TROUBLESHOOTING OIL-WATER SEPARATORS BY MEASURING THEIR RESIDENCE-TIME DISTRIBUTION

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INTRODUCTION

Separation of oil and water (particularly the separation of small volumes of oil from large volumes of water) is a problem of increasing importance to the oil industry. The economics of handling large volumes of fluids often dictates the use of simple gravity-type separators for most of these separations. So long as the separators fulfill their function, there is little concern about flow characteristics, but when they fail in this function, normal oilfield practice is either to increase chemical, to add additional capacity, or to use some combination of both. It is often true, however, that the fault is due not to inadequate capacity or improper treatment, but is due rather to poor hydraulic characteristic of the separator. The only feasible method for determining the flow characteristics of a continuous separator is by the use of a tracer technique.

The presence of such phenomena as short circuiting, the existence of stagnant flow regions, the presence of high rates of mixing and dispersion in the vessel, and other such hydrodynamic ills are easily identified by use of the tracer-response technique. Measurements can be made during the operation of the separator without interfering with it in any way, and thus measurements can be used to check the effect of variations in any of the operating parameters of the system. The causes of such hydrodynamic problems are numerous. They are rarely obvious from superficial examination of the system and, in our experience, are the rule rather than the exception. Plug flow is a very rare phenomenon in oil-field separators. Poor hydraulic characteristics of a separator can result in inadequate capacity, if a substantial fraction of the fluids spend insufficient time in the separator due to poor flow paths. Poor hydraulic characteristics may also contribute to poor treatment efficiency by introducing shear forces which decrease the droplet sizes and make separation more difficult for the same time interval.

In this paper, the procedures required to make such measurements in the field are discussed, and the details of a successful method are described. Some of the results obtained in field measurements will be shown and the results discussed in terms of the hydraulic characteristics of the separators.

TYPES OF TRACER RESPONSES

The conditions under which a fluid passes through a continuous flow system is best studied by observation of the response of the system to a disturbance or stimulus at the inlet. This may be done by changing one of the parameters as, for example, concentration of the flowing stream. It may be done more conveniently by adding a tracer material whose flow behavior is identical to that of the stream itself. The other requirements of such a tracer material are that its injection should not otherwise interfere with normal flow in the separator, and it should obviously be easily monitored at the outlet of the system. There are a number of ways by which a tracer stimulus may be provided for the system. By far the most common and popular is introduction of a very sharp narrow pulse of tracer so that it behaves very much like a "Delta Function", i.e., it approximates an infinitely long pulse of infinitesimal duration whose area is proportional to the amount of tracer added. A second procedure which is often used is the

introduction of a "step function", i.e., a tracer of a fixed concentration is introduced to the system at a constant rate until the outlet concentration is equal to the input. There are also other types of input by which the tracer may be injected. For linear systems, all of these methods give the same information; however, for most cases of oilfield use, a sharp pulse which approximates a Delta function is the easiest to apply and takes the least amount of tracer to achieve.

If a sharp pulse of tracer is input into the system and the concentration of the tracer at the exit is recorded as function of time, a concentration-versus-time curve may be obtained. This curve, in effect, displays the distribution of residence time due to the elements of fluid moving along flow paths of unequal length connecting the inlet and the outlet of the vessel. The mean of this distribution is the mean residence time of the flowing fluid and is, in fact, the true mean residence time in a vessel as calculated by the volume divided by the flow rate. If (1) the concentration of measured tracer is made dimensionless (normalized by dividing it by C_o, where C_o is the total tracer added divided by the total volume of the system, and (2) the measured time is normalized by dividing it by the mean residence time and called the Greek letter θ, then a dimensionless distribution function $E\theta = C/Co$, is obtained. This function is independent of the amount of tracer used and independent of the total volume of the system. The shape of the distribution obtained from these tracer-response studies gives qualitative information on the type of flow in the system. This is usually adequate for troubleshooting. However, by use of mathematical and physical models, one can extract, in addition, a considerable amount of quantitative information for more fully describing some of these systems.

CHOICE OF TRACER

Any material can be used as a tracer for a response study, if (1) its flow follows accurately the flow of the process stream, (2) it can be monitored with reasonable ease, and (3) it can be introduced in sufficient quantity without disturbing the flow of the process stream. Some types include dyes, various other organic compounds, soluble inorganic compounds, such as table salt, and radioactive tracers.

