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No. 392

EXPERIMENTAL INVESTIGATION OF THE PHYSICAL PROPERTIES OF MEDIUM AND HEAVY OILS, THEIR VAPORIZATION AND USE IN EXPLOSION ENGINES

By Fritz Heinlein

PART IV

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The diffusion coefficients in Table XVII are to be regarded as mean values, since they were obtained from the vaporization speeds, which were, indeed, based on the same experimental duration for the individual fuels, but which could not take account of the very rapid changes in speed and were consequently obtained only as mean vaporization speeds. They can, however, be used as comparative values for the individual fuels in the theoretical discussion of the vaporization process.

Table XVII.

Barometer mm Hg	Temperature °C	k"	d_1	p mm Hg	Diffusion Coef. k
	Gas oil. d = 9.74				
721	20	0.0369	9.07	1.0	0.6230
721	30	0.0436	8.55	1.2	0.6530
721	35	0.0557	8.11	1.6	0.6620
721	70	0.1347	7.76	4.0	0.6710
721	92	0.2795	7.28	7.5	0.6910

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* "Experimentelle Untersuchung der physikalischen Eigenschaften mittlerer und schwerer Brennstoffe, ihre Verdampfung und Verwendung im Explosionsmotor," from "Der Motorwagen," Sept. 30, (pp. 617-624) and Nov. 10, (pp. 775-779), 1926. For Parts I, II, and III, see N.A.C.A. Technical Memorandums Nos. 362, 363 and 384.

Table XVII (Cont.)

Barometer mm Hg	Temperature °C	k''	d_1	p mm Hg	Diffusion Coef. k
		Paraffine oil.	d = 25.2		
724	22	0.2670	23.13	2.0	0.8980
724	50	0.5250	21.80	4.0	0.9340
724	70	0.6960	19.90	5.5	0.9870
724	97	1.5500	18.45	12.5	1.0350
		Coal-tar oil.	d = 6.48		
722	22	0.1912	5.92	16.0	0.3098
722	40	0.4480	5.65	28.0	0.4314
724	52	0.5680	5.41	36.0	0.4410
724	70	0.8490	5.16	51.0	0.4850
724	90	1.6420	4.88	66.0	0.7780
		Benzol. d = 3.19			
720	30	0.2530	2.875	85.0	0.1540
720	42	0.4380	2.756	145.0	0.1412
720	50	0.6680	2.695	168.0	0.2070
722	70	2.1870	2.504	281.0	0.3800
		Gasoline. d = 4.2			
719	17	0.2337	3.952	29.0	0.3065
720	28	0.3760	3.810	41.0	0.3635
720	25	0.5130	3.720	50.0	0.4125
720	43	0.6620	3.630	60.0	0.4510
720	50	0.8490	3.550	68.0	0.5190
720	74	1.0650	3.342	96.0	0.8840

Theoretical Treatment of the Vaporization Process

After the most important physical characteristics for the vaporization of fuels have been experimentally determined, we are prepared to deal mathematically with the vaporization process of the fuels during the intake stroke of an explosion engine. Before undertaking the analytical treatment of this process, there are still a few general preliminary remarks to be made on the manner of introducing the fuel and forming the mixture.

In contrast with the Diesel engine and the heavy-oil engines mentioned in the introduction, which function with high- or medium-pressure fuel injection, light oils have hitherto been almost exclusively used in carburetor explosion engines, since the experiments with carburetors, heavy-oil atomizers and explosive partial combustion have yet yielded no satisfactory results.

The vaporization of the fuel before entering the cylinders of an explosion engine is accomplished by means of a mechanism, generally known by the name "carburetor." This term (which would be literally translated from the German "Vergaser" by the English word "vaporizer") might give one the impression that the complete vaporization of the light oils is effected in it in combination with the incoming air. In reality, this condition is not fully attained in the now almost universally employed spraying nozzle carburetors, even with light fuels. The chief function of such a carburetor is rather to produce a uniform mixture of the fuel and air. Thus the fuel, while still in the liquid state, forms a sort of "cloud" in combination with the air. The more homogeneous the mixture produced, the more stable is this liquid cloud.

