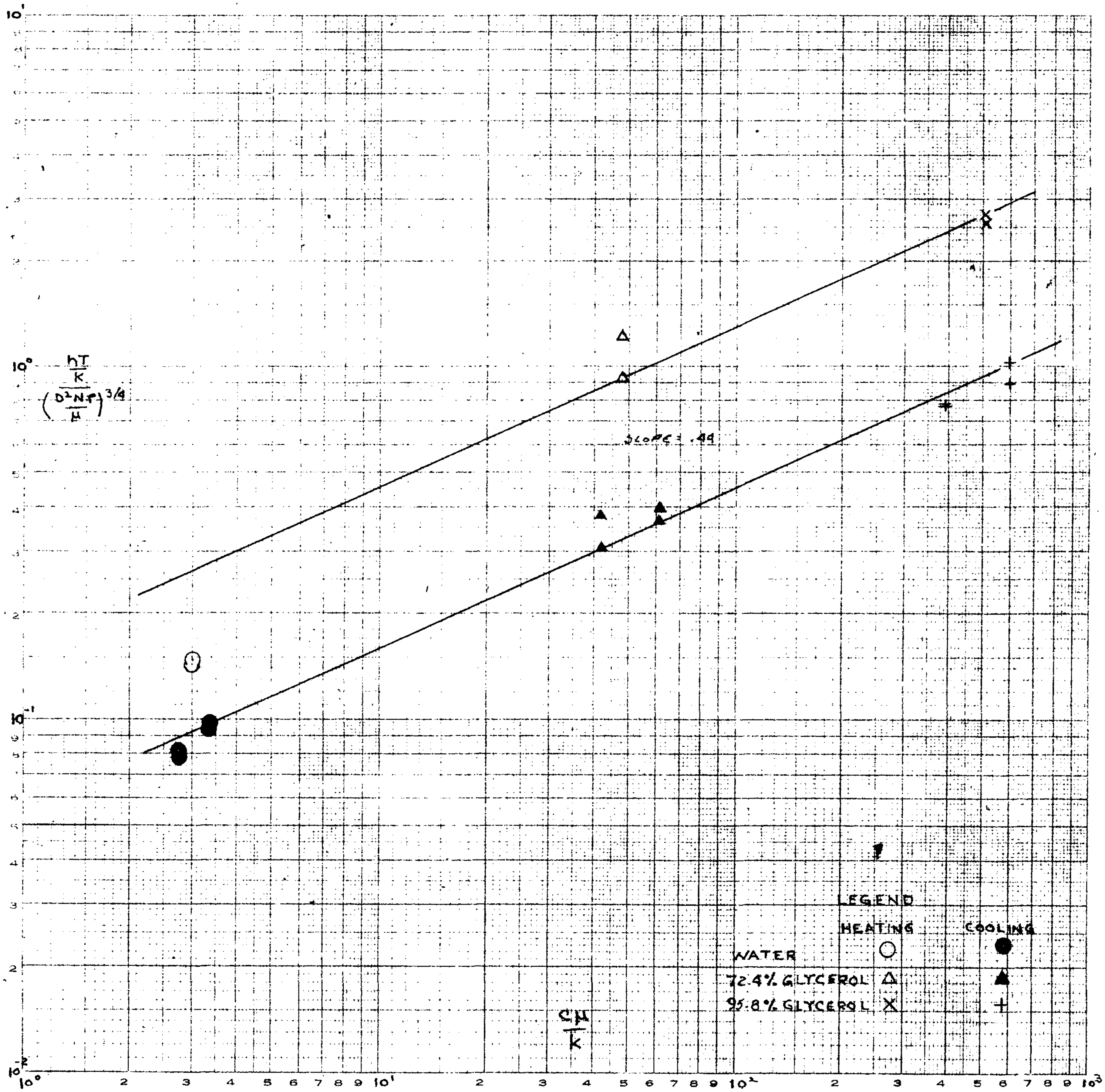

FIG. 29 DETERMINATION OF EXPONENT OF PRANDTL No.
No. 4 AGITATOR

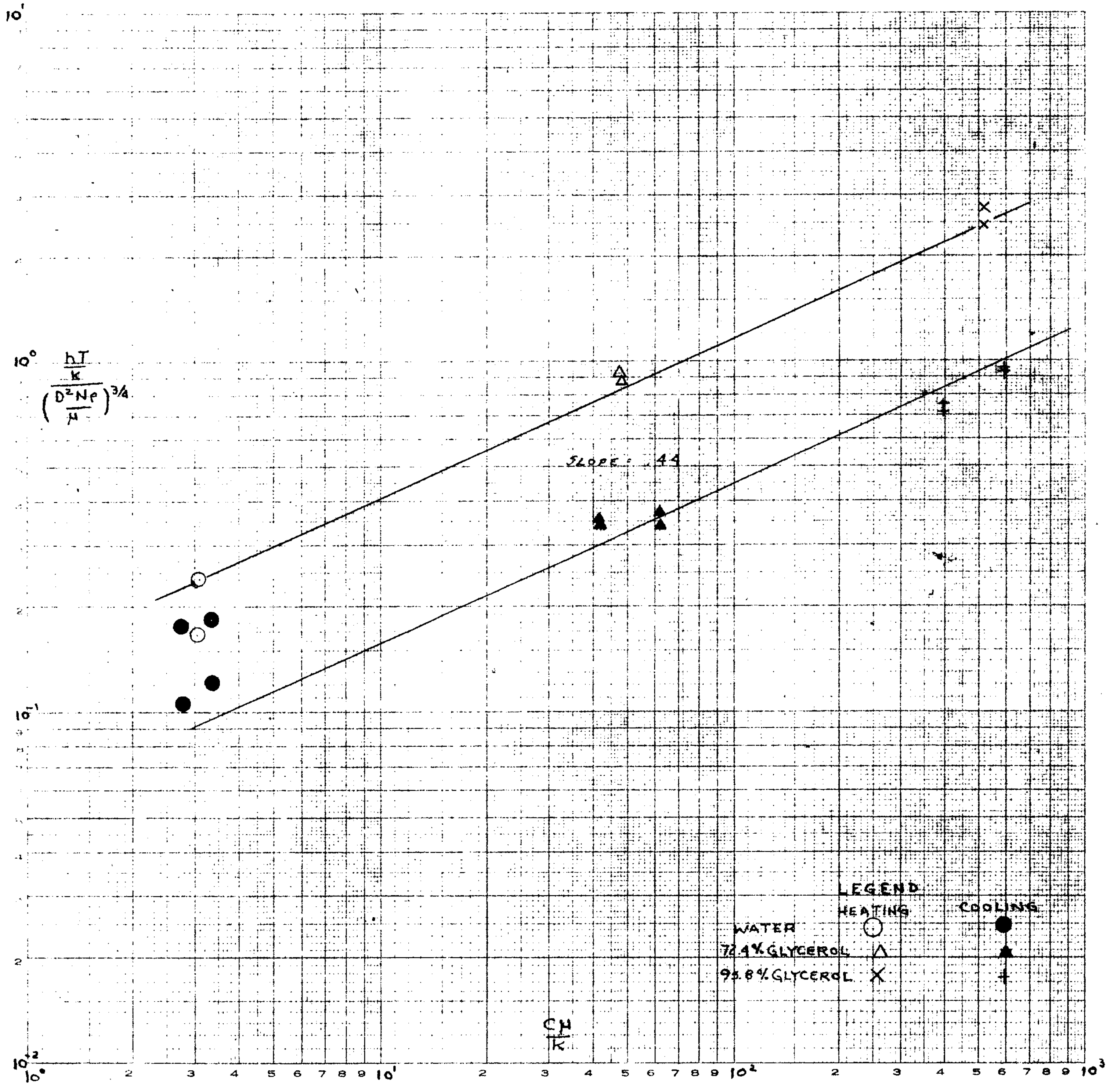

FIG. 30 DETERMINATION OF EXPONENT OF PRANDTL NO.
No. 5 AGITATOR,

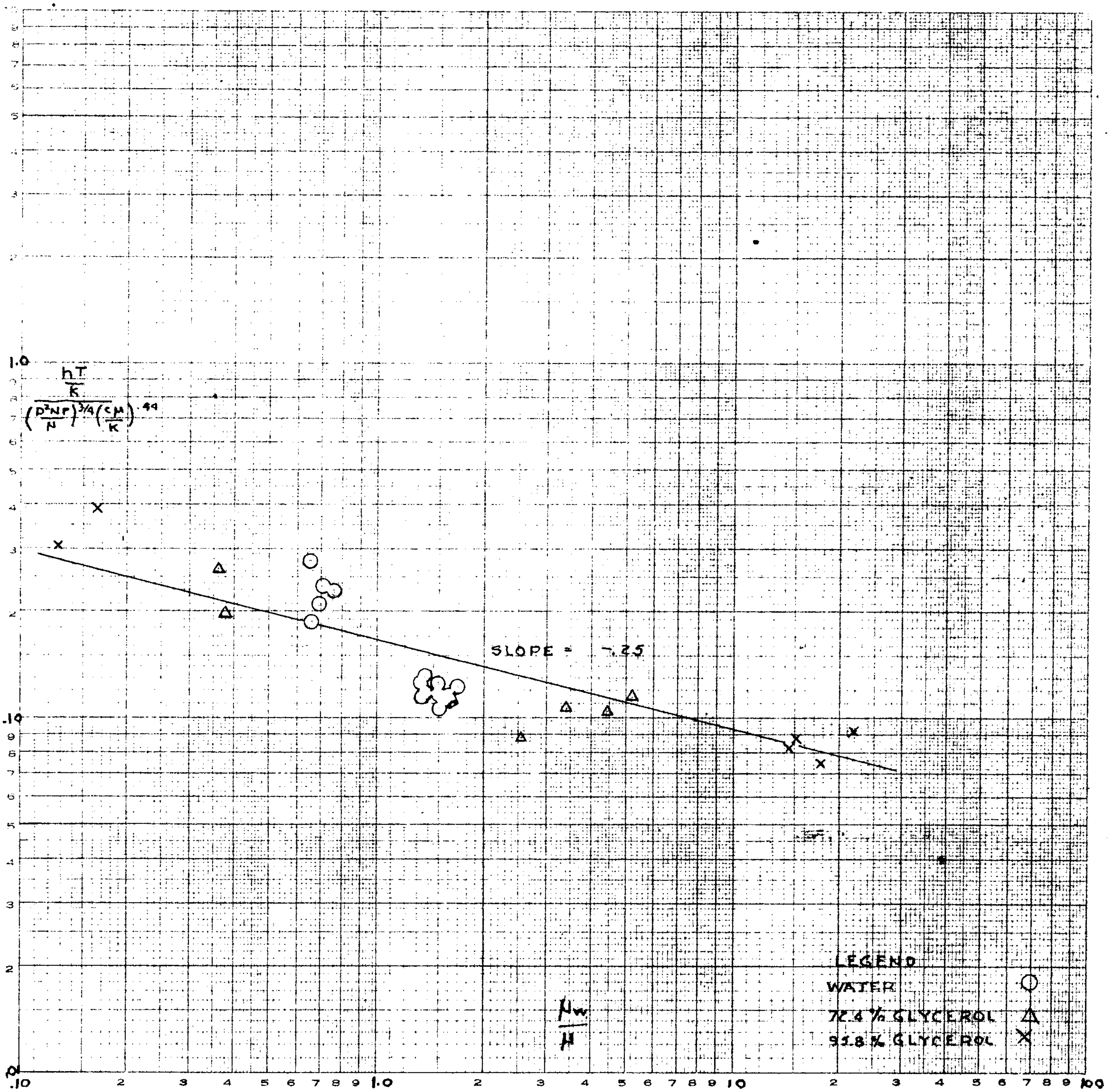

FIG. 31 DETERMINATION OF EXPONENT OF $\left(\frac{\mu_w}{\mu}\right)$, No. 1 AGITATOR

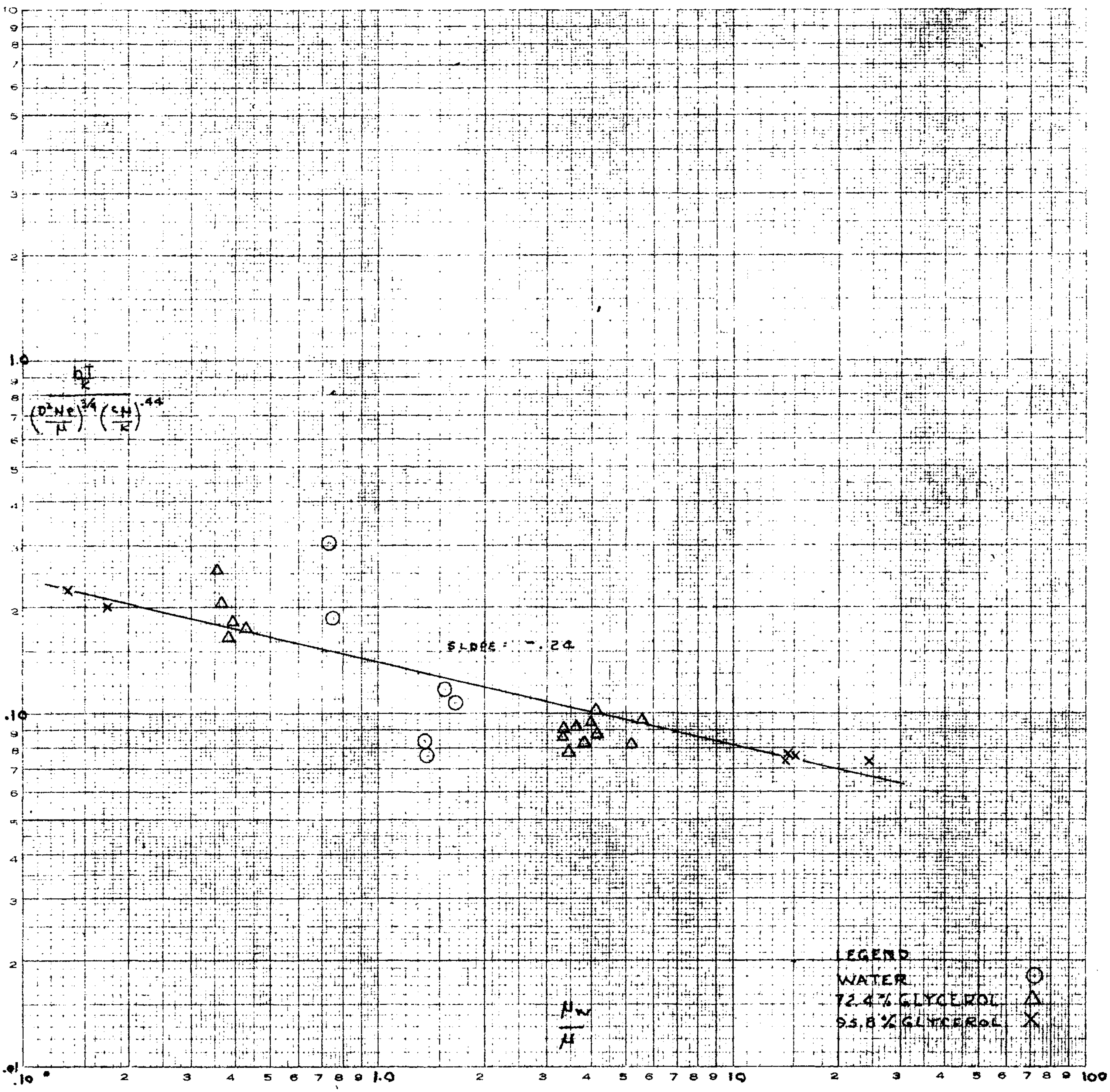

FIG. 32 DETERMINATION OF EXPONENT OF $\left(\frac{\mu_w}{\mu}\right)$, No.2 AGITATOR

