Paper 17

AERATION IN HYDRAULIC SYSTEMS—ITS ASSESSMENT AND CONTROL

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Air can exist in a hydraulic fluid in two forms—dissolved air and entrained air. Dissolved air has no appreciable effect upon the mechanical properties of the fluid but entrained air creates a serious problem, largely because it produces a great reduction in bulk modulus.

Problems being investigated at the National Engineering Laboratory (N.E.L.) include methods of measuring the bubble content and the dissolved air content of hydraulic fluids, the effect of air bubbles upon the viscosity of oil, the solubility of air in various fluids, the rate at which air bubbles dissolve in oil when its pressure is increased, and the precipitation of dissolved air to form bubbles when the pressure on a fluid is reduced. A well-known formula for the effect of entrained air upon the bulk modulus of oil is discussed and shown to be wrong.

The paper concludes with a set of rules which the practising hydraulic engineer can apply in order to avoid aeration troubles.

INTRODUCTION

THE SUBJECT OF AERATION in hydraulic circuits is a complicated one. One of the difficulties in the way of a clear presentation of the subject is that the term 'aeration' conveys different ideas to different people.

It will, therefore, be necessary to begin by stating the various factors involved in aeration, which together give a picture of the phenomena covered by the term.

This will be followed by a description of the research into various aspects of aeration which is at present going on at N.E.L., together with a summary of the results obtained so far.

Finally, some suggestions will be made as to how the hydraulic engineer can apply this knowledge and so avoid aeration troubles in his circuits.

FACTORS INVOLVED IN AERATION

Dissolved and entrained air

Air may be present in oil either as dissolved air or as entrained air. Dissolved air is part of a homogeneous single-phase having entirely the properties of a liquid; entrained air normally occurs as small bubbles distributed in the oil, which may aggregate as larger pockets of air trapped between the surface of the oil and a solid boundary, for example, at the top of a pipe.

In a normal hydraulic system dissolved air is always present but entrained air ought not to be found. Entrained air may be produced in two ways:

(1) mechanically; for example, by agitating a free surface of oil in contact with air, or
(2) by the release of dissolved air.

The solubility law

According to Henry's law the solubility of a gas in a liquid is directly proportional to the partial pressure of the gas. This law has been verified by various workers with very many combinations of liquids and gases. In the case of air the solubility of oxygen and nitrogen is governed by their separate solubility coefficients, which are such that oxygen dissolves rather more readily in almost all liquids than nitrogen. If this effect is ignored, the solubility of air in oil can be taken as being proportional to the total absolute air pressure. Tests at N.E.L. with air and a typical hydraulic oil showed that this adhered very closely to the law (Fig. 17.1).

The solubility of air in a liquid may, therefore, be expressed as 'x per cent per atmosphere', where 'x per cent' is the ratio of the volume of dissolved air (reduced to S.T.P.) to the volume of liquid. The value of 'x' is about 2 for water, between 6 and 12 for mineral oils, and between 15 and 25 for fuels and silicone fluids.

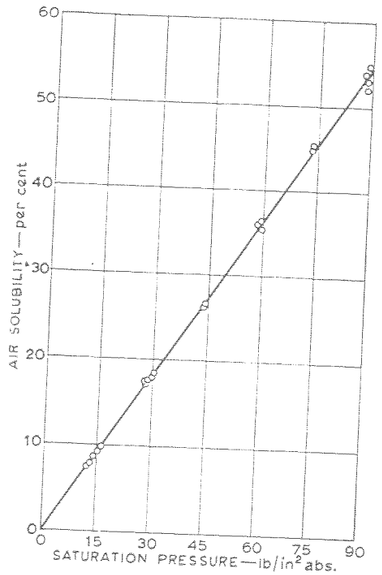

Fig. 17.1. Pressure-solubility curve for air in Tellus 21 hydraulic oil

Degree of saturation

A solution of air in liquid is said to be 'saturated' when it is in stable equilibrium whilst in contact with an excess of undissolved air. A liquid may temporarily hold more than this equilibrium amount of dissolved air; in this case the solution is said to be 'supersaturated', and the excess of dissolved air will tend to be released. If the liquid holds less than the equilibrium amount of dissolved air the solution is said to be 'undersaturated' and it will tend to dissolve more air until equilibrium is reached.

This is of great practical importance. If oil containing entrained air is compressed, the solubility rises with the pressure and the oil becomes undersaturated, so that the entrained air will tend to dissolve. On the other hand, if saturated oil, free from entrained air, is subjected to a drop in pressure, the solubility will drop, the oil will become supersaturated, and air will tend to come out of solution and become 'entrained air'.

Rate of solution and evolution

The rates at which an undersaturated solution dissolves air and a supersaturated solution evolves air are difficult to predict. They are affected by pressure, temperature, the degree of agitation of the liquid, the nature of the liquid and, probably, by other factors too.

