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## FUEL VAPOR PRESSURES AND THE RELATION OF VAPOR PRESSURE TO THE PREPARATION OF FUEL FOR COMBUSTION IN FUEL INJECTION ENGINES

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### SUMMARY

*This investigation on the vapor pressures of fuels was conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., in connection with the general research on combustion in fuel injection engines. The purpose of the investigation was to study the effects of high temperatures such as exist during the first stages of injection on the vapor pressures of several fuels and certain fuel mixtures, and the relation of these vapor pressures to the preparation of the fuel for combustion in high-speed fuel injection engines.*

The apparatus employed in the tests consisted of a gas-tight steel bomb, a Bourdon spring pressure gauge, an electric furnace, a thermocouple, and a potentiometer. The bomb was partially filled with the fuel to be tested, the space above the fuel filled with nitrogen to prevent combustion, and the bomb heated in an electric furnace. Pressure and temperature readings were taken simultaneously during the heating and cooling periods over a temperature range from 175° to approximately 900° F. Vapor and gas pressures up to 5,000 pounds per square inch were measured. The fuels tested were gasoline, kerosene, Diesel engine fuel oil, ethyl alcohol, methyl acohol, benzol, mixtures of methyl alcohol and gasoline, and mixtures of benzol and gasoline. An aircraft engine lubricating oil was also tested. Water was tested as a standard in order to compare these results with those of other investigators. The conditions of the tests were similar to those met in the combustion chamber of a fuel injection engine and consequently the data apply to those conditions.

It was found that the vapor pressures of the fuels increased rapidly at high temperatures, the rate of pressure increase becoming greater as the temperatures approached the critical value. Beyond the critical temperature, the rate of pressure increase was constant except at one or more temperatures in the case of certain fuels and their vapors in which chemical changes took place. The chemical changes in some of the fuels were such that the cooling curves were materially different from those obtained during the heating periods. Permanent gases were generated during the heating and cooling periods in the case of the alcohols, gasoline, kerosene, and Diesel engine fuel oil so that the fuels removed from the bomb were materially different from those placed in it. The vapor pressures of the fuels differed from each other considerably, methyl alcohol having the highest vapor pressure, 4,370 pounds per square inch, and Diesel engine fuel oil the lowest, 140 pounds per square inch, for the maximum temperature investigated, approximately 850° F.

The data for the vapor pressures of the fuels at high temperatures indicate the compression temperatures required to produce rapid vaporization of the injected fuel for combustion.

### INTRODUCTION

In order to control and minimize the maximum cylinder pressures developed in high-speed fuel injection engines, particularly in engines designed for aircraft service, it is desirable to have the combustion proceed in accordance with the dual cycle, which requires the first and smaller part of the injected fuel charge to burn at constant volume and the remainder to burn at con-

stant pressure. The constant volume combustion usually determines the maximum pressure developed in the engine cylinder. It is necessary, therefore, to investigate and control the injection and engine factors that affect the amount of constant volume combustion, in accordance with the spray formation, vaporization, ignition, and combustion requirements of the fuel.

Recent progress in the performance of high-speed fuel injection engines has emphasized the time lag of auto-ignition of the injected fuel as one of the major factors that affect the amount of constant volume combustion. In order to minimize the amount of constant volume combustion in engine operation, it is necessary to distribute the small fuel particles properly in the combustion chamber and raise them to their auto-ignition temperature during injection of the first part of the fuel charge. The maximum cylinder pressure developed is proportional to the fraction of the fuel charge that is injected and prepared for combustion at the instant that auto-ignition occurs. Thus, the earlier that auto-ignition takes place, the start and rate of injection remaining the same, the less will be the amount of constant volume combustion. The cylinder pressures of the constant pressure phase of the dual cycle may be controlled, therefore, by varying the rate of injection of the remainder of the fuel charge. (Reference 1.)

The injected fuel in an aircraft oil engine must be prepared for ignition in less than 10° of crank-shaft rotation for uniform rates of injection if the time lag of auto-ignition is to be short enough for operation with low cylinder pressures. This time lag is dependent upon the type of injection system used; the timing and rate of injection; the fuel spray velocity and penetration; the degree of atomization obtained; the distribution of the spray in the combustion chamber and of the oil particles within the spray; the compression ratio used in the engine and the dependent cylinder pressures and temperatures; the timing, direction, and amount of turbulence employed; the amount of radiation from hot surfaces in the combustion chamber; the initial temperature of the injected fuel; and the chemical and physical properties of the fuel. It is probable that in the past sufficient consideration has not been given to the physical and chemical properties, which is due in part to the lack of experimental data in the range of high temperatures occurring during the first stages of injection in fuel injection engines. This research was conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., to obtain data on the effect of high temperatures on the vapor pressures of several fuels under conditions approximating those in fuel injection engines. In addition the data afford opportunity for analysis of the relation of this fuel property to the preparation of the fuel for combustion.

The principal investigations made heretofore on the effect of temperature on the vapor pressures of liquids have been on water, methyl alcohol, and ethyl alcohol. (Reference 2.) The temperature range investigated has been from room temperature to the critical temperature of the liquid, approximately 500° F. The United States Bureau of Mines in 1922 (reference 3) conducted some experiments on gasoline and kerosene over a similar temperature range. Several of the tar and paraffin oils have been investigated in Germany up to 800° F. (Reference 4.) However, as far as is known, complete data on the effects of high temperatures on the vapor pressures of such fuels as are used in fuel injection engines have not been reported, particularly in the range above the critical temperatures, and data for those fuel mixtures that are used to suppress detonation in gasoline engines are entirely lacking.