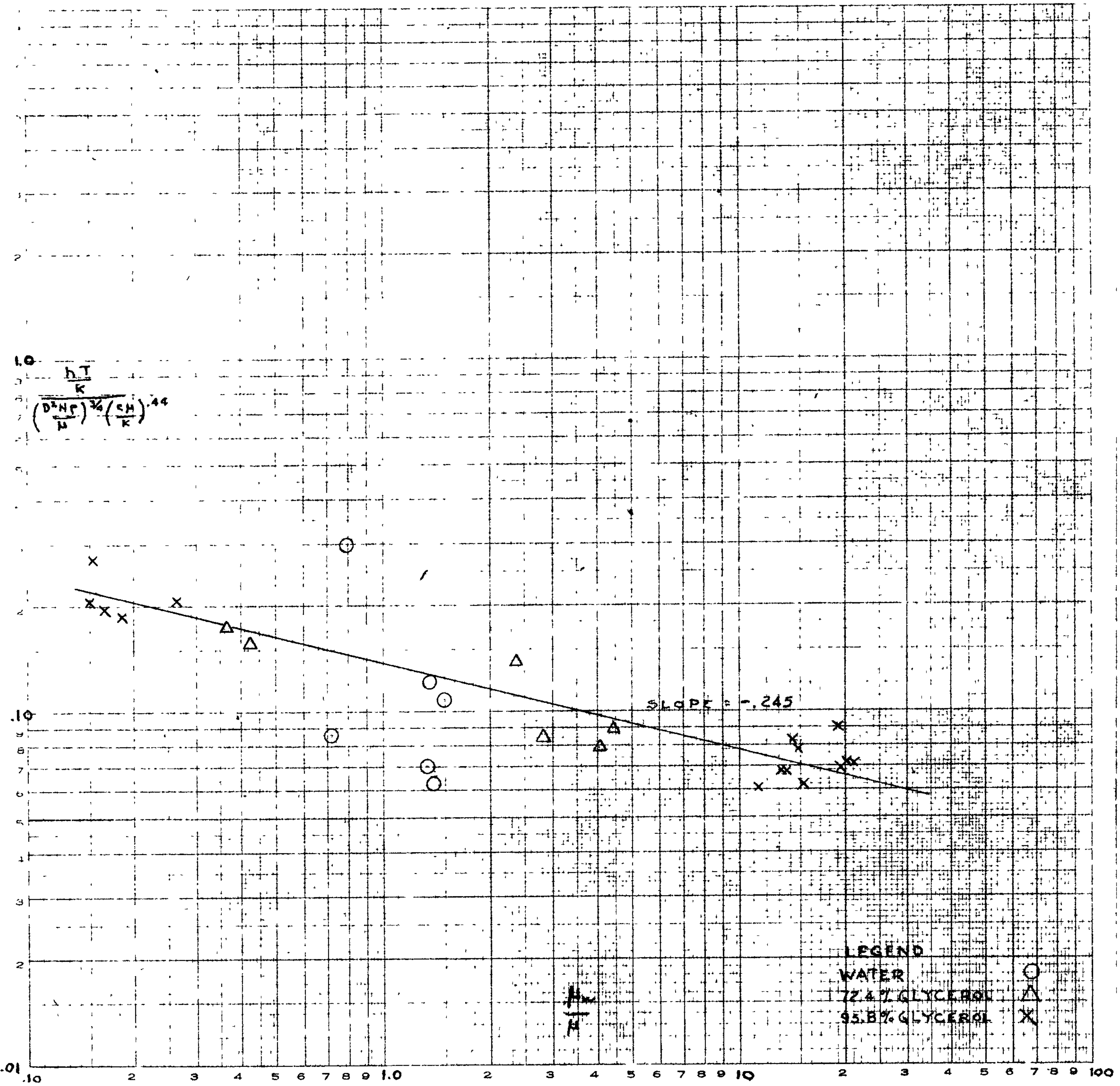

FIG. 33 DETERMINATION OF EXPONENT OF $\left(\frac{\mu_w}{\mu}\right)$, No. 3 AGITATOR

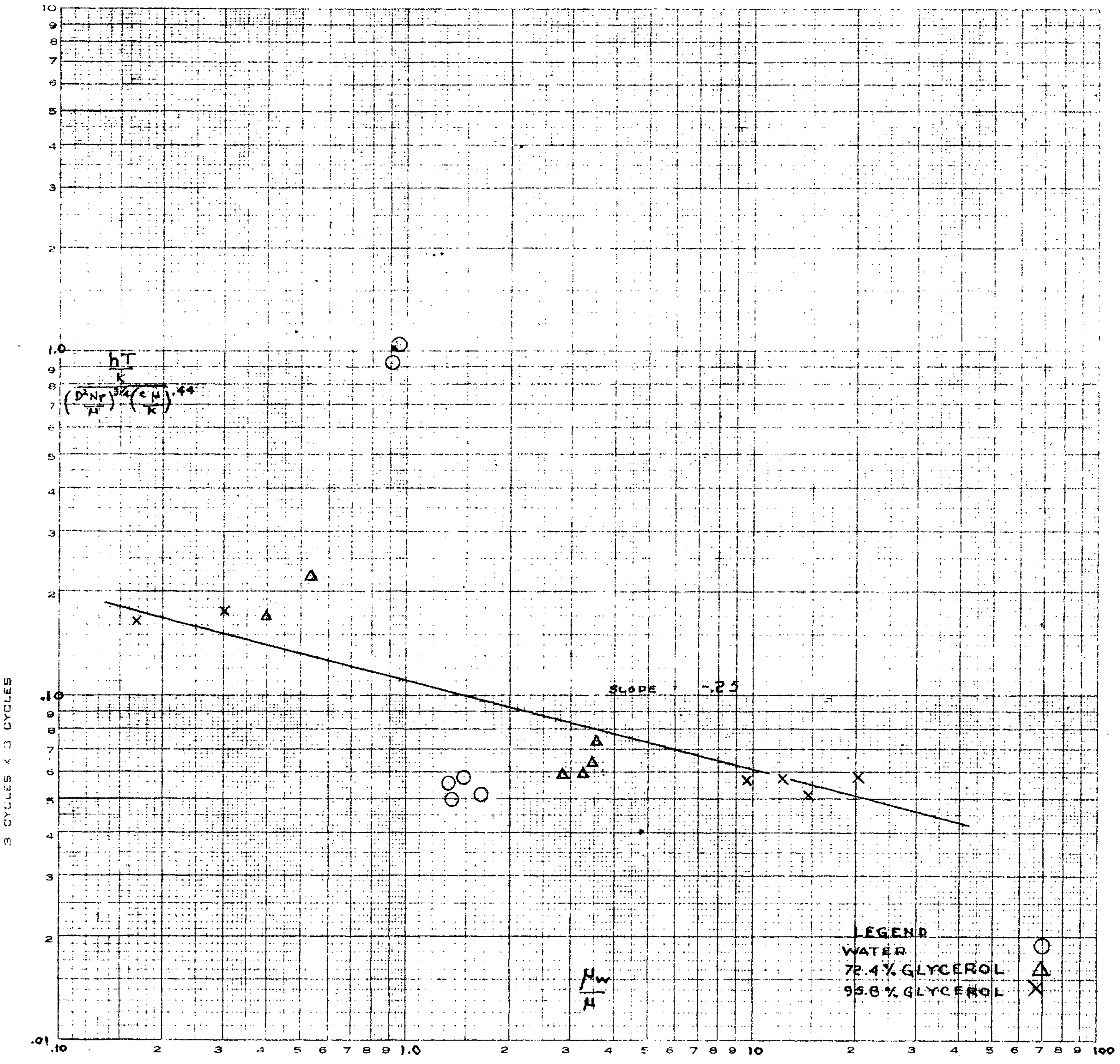

FIG. 34 DETERMINATION OF EXPONENT OF $\left(\frac{\mu_w}{\mu}\right)$, No. 4 AGITATOR

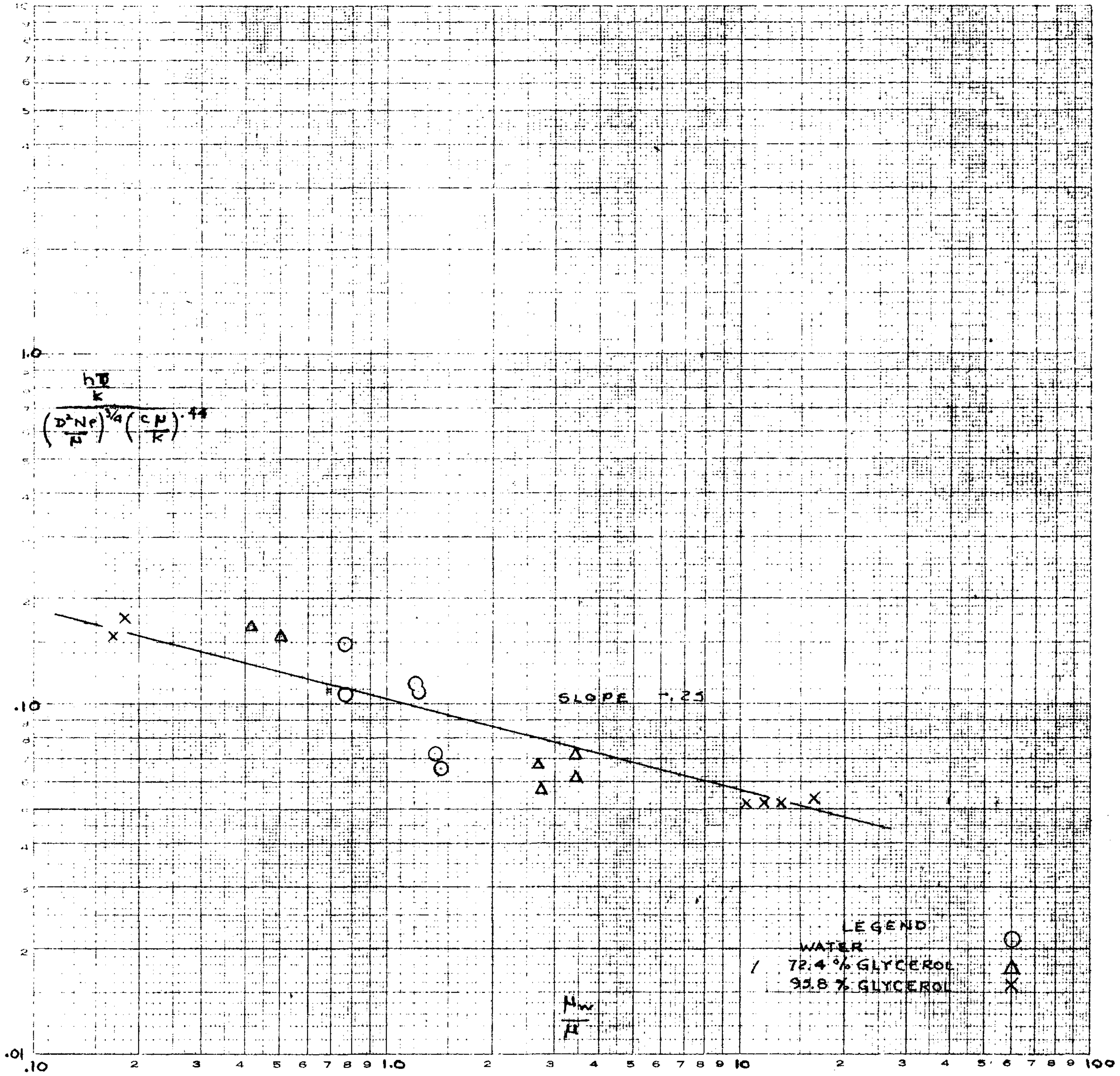

FIG. 35 DETERMINATION OF EXPONENT OF $\left(\frac{\mu_w}{\mu}\right)$, No.5 AGITATOR

