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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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THE CIRCULATION OF FUEL IN TANKS AND THE PICK UP OF PETROL BY FOAM

by

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Summary

It is shown that it is possible to correlate the amount of petrol picked up by foam injected at the base of a petrol tank with the velocity induced in the rising stream of petrol. Only results obtained with small inlets are anomalous and some explanation is offered for this.

The relevance to the scaling of results obtained in small diameter tanks to large ones is also discussed.

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1. Introduction

Although it has been observed (1) that a foam layer produced by injecting foam at the base of a petrol tank arrives at the surface containing petrol, the mechanism of this pick-up is not yet fully understood. The concentration of petrol in the foam is presumably not the only factor in deciding whether a particular set of foam properties are suitable for base injection - the stability of the foam when on the petrol surface and subjected to radiation would be another- it is clearly necessary for this concentration of petrol to be less than some critical value. French and Hinkley concluded (1) that a petrol pick-up of less than 10 per cent of foam liquid was necessary for extinction. The present paper puts forward the hypothesis that the velocity of the petrol induced by the stream of foam is an important factor in determining the pick-up of petrol. One reason for supposing this to be so is that the pressure induced in the foam layer by the foam particles driven against it is determined largely by this velocity. This pressure is the same order of magnitude as the critical shearing strength of foam and as this property is known to be of great importance in determining the pick-up (1) (2) it is possible that the impact of foam particles against the coherent layer is also important. The results of relating petrol pick-up to the calculated velocity of the rising petrol support this view. The anomaly of certain results with small inlets or high velocities is discussed and it is suggested that it is a feature of small-scale experiments only. The rising velocity of the petrol is calculated from the analogy with turbulent heated jets for which theoretical and experimental results are available (a review is given by Batchelor (3)).

2. Tank circulation

At the top of the tank there will be a circulation of liquid of the form shown in Figure 1.

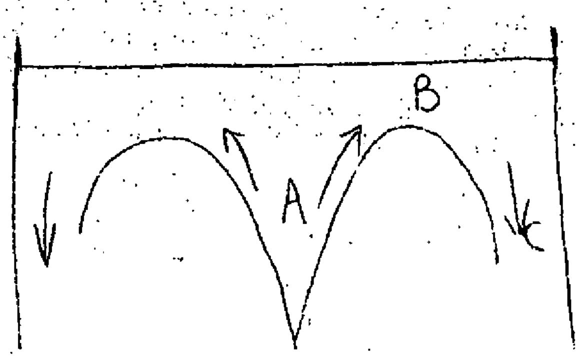

Figure 1. Circulation in tanks.

There are three regions

A. the rising jet of liquid and foam
B. radially moving liquid. - This carries foam from the point above the source towards the periphery of the tank.
C. a downward moving stream of liquid.

The assumption is made that C does not interfere with A. It is possible from the calculated cone angles of a jet in an infinitely wide tank to estimate the diameter of the jet at any height. Thus it can be stated whether a tank has a height/diameter ratio where A and C are separated. Clearly if this ratio is large the upward and downward circulation interfere.

Theory of jets

It should be possible to make use of the theory of turbulent heated jets to investigate the velocity distribution in a tank of liquid fuel when foam is applied in base injection. The analogy between the two systems has been discussed by Batchelor (3) and is based on the similarity between the two kinds of buoyancy forces. Owing to the fact that foam does not mix with the fuel the analogy is incomplete but the distribution of velocity in the oil should be of a similar form to that in a heated air jet.

One should consider a theory of vertical heated jets that includes an adequate consideration of conditions at the injection zone. This is generally considered to be a point source. In most theoretical treatments (see Batchelor (3) for a review) it is assumed that the distribution of velocity across the jet is similar at all heights. Above a finite source this similarity will only apply at heights above about 8 source diameters. In terms of tank heights and actual inlet diameters this is not a severe restriction. However, most theories assume the conditions at the source to be given by a certain quantity of heat (or weight deficiency). This leads to infinite temperatures and infinite velocities at the source of zero size. However, Priestley and Ball (4) give a theory that takes into account a given inlet velocity (or momentum) and a given heat flux (or weight deficiency). For a finite source, the jet is regarded as originating at a point a certain calculable distance below the actual source.

Although this makes a negligible correction to the total effective height at several diameters above the source it enters into the theory in a more direct manner as will be seen below and introduces certain complications.

The variation of vertical velocity with height is obtainable from dimensional considerations alone in the simple theory assuming an infinite inlet velocity. The form of the distribution of velocity across the jet is calculable according to one of several possible turbulent exchange theories, but may be assumed to be similar to the normal error curve.

