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THE TRACER GAS METHOD OF DETERMINING THE CHARGING EFFICIENCY OF TWO-STROKE-CYCLE DIESEL ENGINES

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THE TRACER GAS METHOD OF DETERMINING THE CHARGING EFFICIENCY OF TWO-STROKE-CYCLE DIESEL ENGINES

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SUMMARY

A convenient method has been developed for determining the scavenging efficiency or the charging efficiency of two-stroke-cycle engines. The method consists of introducing a suitable tracer gas into the inlet air of the running engine and measuring chemically its concentration both in the inlet and exhaust gas. Monomethylamine CH_3NH_2 was found suitable for the purpose as it burns almost completely during combustion, whereas the "short-circuited" portion does not burn at all and can be determined quantitatively in the exhaust. The method was tested both on four-stroke and on two-stroke engines and is considered accurate within 1 percent.

INTRODUCTION

The development of two-stroke-cycle engines usually centers around the problem of obtaining good scavenging efficiency (reference 1). The concept "scavenging efficiency" is, however, rather elusive. No generally accepted definition exists and attempts to measure the success of scavenging experimentally have been unsatisfactory. The object of this paper is first to establish a consistent terminology and then to describe a simple experimental method to measure and evaluate the success of scavenging and charging a two-stroke-cycle engine.

This work was done in the Engineering Experiment Station of The Pennsylvania State College under the direction of Professor F. G. Hechler who followed the progress of and assisted in the work.

The primary phase of the preliminary investigation was done by Dr. Kuo Ping, research assistant. Mr. W. H. Hough and Mr. I. Zipkin, senior and graduate students, helped in the chemical phase of the work. Valuable advice was given by Dr. C. C. Wright, associate professor of Fuel Technology and Dr. J. D. Aston, professor of organic chemistry, The Pennsylvania State College. Their assistance is gratefully acknowledged.

TERMINOLOGY

In any internal-combustion engine the output is largely determined by the number of oxygen molecules that can be packed into the cylinder every minute. The maximum amount of fuel burned will be controlled by the amount of oxygen available and the power output will vary in direct ratio to it provided that the thermal efficiency and the excess-air factor are constant.

In a four-stroke-cycle engine burning liquid fuel with atmospheric air, the volumetric efficiency may serve as a measure of the success of filling the cylinder with oxygen. Volumetric efficiency is defined as the amount of fresh air in the cylinder when the inlet valve closes, expressed in units of volume at normal temperature-pressure conditions (60° F temperature and 29.92 in. Hg pressure), divided by the displacement volume. This value is a true index of the filling success because the number of oxygen molecules trapped in the cylinder and available for combustion will be in direct ratio to the volumetric efficiency. It can be shown that in a four-stroke-cycle engine a linear relation exists between the brake mean effective pressure and the volumetric efficiency as follows:

$$\text{bmep} = 180 \frac{0.4}{f} \frac{14.5}{\lambda r_{th}} \eta_{vol} \tag{1}$$

where η_{vol} denotes the volumetric efficiency as defined, f the specific fuel consumption, pounds per brake horsepower-hour, and λ the excess-air factor, which is the ratio between the actual air-fuel ratio and the theoretical, or stoichiometric, air-fuel ratio r/r_{th}. Since the actual air-fuel ratio is the ratio between the weight of air available for combustion V_{pure} and the weight of fuel burned, and the stoichiometric air-fuel ratio is

equal to the ratio of the weight of the theoretical amount of air V_{th} required to completely burn the same amount of fuel to the weight of fuel,

$$\lambda = \frac{r}{r_{th}} = \frac{V_{pure}}{V_{th}}$$

For an average Diesel fuel the theoretical air-fuel ratio is 14.5 and the specific fuel consumption of an average engine is 0.4 pound per brake horsepower-hour; for an average case, equation (1) can, therefore, be written as

$$bmep = 180 \frac{\eta_{vol}}{\lambda}$$

If the specific fuel consumption f is expressed as pounds of fuel per indicated horsepower, equation (1) gives the mean indicated pressure mip instead of brake mean effective pressure.

For an engine in which the cylinder charge is pure air, equation (1) holds exactly. Even in four-stroke-cycle engines, however, there is some contamination of the charge by the residual gases of the preceding combustion and in a two-stroke-cycle engine the contamination is appreciable. Equation (1) no longer holds in that case because the brake mean effective pressure is much affected by an additional factor, the scavenging efficiency, which expresses the degree of contamination of the cylinder charge.

In the English literature the term "scavenging efficiency" has been variously defined and frequently used in an equivocal manner without definition. The value of a consistent system of definitions becomes apparent by an analysis of the charging and scavenging processes.

Figure 1 is a diagrammatic representation of the charging process in the engine. The hatched areas represent pure air and the cross-hatched areas, combustion gases. The widths of the channels represent the quantity of the gases expressed by volume at normal temperature-pressure conditions.

In a two-stroke-cycle engine, air is delivered to the cylinders either by a separate blower or by the piston of the working cylinder acting as a blower. In either case

the air delivery V_{del} is split into two parts: the air short-circuited V_{short}, which leaves through the exhaust port without remaining in the cylinder and the air retained V_{ret}, which stays in the cylinder after port closure and participates in the subsequent combustion. The air retained V_{ret} together with the residual gas V_{res} remaining in the cylinder after scavenging constitutes the cylinder charge V_{ch}. This charge may be more or less than the displacement volume V_{disp} depending on the volumetric efficiency, which is

$$\eta_{vol} = \frac{V_{ch}}{V_{disp}} = \frac{V_{ret} + V_{res}}{V_{disp}} \tag{2}$$

The volumetric efficiency is a measure of the success in filling the cylinder irrespective of the composition of the charge. It is predominantly controlled by the scavenging pressure and by the port heights.

During combustion, part of the air contained in the cylinder charge burns but part of it, the excess air, is not involved in the attendant chemical reactions. Part of this excess air escapes through the exhaust ports with the combustion products and part of it, $V_{res} - V_{cp}$ (V_{cp} represents combustion products in the residual gas), remains in the cylinder and participates in the subsequent cycle. Therefore, the cylinder charge consists of three parts: the retained portion of the air delivered, part of the combustion products from the preceding cycle, and part of the excess air from the preceding cycle.

The scavenging efficiency is a measure of the success in clearing the cylinder from the residual gases of the preceding cycle, and is defined as

$$\eta_{sc} = \frac{V_{ret}}{V_{ch}} = \frac{V_{ret}}{V_{ret} + V_{res}} \tag{3}$$

This efficiency is an indication of the contamination of the air charge. Naturally it increases when the retained portion of the air delivery increases, or the short-circuited portion decreases, and also when the residual gas decreases. The method of scavenging will have a predominant effect on the scavenging efficiency and the merit of

the various scavenging arrangements (cross, loop, and uniflow) can well be judged by it.

Another useful concept is the utilization factor defined as

$$\eta_{ut} = \frac{V_{ret}}{V_{del}} = \frac{V_{ret}}{V_{ret} + V_{short}} \tag{4}$$

The utilization factor is a measure of the success in utilizing the delivered air without much waste. The smaller the amount of air short-circuited the higher the utilization factor. It is largely controlled by the scavenging arrangement.

High utilization factor is one way to increase the air in the cylinder, another way is high total delivery. Delivery ratio is defined as

$$L = \frac{V_{del}}{V_{disp}} = \frac{V_{ret} + V_{short}}{V_{disp}} \tag{5}$$

Delivery ratio is predominantly controlled by the capacity of the scavenging pump or blower.

The total fresh air available for combustion is described by the term "charging efficiency:"

$$\eta_{ch} = \frac{V_{ret}}{V_{disp}} \tag{6}$$

Charging efficiency in a two-stroke-cycle engine is a quantity which is parallel to the volumetric efficiency of a four-stroke-cycle engine. The engine output is approximately proportional to it.

There are definite and useful relations between these indices. From equations (2), (3), (4), (5), and (6)

$$\eta_{ch} = \eta_{sc}\,\eta_{vol} = \eta_{ut}\,L \tag{7}$$

the significance of which will be made clear later.

When the scavenging efficiency is 100 percent, equa-

tion (1) expresses the relation between the brake mean effective pressure and the scavenging factors. When the scavenging efficiency is less than 100 percent the brake mean effective pressure is naturally less. The corresponding formula, the derivation of which is given in appendix A, is

$$\text{bmep} = 180 \frac{0.4}{f} \frac{14.5}{r_{th}} \frac{\eta_{sc}}{1 + (\lambda - 1)\,\eta_{sc}} \eta_{vol} \tag{8}$$

When equation (7) is considered, this equation can be written also as

$$\text{bmep} = 180 \frac{0.4}{f} \frac{14.5}{r_{th}} \frac{1}{\frac{1}{\eta_{ch}} + \frac{\lambda - 1}{\eta_{vol}}} \tag{9}$$

This relation is useful as it permits the prediction of the output of a two-stroke-cycle engine. The maximum value is obtained if $\eta_{ch} = 1$ and $\lambda = 1$. Then, with 14.5 theoretical air-fuel ratio and 0.4 pound per brake horsepower specific fuel consumption, the brake mean effective pressure = 180 pounds per square inch. This represents the upper limit but any decrease in η_{ch} and η_{vol} or increase in λ will reduce the attainable brake mean effective pressure.

It is also evident that if $\eta_{sc} = 1$, as is approximately true in four-stroke-cycle engines, equation (8) gives

$$\text{bmep} = 180 \frac{0.4}{f} \frac{14.5}{\lambda r_{th}} \eta_{vol}$$

which is identical with equation (1) and also gives 180 pounds per square inch for top limit with $\eta_{vol} = 1$.

MEASUREMENT OF SCAVENGING EFFICIENCY

Tests for the experimental determination of the scavenging efficiency have been made on running engines, on motored engines, and on models. No one test method has become popular and, in practical engine development, the

measuring of the scavenging efficiency has been generally ignored.