In practice, the opacity of most oilfiled brines excludes the use of dyes or other visual types of indicators. In addition, relatively low sensitivity of most analytical procedures to a large extent excludes most of the common soluble materials for field procedures unless samples are taken to larger laboratories where special instrumental methods can be used. This requires that the effluent samples be gathered over a long period of time. Sampling schedules are difficult to set up, particularly when short circuiting or severe mixing causes very early breakthrough of tracer.

Radioactive tracers, whether in the form of organic or inorganic soluble compounds, overcome most of these problems. They can (1) be measured with very high sensitivity and selectivity so that very small quantities of tracers can be used, (2) be monitored in the field using relatively inexpensive equipment, and (3) be continuously measured through the pipe without sample-gathering by mounting a detector on the outside of the pipe. The only disadvantage to the use of radioactive tracers is the hazard involved in handling radioactive materials. In order to reduce this hazard to a minimum, Shell has devised a procedure which makes use of filed equipment for injecting the radioactive tracer by remote control. This procedure has been demonstrated satisfactorily to personnel from the nuclear regulatory agencies of the States of Texas and California. When using the procedure, personnel are monitored with dosimeters and film badges. Extensive use has established that the procedure is safe when properly performed.

Because of the high sensitivity with which radioactive tracers can be measured, this procedure lends itself particularly well to the pulse-injection procedure, since the volume of tracer needed is on the order of a tenth of an ounce. The reduction in tracer concentration by dilution, dispersion, and decay of the radioactive tracers in the effluent, ensures that no special disposal is required. In addition, since most waters are reinjected into the ground, any disposal problem is avoided. A wide variety of radioactive isotopes are available with energies varying in penetrating ability and with half lives varying from a few minutes to many years. For most tests performed, radiocative iodine, with an eight day half-life, and radioactive bromine, with a one and one-half day half-life, have been used.

Radiation from these isotopes is sufficiently penetrating to pass easily through the walls of tubing and pipe found in the oilfield. The choice of these isotopes is a matter of convenience. Other isotopes would probably have done equally well.

INJECTION EQUIPMENT

The equipment used to inject a tracer is shown in Figure 1. The lead-shielded steel tubing contains a sealed glass vial of radioactive tracer which has been transferred from a lead-shielded storage chamber. Once the chamber is in place, the piston smashes the vial, transferring the radioactivity into the stream itself. The initial transfer is done with a long rod and the smashing is done using a hydraulic hand pump.

The tracer injector consists of four parts, a 1/2-inch inside-diameter steel transfer tube fitted at one end with hardened-steel teeth, a 3-inch diameter lead shield which is set at the other end of the tube, a piston assembly complete with a latching device, and a hand-operated hydraulic pump used to drive the piston into the chamber. These features are shown schematically in Figure 1. In this figure, the tracer injector — already assembled and containing the vial of radioactive isotope — is inserted into the input line through a valve. The valve is fitted with a lubricator in order to prevent leakage along the tracer injector. The tracer is injected by driving the sealed glass vial against the sharpened breaker points by use of the hydraulic pump. The end of the tube in the flowing stream is fitted with slots to permit quick release of the tracer solution into the