After we understand that the fuel is mixed with the air in the form of small liquid drops, we are interested in the vaporization of these drops in the air passing through the carburetor until the ignition at the end of the compression stroke. We must, therefore, deal analytically and mathematically with the vaporization of the liquid drops of the light oils, gasoline and benzol (or benzene), of the medium oil, kerosene, and of the heavy oils tested, under the same pressure, temperature and time relations, in order to discover ways for using heavy oils in carburetor engines. The computation is based on a very instructive article by Dr. Klaften, which treats of the vaporization of water drops in the air stream.*

The process of vaporization of an oil drop existing in the vapor in the intake air of an engine, under given pressure, temperature and time relations, must be thought of as adiabatic. The quantity of heat required for the vaporization is abstracted from the air and fuel. We think of the fuel drop as surrounded by an envelope of air and of the rate of vaporization of the drop as expressed by the rate of diffusion of the saturated vapor on the surface of the drop in this envelope of air. The process of vaporization will now be computed in two different ways:

I. Purely thermodynamically;

II. On the basis of the diffusion theory.

It is hereby assumed that the oil drops are spherical and evenly distributed throughout the cross section of the intake pipe.

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* B. Klaften, "Analytische und experimentelle Untersuchungen über die Verdampfung zerstäubter Flussigkeiten," published in "Der Motorwagen" of April 20, April 30, and May 20, 1921.

I.

The quantities of air, liquid and vapor flowing through a cross section of the intake pipe are expressed, all together, in weights per unit of time in kg/sec; the specific heat, in cal/kg; the temperature in $t^{\circ}C$; the vaporization heat r, in cal/kg; the quantities of heat without relation to the weight, by J; and the quantities of heat per kg, by i. The weight relations are indicated by g. The indices are: 1 for air, 2 for oil, 3 for oil vapor.

The formulas, now to be developed, lead to the establishment of an equation for the vaporization time of a fuel drop through the radius of the drop after the atomization and through the experimentally determined physical characteristics. If, therefore G represents the total amount flowing through the cross section of the intake pipe, we then have

$$G = G_1 + G_2 + G_3 .$$

Moreover, we represent the ratio of the air to the liquid and vapor as the mixture ratio m, so that

$$m = \frac{G_1}{G_2 + G_3} .$$

Then, with the adiabatic course of the vaporization process after the successful atomization of the oil, the whole heat content of the mixture remains unchanged and can be expressed through the heat content of the individual components of the mixture

$$J = G_1 i_1 + G_2 i_2 + G_3 i_3.$$

in which $i_1 = c_1 t$ is the heat content of the air at the temperature t; $i_2 = c_2 t$ is the heat content of the liquid fuel at the temperature t; and $i_3 = r_t + c_2 t$, that is, the sum of the vaporization heat r_t and the heat in the liquid fuel.

The heat equation

$$\text{I.} \quad G_1 c_1 t_a + G_{2a} c_2 t_a = J.$$

then holds good in cross section a of the intake pipe in which the atomized fuel, having the temperature t_a, mingles with the outer air having the same temperature t_a, before any vaporization of the fuel occurs.

The following equation

$$\text{II.} \quad G_1 c_1 t + G_2 c_2 t + G_3 (r_t + c_2 t) = J,$$

applies in a cross section lying beyond a, in which, due to vaporization, there is a temperature t which is lower than t_a. If we put

$$\frac{G_3}{G_2 + G_3} = g_3 \text{ (vapor portion)}$$

and introduce the quantity $W = G_2 + G_3$ for shortening and transforming the equation (whereby it is to be noted that W is identical with G_{2a} of the cross section a), we then have

$$\frac{G_3}{W} = g_3; \; m = \frac{G_1}{W} \text{ and } G_2 - W = G_3.$$

By subtracting equation II from equation I, we then obtain

$$g_3 = \frac{(m\ c_1 + c_2)\ (t_a - t)}{r_t}, \qquad (1)$$

If $g_3 = 1$ with complete vaporization of the oil, we can calculate from equation I the temperature at the end of the vaporization as

