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Density measurements with two-phase mixtures in adiabatic and heated channels at high pressure by means of a quick closing valve method

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DENSITY MEASUREMENTS WITH TWO-PHASE MIXTURES IN ADIABATIC AND HEATED CHANNELS AT HIGH PRESSURE BY MEANS OF A QUICK CLOSING VALVE METHOD

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Abstract

This report describes a measurement technique based on the use of two quick-closing valves simultaneously operated at the inlet and outlet of channels, for the determination of density in two-phase (gas+liquid) mixtures in adiabatic and heated conditions.

The errors inherent in the measurement technique are also discussed.

Systematic experiments were carried out under the following conditions:

Flow: vertical
Geometry: round conduits 1.5 cm I.D. ; 0.9 cm I.D.
19 rod bundle 1.0 cm O.D., rod-rod clearance=rod-pressure tube clearance = 0.138 cm, with and without filling rods.
Fluids: argon-water mixtures
argon-ethylalcohol mixtures
argon-acetone mixtures
steam-water mixtures
Flowrate: 5 ÷ 250 g/cm^2s
Quality (by weight): adiabatic conditions (average) 0 ÷ 0.80
heated conditions (inlet) - 0.15 ÷ -0.02
Heat flux (with steam-water mixtures): 0 ÷ 200 W/cm^2

Only experimental data are reported here. An interpretation of the results will be presented in a further report.

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1. INTRODUCTION

1.1. Density (local and average) of two-phase mixtures in steady and transient conditions (or liquid or gas volume fraction, also called "void fraction") is one of the most important quantities for the design of steam generating power channels for nuclear reactors. In particular, in the case of pressure tube reactors, heavy water moderated, light water cooled and natural uranium fuelled, the water hold up in the channels (or the mixture density with reference to a given channel volume) has a direct impact on the core reactivity; as a consequence this limits the fuel neutronic life and, what is also important, determines the reactor behaviour from the reactor control and safety point of view.

A great deal of both theoretical and experimental work has been undertaken in the last years on this subject.

A brief review of the literature available has been carried out in(1) where the results of an experimental investigation carried out at CISE in this field is described in detail. Since the publication of this reference, new approaches have been attempted(2)(3) and some new data have been presented(4)(5)(6); however, even at the present time, among the data so far published, those obtained in a range of flowrates, quality, physical properties and geometries of interest for the CIRENE reactor (D_2O moderated evaporating light water cooled, natural uranium fuelled(7)) are very scarce; besides the influence of heat addition is far from being clear.

1.2. The problem still exists of obtaining a measurement method which should be accurate enough in the range of interest. In fact, in the case of high quality mixtures, such as those foreseen for the CIRENE power channels, the quantity to be measured directly is *not* the void or gas volume fraction since the density does depend only weakly upon this quantity(*), but the *liquid* volume fraction or the slip ratio. Thus, the methods for measuring α, as for example the radiation attenuation techniques or the dilatation technique for one component systems, may have heavy drawbacks in this range. Furthermore the method must be suitable for eventual measurements in complex geometries such as rod bundles.

Several methods have been developed at CISE for directly measuring the liquid volume fraction or the mixture density. In the case of two--phase two-component mixtures in adiabatic conditions through successive investigations, a dilatation technique was developed, which was based on the variation of a liquid level in the separator(8): this method proved to be quite accurate since $(1-\alpha)$ was the quantity directly measured but it was found that the measuring time was quite long.

For measuring the density of steam-water mixtures at high pressure with and without heat addition a method based on the use of a dilatation technique was developed, first for operation in closed-loop facilities(9), successively in open-loop facilities(10)(6).

As it has applied to steam-water mixture system, the method gives the void fraction of the test element through the mass balance of the fluid filling the overall loop (open or closed).

(*) Since

$$\rho = (1-\alpha)\rho_l + \alpha\rho_g$$

$$\left|\frac{\delta\rho}{\rho}\right| = \left|\frac{\delta(1-\alpha)}{1-\alpha}\right| \left(1 - \rho_g/\rho\right)$$

$$\left|\frac{\delta\rho}{\rho}\right| = \left|\frac{\delta\alpha}{\alpha}\right| \left(\rho_l/\rho - 1\right)$$

This method requires consequently a proper design of the experimental facility in order to minimize the density variations (versus quality) of the fluid along the primary duct outside the test element: therefore the accuracy of density measurement, which is derived from the void fraction value, can be unsatisfactory in the case of large quality mixtures and even more so, when the inlet quality is positive. Nevertheless the use of this method, provided fully developed, is valuable since it can be applied also in the case of complex geometries such as rod bundles.

1.3. In order to overcome the difficulties inherent in the development of the dilatation technique (which were not such as to discard this method) a measurement technique based on the use of two quick-closing valves simultaneously operated and located respectively at the channel inlet and outlet was developed.

In principle this technique has the great advantage of the dilatation technique, that is, it can be applied to whatever geometry; morever in the case of two-phase two-component mixtures in adiabatic conditions the liquid volume fraction is directly measured while with one-component mixtures, (in heated or adiabatic channel) the mixture density in the channel is directly measured.

The method has however a drawback since only average density measurements over the power channel length can be performed (the difficulty however can be overcome by a proper procedure which will be discussed further on).

Incidentally in transient conditions discrete but high accuracy measurements can be performed while it is impossible to have a continuous recording of density transients.

1.4. The work referred to in this report was carried out with two experimental facilities available at CISE.

The experiments carried out with two-phase two-component mixtures (with different geometries) were obtained with the IDRA facility installed at the CISE laboratories and which is fully described in(11).

The experiments carried out with steam-water mixtures in heated tubes were obtained with the IETI-1(12) experimental plant located at the Emilia thermal power station of ENEL at Piacenza.

This report describes the quick closing valve technique and gives a brief presentation of the results. Detailed analysis of the experimental data will be reported furtherly.

2. GENERAL CONSIDERATIONS ON THE MEASUREMENT TECHNIQUE

In principle the measurement of average density or of overall mass content in a channel of a two-phase mixture by means of the quick-closing-valve method is rather simple. But in practice it requires the solution of some weighty technological problems, especially in the case of heated channels at high temperature and pressure. In fact the method has been applied by a number of researchers to adiabatic channels with gas-liquid mixtures at low pressures(13)(14).

Briefly, the experimental procedure consists, once operative conditions have been reached, in closing simultaneously a set of two suitable valves located at the channel both ends and draining and weighing the relevant mass content.

The reliability of this method is strictly connected with the following requirements:

- the mass hold-up of the channel must not change during the closing transient;
- the volume comprised between each one of the two valves and the channel ends must be small enough, compared to the channel volume;
- the mass content must be drained so as to make any possible loss of mass negligible.

Obviously these requirements can be fulfilled in different ways according to the experimental conditions e.g.: one or two-component mixtures, adiabatic or heated channels, as well as pressure and temperature.

2.1. Adiabatic channel

Let us consider first the case of an adiabatic channel, closed at the ends by two valves (Fig. 1a): the overall mass content M_{TS}, which is present in the volume V_{TS} of the channel at time 0 for fixed values of P, G and X, does not change during the closing time τ, if we have:

$$\int_0^{\tau} G_{in} A_{in} \, dt = \int_0^{\tau} G_{ex} A_{ex} \, dt$$

When the two valves have the same configuration and are operated simultaneously, since $X_{in} = X_{ex} = X$, the flow resistances across the inlet and exit valve respectively are always equal during the closing transient. Therefore the flowrate transients are similar and the error in the M_{TS} measurement is negligible even if τ is not very small.

Obviously τ must be smaller than the transit time $T = \rho \frac{L}{G}$ of the mixture over the channel length, in order to avoid the development of a different phase distribution or hydraulic regime, which would correspond to the lower values of G which can set in, before the valves are fully closed$^{(1)}$.

According to some experimental measurements, the density results begin to change only when this time is approximately equal to or longer than the transit time of the channel.

For this reason, in the choice of a valve for adiabatic measurements, the closing time should not be longer than about $T = \rho \frac{L}{G}$.

When the valves are located right at the channel ends one gets

$$M = M_{TS} \qquad \rho_{TS} = \frac{M_{TS}}{V_{TS}} = \frac{M}{V_{TS}}$$

However in the case of complex geometries such as rod bundles, at high temperature and pressure, sometimes it is not possible to locate the valve at the channel end, and thus there are two volumes V' and V'', respectively upstream and downstream of the test section ends. Thus:

$$M = M_{TS} + M' + M''$$

$$\rho_{TS} = \frac{M_{TS}}{V_{TS}} = \frac{M}{V_{TS}} - \left[\rho'(X)\,\frac{V'}{V_{TS}} + \rho''(X)\,\frac{V''}{V_{TS}}\right]$$

If the configurations of V' and V" are similar, $\rho''(X) = \rho'(X)$ and we obtain

$$\rho_{TS} = \frac{M}{V_{TS}} - \rho'(x)\,\left(\frac{V' + V''}{V_{TS}}\right)$$

$\rho'(x)$ or $\rho''(x)$ can be evaluated in a first approximation on the basis of empirical correlations developed for other experimental data, relevant to experimental conditions not too dissimilar or it can be measured by connecting V' directly to V", eliminating the test section. The overall measurement error $\delta\rho_{TS}$, neglecting the error inherent in the determination of the volumes V', V" and V_{TS}, is given by

$$\delta\rho_{TS} = \frac{\delta M}{V_{TS}} + \delta\rho'\,\frac{(V' + V'')}{V_{TS}}$$

The impact of $\delta\rho'$ on the results decreases with the decrease of the ratio $\frac{V' + V''}{V_{TS}}$.

The draining procedure of the mass closed between the valves is slightly different for a one-component mixture than for a two-component mixture.

In the first case, with relative high temperature and pressure operating conditions, the overall mass is cooled before being collected in order to condense the steam phase and to lower the temperature below the saturation temperature at atmospheric pressure. However, as a consequence of the condensing operation, the pressure decreases and external gas must be supplied in order to purge the channel.

Two-component mixtures are generally at room temperature and therefore the closed mass can be drained directly into a separator: thus only the liquid mass $(1-\alpha)\,\rho_l\,V_{TS}$ is collected (the gas phase can be used as purging gas).

With both draining procedures a mass M_L, not completely drained or saturating the purging gas, may be lost. This loss can be evaluated, for example, by comparing the value of a known mass introduced in the channel with the one correspondingly drained.

2.2. Heated channel

In the case of a heated channel the following remarks must be made:

- the inlet quality X_{in} is different from the exit quality X_{ex};
- at time 0 the channel is electrically heated and the corresponding power is W_{TS}.

2.2.1. Since $X_{ex} > X_{in}$, the equality and the synchronism of the two valves is not sufficient to insure that inlet and exit flowrate transient are similar: in fact the pressure drops across the valves, other operating conditions being fixed, increase with quality.

Hence in the time τ the inlet flowrate decreases more slowly than the exit flowrate. In this case one gets:

$$M = M_{TS} + \delta M$$

$$\delta M = \int_0^{\tau} G_{in} A_{in}\, dt - \int_0^{\tau} G_{ex} A_{ex}\, dt \geq 0$$

The value of δM is not easy to be derived but an evaluation of its limit is possible. In fact δM will be maximum if (Fig. 2a):

- at time 0 $\quad G_{in} A_{in} = G_{ex} A_{ex} = GA = \Gamma$
- during the time interval $0 \div \tau$ $\quad G_{ex} A_{ex} = 0$

$$G_{in} A_{in} = GA = \Gamma$$

- at time τ $$G_{ex}A_{ex} = G_{in}A_{in} = 0$$

Then in the worst conditions one gets:

$$\delta M = G\,A\,\tau$$

and the maximum error $\delta\bar{\rho}_{TS}$ will be

$$\delta\bar{\rho}_{TS} = \frac{\delta M}{V_{TS}} = \frac{G\,A\,\tau}{A\,L} = \frac{G}{L}\tau \qquad \text{(see Fig. 3)}$$

Keeping in mind that $T = \bar{\rho}_{TS}\frac{L}{G}$ we obtain:

$$\frac{\delta\bar{\rho}_{TS}}{\bar{\rho}_{TS}} = \frac{\tau}{T}$$

This calculation gives the upper limit of the error of the measured density: the actual inlet and exit flowrate transients will be as shown in Fig. 2b.

Moreover this treatment shows that the valve closing time is far more important than in the case of adiabatic channels: in fact if $\tau = T$ the upper limit of the relative error is 100%.

2.2.2. When the valves cannot be located right at the ends of the heated length, the contribution of the two consequent adiabatic volumes V' and V", located upstream and downstream respectively, must be taken into account (Fig. 1b). In this case one gets:

$$M = M_{TS} + M' + M''$$

$$\bar{\rho}_{TS} = \frac{M_{TS}}{V_{TS}} = \frac{M}{V_{TS}} - \frac{M'}{V_{TS}} - \frac{M''}{V_{TS}} = \frac{M}{V_{TS}} - \frac{V'}{V_{TS}}\rho'(X_{in}) - \frac{V''}{V_{TS}}\rho''(X_{ex})$$

where ρ' and ρ'' are functions of inlet quality (X_{in}) and exit quality (X_{ex}) respectively.

The overall maximum measurement error $\delta\bar{\rho}_{TS}$, neglecting the errors inherent in the measurement of volumes V', V" and V_{TS}, is given by:

$$\delta\bar{\rho}_{TS} = \frac{\delta M}{V_{TS}} + \frac{V'}{V_{TS}}\delta\rho' + \frac{V''}{V_{TS}}\delta\rho''$$

When $X_{in} < 0$, ρ' is known with a good degree of accuracy from the measurement of the test section inlet temperature T_{in}, since $\rho' = \rho'(T_{in})$.

If X_{in} and $X_{ex} > 0$, ρ' and ρ'' can be evaluated in the same way as suggested for the case of an adiabatic channel: the impact of $\delta\rho'$ and $\delta\rho''$ on the results decreases with the decrease of the ratios $\frac{V'}{V_{TS}}$ and $\frac{V''}{V_{TS}}$ respectively.

It is worth mentioning that in the case of heated channels the problem of minimizing the volumes V' and V" is far more difficult: in the usual configurations of annular and rod cluster test sections it is hard to reduce the ratios $\frac{V'}{V_{TS}}$ and $\frac{V''}{V_{TS}}$ to less than 0.1 and only in the case of circular tubes, can these ratios be made negligible, by using ball valves.

The draining procedure of the mass closed between the valves is the same as in the case of an adiabatic channel with a one-component mixture.

2.2.3. Normally the power W_{TS} is switched off when both valves are fully closed in order to make any variation of the quality profile negligible along the channel during the valve closure; when τ is very short, no significant errors can arise even if the power is switched off during the closing time.

Therefore the shutdown transient of the power W_{TS} must be examined essentially with regard to a possible test element damage.

If the power W_{TS} is 0 at a time $\tau_0 > \tau$ we have, in the $\tau_0 - \tau$ interval, a heat input $Q = \int_{\tau}^{\tau_o} W_{TS}\,dt$ to the channel. Since the heat transfer coefficient is high in two-phase flow, in a first approximation we may consider that the overall Q is transferred to the mixture, which undergoes an isovolumetric transformation, since the channel ends are closed.

The consequent increase in pressure and temperature can be evaluated by the first principle of thermodynamics. One gets in fact (neglecting V' and V"):

$$M_{TS}\,\Delta H - \Delta(P\,V_{TS}) = \int_{\tau}^{\tau_o} W_{TS}\,dt = Q\,(W_{TS},\ \tau_o)$$

$$M_{TS} = \bar{\rho}_{TS}\,V_{TS}$$

$$\bar{\rho}_{TS}\,V_{TS}\,\Delta H - V_{TS}\,\Delta P = Q$$

where H is the specific enthalpy of the mixture.

Hence the pressure increase ΔP is given by

$$\Delta P - \bar{\rho}_{TS}\Delta H + \left(\frac{Q}{V_{TS}}\right)_{V\,=\,\mathrm{cost}} = 0$$

This equation, for fixed values of Q, V_{TS}, $\bar{\rho}_{TS}$, can be solved by Mollier diagram for water-steam (or any table of thermodynamic properties), keeping in mind that P and H change at constant specific volume $v_{TS} = 1/\bar{\rho}_{TS}$.

In Fig. 4 a graph is shown of ΔP versus Q/V_{TS} for different v_{TS}, assuming P = 50 kg/cm^2 at time τ: the increase in temperature can be calculated by reading the saturation temperature in correspondence with the value of P.

Pressure may reach dengerous values with regard to the safety of the experimental plant, while the corresponding temperature is not too high for the usual structural materials of the heated channels: in fact in the saturation region the maximum pressure is 225 kg/cm^2 while the maximum temperature is 374 °C.

Moreover it must be noticed that, other conditions being fixed, ΔP increases with the specific mass flowrate G because W_{TS} and the consequent Q value is higher.

2.2.4. In conclusion, the main difficulties limiting the use of the quick closing valve method in the case of heated channels at high temperature and pressure, are inherent in the valve requirements, namely:

- operation at high temperature and pressure;
- short closing time: less than 0.01 second for most channel lengths and specific mass flowrates considered (see Fig. 3);
- tight seal without any leakage, even after several opening and closing operations.

3. ADIABATIC CHANNEL

3.1. Experimental apparatus

The measurements of the liquid volume fraction in adiabatic conditions, by means of the closing valves method, have been carried out with the IDRA experimental facility, already described in(11) and whose schematic flowsheet is presented in Fig. 5. This experimental facility may operate at room temperature up to a pressure of 25 kg/cm^2 with a two-phase two-component mixtures.

The two-phase mixture is formed in a tee-mixer with the gas entering the rum side, the liquid is injected through an annular shot with an adjustable aperture. After passing through a calming section the mixture enters the vertical test section, which leads into a high efficiency separator out of which each separated phase returns to its own circuit.

The experiments have been performed with a circular tube and a 19 rod bundle.

circular tube

- inner diameter	1.5	cm
- length (between the closing valves)	210	cm

- valves: ball valves having a bore diameter equal to that of the tube

rod bundle (Fig. 6)

- number of rods	19	
- external diameter of rod	1.02	cm
- gap	0.138	cm
- inner diameter of shell	5.76	cm
- length (between the closing valves)	200	cm

without filling rods

- equivalent diameter	0.534 cm
- flow area	10.55 cm^2

with filling rods

- filling rods	n. 12 Ø 0.4 cm n. 6 Ø 0.5 cm
- equivalent diameter	0.303 cm
- flow area	7.86 cm^2

- valves: rotating plate valves (see Figs. 7-8), whose cross flow area in the open position has the same configuration as that of the cluster, in order to avoid disturbances on the velocity profile.

In both assemblies the connecting volume V' and V'' can be neglected if compared with the volume of the test element. The valves are connected by means of a wire in order to be closed simultaneously and are operated by means of a load spring: the closing time was about 0.5 second.

3.2. Experimental procedure

The experimental procedure is as follows:

a) achievement of flowrate, pressure and quality operating conditions which is given by

$$X = \frac{\Gamma_g}{\Gamma_l + \Gamma_g}$$: the main valves are in the open position;

b) valves closed;

c) drainage of liquid mass content, that is collected in a separator, the gas phase being used as purging gas;

d) opening of the valves and achievement of new operating conditions.

The drained mass has been corrected for the loss M_L, which has been evaluated by comparing a known mass, introduced in the channel, with that correspondingly collected. On the basis of our measurements, M_L resulted of the order of 0.01 $\rho_l V_{TS}$.

3.3. Results

About 250 data with the circular tube and 350 data with the rod bundle have been obtained; the ranges of experimental conditions are summarized in Table A, while the results are presented as $(1-\alpha)$ versus $(1-X_v)$ in Table 1-27.

The experimental errors can be evaluated as follows:

- $\delta(1-\alpha) = 0.01$
- $\delta\rho = 0.008\ g/cm^3$
- $\delta X = 0.01 \div 0.02$

The experiments have been performed at room temperature with argon, as gas phase, and water, alcohol or acetone as liquid phase, in order to investigate also the influence of the liquid physical properties on $(1-\alpha)$.

The trend of the physical properties of the employed fluids versus temperature and pressure are shown in Figs. 9 - 10 - 11 - 12 where also those of steam-mixtures are reported.

In Figs. 13 - 19 some results are plotted as $(1-\alpha)$ versus $(1-X_v)$.

A comparison of the data obtained by the dilatation technique(1) with those obtained by closing valve technique is shown in Fig. 13: the agreement is quite good and the small differences for low and high quality values can be due to the dilatation technique which gives a greater error in these regions.

In Figs. 14-15 the effect of surface tension is presented: the trends of data, obtained with alcohol or acetone (Fig. 14) respectively as liquid phase, are different in the high quality region, being the other experimental conditions fixed. Alcohol and acetone have about the same density as well as the same surface tension while the viscosity of alcohol is about three times larger than that of acetone; for this reason the different trends can be explained on the basis of the different values of viscosity or of some other unknown physical properties.

The influence of specific mass flowrate is outlined in Figs. 16 - 17 while the effect of gas density can be observed in Figs. 18 - 19.