The rates are proportional to the area of the air–liquid interface; as a result, evolution is generally far more rapid than solution, since the evolution of bubbles greatly enlarges the interfacial area.

Effect of dissolved air

Dissolved air, in the concentrations in which it occurs in the oil in a normal hydraulic circuit, is generally assumed to have no measurable effect upon the mechanical properties of the oil.

To check this, comparative tests have been made on a hydraulic oil saturated with dissolved air at atmospheric pressure (air content 8 per cent) and on the same oil after deaeration (air content $\frac{1}{4}$ per cent). The viscosity and the bulk modulus of the oil were measured before and after deaeration and both were found to be unchanged.

It may be regarded as an established fact that air, so long as it remains dissolved, does not materially affect the viscosity and the compressibility of oil.

Effect of entrained air

Air at atmospheric pressure is more than 10 000 times as compressible as a hydraulic oil. Even a small quantity of entrained air will, therefore, cause an appreciable reduction in the 'stiffness' of a hydraulic system. It is also held by some authorities that the sudden compression of entrained air when it passes through a pump results in local overheating, with subsequent oxidation of the oil and damage to pump surfaces. This may be so if the air passes through the pump in large gulps, but experience at N.E.L. suggests that normal-sized bubbles are likely to compress isothermally and not adiabatically.

The existence of entrained air thus creates a serious problem. This paper is, therefore, concerned with the problem of entrained air in hydraulic circuits: the factors leading to its formation, the magnitude of the effects caused by it, and some methods of preventing its occurrence.

RESEARCH AT N.E.L.

Measurement of bubble content

'Bubbly oil' may be defined as oil in which discrete bubbles of gas are entrained, and are separated from each other by relatively thick films of oil. This definition distinguishes bubbly oil from 'foam', in which the bubbles are closely packed.

It is worth mentioning that foam is not normally a problem in hydraulic circuits, but bubbly oil often is. Silicone additives which inhibit foaming also tend to stabilize bubbly oil by reducing the rate at which bubbles rise to the surface. Thus on balance antifoaming agents in a hydraulic oil may do more harm than good.

Considering the important subject of 'bubbly oil', an essential preliminary to research with this material is a reliable method of measuring its bubble content. This may be defined as the ratio of the volume of bubbles to the total volume of bubbly oil, expressed as a percentage. Three methods have been developed (1)* and are shown in Fig. 17.2.

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* *A numerical list of references is given in Appendix 17.III.*

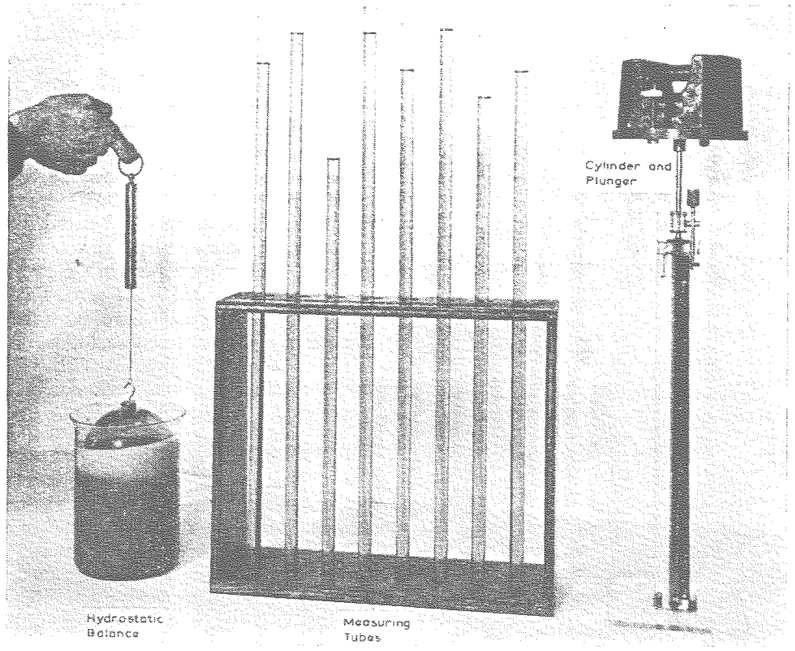


Fig. 17.2. Instruments for the measurement of bubble content

The hydrostatic balance with a large sinker, loaded so that it only just sinks in the bubbly oil, is the most accurate method but can only be used when fairly large quantities of oil are available.

The specially made measuring tubes are useful when a slowly flowing stream of bubbly oil has to be sampled. They are of 100 ml. capacity and are graduated from zero at the top to 100 at the bottom by 0·2 ml. divisions. These are filled to overflowing and allowed to stand for an hour or two until all the bubbles have disappeared; the surface level of the oil then indicates directly the original bubble content as a percentage. If the bubbly oil is warm at the time of filling the tubes a correction is applied on account of thermal contraction.