$$t_e = \frac{m\ c_1 + c_2\ t_a - r_t}{m\ c_1 + c_2}, \qquad (2)$$

and the temperature drop, due to the vaporization, is

$$t_a - t_e = \frac{r_t}{m\ c_1 + c_2}. \qquad (3)$$

If t_e is given, this final temperature then corresponds to an initial temperature of

$$t_a = \frac{(m\ c_1 + c_2)\ t_e + r_t}{m\ c_1 + c_2}. \qquad (4)$$

These equations hold good for the case when the intake air and the fuel leaving the nozzle have the same temperature. In case the air and the fuel have different temperatures, we then introduce into the heat equations the mixture temperature t_m as the initial temperature and thus obtain

$$t_m = \frac{m\ c_1\ t_{a_1} + c_2\ t_{a_2}}{m\ c_1 + c_2} \qquad (5)$$

For determining the vapor portion g_3 at any point of the intake pipe for which equation 1 was developed, a second formula can be established on the following basis.

If, as hitherto, in any cross section of the intake pipe at a temperature t of the mixture, G_3 = the weight of the vapor, then

$$g_3 = \frac{G_3}{G_2 + G_3}$$

$$g_1 = m = \frac{G_1}{G_2 + G_3}$$

and hence

$$g_3 = \frac{G_3}{G_1} m. \qquad (6)$$

If, moreover, b_t = the pressure of the mixture in the above-mentioned cross section of the intake pipe at the temperature t, with p_{3t} = the saturation pressure at $t^{\circ}C$ and φ_t = the degree of saturation at the temperature t, which is represented as a proper fraction and corresponds to the relative humidity in water vapor, i.e., with $\varphi_t \, p_{3t}$ = the pressure of the oil vapor in the mixture of vapor and air with γ_1 = density of the air at $t^{\circ}C$ and γ_2 = density of the fuel vapor at $t^{\circ}C$, then the ratio G_3/G_1 can be determined according to Dalton's law on the partial pressures.

The partial pressure of the air in the mixture, according to the given definitions, is $b_t - \varphi \, p_{3t}$. At the same temperature, the partial pressures are proportional to the number of the molecules in the air or fuel and hence, according to Avogadro's law, to the volumes of the air and vapor. These volumes are

$$\frac{G_1}{\gamma_1} \text{ or } \frac{G_3}{\gamma_3} \left(\frac{\text{weight}}{\text{density}}\right)$$

Hence

$$\frac{b - \varphi_t\ p_{3t}}{\varphi_t\ p_{3t}} = \frac{\frac{G_1}{\gamma_1}}{\frac{G_3}{\gamma_3}} = \frac{G_1}{G_3}\ \frac{\gamma_3}{\gamma_1}$$

Since, according to equation 6 $\frac{G_1}{G_3} = \frac{m}{g_3}$

it follows that

$$\frac{b - \varphi_t\ p_{3t}}{\varphi_t\ p_{3t}} = \frac{m}{g_3}\ \frac{\gamma_3}{\gamma_1}$$

and therefrom that

$$g_3 = \frac{m\ \varphi_t\ p_{3t}\ \frac{\gamma_3}{\gamma_1}}{b - \varphi_t\ p_{3t}} \qquad (7)$$

These formulas find further applications in the following consideration of the vaporization of atomized fuels in the air stream on the basis of the diffusion theory.

In continuing the mathematical treatment of the vaporization process, we will consider the vaporization of an oil drop in the air stream and the effect of the mixture ratio.

For the air stream in the intake pipe of the engine at the temperature t and the pressure b, it is assumed that the velocity is uniform throughout the entire cross section and that the atomized drops of fuel are likewise uniformly distributed in the form of small spheres of uniform size. It is also assumed that there is no motion of the oil drops with reference to the air stream. The same indices as above (1 for air, 2 for oil and 3 for oil vapor) will be employed and also ρ as the radius of an air, liquid or vapor sphere. At the same time ρ is the vector employed in the general diffusion equation, after conversion to polar coordinates, which radius depends alone on the time z, if we assume that the spherical surfaces around the common center of the drop and air sphere have the same partial pressure at every point. This spherical surface is then a pressure surface of uniform partial pressure.