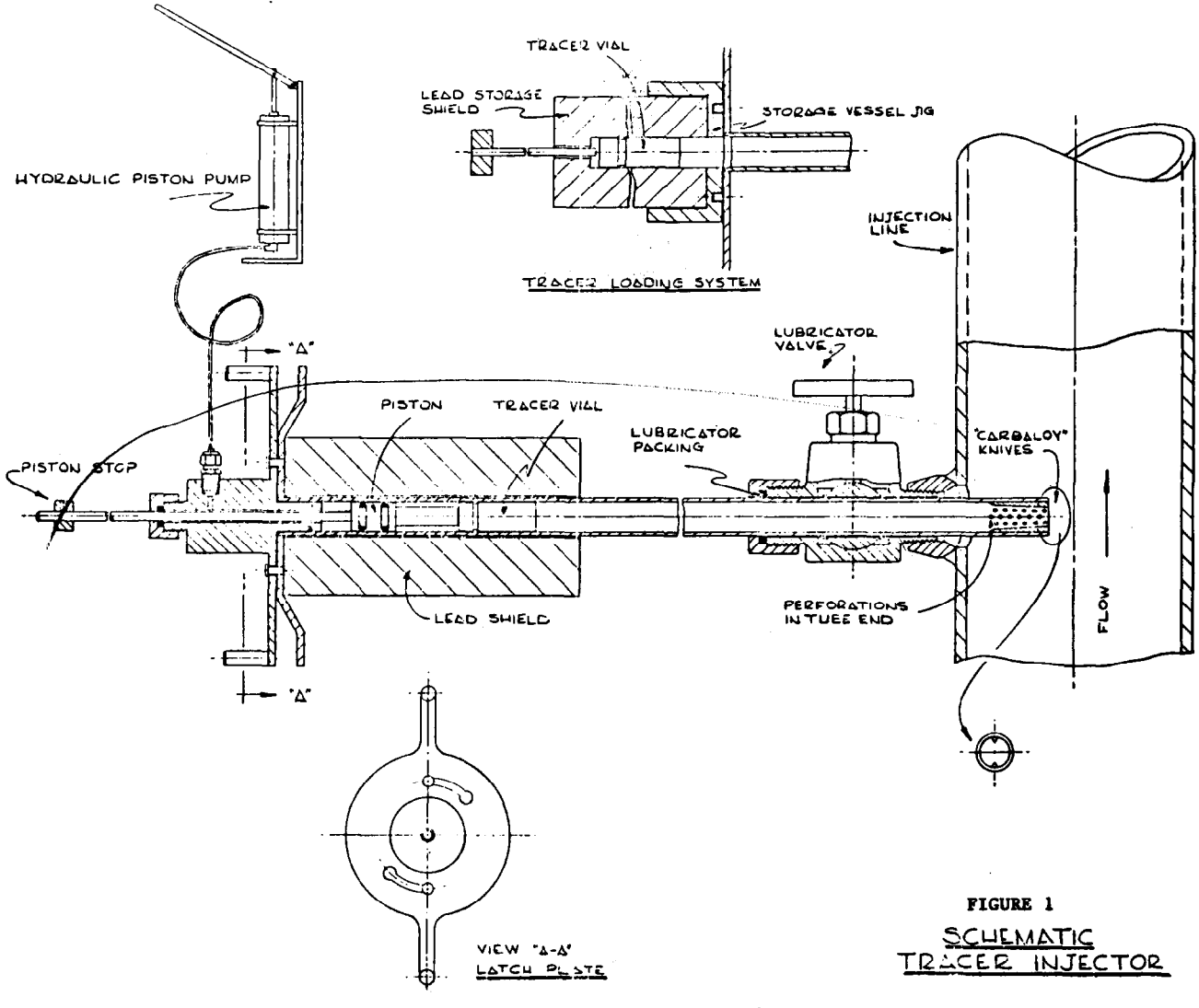

FIGURE 1—SCHEMATIC TRACER INJECTOR

incoming stream when the vial is broken. The back end of the piston is fitted with an adjustable stop in order to limit the total travel of the piston. The hydraulic pump is operated at a distance of 2 or 3 feet away from the tracer injector so that the operating personnel are not exposed to radiation. The radiation level in the immediate vicinity of the tracer-injector returns to background within a few seconds after the vial is smashed inside the input line. After the injection is completed, the lubricator is loosened enough to let the tracer-injector be drawn through the valve, the valve is closed and the tracer-injector then removed from the system. The lubricator in use here is simply a 3/4-inch steel tube fitted at one end with a nut and rubber "O" ring.

Before the tracer injector is loaded, it is inserted in the lubricator with the valve closed. The lubricator is tightened and tested for leaks by opening the valve temporarily. The valve is then closed, the piston assembly is removed, and the vial containing the radioactive isotopes is transferred from a shielded transfer case by means of a short steel rod which is used to push the vial into the lead shielded area of the injector assembly. The piston is then reinserted and locked into place by twisting the latching mechanism. The valve is then opened, the lubricator loosened enough to permit the injector to slide into the input line, and then the lubricator is retightened. The injector is now ready for injection. The handle of the latching mechanism serves as a handle for pushing the injector in and out of the valve. If the injection equipment is to be used in a vertical position, a small plug of polyurethane is normally pushed into the assembly before the tracer vial is inserted in order to prevent forward motion of the tracer vial before the hydraulic pump drives the piston forward.

HANDLING OF RADIOACTIVE TRACERS

Radioactive tracers, when properly handled, are safe to use and often present less hazard than many more common oil-field chemicals. However, because they are not common oil-field chemicals the procedures required for safe handling and the methods by which they are measured and monitored need to be spelled out.

The regulations of the Nuclear Regulatory Commission and of those states which have taken over the regulation of radioactive materials within their borders set forth the requirements and conditions for the safe use of these materials. In the state of Texas they are covered by Texas regulations. There are many excellent texts on the subject of safe handling of radioactive materials.