When a quick reading is needed the cylinder-and-plunger apparatus is used. The cylinder is filled to overflowing, then the cap is screwed on and the plunger, which carries a weight of 15 lb, is inserted. This creates a pressure of 300 lb/in^2 and forces the air bubbles to dissolve. The consequent reduction in volume is measured by the movement of the plunger against a scale, which is calibrated directly in percentage bubble content.

Bubble size distribution

A photographic method has been used to measure the sizes of the bubbles in a sample of bubbly oil. A sample is rapidly trapped in a film $\frac{1}{16}$-in. thick between a sheet of black plastic and a sheet of transparent plastic, and then photographed. By examining an enlargement the proportion of bubbles in each size group can be estimated.

Samples of bubbly oil produced in several different ways were thus examined, and it was found that in every case a similar size distribution of bubbles was obtained, the great majority of bubbles being in the size range 0·010 to 0·020 in. diameter. The measurements were all made at atmospheric pressure and room temperature. It was concluded that this size of bubble is that most likely to occur in practice. Bubbly oil of this type is, therefore, employed in all the experiments at N.E.L.

Viscosity of bubbly oil

Leakage oil from hydraulic machines or pressure-fed bearings often contains a high proportion of bubbles, and in this condition is allowed to flow under gravity through pipes to a sump where the bubbles are allowed to separate. If the pipework is to be designed efficiently a knowledge of the effect of air bubbles upon the viscosity of oil is necessary. This knowledge did not appear to be available and a special viscometer for measuring the viscosity of bubbly oil has, therefore, been built (2).

This viscometer, shown in Fig. 17.3, is of the efflux type, but it differs from conventional efflux viscometers in having a very large 'cup' which takes the form of a perspex tank about 2 ft high and 1 ft square. This is needed in order to

ensure that the bubble content of the oil remains constant throughout the test.

Oil is pumped into the tank through an aerator, which resembles a simple Venturi-jet suction pump. Atmospheric air is sucked into this aerator and by controlling the rate of admission of air the bubble content of the oil emitted from the aerator can be regulated. Bubbly oil thus enters the tank at a rate of about 10 gal/min. Most of it passes out again over a weir at the top of the tank, but some of it flows out under a constant head through the viscometer tube, which is set in one wall of the tank about 6 inches above the bottom.

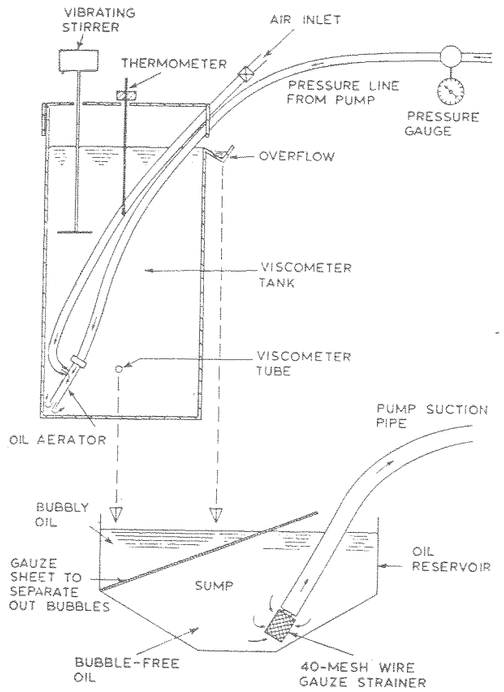


Fig. 17.3. Bubbly oil viscometer

The viscometer tube is of steel with a honed bore $\frac{1}{4}$ inch in diameter and is approximately 6 inches long. The rate of flow of the oil passing through it is measured with a measuring cylinder and stop-watch and its bubble content with the measuring tubes described in the section on Measurement of Bubble Content.

A large number of tests was made with each oil over the range of bubble contents 0–25 per cent, and at temperatures from 20 to 45°C. The flow rates of the same oil in a bubble-free condition were also measured over the same temperature range. Then if Q_B and Q_0 are the flow rates and μ_B and μ_0 are the viscosities of bubbly and bubble-free oil respectively (at identical temperatures) and p_B and p_0 are the calculated pressure drops through the viscometer tube:

$$\frac{\mu_B}{\mu_0} = \frac{Q_0}{Q_B} \cdot \frac{p_B}{p_0} \quad . \quad . \quad . \quad . \quad (17.1)$$

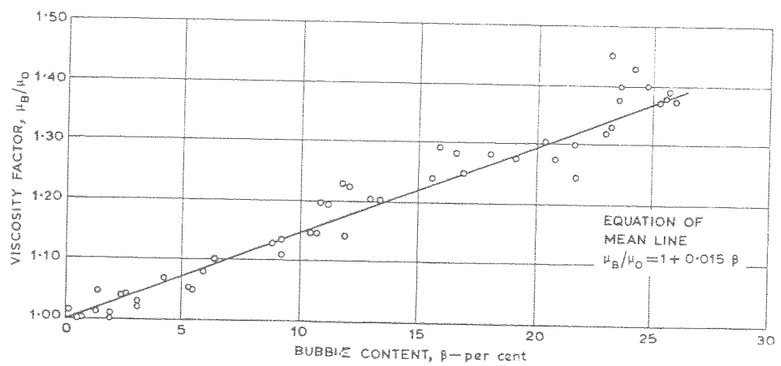
The ratio μ_B/μ_0 has been termed 'viscosity factor' and is a measure of the effect of the air bubbles upon the viscosity of the oil. It is shown plotted against bubble content for a straight mineral oil of viscosity 30 cS at 30°C in Fig. 17.4.