The sampling-valve method has been used more than any other, perhaps first by Sulzer Brothers (reference 2). By a synchronized valve that opens every cycle for a short period between port closure and injection beginning, samples are withdrawn from the cylinder and analyzed for oxygen or CO_2 content. A similar test on a motored engine with artificial CO_2 contamination was made by DeJuhasz (reference 3). Specially made scavenging machines were used by Curtis (reference 4), and by Sulzer (reference 5) and performed useful service in the study of the results obtainable with various scavenging arrangements.

The chief objection to the sampling-valve method is the difficulty of obtaining a representative sample because the composition of the cylinder charge is not uniform at different points of the cylinder. Another objection to the method is that it is laborious. The model tests suffer, in addition, from the fact that the temperature, the density, and the viscosity of the gases appreciably influence their motion and actual conditions cannot be reproduced in a cold model.

In order to overcome these objections, List (reference 6) employed a two-part piston in a specially built test engine. While the engine was running, during a compression stroke, the cylinder content was pushed into a large container by suddenly opening a valve in the cylinder head. When the pressure was removed, the loose top part of the piston stayed at top dead center, isolating the cylinder charge. The composition of the cylinder content could then be leisurely analyzed. This method probably gave dependable results but, because of its complication, cannot be expected to become popular.

Because of the lack of a simple method, information on scavenging efficiency sometimes was obtained in a roundabout way by power measurements. Equation (8) can be used for this purpose.

The excess-air factor is close to 1.0 in gas and carburetor engines. In those engines, therefore, power measurement can be substituted for measurement of scavenging efficiency if the volumetric efficiency is known or can be estimated.

In a Diesel engine the excess-air factor may vary from 1.2 to 2.2 at full load and, its value being unknown, a possible solution is to run the engine as a gas engine with porting and operating conditions unchanged. Then, on the assumption that the scavenging efficiency is still the same, it can be calculated from equation (8).

Another possible solution is to determine the excess-air factor λ from a four-stroke-cycle engine, which is similar to the investigated two-stroke-cycle engine in its combustion characteristics. For such an engine λ can be determined from equation (1). By substitution of the thus-determined λ in equation (8), the scavenging efficiency can be calculated from power measurement.

Utilization Factor

The scavenging efficiency of a two-stroke-cycle engine may be determined in an entirely different way. From equation (7)

$$\eta_{sc} = \frac{\eta_{ut}\ L}{\eta_{vol}} \tag{10}$$

If η_{ut}, L, and η_{vol} are easier to determine than η_{sc}, the direct determination of η_{sc} may be dispensed with.

Another point favors this course. Scavenging efficiency is the term most widely used in characterizing the success of scavenging but, as has been correctly pointed out in reference 1,* the significant quantity is not the scavenging efficiency but the charging efficiency,

$$\eta_{ch} = \eta_{sc}\ \eta_{vol}$$

because the engine output is approximately proportional to it. The success, therefore, of the scavenging and the rel-

*In reference 1 the term "scavenging efficiency" is used in almost the same sense as the term "charging efficiency" is used in this paper. The authors define scavenging efficiency as the weight of air charge in the cylinder at the time the inlet valve closes divided by the product of total cylinder volume and inlet density. Except for the use of inlet density instead of the density of normal atmospheric air and the use of total cylinder volume instead of displacement volume, that definition agrees with the definition of equation (6).

ative merit of various scavenging arrangements can better be evaluated by the charging efficiency, which happens to be the product of the conventional scavenging efficiency and the conventional volumetric efficiency. If charging efficiency is the quantity in which interest is centered, the determination of the volumetric efficiency can be omitted and the charging efficiency can be determined according to equation (7) as

$$\eta_{ch} = \eta_{ut} L$$

The delivery ratio L can be very conveniently determined by measuring the air flow with a gas meter or a standardized flowmeter nozzle on the intake side of the engine or on the intake side of the scavenging blower. A convenient determination of η_{ut} will be described.

The utilization factor η_{ut} alone is a very significant index as it shows the ratio between air retained and air delivered and is, therefore, the best possible index of the merit of the scavenging proper. The other factor L is largely controlled by the scavenging blower and is an index of the success in supplying a large air charge. The product of the two η_{ch} is a measure of the amount of fresh air introduced into the cylinder and of the power attainable from it.

The Tracer Gas Method

Formula (4) for the utilization factor can also be written as

$$\eta_{ut} = \frac{V_{del} - V_{short}}{V_{del}} = 1 - \frac{V_{short}}{V_{del}} \qquad (11)$$

Accordingly, if the ratio between the amount of air short-circuited and the total air delivered is known, the problem is solved. The relative amount of short-circuited air can be determined by a tracer gas.

If a small amount of a suitable tracer gas is continuously fed into and mixed with the inlet air of a running two-stroke-cycle engine, the gas will divide in the same proportion as the air delivered. Part of it will be short-circuited and part of it will be retained in the cylinder. The trapped portion of the tracer gas is assumed

to burn in the cylinder during combustion. The short-circuited portion is assumed to be present in the exhaust gases. By measurement of the amount of tracer gas present in the exhaust, the utilization factor can be determined.

It is usually simpler to measure the concentration of a tracer gas in the diluent than its absolute quantity. If the volume of the exhaust gas is equal to the volume of the inlet air (both volumes being at normal temperature-pressure conditions), if the tracer gas that is trapped in the cylinder burns completely during the combustion, and if none of the tracer gas decomposes or oxidizes during the scavenging or the exhaust period, the ratio of the concentration of the tracer gas in the exhaust gas to the concentration of the tracer gas in the inlet air is equal to the ratio of the amount of air short-circuited to the amount of air delivered. The utilization factor, may therefore be expressed as

$$\eta_{ut} = 1 - \frac{\text{concentration tracer gas in the exhaust gas}}{\text{concentration tracer gas in the inlet air}} = 1 - \alpha \qquad (12)$$

The assumptions mentioned may not hold exactly, but the utilization factor may still be calculated on the basis of equation (12) if the assumptions hold approximately or if appropriate corrections are made.

The first problem is the selection of a suitable tracer gas. The gas should meet the following requirements:

1. It should be easy and safe to handle

2. It should be conveniently determinable quantitatively

3. It should burn completely when exposed to the combustion in the cylinder

4. It should remain unchanged in the cylinder during the scavenging period and in the exhaust pipe

Experimental work to determine their suitability as tracer gases has been done with ammonia, carbon monoxide, carbureted water gas, monomethylamine and dimethylamine.

Correction for Change in Volume After Combustion

Petroleum fuels used in internal-combustion engines consist of hydrogen and carbon. The carbon-hydrogen ratio may vary between 6 and 8, the variation depending on the source and the processing of the fuel. One pound of hydrogen requires 32/4 or 8 pounds of oxygen for its complete combustion and 1 pound of carbon requires 32/12 or 2.666 pounds of oxygen for its complete combustion. One pound of atmospheric air contains 0.2315 pound of oxygen; 1 pound of hydrogen will consequently require 8 ÷ 0.2315 or 34.5572 pounds of air and 1 pound of carbon will require 2.667 ÷ 0.2315 or 11.5191 pounds of air for complete combustion.

A pound of fuel that contains 1 weight of hydrogen and 7 weights of carbon will require

$$\frac{34.5572 + 7 \times 11.5191}{8} = 14.4 \text{ pounds of air}$$

for its complete combustion.

The quantities of combustion products that will result from the complete combustion of this fuel will be as follows:

$$\frac{1}{8} \times \frac{36}{4} = 1.125 \text{ pounds of } H_2O$$

$$\frac{7}{8} \times \frac{44}{12} = 3.205 \text{ pounds of } CO_2$$

The amount of nitrogen remains unchanged

$$14.4 \times \frac{76.85}{100} = 11.1 \text{ pounds of } N_2$$

The volume of 14.4 pounds of air under normal temperature-pressure conditions will occupy 178.6 cubic feet. If the fuel is liquid its volume may be neglected. After combustion, at normal temperature-pressure conditions

1.125	pounds H_2O	will occupy	22.42 cubic feet
3.205	pounds CO_2	will occupy	26.12 cubic feet
11.1	pounds N_2	will occupy	142.2 cubic feet
		Total	190.75 cubic feet

As compared with the original volume of 178.6 cubic feet, this volume represents an increase of 6.5 percent. With the water vapor condensed out, however, the total exhaust gas volume is 190.74 - 22.42 = 168.32 cubic feet, which represents a decrease of 6 percent.

If the air-fuel ratio is greater than the stoichiometric ratio, as is the case in Diesel engines, the change in volume after combustion will be less. Figure 2 shows the change in volume due to combustion of fuel with a carbon-hydrogen ratio of 6, 7, and 8 to 1 and at an air-fuel ratio from 14.5:1 to 50:1. A typical Diesel fuel with a carbon-hydrogen ratio of 7:1 burned with an air-fuel ratio of 20:1 would cause a loss of 4 percent in volume, if the water-free exhaust gas is compared with the inlet air, both at normal temperature-pressure conditions. This amount is the correction that must be applied to the ratio of tracer-gas concentrations in the inlet air and in the exhaust gases.

Preliminary Tests

Most of the preliminary work was done with ammonia and with methylamines. The work included bench and engine tests. One bench test was made to determine the decomposition of ammonia at various temperatures, other tests were made to check the effectiveness of ammonia and methylamine absorption by sulphuric-acid solution. Preliminary engine tests were conducted on various four-stroke-cycle engines. A four-stroke-cycle engine with no valve overlap must have a utilization factor of 100 percent; the amount of tracer gas found in the exhaust could therefore be used as a check on the method. Load, speed, compression ratio, intake-air temperature, and tracer-gas concentration were varied in the tests.