The tests reported herein were conducted on gasoline, kerosene, Diesel engine fuel oil, ethyl alcohol, methyl alcohol, benzol, mixtures of ethyl alcohol and gasoline, mixtures of benzol and gasoline, and an aircraft engine lubricating oil. Water was tested as a standard to compare these results with those of other investigators. Temperatures from 175° to approximately 900° F. were investigated and vapor pressures up to 5,000 pounds per square inch were recorded.

## METHODS AND APPARATUS

The method employed in the determination of the vapor pressure of a fuel consisted of partially filling a steel bomb with the fuel to be tested and heating it in an electric furnace through the desired temperature range. The bomb was made of steel instead of some inactive substance so that the test conditions in this respect would approach those met in an engine cylinder. The space above the fuel was filled with nitrogen since it would prevent combustion and because the

gas in the combustion chamber of the fuel injection engine preceding injection of the fuel consists of approximately 77 per cent by weight of nitrogen. Temperature and pressure readings were taken simultaneously at regular intervals during both the heating and cooling of the bomb and fuel. The bomb was not held at each recorded temperature until equilibrium conditions were reached, since such a condition does not exist in the combustion chamber.

A photograph of the apparatus is shown in Figure 1 and a diagrammatic sketch of it in Figure 2. The apparatus consisted of a gas-tight steel bomb, a cooling pan, a valve block, a pressure gauge, connecting tubes, an electric furnace, a thermocouple, and a potentiometer.

The steel bomb was made from a piece of 1¾-inch diameter chrome-nickel steel 5½ inches long. A well for holding the fuel and its vapor was drilled in the bomb slightly off center to a depth of 4½ inches. Two small holes were drilled into this well from the other end of the bomb, one to serve as a filling hole connection and the other as an outlet connection to the pressure gauge. Two drilled hexagonal steel bars approximately 8 inches long were screwed and shrunk into these holes. The upper ends of the bars were provided with union fittings, thus providing a separable joint above the cooling pan. Steel tubes with union fittings were fastened to the drilled bars, a gooseneck bend being made in one of the tubes to provide for unequal expansion of the hexagonal bars and tubes. The lower end of the bomb was closed by a plug which was also screwed and shrunk into place. The volume of the well was approximately 22 cm³.

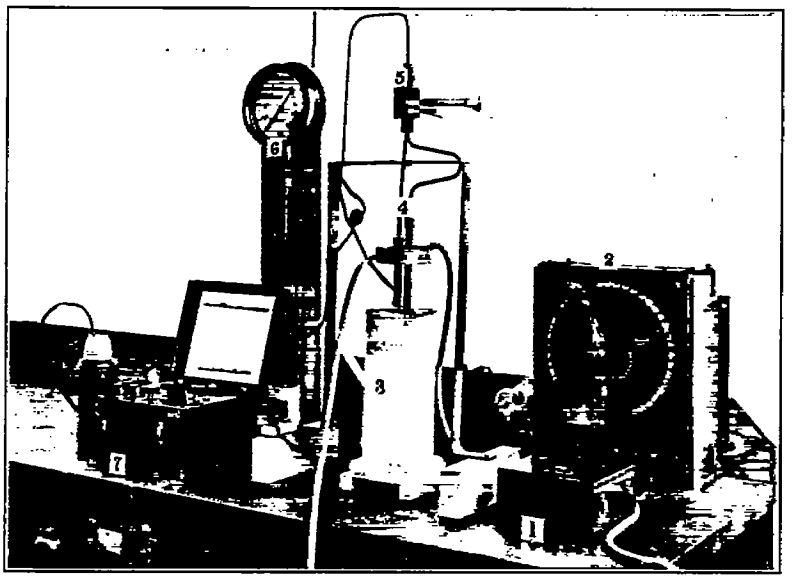


FIGURE 1.—Vapor pressure apparatus. 1. Voltmeter for measuring potential across electric furnace. 2. Rheostat for regulating potential across electric furnace. 3. Electric furnace containing bomb. 4. Cooling pan. 5. Valve block. 6. Bourdon pressure gauge. 7. Potentiometer for indicating temperature of bomb. The thermos bottle holding the cold junction of the thermocouple can be seen immediately to the left of the potentiometer

It was necessary to have both an inlet and an exhaust opening in the apparatus for the efficient cleaning of the bomb, for filling the bomb with the fuel to be tested, and for displacing the air above he fuel with nitrogen before the start of each test. These openings were placed in the valve block where they could be closed by needle valves and were connected by drilled holes in the valve block to the two tubes from the bomb. In addition, the tube connected to the inlet opening was also connected by a drilled hole through the valve block to the tube for transmitting the vapor pressures to the pressure gauge.

Several Bourdon spring pressure gauges were used for measuring the pressures exerted by the vapors, their ranges varying from 0 to 200 pounds per square inch to 0 to 5,000 pounds per square inch, depending on the maximum pressure to be obtained with the fuel under test. The gauges were altered by making the entrances to them very small so that the oil placed in the Bourdon spring could not easily escape. In addition a gooseneck bend was made in the steel tube connecting the gauge to the valve block. This tube was also filled with oil and its position arranged so as to maintain oil in the gauge and tube in all the tests. The gauges were calibrated by means of a dead-weight gauge tester.