The effect of the physical properties as well as the effect of mass flowrate and test element geometry on the volume fraction of liquid, will be analyzed in detail in a report to be published.

For the time being it is worth mentioning that on the basis of the present results, the dependences of the liquid volume fraction upon the aforementioned parameters appear to be quite similar to those outlined in a previous work performed at CISE(1).

4. HEATED CHANNEL

4.1. Experimental apparatus

The requirements for the application of the quick-closing valve method to heated channels, have been fulfilled by the design and construction of a special hydraulic valve directly closed, by means of a piston, by the channel pressure itself (Fig. 20).

The calculation of the closing time τ is given by the equation:

$$\tau = \sqrt{\frac{2\ s\ m}{F - F_f}} = \sqrt{\frac{2\ s\ m}{\Omega (P - P_f)}}$$

where

s = closing stroke

m = mass of moving parts of the valve

F = pushing force

F_f = friction force

Ω = piston cross section

P = channel pressure

P_f = minimum closing pressure required for overcoming the friction of the piston seal.

In the case of the valve adopted for the experiments described here we had:

m = 110 g

s = 0.55 cm

P_f = 4 kg/cm^2

Ω = 2.54 cm^2

In correspondence with P = 10 kg/cm^2, τ is 0.31 10^{-2} s (the experimental values equal to 0.4 10^{-2} agree well with this figure).

This valve model proved to be very satisfactory behaviour up to

50 kg/cm^2 and by some improvements it can operate at an even higher pressure.

The experiments were carried out with the IETI-1 plant of CISE: a flow diagram of the plant (which is an open circuit) is given in Fig. 21, while the quick-closing-valve apparatus is shown in detail in Fig. 22. The main components of the plant are(12):

- a volumetric pump system (reciprocating, 4 pistons with flow dampers) providing a flowrate of 1200 kg/h and a head of 180 kg/cm^2, operating at room temperature;
- a water preheater heated by means of electrical a.c. power, controlled from 0 up to 700 kW;
- a test section, heated by means of 8 d.c. rotating generators, providing a maximum power input of 200 kW;
- a condenser and cooler system, lowering the temperature of the fluid below 100 °C.

The test section pressure is controlled by means of the valve located at the cooler outlet, the fluid being discharged at atmospheric pressure.

For density measurement three valves have been provided (Fig. 22): two (IV and EV), having larger-sized pistons, for closing the test section ends, and one BV, with smaller piston, for closing the by-pass channel.

The main valves of the test section are connected by means of a stay rod, so as to be operated simultaneously, and are manually opened by a jackscrew. The by-pass valve BV is opened directly by valves IV and EV in the closing stroke; thus the flow is by-passed and the loop thermohydraulic regime changes very slightly during the measurement operation.

A comparison between calculated and measured closing times of test section valves is shown in Fig. 23: τ is less than 0.01 second for pressures higher than 5 kg/cm^2.

The input power W_{TS} is switched off by the main valves at the end of the closing stroke.

The mass content of the test section is drained through IV, which is at the apparatus bottom, condensed by a small surface condenser, collected in a separator and then weighed by a precision balance.

During the drainage, gas can be supplied to the test section through the valve EV, which is at the apparatus top, in order to pressurize and purge the channel; otherwise the decrease of test section pressure would lead to the opening of the main valves IV and EV.

4.2. Experimental procedure

The experimental procedure is the following (see Fig. 22):

a) achievement of operating conditions of flowrate, pressure, inlet quality and test section power input: IV and EV open, BV closed;
b) IV and EV closed and BV opened simultaneously, W_{TS} switched off;
c) GV opened;
d) DV opened, mass content M drained and weighed;
e) DV and GV closed;
f) IV and EV opened and BV closed simultaneously;
g) achievement of new operating conditions.

Some preliminary measurements have been performed at $W_{TS} = 0$, $X_{in} < 0$, in order to compare the experimental density with the density calculated on the basis of a measured mean temperature of the liquid. The error of mass content, drained with this procedure, resulted in 1 g, under the worst conditions.

In the case of negative inlet quality X_{in}, preference was given to a different procedure for data collection minimizing the error due to the contribution of the mass M_L, which is not completely drained or vented through the saturated purging gas.

The procedure consists of two different tests: one corresponding to $W_{TS} = 0$ and $X_{in} = X_{ex} < 0$ and the other corresponding to the desired conditions: since M_L is essentially a function of the drainage procedure, at the same values of P, G, X_{in} and different W_{TS}, one gets:

- when $W_{TS} = 0$ $\qquad X_{ex} = X_{in} < 0$

$$M(0) = M' \; (X_{in}) + M_{TS}(0) + M'' \; (X_{in}) - M_L \tag{1}$$

- when $W_{TS} > 0$ $\qquad X_{ex} > X_{in}$

$$M(W_{TS}) = M' \; (X_{in}) + M_{TS} \; (W_{TS}) + M'' \; (X_{ex}) - M_L \tag{2}$$

by subtracting (1) - (2) we obtain:

$$M(0) - M(W_{TS}) = M_{TS}(0) - M_{TS}(W_{TS}) + M'' \; (X_{in}) - M'' \; (X_{ex})$$

Keeping in mind that:

$$M_{TS}(0) = \rho(X_{in}) \; V_{TS}; \; M''(X_{in}) = \rho'' \; (X_{in}) \; V''; \quad M''(X_{ex}) = \rho'' \; (X_{ex})V'';$$

$$\bar{\rho}_{TS} \; (W_{TS}) = \frac{M_{TS} \; (W_{TS})}{V_{TS}}$$

one has:

$$\bar{\rho}_{TS} \; (W_{TS}) = \rho(X_{in}) - \frac{M(0) - M(W_{TS})}{V_{TS}} + \left[\frac{V''}{V_{TS}} \; \rho'' \; (X_{in}) - \rho'' \; (X_{ex}) \right]$$

where $\bar{\rho}_{TS}(W_{TS})$ is the channel average density in correspondence with the heat input W_{TS} (to which an exit quality equal to X_{ex} corresponds).

Thus V' has no influence on results, and the contribution due to M_L is made negligible.

The test section geometry (Fig. 22) at 20 °C is the following:

- inner diameter 0.9 cm

- heated length	200	cm
- heated volume V_{TS}	127.5	cm^3
- adiabatic inlet volume V'	28.5	cm^3
- adiabatic exit volume V"	23.3	cm^3

In this preliminary apparatus $\frac{V'}{V_{TS}}$ and $\frac{V''}{V_{TS}}$ ratios were not reduced to the minimum possible values.

4.3. Preliminary results and errors

After setting up valves, seal and control system, experimental runs at 30 and 50 kg/cm^2 were performed: the results are presented in Tables 28-35 and in $\bar{\rho}_{TS}$ vs. X_{ex} diagrams for constant values of P, G and X_{in} (Figs. 24 - 25). The method has given very good results, with a reproducibility better than 0.01 g/cm^3 (Fig. 26) in the whole range; the closing time of the valves was lower than 0.01 second. The maximum density error of the presented results, which - being preliminary - do not correspond to the best performance of the apparatus, is ± 0.01 g/cm^3 for lower G and ± 0.016 g/cm^3 for high G, while the quality error is $\pm 0.01 \div 0.02$.

The density of the mixture in the exit volume V" has been evaluated, for the calculation of $\bar{\rho}_{TS}$, on the basis of measurements carried out in adiabatic conditions on IDRA plant: the volumes V' and V" have been directly connected and the correspondent density or $(1-\alpha)$, for different values of G, have been measured by using a two-phase two-component mixture, simulating steam-water mixture at a given pressure (Fig. 27).

5. CLOSING REMARKS

It appears from the results obtained that the quick-closing valve technique is quite suitable for mixture density measurements in adiabatic as well as in heated channels, since it gives a sensitivity and an accuracy better than most other techniques (local and global) in the overall range of quality.

This technique can be applied to any experimental plant for two-phase flow studies, without any important modification. No significant difficulty arises in the case of complex geometries such as rod cluster channels.

In the case of heated channels this technique gives only a direct measurement of the overall mass content or of the average density.

Nevertheless any useful information on the density profile along the channel, can be obtained by this technique under the following conditions:

- subcooled void fraction negligible or positive inlet quality;
- heat flux effect, in the positive quality region, significant but not high, as it appears from the very few existing data and also from the analysis of heat flux effect on the entrainment.

We can integrate the density adiabatic profile, obtained under the same conditions of pressure, flowrate, geometry, versus quality, taking as integration limits the inlet and exit quality of the heated channel respectively, and we can compare the average value of density so calculated with the experimental one obtained in heated conditions.

When the two values are not in agreement, a significant heat flux effect is present and it may distributed along the adiabatic density profile, according to tentative criteria, in order to obtain a modified density profile having the same average value as the measured density in heated conditions.

Moreover, by changing the heated length or inlet quality at the same experimental conditions, it is possible to get more information on the heat flux effect and even on the subcooled void fraction.

Obviously this procedure for density profile calculation is approximate but it may give more accurate results than it may be obtained by local void technique, which are generally affected by a greater error with respect to the quick closing valve method.

Nomenclature

A	flow area
F	force
G	total specific mass flowrate
H	specific enthalpy
M	mass hold-up between closed valve
m	piston mass
P	absolute pressure
Q	heat input
s	valve stroke
T	transit time $= \rho \frac{L}{G}$
V	volume
v	specific volume $= 1/\rho$
W	power input
Γ	mass flowrate
Ω	piston cross section
X	mass quality
X_v	volume quality
ρ	density
τ	closing time
τ_o	time at $W_{TS} = 0$

Subscripts

ex	exit
F	friction
g	gas
in	inlet
l	liquid
L	loss
TS	test section

Superscripts

'	inlet adiabatic volume
"	exit adiabatic volume
–	average value

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TABLE A

Geometry	Mixture	Gas density g/cm^3	G $g/cm^2 s$	$1 - X_v$	Table
Round tube I.D. 1.5 cm	water-argon	$36 \cdot 10^{-3}$	$50 \div 250$	$0.01 \div 1$	1
	acetone-argon	$3.46 \cdot 10^{-3} \div 42 \cdot 10^{-3}$	$50 \div 250$	$0.01 \div 1$	5-6-7-8-9-10
	alcohol-argon	$10 \cdot 10^{-3} \div 36 \cdot 10^{-3}$	$50 \div 250$	$0.01 \div 1$	2-3-4
Cluster 19 rods O.D. 1 cm (without filling rods)	water-argon	$3.46 \cdot 10^{-3} \div 36 \cdot 10^{-3}$	$2 \div 100$	$0.01 \div 1$	11-12-13-14-15
	acetone-argon	$10 \cdot 10^{-3} \div 36 \cdot 10^{-3}$	$2 \div 100$	$0.01 \div 1$	16-17-18-19
Cluster 19 rods O.D. 1 cm (with filling rods)	water-argon	$10 \cdot 10^{-3} \div 36 \cdot 10^{-3}$	$2 \div 100$	$0.01 \div 1$	20-21-22-23
	acetone-argon	$10 \cdot 10^{-3} \div 36 \cdot 10^{-3}$	$2 \div 67$	$0.01 \div 1$	24-25-26-27

Element: round tube 1.5 cm. I.D.
Gas phase: argon
Adiabatic conditions

TABLE 1

Liquid phase: water
ρ_g = 36×10^{-3} g/cm³
t. 18 ℃
P_v 21.7 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.035	0.50	0.625	1.688
	0.098	0.25	0.432	2.268
	0.172	0.15	0.321	2.674
	0.245	0.10	0.243	2.877
	0.400	0.05	0.153	3.42
	0.540	0.03	0.1020	2.70
	0.780	0.01	0.045	4.49
100	0.0155	0.70	0.760	1.357
	0.0625	0.35	0.497	1.845
	0.172	0.15	0.293	2.339
	0.245	0.10	0.229	2.68
	0.320	0.07	0.183	2.962
	0.540	0.03	0.0886	3.15
	0.780	0.01	0.031	3.065
200	0.00765	0.83	0.84	1.074
	0.0155	0.70	0.71	1.048
	0.035	0.50	0.574	1.347
	0.0635	0.35	0.48	1.715
	0.098	0.25	0.389	1.913
	0.172	0.15	0.2525	2.016
	0.245	0.10	0.189	2.1
	0.320	0.07	0.1455	2.26
	0.400	0.05	0.104	2.194
	0.540	0.03	0.06	2.063
	0.665	0.018	0.036	2.039
	0.780	0.01	0.0215	2.035
250	0.0765	0.83	0.858	1.255
	0.035	0.50	0.571	1.326
	0.098	0.25	0.376	1.816
	0.245	0.10	0.1715	1.88
	0.400	0.05	0.0876	1.826
	0.540	0.03	0.0534	1.816
	0.780	0.01	0.0197	1.99

TABLE 2

Liquid phase: alcohol
ρ_g = 10×10^{-3} g/cm³
t. 18 ℃
P. 6.15 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
100	0.01245	0.50	0.59	1.44
	0.0185	0.40	0.53	1.69
	0.0479	0.20	0.348	2.14
	0.1016	0.10	0.216	2.48
	0.143	0.07	0.16	2.53
	0.193	0.05	0.126	2.74
	0.232	0.04	0.0955	2.32
	0.289	0.03	0.055	1.79
	0.329	0.025	0.031	1.21
	0.381	0.02	0.015	0.865
	0.554	0.01	0.0075	0.75
200	0.01245	0.50	0.562	1.28
	0.0185	0.40	0.495	1.47
	0.0479	0.20	0.293	1.66
	0.1016	0.10	0.188	2.08
	0.143	0.07	0.131	2.00
	0.193	0.05	0.0764	1.57
	0.232	0.04	0.0432	1.08
	0.289	0.03	0.0225	0.744

TABLE 3

Liquid phase: alcohol
ρ_g = 18.8×10^{-3} g/cm³
t. 19 ℃
P. 11.6 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
100	0.01325	0.65	0.702	1.26
	0.035	0.40	0.518	1.61
	0.086	0.20	0.341	2.07
	0.175	0.10	0.200	2.25
	0.24	0.07	0.1417	2.19
	0.318	0.05	0.0846	1.76
	0.373	0.04	0.0528	1.33
	0.442	0.03	0.0255	0.85
	0.54	0.02	0.017	0.85
	0.70	0.07	0.1417	2.19
200	0.01	0.70	0.770	1.22
	0.035	0.40	0.47	1.33
	0.086	0.20	0.38	1.56
	0.175	0.10	0.16	1.71
	0.24	0.07	0.096	1.41
	0.275	0.06	0.0612	1.092
	0.318	[illegible]	0.032	0.75
	0.54	0.02	0.015	0.80
	0.70	0.01	0.026	[illegible]

TABLE 4

Liquid phase: Alcohol
ρ_g = 36×10^{-3} g/cm³
t. 18 ℃
P. 21.7 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.035	0.56	0.61	1.23
	0.098	0.30	0.46	1.99
	0.172	0.185	0.33	1.905
	0.245	0.125	0.248	2.31
	0.40	0.063	0.143	2.48
	0.54	0.0375	0.073	2.02
	0.78	0.0125	0.025	2.03
100	0.0155	0.76	0.746	0.93
	0.0625	0.41	0.53	1.62
	0.172	0.185	0.293	1.82
	0.245	0.125	0.220	1.97
	0.32	0.088	0.151	1.84
	0.54	0.0375	0.0432	1.16
	0.78	0.0125	0.011	0.89
	0.665	0.022	0.02	0.91
200	0.0155	0.76	0.763	1.07
	0.035	0.56	0.596	1.16
	0.0625	0.41	0.473	1.29
	0.098	0.30	0.369	1.37
	0.172	0.185	0.23	1.92
	0.245	0.125	0.1597	1.37
	0.32	0.088	0.099	1.14
	0.40	0.063	0.0565	0.89
	0.54	0.0375	0.02	0.70
	0.665	0.022	0.017	[illegible]
	0.78	0.0125	0.01	0.79
250	0.035	0.56	0.592	1.14
	0.098	0.30	0.35	1.26
	0.245	0.125	0.15	1.24
	0.40	0.063	0.052	0.815
	0.54	0.0375	0.03	0.734
	0.78	0.0125	0.009	[illegible]

Element: round tube 1.5 cm I.D.
Gas phase: argon
Adiabatic conditions

TABLE 5

Liquid phase: acetone
S_g = 3.46×10^{-2} g/cm³
T = 18 °C
P = 2.14 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.0166	0.203	0.40	2.62
50	0.040	0.095	0.261	3.37
50	0.0644	0.060	0.203	3.99
50	0.095	0.040	0.146	4.17
50	0.177	0.020	0.088	4.79
50	0.30	0.010	0.047	8.78
100	0.00549	0.435	0.568	1.71
100	0.0082	0.34	0.466	1.83
100	0.0168	0.203	0.36	2.21
100	0.031	0.120	0.24	2.31
100	0.05	0.076	0.180	2.67
100	0.09	0.042	0.125	3.26
200	0.00374	0.53	0.618	1.43
200	0.0055	0.44	0.532	1.45
200	0.00833	0.340	0.445	1.56
200	0.0165	0.205	0.31	1.74

TABLE 6

Liquid phase: Acetone
S_g = 10×10^{-3} g/cm³
T = 18 °C
P = 6.15 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.0479	0.20	0.373	2.38
	0.1016	0.10	0.233	2.74
	0.143	0.07	0.190	3.11
	0.193	0.05	0.152	3.40
	0.289	0.03	0.105	3.79
	0.381	0.02	0.078	8.05
	0.554	0.01	0.0385	3.96
100	0.01245	0.50	0.552	1.23
	0.0185	0.40	0.478	1.37
	0.0479	0.20	0.32	1.88
	0.1016	0.10	0.20	2.25
	0.143	0.07	0.153	2.40
	0.193	0.05	0.118	2.54
	0.289	0.03	0.076	2.66
	0.381	0.02	0.044	2.26
	0.554	0.01	0.0185	1.87
200	0.00623	0.663	0.70	1.19
	0.01245	0.50	0.54	1.17
	0.0185	0.40	0.455	1.25
	0.0479	0.20	0.276	1.54
	0.1016	0.10	0.165	1.76
	0.143	0.07	0.1275	1.94
	0.193	0.05	0.09	1.88

TABLE 7

Liquid phase: Acetone
S_g = 18.8×10^{-3} g/cm³
T = 18 °C
P = 11.6 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.035	0.40	0.50	1.
	0.086	0.20	0.36	2.
	0.175	0.10	0.227	2.
	0.24	0.07	0.1748	2.
	0.316	0.05	0.139	3.
	0.54	0.02	0.0686	3.
	0.70	0.01	0.036	3.7
100	0.01325	0.65	0.655	1.0
	0.035	0.40	0.468	1.3
	0.086	0.20	0.310	1.8
	0.175	0.10	0.185	2.0
	0.24	0.07	0.135	2.0
	0.318	0.05	0.0995	2.1
	0.54	0.02	0.036	1.8
	0.70	0.01	0.017	1.7
200	0.035	0.40	0.43	1.
	0.01	0.70	0.715	1.0
	0.086	0.20	0.2575	1.3
	0.175	0.10	0.15	1.5
	0.240	0.07	0.108	1.6
	0.318	0.05	0.074	1.5
	0.54	0.02	0.025	1.2
	0.70	0.01	0.0125	1.2

TABLE 8

Liquid phase: acetone
S_g = 25.9×10^{-3} g/cm³
T = 18 °C
P = 15.8 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.03	0.512	0.572	1.27
	0.06	0.3375	0.445	1.58
	0.10	0.2265	0.368	1.99
	0.25	0.0888	0.20	2.56
	0.40	0.0465	0.125	2.93
	0.60	0.0212	0.064	3.16
	0.80	0.00806	0.027	3.42
100	0.01	0.763	0.790	1.17
	0.03	0.512	0.554	1.18
	0.06	0.3375	0.420	1.42
	0.10	0.2265	0.332	1.70
	0.25	0.0888	0.160	1.15
	0.40	0.0465	0.09	2.03
	0.60	0.0212	0.035	1.72
	0.80	0.00806	0.0138	1.72
200	0.01	0.763	0.765	1.01
	0.03	0.512	0.54	1.12
	0.06	0.3375	0.37	1.15
	0.10	0.2265	0.27	1.26
	0.25	0.0888	0.121	1.41
	0.40	0.0465	0.051	1.33
	0.60	0.0212	0.024	1.13
	0.80	0.00806	0.0095	1.18