The results of those preliminary tests can be summarized as follows:

1. Ammonia and monomethylamine do not burn or decompose under temperatures existing in the exhaust of two-stroke-cycle engines.

2. Ammonia and its derivates are readily and completely absorbed by aqueous sulphuric-acid solution held in a Van Slyke-Cullen urea flask, which makes their quantitative determination convenient, as it measures, by a gas meter, the amount of gas necessary to neutralize the

sulphuric-acid solution. If a few drops of indicator solution are added to the sulphuric-acid solution, the neutralization point can be conveniently detected by a sharp color change.

3. Monomethylamine was found to burn almost completely in the cylinder if the engine load was 75 percent or higher, irrespective of the engine speed and the compression ratio. A typical test performed on a four-stroke-cycle engine is represented by figure 3.

4. The concentration of the monomethylamine had little effect on its burning efficiency and a concentration of 0.5 to 1 percent was found most satisfactory as a tracer gas.

5. No other gas was found to fill the requirements of a tracer gas as satisfactorily as monomethylamine. Ammonia was found to burn only incompletely in the cylinder during the available short-time interval. Dimethylamine partly decomposed in the exhaust pipe. Carbon monoxide, hydrogen, and methane were found to require laborious analysis and to give insufficient accuracy.

The Methylamine Method

The inlet air and the exhaust gas are analyzed for their monomethylamine content by withdrawing, under a slight vacuum, a sample through a Van Slyke-Cullen urea apparatus (fig. 4) containing a known quantity of standardized sulphuric-acid solution, which retains the monomethylamine. The amine-free gas sample then continues on to a flowmeter. A few drops of mixed indicator solution are added to the sulphuric-acid solution as an indicator. When the acid solution becomes neutralized by the monomethylamine, the color changes from purple to green and at this point the quantity of monomethylamine free gas that passed through the sulphuric-acid solution and the flowmeter is recorded. The quantity of sulphuric-acid solution used being known, the percentage ammonia in the gas mixture can be calculated.

If there is any suspicion that a greater volume of gas has passed through the sulphuric-acid solution than is necessary to neutralize the acid, the actual quantity of acid neutralized can be determined, by titration, by adding a few more cubic centimeters of sulphuric acid and back-titrating with standardized NaOH.

Correcting the Experimental Results

If the monomethylamine burned completely in the cylinder and none of it burned in the exhaust pipe and if the volume of the exhaust gases were equal to the volume of the inlet air at normal temperature-pressure conditions then, according to equation (12), the utilization factor could be calculated from the measured amine concentrations, as

$$\eta_{ut} = 1 - \alpha$$

where

$$\alpha = \frac{\text{percent tracer gas in the exhaust gas}}{\text{percent tracer gas in the inlet air}}$$

It is known, however, that the volume of the water-free exhaust gas is 1 to 6 percent less than the volume of inlet air, depending on the air-fuel ratio of the charge and the carbon-hydrogen ratio of the fuel. (See fig. 2.) It is also known that the combustion of the monomethylamine is not complete in the cylinder but varies between 95 and 100 percent, depending largely on the combustion temperature. As regards the burning of monomethylamine in the exhaust pipe, the evidence indicates that this condition need not be considered because the amount burned is either zero or negligible.

If the volume shrinkage of the water-free exhaust gas relative to the inlet air is denoted by s and the burning efficiency of the tracer gas by e, it can be shown that the true utilization factor is

$$\eta_{ut} = \frac{1 - \alpha}{e - \alpha s} \tag{13}$$

The derivation of this formula is found in appendix B.

If the burning efficiency were 96 percent and the volume shrinkage 5 percent (rather extreme cases), with an α of 0.2 the uncorrected formula would give

$$\eta_{ut} = 1 - 0.2 = 0.8$$

whereas the true utilization factor would be

$$\eta_{ut} = \frac{0.8}{0.96 - (0.2 \times 0.05)} = 0.84$$

The determination would therefore be in error by 4 percent.

The determination can, however, be improved considerably by the use of equation (13). It is easy to estimate the volume shrinkage from figure 2. For a typical Diesel fuel with a carbon-hydrogen ratio of 7:1 and an air-fuel ratio of 20:1, the volume shrinkage is approximately 4 percent. It is also possible to estimate the burning efficiency of the monomethylamine as about 97 percent, more or less, depending on the combustion temperature. Application of the correction formula, equation (13), would give

$$\eta_{ut} = \frac{0.8}{0.97 - (0.2 \times 0.04)} = 0.83$$

This amount is likely to be correct within 1 percent.

Testing a Two-Stroke-Cycle Engine

The method developed was considered satisfactory for testing the scavenging of a two-stroke-cycle engine.

The first problem encountered in adopting the monomethylamine method was: Where along the exhaust line shall the exhaust sample be withdrawn? When the exhaust port just opens, exhaust gases issue from the exhaust ports at a very high velocity. After the blow-down period, when scavenging takes place, the velocities through the exhaust ports have decreased considerably and later the air that is short-circuited flows through the exhaust ports at a relatively slow rate until the exhaust ports close. From the time of exhaust-port closing to the next exhaust-port opening, pressure and velocity oscillations continue all along the exhaust duct. If a sample is withdrawn a few inches from the exhaust port, these considerations would indicate that the concentration of the tracer gas at this point would be higher than the true value, which would be obtained if thorough mixing had occurred.

Experiments on a 10½- by 12-inch single-cylinder, two-stroke-cycle, crankcase-scavenged Venn Severin Diesel engine (fig. 5) have shown that the concentration of monomethylamine withdrawn at various points along the exhaust

line varied, as had been expected. Very high concentrations were found in samples withdrawn 6 inches from the exhaust port. The concentration of monomethylamine in samples withdrawn 3 feet from the exhaust ports was appreciably less than the concentration found 6 inches from the exhaust ports. Further along the exhaust line, the concentrations increased again and then fluctuated slightly all along the exhaust line up to 15 feet away from the exhaust ports. No samples were withdrawn at a distance greater than 15 feet from the engine.

In order to get a representative concentration of monomethylamine in the exhaust gas, the exhausted products of combustion and the short-circuited air and monomethylamine should be completely mixed. This result could be accomplished if a mixing chamber were introduced into the exhaust line. The addition of a chamber, however, affects the tuning of the exhaust and the results obtained would not be representative of normal operating conditions.

Another manner in which a reliable sample may be obtained would be to take an average of the concentrations of the monomethylamine all along the exhaust line. This sample can be taken very easily without disturbing the normal engine exhaust system. The least number of sampling points necessary to obtain a reliable sample has not been ascertained. Four locations, however, evenly distributed along the exhaust line are considered to be adequate to give a reliable average concentration, the first sample tube being located at a distance not less than that distance corresponding to an exhaust-pipe volume equal to 1.5 times piston displacement.

In the final tests on the Venn Severin engine, one inlet and four exhaust samples were withdrawn in each test.

Two tests were made with each air delivery and the air delivery was varied by placing a restricting orifice in the inlet-air duct next to the engine. The Van Slyke-Cullen urea apparatus was used for absorbing the monomethylamine in the inlet and exhaust samples. Figure 6 shows the arrangement used to withdraw an inlet sample through the Van Slyke-Cullen apparatus. All four exhaust samples were withdrawn simultaneously. The sampling tube and the stopcock are shown in figure 7. The amine-free sample issuing from each aeration tube flowed to a header from which the combined monomethylamine-free exhaust samples flowed to a gas meter with which the volume of the combined

samples was determined. The sample flow to each exhaust sample aeration tube was stopped, one at a time, as the as the color of the solution in the individual tubes changed from purple to green. The volume of the combined sample was then corrected by titration. All exhaust-sample volumes were corrected by titration because of moisture that had condensed out of the exhaust sample and had been deposited along the inner walls of the glass tubing through which the sample flowed before emerging in the form of bubbles into the sulphuric-acid solution in the aeration test tube. This condensation absorbs some of the monomethylamine in the exhaust sample and does not take any part in causing the initial color change. It is, therefore, important that the aeration tubes be washed and the mixture of the original contents of the tube and the products of the washing operation be titrated to determine the correct quantity of monomethylamine contained by the measured sample.

The value of α was then calculated by the use of the inlet and the combined exhaust-sample volumes and the quantity of sulphuric acid neutralized by each sample. The procedure is described in the next section.

When a burning efficiency of $e = 0.97$ and a volume shrinkage of $s = 0.04$ was assumed η_{ut} was calculated from equation (13). The test results and the calculations are listed in table I.

With no throttling of the intake air, the utilization factor was 84 percent; with a 3-inch-diameter orifice used in the inlet duct, the utilization factor was 82 percent and, with a 2-inch-diameter orifice, 86.8 percent according to the tests.

As a further step, the respective charging efficiencies were determined according to equation (7). For this equation, the delivery ratio must be known. This procedure involves the measurement of air deliveries.

A flowmeter nozzle of 3.145-inch diameter was inserted in the intake side of a surge tank. The pressure drop across the nozzle was measured by a micromanometer. The micromanometer shown on figure 8 was developed by Professor F. C. Stewart of the Pennsylvania State College. It consists of two connected equal-diameter tubes, one exposed to the atmosphere and the other connected to the pressure hole of the flowmeter nozzle. The height of the water

level in the open tube is measured by a dial indicator to which a sharp pointer is attached. When the pointer touches the water level, an electric circuit is closed through a neon lamp and the neon glows. With this instrument the difference in water levels can be conveniently determined with an accuracy of ±0.002 inch and the necessity of using small nozzles for accentuating the pressure drop disappears. The measured air delivery was 125 cubic feet per minute at 381 rpm or 0.328 cubic feet per cycle. This value gave a delivery ratio of 0.544 with no throttling.