The cooling pan was placed midway between the valve block and the bomb to cool and condense the hot vapors before they reached the valve block. Cold water was kept flowing through this pan during the tests. Steel wires were inserted in the hexagonal bars in order to prevent the condensed vapors from dropping back into the bomb, the liquid being retained in

the bars by surface tension and capillarity, aided by the small annular space between the wire and the drilled hole.

Heat was supplied by a cylindrical electric furnace of slightly larger diameter than the bomb. The heat energy in the furnace was sufficient to heat the bomb considerably above the maximum test temperature. This relation, in addition to the fact that the heat capacity of the bomb was considerably in excess of that of the fuel placed in it, assured a steady though slightly decreasing rate of temperature rise. A hole was drilled in the thickest part of the bomb wall from the bottom of the bomb to a depth of 3½ inches, and the hot junction of the thermocouple placed approximately 1 inch from the top of this hole in order to locate the hot junction near the dividing line of the fuel and the vapor. The cold junction of the thermocouple was surrounded by melting ice in a thermos bottle. The electrical potential generated in the thermocouple which was indicated by the potentiometer was converted into degrees Fahrenheit from a calibration of the thermocouple made by means of a certified thermometer.

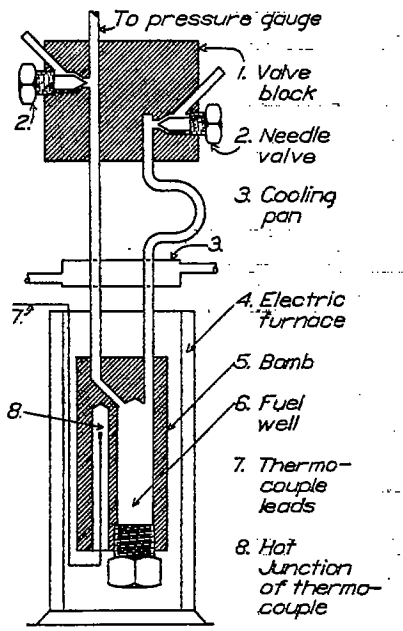


FIGURE 2.—Diagrammatic sketch of vapor pressure temperature apparatus

The test procedure followed was the same for all the fuels. The bomb was first washed thoroughly with the fuel to be tested. It was then placed in the electric furnace with opened needle valves and heated to a temperature in excess of that to be used in the test. This was done to complete any chemical reaction that might take place between the metal of the bomb and the fuel and to vaporize any impurities that might be present. When the bomb had again cooled to room temperature, approximately 13 cm³ of the fuel to be tested were placed in it. A tank containing nitrogen was connected to the inlet opening and nitrogen passed through the bomb and connecting tubes for a definite time interval at a slow, steady rate interrupted with occasional intervals of slightly increased flow. Following this replacement of the air in the apparatus by nitrogen, the pressure in the bomb was adjusted to atmospheric pressure, the inlet and exhaust valves closed, and the electric current turned on in the furnace. When a temperature of approximately 175° F. was indicated, the observer began recording the readings of the potentiometer and of the pressure gauge simultaneously. Readings were taken at intervals of pressure of from 1 to 50 pounds per square inch, depending on the range of pressures to be covered during the test. When the maximum temperature desired was reached, the electric current in the furnace was turned off and readings were taken during the cooling period in the same manner. The time for a complete test was approximately three hours. Specimens of the fuel and of the gas remaining in the bomb were collected at the completion of each test. The tests were repeated several times with varying amounts of fuel, the bomb being completely prepared previous to each test by washing, heating, and cooling as described above.

Several series of computations and corrections in addition to the temperature and pressure calibrations were made to the recorded data in order to obtain the true temperatures and pressures of the vapor under test. These computations and corrections related chiefly to the nitrogen pressure which was calculated for each temperature, assuming a constant volume relationship to exist in the bomb. The nitrogen pressure was then subtracted from the corrected recorded pressure and the atmospheric pressure added to obtain the vapor pressure of the fuel being tested.

## TEST RESULTS

The experimental data from these tests are plotted in Figures 3 to 12. It may be noted that critical points were recorded for most fuels and that pressure fluctuations or other physical-chemical phenomena have taken place. The data for all curves on any fuel were reproducible

with a satisfactory degree of accuracy up to the critical point. Beyond the critical point the date for each fuel were reproducible in their general characteristics, but the vapor pressure for any given temperature increased with the amount of the fuel originally placed in the bomb. The phenomena that were most evident follow.

1. Critical Points.—The critical point is the point at which the curve changes from one of increasing slope to one of constant slope. It is clearly defined in the curves for gasoline (fig. 3), methyl alcohol (fig. 7), ethyl alcohol (fig. 8), benzol (fig. 9), and the mixtures of gasoline with ethyl alcohol (fig. 11), and with benzol (fig. 12). The temperature indicated at this point is known as the critical temperature of the liquid. At this temperature physical distinctions between the liquid and its vapor disappear.