TABLE 9

Liquid phase: acetone
S_g = 36×10^{-3} g/cm³
T = 18 °C
P = 21.7 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.035	0.56	0.58	1.08
	0.098	0.30	0.42	1.69
	0.172	0.185	0.319	2.06
	0.245	0.125	0.248	2.31
	0.400	0.063	0.155	2.73
	0.540	0.0375	0.094	2.66
	0.780	0.0125	0.037	3.04
100	0.0155	0.76	0.76	1.00
	0.0625	0.41	0.485	1.38
	0.172	0.185	0.280	1.71
	0.32	0.088	0.156	2.09
	0.54	0.0375	0.0617	1.69
	0.78	0.0125	0.020	1.61
	0.665	0.022	0.0365	1.69
	0.245	0.125	0.209	1.85
200	0.0155	0.76	0.76	1.00
	0.035	0.56	0.568	1.03
	0.0625	0.41	0.432	1.095
	0.098	0.30	0.34	1.20
	0.172	0.185	0.227	1.29
	0.245	0.125	0.16	1.33
	0.32	0.088	0.115	1.35
	0.40	0.063	0.0766	1.27
	0.54	0.022	0.0252	1.15
	0.78	0.0125	0.0161	1.29
250	0.035	0.56	0.575	1.06
	0.098	0.30	0.337	1.19
	0.245	0.125	0.1525	1.26
	0.40	0.063	0.0755	1.21
	0.54	0.0375	0.035	1.04
	0.78	0.0125	0.0125	1.00

TABLE 10

Liquid phase: acetone
S_g = 42×10^{-3} g/cm³
T = 18 °C
P = 25.5 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
g/cm² s				
50	0.03	0.63	0.67	1.19
	0.06	0.452	0.526	1.35
	0.10	0.322	0.445	1.69
	0.25	0.1365	0.265	2.27
	0.40	0.0758	0.167	2.44
	0.60	0.0339	0.0828	2.57
	0.80	0.013	0.035	2.75
	0.15	0.23	0.375	2.01
100	0.03	0.63	0.64	1.04
	0.06	0.452	0.508	1.25
	0.10	0.322	0.41	1.47
	0.25	0.1365	0.223	1.82
	0.40	0.0756	0.124	1.73
	0.60	0.0339	0.053	1.59
	0.60	0.013	0.0185	1.44
	0.15	0.23	0.328	1.63
200	0.01	0.84	0.842	1.01
	0.03	0.63	0.64	1.04
	0.06	0.452	0.478	1.11
	0.10	0.322	0.365	1.21
	0.25	0.1365	0.173	1.32
	0.40	0.0756	0.09	1.21
	0.60	0.0339	0.037	1.09
	0.80	0.013	0.0145	1.12
	0.15	0.23	0.278	1.21

Element: cluster 19 rods O.D. 1 cm.
Gas phase: argon
Adiabatic conditions

TABLE 11

Liquid phase: water
γ_g = 3.46x10^{-3} g/cm³
t = 18 °C
P = 3.11 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
$g/cm^2 s$				
5	0.06	0.0515	[illegible]	11.02
	0.10	0.0303	[illegible]	[illegible]
	0.20	0.0137	0.205	18.57
	0.40	0.00515	0.128	26.34
	0.60	0.0023	0.094	35.02
10	0.02	0.101	0.41	6.19
	0.06	0.0515	0.31	8.28
	0.10	0.0303	0.24	10.11
	0.20	0.0137	0.156	13.30
	0.40	0.00515	0.097	21.38
	0.60	0.0023	0.068	31.66
20	0.01	0.235	0.535	3.26
	0.003	0.101	0.358	4.96
	0.06	0.0515	0.253	6.25
	0.10	0.0303	0.199	7.42
	0.20	0.0137	0.133	10.30

TABLE 12

Liquid phase: water
γ_g = 10x10^{-3} g/cm³
t = 18 °C
P = 6.15 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
$g/cm^2 s$				
5	0.03	0.247	0.608	4.73
	0.06	0.134	0.502	6.52
	0.10	0.082	0.419	8.07
	0.20	0.038	0.308	11.27
	0.40	0.0147	0.202	16.98
	0.60	0.0064	0.141	27.19
10	0.015	0.40	0.66	2.91
	0.03	0.247	0.55	3.73
	0.06	0.134	0.43	4.88
	0.10	0.082	0.35	6.03
	0.20	0.038	0.238	7.90
	0.40	0.0147	0.145	11.36
	0.60	0.0064	0.098	16.88
	0.80	0.0025	0.065	27.72
20	0.01	0.50	0.684	2.17
	0.03	0.247	0.485	2.87
	0.06	0.134	0.38	3.96
	0.10	0.082	0.292	4.62
	0.20	0.038	0.194	6.10
	0.40	0.0147	0.116	8.80
	0.60	0.0064	0.083	14.06
50	0.005	0.66	0.757	1.60
	0.01	0.50	0.647	1.83
	0.03	0.247	0.444	2.43
	0.06	0.134	0.326	3.13
	0.10	0.082	0.25	3.73
	0.20	0.038	0.163	4.93
75	0.005	0.66	0.752	1.56
	0.01	0.50	0.64	1.78
	0.30	0.247	0.43	2.30
	0.06	0.134	0.312	2.93
	0.10	0.082	0.232	3.38

TABLE 13

Liquid phase: water
γ_g = 18.8x10^{-3} g/cm³
t = 18 °C
P = 11.6 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
$g/cm^2 s$				
5	0.04	0.315	0.65	4.03
	0.06	0.23	0.562	4.29
	0.10	0.145	0.474	5.31
	0.20	0.07	0.355	7.31
	0.40	0.0275	0.26	12.42
	0.60	0.0127	0.134	17.52
10	0.03	0.385	0.622	2.63
	0.06	0.23	0.50	3.14
	0.10	0.145	0.407	4.05
	0.20	0.07	0.302	6.60
	0.40	0.0275	0.181	7.81
	0.60	0.0127	0.13	11.61
20	0.01	0.66	0.78	1.83
	0.03	0.385	0.592	2.34
	0.06	0.23	0.45	2.74
	0.10	0.145	0.366	3.40
	0.20	0.07	0.248	4.38
	0.40	0.0275	0.152	6.33
	0.60	0.0127	0.105	9.12
50	0.01	0.66	0.745	1.50
	0.024	0.445	0.60	1.98
	0.03	0.385	0.545	1.91
	0.06	0.23	0.405	2.28
	0.10	0.145	0.222	3.02
	0.20	0.07	0.21	3.53
	0.40	0.0275	0.127	5.14
	0.60	0.0127	0.082	6.95
75	0.01	0.66	0.713	1.28
	0.03	0.389	0.524	1.76
	0.06	0.23	0.40	2.23
	0.10	0.145	0.31	2.65
	0.20	0.07	0.195	3.62

TABLE 14

Liquid phase: water
γ_g = 25.9x10^{-3} g/cm³
t = 18 °C
P = 15.8 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
$g/cm^2 s$				
2	0.305	0.132	0.60	9.10
	[illegible]	[illegible]	[illegible]	11.81
5	0.06	0.29	0.615	3.86
	0.10	0.169	0.438	5.00
	0.20	0.094	0.315	6.85
	0.40	0.0324	[illegible]	11.36
	0.60	0.017	0.094	16.09
10	0.03	0.46	0.59	2.66
	0.06	0.29	0.45	2.99
	0.10	0.169	0.37	3.28
	0.20	0.094	0.342	4.21
	0.40	0.0324	0.227	7.57
	0.60	0.017	0.151	10.28
20	0.015	0.61	0.72	1.97
	0.03	0.46	0.643	2.15
	0.06	0.29	0.488	2.52
	0.10	0.169	0.41	2.96
	0.20	0.094	0.292	3.79
	0.40	0.0324	0.169	5.22
	0.60	0.017	0.114	7.60
50	0.01	[illegible]	0.292	[illegible]
	0.03	[illegible]	0.592	1.73
	0.06	0.29	0.462	2.10
	0.10	[illegible]	0.306	2.51
	0.20	[illegible]	0.293	3.36
	0.40	0.0324	[illegible]	[illegible]
	0.60	0.017	0.105	6.76
75	0.01	[illegible]	[illegible]	[illegible]
	0.03	[illegible]	0.589	1.56
	0.06	[illegible]	0.444	[illegible]
	0.10	[illegible]	[illegible]	2.32
	0.20	[illegible]	[illegible]	2.65

TABLE 15

Liquid phase: water
γ_g = 26x10^{-3} g/cm³
t = 18 °C
P = 21.7 Kg/cm²

G	X	$1-X_v$	$1-\alpha$	S
$g/cm^2 s$				
5	0.06	0.36	0.60	3.95
	0.10	0.245	0.596	4.56
	0.20	0.127	0.46	5.85
	0.40	0.05	0.345	10.00
	0.60	0.0235	0.258	14.45
10	0.03	0.51	0.77	2.65
	0.06	0.36	0.612	2.81
	0.10	0.249	0.52	3.31
	0.20	0.132	0.388	4.35
	0.40	0.05	0.26	6.68
	0.60	0.0235	0.163	9.30
	0.80	0.009	0.128	16.17
20	0.015	0.71	0.84	2.14
	0.03	0.54	0.72	2.19
	0.60	0.36	0.575	2.41
	0.10	0.245	0.455	2.57
	0.20	0.127	[illegible]	3.35
	0.40	0.05	0.209	5.02
	0.60	0.0235	0.14	6.95
	0.80	0.009	0.095	11.55
50	0.01	0.78	0.854	1.65
	0.03	0.51	0.626	1.79
	0.06	0.36	0.529	2.10
	0.10	0.245	0.40	2.94
	0.20	0.127	0.355	4.10
	0.40	0.0235	0.192	5.28
100	0.01	0.78	0.90	[illegible]
	0.03	0.51	0.654	1.41
	0.06	0.36	0.5	1.54
	0.10	0.245	0.331	2.15
	0.20	0.127	0.279	2.45

Element : cluster 19 rods O.D. 1 cm.
Gas phase : argon
Adiabatic conditions

TABLE 16

Liquid phase: acetone

S_g = 10x10^{-3} g/cm³

T. 18 ℃

P. 6.15 Kg/cm²

G g/cm²s	X	$1-X_v$	$1-\alpha$	S
10	0.012	0.50	0.73	2.70
	0.06	0.165	0.465	4.40
	0.12	0.084	0.33	5.37
	0.40	0.0185	0.155	9.73
20	0.006	0.675	0.835	2.44
	0.01	0.56	0.745	2.29
	0.03	0.29	0.53	2.76
	0.06	0.165	0.395	3.30
	0.10	0.1025	0.302	3.79
	0.20	0.048	0.193	4.74
	0.40	0.0185	0.115	6.81
	0.60	0.0083	0.079	10.25
50	0.003	0.81	0.89	1.90
	0.006	0.675	0.785	1.76
	0.01	0.56	0.71	1.92
	0.03	0.29	0.478	2.24
	0.06	0.165	0.344	2.65
	0.10	0.1025	0.258	3.05
	0.20	0.048	0.168	4.00
	0.40	0.0185	0.096	6.15
75	0.01	0.56	0.69	1.75
	0.03	0.29	0.457	2.06
	0.06	0.165	0.334	2.54
	0.10	0.1025	0.248	2.89

TABLE 17

Liquid phase: acetone

S_g = 18.8x10^{-3} g/cm³

T. 18 ℃

P. 11.6 Kg/cm²

G g/cm²s	X	$1-X_v$	$1-\alpha$	S
20	0.01	0.70	0.825	2.02
	0.03	0.44	0.63	2.17
	0.06	0.27	0.49	2.60
	0.10	0.175	0.382	2.91
	0.20	0.086	0.257	3.68
	0.40	0.036	0.155	4.91
	0.60	0.016	0.101	6.91
	0.70	0.01	0.077	8.35
50	0.01	0.70	0.78	1.52
	0.03	0.44	0.585	1.80
	0.06	0.27	0.44	2.12
	0.10	0.175	0.337	2.40
	0.20	0.086	0.226	3.10
	0.40	0.036	0.13	4.00
	0.60	0.016	0.078	5.20
75	0.01	0.7	0.765	1.40
	0.03	0.44	0.565	1.65
	0.06	0.27	0.418	1.94
	0.10	0.175	0.32	2.22
	0.20	0.086	0.211	2.84
	0.40	0.036	0.122	3.72
	0.50	0.024	0.092	4.12

TABLE 18

Liquid phase: acetone

S_g = 25.9x10^{-3} g/cm³

T. 18 ℃

P. 15.8 Kg/cm²

G g/cm²s	X	$1-X_v$	$1-\alpha$	S
2	0.125	0.183	0.61	6.98
	0.25	0.087	0.51	9.13
5	0.05	0.38	0.66	3.17
	0.08	0.27	0.585	3.81
	0.10	0.225	0.545	4.21
	0.20	0.1125	0.425	5.84
	0.40	0.0465	0.265	7.39
	0.60	0.0212	0.186	10.56
	0.70	0.0135	0.160	13.91
10	0.03	0.51	0.715	2.41
	0.06	0.335	0.585	2.80
	0.10	0.225	0.475	3.11
	0.20	0.1125	0.36	4.44
	0.40	0.0465	0.205	5.29
	0.60	0.0212	0.131	3.51
	0.80	0.008	0.078	10.49
20	0.015	0.68	0.785	1.72
	0.03	0.51	0.68	2.04
	0.06	0.335	0.536	2.53
	0.10	0.225	0.42	2.49
	0.20	0.1125	0.258	3.35
	0.40	0.0465	0.168	4.14
	0.60	0.0212	0.109	5.65
	0.80	0.008	0.062	8.20
50	0.01	0.77	0.86	1.84
	0.03	0.51	0.635	1.67
	0.06	0.335	0.456	2.16
	0.10	0.225	0.375	2.07
	0.20	0.1125	0.255	2.70
	0.40	0.0465	0.149	3.59
	0.60	0.0212	0.085	4.29
	0.80	0.008	0.0535	7.01
100	0.20	0.1125	0.235	2.43
	0.30	[illegible]	0.172	2.80

TABLE 19

Liquid phase: acetone

S_g = 36x10^{-3} g/cm³

T. 18 ℃

P. 21.7 Kg/cm²

G g/cm²s	X	$1-X_v$	$1-\alpha$	S
10	0.03	0.6	0.765	2.17
	0.06	0.42	0.63	2.35
	0.10	0.295	0.53	2.69
	0.20	0.158	0.39	3.41
	0.40	0.064	0.237	4.54
	0.60	0.03	0.155	5.93
20	0.015	0.76	0.86	1.94
	0.030	0.60	0.736	1.86
	0.060	0.42	0.595	2.03
	0.10	0.295	0.48	2.21
	0.20	0.158	0.328	2.28
	0.40	0.064	0.198	3.61
	0.60	0.030	0.125	4.62
	0.80	0.012	0.074	6.58
50	0.03	0.60	0.705	1.59
	0.06	0.42	0.55	1.69
	0.10	0.295	0.44	1.88
	0.20	0.158	0.30	2.28
	0.40	0.064	0.173	3.06
	0.60	0.03	0.102	3.67
	0.80	0.012	0.054	4.70
100	0.15	0.21	0.33	1.85
	0.20	0.158	0.28	2.07
	0.30	0.097	0.204	2.38
	0.40	0.064	0.155	2.68
	0.50	0.0435	0.11	2.72
	0.60	0.03	0.065	3.00

Element: cluster 19 rods O.D. 1 cm. with filling rods
Gas phase: argon
Adiabatic conditions

TABLE 20

Liquid phase: Water
ρ_g = 10x10^{-3} g/cm³
t. 18 °C
P. 6.1 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
[illegible]	0.01	0.5	0.720	3.33
	0.03	0.247	0.508	3.24
	0.06	0.134	0.391	4.15
	0.10	0.082	0.310	5.03
	0.20	0.036	0.220	7.14
	0.40	0.0147	0.144	11.28
[illegible].1	0.005	0.66	0.793	1.75
	0.01	0.50	0.652	1.87
	0.03	0.247	0.465	2.45
	0.06	0.134	0.350	3.40
	0.10	0.082	0.275	4.25

TABLE 21

Liquid phase: Water
ρ_g = 16.8x10^{-3} g/cm³
t. 18 °C
P. 11.6 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
[illegible]	0.01	0.58	0.750	1.87
	0.03	0.365	0.600	2.30
	0.06	0.23	0.450	2.92
	0.10	0.143	0.342	3.67
	0.20	0.07	0.245	5.31
	0.40	0.0275	0.150	6.24

TABLE 22

Liquid phase: Water
ρ_g = 25.[illegible]x10^{-3} g/cm³
t. 18 °C
P. [illegible] Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
0.68	0.125	0.152	0.30	5.36
	0.250	0.072	0.40	[illegible]
6.1[illegible]	0.06	0.29	0.43	4.17
	0.10	0.189	0.375	3.68
	0.20	0.094	0.335	4.86
	0.40	0.0374	0.267	9.36
	0.60	0.017	0.20	14.46
	0.70	0.011	0.16	19.73
67.1	0.01	0.72	0.830	1.90
	0.03	0.456	0.608	1.85
	0.06	0.29	0.475	2.22
	0.10	0.169	0.383	2.66
	0.20	0.094	0.268	3.53
	0.40	0.0374	0.178	5.19
	0.60	0.017	0.103	6.64

TABLE 23

Liquid phase: Water
ρ_g = 36x10^{-3} g/cm³
t. 18 °C
P. 21.7 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
13.42	0.03	0.54	0.75	3.02
	0.06	0.36	0.61	2.78
	0.10	0.245	0.49	2.96
	0.20	0.127	0.353	3.73
	0.40	0.05	0.274	7.17
	0.60	0.0235	0.190	9.75
	0.80	0.009	0.15	19.43
67.10	0.01	0.78	0.85	1.60
	0.03	0.54	0.674	1.76
	0.06	0.36	0.53	2.00
	0.10	0.245	0.42	2.23
	0.20	0.127	0.307	3.03
	0.40	0.05	0.195	[illegible]
	0.60	0.0235	0.135	[illegible].19
101	0.01	0.78	0.825	1.43
	0.03	0.54	0.70	1.65
	0.06	0.36	0.51	1.85
	0.10	0.245	0.408	2.12
	0.20	0.127	[illegible]	[illegible]

TABLE 24

Liquid phase: Acetone
ρ_g = 10x10^{-3} g/cm³
t. 18 °C
P. 6.19 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
26.85	0.006	0.675	0.856	3.21
	0.03	0.29	0.54	3.28
	0.06	0.165	0.40	3.37
	0.10	0.1025	0.33	3.93
	0.20	0.048	0.218	5.53
	0.40	0.0165	0.120	7.93
67.1	0.003	0.81	0.91	2.37
	0.01	0.56	0.72	2.02
	0.03	0.29	0.49	2.19
	0.06	0.165	0.363	2.[illegible]
	0.10	0.1025	0.274	3.39

TABLE 25

Liquid phase: Acetone
ρ_g = 18.8x10^{-3} g/cm³
t. 18 °C
P. 11.6 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
67.1	0.01	0.70	0.805	1.77
	0.03	0.44	0.564	1.72
	0.06	0.27	0.447	1.89
	0.10	0.175	0.357	2.[illegible]
	0.20	0.086	0.215	3.[illegible]
	0.40	0.036	0.14	4.36

TABLE 26

Liquid phase: [illegible]
ρ_g = 25.[illegible]x10^{-3} g/cm³
t. 18 °C
P. [illegible].6 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	0.504	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	3.01
	[illegible]	[illegible]	0.54	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible].12	[illegible]	[illegible]

TABLE 27

Liquid phase: Acetone
ρ_g = 16x10^{-3} g/cm³
t. 18 °C
P. 21.7 Kg/cm²

G	X	1-X_v	1-α	S
g/cm² s				
13.43	0.01	[illegible]	[illegible]	[illegible]
	0.10	[illegible]	[illegible]	[illegible]
	0.20	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
67.1	0.03	[illegible]	[illegible]	[illegible]
	0.10	[illegible]	[illegible]	[illegible]
	0.20	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]

Element : round tube 0.9 cm. I.D.
Mixture : steam-water
Heated length : 200 cm.