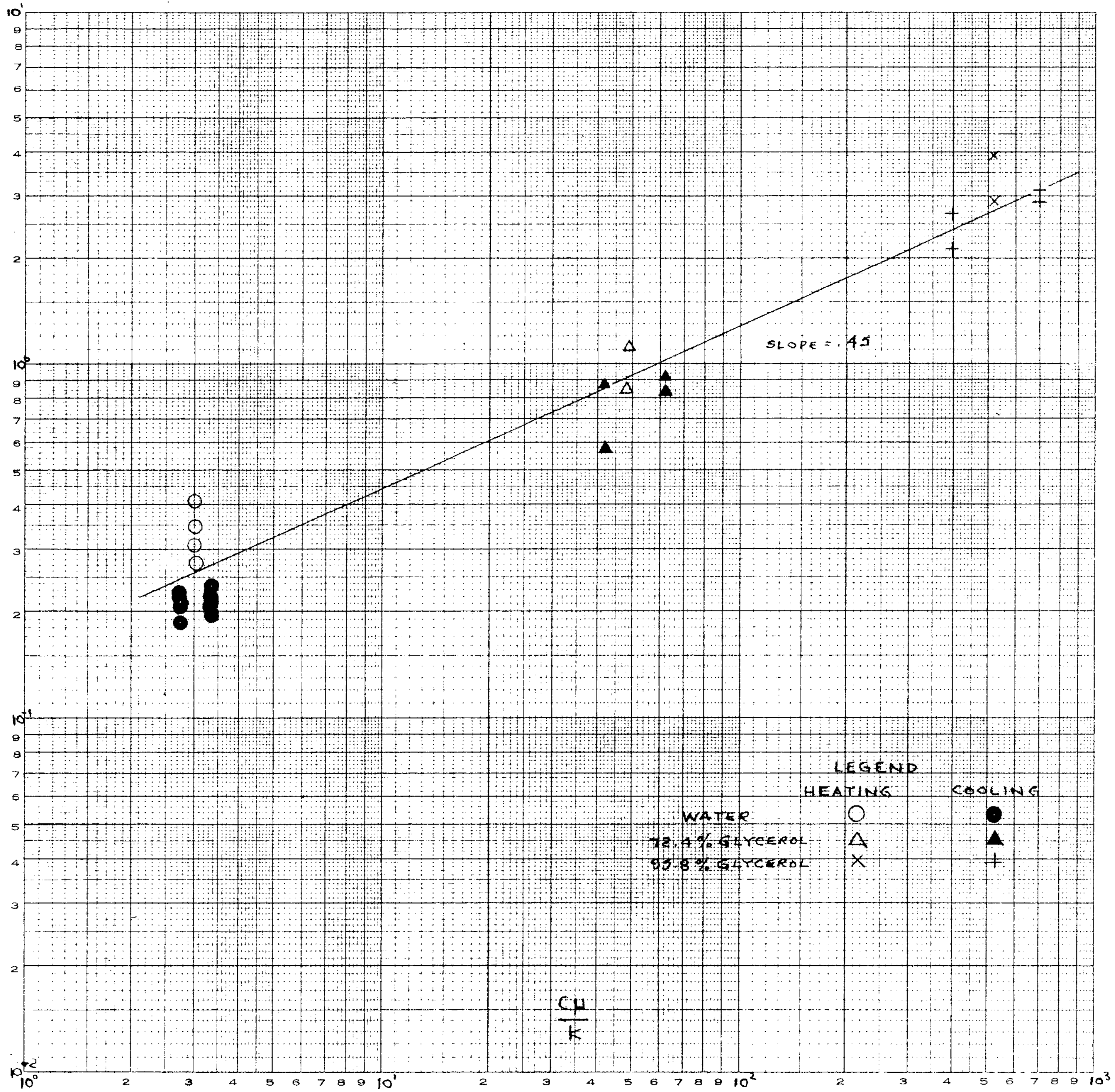

FIG. 36 REDETERMINATION OF EXPONENT OF PRANDTL No.
No. 1 AGITATOR

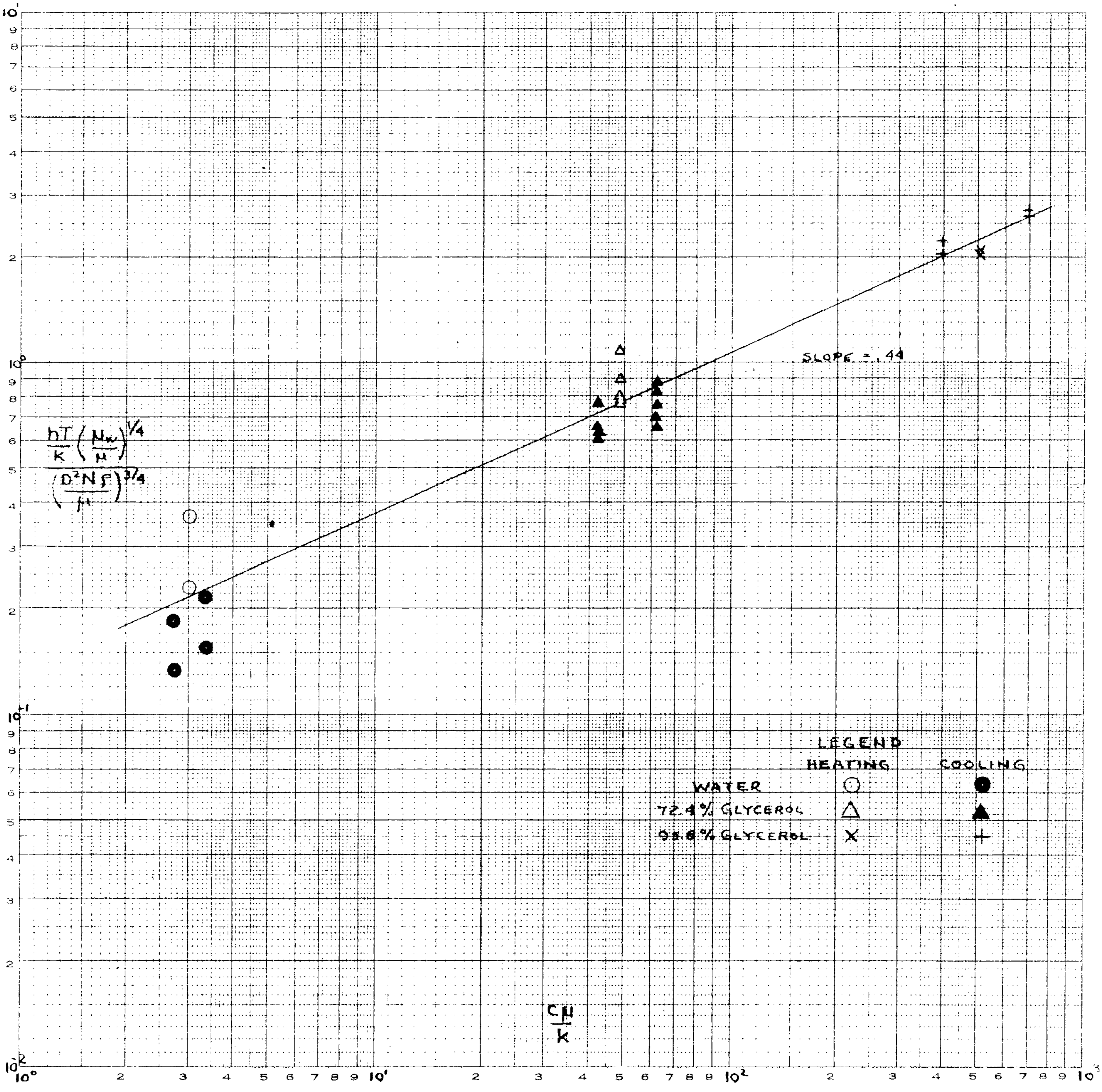

FIG. 37 REDETERMINATION OF EXPONENT OF PRANDTL No.
NO. 2 AGITATOR

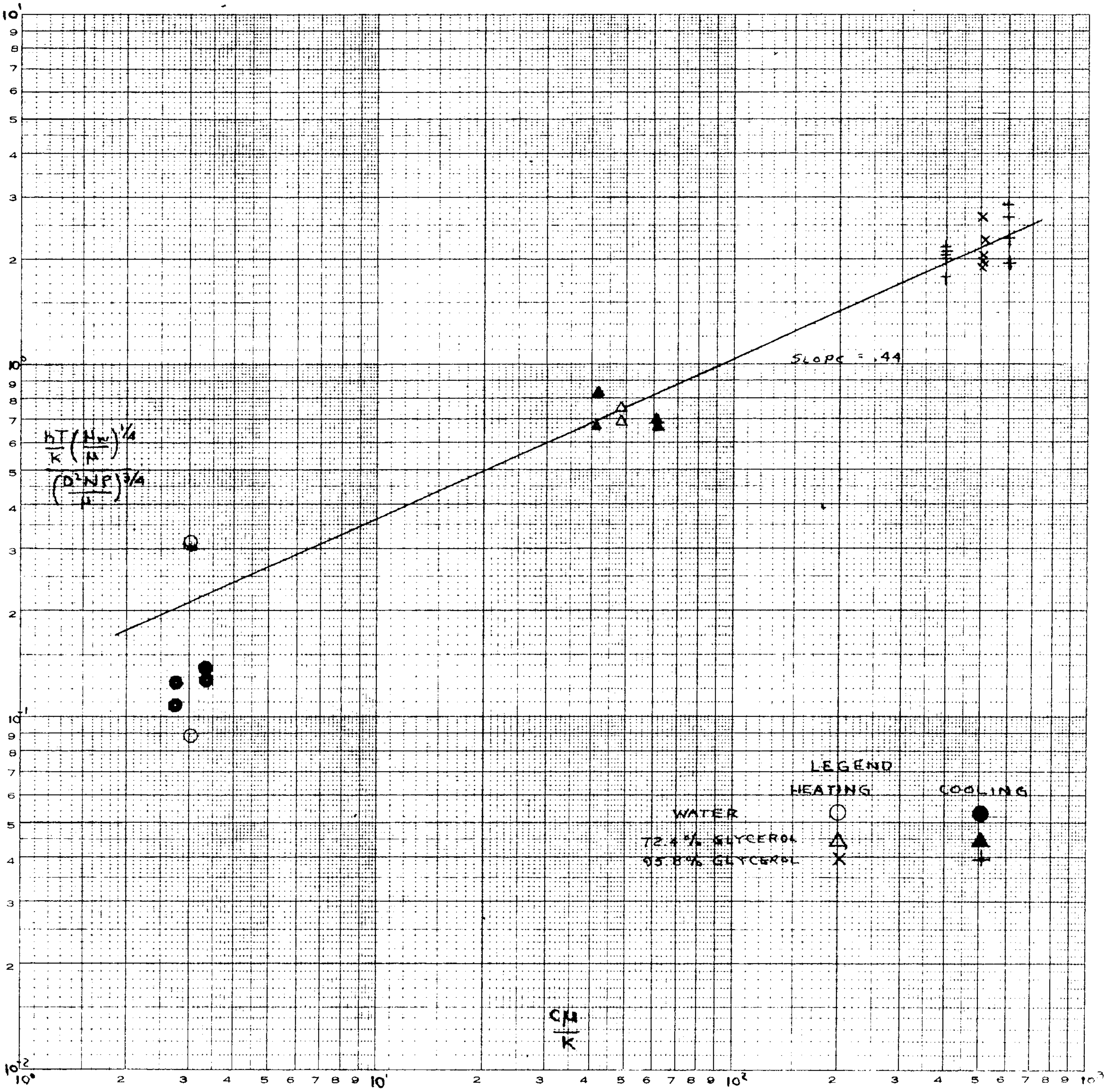

FIG. 38 REDETERMINATION OF EXPONENT OF PRANDTL No.
No. 3 AGITATOR

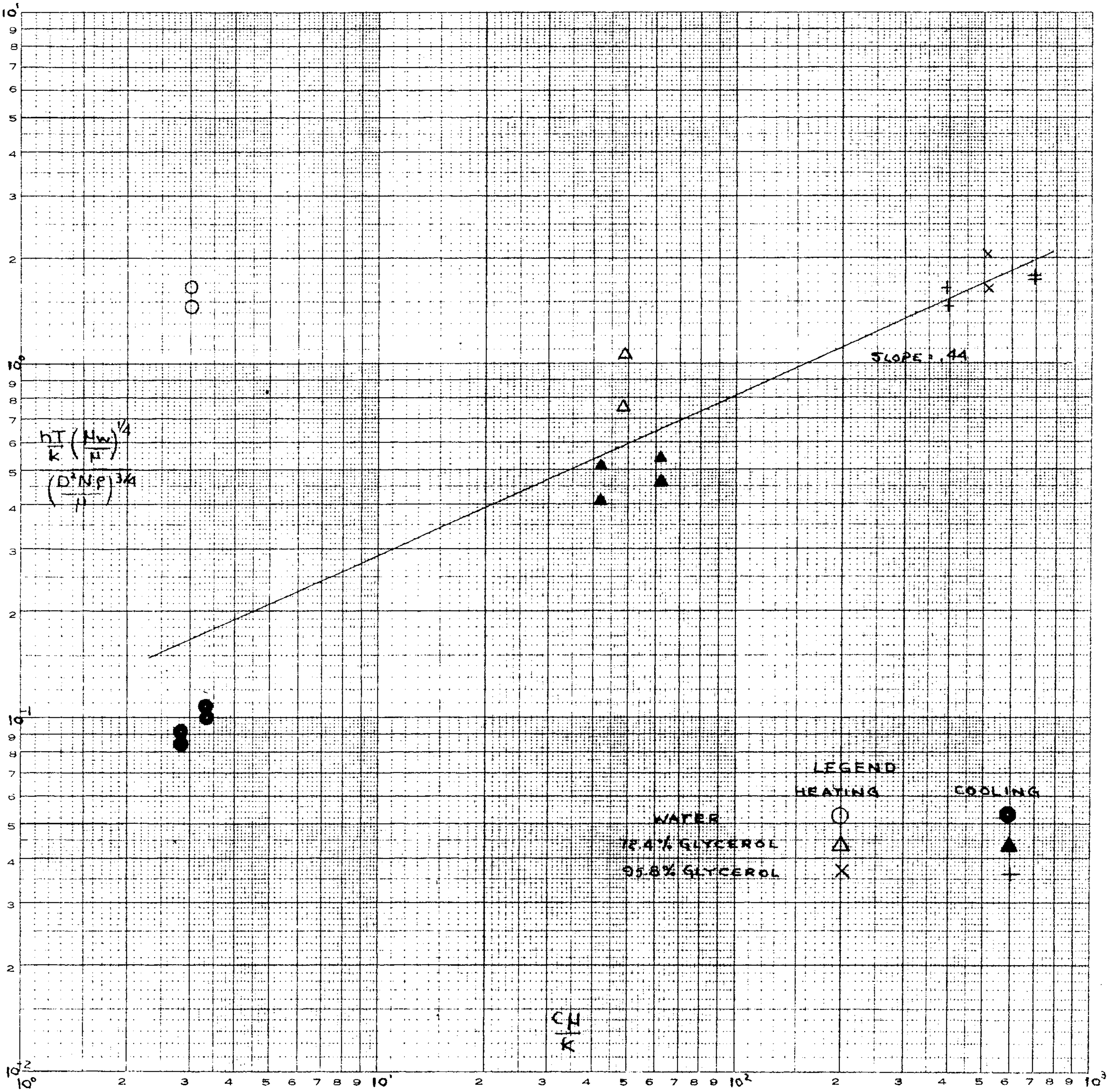

FIG. 39 REDETERMINATION OF EXPONENT OF PRANDTL No.
No. 4 AGITATOR

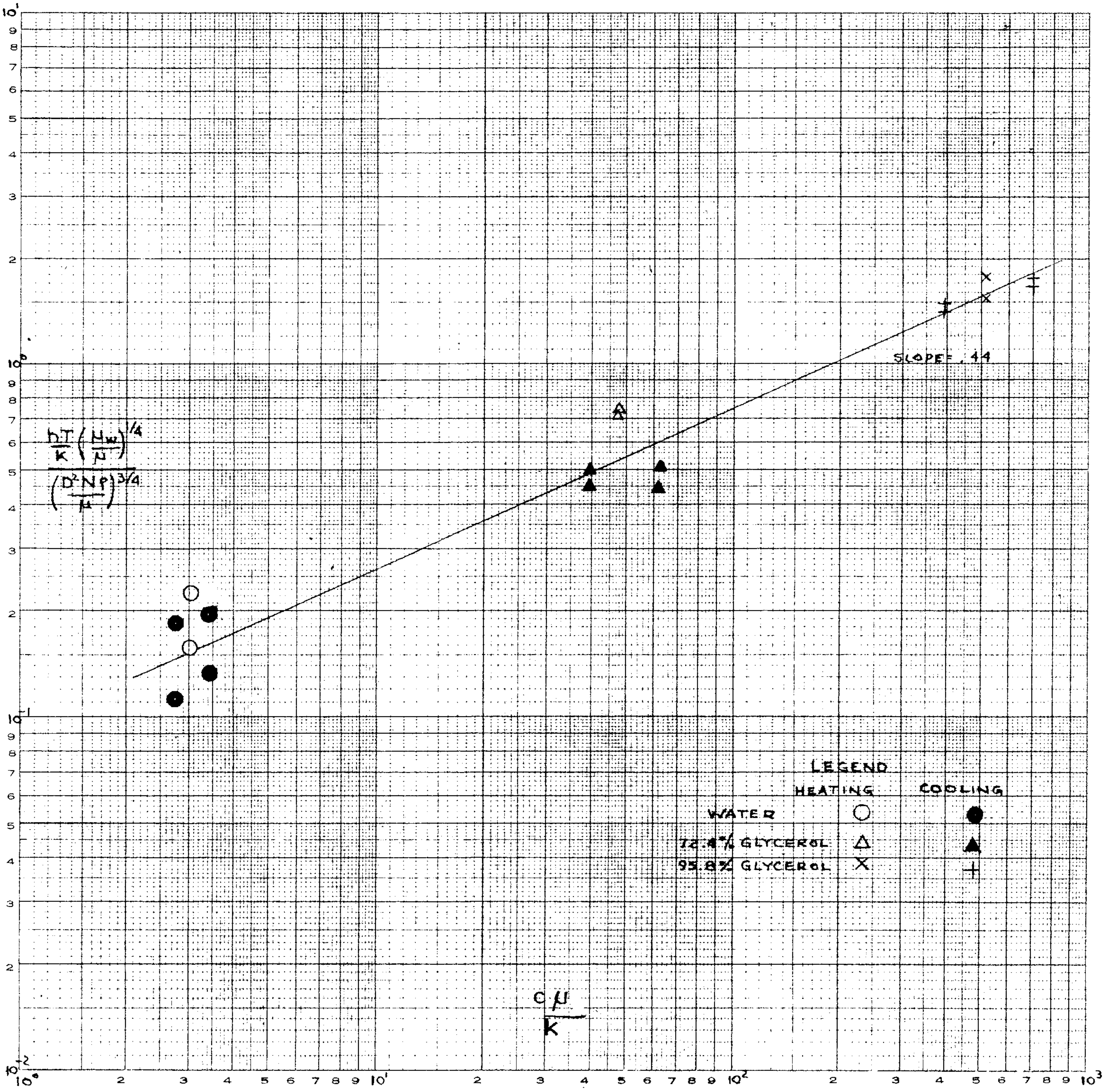

FIG. 40 REDETERMINATION OF EXPONENT OF PRANDTL No.
NO.5 AGITATOR

was made by plotting log $N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}$ versus N_{Re}. This is shown in Figures 40 to 45 inclusive. By eye, this confirmed the 3/4 exponent of the Reynolds Number. Also, by inference, it confirmed the -1/4 exponent for the ratio (μ_w/μ). From these plots, the following equations were derived which compare with equations 48, 49, 50 and 51 for the previous investigators.

(58) $N_{Nu} = 0.176\ N_{Pr}^{.44}N_{Re}^{3/4}(\mu_w/\mu)^{-\frac{1}{4}}$ for No. 1 agitator.

(59) $N_{Nu} = 0.150\ N_{Pr}^{.44}N_{Re}^{3/4}(\mu_w/\mu)^{-\frac{1}{4}}$ for No. 2 agitator.