ρ_o = radius of surface of drop at any given instant. It decreases as the time increases.

$\rho_a = \rho_o$ at beginning of vaporization process.

G_1, G_2, G_3, = respective quantities of air, oil, and oil vapor.

g = ratio of a quantity to the sum of the quantities of liquid and vapor with the momentary indices.

γ = density in kg/m³.

b = total pressure in mm Hg at 0°C.

p_3 = saturation pressure of vapor in mm Hg at 0°C.

t = temperature in °C.

t_a = temperature at beginning of vaporization.

t_e = temperature at end of vaporization.

φ = ratio of actual vapor portion to the saturation pressure (relative humidity).

m = mixture ratio.

p_{3a} = saturation pressure in mm Hg at beginning of vaporization

p_{3e} = saturation pressure in mm Hg at end of vaporization.

The general equation for the diffusion of two gases, as developed by Stefan for the vaporization of liquids, reads

$$\frac{d\ Z}{d(\varphi\ p_3)} = k\ \left[\frac{\theta^2(\varphi\ p_3)}{\theta\ x^2} + \frac{\theta^2(\varphi\ p_3)}{\theta\ y^2} + \frac{\theta^2(\varphi\ p_3)}{\theta\ u^2}\right., \qquad (8)$$

in which

$\frac{\theta\ (\varphi\ p_3)}{\theta\ Z}$ = the pressure drop per unit of time which varies with the temperature; k = the diffusion coefficient plotted against the kind of material, temperature and pressure; x, y and u = the spatial coordinates with the center of the drop as the origin. Equation 8 changes to

$$\frac{\theta\ (\varphi\ p_3)}{\theta\ Z} = k.\ \left[\ \frac{\theta^2(\varphi\ p_3)}{\theta\ \rho^2} + \frac{2}{\rho}\ \frac{\theta\ (\varphi\ p_3)}{\theta\ \rho}\right. \qquad (9)$$

under the assumption that the spherical surface of the drop is a surface of uniform partial pressure and that the partial pressure depends on the time and on the vector, expressed in polar coordinates. The solution of the differential equation 9 is given by Dr. Klaften with

$$\varphi\ p_3 = \frac{\sin\ (\alpha\ \rho)}{\alpha\ \rho}\ \ C\ e^{-\alpha^2 kZ}.$$

In equation 10 we have a very general relation between the vaporization time and the partial pressure existing at the time. This equation holds good both for the surfaces of the drops and also for the air spheres which concentrically surround the surfaces. The radius of the drop or air sphere is commonly designated by ρ. The determination of both constants C and α from the limiting conditions at the beginning and end of the vaporization enables the discovery of a relation between the radius of the liquid drop and the vaporization time for this drop. The radius of the liquid drop at any desired time point of the vaporization process is therefore designated by ρ_o and the special value of ρ_o at the beginning of the vaporization by ρ_a. The determination of the constants C and α follows from the limiting conditions at the beginning and end of the vaporization.

At the beginning of the vaporization process for $z = 0$, the full saturation pressure p_3 prevails on the surface of the drop at $\rho = \rho_o = \rho_a$, so that $\varphi = 1$. From this we obtain

$$C = \frac{p_a}{\frac{\sin(\alpha\ \rho_a)}{\alpha\ \rho_a}}$$

and consequently,

$$\varphi\ p_3 = p_{3a} \frac{\sin(\alpha\ \rho)}{\alpha\ \rho} \quad \frac{\alpha\ \rho_a}{\sin(\alpha\ \rho_a)} \quad e^{-\alpha^2 kZ} \tag{11}$$