Two important conclusions are apparent from Fig. 17.4. Firstly, that the effect of air bubbles upon viscosity is relatively small and for low bubble contents can be neglected for practical purposes. Secondly, that the increase in viscosity is directly proportional to the bubble content according to the empirical law:

$$\frac{\mu_B}{\mu_0} = 1 + 0{\cdot}015\beta \quad . \quad . \quad . \quad (17.2)$$

where β is the percentage bubble content.

Two hydraulic oils containing anticorrosive, antioxidant and antifoaming additives were also tested. These had viscosities of 30 and 170 cS at 30°C. They both gave



Viscosity 30 cS at 30°C

Fig. 17.4. Viscosity factor against bubble content for straight mineral oil

results agreeing with the law expressed in equation (17.2). It, therefore, seems reasonable to suppose that all normal oils are likely to follow this law, so that it may be used for design purposes with any oil.

Measurement of dissolved air content

Since the liability of a hydraulic fluid to release air bubbles from solution depends upon its degree of saturation, it is necessary to be able to measure the content of dissolved air of a fluid. The normal methods of measuring this quantity involve the use of complicated and fragile apparatus. Research at N.E.L. has been directed to the development of simple portable instruments suitable for use in engineering laboratories and workshops.

The first of these instruments was introduced by Firth and Kane (3). This gives satisfactory results with low viscosity oils at atmospheric pressure, but is subject to a number of limitations. It cannot be used with viscous oils or with fluids of appreciable vapour pressure, such as water-based fluids, and it cannot be used to sample oil in a system under pressure or under vacuum.

Two new instruments have recently been introduced (4) of which the most versatile is the 'funnel' apparatus shown in Fig. 17.5. The sample bottle is first detached from the rest of the apparatus and completely filled with oil in a manner that excludes all extraneous air. The bottle shown is for use with oil at atmospheric pressure; bottles of another design may be used to sample oil in a system under pressure or under vacuum without exposing it to atmospheric pressure. When filled, the bottle is connected to the funnel-shaped chamber, as shown, with the connecting valve shut. Next the chamber is evacuated to a pressure of about 0·02 mm of mercury absolute and the valve leading to the vacuum pump is then closed so as to isolate the chamber. Then the sample bottle valve is opened to admit the oil to the chamber where it gives off its dissolved air. The de-aeration process is greatly accelerated by the inclusion of a vibrating stirrer in the chamber.

The liberated air causes the pressure in the chamber to rise slightly. This pressure rise is measured with a 'Vacustat' vacuum gauge and since the volumes of the sample bottle and the chamber are known the original air content of the sample may be calculated by applying the gas laws.

This apparatus is easier to use than that of Firth and Kane and has been used successfully with highly viscous oils. In its present form it can be used with water-based fluids but its accuracy with these fluids is low. A modified form of the apparatus is under construction which it is hoped will give accurate results with all fluids.

Solubility of air in various fluids

Because the solubility of air in liquids varies widely it was thought desirable to investigate the air solubility of a wide range of hydraulic fluids to see whether any relationships could be detected between this property and the other properties of the fluids.