(60) $N_{Nu} = 0.138\ N_{Pr}^{.44}N_{Re}^{3/4}(\mu_w/\mu)^{-\frac{1}{4}}$ for No. 3 agitator.

(61) $N_{Nu} = 0.100\ N_{Pr}^{.44}N_{Re}^{3/4}(\mu_w/\mu)^{-\frac{1}{4}}$ for No. 4 agitator.

(62) $N_{Nu} = 0.097\ N_{Pr}^{.44}N_{Re}^{3/4}(\mu_w/\mu)^{-\frac{1}{4}}$ for No. 5 agitator.

In order to correlate the geometric variables, the five coefficients from equations 58 to 62 were tabulated in Table XVI. Along with these were tabulated the kettle diameter T, the corresponding stirrer diameter D, stirrer width D_w, elevation of stirrer above bottom C, and the distance Z between batch surface and bottom. From these, the ratios (T/D), (D_w/D), (C/D), and (Z/D) were calculated and tabulated.

To determine the exponent of the (T/D) ratio, log $N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}N_{Re}^{3/4}$ was plotted against log (T/D). This is shown in Figure 46. By eye it appeared that the correlating line had a slope of 1/2.

A plot of log $N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}N_{Re}^{3/4}\ (T/D)^{\frac{1}{2}}$ versus log (D_w/D) was made in Figure 47 to determine the exponent of that ratio. A line having a slope of 0.13 appeared to correlate the data.