At the end of the vaporization process, for which there is assumed to be a sufficiently large air volume to enable complete vaporization at the prevailing temperature, $\rho_o = 0$ at the instant when the drop has just been completely vaporized. In the center of the drop, for which $\rho = \rho_o = 0$, the relation $\varphi = 1$ prevails at this instant, after the lapse of the vaporization time z. With $\rho = \rho_o = 0$ in equation 11

$$\frac{\sin(\alpha\ \rho)}{\alpha\ \rho} = 1.$$

From this we obtain, as the vaporization time of a drop having an original radius ρ_a,

$$p_{3e} = p_{3a} \frac{\alpha \rho_a}{\sin (\alpha \rho_a)} e^{-\alpha^2 k Z_e}$$

or

$$Z_e = \frac{\ln \frac{p_{3a}}{p_{3e}} - \ln \frac{\sin (\alpha \rho_a)}{\alpha \rho_a}}{\alpha^2 k} \qquad (12)$$

The equation holds good only when complete vaporization is possible, hence when an ample volume of air ($m > m'$) is present. The importance of the constant α becomes evident, when we consider the limiting case of equation 12, for which $Z_e = \infty$. Z_e becomes ∞, when $\frac{\sin (\alpha \rho_o)}{\alpha \rho_a} = 0$ and consequently $\alpha \rho_a = \pi$. Z_e becomes finite when $\alpha \rho_a < \pi$, that is, when complete vaporization takes place after finite time.

When $\alpha \rho_a > \pi$, $\frac{\sin (\alpha \rho_a)}{\alpha \rho_a}$ becomes negative and its logarithm imaginary, from which it follows that no complete vaporization can take place at this temperature and that an excess of liquid is present. The mixture ratio corresponding to the limiting case $Z_e = \infty$, at which complete vaporization is attained, after infinite time, at the given temperature is called m'. For the same, $g_3 = 1$ and $\varphi = 1$, so that saturation is just attained at complete vaporization. Equation 7 then gives

$$m' = \frac{b = p_{3e}}{\frac{\gamma_3}{\gamma_-} p_{3e}} \qquad (13a)$$

and equation 1, for $g_3 = 1$,

becomes

$$m' = \frac{\frac{r_t}{t_a - t_e} - c_2}{c_1} \qquad (13b)$$

These two equations serve for the determination of the mixture ratio m', which then enables us to compute the value of the constant .

The equations 13a and 13b appear to contain three unknown quantities m', t_e and p_{3e}, but, after p_{3e} and t_e are combined by the vapor-tension curves, p_{3e} is a function of t_e, so that in reality there are only two unknowns, which can be calculated from the two equations. The relation between p_{3e} and t_e is given graphically by the vapor-tension curves, thereby rendering it expedient to employ a graphic method for solving the equations. By making an equation of the right-hand members of equations 13a and 13b, we obtain an equal-sided hyperbola

$$\frac{b - p_{3e}}{\frac{\gamma_3}{\gamma_1} - p_{3e}} = \frac{r_t}{\frac{t_a - t_e}{c_1} - c_2}$$

If we also plot the tension curve, the point of intersection of the two curves will give the desired values p_{3e} and t_e, as shown in Fig. 19. The values for m' and t_a can then be calculated from the equations 13a and 13b. In order to express the constant α in equation 12 by known and computed values and to calculate the vaporization time z for the given temperatures and mixture ratios, for the initial condition before any vapor has been formed, we have the equation $G_1 = m\ G_2$

or, by disregarding the small volume of the drops as compared with the volume of air,

$$\frac{4}{3}\,\rho_1^{\,3}\;\pi\,\gamma_1 = m\,\frac{4}{3}\,\rho_a^{\,3}\;\pi\,\gamma_2$$

hence

$$\rho_1 = \rho_a\sqrt[3]{\frac{m\,\gamma_2}{\gamma_1}} \qquad (14)$$

If we put

$$\alpha\,\rho_a = \pi \quad \text{also} \quad \rho_a = \frac{\pi}{\alpha}$$

as in the limiting case $z = \infty$ and $m = m'$, then equation 14 becomes

$$\rho_1 = \frac{\pi}{\alpha}\sqrt[3]{m'\,\frac{\gamma_2}{\gamma_1}} \quad \text{or} \quad \alpha = \frac{\pi}{\rho_1}\sqrt[3]{m'\,\frac{\gamma_2}{\gamma_1}} \qquad (15)$$

For any other given mixture ratio m, we have

$$\alpha = \frac{\pi}{\rho_a}\sqrt[3]{\frac{m'}{m}} \qquad (16)$$

Since m', according to equations 13a and 13b, depends on the temperatures and physical constants, α is a function of these quantities and also of the initial radius of the drop and of the given mixture ratio.