TABLE 28
P. 30 Kg/cm²
G. 70 g/cm²s
Xin. - 2,5 %

X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.013	0.721	5.39
0.040	0.625	9.23
0.089	0.469	16.18
0.132	0.387	22.29
0.187	0.333	30.10
0.242	0.291	37.91
0.323	0.245	49.41
0.400	0.209	60.35
0.406	0.219	61.20
0.490	0.194	73.13
0.570	0.181	84.49
0.663	0.160	97.69
0.717	0.146	105.86
0.748	0.139	109.76

TABLE 29
P. 30 Kg/cm²
G. 110 g/cm²s
Xin. - 2.3 %

X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.012	0.721	7.80
0.037	0.605	13.38
0.065	0.504	19.62
0.115	0.405	30.77
0.240	0.300	58.64
0.255	0.282	61.99
0.280	0.261	67.56
0.293	0.258	70.46
0.355	0.225	84.29
0.394	0.201	95.22
0.416	0.196	97.89
0.477	0.176	111.50
0.493	0.174	115.06
0.539	0.163	125.32
0.549	0.172	127.55

TABLE 30
P. 30 Kg/cm²
G. 220 g/cm²s
Xin. - 15 %

X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.012	0.839	72.09
0.048	0.772	92.56
0.085	0.680	104.57
0.089	0.678	106.35
0.127	0.609	123.26
0.138	0.592	128.16
0.165	0.545	140.17

TABLE 31
P. 30 Kg/cm
G. 220 g/cm
Xin. - 2 %

X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.000	0.820	8.90
0.007	0.793	12.01
0.019	0.712	16.46
0.035	0.624	24.47
0.052	0.559	32.04
0.077	0.484	43.16
0.112	0.419	58.74
0.150	0.366	75.65
0.183	0.331	90.33
0.217	0.292	105.46
0.251	0.263	120.59

TABLE 32
P. 50 Kg/cm²
G. 70 g/cm²s
Xin. - 2.5 %

X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.018	0.704	5.54
0.076	0.548	13.02
0.125	0.455	19.35
0.191	0.390	27.86
0.285	0.315	39.99
0.386	0.269	53.01
0.452	0.247	61.53
0.484	0.237	65.66
0.573	0.207	77.14
0.671	0.185	89.78
0.740	0.175	98.68

TABLE 33
P. 50 Kg/cm²
G. 110 g/cm²s
Xin. - 2.3 %

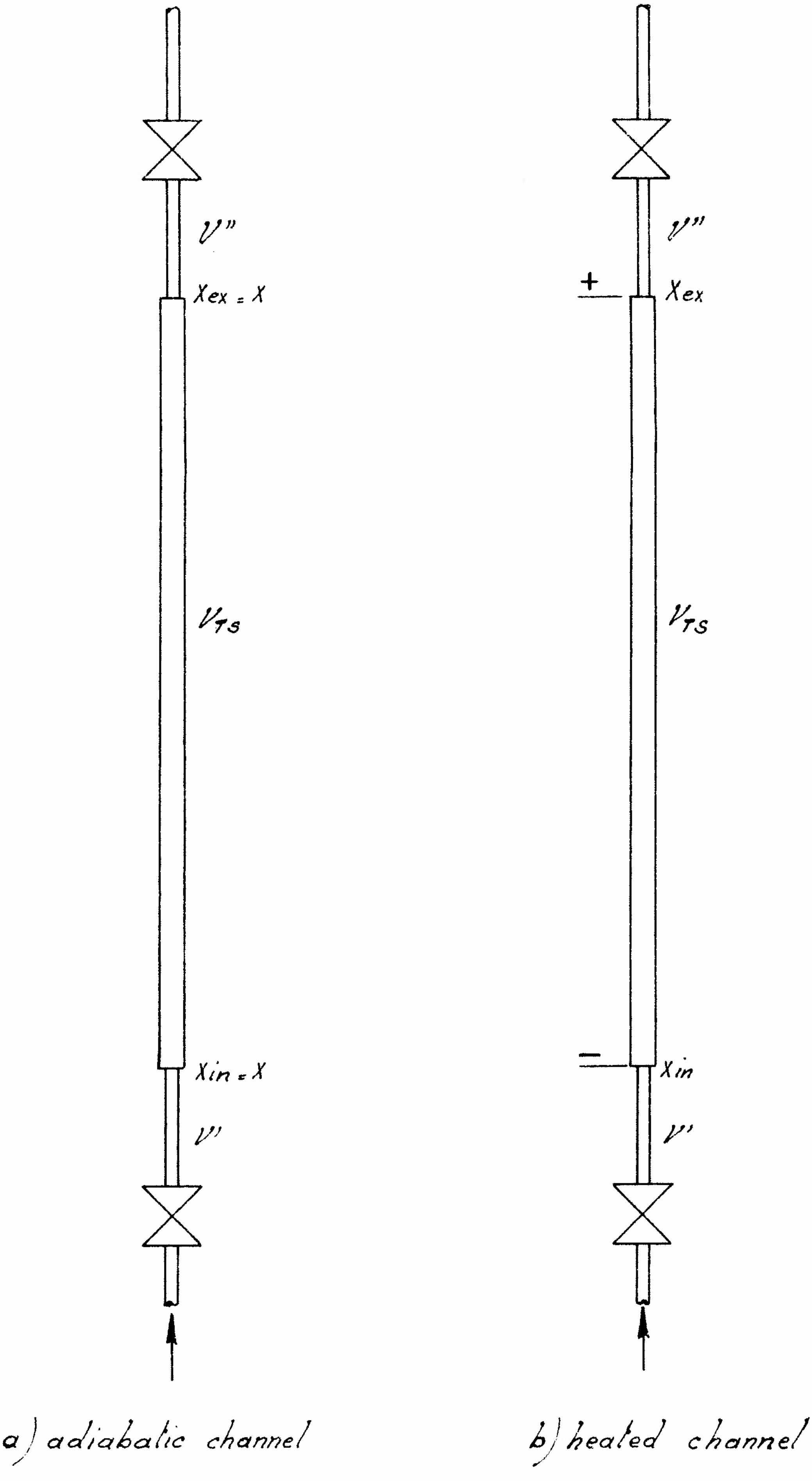
X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.000	0.790	4.69
0.028	0.683	10.40
0.054	0.582	15.70
0.086	0.522	22.23
0.137	0.435	32.64
0.185	0.382	42.43
0.239	0.345	53.44
0.310	0.303	67.93
0.363	0.269	78.74
0.438	0.251	94.04
0.500	0.228	106.69
0.571	0.201	121.17

TABLE 34
P. 50 Kg/cm²
G. 220 g/cm²s
Xin. - 15 %

X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.029	0.772	72.85
0.029	0.770	72.85
0.069	0.693	89.13
0.073	0.683	90.76
0.117	0.618	108.66
0.174	0.547	131.86
0.235	0.483	156.69
0.292	0.436	179.89
0.333	0.404	196.58
0.372	0.377	212.45

TABLE 35
P. 50 Kg/cm
G. 220 g/cm
Xin. - 2 %

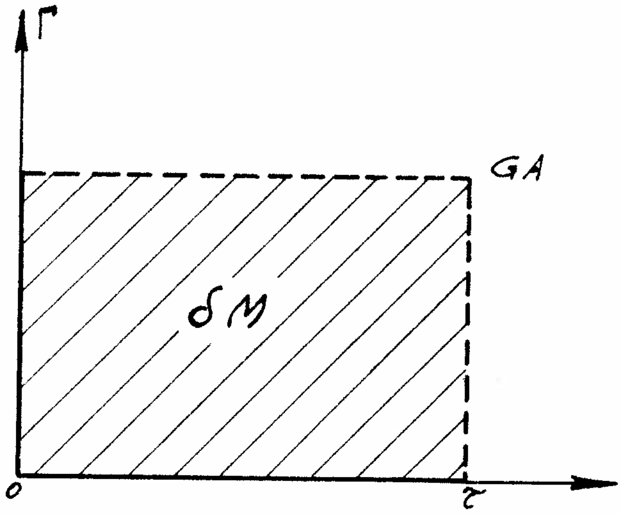
X_{ex}	$\bar{\xi}_{TS}$	ϕ
	g/cm³	W/cm²
0.005	0.767	10.17
0.021	0.694	16.68
0.030	0.662	20.35
0.052	0.585	29.30
0.055	0.570	30.52
0.074	0.530	38.25
0.077	0.514	39.47
0.105	0.466	50.87
0.105	0.468	50.87
0.109	0.450	52.50
0.110	0.449	52.91
0.112	0.451	53.72
0.131	0.421	61.45
0.145	0.400	67.15
0.158	0.395	72.44
0.171	0.388	77.73
0.176	0.378	79.77
0.190	0.363	85.47
0.228	0.325	100.93
0.247	0.313	108.66
0.260	0.306	113.96
0.265	0.307	115.99
0.306	0.284	132.68
0.330	0.273	142.45
0.334	0.264	144.07
0.357	0.261	153.43
0.362	0.257	155.47
0.369	0.242	169.31
0.393	0.237	168.09



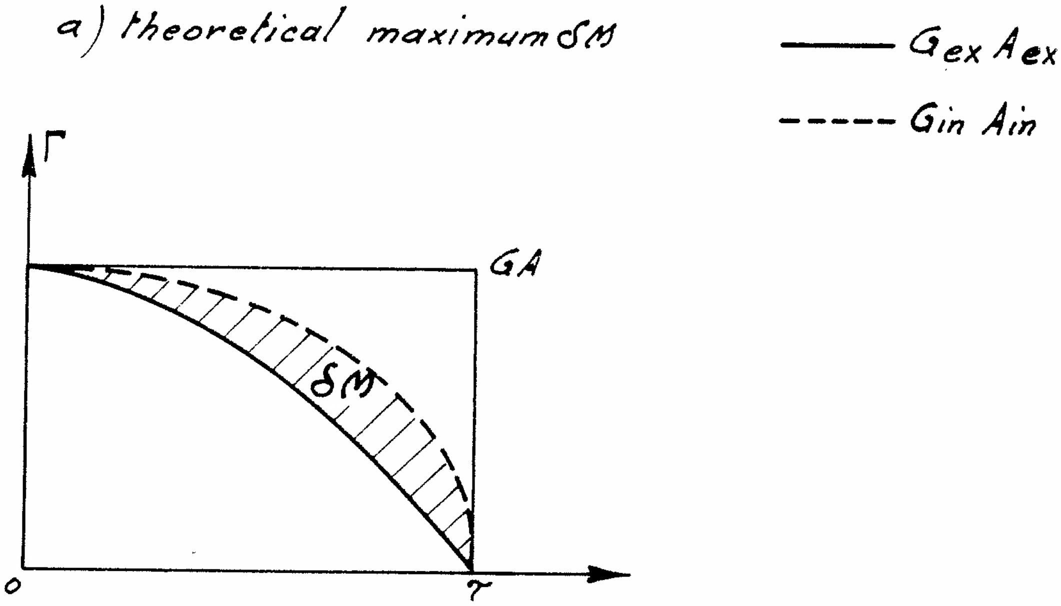
a) adiabatic channel

b) heated channel

Fig. 1 - Sketch of channel configurations.



a) theoretical maximum δM



b) actual δM

Fig. 2 - Flowrate transients during the closing time.

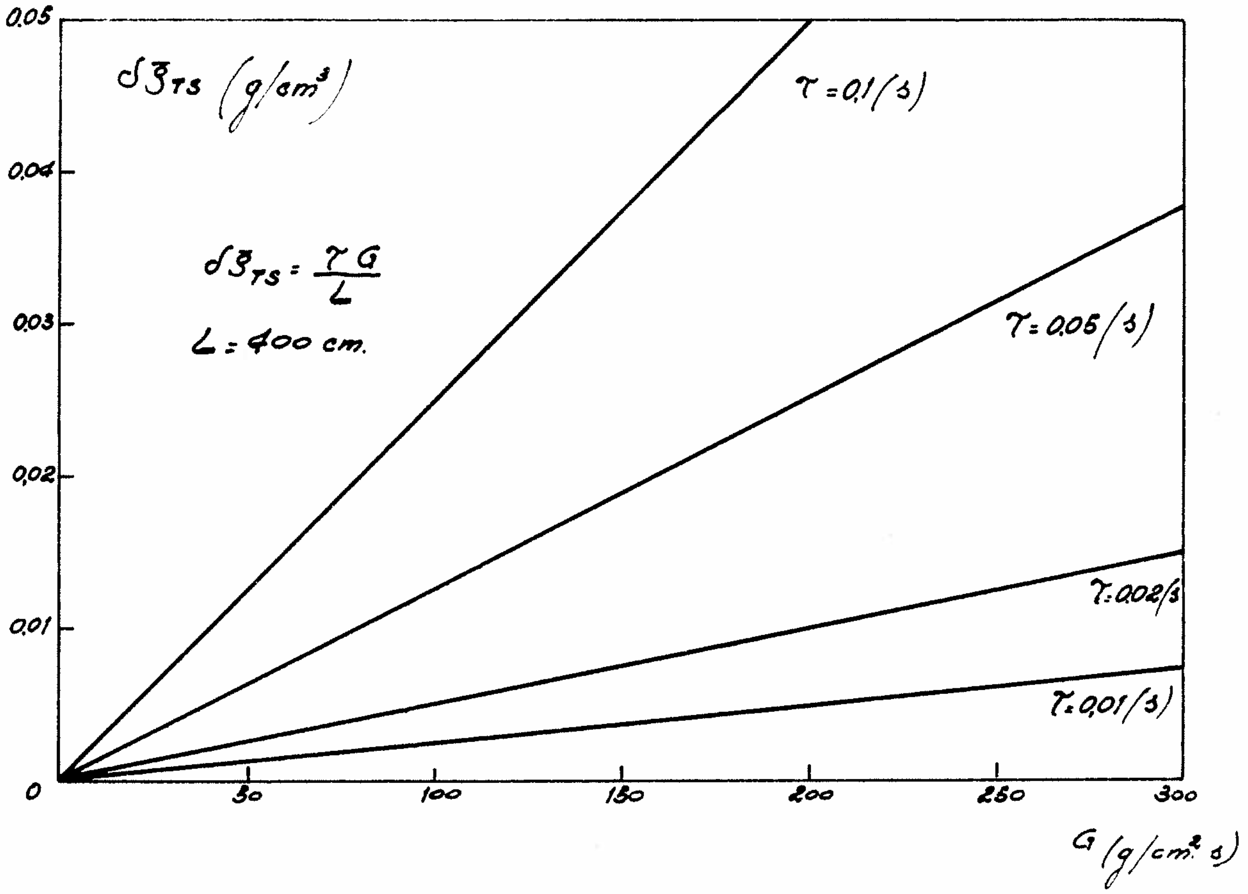


Fig. 3 - Maximum theoretical error of measured density as a consequence of closing time.

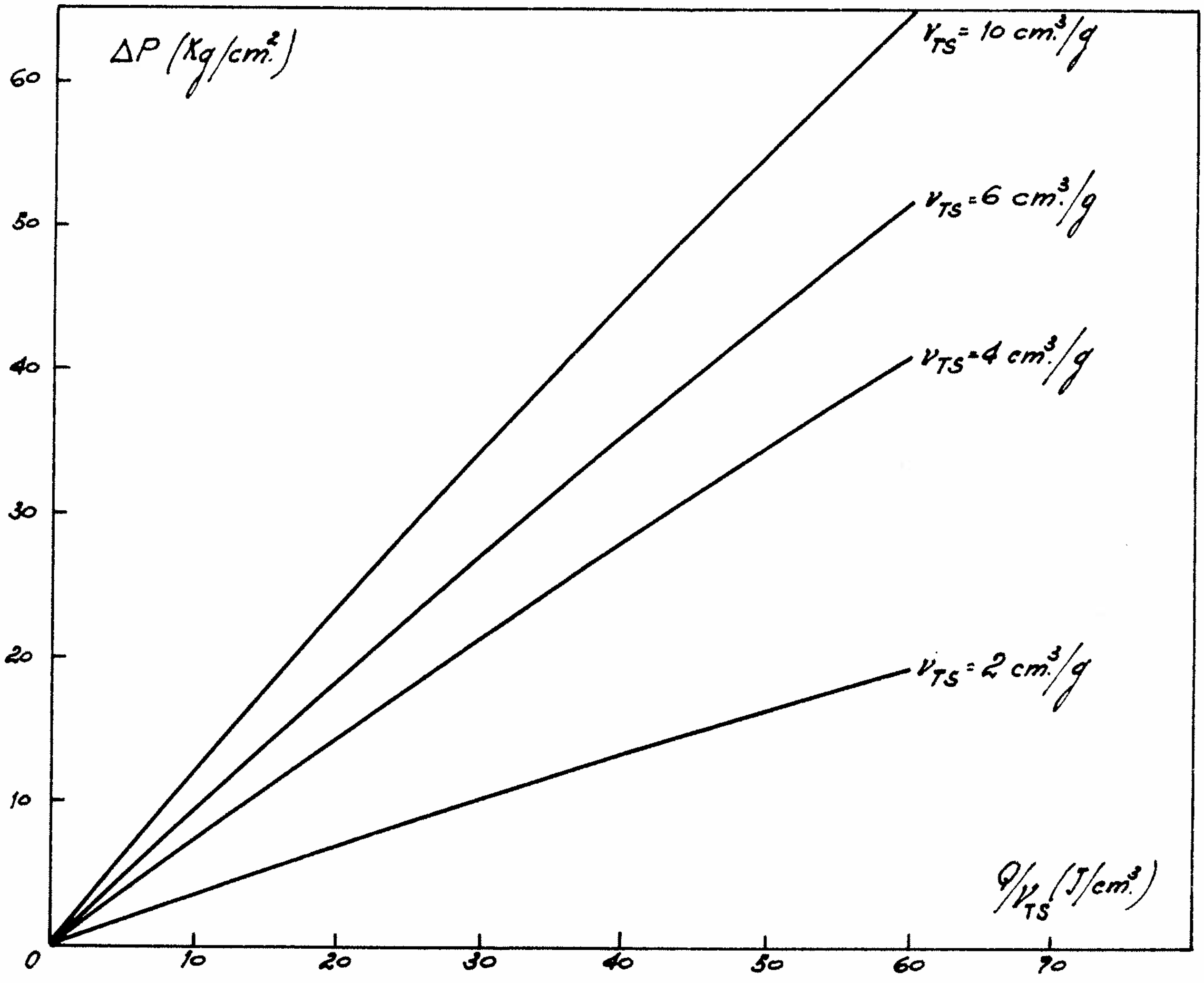


Fig. 4 - Channel pressure rise as a function of the heat input after the valve closure.

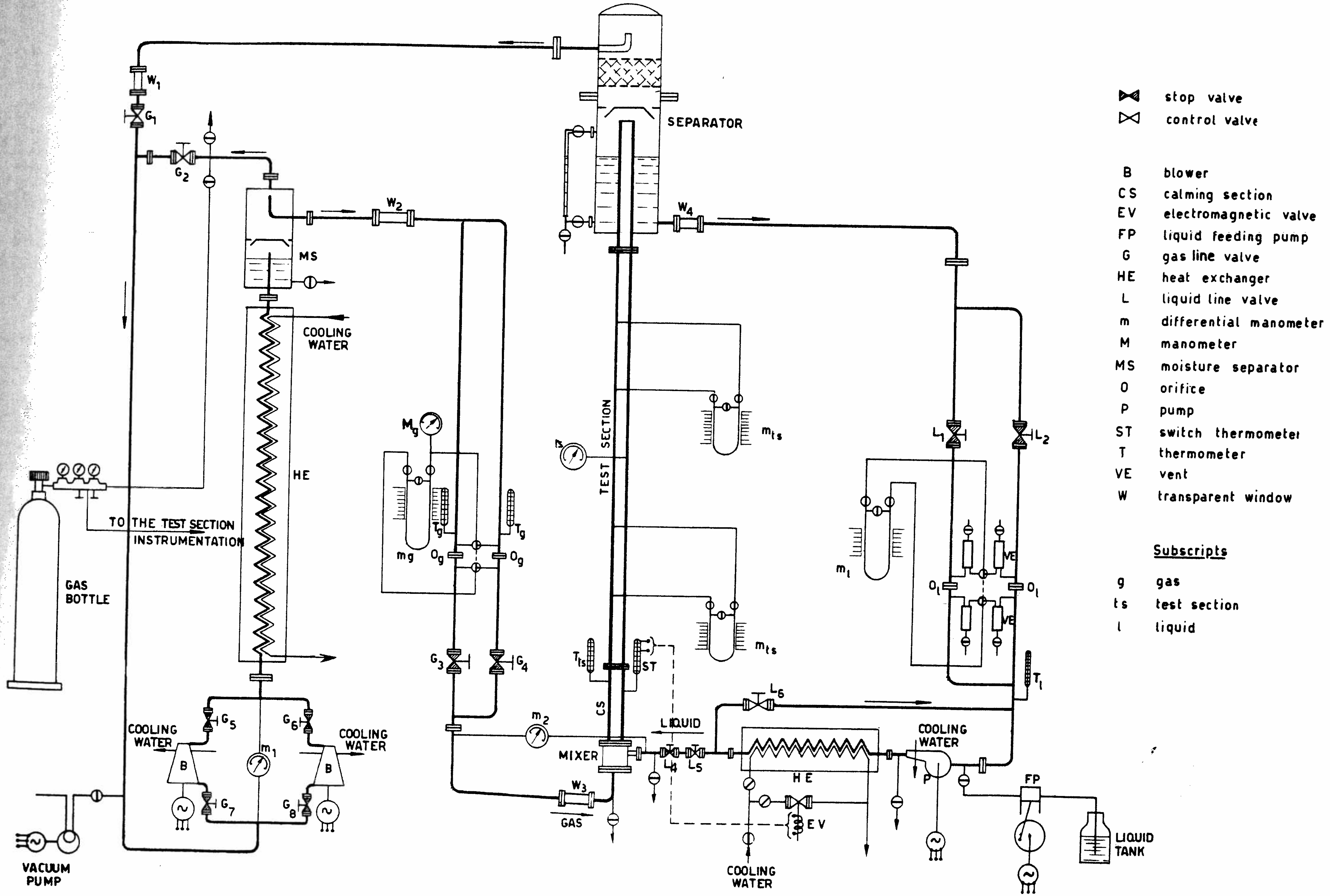
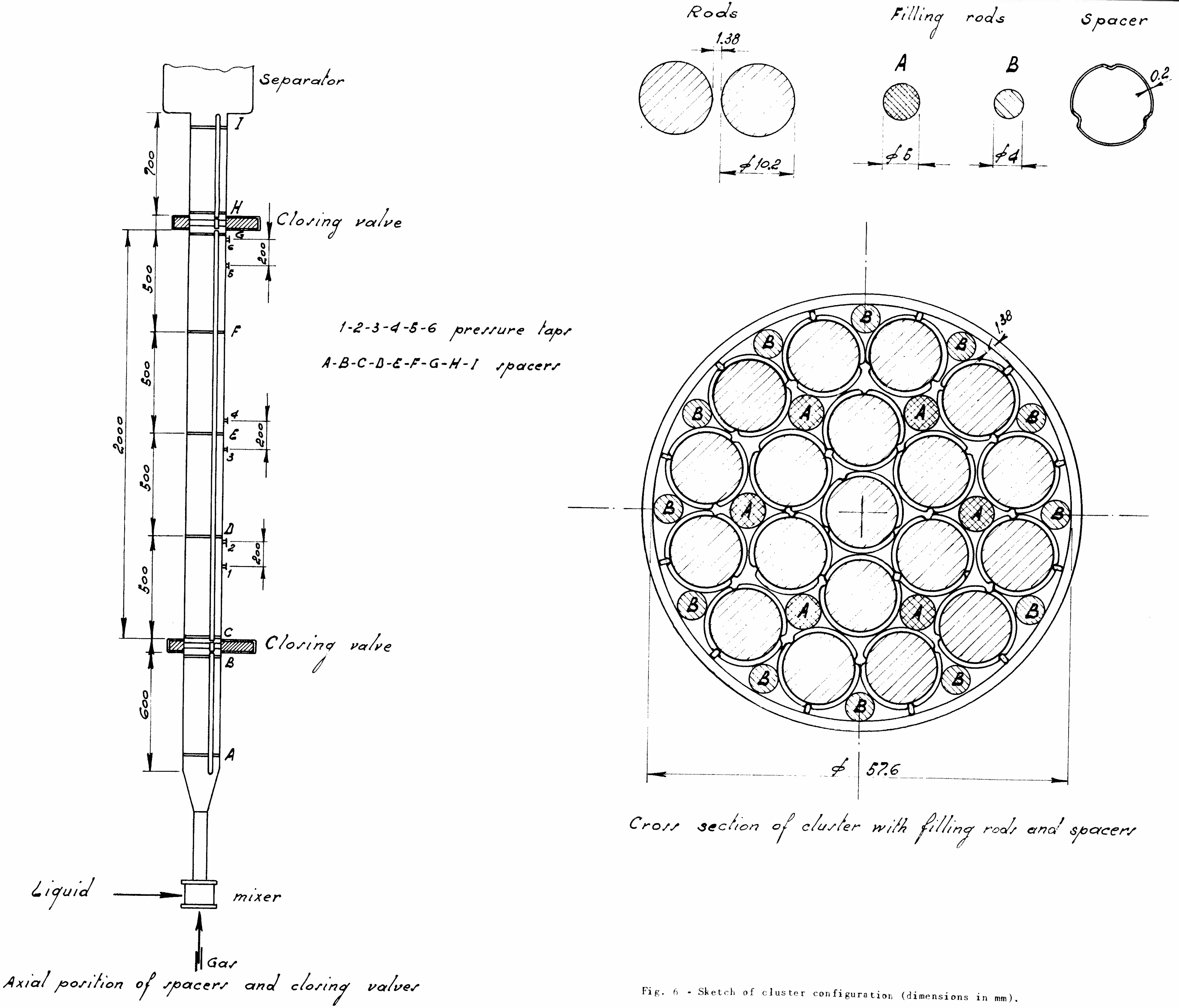