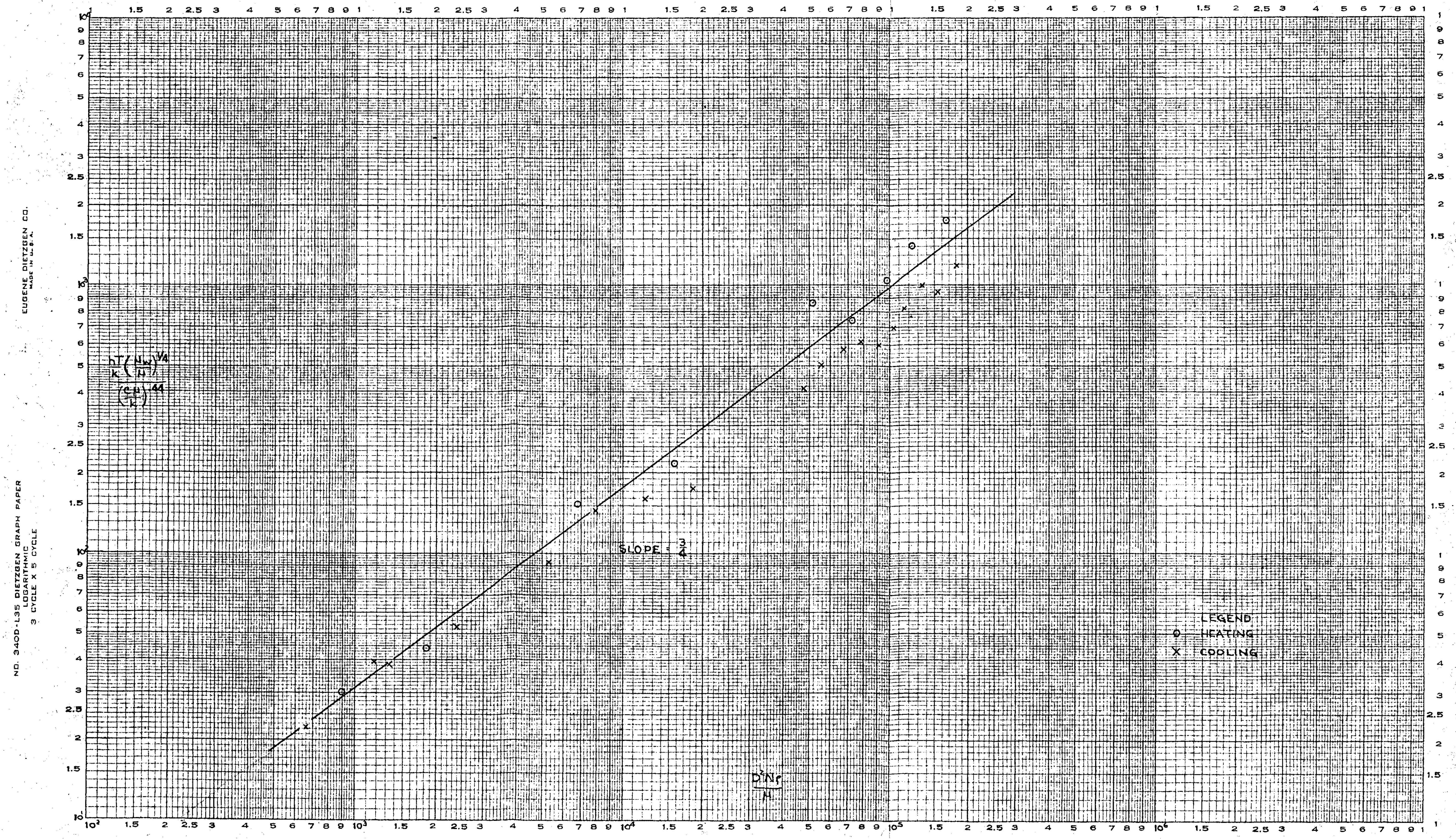

FIG. 41 REDETERMINATION OF EXPONENT OF REYNOLDS NO., NO. 1 AGITATOR

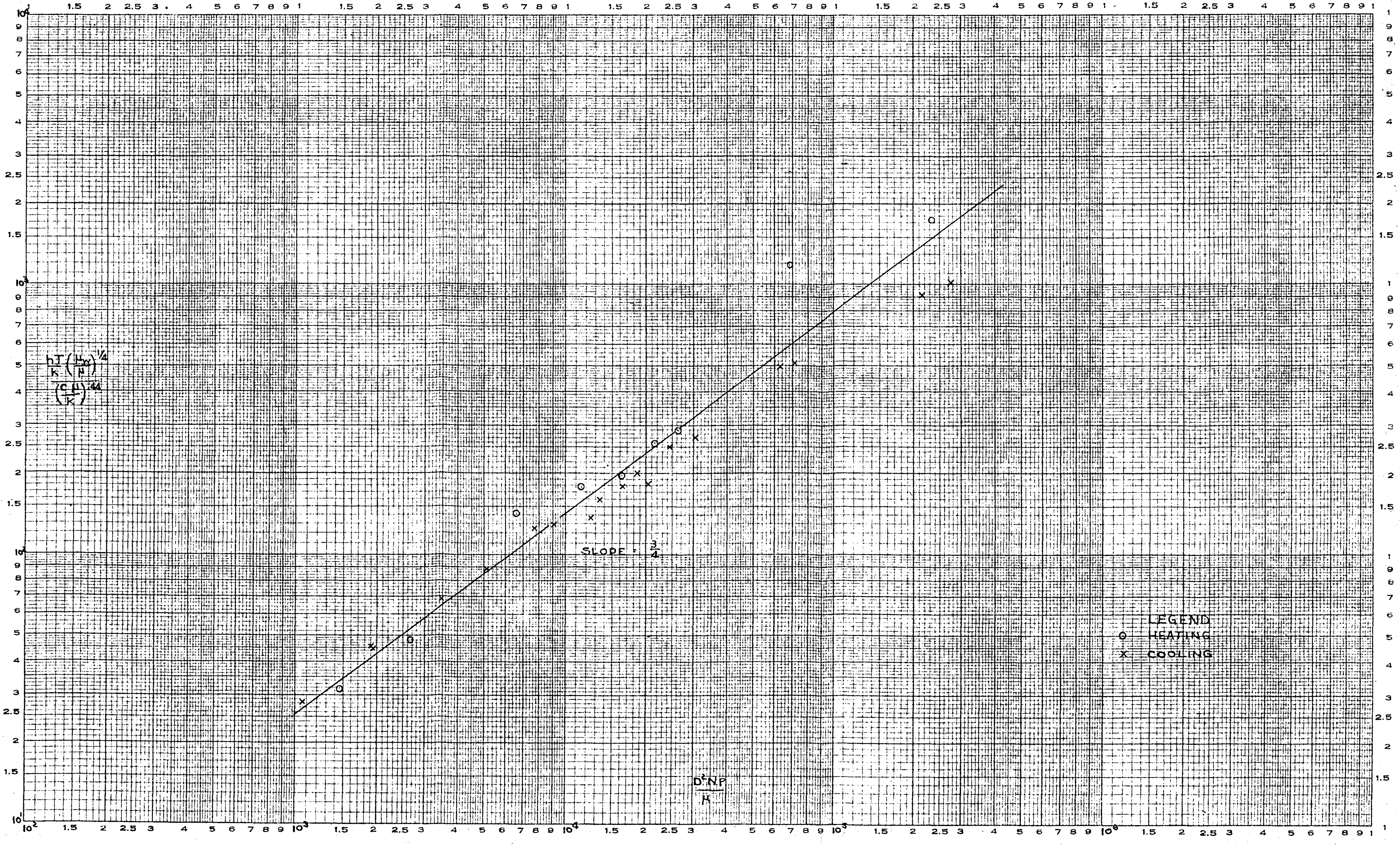

FIG. 42 REDETERMINATION OF EXPONENT OF REYNOLDS NO., NO. 2 AGITATOR

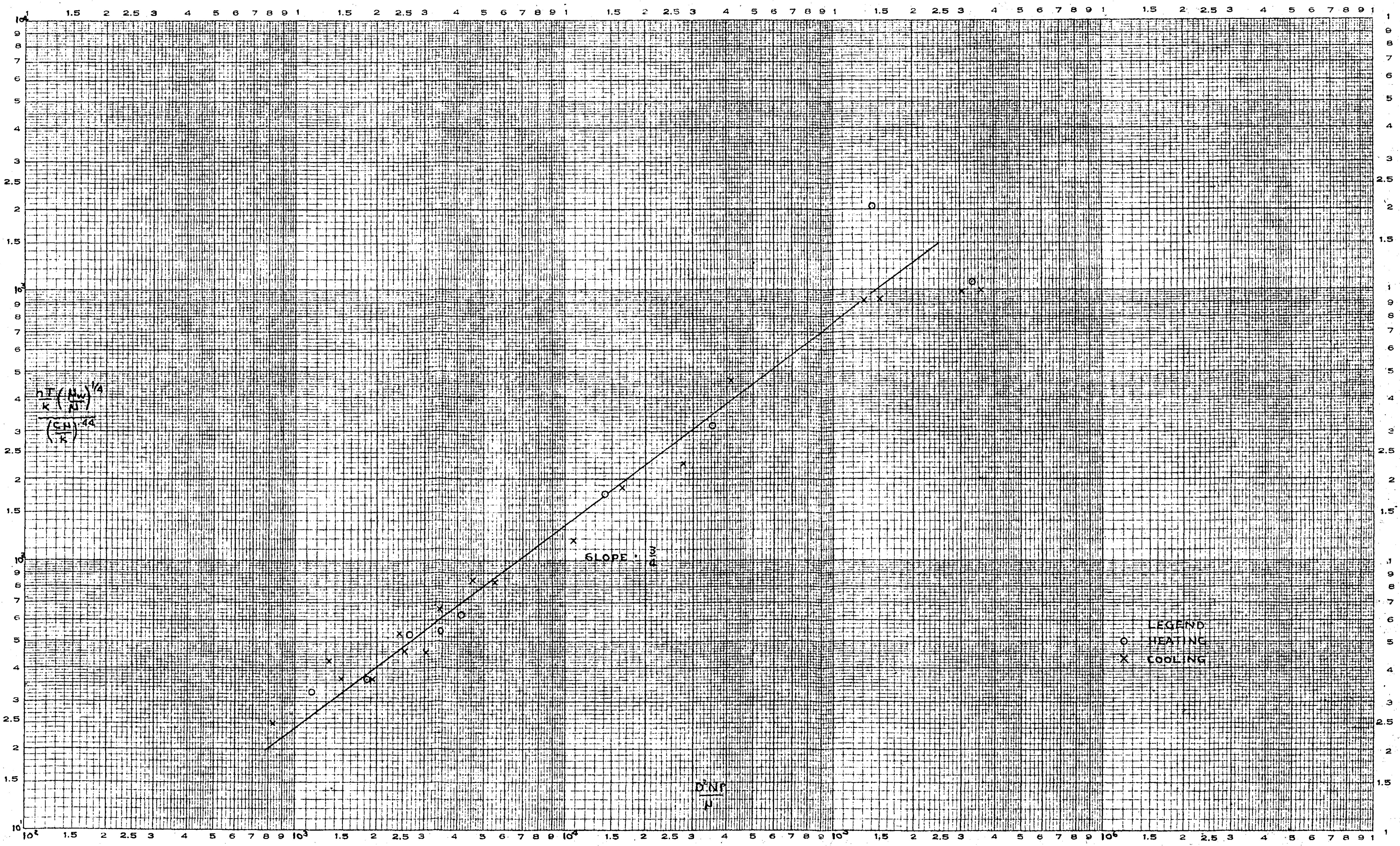

FIG. 43 REDETERMINATION OF EXPONENT OF REYNOLDS NO, NO.3 AGITATOR

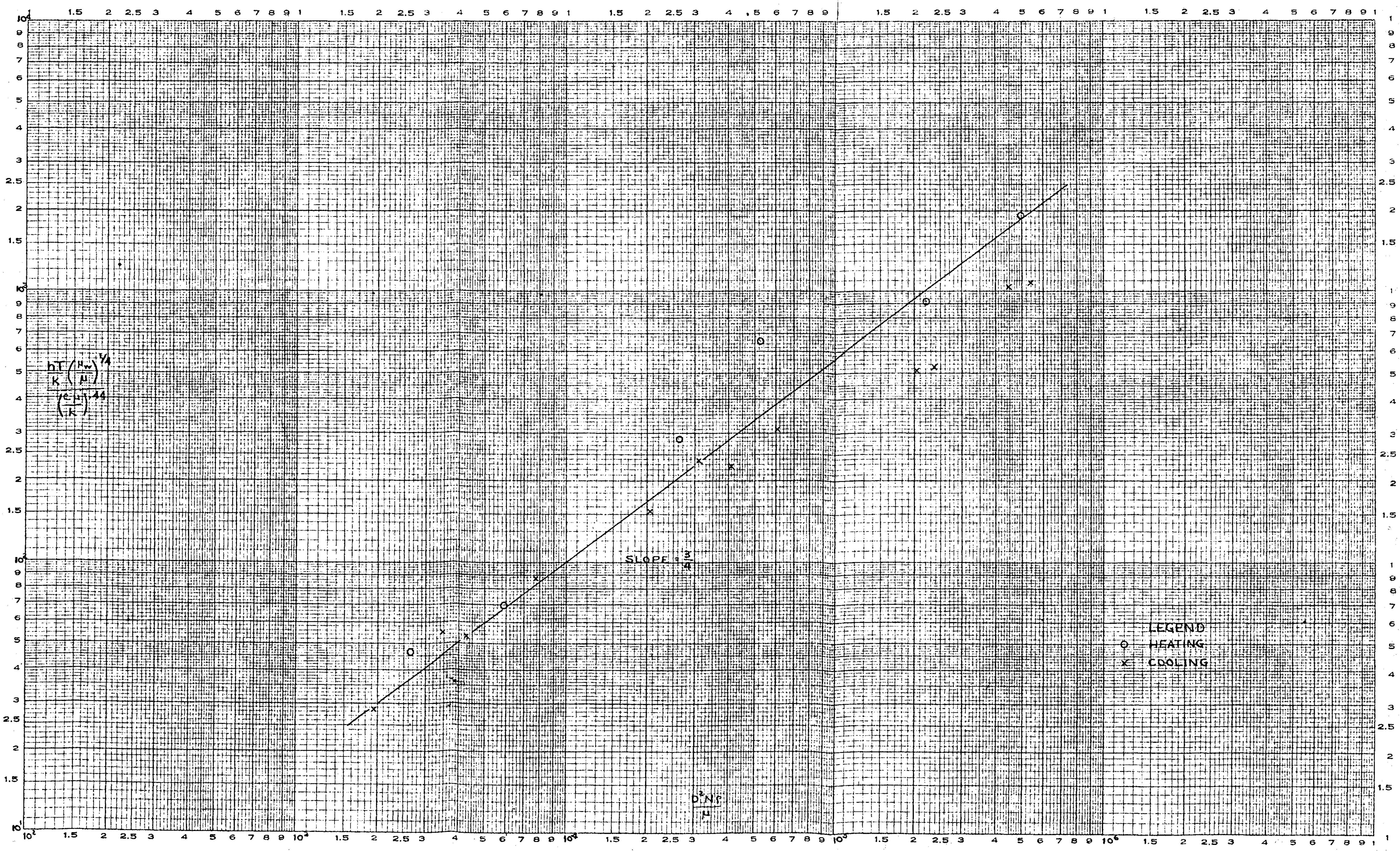

FIG. 44 DETERMINATION OF EXPONENT OF REYNOLDS NO., NO. 4 AGITATOR

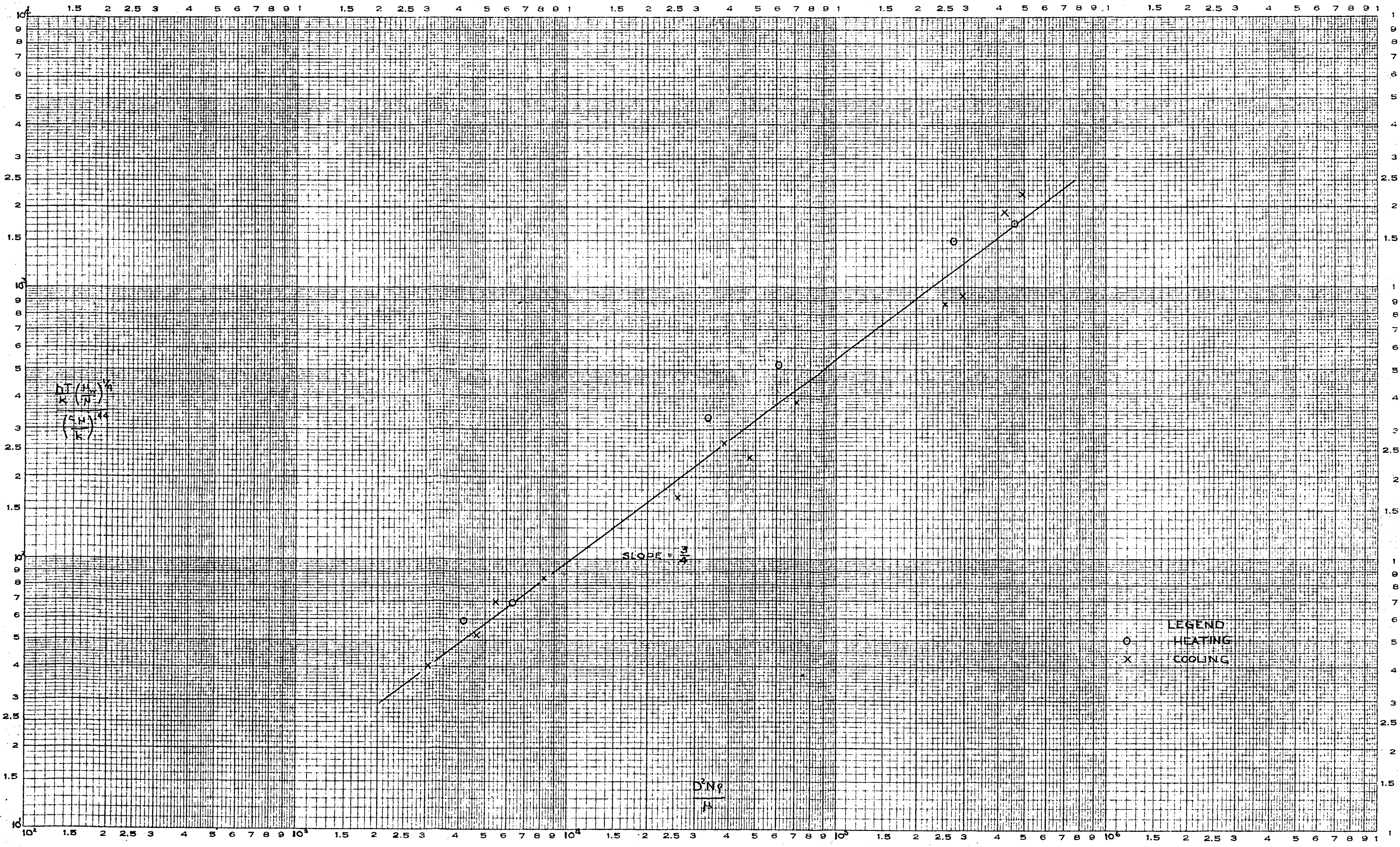

FIG. 45 REDETERMINATION OF EXPONENT OF REYNOLDS NO., NO.5 AGITATOR

TABLE XVI

CORRELATION OF GEOMETRIC VARIABLES

AGIT. NO.	D	D_W	T	Z	C
1	.4896	.250	2.0	2.0	.708
2	.6771	.250	2.0	2.0	.708
3	1.000	.250	2.0	2.0	.708
4	1.427	.250	2.0	2.0	.708
5	1.594	.250	2.0	2.0	.708

AGIT. NO.	T/D	D_W/D	Z/D	C/D	$\frac{N_{Nu}\left(\frac{\mu_w}{\mu}\right)^{1/4}}{N_{PR}^{.44}\,N_{Re}^{3/4}}$
1	4.083	.511	4.09	1.450	.176
2	2.952	.369	2.96	1.048	.150
3	2.000	.250	2.00	.708	.134
4	1.401	.1751	1.402	.497	.100
5	1.255	.1568	1.253	.444	.097

AGIT. NO.	$\frac{N_{Nu}\left(\frac{\mu_w}{\mu}\right)^{1/4}}{N_{Pr}^{.44}\,N_{Re}^{3/4}\left(\frac{T}{D}\right)^{1/2}}$	$\frac{N_{Nu}\left(\frac{\mu_w}{\mu}\right)^{1/4}}{N_{Pr}^{.44}\,N_{Re}^{3/4}\left(\frac{D_w}{D}\right)^{.13}}$	$\frac{N_{Nu}\left(\frac{\mu_w}{\mu}\right)^{1/4}}{N_{Pr}^{.44}\,N_{Re}^{3/4}\left(\frac{T}{D}\right)^{2/5}}$	$\frac{N_{Nu}\left(\frac{\mu_w}{\mu}\right)^{1/4}}{N_{Pr}^{.44}\,N_{Re}^{3/4}\left(\frac{T}{D}\right)^{2/5}\left(\frac{D_w}{D}\right)^{.13}}$
1	.0871	.1920	.1001	.1095
2	.0873	.1710	.0974	.1106
3	.0946	.1605	.1016	.1218
4	.0844	.1250	.0873	.1096
5	.0807	.1230	.0885	.1124