In general, the form of this radial distribution may be regarded as of secondary importance as it primarily influences certain constants and the radial distribution of velocity is not of primary practical interest. If inlet conditions other than total flux of heat or, as in the present case, weight deficiency do not influence the velocity at the top of the jet, or alternatively, if we are considering low inlet velocities and large distances from the orifice, we have for heated vertical jets from a point source (3).

$$W \propto \frac{F^{1/3}}{Z^{1/3}}$$

where W is vertical velocity at height Z.
F is proportional to the heat flux.

Now the heat flux enters into the problem of the heated jet because it represents the driving buoyancy force. In mechanical units we have F in terms of weight efficiency

$$F = U\left(1 - \rho_f/\rho_L\right) g$$

where U is the volume flux at inlet

ρ_f is the density of the injected fluid - i.e. foam.
ρ_L is the density of the environment - i.e. liquid in tank.
g is the gravitational constant.

we have

ρ_L = 0.7 approx.
ρ_f = $1/E_m$

where E_m = Mean expansion of foam in tank.

Also $\qquad U = E_i \cdot a \cdot r$ (2)

where a = area of tank at fuel surface.

and r = rate of injection of foam liquid per unit area of tank surface.

The suffix i refers to inlet values.

3.1. The equation for vertical velocity

The equation for the velocity at the centre of the heated jet given by Priestley and Ball (4) is, in their notation

$$W^3 = \frac{3Ag}{2\theta_e c^2 z^2} + \frac{B}{z^3} \qquad \text{.................(3)}$$

$$\text{where } A = Q/\pi \rho c \qquad \text{.................(4)}$$

Q is total heat flux

ρ is density

c is specific heat

θ_e is absolute ambient temperature

C is a constant of order 0.1 determining the cone angle of the jet,

and B is a constant.

It is now necessary to find the constant B in terms of the boundary conditions of the problem and then convert into weight deficiency units.

Following Batchelor (3), if F is as defined as in equation 1, $\frac{c\rho\theta_e F}{g}$ is the heat flux - which may be equated with Q.

Thus from equation 4

$$\frac{Ag}{\theta_e} = \frac{F}{\pi}$$

B may be found as follows. The momentum flux is $\rho_c \pi C^2 z^2 w^2$

and near the source this tends to $\rho_f \frac{\pi d_i^2}{4} V_i^2$

where d_i is inlet diameter

V is inlet velocity of foam

$$0.7 C^2 z^2 w^2 = \frac{d_i^2 V_i^2}{4E_i}$$

$$\therefore B = \left(\frac{1.43}{E_i}\right)^{3/2} \left(\frac{V_i d_i}{2C}\right)^3 \qquad (5)$$

For a vertical heated jet Yih [5] (see also Rouse, Yih and Humphreys [6]) quotes the maximum velocity at the centre as

$$W = \frac{4.7\,F^{1/3}}{Z^{1/3}}$$

so that we can obtain a value for 'c' from

$$\frac{3}{2\pi c^2} = 4.7^3$$

$$\therefore \quad c = 0.068$$

$$\therefore \quad W^3 = \frac{104\,F}{Z} + \frac{0.90}{F^{3/2}}\left(\frac{V_1 d_1}{Z}\right)^3 \quad ft^3/s^3 \qquad (6)$$

'W' can then be calculated from equations 1, 2 and 6. Tank dimensions and rate of flow are given in ft-sec units, while shear stress is given in dyne/sq.cm. Calculated values of 'W' are given in both ft/sec and cm/sec, while the values of W^2 are given in units of ft and cm head i. e. $\frac{W^2}{2g}$.

It must be borne in mind that in experiments where inlet energies do not matter compared with those involved in the buoyancy, the existence of only the first of the two terms in the expression for W^3 means that an incorrect value for 'C' affects all values of 'W' alike, but where both terms are important, an error in 'C' affects the compounding of the two terms. Thus, from a quantitative view point, the chosen value for 'C' is important primarily if experimental data are included where inlet energies are important.

The total amount of fuel 'S' moving in the stream 'A' can be calculated if the radial velocity distribution is known. Assuming the normal error distribution we have this amount as:

$$S \doteq 2\pi w \int_0^\infty r\, e^{-r^2/2c^2z^2}\, dr$$

where "r" denotes radial distance

i. e. $$S = 2\pi c^2 z^2 w \qquad (7)$$

For N inlets the total flow is N.S.

4. Application to Base Injection

4.1. The units of petrol pick-up

If all experiments to be correlated were made at the same expansion (and gave similar drainage rates), the value of petrol pick-up to be used in the correlation could be expressed either as per unit of liquid or per unit of foam. However, expansion was varied from 3 to 10 in some experiments but only on the large tank (30 ft x 9 ft)[1]. If the pick-up of petrol is associated with the impact of foam flakes on the foam blanket the inertia of the foam will be important. Thus associated with W^2 the appropriate density should be that of the foam. If this is so, the pick-up should be measured relative to the liquid content. This is the basis of measurement adopted previously [1] [2] and continued here.