The charging efficiency is equal to the utilization factor times the delivery ratio. The charging efficiency was calculated as 46 percent for no throttling, 41 percent for the 3-inch-diameter throttling orifice, and 38 percent for the 2-inch-diameter throttling orifice.

The load was about full load in these tests, as evidenced by a smoke density of about 80 percent by the Penn State smokemeter (reference 7). The power output was not measured.

The values show that the utilization factor does not always deteriorate when the delivery is increased. When a change was made from a 3-inch throttling orifice to no orifice, both the air delivery and the utilization factor improved. Of course, if the air delivery is considerably increased, as by supercharging, the utilization factor must necessarily fall off because the cylinder cannot keep all the extra air supplied.

The low delivery ratios and charging efficiencies obtained in these tests are not typical of the engine but are the result of an inadequate surge-tank capacity and a short 2-inch-diameter tube inserted between the tanks to minimize the pressure fluctuations. This small tube restricted the air delivery to below normal. Subsequently, the air-delivery tests were repeated with a larger surge tank (about 27 times displacement volume), free of restrictions and having two 20-inch-diameter rubber membranes, in addition, to minimize pressure fluctuations. The air delivery thus measured corresponds to a delivery ratio of 0.72. If the utilization factor were the same (0.84), this set-up would give a normal charging efficiency of 60 percent.

RECOMMENDED PROCEDURE

For Determining the Charging Efficiency of a Two-Stroke-Cycle Diesel Engine with Monomethylamine as a Tracer Gas

Test Equipment

Material and equipment:

1. Anhydrous monomethylamine

2. Concentrated sulphuric-acid solution (9 lb)

3. Standard volumetric solution of N/10 sodium hydroxide (32 oz)

The sodium-hydroxide solution must be kept sealed from the air (as much as possible) to prevent CO_2 in the air from being absorbed, thereby changing the normality of the solution.

4. Mixed indicator

Mixed indicator is a mixture of 0.625 gram methyl red indicator and 0.413 gram methyl blue indicator made up with 500 cubic centimeters of ethyl alcohol, that is, the mixture of methyl blue and methyl red must be dissolved in 500 cubic centimeters of ethyl alcohol. This indicator may be obtained, on request, from a chemical house, the proper specifications being given.

5. Distilled water

All chemical equipment must be washed with distilled water. City tap water is not a satisfactory substitute.

6. Van Slyke-Cullen urea apparatus (18 sets)

Each set consists of a Van Slyke test tube and inlet bubbling tube (aeration tube) and an outlet tube with a trap to separate any entrained liquid.

7. Burettes (2) - One for sulphuric acid and the other for sodium hydroxide. Straight stopcock 50 cc

8. Burette support (1)

9. Gas washing bottle (1000 cc)

10. Beakers, Griffin low-form, Pyrex (two 1500 cc, two 1000 cc, one 600 cc, one 250 cc, and one 100 cc)

11. Automatic pipette (25 cc capacity)

12. Aspirator, water (to produce suction for withdrawing samples)

13. Sargent wet-test gas meter (precision)

14. Thick-wall tubing (48 ft of 3/16-in. bore; 48 ft of 3/8-in. bore)

15. Ammonia flow control (Model LW)

Sources of supply:

Item 1, Rohm and Haas Co., 22 W. Washington Square, Philadelphia, Pennsylvania

Items 2 to 14, The Fisher Scientific Co., Pittsburgh, Pennsylvania

Item 15, Hoke Inc., 122 Fifth Avenue, New York, N.Y.

Accessory equipment:

1. Mercury manometer for accurate determination of pressures at the high side of the monomethylamine metering orifice. With a mercury manometer relatively small pressure fluctuations are easily noticed.

2. Vacuum receiver with needle-control valve and vacuum-pressure gage.

Physical Properties of Monomethylamine

Temperature (°F)	Vapor pressure (lb/sq in.)	Specific gravity	Latent heat (Btu/lb)
50	29.8	0.6746	362.6
70	45.2	.6610	356.5
90	66.1	.6471	350.1
110	94.1	.6331	342.9
130	129	.6188	339
150	174	.6042	327
170	228	.5892	317
190	293	.5740	307

Filling Cylinder with Monomethylamine

Extreme care should be used in filling any type of cylinder with any liquified gas. Unless care is used, the cylinder is likely to be completely filled, no provision being made for the thermal expansion of the liquid caused by slight temperature changes. In such cases there is no alternative for the confined liquid but to rupture the cylinder. Ruptures of this kind are particularly dangerous and severe personal injuries may be incurred.

The precautions to be observed are simple. First the weight of the empty cylinder must be determined. Then the capacity, in volume, must be known or estimated. From the specific gravity of the liquid, which is given in the preceding table, the weight of the volume of the monomethylamine (which is equal to two-thirds of the total volume of the cylinder) may be determined. In other words, only two-thirds of the total volume of the cylinder must be occupied by the liquid monomethylamine.

If the cylinder to be charged is at the same temperature as the supply cylinder, the liquid monomethylamine will not flow from the supply cylinder to the cylinder to be charged. When a small quantity of monomethylamine first enters the cylinder, it vaporizes and establishes a vapor pressure equal to that in the supply cylinder and flow immediately ceases.

There are two satisfactory means by which flow may be accomplished:

1. Allow the liquid to flow by means of gravity.

2. Cool the cylinder to be charged to a temperature below that of the supply cylinder. Do not heat the supply cylinder.

Monomethylamine is very soluble in water. Tubes filled with monomethylamine may therefore be bled by means of bubbling the gas into a bucket of water.

If the eyes should become exposed to monomethylamine, very serious burns may be received. Goggles must therefore be worn as a safety measure when monomethylamine is transferred from one cylinder to another.

Test Set-Up

Figure 5 shows the arrangement and the necessary equipment for making an engine scavenging-efficiency test. A mercury manometer is used to determine the monomethylamine metering pressures so that the monomethylamine flow can be accurately controlled. The size of the metering orifice should be selected to give a tracer concentration between 0.3 and 0.6 percent by weight monomethylamine in the inlet air.

Air Measurement

A micromanometer (fig. 8) (an inclined manometer may be used) is used to measure the pressure drop through the air-flow meter. It consists of two cylinders that serve as manometer legs, one of glass, open to the atmosphere and the other of brass, accurately machined to the same diameter as the glass manometer leg; a micrometer screw is mounted above the dial indicator to control the motion of the feeler pin. A neon lamp is inserted in an electrical circuit through the instrument so that, when the feeler pin pierces the water level in the open leg of the manometer, the neon lamp glows. The pressure drop is twice the drop in water level in the open leg of the manometer.

Surge Volume

The size of the surge volume necessary for making air measurements depends upon the speed of the engine and the number of cylinders in the engine under test. Satisfactory results may be obtained by using the following relation:

$$\text{Surge volume} = \frac{(40000)\ (\text{displacement volume})}{(\text{rpm})\ (\text{number of cylinders in engine under test})}$$

When crankcase scavenged engines are tested, particular care should be taken, when the surge system is installed, to avoid restrictions to air flow. Only a few inches of water-pressure drop in the system will adversely affect the engine breathing and will invalidate the result of the test. The air-flow meter should be the smallest restriction in the system. The orifice should be so selected that the pressure drop through it is no greater than 1 inch of water.

Load

Monomethylamine does not burn completely during the combustion period regardless of the tracer concentration used. It is important that the monomethylamine fed to the engine burn almost completely if this method of determining the scavenging efficiency of an engine is to be reliable. Figure 3 shows that monomethylamine burns much more completely at high engine load than it does at low engine load. Above three-quarter load the burning efficiency of monomethylamine does not appreciably increase. From the point of view of the possibility of the occurrence of oxidation and decomposition of monomethylamine during the scavenging and exhaust period until the exhaust sample is withdrawn, it is desirable to keep the engine load down. The engine must, therefore, be operated between three-quarter and full load in order that between 95 and 98 percent of the monomethylamine trapped in the combustion chamber will burn during the combustion period. If the exhaust temperature of the engine is extraordinarily high, the load should be reduced so that the exhaust temperature is below 800° F.

Withdrawing the Sample

The inlet and exhaust samples are withdrawn through the Sargent wet-test gas flowmeter. It is desirable to use a suction receiver because of the ease with which the sample flow may be regulated. The receiver may be evacuated by means of an aspirator, which operates on either air or water; operation on water is preferable because of the increased evacuating capacity that may be obtained. A needle valve is used to regulate the rate of sample flow.

Care of the Monomethylamine Absorption Apparatus

All Van-Slyke test tubes and aeration tubes must be washed with distilled water before the tubes are filled or refilled with sulphuric-acid solution. The aeration tubes must also be dried before being re-used. This drying may be accomplished by means of compressed air.

Charging the Absorption Test Tubes

The inlet-sample test tube is usually charged with 25 cubic centimeters of 0.1 N sulphuric-acid solution

by means of an automatic pipette and distilled water is added until the test tube is half full; three drops of mixed indicator are then added to the solution. When a sample is being bubbled through the solution, the sample bubbles displace the sulphuric-acid solution and raise the level of the solution almost to the top of the tube.

If 25 cubic centimeters of acid are used in the inlet-sample test tubes, 5 cubic centimeters of acid should preferably be used in each exhaust-sample tube, so that when testing an engine with a utilization factor of about 80 percent, approximately the same volume of sample will be used to neutralize the acid in the exhaust-sample test tube as was necessary in the inlet-sample test tube. If an engine of 60 percent utilization factor is being tested, 25 cubic centimeters should be used in the inlet-sample test tube and 10 cubic centimeters in the exhaust-sample test tube. If the sampling is planned in this manner, both time and monomethylamine will be conserved. Free carbon is a decolorizing agent; therefore, with smoky exhaust six drops of mixed indicator must be added to the exhaust-sample test-tube solution.