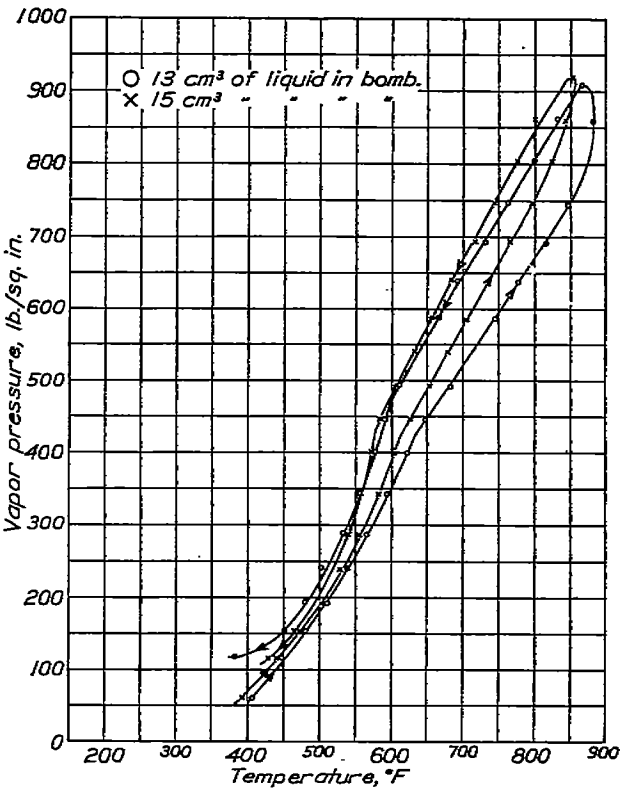


Figure 3.—Effect of temperature on the vapor pressure of gasoline

2. Pressure Fluctuations.—These phenomena occurred during the cooling of the kerosene (fig. 4) and of the Diesel oil (fig. 5). During the pressure fluctuations the indicating hand of the pressure gauge, turned at about the speed of the second hand of a watch, stopped, and then traveled back to within a few pounds of the starting pressure, and then repeated the cycle with gradually increasing and later decreasing maximum pressures. These reactions for the Diesel oil continued until the temperature had dropped from about 825° to about 575° F. The reactions for kerosene were considerably more restricted, taking place between 725° and 680° F.

3. Generation of One or More Permanent Gases from All the Fuels Tested with the Exception of Benzol.—The generation of these permanent gases was indicated by the high residual pressures exerted by the vapors after the bomb had been allowed to cool to room temperatures as shown for gasoline, kerosene, Diesel engine fuel oil, methyl alcohol, and ethyl alcohol. (Figs. 3, 4, 5, 7, and 8.)

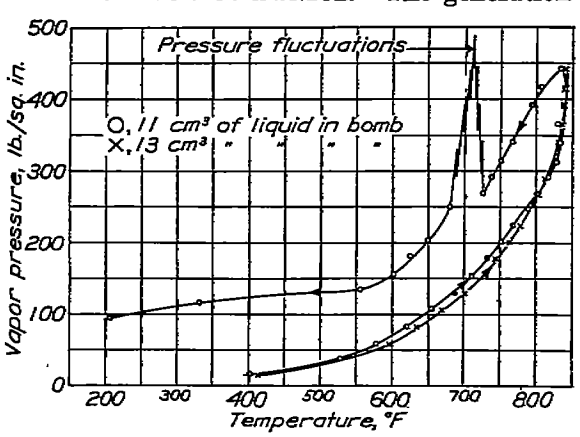


Figure 4.—The effect of temperature on the vapor pressure of kerosene

4. Permanent Decomposition.—Permanent decompositon or cracking was indicated by the fact that the fuel removed from the bomb following the test was different from that put into it. The alcohols, kerosene, and gasoline were changed from clear white thin liquids to liquids that resembled fuel oil or a very light lubricating oil.

5. Generation of Two or More Separate and Distinct Vapors At Or Above the Critical Temperature.—These phenomena are indicated in the curves for the alcohols (figs. 7 and 8) and the benzol (fig. 9). In these curves the straight line temperature-pressure relations above the critical point are made up of two or more straight lines that join but that have different slopes.

6. Rapid Increase in Vapor Pressures.—The vapor pressure of the aircraft engine lubricating oil (fig. 6) increased at such a rate after it had reached approximately 800° F. that it was necessary to open the exhaust needle valve in order to prevent damage to the pressure gauge. The rate of pressure increase was so much greater than that of the temperature increase as to indicate a physical or chemical change in the oil, such as cracking at a higher temperature than used in manufacture.

7. Variation of the Vapor Pressures.—A comparison of the vapor pressures of the fuels tested is shown in Figure 10. These curves are the same as those appearing in Figures

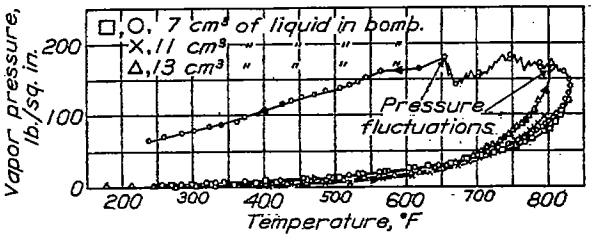


Figure 5.—Effect of temperature on the vapor pressure of Diesel engine fuel oil

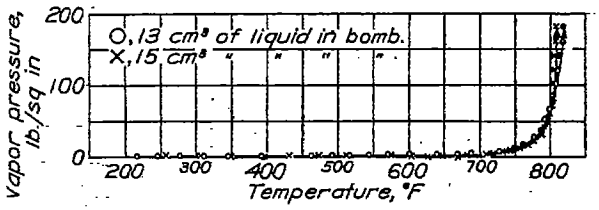


Figure 6.—Effect of temperature on the vapor pressure on aircraft engine lubricating oil

3 to 9 for the tests with 13 cm³ of the fuel in the bomb. The wide variation of the vapor pressures of the six fuels and of the lubricating oil is clearly illustrated.