4.2. Results.

Based on the results of French and Hinkley [1] [2], Figures 2 and 3 show the petrol pick-up per unit quantity of liquid at the surface, as a function of the calculated value of W^2 for the two principal compounds used. Some of the data involved in these graphs (for example, the mean expansion Em) has had to be estimated. It is sufficient to take this mean expansion as the mean of the inlet and surface expansion as these do not differ by more than 30 per cent for the large tank or by more than 15 per cent for the small tanks.

In the experiments on the large tank, the shear strength was not constant. These variations for the large tank experiments account for the use here of a "best" line for a given shear strength equal to that used in the small scale results. This time is calculated from the formulae given by French and Hinkley (2)

4. 3. Discussion of results

It is seen in Figure 2 that the correlation between the data for the large tank varying expansion and that for the small tank varying rate of flow is satisfactory. The data obtained by varying velocity on the small tank do not, however, correlate with the other results.

It is not thought (7) that injecting foam through the small orifices necessary to obtain high inlet velocities for a given rate affects the shear strength of the foam, though if it does so it might explain the increased pick-up. This matter is discussed further below.

4. 4. Dimensional Analysis.

The forces arising in the system would be gravitational, inertia, viscous and those arising from surface and interfacial tensions.

The gravitational stresses in the flake are of the order

$$S_g = l\left(1/\epsilon + 0.7\epsilon\right) g$$

where l is the linear size of particle

ϵ is the concentration by volume of petrol in the foam.

Therefore for $l \approx 1$ cm

and $\epsilon \approx 0.02$.

we have $S_g \approx 300$ dynes/sq. cm.

The viscous forces in the drag on the rising foam can be shown to be negligible in comparison with the inertia fires. However, viscous forces might be important in the foam layer itself. The velocity there would be very small but to overestimate the viscous forces we assume the velocity to be 0.1 cm/sec.✱ To obtain a stress of 300 dynes/sq.cm. the half thickness of a film of petrol would be that given by Δ where

$$300 = \frac{0.003 \times 981 \times 0.1}{\Delta}$$

$$\text{i.e. } \Delta \doteqdot 10^{-3} \text{ cm}$$

0.003 gm. $cm.^{-1}$ sec^{-1} being taken for the viscosity of petrol at 20°C. The petrol concentration by volume in the foam is 0.02 so that the equivalent thickness of a film 1 sq. cm. is 0.02 cm. This implies that there would have to be at least $\frac{0.02}{2 \times 10^{-3}}$ i.e. 10 "layers" of petrol/cm. This is a very much higher degree of dispersion than was in fact observed (2) and therefore viscous forces in the petrol of the foam layer are neglected.

Surface and interfacial tensions 'f' are of the order 5-20 dynes/cm for foam compound & say, 30 dynes/cm for petrol. A small degree of dispersion, say globules 1 mm diameter, would produce stresses in the foam of the same order as the gravitational, the inertia and foam shear.

A dimensional analysis could therefore proceed as follows. The dependent variable can be expressed as a volume to volume concentration "ϵ". In addition to "g", "w", "s" and "ϵ" there are ratios of the foam and petrol densities ρ_f/ρ_c and δ_f/δ_c e. g. the ratios of the surface tension of petrol and the interfacial tension between foam solution and petrol. Also it is probable that the foam particle size "l" is a factor affecting the petrol pick-up. This will be dependent on the inlet conditions but may be regarded

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✱ At this velocity petrol would drain from an inch layer of foam in less than half a minute.

as an independent variable from the point of view of petrol pick-up. We may write

$$G = f_1\left[\frac{sw^2}{\gamma g}, \frac{\rho g \gamma}{s^2}, \frac{s l}{\gamma}, \frac{\rho_f}{\rho_l}, \frac{\gamma_s}{\gamma_s}\ \text{etc}\right]$$

where f_1 is an unknown function.

In this formula "s" and "w" appear in three independent dimensionless groups, but it can be seen that "w" only appears in the form "sw^2". Alternatively, the groups can be written as

$$G = f_2\left[\frac{sw^2}{\gamma g}, \frac{\rho w^4}{\gamma g}, \frac{w^2}{l g}, \frac{\rho_f}{\rho_r}, \frac{\gamma_f}{\gamma_s}\ \text{etc}\right]$$

where "s" only appears as "sw^2".