Inlet-Gas and Exhaust-Gas Analysis

It must be borne in mind that the results of the analysis of a gas sample are no more accurate than the sample analyzed. The monomethylamine should be adequately mixed before withdrawing an inlet sample. This condition may be accomplished by introducing the monomethylamine in a relatively high-velocity section in the surge tank. (See fig. 5.) All inlet and exhaust samples should be withdrawn from the inlet and exhaust ducts through sampling tubes in order that the sample obtained be representative of the gas at that particular location. Figure 7 shows a type of sampling tube that may be used.

At least four exhaust samples must be withdrawn, each at a different location along the exhaust line. The first sample should be withdrawn at a distance equal to a length of exhaust line corresponding to about one and one-half times the displacement volume of the engine cylinder. The remaining sampling tubes should be evenly distributed along the exhaust line in about 1½-foot intervals. The amine-free exhaust samples from each sampling tube should feed into a header so that one gas meter may be used to measure the total volume of the exhaust samples.

It is not necessary to take inlet and exhaust samples simultaneously unless the engine speed does not remain constant for the duration of one complete test (the time necessary to withdraw one inlet and the four simultaneous exhaust samples). In that case two gas meters will be necessary.

If the engine under test will run at a constant speed for the duration of one test, one gas meter is sufficient. The inlet sample should be withdrawn first to determine the concentration of monomethylamine in the inlet air. If all the exhaust samples are withdrawn simultaneously and the rate of sample flow through each tube is regulated to be relatively the same, considerable time will be saved. The rate of the combined sample flow through the gas meter should be about 0.4 cubic foot per minute. As the color of the sulphuric-acid solution in each exhaust-sampling test tube changes from a purple to a light green, the sample flow of that test tube should be stopped. This procedure must be repeated until the acid solution in all four exhaust-sample test tubes have been neutralized. When the flow through the last exhaust-sample aeration tube has been stopped, the volume of the combined samples that passed through the meter should be recorded.

Correction of the Exhaust-Sample Volume by Titration

When the exhaust sample (containing monomethylamine and water vapor) passes through the aeration tube that is at room temperature, some of the water vapor is condensed out of the aeration-tube wall. The condensed water vapor is very effective in absorbing whatever monomethylamine comes in contact with it. The recorded volume of the exhaust samples withdrawn is therefore larger than the true volume necessary to neutralize the sulphuric-acid solution and a correction should be applied.

The solutions in all four exhaust-sampling test tubes should be collected in a large beaker and mixed with the solutions obtained by washing the aeration tubes and the test tubes with distilled water. This washing procedure must be carried out or the results obtained will not be valid. Add 5 cubic centimeters of acid to the solution in the beaker (the color should change from green to purple) and titrate the contents with standardized N/10 sodium-hydroxide solution. When the solution has been titrated, the operator should have the definite number of cubic cen-

timeters of 0.1 N sulphuric-acid solution that were neutralized by the exhaust samples flowing through the various aeration tubes.

Calculation

According to appendix C, α is determined as follows:

$$\alpha = \frac{V_{inl} \Leftrightarrow 25 \text{ cc } 0.1 \text{ N } H_2SO_4}{V_{exh} \Leftrightarrow X \text{ cc } 0.1 \text{ N } H_2SO_4} \frac{X}{25}$$

where the numerator is the number of cubic feet of inlet sample that neutralizes 25 cubic centimeters of approximately 0.1 N acid solution and the denominator is the number of cubic feet of exhaust sample that neutralizes X cubic centimeters of the same acid solution. From equation (13)

$$\eta_{ut} = \frac{1 - \alpha}{e - \alpha s}$$

where e is the burning efficiency of the tracer gas, and s the volume shrinkage, which is dependent upon the C/H ratio of the fuel and the air-fuel ratio. (See fig. 2.)

The charging efficiency is then obtained from equation (7)

$$\eta_{ch} = \eta_{ut} L$$

where

$$L = \frac{V_{del}}{V_{disp}}$$

If the air delivery is determined by flowmeter measurement and a rounded nozzle is used, the quantity of air flowing through the nozzle per second is

$$Q = CA \sqrt{2g \frac{p}{\gamma}}$$

where A is the cross-section area of the flowmeter nozzle, p the pressure drop across the nozzle, γ the specific weight of the air, and C the discharge coefficient, which is about 0.98 in case of a standard flowmeter nozzle.

If p is expressed in inches of water, γ in pounds per cubic foot, and A is in square inches,

$$Q = 0.98\,A\sqrt{\frac{2 \times 385 \times p/27.5}{\gamma/1728}}$$

$$= 0.98\,A\,220\sqrt{\frac{p}{\gamma}} \text{ cubic inches}$$

and the delivery ratio is

$$L = \frac{\frac{60\,Q}{n}}{N\,\frac{D^2\pi}{4}\,S}$$

where n is the engine revolutions per minute, D the cylinder bore, S the stroke, both in inches, and N the number of cylinders in the engine.

CONCLUSIONS

1. The tracer-gas method of determining the charging efficiency of two-stroke-cycle Diesel engines, in which approximately 0.5 percent monomethylamine is used as a tracer gas, is convenient and sufficiently accurate.

2. The test is to be performed with the engine operating at between three-quarter and full load. Under such conditions, it may be assumed that between 95 and 97 percent of the monomethylamine, which is trapped in the cylinder, burns during the combustion period.

3. Oxidation or decomposition of the monomethylamine during the scavenging and exhaust period could not be detected and may be neglected for all practical purposes.

4. A simple correction formula for volume shrinkage and incomplete combustion of the monomethylamine should be applied in evaluating the test results for better accuracy. With such correction the determination of the charging efficiency is expected to be accurate within ±1 percent.

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State College, Pa., November 15, 1941.

APPENDIX A

RELATION BETWEEN SCAVENGING EFFICIENCY AND BRAKE-MEAN-EFFECTIVE PRESSURE

The horsepower output of an engine is

$$hp = \frac{\frac{V_{disp}}{12} \text{ bmep } \frac{2n}{c}}{33000} \tag{A1}$$

where V_{disp} is the displacement volume in cubic inches, n the revolutions per minute, and c the number of strokes per cycle.

Naturally, the horsepower is also equal to the total fuel consumption divided by the specific fuel consumption

$$hp = \frac{F_h}{f} = \frac{V_{pure}\ \rho\ \frac{2n}{c}\ 60}{r\ f\ 1728} = \frac{V_{pure}\ \rho\ \frac{2n}{c}\ 60}{r_{th}\ \lambda\ f\ 1728} \tag{A2}$$

where V_{pure} is the volume of pure air under normal temperature-pressure conditions in the cylinder before combustion (see fig. 1), r the actual, r_{th} the theoretical ratio, $\lambda = r/r_{th}$ the excess-air factor, and ρ the weight of 1 cubic foot of air under normal temperature-pressure conditions.

From equations (A1) and (A2)

$$\text{bmep} = 13{,}750\ \frac{\rho}{\lambda\ f\ r_{th}}\ \frac{V_{pure}}{V_{disp}}$$

One cubic foot of dry air under normal temperature-pressure conditions weighs 0.0765 pound, therefore

$$\text{bmep} = \frac{1050}{\lambda\ f\ r_{th}}\ \frac{V_{pure}}{V_{disp}} \tag{A3}$$

It should be realized that V_{pure} is more than that

part of the air delivered and retained in the cylinder. It includes some pure air of the residual gas remaining in the cylinder from the previous cycle. If figure 1 is referred to, the following definitions and relations can be written:

$$\eta_{sc} = \frac{V_{ret}}{V_{ret} + V_{res}} \tag{A4}$$

$$\eta_{vol} = \frac{V_{ret} + V_{res}}{V_{disp}} \tag{A5}$$

$$\lambda = \frac{V_{pure}}{V_{th}} = \frac{r}{r_{th}} \tag{A6}$$

$$V_{pure} = V_{ret} + V_{res} - V_{cp} \tag{A7}$$

$$\frac{V_{cp}}{V_{res}} = \frac{V_{th}}{V_{ret}} \tag{A8}$$

In equations (A4) to (A8) there are five unknowns: V_{pure}, V_{ret}, V_{res}, V_{cp}, and V_{th}. These equations can be solved for V_{pure} to give

$$V_{pure} = V_{disp} \frac{\eta_{vol}\ \eta_{sc}}{1 + (\lambda - 1)\ \eta_{sc}} \tag{A9}$$

Equations (A3) and (A9) result in

$$bmep = \frac{1050}{f\ r_{th}} \frac{\eta_{vol}\ \eta_{sc}}{1 + (\lambda - 1)\ \eta_{sc}} \tag{A10}$$

which can also be written as

$$bmep = 180\ \frac{0.4}{f}\ \frac{14.5}{r_{th}} \frac{\eta_{sc}}{1 + (\lambda - 1)\ \eta_{sc}}\ \eta_{vol}$$

This expression is identical with equation (8) of the text.

APPENDIX B

CORRECTION FOR UTILIZATION FACTOR

If the amount of unburned tracer gas in the cylinder is zero and the volume shrinkage due to combustion is also zero, the utilization factor

$$\eta_{ut} = \frac{V_{ret}}{V_{ret} + V_{short}} \tag{B1}$$

is equal to $(1 - \alpha)$, where α is the ratio of tracer-gas concentration in the exhaust to the tracer-gas concentration in the inlet and is determined directly by a chemical method.

Because the air retained in the cylinder undergoes a volume shrinkage during combustion, volume shrinkage may be expressed as

$$s = \frac{V_{ret} - V_e}{V_{ret}} \tag{B2}$$

where V_e represents the volume under normal temperature-pressure conditions of that portion of the water-free exhaust gas that was contributed by the combustion in the cylinder. The total exhaust is

$$V_{exh} = V_e + V_{short} \tag{B3}$$

The next thing to consider is that a small portion of the tracer gas escapes combustion in the cylinder. This gas can be accounted for in the burning efficiency e of the tracer gas:

$$e = \frac{t_{ret} - t_{nb}}{t_{ret}} \tag{B4}$$

where t_{ret} and t_{nb} denote the retained portion of the tracer gas and the nonburned portion of the tracer gas, respectively.