The effect of the mixture ratio on the vaporization time is shown by equations 17a and 17b which were derived from equation 12 by introducing the values $\alpha\,\rho_a$ and α.

$$Z_e = \frac{\rho_a^{\,2}}{\pi^2\;k\left(\frac{m'}{m}\right)^{2/3}}\left[\ln\frac{p_{3a}}{p_{3e}} - \ln\frac{\sin\left(\pi\sqrt[3]{\frac{m'}{m}}\right)}{\pi\sqrt[3]{\frac{m'}{m}}}\right] \qquad (17a)$$

or,

$$Z_e = \frac{0.2333\;\rho_a^2}{k\left(\frac{m'}{m}\right)^{2/3}}\left[\log\frac{p_{3a}}{p_{3e}} - \log\frac{\sin\left(\pi\sqrt[3]{\frac{m'}{m}}\right)}{\pi\sqrt[3]{\frac{m'}{m}}}\right]\text{sec.} \qquad (17b)$$

From these equations it is obvious that a slight increase in m, in comparison with the asymptotic mixture ratio m', greatly increases the vaporization time for small values while, for very large values of m, the vaporization time z_e, decreases slowly. The degree of atomization ρ_a, however, has a decisive effect on the vaporization time. Hence, it is not necessary to compute the effect of the mixture ratio on the vaporization time for the individual fuels. On the contrary, the decrease in the radius of the drop, with the lapse of time, must be computed and graphically represented for the various intake temperatures, which occur, for $m > m'$ and $m < m'$, in the two cases already mentioned in the discussion of the constant α. As the mixture ratio for all the fuels, the theoretical ratio was chosen, which, expressed in weights, was obtained from the theoretical consumption of air in the combustion of the fuels.

The decrease in the size of the drop with advancing vaporization time is given by equation 11 for the case when $\rho = \rho_o$, that is, for the surface area for which $\varphi = 1$.

$$\frac{\sin \alpha \rho_o}{\alpha \rho_o} = \frac{p_{3e}}{p_{3a}} \frac{\sin \alpha \rho_o}{\alpha \rho_a} e^{+\alpha^2 k Z} \qquad \text{and} \qquad (18a)$$

$$Z = \frac{2.303}{\alpha^2 k} \left[\log \frac{\sin (\alpha \rho_o)}{\alpha \rho_o} - \log \frac{\sin (\alpha \rho_a)}{\alpha \rho_l} + \log \frac{p_{3a}}{p_{3e}} \right] \qquad (18b)$$

The latter formula holds good, as already explained, in connection with equation 11, only for a mixture ratio of $m > m'$, that is, for initial temperatures at which the air volume (determined from the weight of air theoretically required for the combustion of 1 kilogram of fuel) is sufficient for complete combustion.

In an engine, on the one hand, the available quantity of air is limited by the stroke volume and, on the other hand, with respect to a diminution of the engine power, any great preliminary heating of the mixture of vapor and air is not admissible. Hence, with heavy fuels which vaporize at ordinary temperatures and with the same volume of air as for the light oils, the case will occur where m is smaller than m', since we have defined m' as the mixture ratio which just enables complete vaporization with a given volume in infinite time. In an engine, however, the available vaporization time is extremely small. Consequently, under the assumption of like temperature and air volume in finite time, for a given volume of air and moderate temperature of the mixture, the quantity of fuel which can vaporize in the available time, will be smaller than the quantity corresponding to m'. Even in infinite time, we would not attain the state of complete combustion, because the temperature and the air volume can not be indefinitely increased. The available air will simply become saturated with the fuel vapor and there will be an excess of liquid fuel.