So far, one conclusion has clearly been established: that

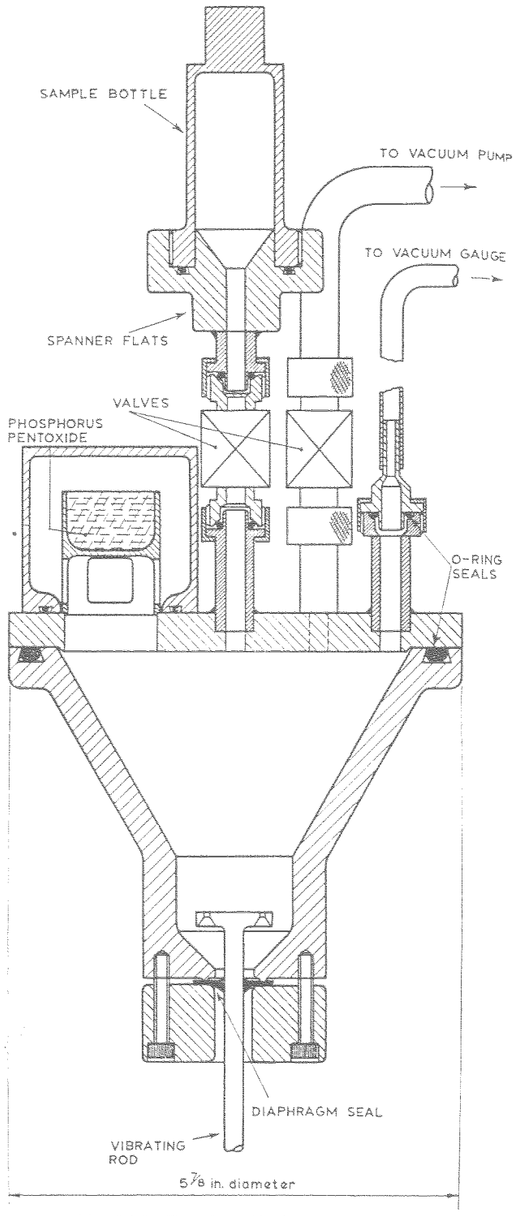


Fig. 17.5. The 'funnel' air-content apparatus

for a given type of oil the air solubility tends to increase as the viscosity decreases. This has been noted by earlier workers (5, 6), and has been confirmed at N.E.L. for the 'Vitrea' and 'Tellus' ranges of oil. Viscosity–solubility curves, as found for these oils, are shown in Fig. 17.6.

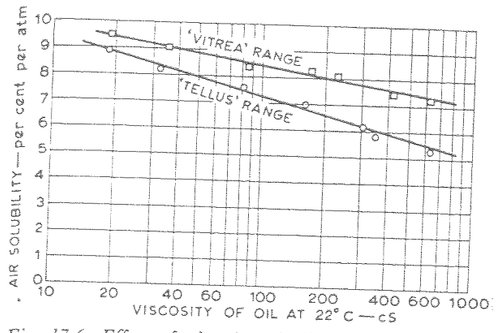


Fig. 17.6. Effect of viscosity of oil upon air solubility

Aeration threshold

If an oil which has been saturated with dissolved air at atmospheric pressure is subjected to sub-atmospheric pressures it is thereby rendered supersaturated and will tend to release some of its dissolved air. If the reduction in pressure is small the release of air will be by the slow process of diffusion from the free surface, if there is one. (If there is no free surface no air will be released under these conditions.) If the pressure is progressively reduced a point will be reached at which air bubbles will start to form within the liquid and the rate of release of air will thus be greatly accelerated. The pressure at which bubbles first appear may be termed the 'aeration threshold'.

Research into this effect is still in the early stages but has already shown that different fluids have different threshold values. It has also been found that the conditions of test have a marked influence upon the threshold. With a fluid completely at rest and initially free from bubbles the aeration threshold is generally as low as the vapour pressure. If the fluid is in motion and if a bubble is present at the start to act as a 'seed' the threshold value is very much higher.

It is obviously desirable for a hydraulic fluid to have as low an aeration threshold as possible. At present there is no way of measuring this property of a fluid. The main aim of this research is, therefore, the development of a standard method of test for aeration threshold which will correspond to the conditions at the low-pressure regions of hydraulic circuits where aeration is likely to occur.

Rate of solution of air bubbles

A detailed study of the rates of solution and evolution of air in various mineral oils and fuels was made in the late 1940's by Schweitzer and Szebehely (7). They used a closed cylinder mounted on a shaker and connected to a manometer. The cylinder was partly filled with the oil being tested, leaving an air space above the oil. The initial air pressure was adjusted to give a known degree of supersaturation or undersaturation and the rate of evolution or solution was deduced from subsequent changes in air pressure.

They found that for any oil the rate of solution was proportional to the degree of undersaturation and the rate of evolution to the degree of supersaturation. Expressed mathematically,

$$\frac{d\alpha}{dt} \propto (\alpha_e - \alpha) \quad . \quad . \quad . \quad . \quad (17.3)$$

where α is the actual air content at time t and α_e is the air content which at that instant would have been required for conditions of equilibrium (i.e. to maintain a saturated solution).

Conditions resembling those employed by Schweitzer and Szebehely, however, are not often found in practice. The most usual practical case is that in which bubbles are formed in a suction line and redissolved after passing through a pump. It was, therefore, decided to carry out research at N.E.L. on the rate of solution of air bubbles in a body of oil subjected to a sudden pressure rise.

Some intricate apparatus is being assembled with which this phenomenon will be studied in detail. Already, however, some interesting results have been obtained using the simple cylinder-and-plunger apparatus which was shown in Fig. 17.2.

When the plunger is suddenly lowered into the cylinder full of bubbly oil the bubbles are compressed. After that the compressed air in the bubbles slowly dissolves in the oil, and the subsequent slow descent of the plunger is a measure of the shrinkage of the bubbles and hence of the rate of solution of the air. By reading the height of the plunger tip every 5 seconds the rate of solution can be determined fairly accurately. By altering the load on the plunger the experiment can be carried out at various pressures.