8. Deviation from Dalton's Law of Partial Pressures.—The values for the vapor pressures of the mixtures of ethyl alcohol and of benzol with the gasoline (figs. 11 and 12), are not the sums of the vapor pressures of the individual liquids as would be expected from Dalton's law. This is probably due to the fact that chemical reactions took place between the two fuels or between the gases existing and generated in the bomb at the high temperatures of the tests.

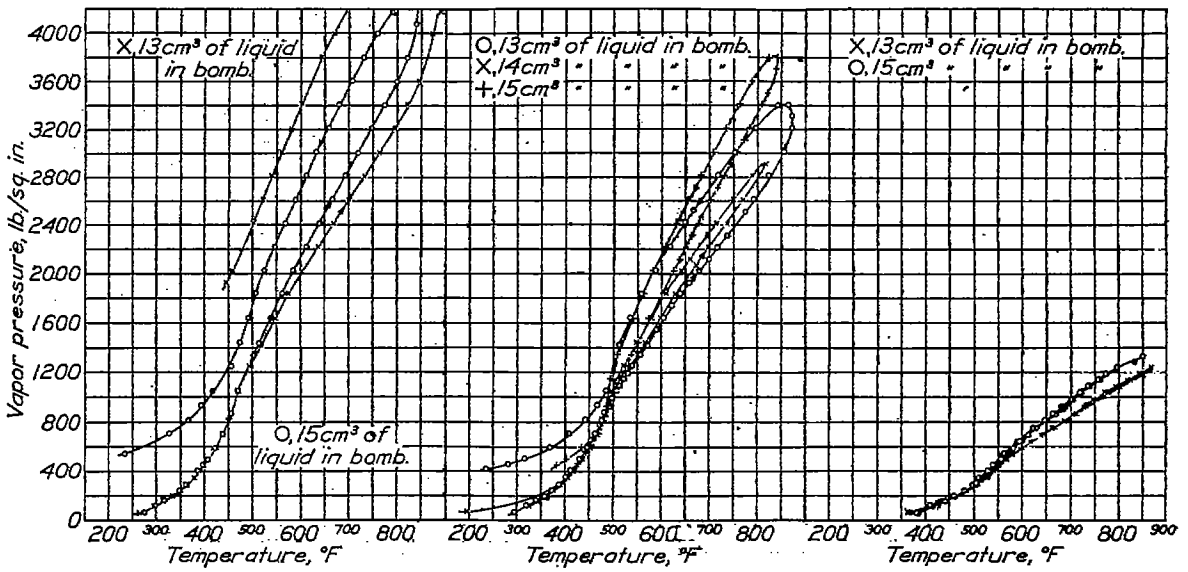


Figure 7.—Effect of temperature on the vapor pressure of methyl alcohol

Figure 8.—Effect of temperature on the vapor pressure of ethyl alcohol

Figure 9.—Effect of temperature on the vapor pressure of benzol

It is particularly interesting to note that in the case of the benzol-gasoline mixtures, at the higher temperatures, the vapor pressures of the mixtures with the exception of the 80 per cent benzol 20 per cent gasoline mixture are less than those of either of the fuels. The curves for these mixtures form a family of curves which has materially different characteristics and trends from the curves for either fuel. This family is further illustrated in Figure 13, which is a cross plot from Figure 12.

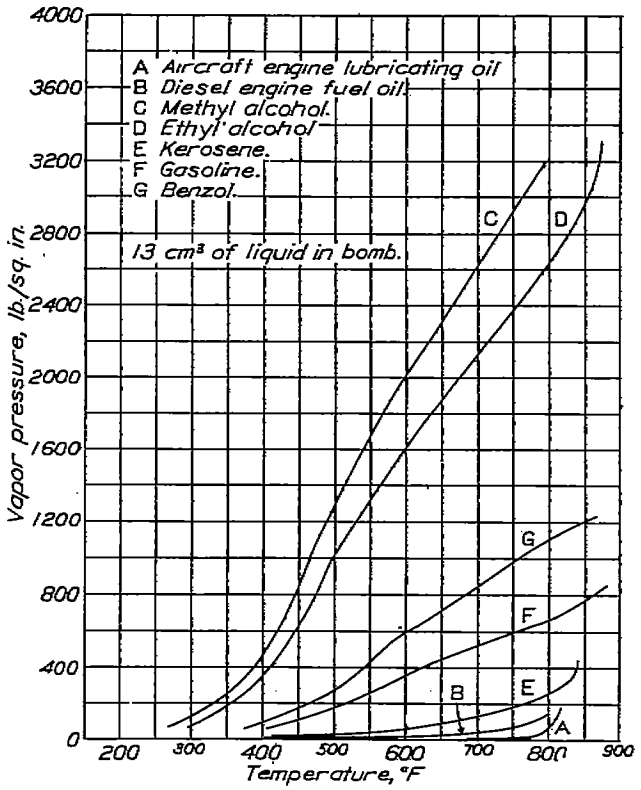


FIGURE 10.—Effect of temperature on the vapor pressure of several fuels and of lubricating oil