In this case we have, for $\varphi = 1$ and $Z = \infty$, with given m according to equation 7

$$g_3 = \frac{m \frac{\gamma_3}{\gamma_1} p_{3e}}{b - p_{3e}}$$

and, for the mixture ratio m' corresponding to a value $g_{3e} = 1$ with $\varphi = 1$,

$$1 = \frac{m' \frac{\gamma_3}{\gamma_1} p_{3e}}{b - p_{3e}}$$

so that

$$g_{3e} = \frac{m}{m'} \tag{19}$$

According to Dr. Klaften, the radius of the drop at the end of the vaporization, is

$$\rho_c = \rho_a \sqrt[3]{1 - g_{3c}} \, .$$

In order to represent the course of the vaporization for this case, in which $m < m'$ and $\rho_c > 0$, the differential equation 9 must generally be solved so that the particular solution found with equation 10 is restricted to the special case $m > m'$, while the general solution holds good for all cases. Dr. Klaften finds this solution with

$$z = \frac{2.303 \, \rho_a^3}{k \, (\rho_o - \rho_c)} \left[\log \frac{\rho_a}{\rho_o} + \log \frac{p_{3a}}{p_{3e}} \right] - \frac{\rho_a \, (\rho_a - \rho_o) \sqrt{\rho_l}}{k \sqrt{\rho_o - \rho_c}} \tag{20}$$

With the aid of the above formulas, we will now calculate the diminution of the radius of the drop with advancing vaporization time for the individual fuels for both cases, Case I, when $m > m'$, that is, when the temperatures are high enough for complete combustion with the weight of air theoretically required, and Case II, when $m < m'$, that is, when the temperatures are not high enough for complete combustion.

We will then show, by plotting the radii of the drops against the vaporization time for the light and heavy oils at like temperatures, how many times finer the initial atomization ρ_a of the heavier fuels must be in order for their vaporization to advance as rapidly as that of the lighter oils in the time rendered available by the revolution speed of the engine.

In order to make the calculation clear, we will now repeat, in logical order, the formulas used for all the fuels:

b = barometer stand (720 mm Hg);

c_1 = specific heat of the air (0.238);

c_2 = " " " " fuels at the corresponding temperatures;

$m = \frac{G_1}{G_2 + G_3}$. The mixture ratio taken as the basis of the calculations was deduced from the weight of air theoretically required per kilogram of fuel.

Hence $m = \frac{G\ \mathrm{air}}{G\ \mathrm{fuel}} = \frac{G\ \mathrm{air}}{1\ \mathrm{kg}}$, G_3 being zero;

r = vaporization heat of the fuel;

γ_3/γ_1 = density of vapor;

t_a = initial temperature of combustion air.

Case I. $m > m'$.

From the two equations (13a and 13b)

$$m' = \frac{b - p_{3e}}{\frac{\gamma_3}{\gamma_1} p_{3e}} \quad \text{and} \quad m' = \frac{r_t - c_2\,(t_a - t_e)}{c_1\,(t_a - t_e)} \qquad (13b)$$

we determined, by the graphic method (Figs. 19-21) the corresponding values t_e and p_{3e}, which satisfy both the tension curve and the curve represented by the formula for m' at the point of intersection of the two curves.

m' and $\alpha \rho_a = \sqrt[3]{\frac{m'}{m}}$ were computed from t_e and p_{3e}, after introducing the above values. ρ_o was introduced into the tables in selected decreasing values from ρ_a to 0, and $\alpha \rho_o$ was similarly obtained after α was determined.

The vapor portion g_3 was deduced from the formula

$$g_3 = 1 - \left(\frac{\rho_o}{\rho_a}\right)^3 .$$

The temperature was found from the formula

$$t = t_a - \frac{g_3 \; r_t}{m \; c_1 + c_2} .$$

p_3 was obtained from the tension curve, and z according to formula 18b.