Typical results with this apparatus are shown in Fig. 17.7 for an inhibited hydraulic oil of viscosity 30 cS at 30°C at loadings of 100 and 300 lb/in². It appears that the rate of solution is rapid and almost linear at first until about 50 per cent of the air in the bubbles is dissolved; after this the rate falls off progressively as the oil around each bubble approaches saturation. The initial rates are approximately 6 and 7 per cent per second at 100 and 300 lb/in² respectively.

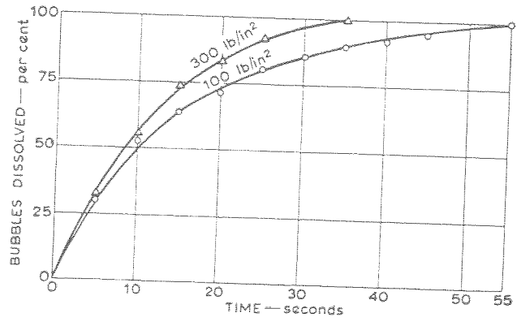


Fig. 17.7. Rate of solution of air bubbles in pressurized Tellus 21 hydraulic oil

Under the conditions of this experiment the degree of undersaturation of the oil is approximately proportional to the applied pressure, P, whilst the surface area of the bubbles is proportional to $P^{-\frac{1}{3}}$. Hence the rate of solution would be expected to be proportional to $P \times P^{-\frac{1}{3}}$, i.e., to $P^{\frac{1}{2}}$. Thus the rate of solution at 300 lb/in² should be faster than the rate at 100 lb/in² by a factor of $\sqrt[3]{3}$, i.e., 1·44. In fact the ratio of the two rates appears from Fig. 17.7 to be much less than this, being about 1·1/1.

It appears that under these conditions the rate of solution of the bubbles is not proportional to the degree of undersaturation of the general mass of oil in the apparatus. This apparent disagreement with Schweitzer and Szebehely's results may be due to the absence of agitation of the oil in the N.E.L. tests; it is possible that local saturation of the oil around each bubble occurs very rapidly and thus biases the results. In the new apparatus it will be possible to investigate this effect by applying varying degrees of agitation while the test is in progress.

Meanwhile it is safe to say that with this oil the rate of solution of bubbles will certainly not be less in practice (where pressures are generally higher and the oil is in motion) than in this test and will probably be considerably more rapid.

That is to say, when an oil of this type containing air bubbles is subjected to a pressure of more than 100 lb/in² in a hydraulic circuit, the bubbles can be expected to dissolve at a rate of at least 6 per cent per second and may, in fact, dissolve much more rapidly than this.

PRACTICAL APPLICATIONS

Although the work at N.E.L. on aeration in hydraulic circuits is still far from complete some useful conclusions may already be drawn which afford direct assistance to the practising engineer.

Effect of air bubbles on bulk modulus

In 1951 Rendel and Allen (8) published the following formula for the bulk modulus of aerated oil along with a series of graphs derived from the formula*:

$$b = \frac{\frac{V_f}{V_a}+1}{\frac{V_f}{V_a}+\frac{Kp_0}{p^2}} \quad . \quad . \quad . \quad . \quad (17.4)$$

This formula has been quoted in several places, including two well-known textbooks (9, 10, 11). The author has investigated this formula and, for reasons which are given in Appendix 17.II, has come to the conclusion that it is incorrect. A more acceptable equation would be:

$$b = \frac{\frac{V_f}{V_a}+\frac{p_0}{p}}{\frac{V_f}{V_a}+\frac{Kp_0}{p^2}} \quad . \quad . \quad . \quad . \quad (17.5)$$

* *For notation see Appendix 17.I.*

Even in this revised form, however, it is very doubtful whether the equation is of any practical value, since the equation ignores the process of solution of the air bubbles under pressure, which as has been shown above takes place very rapidly. The only sound practice is for engineers to eliminate air bubbles entirely from their hydraulic systems, and not to attempt to allow for them by largely theoretical equations.

How to avoid aeration

It has been shown how aeration can occur in two completely different ways; by the mechanical entrainment of atmospheric air or by the release of dissolved air from solution.

The most common cause of mechanical entrainment is probably bad sump design. It is essential that return lines should enter a sump well below the surface of the fluid, since a jet impinging on a solid or a liquid surface will inevitably entrain bubbles. Suction lines must be deepiy immersed so that air cannot possibly be sucked in through surface vortices even when the fluid is at its lowest level. If the oil returning to the sump contains bubbles a separator must be fitted to prevent these bubbles from reaching the suction line. It has been found that a simple screen of 60-mesh wire gauze, fitted across the sump at an angle of 30° to the horizontal, as shown in Figs. 17.3 and 17.8, makes a very effective separator.