Thus a first step in correlating "G" with "s" and "w" is to plot "G" against "sw^2". This is shown in Figure 4 where, the results for the experiments in which velocity was varied by reducing the diameter have been excluded. The correlation for the two different compounds comemuch nearer together. Apart from the data from Figures 2 and 3 Figure 4 includes data given by French and Hinkley (2) for foams, produced with the same inlet conditions, but with various shear strengths from compounds other than A and B. Results for different concentrations of A and B are also included. There is some scatter, some of it due to experimental variation and some possibly due to variation in the parameters $\frac{\rho g \gamma}{s^2}$ and $\frac{s l}{\gamma}$.

In discussing this, it may be noted that the pick-up for Compound B tends to be slightly greater than that for Compound A at equal values of "sw^2". If this is due to the other variables $\rho g \gamma / s^2$ and $s l / \gamma$, data for a given W^2 and varying "s" (e.g. that referred to by X'S in Figure 4.) would be expected to have a smaller slope than the data for a given "s" and varying "w^2 e.g. that used in Figs. 2 and 3. While this is seen to be so for the foams of high shear strength, it is not so for the lower shear strength foams, the slope appearing to be greater for these. These effects appear, however, to be secondary to the effect of "sw^2".

4. 5. The high petrol pick up with small inlets.

The size of the flakes were at no time measured, but according to French and Hinkley (7) the flake size decreased, the lower was the critical shearing stress of the foam. Also for inlets less than 5/16 in. diameter, the flake size appeared to decrease the smaller the inlet. For inlets greater than 5/16 in. diameter, the flakes were of the order $\frac{1}{2}$ - 1 cm in. diameter and did not appear significantly larger with the 2 in. diameter inlet with 30 ft. of petrol.

Little or no data are available for foams, but for air bubbles the linear size increases as a fractional power, viz., the one-third power, of the inlet diameter and may, for reasons of stability, reach a maximum size (8) or random size distribution presumably independent of inlet conditions. If this is so the few observations of flake size would be consistent with it, and the fact that the effect of inlet size is only marked at small inlet sizes would be understandable. Because decreasing "l" the flake size increases the surface of foam per unit volume one would expect the pick-up to be relatively higher for small flakes.

4.6. American Test

A number of experiments, including many at small scale, have been made in the U.S.A. by Tuve & Peterson. (9). In these the time to extinguish the fire was measured and an estimate was made of the limiting condition at which extinction was possible. Since their results are given in terms of drainage time, not shear strength, no direct comparison is possible with the early experiments of French & Hinkley in which shear strength, but not drainage, was measured.

The two properties are for any one compound, closely related and in recent work at the Joint Research Organization on foam, both drainage and shear strength have been measured.

However, if it is assumed that where drainage was not itself a limiting factor by being either too low or too high, the shear strength of the foams used by Tuve & Peterson is similar to that obtained with compound B, it may be calculated that where drainange is not a limiting factor, the maximum value of $\frac{w^2}{2g}$ for any of the experiments was 0.05 ft (1.5 cm) approximately. This, however, was for a condition with an inlet velocity of 25 ft/sec and an inlet diameter of approximately 0.095 in. It will be seen that in Figure 2 this critical value of $\frac{w^2}{2g}$ is approximately that giving a pick-up of petrol for Compound B, equal or not much less than the critical amount of 10 per cent. On the other hand, the small inlet would presumably have increased the pick-up above this estimated figure.

Also, it has not proved possible, in view of the limited data, to correlate the "anomalous" results for small inlets for the two compounds A and B in Figures 2 and 3 with each other or with the results of Tuve & Peterson for small inlets.

There is also one full-scale test reported for petrol. This had a 10 in. depth of petrol above about $15\frac{1}{2}$ feet of fuel oil. The conditions of the test were:-

Tank size 93 ft. diameter.
Depth of fuel 16 ft. 4 in.
Rate 3200 g.p.m. foam (United States gallons.)
Inlet orifice diameter = 12 in.

For these conditions it is possible to calculate "w"
From equations 1 and 6 for one inlet

$$w = 10 \text{ ft/sec (inlet velocity 9.2 ft/sec).}$$

and for two inlets

$$w = 8 \text{ ft/sec (inlet velocity 4.6 ft/sec.)}$$

It is noteworthy that both these inlet velocities are much lower than was found to be suitable for extinction in the small-scale tests (9), and this might be taken to support the view that allowable inlet velocity is not independent of scale.