TEST PROCEDURES

As a rough rule of thumb, in the order of seven millicuries of iodine 131 per thousand barrels of fluid in the tank and about two millicuries of bromine 82 for the same volume have been used. A millicurie is 1/1000 of a curie; a curie is the amount of radioactive material required to emit 3.7×10^{10} disintegrations per second. Prior to the injection, monitoring probes are placed on the outlet lines close to the exit from the tank being tested. These probes consist of a 1-inch diameter, thalium-activated sodium-iodide scintillation crystal, a small portable rate meter, and a recorder. The rate meter provides the required high voltage for the photomultiplier tubes and converts the digital signal obtained from the scintillation crystal to an analog output which can be input to a recorder. The meters and probes used in all measurements were obtained from Ludlum Measurements, Inc., Sweetwater, Texas. Their Model 12 and their Model 21 count-rate meters have been used. Both of these meters are small, rugged instruments weighing only a few pounds, capable of operating on batteries or AC power. Battery power consists of four D cells; operation of several hundred hours on these cells are possible. Both kinds of rate meters were modified by the manufacturer to operate with the recorders which we use in the field. This kind of instrumentation has been used to make measurements in a large number of separation facilities in Texas, Lousiana, California, Illinois, and Alaska. The equipment has held up well in field use and during shipment under a wide variety of conditions.

The tracer injection is performed by injecting a suitable amount of tracer via the tracer injector described above and monitoring the output from the vessel by means of a recorded output from the sodium iodide scintillation detector. Except for setting the equipment up, it is not normally necessary to have personnel attend the monitoring equipment during the test. Since the monitored output presents the data as counts-per-minute as a

function of elapsed time, a material balance can be obtained by simply calibrating the detector to give millicuries per barrel in terms of counts-per-minute for the conditions of the test. Normally, this is unnecessary unless accurate measurement of the flow rate of the material passing through the vessel is required. The data from the recorder is normally used directly in a small computer program. This program calculates and plots a residence time distribution for the fluid passing through the separator under the conditions of test.

INTERPRETATION OF RESULTS

Plug flow represents the most desirable flow required for oil-water separators. Figure 2a shows the distribution to be expected from a reasonable approximation of plug flow and some of the deviations which can and do occur in oil field separators. In these curves, $E\theta$ represents the distribution function and θ is the normalized time which is the elapsed time of measurement divided by the mean residence time of the distribution. At θ equals 1, the elapsed time is precisely equal to the mean residence time. Curve A in Figure 2a represents the best approximation to plug flow that one can anticipate in a separator. This curve indicates a gaussian distribution centering about the mean residence time and with a normal dispersion indicated by the width of the curve. Curve B shows the residence time distribution of a fluid passing through a completely mixed vessel. This is the very opposite of plug flow and is an extremely undesirable flow regime to find in a separator. While the mean residence time is the same here as it is for plug flow only, an infinitesimal element of the fluid has this precise residence time. In reality, due to the high mixing forces, a large fraction of the fluid spends entirely too short a time in the vessel balanced by elements of fluid which spend too long a time in the vessel (and reduce its effective capacity). Curve C shows an intermediate case very commonly seen in separators. Here, most of the flow is basically plug flow, but the dispersion forces are so high that a considerable fraction of the fluid still spends less time in the reactor than is desirable. Figure 2b illustrates a common fault found in oil-field separators, that of short circuiting. Here, most of the incoming fluid bypasses a good deal of the liquid in the tank by finding a more direct path between the inlet and the outlet. This is usually evidenced by a residence time distribution which rised to a peak very much before θ equals 1 followed by a long tail due to exchange of tracer with a stagnant region. Two other common faults are shown in Figures 2c and 2d. Figure 2c represents parallel paths so that there are two moving regions rather than just one as in Figure 2b. Figure 2d shows the effect of recirculation inside the tank where instead of the fluid going through the tank one time, some of it recirculates to the input side and is carried through the tank again. There is a fourth possibility not illustrated here: that of a tracer distribution occurring after θ equals 1, i.e., the mirror image of Figure 2b. This almost always indicated an error in one of the procedures or interaction of the tracer material in the separator causing it to be held back relative to the fluid.