Other common causes of mechanical entrainment are leaking seals and glands and inadequate venting. Special attention should be paid to seals and glands on lines where the pressure falls (even if only momentarily) slightly below atmospheric. A very slight leak here will cause considerable amounts of air to be drawn in, even though the outward seepage of oil is quite negligible. Vents should be provided at all the highest points in a circuit to avoid trapping pockets of air when filling or topping up with oil.

The release of air from solution can be eliminated by

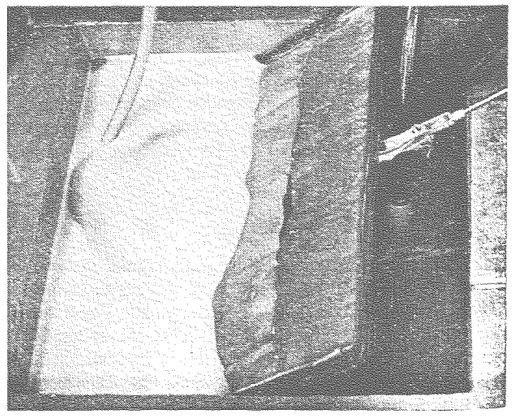


Fig. 17.8. Use of wire gauze screen as a bubble separator in a sump

following two simple rules. Firstly, pressures appreciably below atmospheric should not be tolerated anywhere in the circuit. The places to be watched in this connection are the inlets to pumps, and constrictions (such as orifices and throttle valves) where the venturi effect can create negative pressures. A closed circuit with pressurized return lines is much less liable to give trouble in this way than an open circuit. Secondly, there should be no places in the system where air under pressure comes into contact with oil, as the air in such places will slowly dissolve in the oil and is likely to be released subsequently elsewhere. Air-bottle accumulators and enclosed sumps pressurized with low-pressure air should, therefore, always be fitted with a piston or a membrane to separate the oil from the air.

Good design based upon these simple principles will enable the engineer to forget about the problem of aeration in his own hydraulic systems.

FUTURE RESEARCH

There is still a marked lack of information about certain aspects of the phenomenon of aeration. Research on the lines indicated above is continuing at N.E.L. with the object of filling these gaps.

Meanwhile it may be useful to remind engineers that the facilities at N.E.L. are available to help them with their own problems. The author would be pleased to hear from anyone having a problem in this field which is not covered by the suggestions given above.

ACKNOWLEDGEMENTS

The author is glad to express his indebtedness to Mr John Dallas who rendered valuable assistance with much of the experimental work described in this paper. The work described forms part of the research programme of the National Engineering Laboratory and is published by permission of the Director.

APPENDIX 17.I

Notation

b	Ratio of bulk modulus of aerated oil to bulk modulus of same oil in bubble-free condition.
K	Bulk modulus of oil.
P	Applied pressure.
p	Actual pressure.
p_B, p_0	Calculated pressure drop of bubbly and bubble-free oil respectively.
p_0	Atmospheric pressure.
Q_B, Q_0	Flow rates of bubbly and bubble-free oil respectively.
t	Time.
V_a	Volume of free air at atmospheric pressure.
V_f	Volume of oil at atmospheric pressure.
V_0	Volume at atmospheric pressure.
α	Actual air content.
α_e	Air content for instant for conditions of equilibrium.
β	Percentage bubble content.
μ_B, μ_0	Viscosty of bubbly and bubble-free oil respectively.

APPENDIX 17.II

DERIVATION OF COMPRESSIBILITY FORMULAE

Rendel and Allen (8) defined bulk modulus as:

$$K = -V_0 \frac{dp}{dV} \quad . \quad . \quad . \quad . \quad (17.6)$$

where V_0 is the volume at atmospheric pressure p_0.

This does not correspond to either of the accepted definitions of a bulk modulus (12). It is, however, a fairly close approximation to the tangent modulus (defined by $K = -V\,dp/dV$) for a liquid with low compressibility, where V is the volume at pressure p and differs only slightly from V_0. For a gas the use of V_0 in place of V leads to enormous errors.

V = Volume of air at pressure p + volume of fluid at pressure p.

i.e. $$V = \frac{p_0 V_a}{p} + V_f \left[1 - \frac{(p-p_0)}{K}\right] \quad . \quad . \quad (17.7)$$

Differentiating,

$$\frac{-dV}{dp} = \frac{p_0 V_a}{p^2} + \frac{V_f}{K} \quad . \quad . \quad . \quad . \quad (17.8)$$

If equation (17.8) is combined with equation (17.6) (which, as shown above, is approximately true for the liquid phase but not applicable to the gas phase), this leads to:

$$\text{Bulk modulus of mixture} = bK = \frac{V_f + V_a}{\frac{V_f}{K} + \frac{p_0 V_a}{p^2}}$$

and

$$b = \frac{\frac{V_f}{V_a}+1}{\frac{V_f}{V_a}+\frac{Kp_0}{p^2}} \quad . \quad . \quad . \quad . \quad (17.9)$$

Equation (17.9), owing to the misapplication of equation (17.8) is not valid, and, for instance, yields values of b greater than unity for air–oil mixtures at pressures greater than 1750 lb/in².