From Figures 2 and 3, it is seen that the expected petrol pick-up in the test with two inlets is much greater than 10 parts per 100 of liquid, and from a comparison with the results of French and Hinkley extinction might not have expected. While it might be thought from this that the large-scale behaviour cannot be predicted from small-scale, it must be pointed out that the flow of liquid in the rising stream calculated from equation 7 is too great for the experiment to be regarded as pertaining to petrol. Thus from equation 7

$$S \doteq 73 \text{ cub ft/sec for one inlet.}$$
$$\doteq 115 \text{ cub ft/sec for two inlets.}$$

Now foam was applied through one inlet for 5 minutes and through two inlets for 9 minutes, making the total of oil circulated 70,000 cub ft. This is about thirteen times the amount of petrol present (5,600 cub ft.) so that considerable mixing would have occurred and the results cannot necessarily be regarded as pertaining to petrol.

4.7. Application to large tanks.

4.7.1. The number of inlets necessary.

If we take S = 160 dynes/sq. in. then "w" must be less than about 2 ft./sec. for the petrol pick-up to be less than 10 per cent. (See Figure 3.) In what follows it is assumed that the correlations in Figure 3 can be applied to large diameter tanks. This assumption is discussed in the following section.
If $E_i = 3.5$, R = 1/16 g.p.m. sq.ft. (= 1/(16 x 375)ft/sec.) then from equation 6 which can now be regarded as applying to each stream of foam we have

$$8 = 7.9\left[\frac{D^2}{10HN}\right] + \left(\frac{21}{10d}\right)^3\left(\frac{D^2}{10HN}\right)^3$$

where D = diameter of tank in ft.
H = depth of petrol in ft.
N = number of inlets
d = diameter of inlet in ft.

If "d" is over 1 ft. the second term is negligible in comparison with the first, for $\frac{D^2}{10HN}$ is approximately unity.

For a 100 ft. diameter tank and H = 30 ft., N must be 33, giving an inlet velocity of 0.18 ft/sec. This is the smallest number of inlets that can be used. The value of N depends on w^3 and, in view of the scatter in Figures 2 and 3 there is some ambiguity in the necessary value of w. Taking the point P in Figure 3, w = 2.5 ft/sec and the estimate of N is reduced to 17. Despite this ambiguity, these results suggest for large tanks of petrol base injection cannot make use of the existing installations and requires a special construction. Since this conclusion is at variance with previous thought on this subject, it becomes even more imperative to conduct full-scale trials.

4.7. 2 . Possible scale effects

There are, however, some grounds for thinking that the above discussion presents an incomplete view of the situation. It has been suggested that pick-up is associated with the impact of individual foam particles with each other, in particular with the foam layer. In small diameter tanks the foam particles move to the tank wall before joining together in a foam layer, and this means that the individual particles are forced against a foam layer which is restrained by the tank wall. For a very large tank this will not be so.

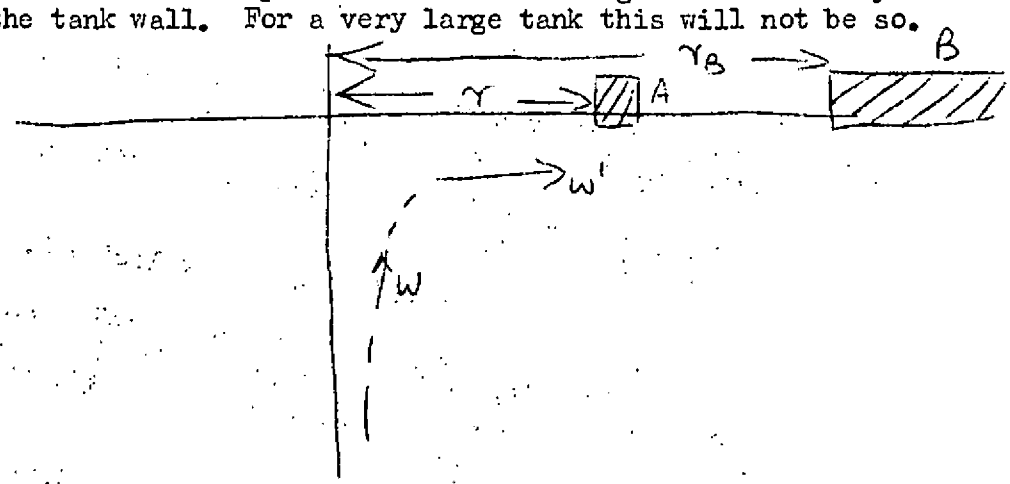

Figure 5

In Figure 5 it is seen that the velocity of the foam particle A is determined by the local velocity w^1 of the radially moving stream. w^1 is of the same order of magnitude as w near to the rising stream but is also dependent on the value of "r". However, since w decreases as "r" increases it follows that the pick-up of petrol when particle A joins the layer B is less, the greater is "r_B". Now the greater the diameter of the tank the greater the amount of foam in the rising stream. This may well tend to decrease the distance "r_B" at which separate foam particles form together. This would tend to raise the petrol pick-up. There will, however, be an opposite effect since there is a maximum size of tank at which the layer forms at the tank wall. For tanks greater than this critical size, foam particles will join a layer of foam which is, at first, moving radially because it is unrestrained by the tank wall. Under these conditions the impact velocity will be less and so presumably will the petrol pick-up.