Finally, α is the ratio of the actually measured

concentrations in the exhaust and inlet

$$\alpha = \frac{\dfrac{t_{exh}}{V_{exh}}}{\dfrac{t_{del}}{V_{del}}} = \frac{V_{del}}{V_{exh}} \frac{t_{exh}}{t_{del}} \tag{B5}$$

A formula is sought

$$\eta_{ut} = f\ (\alpha,\ s,\ e)$$

that would give the utilization factor in terms of the correction factors.

Known relations are:

$$\frac{V_{ret}}{V_{short}} = \frac{t_{ret}}{t_{short}} \tag{B6}$$

$$V_{del} = V_{ret} + V_{short} \tag{B7}$$

$$t_{del} = t_{ret} + t_{short} \tag{B8}$$

$$t_{exh} = t_{short} + t_{nb} \tag{B9}$$

$$V_{exh} = V_e + V_{short} \tag{B10}$$

From equations (B1) and (B6)

$$\eta_{ut} = \frac{1}{1 + \dfrac{t_{short}}{t_{ret}}} \tag{B11}$$

From equations (B7), (B10), and (B6)

$$\frac{V_{del}}{V_{exh}} = \frac{V_{ret} + V_{short}}{V_e + V_{short}} = \frac{1 + \dfrac{t_{short}}{t_{ret}}}{\dfrac{V_e}{V_{ret}} + \dfrac{t_{short}}{t_{ret}}} \tag{B12}$$

But from equation (B5)

$$\frac{V_{del}}{V_{exh}} = \alpha \frac{t_{del}}{t_{exh}} \tag{B13}$$

From a comparison of (B12) and (B13)

$$\alpha \frac{t_{del}}{t_{exh}} = \frac{1 + \frac{t_{short}}{t_{ret}}}{\frac{V_c}{V_{ret}} + \frac{t_{short}}{t_{ret}}} \tag{B14}$$

On the other hand, from equation (B2)

$$\frac{V_c}{V_{ret}} = 1 - s \tag{B15}$$

and from equation (B11)

$$\frac{t_{short}}{t_{ret}} = \frac{1}{\eta_{ut}} - 1 \tag{B16}$$

From equations (B14), (B15), and (B16), therefore, is derived

$$\bar{\alpha} \frac{t_{del}}{t_{exh}} = \frac{1 + \frac{1}{\eta_{ut}} - 1}{1 - s + \frac{1}{\eta_{ut}} - 1} = \frac{1}{1 - s\,\eta_{ut}} \tag{B17}$$

Dividing equation (B8) by equation (B9) gives

$$\frac{t_{del}}{t_{exh}} = \frac{t_{ret} + t_{short}}{t_{nb} + t_{short}} = \frac{1 + \frac{t_{short}}{t_{ret}}}{\frac{t_{nb}}{t_{ret}} + \frac{t_{short}}{t_{ret}}} \tag{B18}$$

and if equation (B16) is considered

$$\frac{t_{del}}{t_{exh}} = \frac{1 + \frac{1}{\eta_{ut}} - 1}{1 - e + \frac{1}{\eta_{ut}} - 1} = \frac{1}{1 - e\,\eta_{ut}} \tag{B19}$$

When equation (B17) is compared with equation (B19)

$$\alpha \frac{1}{1 - e\,\eta_{ut}} = \frac{1}{1 - s\,\eta_{ut}} \tag{B20}$$

from which

$$\eta_{ut} = \frac{1 - \alpha}{e - \alpha s}$$

This equation is identical with equation (13) used in the text.

APPENDIX C

DETERMINATION OF α

Chemical Reaction between Mononethylamine and Sulphuric-Acid Solution

A convenient solution to use for reaction with the monomethylamine in the absorption apparatus is an approximately 0.1 N solution of H_2SO_4.

A normal solution is one that contains the gram equivalent weight of a substance in 1000 cubic centimeters of solution. The equivalent weight of a substance is the weight of it which combines with, or replaces, 1.008 grams of hydrogen. Inasmuch as H_2SO_4 contains two replaceable hydrogen atoms, its equivalent weight is the molecular weight divided by 2 (98/2 or 49 grams). Consequently, any solution containing 49 grams of sulphuric acid per liter is a normal solution of H_2SO_4, and any solution containing 4.9 grams of H_2SO_4 per liter is a 0.1 N solution.

Concentrated sulphuric acid is 96 percent pure and has a specific gravity of 1.84. One cubic centimeter of concentrated sulphuric acid therefore contains 1.77 grams of H_2SO_4; or the volume of sulphuric acid that contains 4.9 grams of H_2SO_4 is

$$\frac{4.9}{1.77} = 2.77 \text{ cubic centimeters concentrated } H_2SO_4$$

Then, by the addition of 2.77 cubic centimeters of concentrated sulphuric acid to distilled water to make a total of 1000-cubic-centimeter solution, a 0.1 N solution of sulphuric acid will be obtained.

A solution of this kind may not be exactly 0.1 N and, therefore, the exact normality may be determined by titration with a standardized solution of 0.1 N NaOH, which may be obtained from a chemical company.

The actual concentration of H_2SO_4 used in the tests was 0.121 N.

Concentration of Monomethylamine in Air

When monomethylamine reacts with sulphuric acid, monomethylamine sulphate is formed as indicated by the following reaction:

$$CH_3NH_2 + H_2SO_4 \longrightarrow CH_3NH_2 \quad H_2SO_4$$

Since a 1 N aqueous solution of H_2SO_4 contains 49 grams H_2SO_4 per 1000 cubic centimeters of total solution, 1 cubic centimeter of 1 N H_2SO_4 solution contains 0.049 gram of H_2SO_4. Hence, 1 cubic centimeter of a (N) normality H_2SO_4 solution contains 0.049 (N) gram of H_2SO_4. According to the foregoing stoichiometric equation, the quantity of monomethylamine equivalent to 1 cubic centimeter of (N) H_2SO_4 may be calculated, as indicated, by the following method:

$$\frac{(0.049)\ (N)}{98} = \frac{w}{31}$$

where 98 and 31 represent the molecular weights of H_2SO_4 and CH_3NH_2, respectively, and w the equivalent weight of CH_3NH_2, which gives

$$w = \frac{31}{2}\ (10^{-3})\ (N)\ g\ CH_3NH_2$$

If Xcc is the volume of (N) H_2SO_4 solution used for the sample test, the weight W of CH_3NH_2 equivalent to it would be

$$W = \frac{31}{2}(10^{-3})(N)(X)\ g = \frac{(31)(10^{-3})}{(2)(454)}(N)(X)\ lb$$

$$W \rightleftharpoons X\ cc\ (N)\ H_2SO_4$$

The $\rightleftharpoons$ symbol represents that the quantities on the right and left side neutralize each other.

This weight of monomethylamine is contained in a volume V of gas. The concentration is

$$\text{Concentration } CH_3NH_3 = \frac{\frac{(31)(10^{-3})}{(2)(454)}(N)(X)}{V}$$

where

(N) normality of acid solution

V volume of monomethylamine free sample $\rightleftharpoons$ X cc of (N) normality H_2SO_4.

If the volume occupied by the amine in the gas is neglected, only the fourth decimal will be affected.

Calculation of the Concentration Ratio of Monomethylamine in the Exhaust and Inlet Samples

The symbol α denotes the ratio

$$\alpha = \frac{\text{concentration } CH_3NH_2 \text{ in the exhaust}}{\text{concentration } CH_3NH_2 \text{ in the inlet}}$$

If substitution is made, there is obtained

$$\alpha = \frac{3.414 \times 10^{-3}\ \frac{(N)\ X}{V}_{exh}}{3.414 \times 10^{-3}\ \frac{(N)\ X}{V}_{inl}}$$

$$\alpha = \frac{\frac{(N)\ X}{V}_{exh}}{\frac{(N)\ X}{V}_{inl}}$$

If the same solution of H_2SO_4 of about 0.1 N is used for both the inlet and the exhaust tests and, if the specific weights of the two monomethylamine free gas samples are equal

$$\alpha = \frac{V_{inl} \;\; \Rightarrow \;\; X_{inl} \; (N) \; H_2SO_4 \; \frac{X_{exh}}{X_{inl}}}{V_{exh} \;\; \Rightarrow \;\; X_{exh} \; (N) \; H_2SO_4}$$