A better analysis, using the same notation but letting K stand specifically for the tangent bulk modulus as defined above is as follows:

For air alone:

Assuming that the air compresses isothermally and does not dissolve under pressure,

$$V = \frac{p_0 V_a}{p} \quad . \quad . \quad . \quad . \quad (17.10)$$

For hydraulic fluid alone:

By definition,

$$\frac{dp}{dV} = \frac{-K}{V}$$

Integrating, and treating K as constant (the error involved in this assumption in the present context is very small indeed) leads to:

$$V = V_f e^{-p/K} \quad . \quad . \quad . \quad . \quad (17.11)$$

For the mixture:

Combining equations (17.10) and (17.11),

$$V = \frac{p_0 V_a}{p} + V_f e^{-p/K} \quad . \quad . \quad . \quad (17.12)$$

Differentiating equation (17.12) leads to:

$$\frac{dp}{dV} = \frac{-Kp^2}{Kp_0 V_a + p^2 V_f e^{-p/K}} \quad . \quad . \quad (17.13)$$

Tangent bulk modulus of mixture $= bK = -V \frac{dp}{dV}$

Hence, using equations (17.12) and (17.13),

$$bK = \frac{Kp^2}{p_0 V_a K + V_f p^2 e^{-p/K}} \times \frac{p_0 V_a + p V_f e^{-p/K}}{p} \quad . \quad (17.14)$$

Therefore $$b = \frac{\frac{V_f e^{-p/K}}{V_a} + \frac{p_0}{p}}{\frac{V_f e^{-p/K}}{V_a} + \frac{p_0 K}{p^2}}$$

The exponential term allows for the decrease in V_f under pressure. Compared with the other quantities in equation (17.14) this decrease is very small, and the exponential may be neglected without introducing any appreciable error.

The equation then becomes:

$$b = \frac{\frac{V_f}{V_a} + \frac{p_0}{p}}{\frac{V_f}{V_a} + \frac{p_0 K}{p^2}} \quad . \quad . \quad . \quad . \quad (17.15)$$

APPENDIX 17.III

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Paper 18

CLEANLINESS IN HYDRAULIC SYSTEMS

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Everyone in the field of hydraulics has encountered instances of component failure or damage caused by contamination of the fluid. The necessity of arranging for continuous dirt removal arises from the fact that fluid once cleaned will not remain clean; systems tend to be self-contaminating so that even without ingress of dirt the level of contamination steadily increases.

In this paper the nature and origins of contamination in industrial hydraulic systems, and its effect on performance and reliability are discussed. The various measures that can be taken to control contamination are enumerated, and the characteristics of strainers, micro-filters and magnetic filters are described.

The purpose of the paper is to assist designers and users to adopt a realistic and objective approach to the problem of cleanliness.

INTRODUCTION

EVERYONE IN THE FIELD of hydraulics has encountered instances of component failure or damage caused by contamination of the fluid. While, however, it is generally agreed that a relatively high level of cleanliness is required to ensure reliable operation over long periods, there are conflicting opinions as to what level of cleanliness is required or what measures must be employed to maintain such a condition. The minimum acceptable level obviously depends on the type of equipment and its duty; the extent of the measures required will depend on the environment. Usually there is an optimum cleanliness for each system which depends largely on space and cost considerations.

Recently several papers have been published in the United States of America relating to filtration in missile and aircraft systems. These discuss the measures that have been found necessary to ensure reliable operation of such systems, and describe new types of filters, new methods of performance assessment and new techniques of filtration that have been developed.

Many of these recent data are, however, inapplicable to industrial hydraulic systems where the relative needs of economy, performance and reliability tend to form a different pattern. Little published information is available for the guidance of designers and users of less sophisticated systems.

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In this paper the nature and origins of contamination in industrial hydraulic systems, and its effect on performance and reliability are discussed. The various measures that can be taken to control contamination are enumerated, but particular commercial filters, of which there is a large variety, are not described. The aim of the paper is to establish the principles of filtration and to discuss the general characteristics of different methods of filtration.

Industrial users of hydraulic equipment have in the past been reluctant to adopt filtration, and indeed it has often been of doubtful necessity, but with increasing use of servo-valves and high performance equipment, filtration requirements can no longer be ignored or treated in an arbitrary manner.

It is hoped that this paper will assist designers and users to adopt a realistic approach to the subject.

Notation

C_d Drag coefficient.
d Effective diameter of capillary.
K Flow constant.
L Length of flow path.
n Number of capillaries per unit area of filter element.
P Pressure difference.
Q Flow per unit area of filter element.
$\mathcal{R}e$ Reynolds number.
s Specific gravity.
V Settling velocity.
γ Fluid viscosity (kinematic).