It is not possible to say which of these two effects is predominant or whether they are of importance at all. It is, however, clear that it may not necessarily be possible to deal with the problem of large diameter tanks by extrapolation from the data for small diameter tanks.

Similar considerations would apply if the petrol pick-up was determined by an amount initially picked up as the foam particle reaches the free surface and the amount actually present in the layer determined by the drainage in the time to travel across the petrol surface to the coherent foam layer.

5. Discussion and conclusions

The hypothesis that the petrol pick-up is dependent on "w" the velocity with which petrol or other fuel reaches the surface correlates a number of different experiments at different scales and the behaviour of two different compounds. The principle anomaly is the effect of small inlets and some tentative explanation of this has been put forward. This is that small inlet diameters may reduce the foam flake size below a critical size normally determined by foam shear strength, interfacial tension and stability considerations. The theory otherwise seems capable of allowing for the other effect of inlet conditions on the magnitude of "w".

There do not appear to be any grounds, theoretical or otherwise, for assuming that the allowable velocity of injection is independent of scale: the theory suggest that the rate of flow per inlet is a more important, but not the only criterion. Since on the assumption that the small experiments can be used to predict behaviour in tanks of 100 ft diameter, the number of inlets calculated to be necessary is sufficiently large to rule out the successful use of a single product line inlet, it is particularly necessary for full-scale tests to be carried out.

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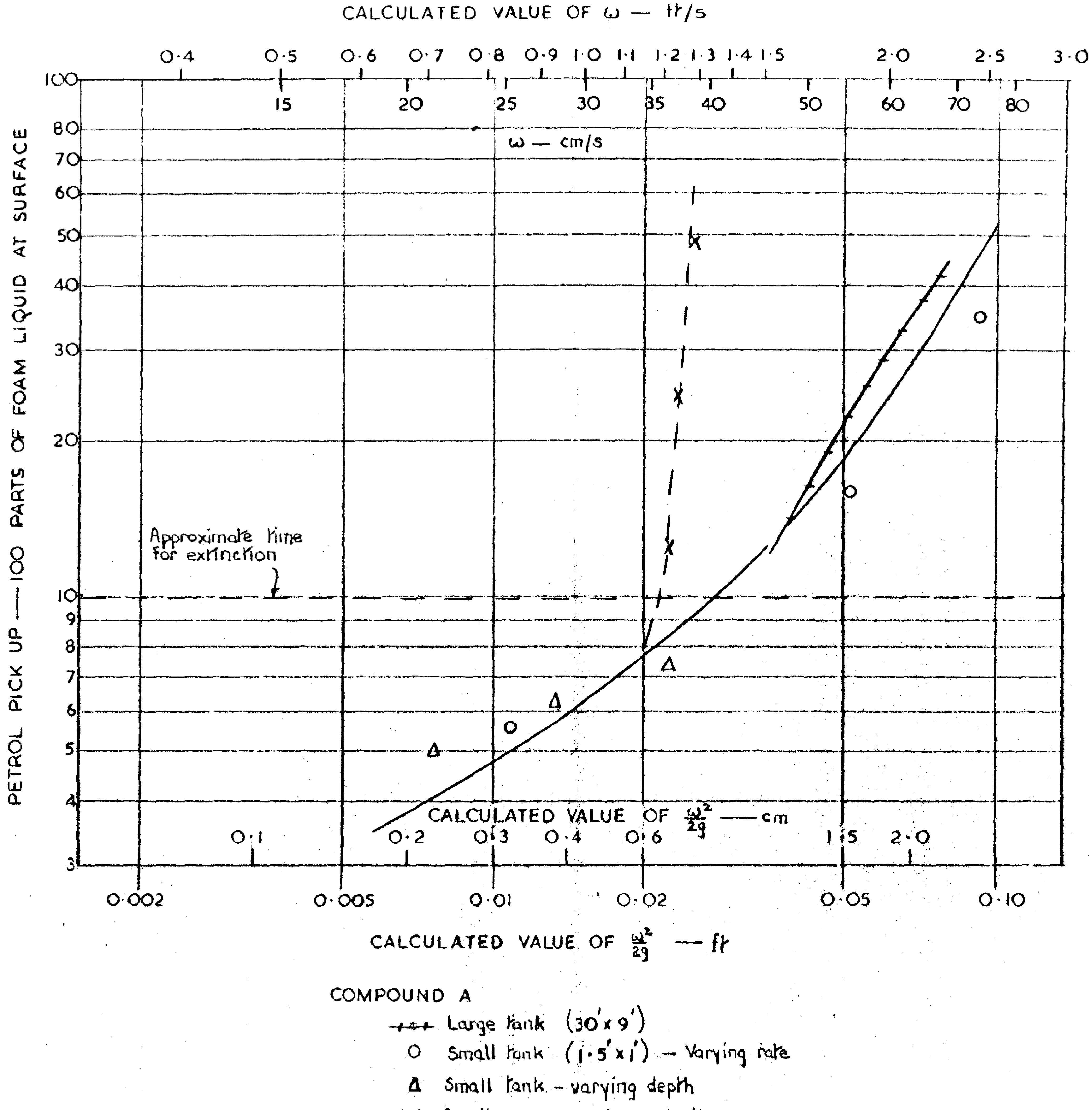