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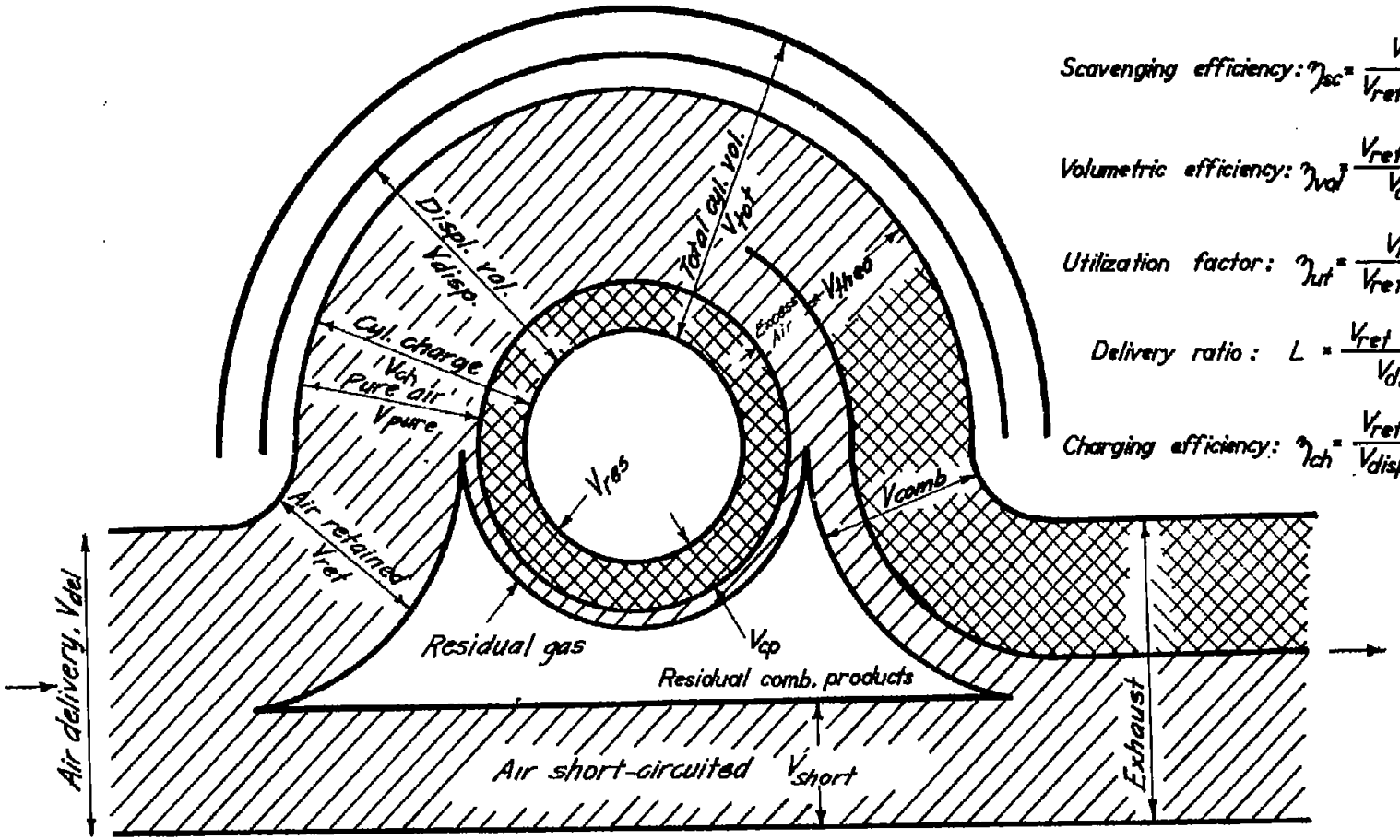
TABLE I

DETERMINATION OF THE CHARGING EFFICIENCY OF A VENN SEVERIN TWO-STROKE-CYCLE CRANKCASE SCAVENGED DIESEL ENGINE

(Rated 30 hp at 400 rpm; 10.5-in. bore; 12-in. stroke; inlet port opens 132° A.T.C.; exhaust port opens 117° A.T.C.; inlet port closes 228° A.T.C.; exhaust port closes 243° A.T.C.; barometer, 28.85 in. Hg)

Test	1	2	3	4	5	6
Engine speed, rpm	378	378	380	378	382	380
Exhaust temperature, °F	580	575	610	620	595	590
Water-jacket temperature, °F	158	136	150	150	146	152
Mean crankcase pressure, pounds per square inch	$1\frac{1}{8}$	$1\frac{1}{8}$	$\frac{3}{4}$	$\frac{3}{4}$	$1\frac{1}{4}$	$1\frac{1}{8}$
Maximum cylinder pressure, pounds per square inch	575	575	570	575	585	590
Inlet-air temperature, °F	93	94	95	102	101	101
Relative smoke density obtained with Penn State smokemeter	.82	.76	.86	.84	.84	.84
Monomethylamine feed, orifice 5,	5	5	5	5	5	5
inches Hg pressure	30	30	22	22	33	33
Inlet sample ⇒ 20 cc 0.09873 N H_2SO_4, cubic feet	.202	.202	.200	.197	.202	.207
Sample through sample header ⇒ 16 cc 0.09873 N H_2SO_4 (4 cc 0.09873 N H_2SO_4 in each aeration tube) four such tubes used - one withdrawing a sample 6 feet from exhaust port and the others each withdrawing samples at locations 9 feet, 12 feet, and 15 feet from the exhaust ports, respectively, all leading to a common header which leads to a wet-test gas meter, cubic feet	.852	.802	1.000	1.031	.898	.911
Volume of sample passing through header corrected by titration 16 cc 0.09873 N H_2SO_4	.761	.761	.970	.996	.840	.855
α, $\frac{\text{percent tracer in exhaust}}{\text{percent tracer in inlet}}$	.212	.212	.165	.158	.192	.194
Average α for each run	.212		.162		.193	
Size of thin-plate orifice placed in the 4.5-inch-diameter inlet air duct at the crankcase, inches	3	3	2	2	none used	none used
Pressure drop through 3.145-inch-diameter air-flow orifice (discharge coefficient 0.98), inches water	.284	.272	.202	.200	.324	.316
Inlet-air specific weight, pounds per cubic foot	.0703		.0686		.0689	
Air velocity through the air-flow orifice, feet per second	36.35		31.35		39.55	
Air-delivery ratio	.504		.433		.544	
η_{ut}	.82		.87		.83	
η_{ch}	.41		.38		.46	



Scavenging efficiency: $\eta_{sc} = \frac{V_{ret}}{V_{ret} + V_{res}}$

Volumetric efficiency: $\eta_{vol} = \frac{V_{ret} + V_{res}}{V_{disp}}$

Utilization factor: $\eta_{ut} = \frac{V_{ret}}{V_{ret} + V_{short}}$

Delivery ratio: $L = \frac{V_{ret} + V_{short}}{V_{disp}}$

Charging efficiency: $\eta_{ch} = \frac{V_{ret}}{V_{disp}}$

Excess-air factor: $\lambda = \frac{V_{pure}}{V_{theo}}$

Fig. 1. Diagram showing two-stroke engine process.

Light shading - pure air, heavy shading - burning products.

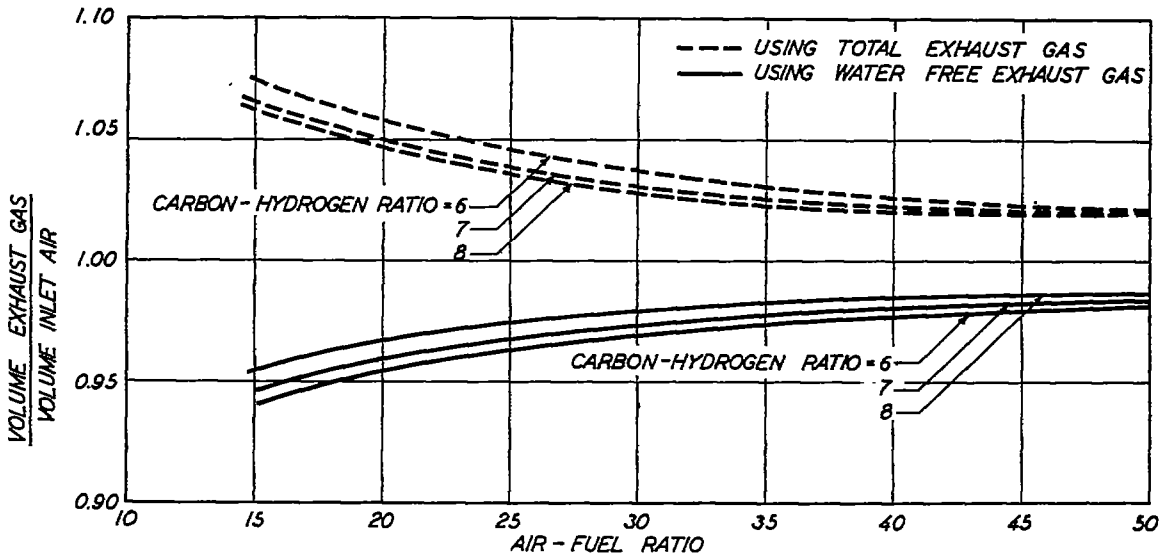


FIG. 2. CHANGE IN VOLUME AFTER COMBUSTION. VOLUMES HAVE BEEN COMPUTED AT N.T.P. CONDITIONS WITH AND WITHOUT WATER VAPOR

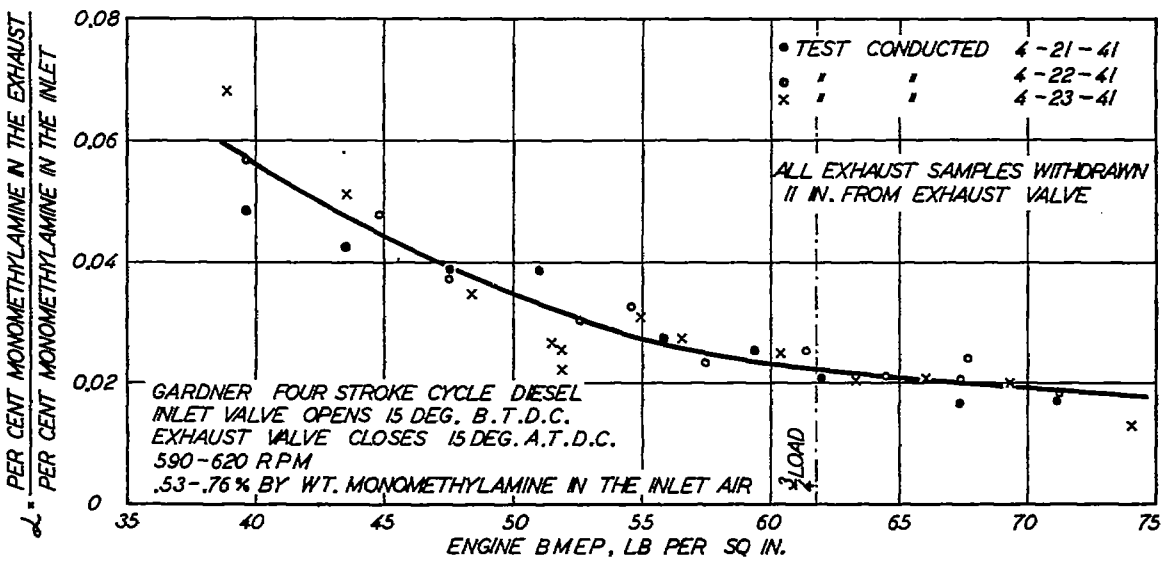


FIG. 3. BURNING EFFICIENCY OF MONOMETHYLAMINE IN A GARDNER DIESEL ENGINE. Van Slyke-Cullen Urea apparatus.