Fig. 5 - Schematic flowsheet of the circuit.



Axial position of spacers and closing valves

Cross section of cluster with filling rods and spacers

Fig. 6 - Sketch of cluster configuration (dimensions in mm).

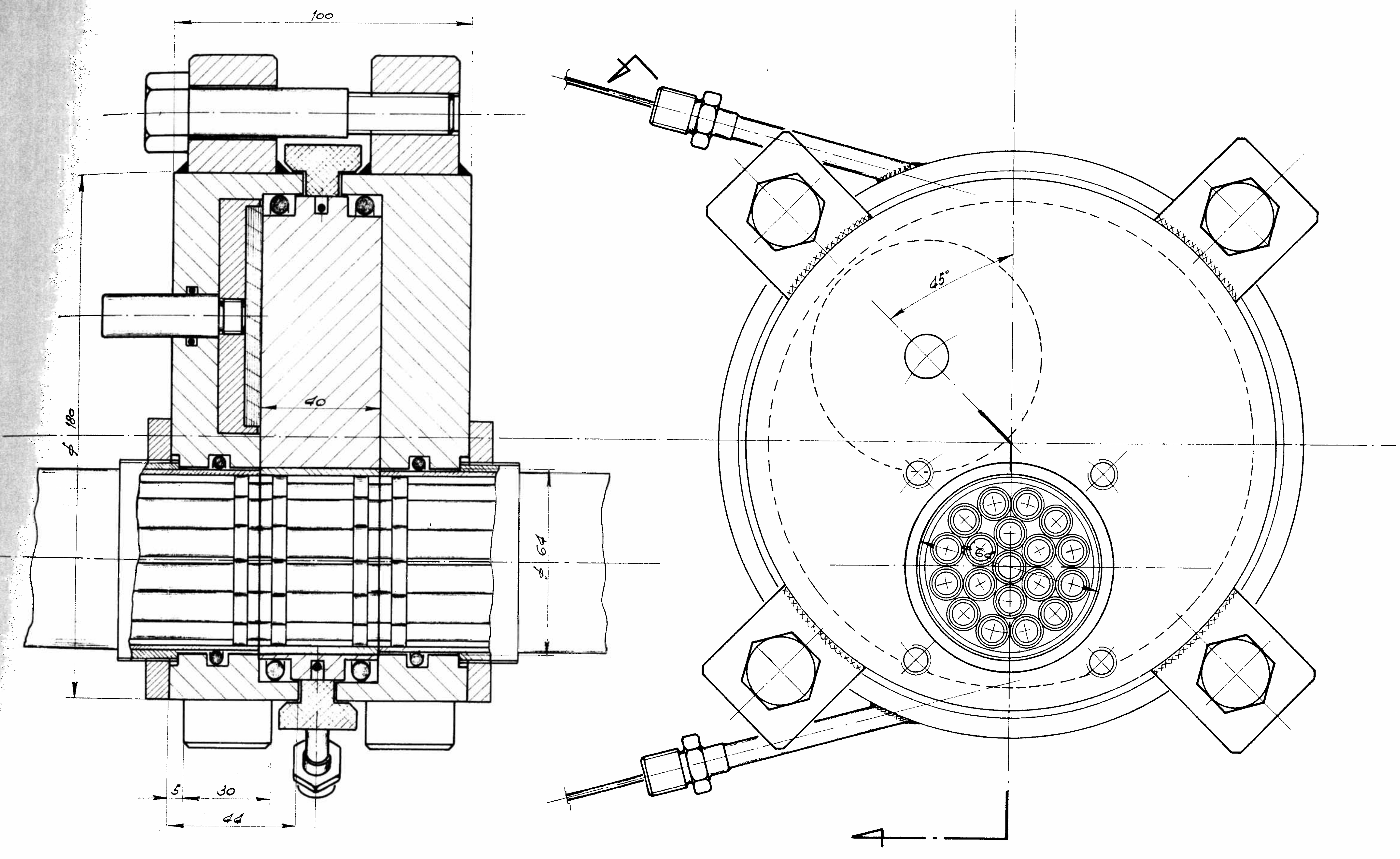


Fig. 7 - Rotating plate valve.

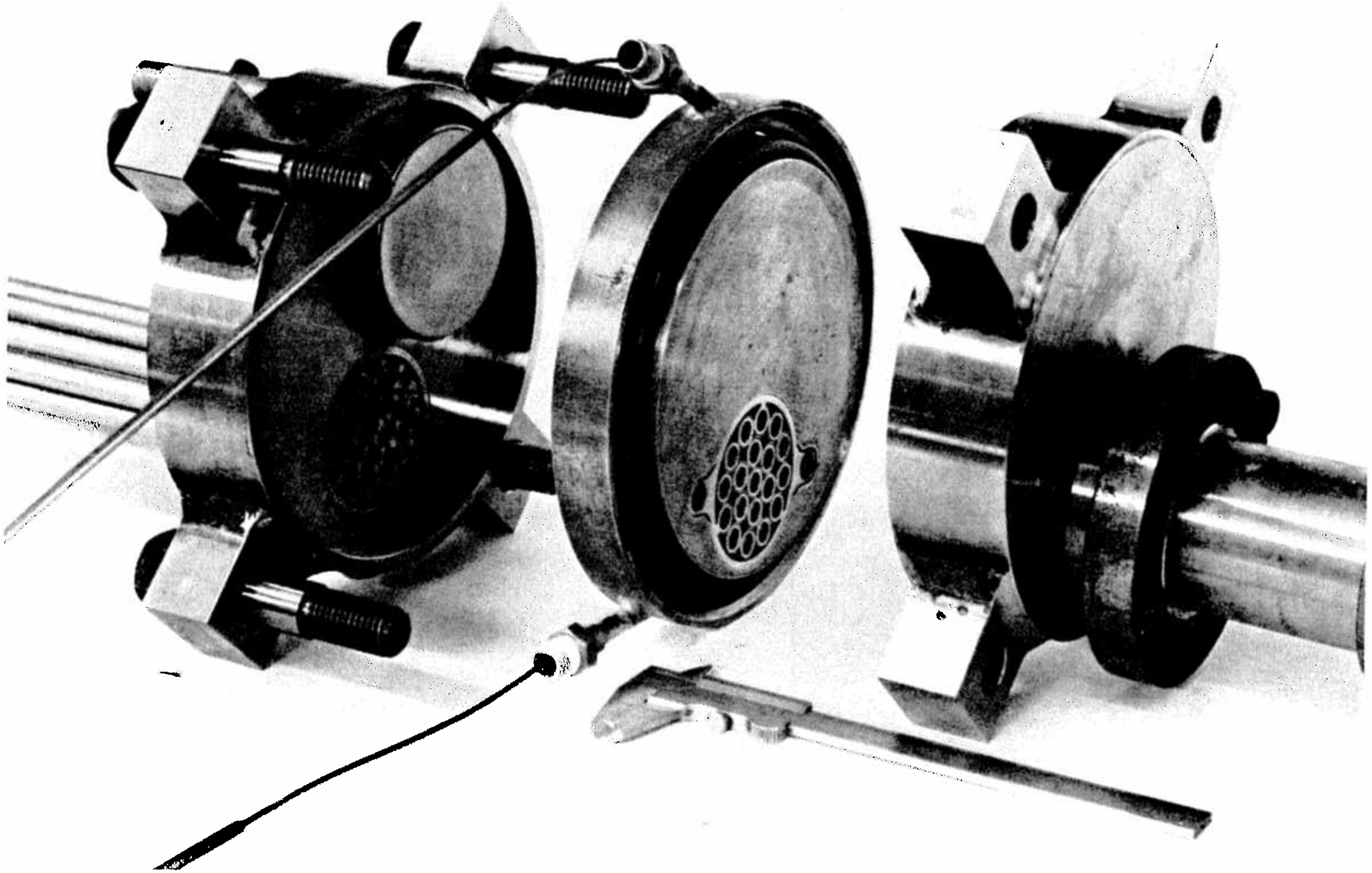


Fig. 8 - Rotating plate valve.

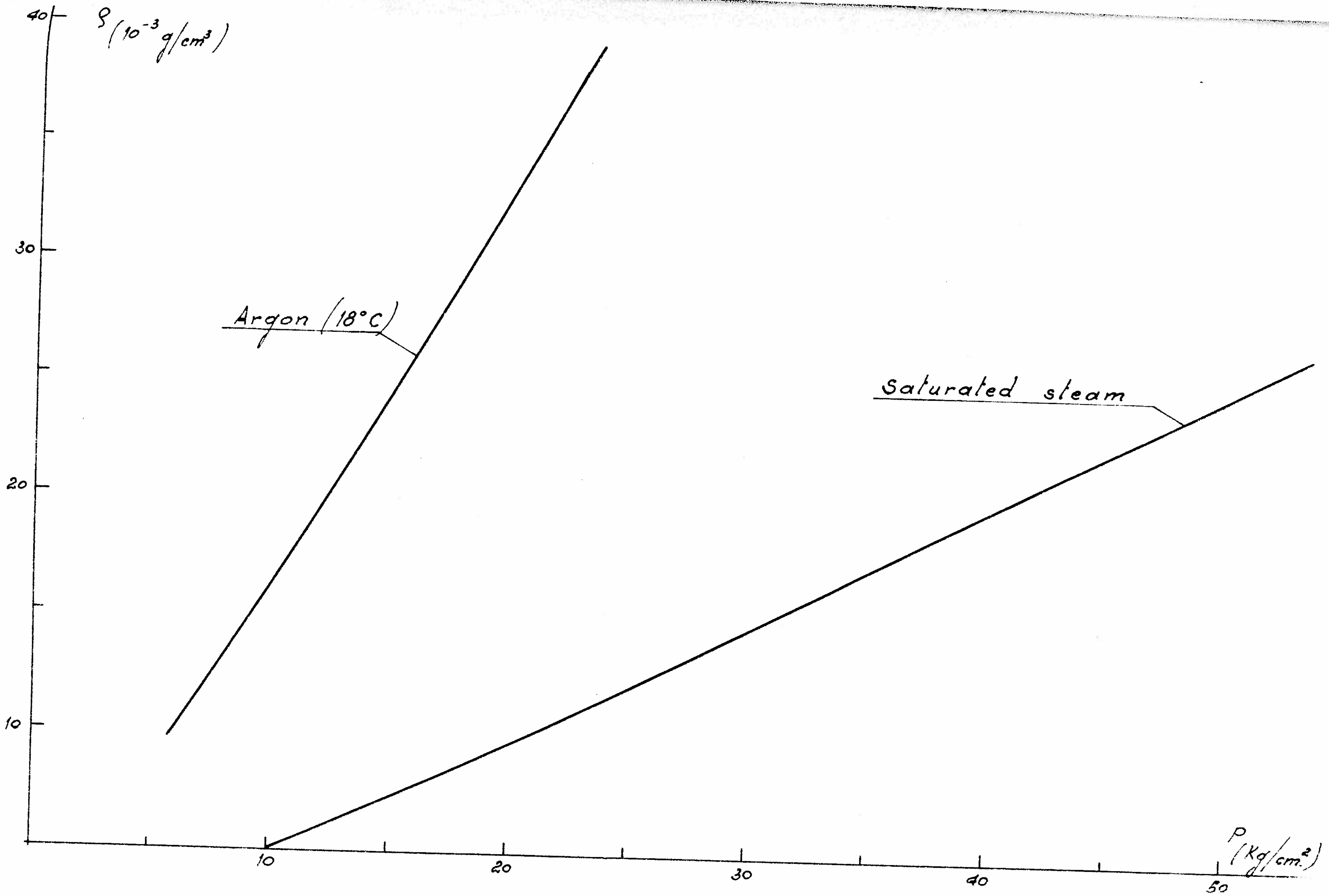


Fig. 9 - Density of employed gases versus pressure.

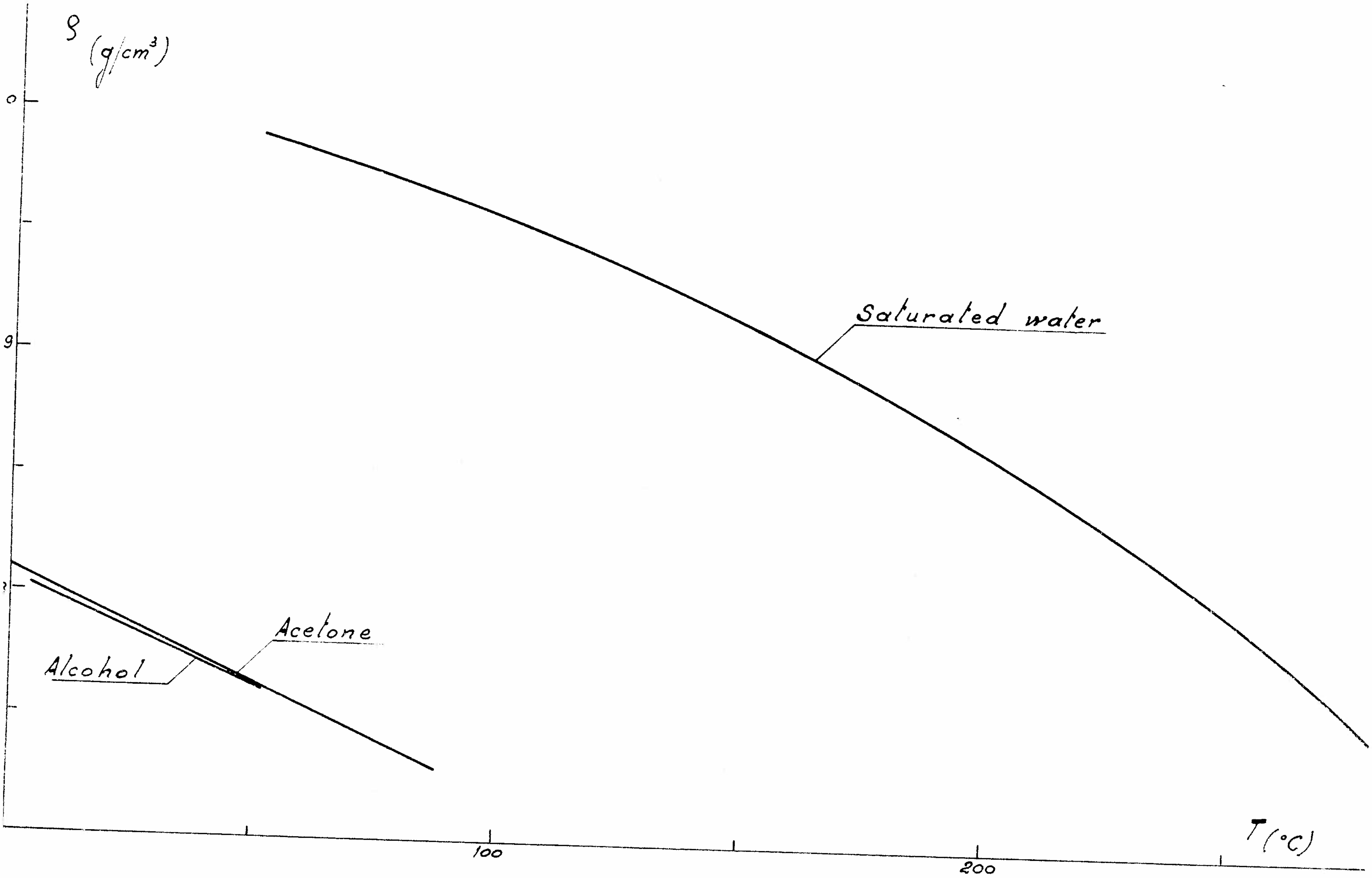


Fig. 10 - Density of employed liquids versus temperature.