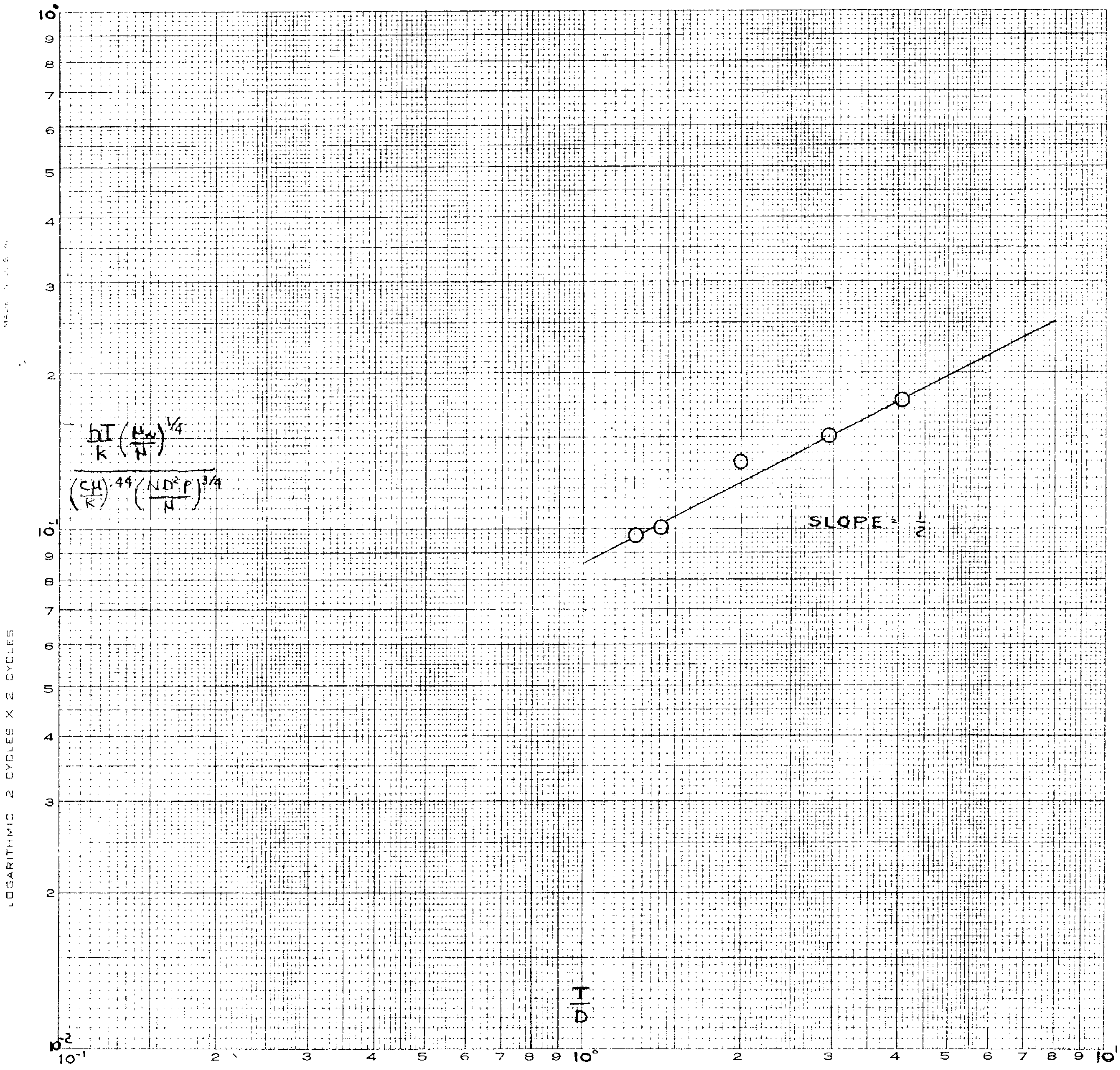

FIG. 46 DETERMINATION OF EXPONENT OF (T/D)

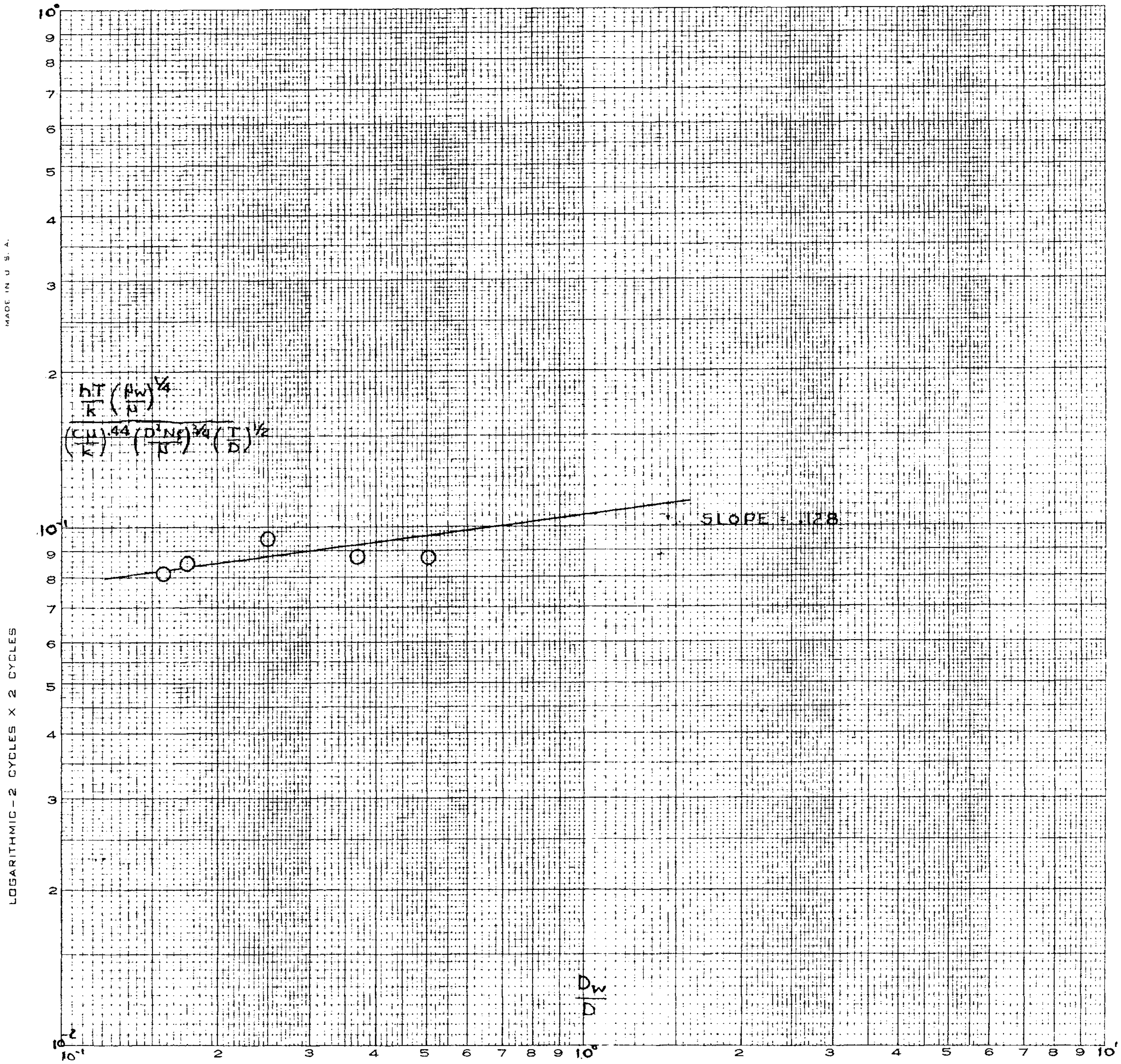

FIG. 47 DETERMINATION OF EXPONENT OF (D_w/D)

To recheck the exponent determined for (T/D), $\log N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}N_{Re}^{3/4}(D_w/D)^{.13}$ was plotted in Figure 48 against log (T/D). A line having a slope of 0.13 appeared to correlate the data. A plot of $\log N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}N_{Re}^{3/4}(T/D)^{.4}$ versus $\log (D_w/D)$ was then made to recheck that exponent. A line having a slope of 0.13 appeared to correlate the data. This confirmed these two exponents.

To determine the exponent of the ratio (Z/D), $\log N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}N_{Re}^{3/4}(D_w/D)^{.13}(T/D)^{.40}$ was plotted against (Z/D) in Figure 50. The data was not sufficiently good to draw a conclusion as to the slope. In the same way, Figure 51, the same ordinates plotted against (C/D) produced points which did not permit drawing a conclusion on slope. Therefore, these two groups were not used in the correlation.

As a final calculation, $\log N_{Nu}(\mu_w/\mu)^{\frac{1}{4}}/N_{Pr}^{.44}(T/D)^{.40}(D_w/D)^{.13}$ was plotted against $\log N_{Re}$. All data of this paper are included in this plot, Figure 52. This results in a line having the equation

$$(63)\quad \frac{hT}{K} = 0.112\left(\frac{C\mu}{K}\right)^{.44}\left(\frac{D^2N\rho}{\mu}\right)^{.75}\left(\frac{\mu_w}{\mu}\right)^{-.25}\left(\frac{T}{D}\right)^{.40}\left(\frac{D_w}{D}\right)^{.13}$$

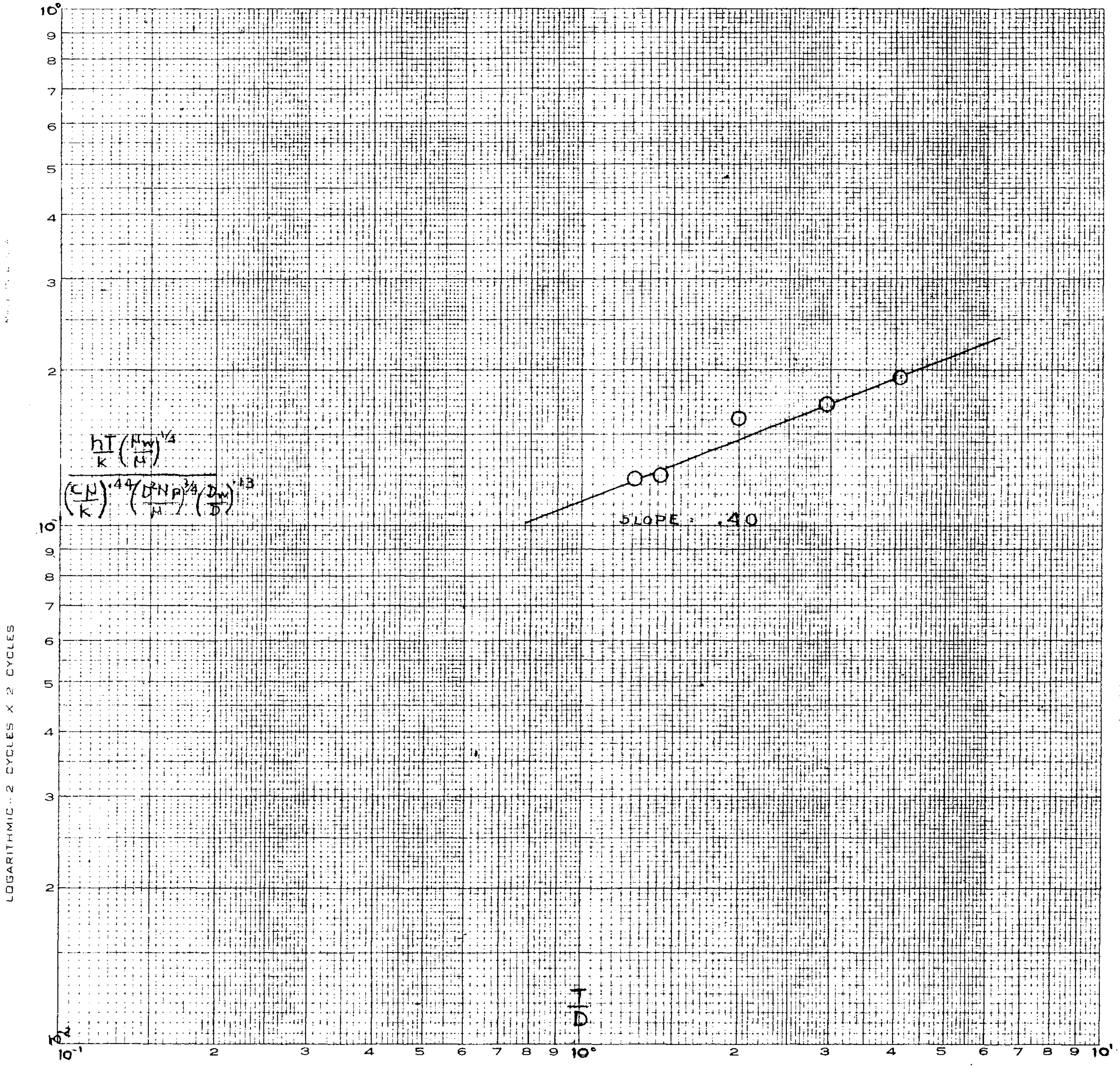

FIG. 48 REDETERMINATION OF EXPONENT OF (T/D)