FIG. 4. VAN SLYKE - CULLEN UREA FLASK

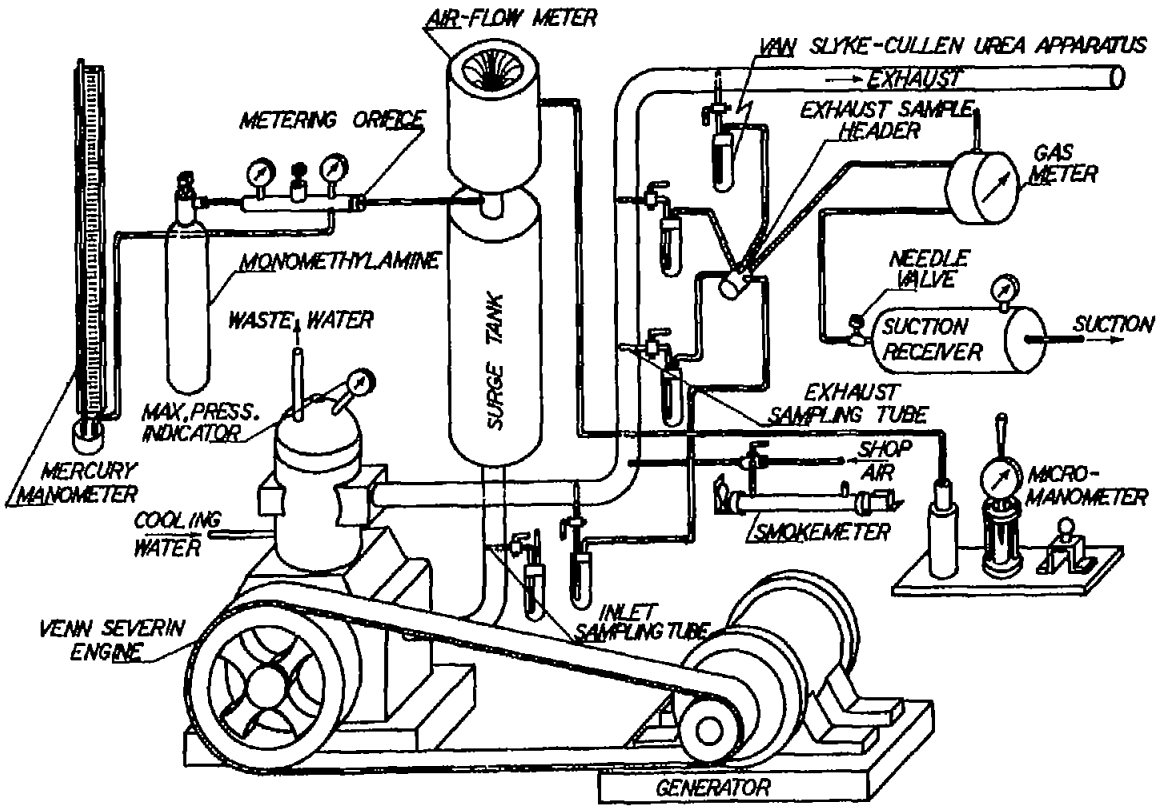


FIG. 5. VENN SEVERIN ENGINE TEST SET-UP

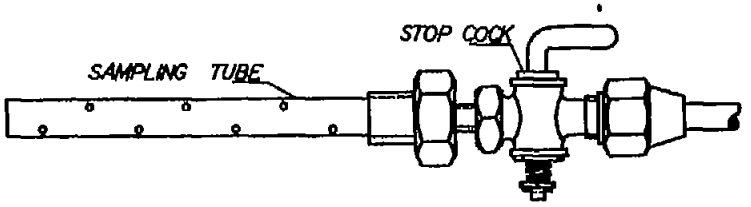


FIG. 7. SAMPLING TUBE AND STOP COCK

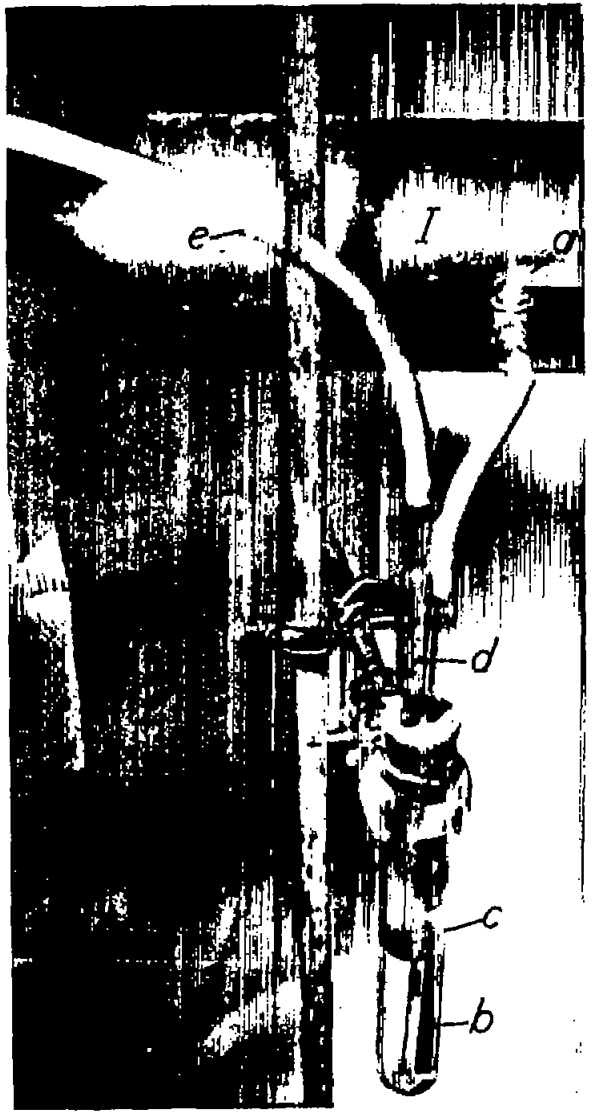


Figure 6.- Arrangement used to withdraw a sample through the Van Slyke-Cullen urea apparatus.
I, inlet-air duct
a, sampling-tube stopcock
b, aeration tube
c, test tube containing sulphuric-acid solution
d, trap to separate any entrained liquid
e, outlet tube to gas-flow meter

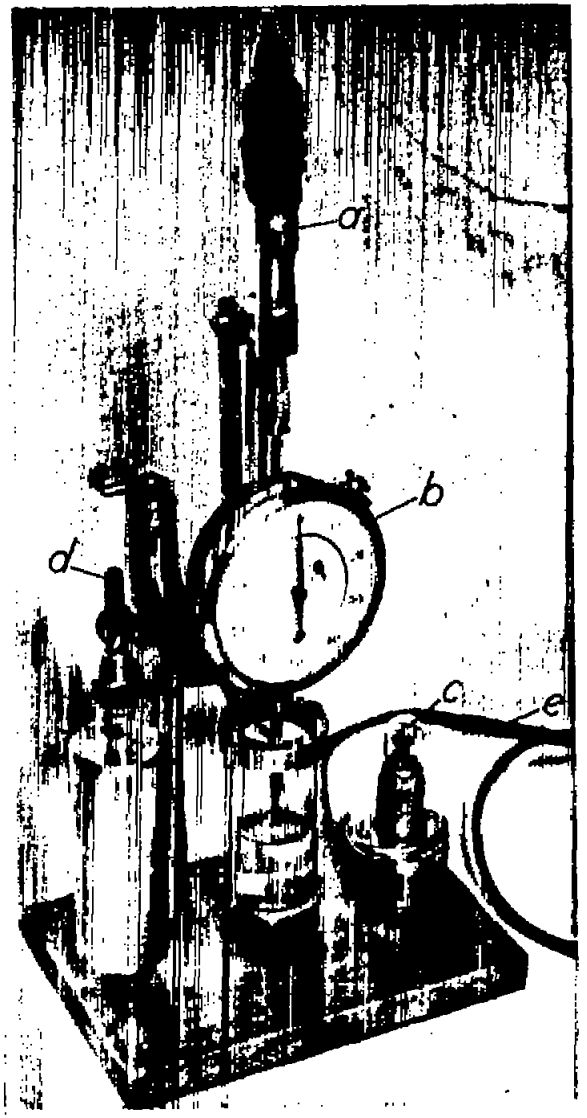


Figure 8.- Micromanometer.
a, micrometer screw
b, dial indicator
c, neon lamp
d, connection to low pressure side of air-flow nozzle
e, alternating-current power source

TITLE: The Tracer Gas Method of Determining the Charging Efficiency of Two-stroke-cycle Diesel Engines

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ABSTRACT:

The development of two-stroke-cycle engines centers around problem of obtaining good scavenging efficiency. A suitable tracer gas, monomethylamine, is introduced into inlet air of running engine. Its concentration is measured chemically in inlet and exhaust gas. Correction formula for volume shrinkage and incomplete combustion of tracer gas is given for evaluating test results with better accuracy.

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