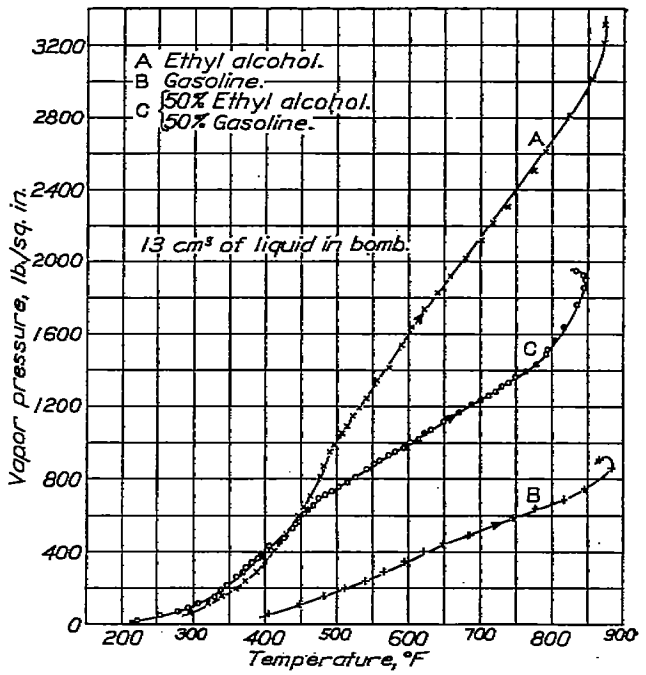


FIGURE 11.—The effect of temperature on the vapor pressure of ethyl alcohol, gasoline, and mixtures of ethyl alcohol and gasoline

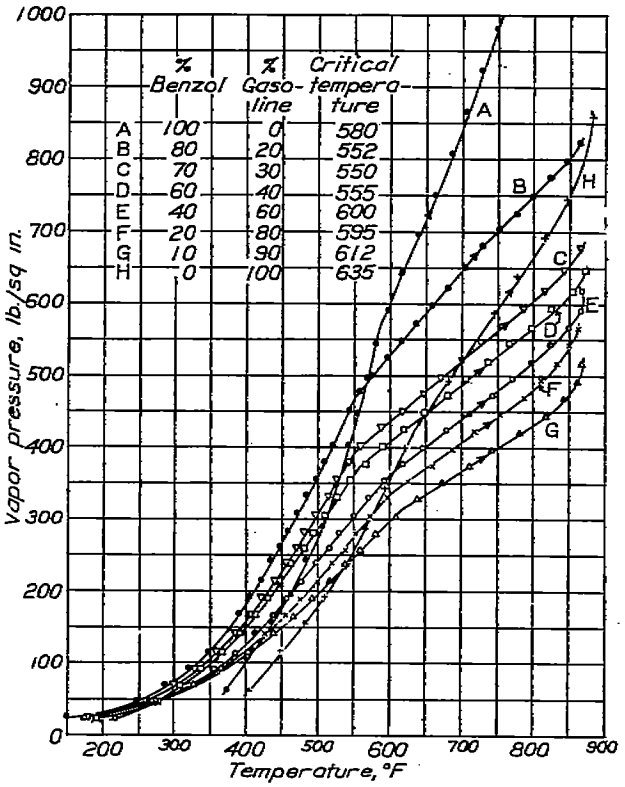


FIGURE 12.—Effect of temperature on the vapor pressure of benzol, gasoline, and benzol-gasoline mixtures

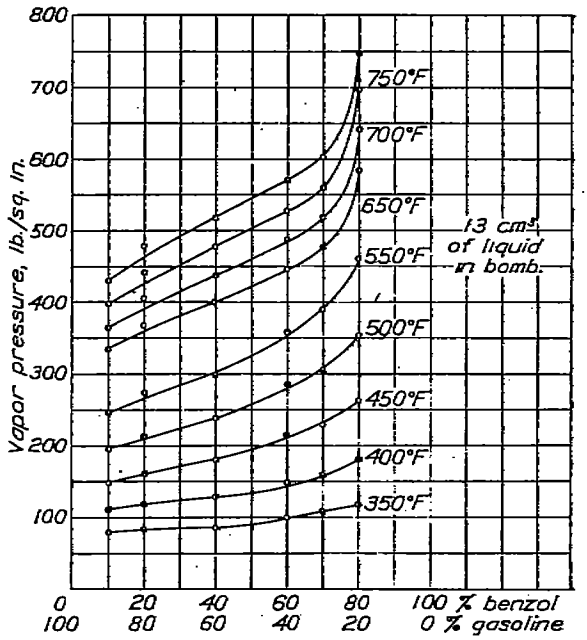


FIGURE 13.—Effect of composition on the vapor pressure of benzol-gasoline mixtures at constant temperatures

## ACCURACY OF TEST RESULTS

VAPOR PRESSURES.—The accuracy of the computed vapor pressures depended on the error of observation in the vapor pressure readings, the gauge calibrations, and the computed nitrogen pressures. The error of observation in the pressure gauge readings was 0.5 per cent to 1.0 per cent of the maximum reading of the gauge. The accuracy of the gauge calibration depended upon the accuracy of the standard used. The possible error in this standard, the dead-weight gauge tester, was so small in comparison with that of the Bourdon gauge as to be negligible. However, there was an error in the computation of the nitrogen pressure because its volume did not remain constant as was assumed. The volume occupied by the vapors changed during the test due to the thermal expansion of the bomb and the liquid, the pressure expansion of the bomb and compression of the liquid, and the vaporization of the liquid. The following method was used to determine the magnitude of the error introduced by assuming that the volume of the vapor remained constant.