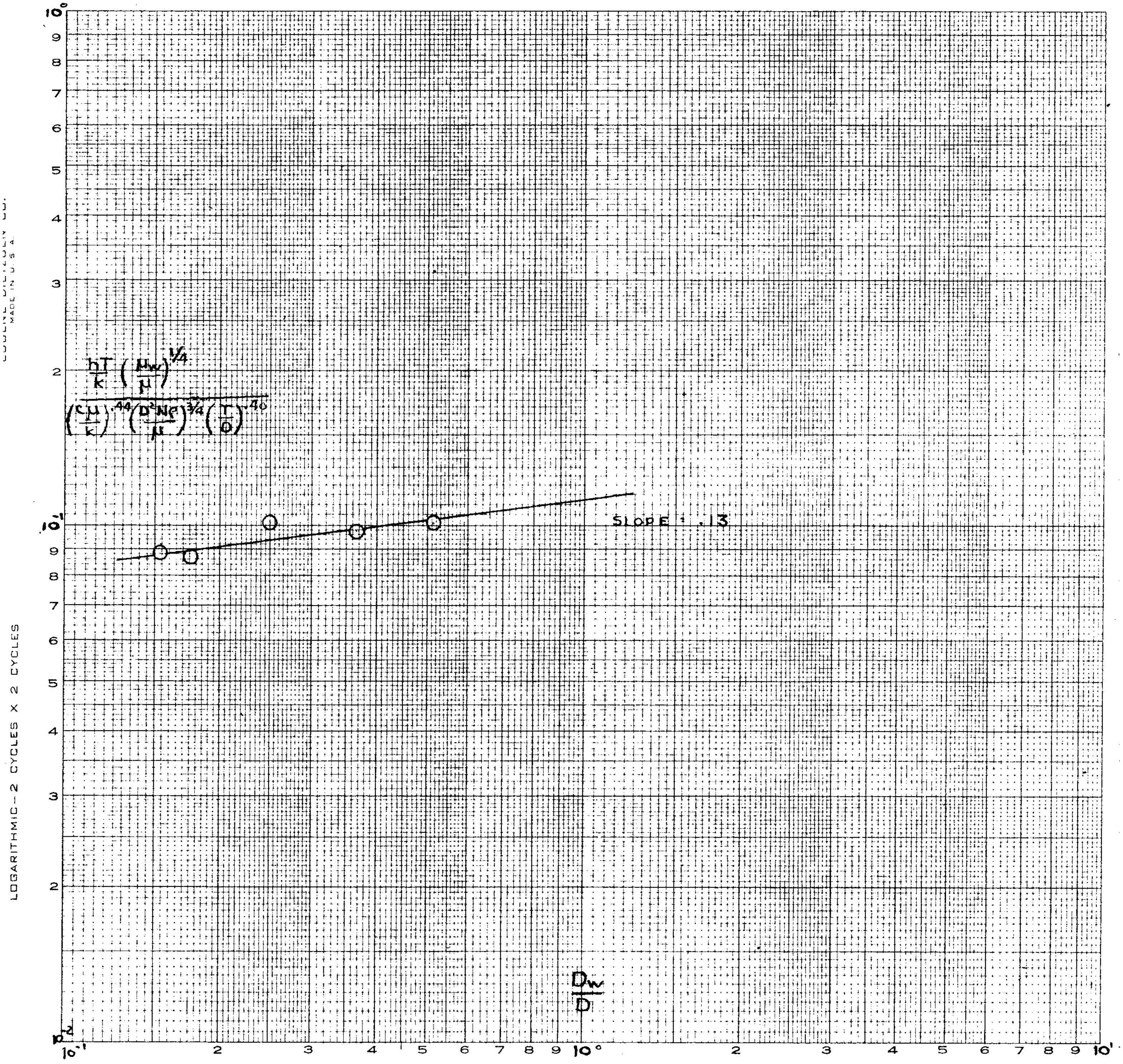

FIG. 49 REDETERMINATION OF EXPONENT OF (D_w/D)

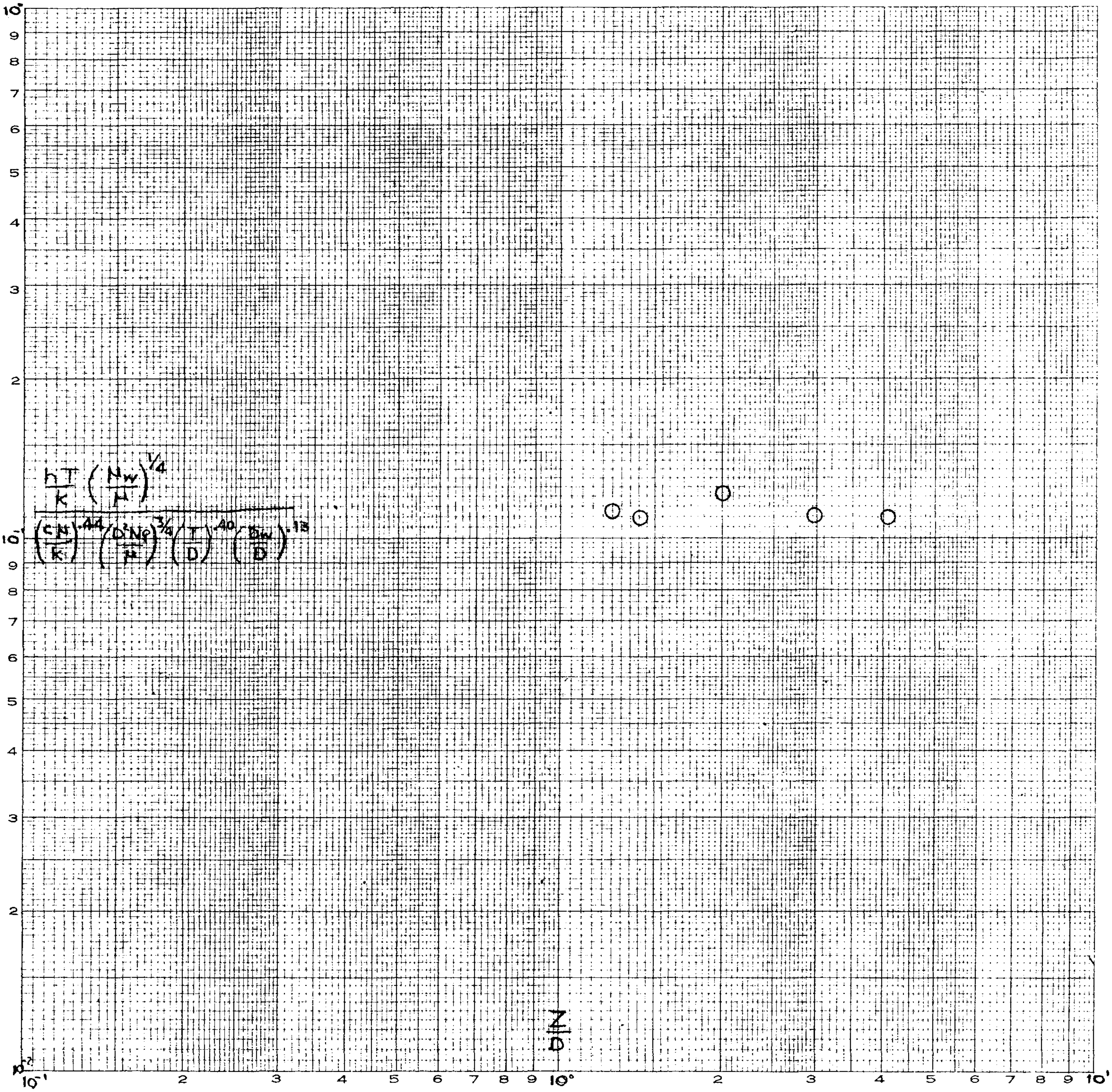

FIG.50 DETERMINATION OF EXPONENT OF (Z/D)

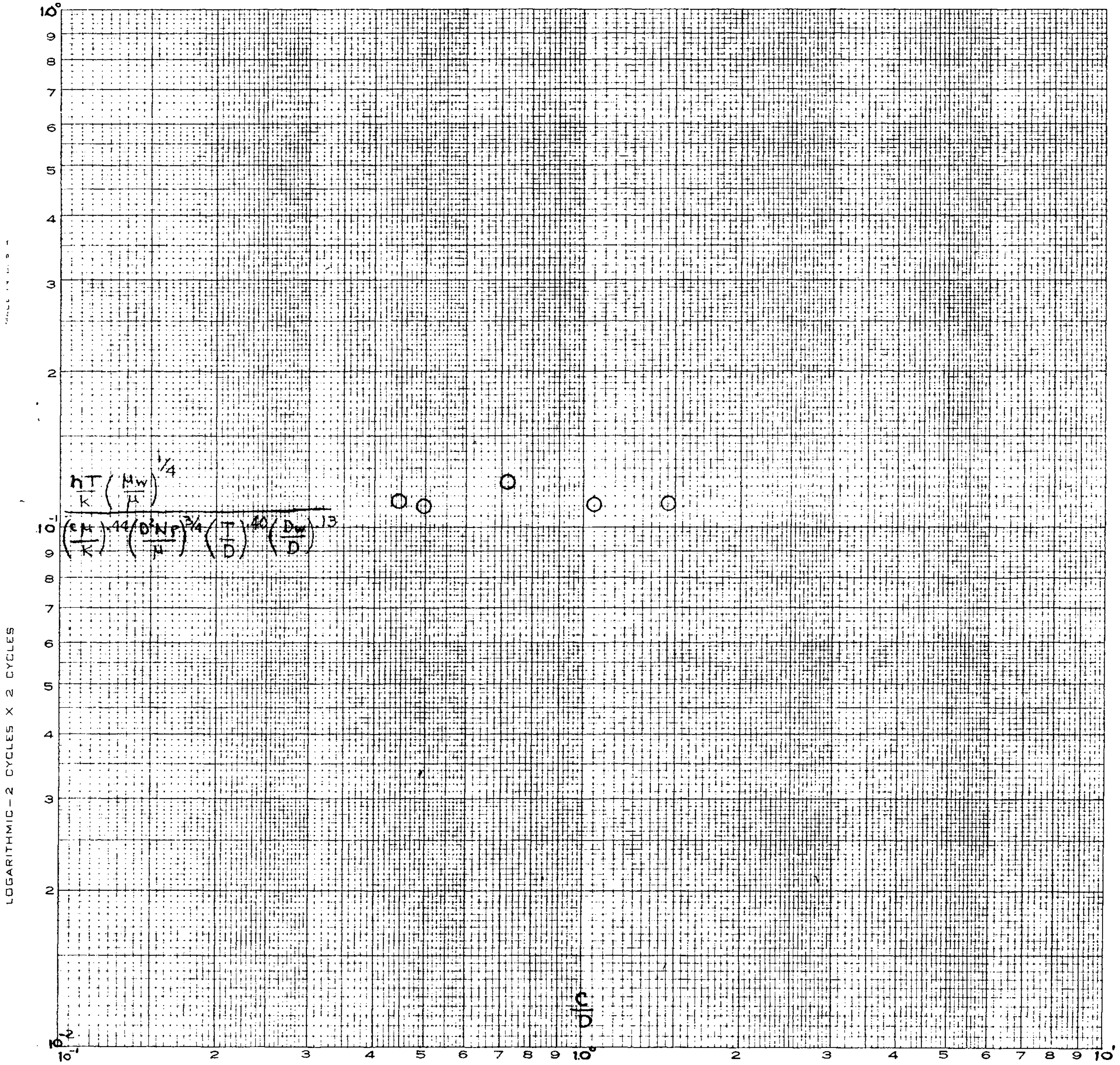

FIG. 51 DETERMINATION OF EXPONENT OF (C/D)

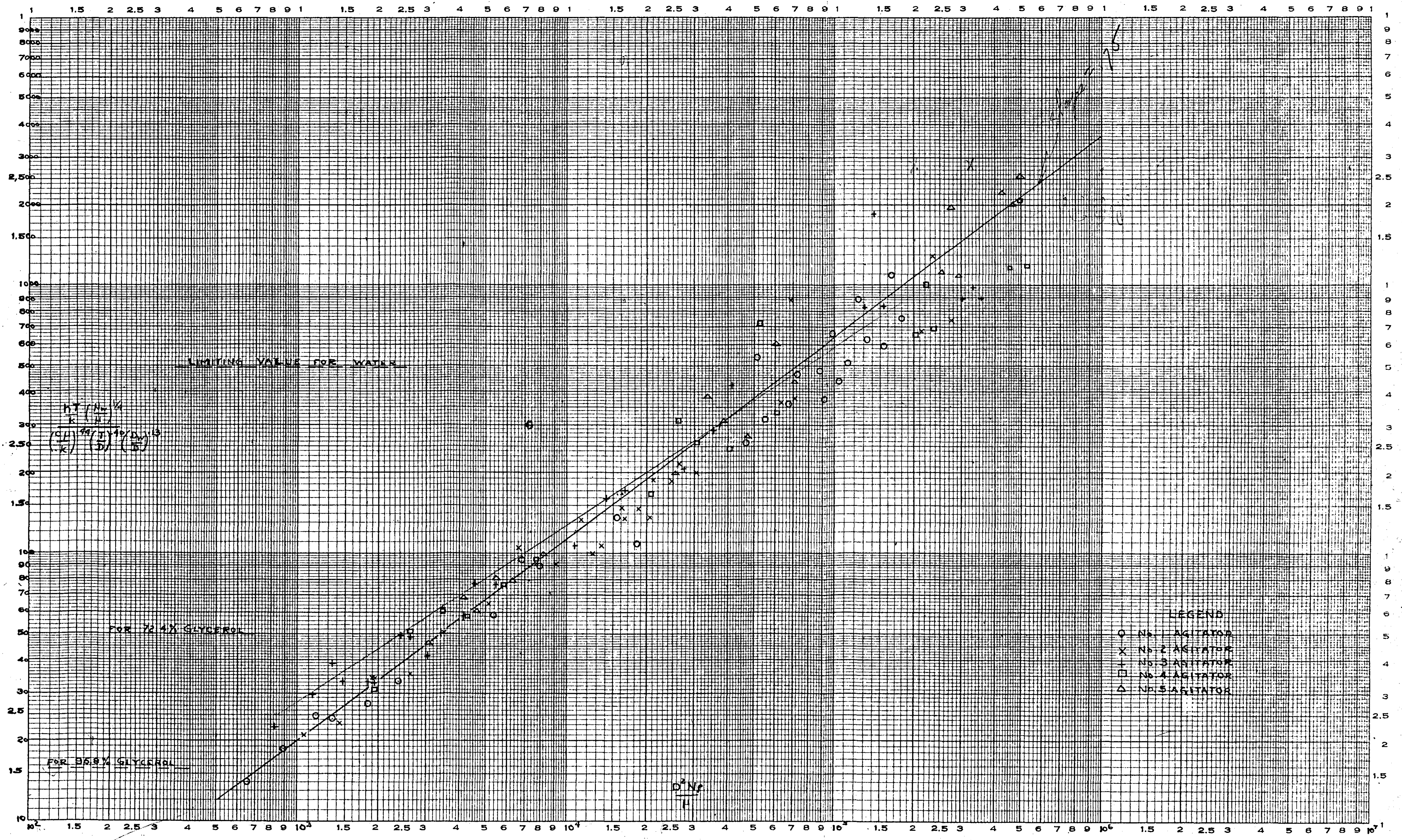

FIG. 52 FINAL CORRELATION OF DATA

VII. RESULTS

all of the data of this paper has been correlated in a single equation (63). This equation is compared with the data of all previous investigators in Figure 53. The variables investigated including the ranges covered are summarized in Table XVII. The equipment used by all investigators is summarized in Table XVIII.

XVIII. DISCUSSION

The primary object of this paper was to show that a single equation could be derived which would express all published data. This has been accomplished by the derivation of equation 63. As shown in Figures 52 and 53, this equation gives adequate expression of the data of this paper as well as that of the four previous investigators.

The dimensional analysis, in equation 36, showed that eleven dimensionless groups are required for a complete correlation of variables in such a system. In this paper, six of the eleven groups are investigated and correlated. Data was available on the ratios (C/D) and (Z/D) but it was not good enough for correlation. Previous investigators had investigated and correlated only four of these groups.