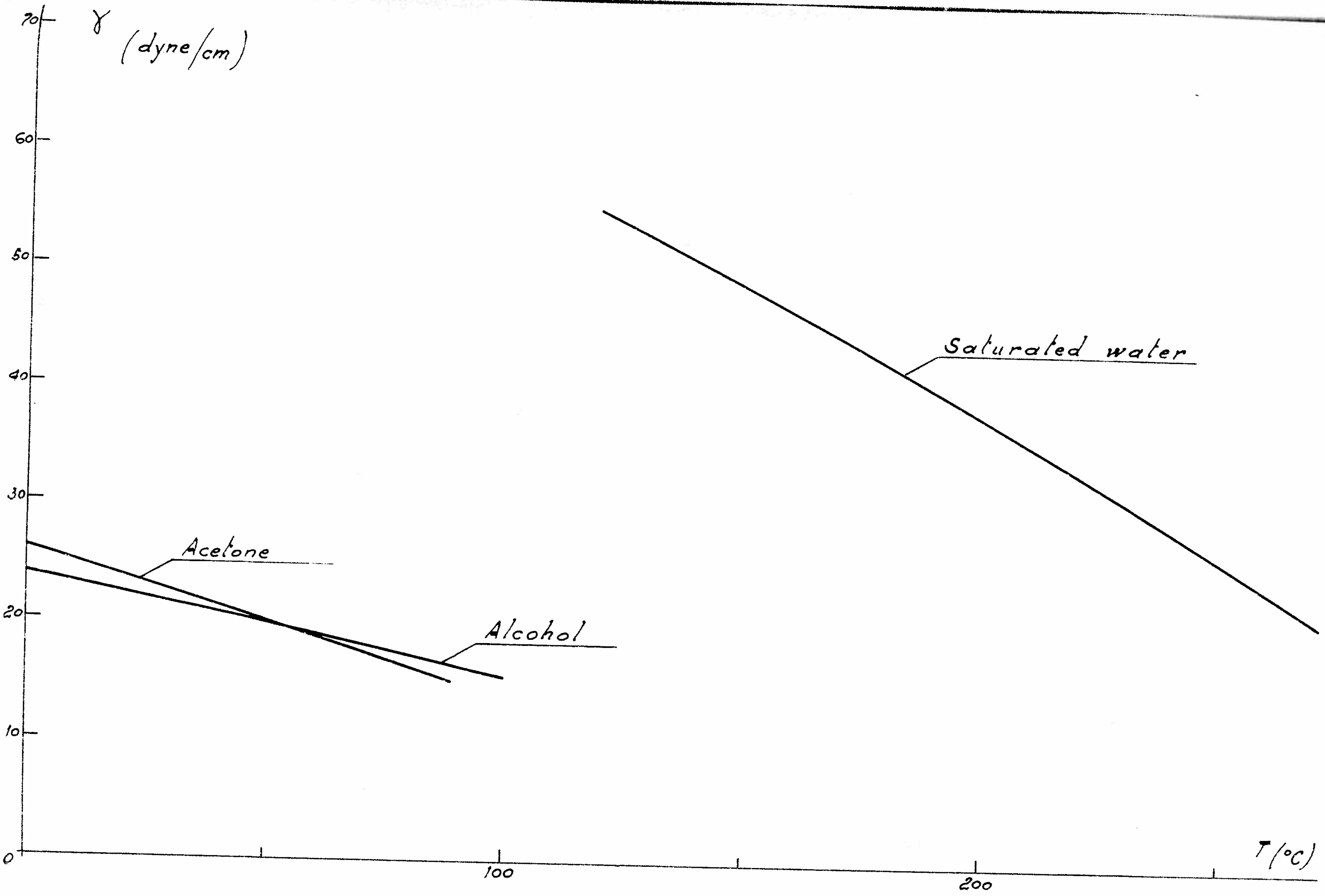


Fig. 11 · Surface tension of employed liquids versus temperature.

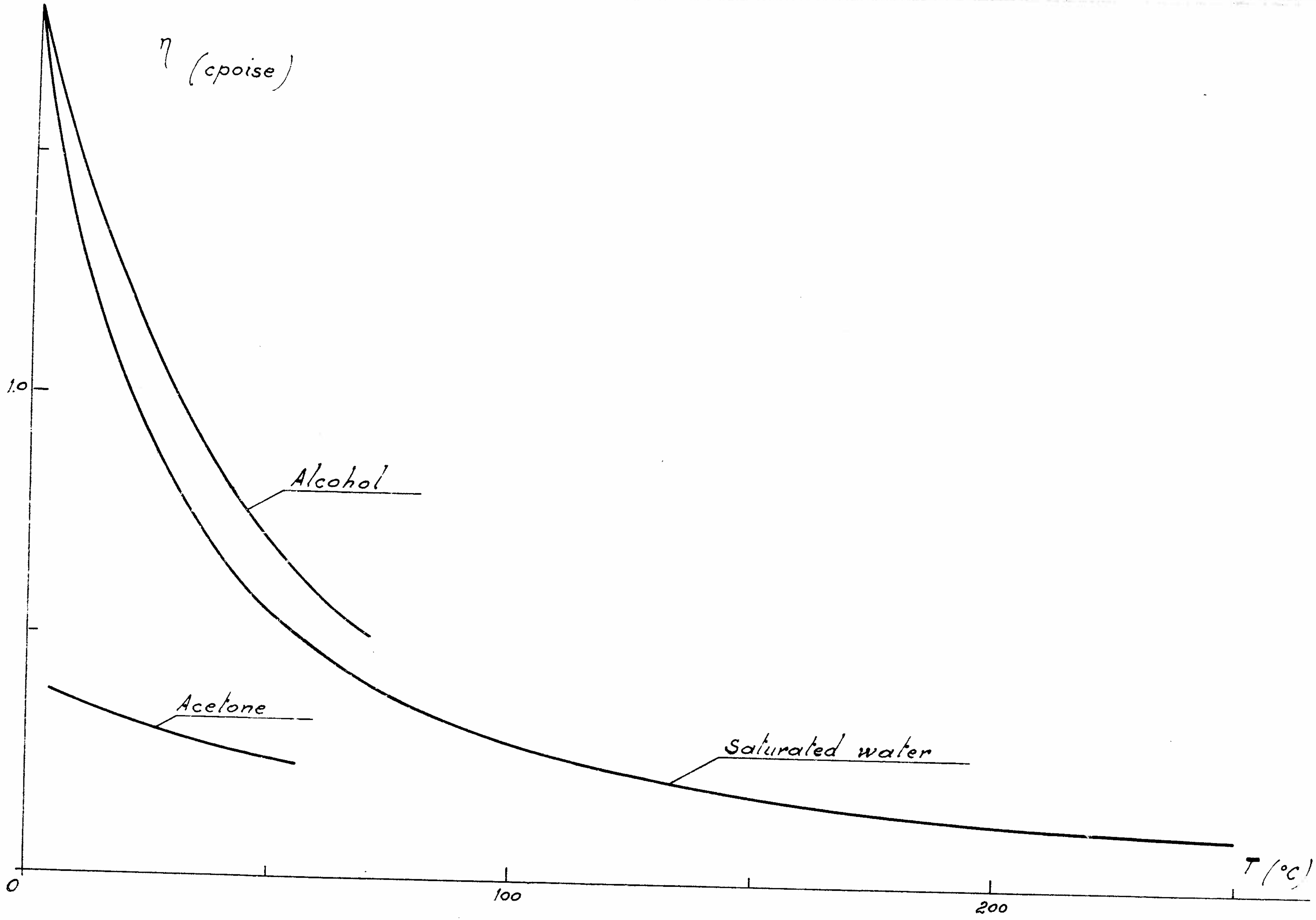


Fig. 12 - Viscosity of employed liquids versus temperature

Fig. 12 - Viscosity of employed liquids versus temperature.

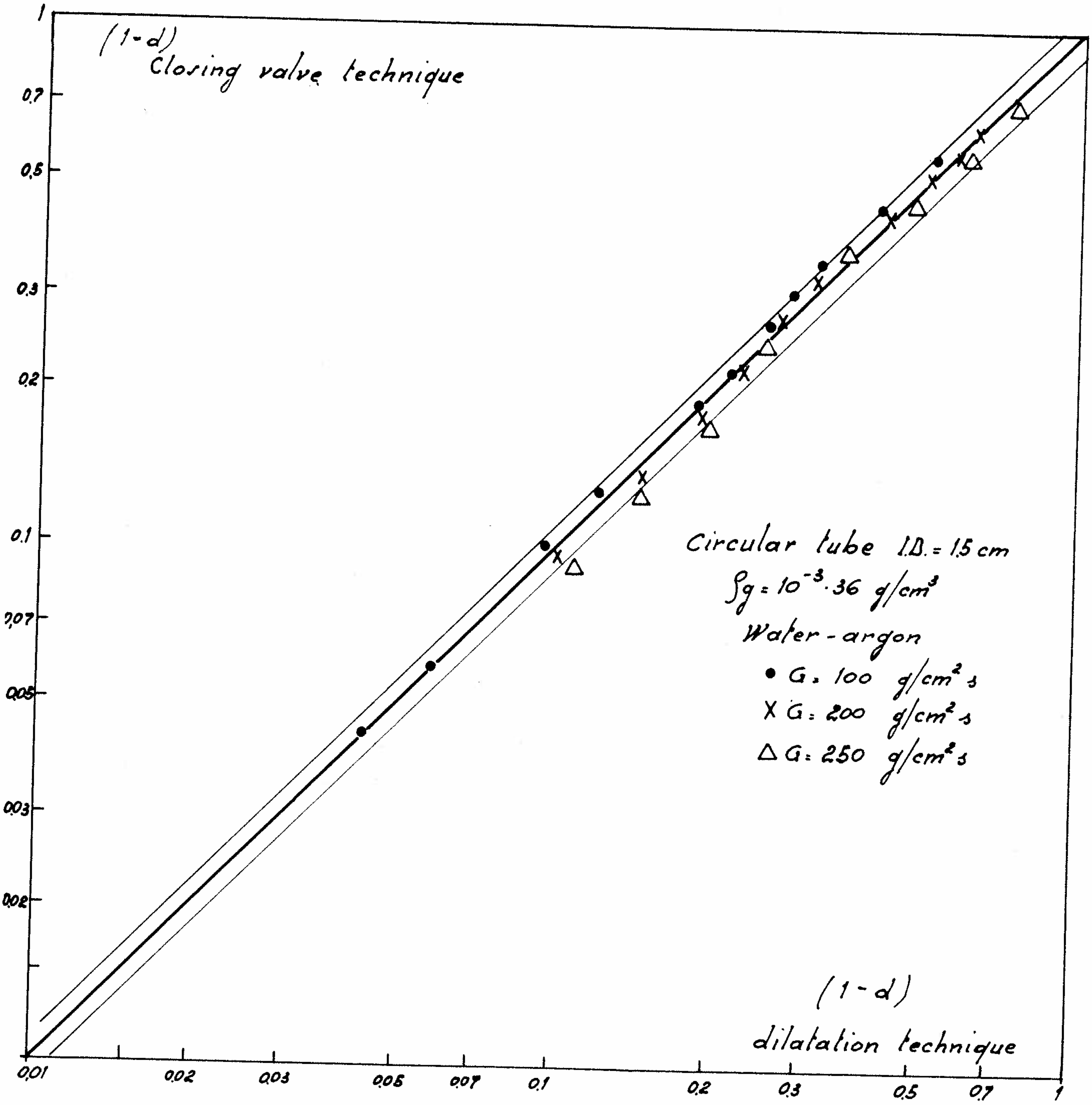


Fig. 13 - Comparison of results obtained by means of the dilatation technique and by means of the valve technique respectively.

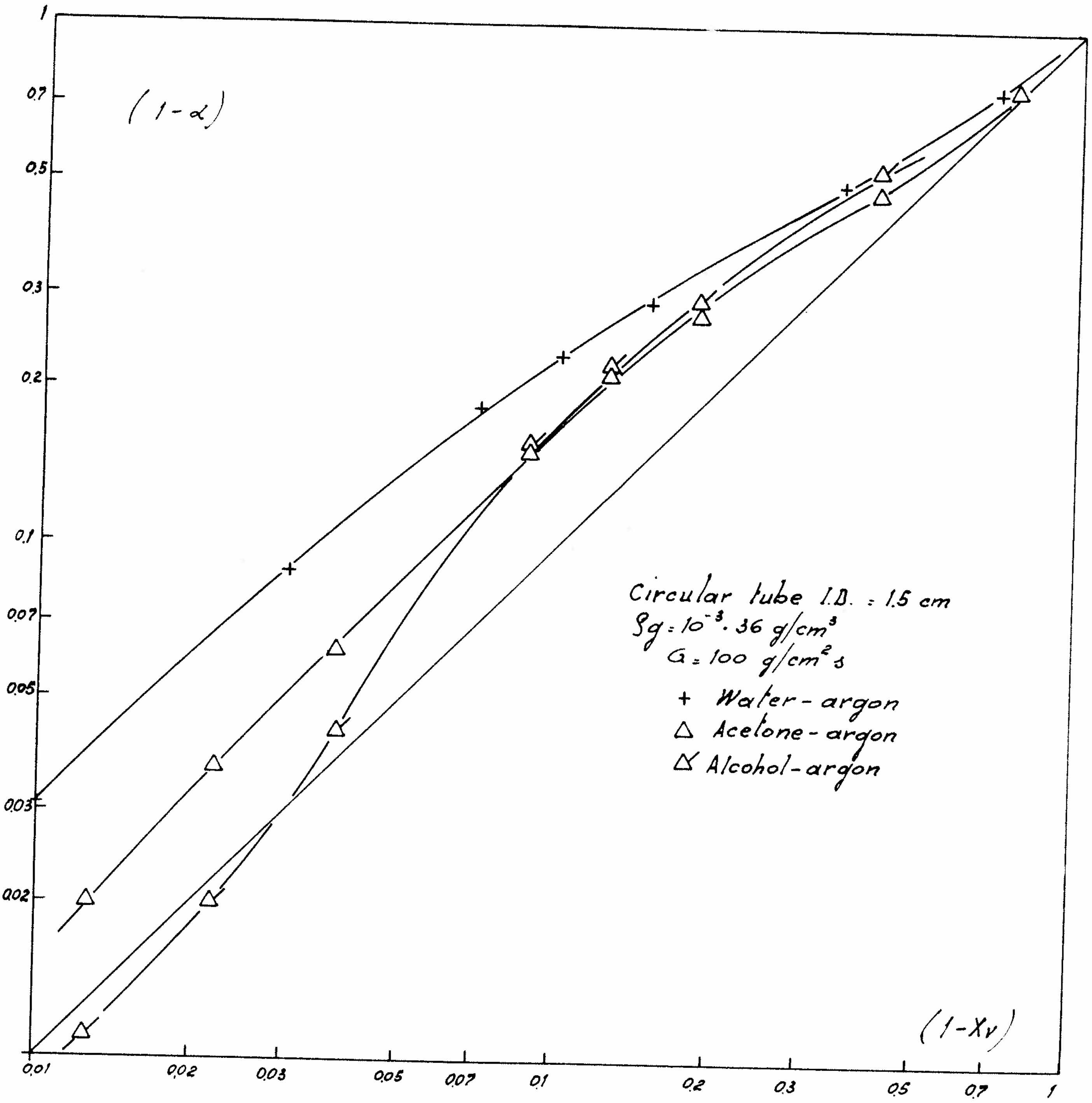


Fig. 14 - Influence of surface tension on liquid volume fraction.

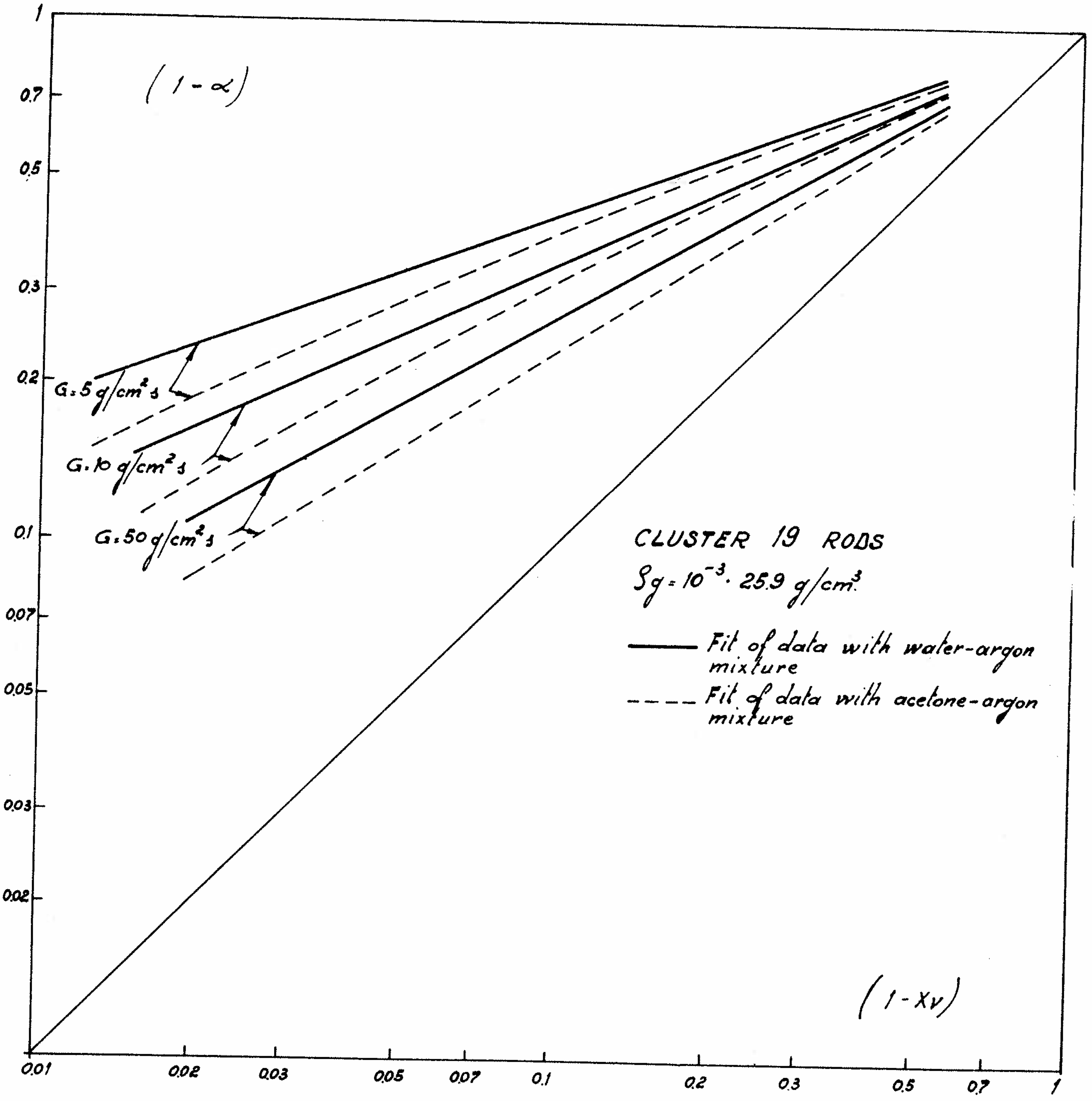


Fig. 15 - Influence of surface tension on liquid volume fraction.

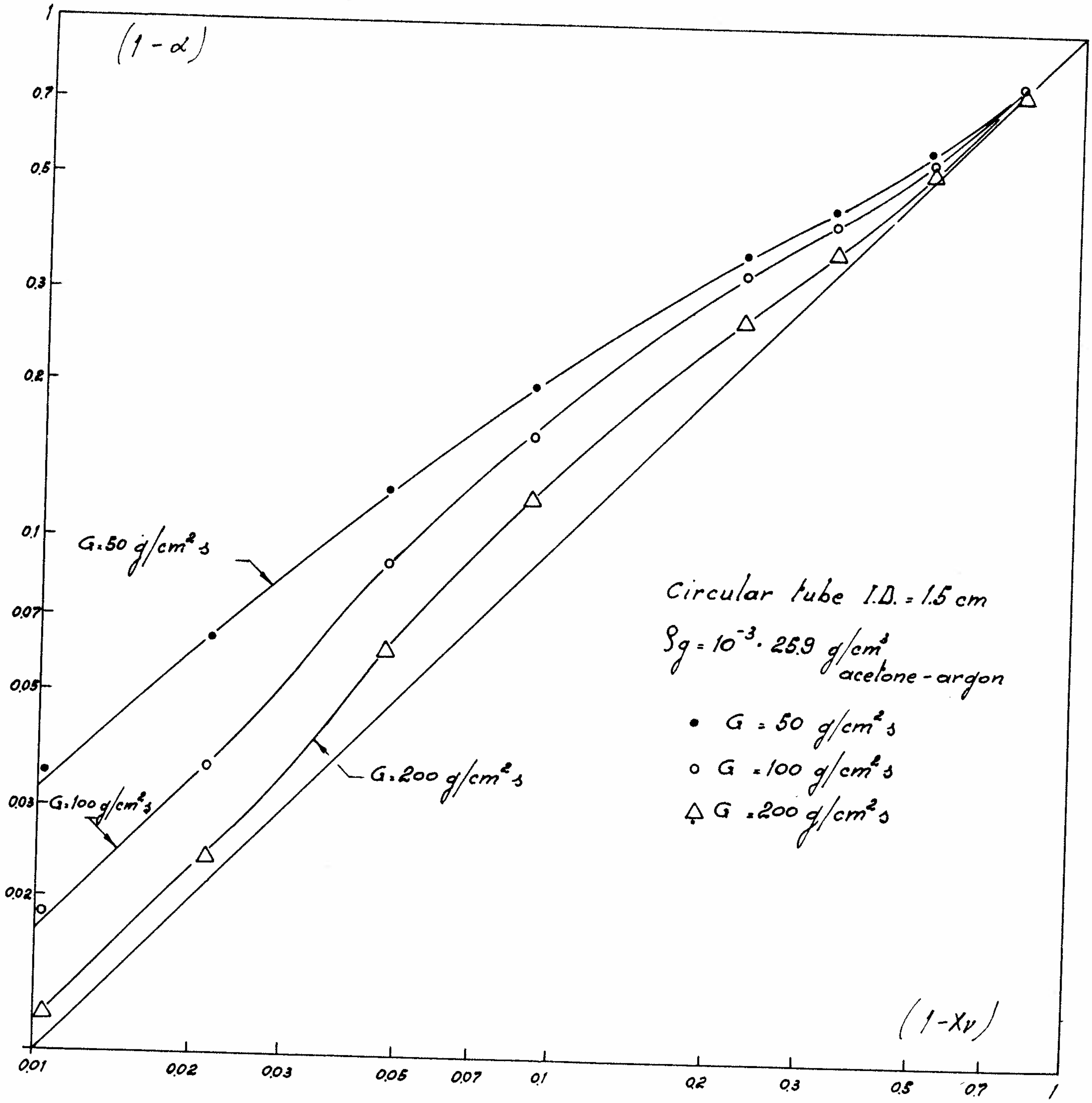


Fig. 16 - Influence of specific mass flowrate on liquid volume fraction.