FIELD DATA

Table 1 and Figure 3 show results obtained from a tracer profile on a 2000-barrel wash tank. The first

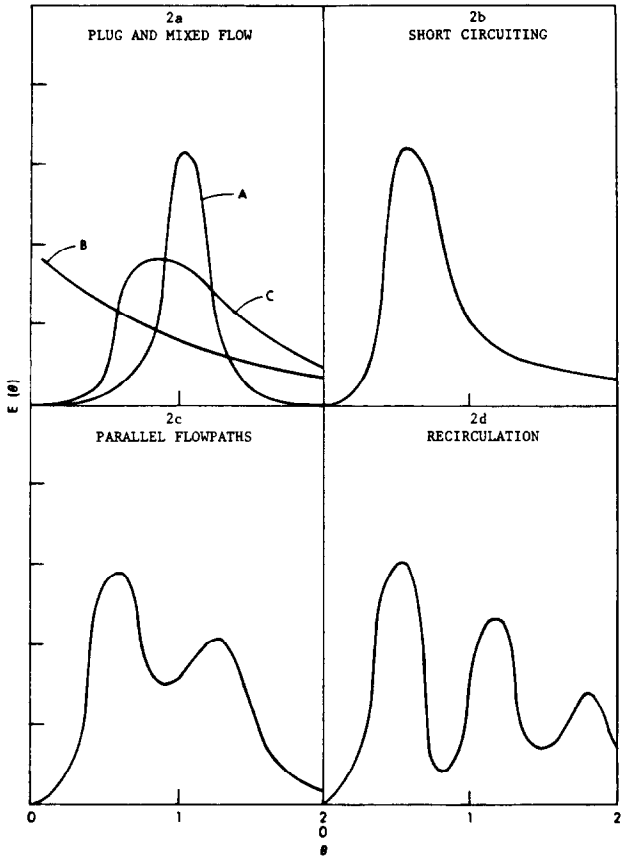

FIGURE 2—RTD CURVES FOR DIFFERENT FLOW PATTERNS

two columns in Table 1 give the experimental data obtained from the tracer-response experiement in a 2000 barrel wash tank at an onshore water treating facility near Kenai, Alaska. Fifteen millicuries of iodine 131 were injected by the standard injector, and the computer program calculated the mean residence time (455 minutes) and derived the numbers in Columns 3 and 4 for the dimensionless distribution function as a function of θ, the dimensional time. The results are shown in Figure 3. This is very clearly a case of extreme short circuiting similar to that shown in Figure 2b. This distribution curve peaks at about 5 percent of the mean residence time, and indicates the presence of a very short path between inlet and the outlet. The long tail in the distribution curve is due to the slow exchange of tracer with the relative stagnant body of water in the tank. As expected from this type of flow distribution, this wash tank has not been a particularly effective oil-water separator.

TABLE I—2000 BBL WASH TANK, KENAI, ALASKA FACILITY

Elapsed Time t_i	Measured Activity C_i	Dimensionless Time θ	Distribution Function $E(\theta)$
9.6	.0	.0211	.0000
10.5	1.0	.0231	.1594
11.0	2.9	.0242	.4623
12.0	6.6	.0264	1.0522
13.0	9.0	.0286	1.4268
14.0	12.7	.0308	2.0247
15.0	15.4	.0330	2.4551
16.0	17.2	.0352	2.7421
23.0	16.9	.0506	2.6942
32.0	8.9	.0704	1.4189
37.0	7.6	.0814	1.2116
44.0	5.2	.0968	.8920
54.0	5.2		
57.0	5.2		
97.0	4.9		
117.0	4.3		
217.0	3.7		

Mean Residence Time, $\bar{t}$ = 454.5 minutes

Summary and Conclusions

The tracer technique described here is a valuable tool for investigating not only gravity separators for separating oil and water but any continuing process in surface equipment. The measurements can be made quickly; more importantly they can be made under any set of operating conditions. This procedure can be used to measure the effect of changes in any of the flow variables such as the introduction of baffles, changes in flow rate, or elimination of thermal gradients by insulation of the tanks.

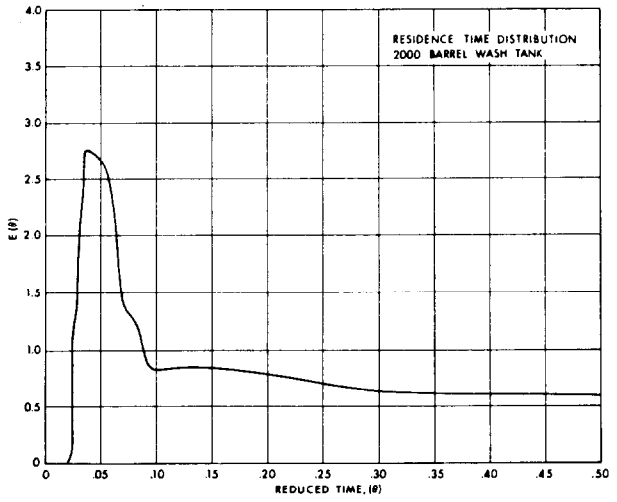

FIGURE 3

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