For many reasons, it is not now possible to obtain perfect correlation of all data in a single straight line on a plot such as Figure 52 or Figure 53. First and foremost,

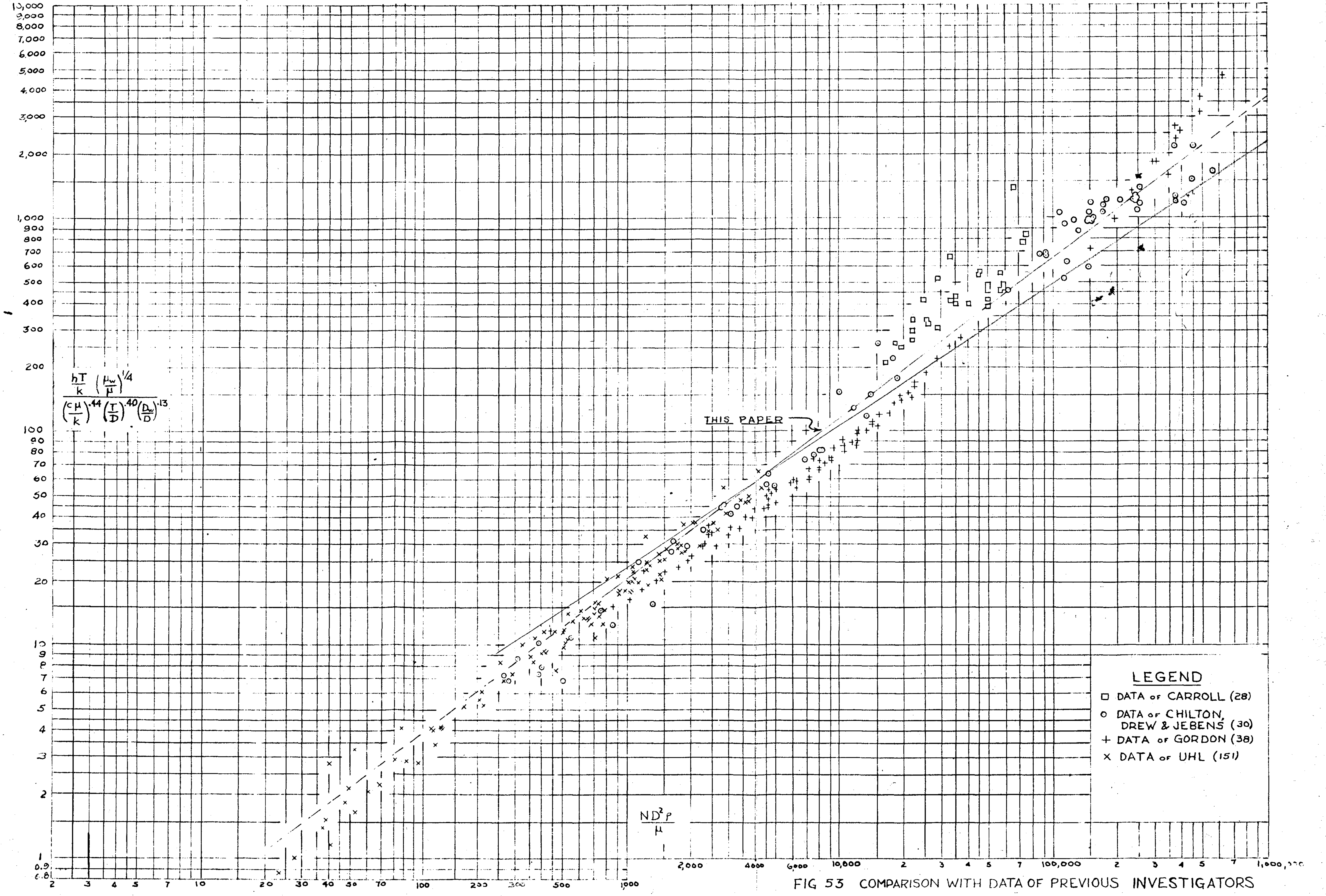

FIG 53 COMPARISON WITH DATA OF PREVIOUS INVESTIGATORS

TABLE XVII

SUMMARY OF VARIABLES INVESTIGATED

		THIS PAPER	DATA OF CARROLL (28)	DATA OF CHILTON *et al* (30)	DATA OF GORDON (38)	DATA OF UHL (151)
Nusselt, Number	Max.	31,300	2863	14,100	7,960	1841
	Min.	203	998	21.0	552	102.1
Prandtl, Number	Max.	698	11.48	6140	1359	173,000
	Min.	2.75	1.829	1.934	1.904	1,010
Reynolds, Number,	Max.	538,000	74,500	563,000	612,000	4,420
	Min.	656	16,810	270	462	23.7
μ_w/μ	Max.	24.1	.723	16.03	.944	151.5
	Min.	.128	.392	.201	.1610	.0454
T/D	Max.	4.083	2.66	1.667	1.96	1.68
	Min.	1.255	--	--	--	--
D_w/D	Max.	.511	.776	.1667	.750	.1695
	Min.	.1568	--	--	--	--
C/D	Max.	1.450	.389	1.50	.222	.168
	Min.	.444	--	(appr.)	(appr.)	(appr.)
Z/D	Max.	4.09	1.0	.833	.895	1.06
	Min.	1.253	--	(appr.)	(appr.)	(appr.)
Fluids Tested		Water 95.8% Glyc. 72.4% Glyc.	Water Glyc. Sols.	Water 92% Glyc. LM Oil Al_2 Oil	Water #10 oil #30 oil #50 oil	Bodied Linseed Oil and Cylinder Oil

TABLE XVIII

SUMMARY OF EQUIPMENT USED

	THIS PAPER	DATA OF CARROLL (28)	DATA OF CHILTON et al (30)	DATA OF GORDON (38)	DATA OF UHL (151)
TYPE OF TEST	BATCH	STEADY STATE	BOTH	BATCH	BATCH
MEANS OF MEASURING h	WILSON PLOT	CALC.	WALL TEMP.	WALL TEMP.	WILSON PLOT
KETTLE, DIA.(T) inches.	23½	12	12	23½	23½
" , Material	STEEL	STEEL	STEEL	COPPER	MONEL
" , Bottom	DISH	FLAT	DISH	DISH	DISH
AGITATOR, DIA.(D) IN.	5 7/8 8 1/8 12 17 1/8 19 1/8	4 17/32	7.2	12	14
, WIDTH (D_W)	3	3½	1.2	9	2 3/8
, SPEED RANGE RPM	0 to 230	106	50 to 300	50 to 150	52 to 305
, ELEVATION,IN ABOVE BOTTOM (C)	8½	1 3/4	1.8	ca. 2	ca. 4
FLUID DEPTH,IN.	25	ca. 12	10	ca.21	ca.25

there are the other geometric variables which have not as yet been investigated. Second and very important, the errors in measurement and in the measuring devices used and the experimental techniques of the various investigators are reflected in the spread of data. In such an empirical study as this, and considering the difficulty involved in obtaining truly accurate data, these are in remarkably good agreement.

Looking closely at Figure 53, it can be seen that the equation line of this paper almost perfectly bisects both the data of Chilton et al (30)and that of Uhl (151). It may be surmised that this is largely because of the similarity of these systems with the author's. This is particularly true as regards shape. The agitators were of similar shape and arrangement and kettles having a dished bottom were used in these three papers.

It will also be noted in Figure 53 that most of the data of Carroll (28) fell above the equating line. There are two possible explanations. First, Carroll attempted to determine the film resistance from the overall resistance by difference using a calculated steam film coefficient. There is no equation now available in the literature which permits calculation of steam film coefficients in the annular jacket which includes both the cylindrical side and the bottom. Also, this method permitted no evaluation of dirt film resistances, if any. Second, Carroll used a kettle which had a flat bottom and his equipment differed in this respect from all other investigators. The extent of the effect of these differences cannot be calculated.

The data of Gordon (38) curves across the equating line in Figure 53. The reason for the curvature is unknown and no curvature has been observed in the data of any of the other investigators. The only report of any curvature in any similar data was in the data of Uhl (151) for the anchor type agitator at low Reynolds Numbers. As previously described Gordon did not use the jacket for cooling. A major difference between Gordon's work and that of the other investigators was in the shape of the agitator. Gordon's agitator, although a paddle, was very wide with respect to its diameter and the bottom was curved to match the dish of the kettle bottom. It is also possible that the curvature is the result of working in the range wherein natural convection heat transfer is effective. There is no data to support this possibility.

The effect of natural convection is indicated on Figure 52. Since the film resistance of heat transfer tends to reach a maximum where there is no forced convection, or agitation, the Nusselt number tends to reach a minimum at that point. Thus for any given fluid in a given kettle, the data tends to level out at a constant value in a plot such as Figure 52. There is no accurate means for determining the coefficient under natural convection conditions. Therefore, the approximate means previously described was used in this paper. It was thus possible to make sure that all data was well above the natural convection region.

Prior to this paper, it was possible only to use the published data for design purposes with confidence in geometrically similar systems. As shown before in Table XVII, the range of geometric variables expressed as ratios was small. This paper expanded the ranges studied within the practical limits of (T/D) and (D_W/D). Equations 58 through 62 express the data of this paper for each of the five agitators without these groups in the correlation. The coefficients range from 0.097 to 0.176. These differ by a factor of almost 2. If an average of these two were used, 0.136, to express all data, the data for the largest and smallest agitators would be in error by about 50%. Thus the introduction of the functions of these two groups brings these data into very close agreement. Also, it permits the use of all published data for design purposes with confidence within the relatively wide ranges studied. These data also indicate that some extrapolation of this data can be made safely.

The effect of baffles was not studied in this paper. Chilton <u>et al</u> (30) and Uhl (151) made tests both with and without baffles and were able to detect no differences in the correlations between the baffled and unbaffled states. It might be postulated that the effect of baffles is to change the direction of flow from horizontal to vertical rather than the magnitude of the velocity at the wall. Since the heat transfer coefficients are proportional to velocity and, in this case, independent of direction, the same correlations should result. It is, of course, known that a marked difference exists in the power correlation between the baffled and unbaffled states. Thus for design purposes, it is possible to use equation 63 for economic design of an agitated system.

IX. CONCLUSIONS

From the preceeding data and calculations, it is concluded that:

1) A better correlation of published data is obtained using the exponent 3/4 for the Reynolds number, the exponent 0.44 for the Prandtl number, and the exponent -1/4 for the ratio (μ_w/μ);

2) All published data can be correlated with the data of this paper in the single equation 63 by introducing the dimensionless ratios (T/D) and (D_w/D);

3) Sufficient data to determine the functions of the ratios (C/D) and (Z/D) is not available.

4) Equation 63 can be used with confidence for design purposes over a wide range of fluid and geometric variables.

X. RECOMMENDATIONS

1) It is recommended that the data and conclusions of this paper be submitted for publication and thus made available for general use.

2) It is recommended that an investigation be made of the power requirements of the equipment used in this paper.

3) It is recommended that an investigation be made to determine the functions of the ratios (C/D), (Z/D), (J/D), (B/x), and (Y/y) in equation 36.

XI. NOMENCLATURE:

Based on A.I.Ch.E. Agitator Test Code (Tentative Code 3-8-54 Section A.I. 40.)

Note. The dimensions shown in the following are those used in this paper. Any consistent set of units may be used.

A	Area of inside heating surface, sq.ft.
B	Number of baffles
c	Specific heat of fluid BTU/LB °F
C	Impeller distance off tank bottom, measured from the lowermost point on the tank bottom to a point midway between the upper and lower extremities of the impeller blades, excluding the hub, ft.
D	Impeller diameter, ft.
D_W	Width of impeller blade, ft.

e	External diameter of coil tubing, ft.	
f	Friction drag coefficient; function of ----	
F	Force	
g_c	Acceleration of gravity ft/sec^2	
h	Film coefficient of heat transfer, batch side, BTU/hr ft^2 °F	
h_o	Film coefficient of heat transfer, jacket side, BTU/hr ft^2 °F	
H	Heat	
HP	Horsepower	
I	Exponent of N	
J	Baffle width, ft.	
j	Mechanical equivalent of heat	
k	Thermal conductivity, BTU/hr ft^2 °F/ft	
K	A constant	
l	Length of side of a square vessel, ft.	
L	Length	
m	Mean coil diameter, ft.	
M	Mass	
N	Impeller speed, rev/hr.	
N_F	Freud No., N^2D/g_c	dimensionless
N_{Nu}	Nusselt No., hT/k	dimensionless
N_P	Power No., $Pg_c/\rho N^3D^5$	dimensionless
N_{Pr}	Prandtl No., $\mu c/k$	dimensionless
N_{Re}	Reynolds No., $ND^2\rho/\mu$	dimensionless
P	Power	
q	Heat transfer rate, BTU/hr	

r	Overall height of coil, ft.
r_d	Resistance of dirt film hr. ft^2 $^\circ$F/BTU
r_m	Resistance of metal wall hr. ft^2 $^\circ$F/BTU
r_o	Resistance of jacket side film hr. ft^2 $^\circ$F/BTU
R_c	$r_d + r_m + r_o$
s	Gap between turns of coil, ft.
t_b	Average fluid temperature, $^\circ$F
t_{b1}	Initial fluid temperature, $^\circ$F
t_{b2}	Final fluid temperature, $^\circ$F
t_{ji1}	Initial jacket inlet temperature, $^\circ$F
t_{ji2}	Final jacket inlet temperature, $^\circ$F
t_{jo1}	Initial jacket outlet temperature, $^\circ$F
t_{jo2}	Final jacket outlet temperature, $^\circ$F
t_w	Inside wall temperature of kettle, $^\circ$F
Δt_m	Mean temperature difference between batch and jacket $^\circ$F
Δt_w	Mean temperature difference across h, $^\circ$F
T	Tank diameter, ft. : Temperature
U	Overall heat transfer coefficient BTU/hr.ft^2 $^\circ$F
w	Weight of batch, lbs.
x	Reference number
y	Reference number
Y	Number of agitator blades
Z	Liquid depth, ft.
γ	Constant in dimensional analysis
δ	1.13 (pitch angle -12)
θ	Time

Θ_1	Initial time of measurement
Θ_2	Final time of measurement
μ	Fluid viscosity at t_b, LB/ft.sec.
μ_w	Fluid viscosity at t_w, LB/ft.sec.
ρ	Density, lb/ft^3

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