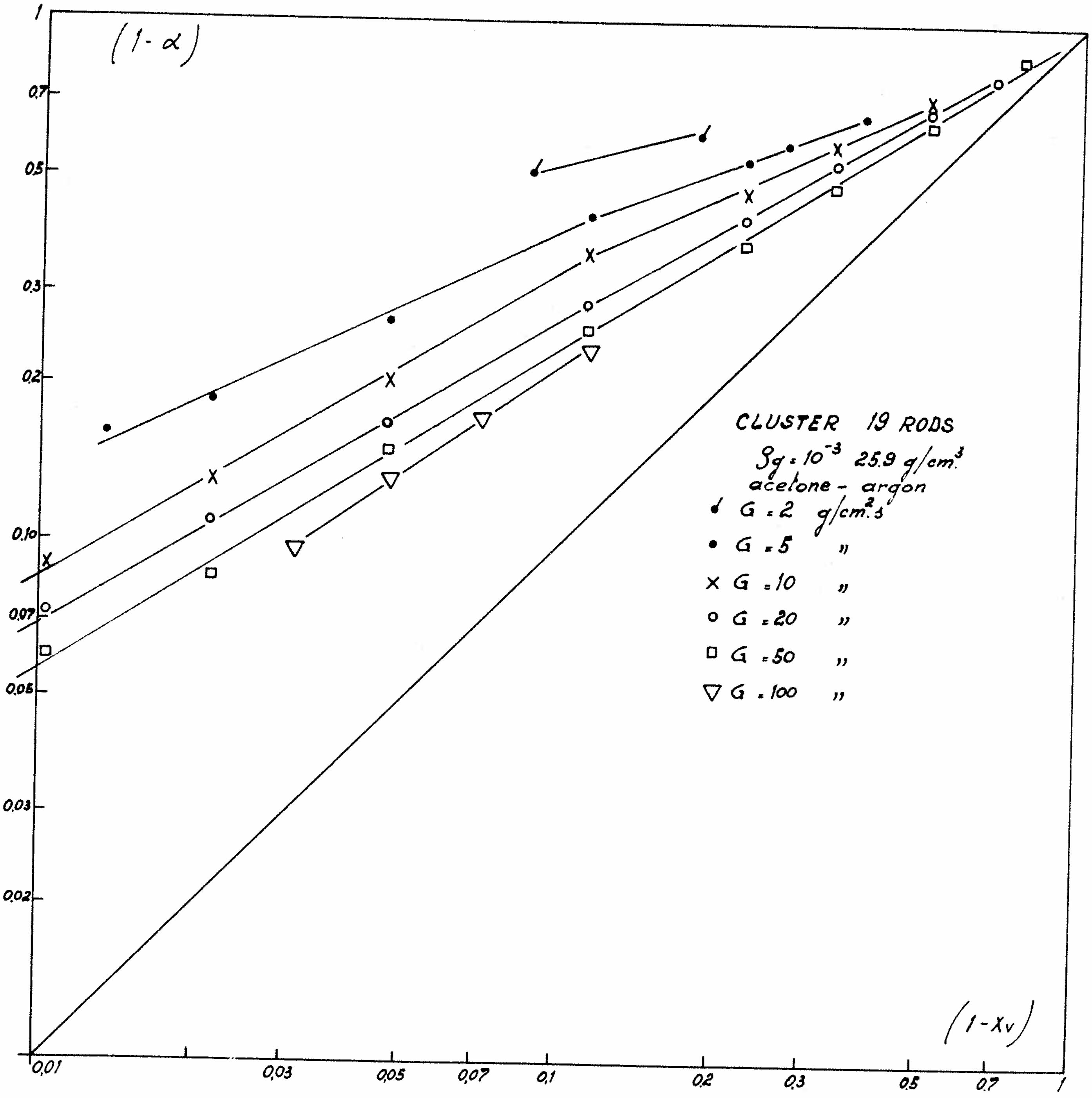


Fig. 17 - Influence of specific mass flowrate on liquid volume fraction.

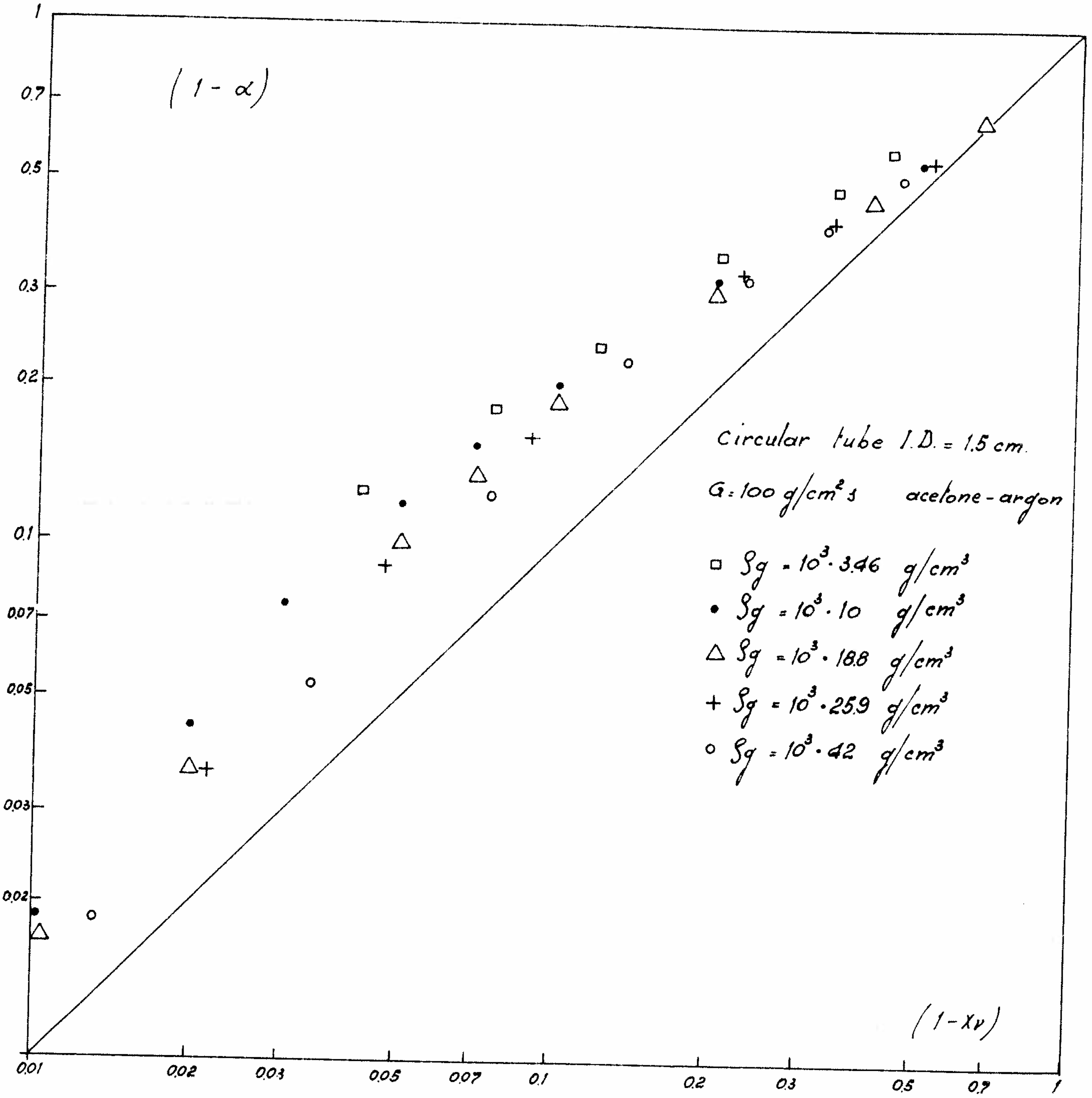


Fig. 18 - Influence of gas density on liquid volume fraction.

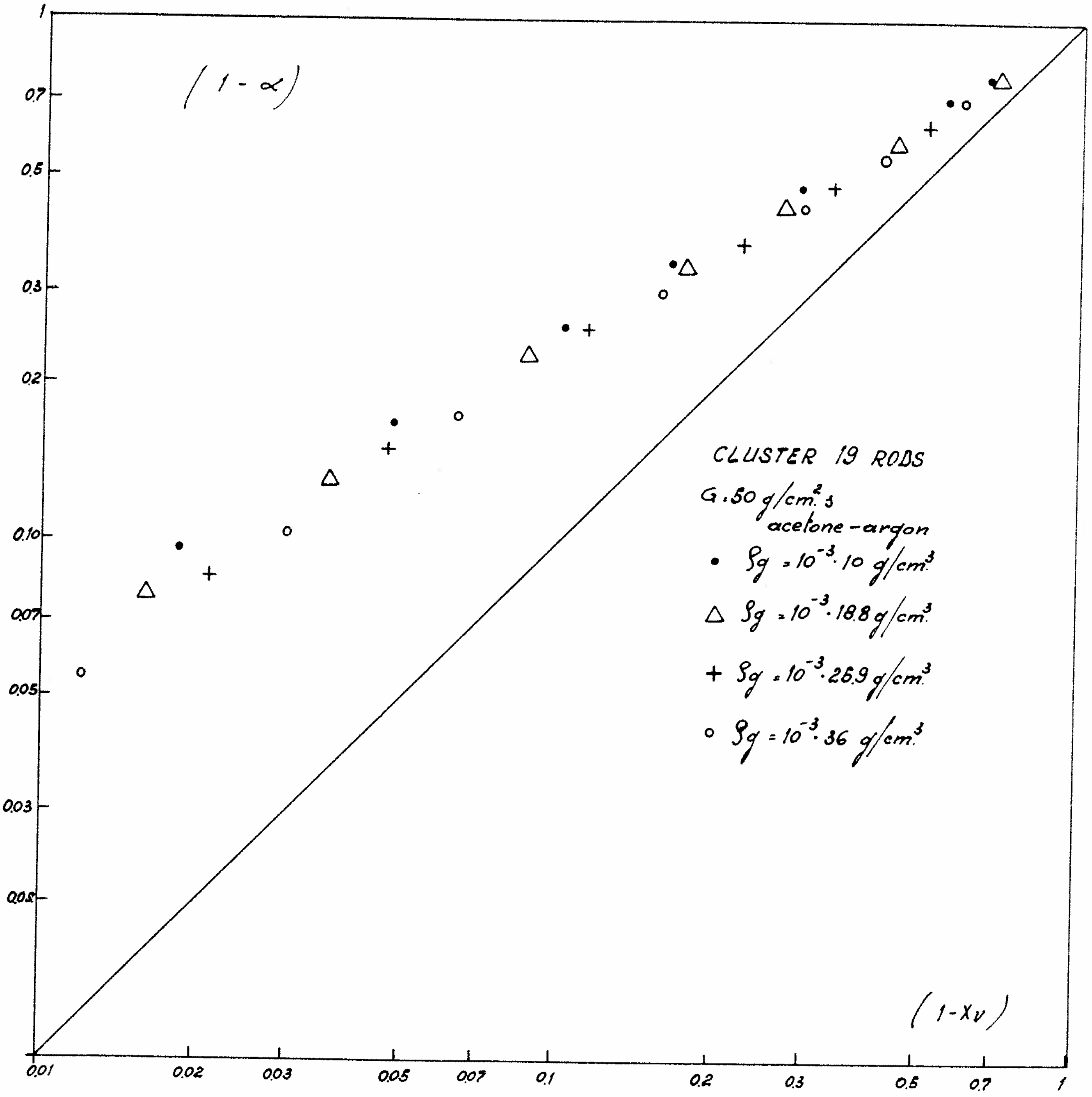


Fig. 19 - Influence of gas density on liquid volume fraction.

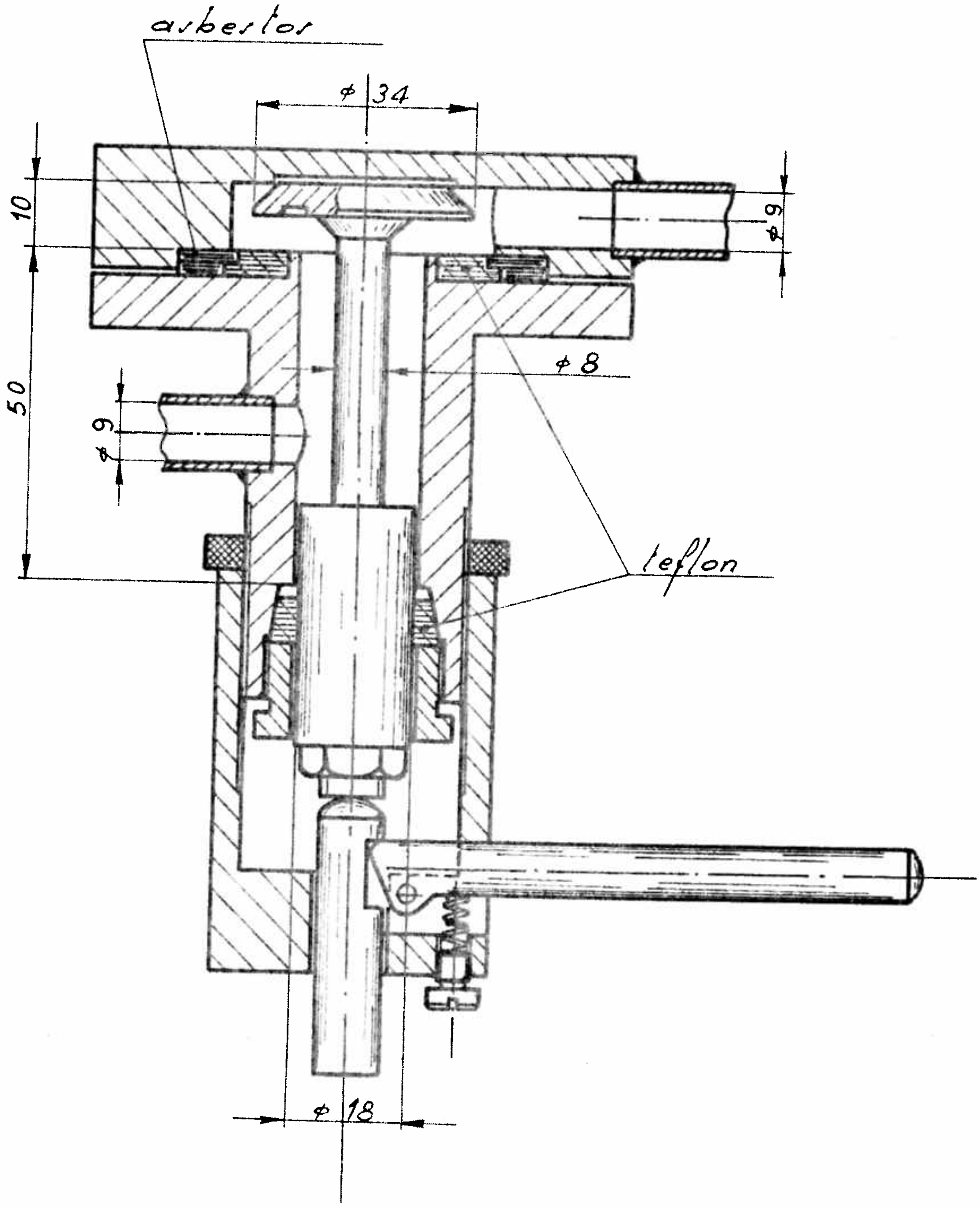


Fig. 20 - Quick closing valve.

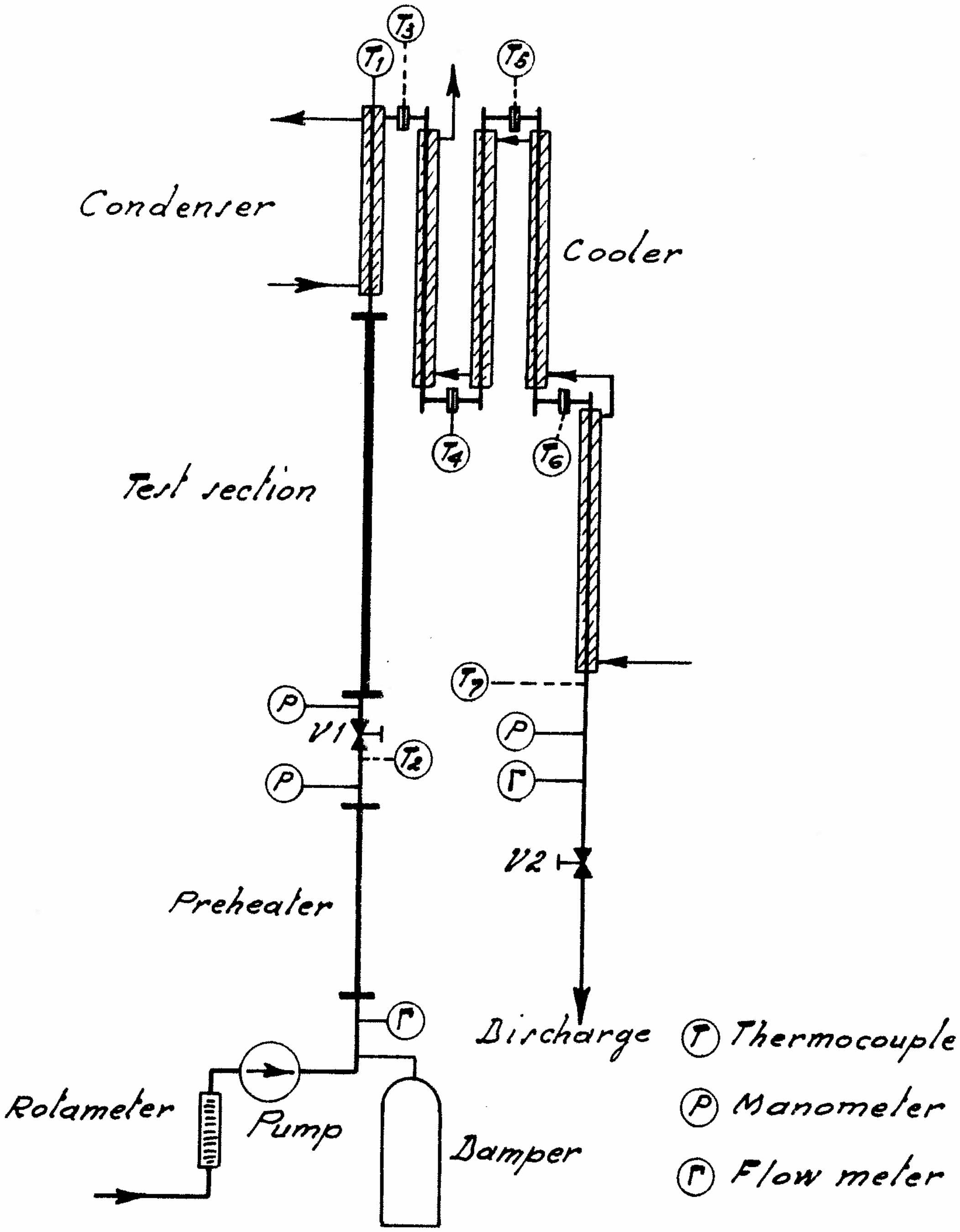


Fig. 21 · Schematic flowsheet of the experimental circuit.