The change in the volume of the bomb due to the increase in the temperature and the pressure was computed. The volume of the liquid at the temperature and pressure under considera-

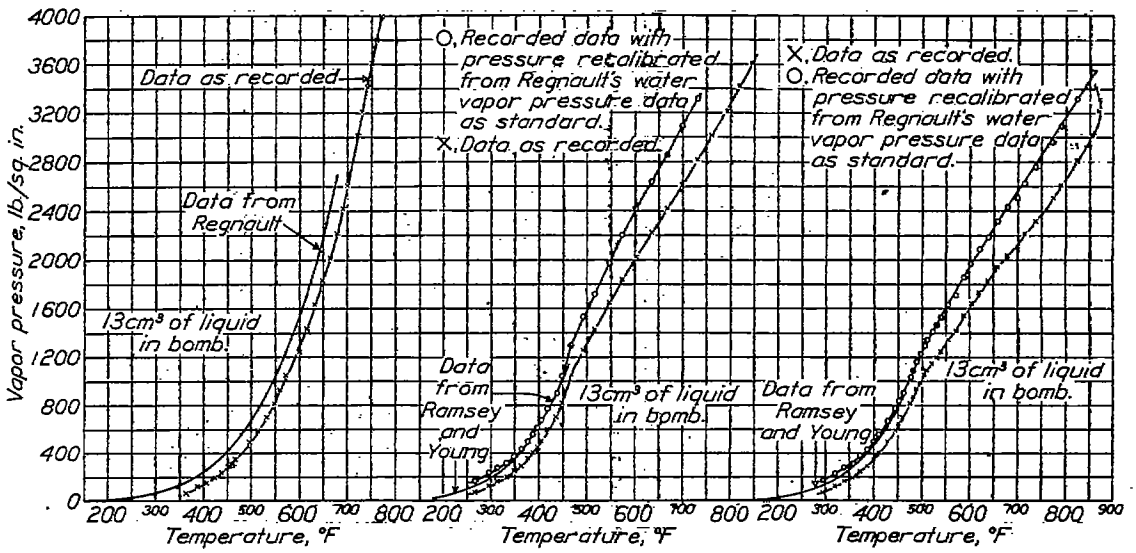


FIGURE 14.—Effect of the conditions of test on the vapor pressure of water

FIGURE 15.—Effect of the conditions of test on the vapor pressure of methyl alcohol

FIGURE 16.—Effect of the conditions of test on the vapor pressure of ethyl alcohol

tion was derived. The volume of the liquid was subtracted from the total volume to obtain the volume occupied by the vapor. The weight of the vapor was computed and subtracted from the total weight of the liquid under test.—The volume occupied by the remaining liquid was again computed and these calculations repeated until the true volume of the vapor was found within the accuracy desired. For methyl alcohol at the critical temperature, 473° F., and the corresponding critical pressure, 1,100 pounds per square inch, the true nitrogen pressure was 3.6 pounds per square inch greater than the value obtained by assuming that the vapor volume remained constant. Consequently the vapor pressure computed with this assumption was in error by only 0.33 per cent.

TEMPERATURE.—The accuracy of the temperatures depended on the potentiometer and thermocouple calibration, the error of observation in the potentiometer readings, the temperature gradient between the hot junction of the thermocouple and the vapor, and the conduction losses along the thermocouple wires. The thermocouple and the potentiometer were calibrated by means of a 680° F. thermometer that had previously been calibrated and certified by the United States Bureau of Standards. The maximum variation from the mean of any one reading was 2° F. The error of observation in the potentiometer reading was 0.5° F. The temperature gradient between the hot junction of the thermocouple and the inside wall of the bomb was

computed to be 0.1° F. The wire of the thermocouple was wrapped around the bomb several times to prevent conduction losses from the hot junction along the thermocouple wires. The maximum error of the temperature readings was therefore approximately 2.6° F.

COMPARISON OF DATA WITH THAT OF OTHER INVESTIGATIONS.—Water was tested as a standard for comparison of the data presented with that given by other investigators. This comparison was made to determine whether other factors than those considered affected the experiments. The experimental results from these tests on water are shown in comparison with the values given by Regnault (reference 2) in Figure 14. If the discrepancy in the water data was caused by some factor inherent in the apparatus, the same discrepancy should appear in the data for all the liquids tested which were affected in the same manner by this factor. In order to determine whether or not the same error did appear in the data for the alcohols, the difference in pressures from Figure 14 were added to the vapor pressures as computed from the tests and plotted together with the results obtained by Ramsey and Young for these two liquids (reference 2) in Figures 15 and 16. The conclusion is drawn from an examination of these curves that at any given temperature the effect on the vapor pressure is approximately the same for water and the alcohols. The discrepancy is probably due in part to the different catalytic effects of the materials of the bomb on the liquids. The data presented in this report can only be applied therefore to these fuels when heated under conditions similar to those existing in the tests.