FIG. 2. PETROL PICK UP AS A FUNCTION OF VELOCITY HEAD OF RISING PETROL FOR COMPOUND A

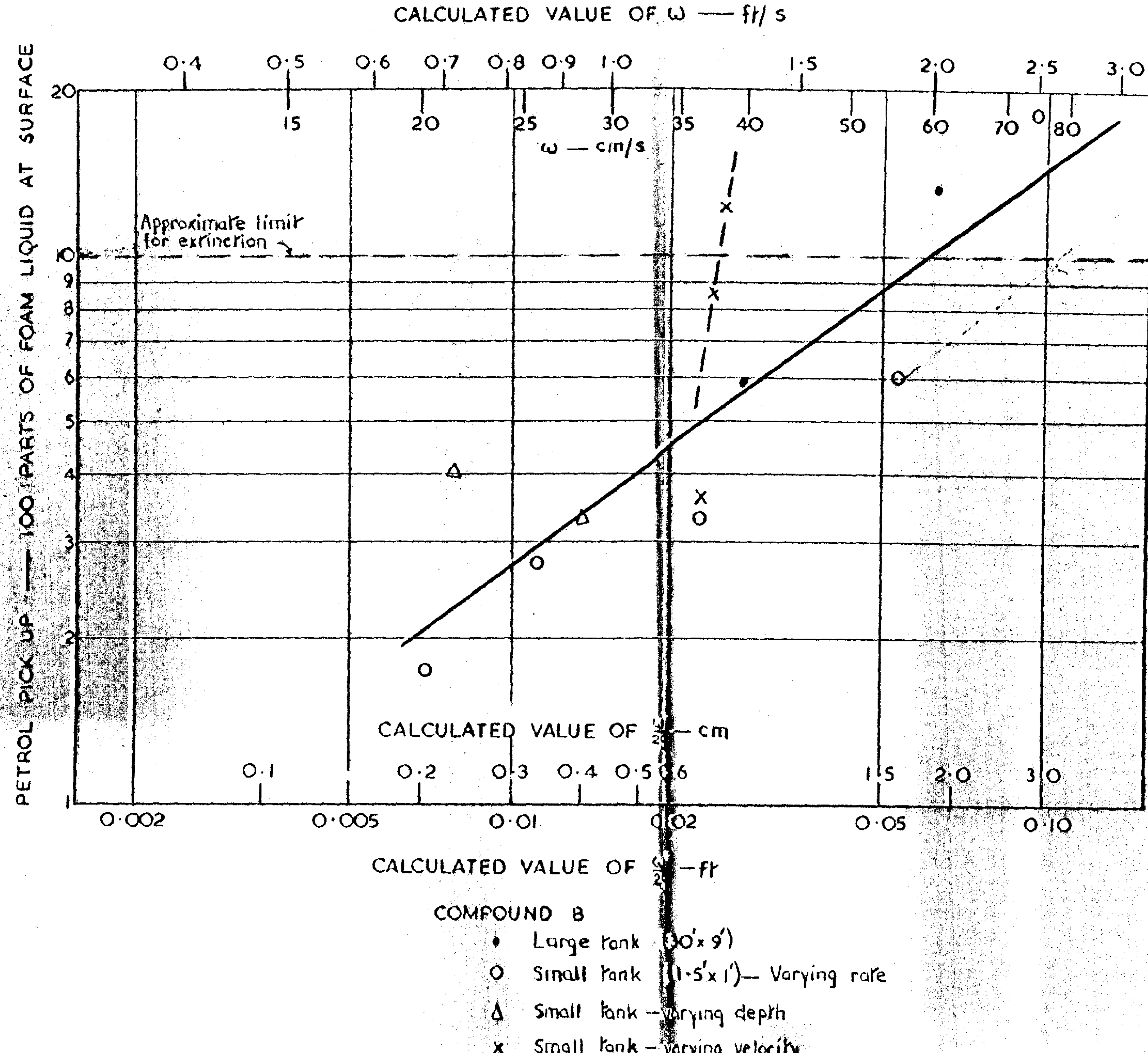
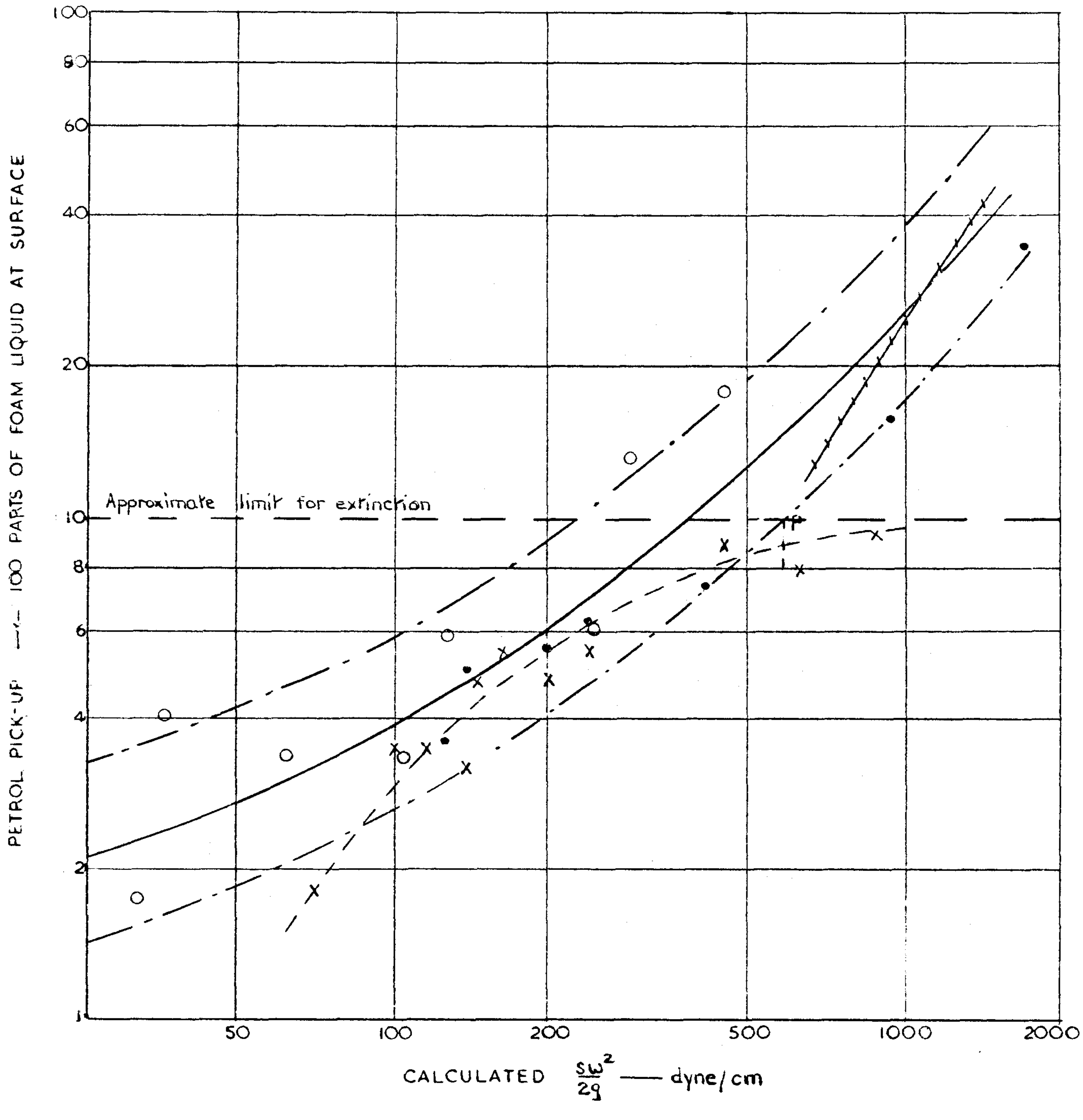


FIG. 3. PETROL PICK UP AS A FUNCTION OF VELOCITY HEAD OF RISING PETROL FOR COMPOUND B



o Compound B — s = 160

• and +++ Compound A — s = 590

x Compounds A + B + others at various values of 's'

FIG. 4. PETROL PICK-UP AS A FUNCTION OF $\frac{sw^2}{2g}$