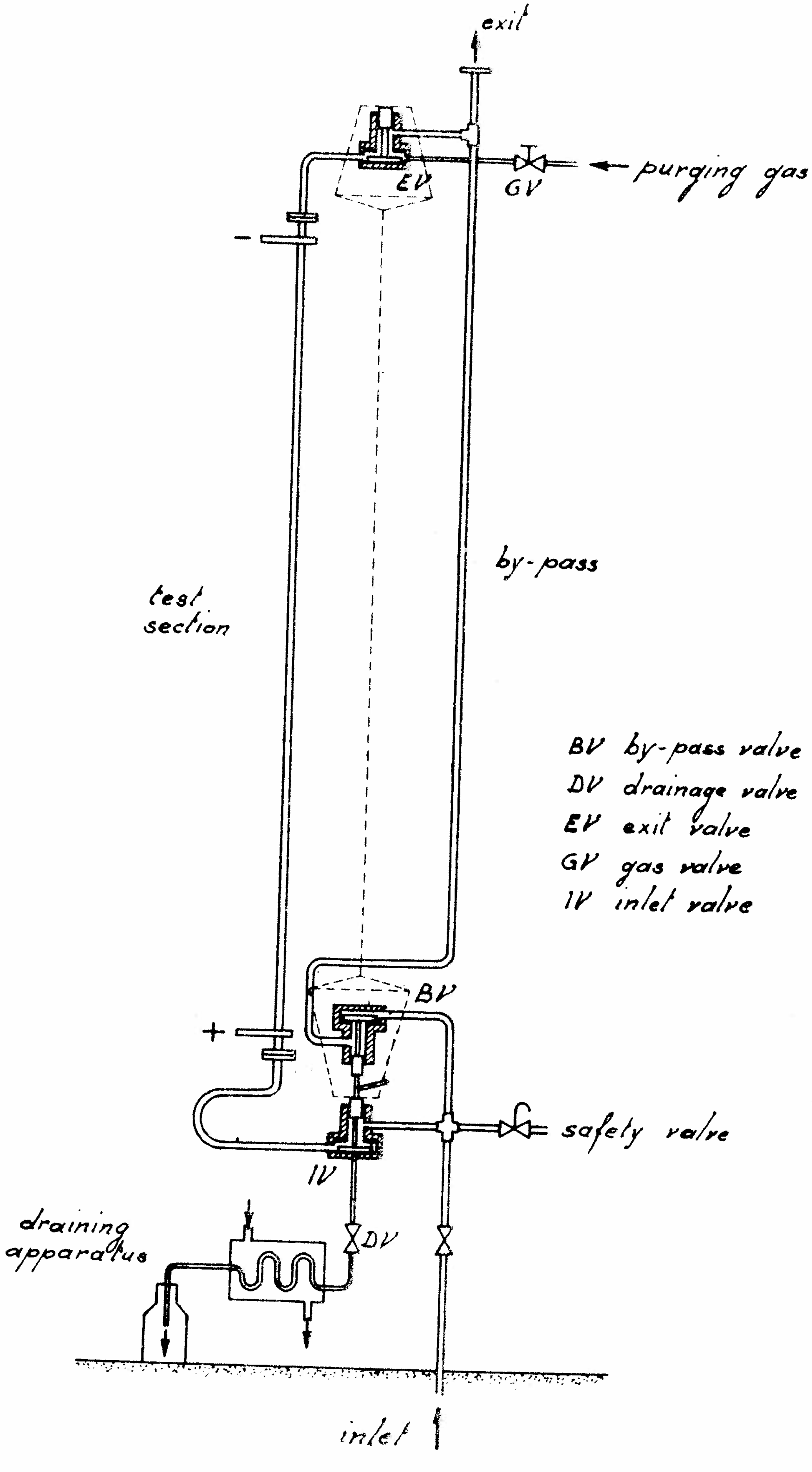


Fig. 22 - Schematic diagram of the quick closing valve apparatus.

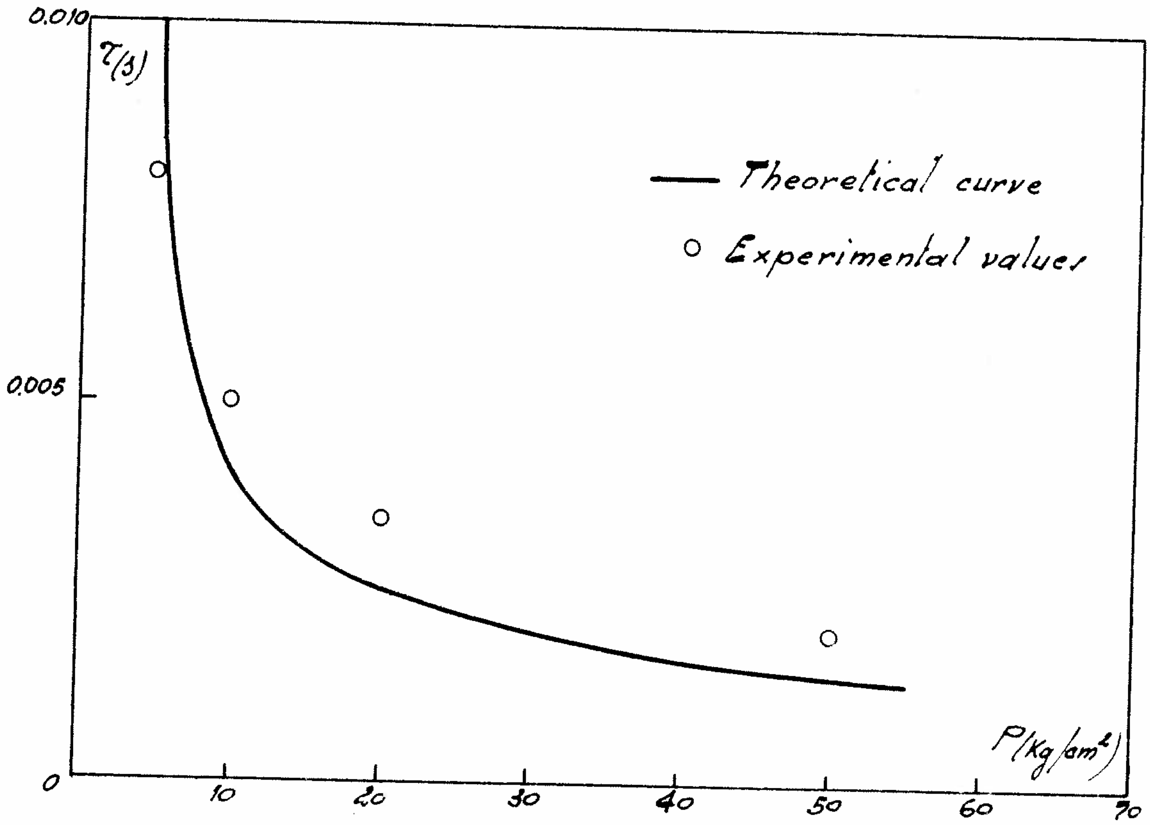


Fig. 23 - Closing time of the valve apparatus as a function of the operating pressure.

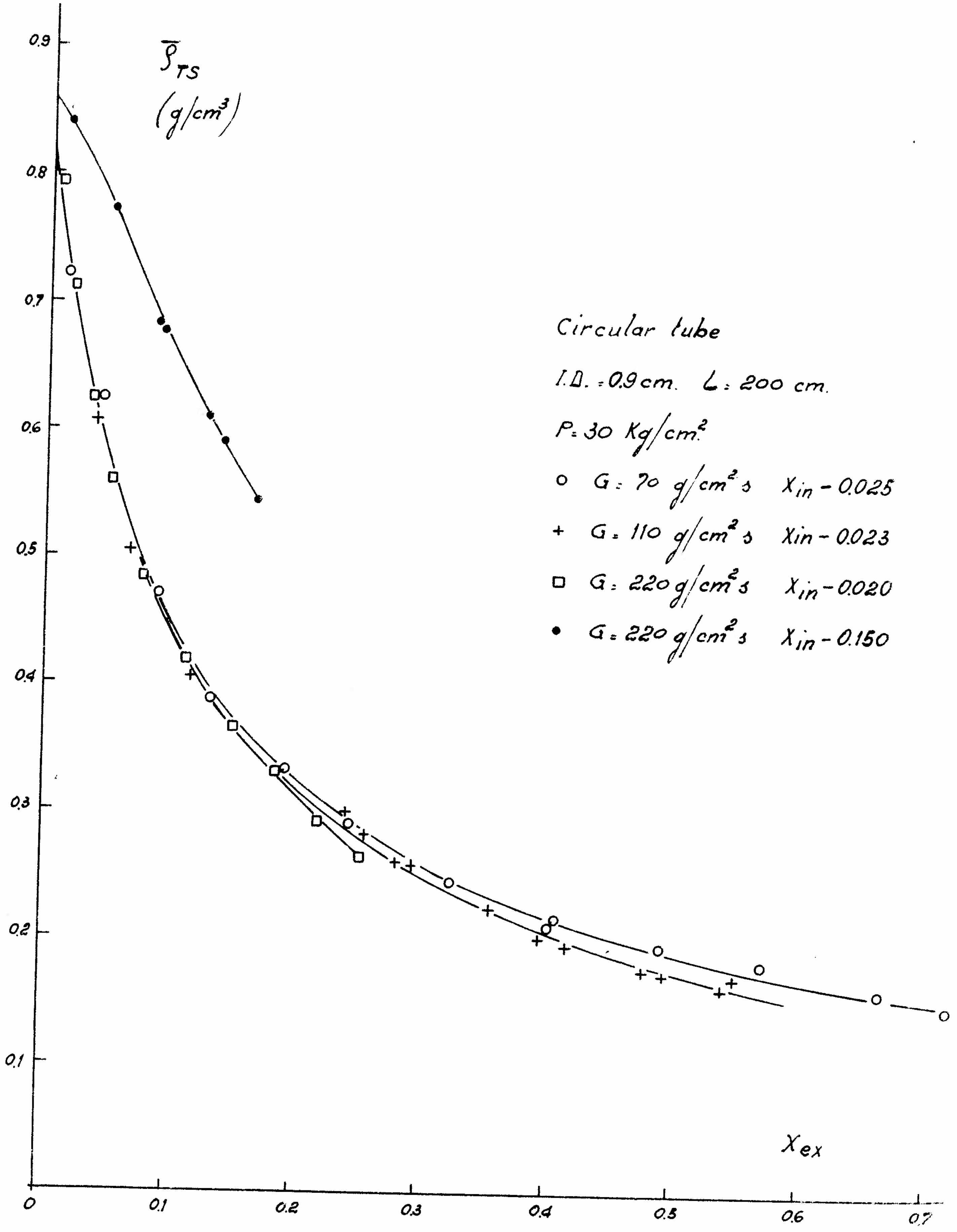


Fig. 24 - Experimental data of average density versus exit quality.

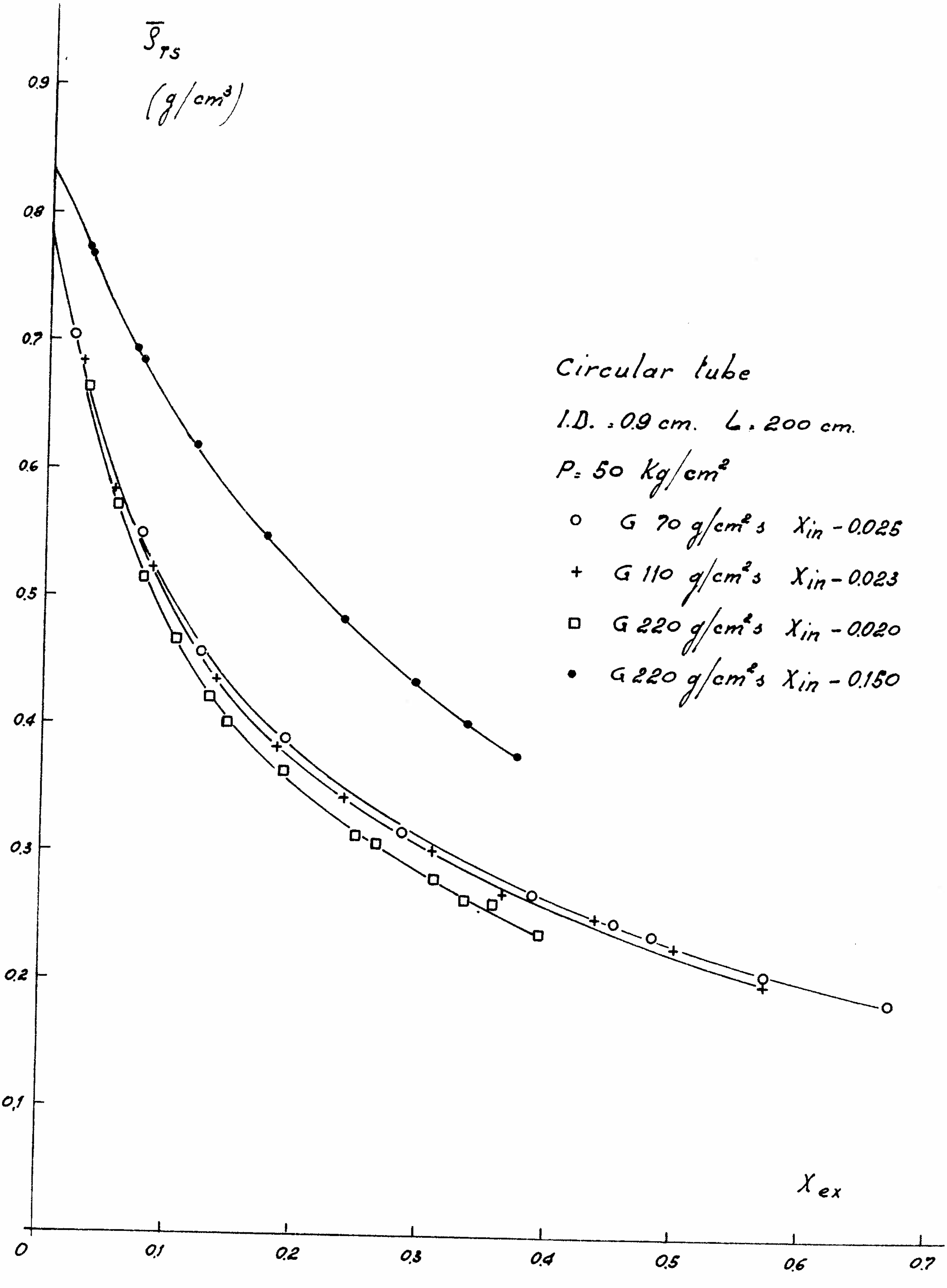


Fig. 25 - Experimental data of average density versus exit quality.

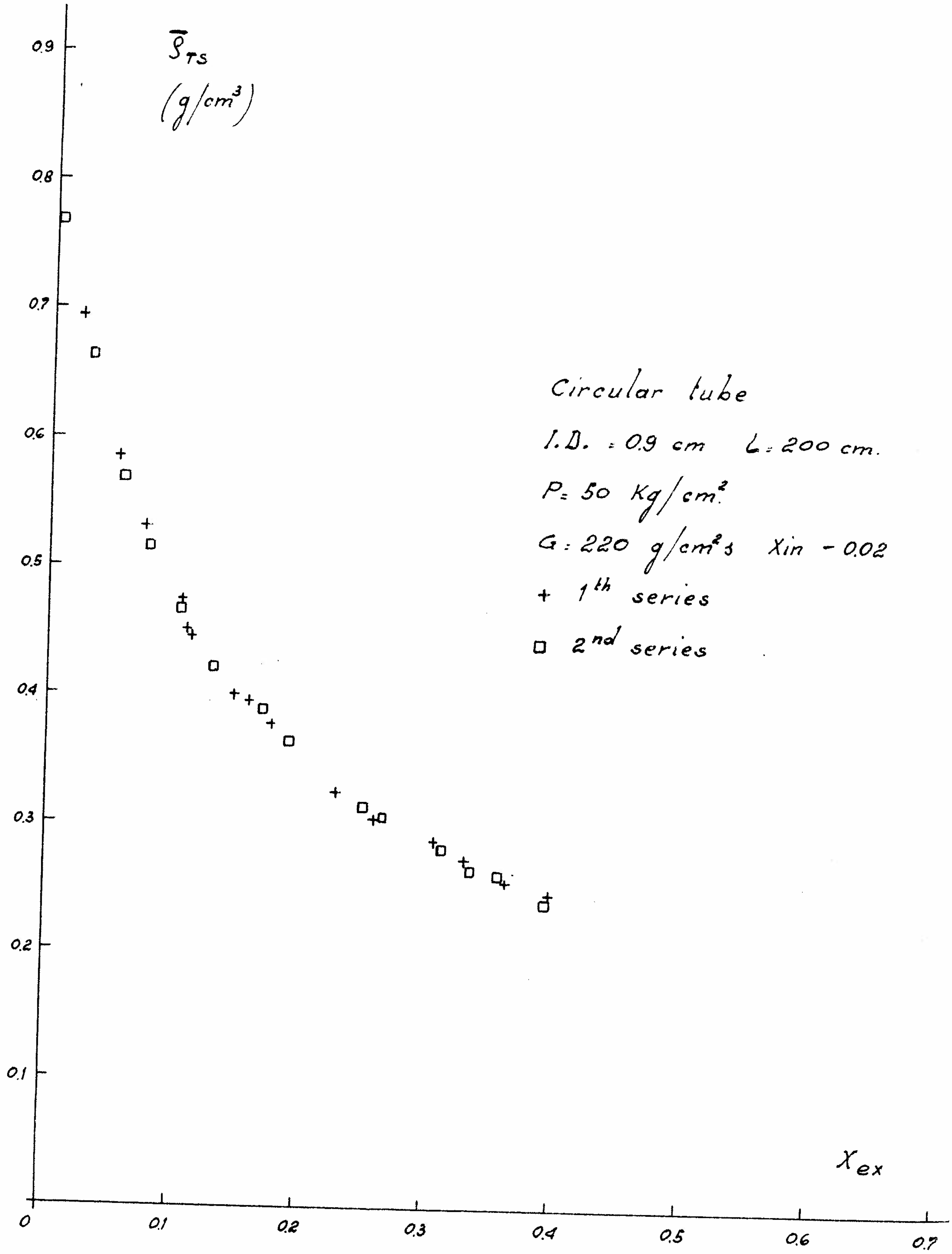


Fig. 26 - Results of reproducibility runs.

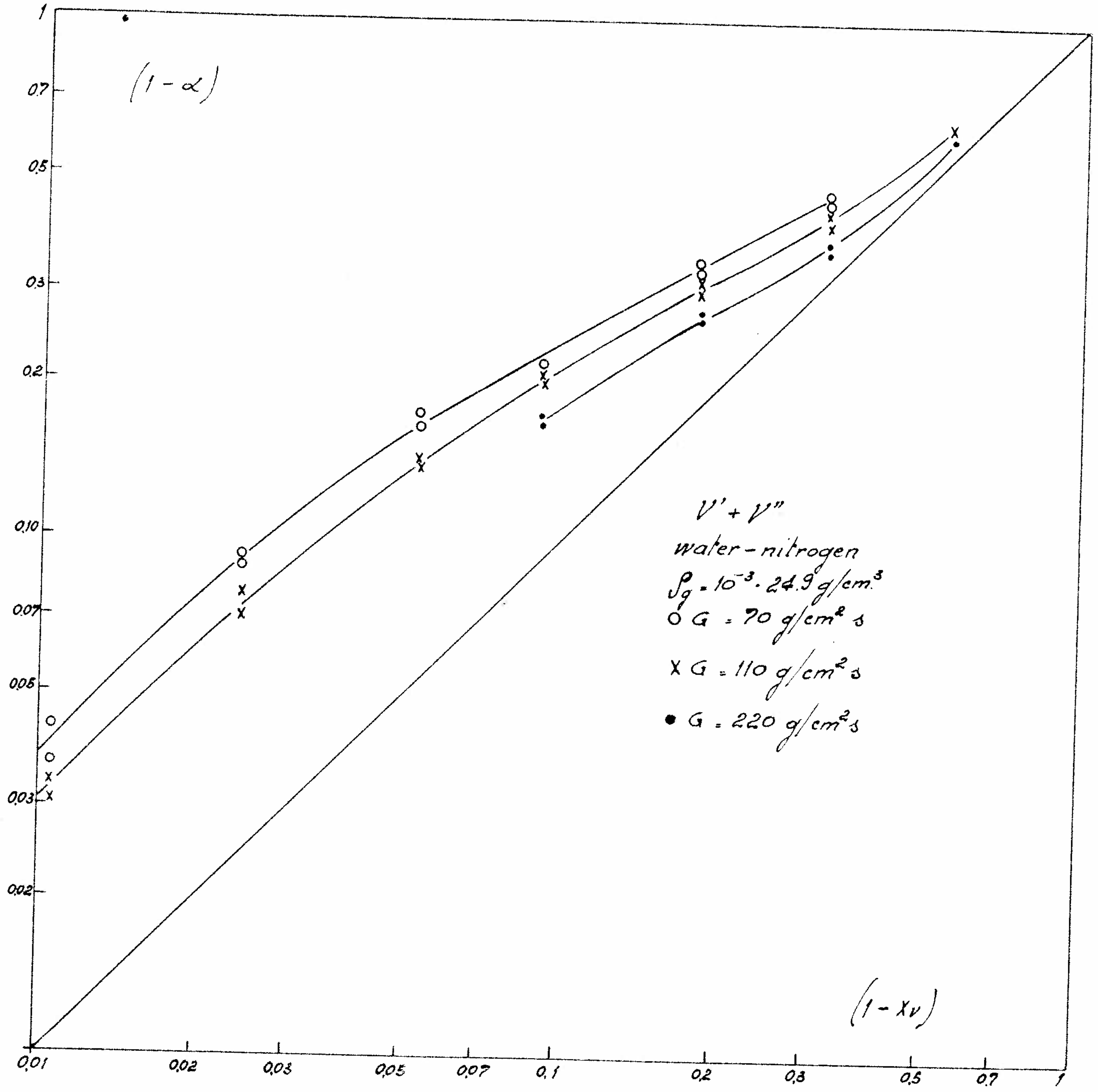


Fig. 27 - Liquid volume fraction in volume (V' + V") with two component mixture under adiabatic conditions.

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