## ANALYSIS

Several changes take place in fuels for oil engines when they are injected into the combustion chamber of the engine. The high temperature of the air in the combustion chamber heats the fuel particles, begins to vaporize them, and in some cases decomposes them into new hydrocarbons. The processes continue until some of the fuel reaches its auto-ignition temperature and combustion is initiated. The combustion spreads through the combustion chamber at a rate depending on the degree with which the fuel is mixed with the air and on the rapidity with which the fuel is raised to the auto-ignition temperature. The endeavor to decrease the time lag of auto-ignition is an effort to speed up the processes of preparing the comparatively cold, liquid fuel chemically and physically for auto-ignition. The physical properties of the fuel partially control the time necessary to carry out these processes. Among these properties may be mentioned the specific heat, the heat of vaporization and the saturated vapor pressure of the fuel, and the specific heats of the fuel vapors.

The vapor pressures presented in this report are not in every case the vapor pressures of the fuels originally placed in the bomb. With the exception of the alcohols and benzol, the fuels were a combination of saturated and unsaturated hydrocarbons, and the increasing temperature caused chemical as well as physical changes. The vapor above the fuel formed hydrocarbons which did not appear in the fuel.

The pressure of a vapor is caused by the impact of the swiftly moving molecules on the walls of the retaining vessel. The pressure is proportional to both the number and the magnitude of these impacts. The magnitude is determined by the mean kinetic energy of the molecules. This is equivalent to $\frac{1}{2} m v^2$ in which $m$ is the mass of the molecule and $v$ is its mean velocity. The vaporization process consists of energizing the molecules by heating them until they possess sufficient kinetic energy to overcome the surface tension of the liquid and enter the vapor. A decrease of the surface tension of the liquid or an increase in the mean kinetic energy of the molecules in the liquid will result in a greater number of the molecules entering the vapor. When a liquid is subjected to an increasing temperature the surface tension is lowered (reference 5) and the mean kinetic energy of the molecules is raised. As a result the vaporization and consequently the vapor pressure increases at a more rapid rate than the temperature. This is illustrated in all the experimental results.

According to the kinetic theory of gases, for equal volumes and temperatures the number of molecules in any two vapors is proportional to the pressures exerted by the vapors. The total amount of vaporization—that is, total number of free molecules—for equal vapor volumes of any two liquids at a given temperature is, therefore, proportional to their vapor pressures.

An examination of experimental data (fig. 10) indicates that the order of the preparation of the several fuels for combustion in the range of temperatures between 200° and 800° F. is ethyl alcohol, benzol, gasoline, kerosene, and Diesel engine fuel oil. The vapor pressures of these fuels at 450° F. are given in Table I. They are in the ratios 120:35:22:4:1, respectively. The specific heats of the fuels at 104° F., and the latent heats of vaporization at the boiling temperatures are also given in Table I.

TABLE I

| Fuel | Vapor pressures, pounds per square inch at 450° F. | Specific heat at 104° F. | Latent heat of vaporization, B. t. u. per pound |
|---|---|---|---|
| Ethyl alcohol | 600 | [1] 0.648 | 369 at 173° F.[1] |
| Benzol | 175 | [1] .423 | 166 at 176° F.[1] |
| Gasoline | 115 | [2] .501 | 137 at 194° F.[2] |
| Kerosene | 20 | [2] .482 | 135 at 244° F.[2] |
| Diesel engine fuel oil | 5 | [2] .472 | 115 at 338° F.[2] |

[1] Reference 2. [2] Reference 7. [3] Reference 6.

Actual practice indicates that in carburetor engines burning ethyl alcohol or gasoline the alcohol is the more difficult to ignite. This variance from the vapor-pressure data which shows there are a lesser number of free molecules produced in the easily ignited gasoline is due to the comparatively high specific heat and latent heat of evaporization of the alcohol. Ethyl alcohol therefore requires some form of preheating, such as hot spots, high inlet air temperatures, or high compression ratios to supply this heat energy in order to obtain sufficient vaporization for the production of an ignitable and rapidly combustible mixture.

Above 800° F. the vapor pressures of the Diesel engine fuel oil increase at such a rapid rate that a comparatively small change in the temperature, and consequently in the compression ratio of an engine, will result in a considerable decrease in the lag of auto-ignition.

The rapid increase in the vapor pressure of the lubricating oil indicates the maximum temperature at which this oil may be used for lubricating or cooling purposes.

The rate of the increase of vapor pressure with temperature increases rapidly with the temperature. For this reason a small increase in the compression temperature of an engine will result in a marked increase in the vapor pressure of the fuel. The data for the vapor pressures of the fuels, therefore, indicate the compression temperature required to produce the rapid vaporization of the injected fuel for combustion.

## CONCLUSIONS

Several conclusions are drawn from the experimental results. The vapor pressures of the fuels tested, which are measures of the number of free molecules produced by the vaporization processes, vary over a wide range of pressure at any given temperature. The rate of change of vapor pressure with temperature for any one fuel increases rapidly until the critical temperature is reached. Above this temperature the rate of increase of the vapor pressure remains at a constant value, which depends on the ratio of the mass of the vapor and liquid per unit volume. At high temperatures the fuel vapors form new hydrocarbons which in some cases on condensation form a fuel of different composition from that originally placed in the bomb. The vapor pressures of the fuel mixtures investigated do not follow Dalton's law of partial pressures, the vapor pressures of the mixtures being either greater or less than the vapor pressures of either of the unmixed fuels. The data for the vapor pressures of the fuels at high temperatures indicate the compression temperatures required to produce rapid vaporization of the fuel for combustion.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *October 16, 1928.*

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