In the limiting case, where $m = m'$, p_3 was calculated directly from the formula

$$p_3 = \frac{b \; g_3}{m \frac{\gamma_3}{\gamma_1} + g_3}$$

Since $g_3 = 1$ and t_e and $t_a = \dfrac{(m \; c_1 + c_2) \; t_a + r_t}{m \; c_1 + c_2}$

$$m' = \frac{b - p_3}{\frac{\gamma_3}{\gamma_1} p_3}$$

$\alpha \rho_o$ and z were calculated according to equation 20.

Case II. $m < m'$.

The values of p and t were determined graphically from the two equations for g_3.

$$g_{3e} = \frac{m \frac{\gamma_3}{\gamma_1} p_3}{b - p_3}; \quad g_{3e} = \frac{(m\ c_1 + c_2)\ (t_a - t_e)}{\nu_t}$$

Therefrom

$$g_{3e} \quad \text{and} \quad m' = \frac{b - p_3}{\frac{\gamma_3}{\gamma_1} p_3} .$$

In the tables, the values between 0 and g_3 were assumed and the corresponding values of $\rho_o = \sqrt[3]{1 - g_3}$ were calculated.

$$t = \frac{(m\ c_1 + c_2)\ t_a - g_3\ \nu_t}{m\ c_1 + c_2}$$

p_3 was deduced from the tension curve and z was found according to equation 20, after the diffusion coefficients k, corresponding to the temperatures, had been obtained from the $t - k$ curve. φ was computed in both cases from equation 7.

$$\varphi = \frac{b\ g_3}{p_3\ (m \frac{\gamma_3}{\gamma_1} + g_3)}$$

The computed values are given in Tables XVIII to XX.

Table XVIII.

Gasoline.

$c_1 = 0.238$; $m = 16.35$; $\nu_t = 74.9$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 4.2$

ρ_o cm	$\alpha\ \rho_o$	g_3	t °C	p_3 mm Hg	k cm²/s	z sec.
		$t_a = 30^\circ C$;		$c_2 = 0.57$		
ρ_a	2.660	--	30.00	44.00	0.380	--
0.9 ρ_a	2.394	0.271	25.50	38.00	0.350	0.256 ρ_a^2
0.7 ρ_a	1.862	0.657	19.00	31.50	0.315	0.636 ρ_a^2
0.5 ρ_a	1.330	0.875	15.30	27.00	0.290	0.938 ρ_a^2
0.2 ρ_a	0.532	0.992	13.40	25.00	0.280	1.145 ρ_a^2
0.1 ρ_a	0.266	0.999	13.20	25.00	0.278	1.170 ρ_a^2
--	--	1.000	13.15	25.00	0.278	1.19 ρ_a^2
		$t_a = 20^\circ C$;		$c_2 = 0.56$		
ρ_a	2.860	--	20.00	32.00	0.320	--
0.9 ρ_a	2.574	0.271	15.50	27.00	0.295	0.316 ρ_a^2
0.7 ρ_a	2.002	0.657	9.00	21.00	0.260	0.922 ρ_a^2
0.5 ρ_a	1.430	0.875	5.30	18.00	0.230	1.347 ρ_a^2
0.2 ρ_a	0.572	0.992	3.40	16.80	0.220	1.62 ρ_a^2
0.1 ρ_a	0.286	0.999	3.20	16.60	0.210	1.73 ρ_a^2
--	--	1.000	3.20	16.60	0.210	1.734 ρ_a^2
		$t_a = 13.0^\circ C$;		$c_2 = 0.55$		
ρ_a	3.060	--	13.00	24.50	0.280	--
0.9 ρ_a	2.754	0.271	8.50	20.50	0.250	0.636 ρ_a^2
0.7 ρ_a	2.142	0.657	2.00	16.00	0.220	1.36 ρ_a^2
0.5 ρ_a	2.530	0.875	-1.70	13.50	0.200	1.85 ρ_a^2
0.2 ρ_a	0.612	0.992	-3.60	12.00	0.190	2.09 ρ_a^2
0.1 ρ_a	0.306	0.999	-3.80	12.00	0.190	2.24 ρ_a^2
--	--	1.000	-3.80	12.00	0.190	2.24 ρ_a^2
		$t_a = 11.5^\circ C$;		$c_2 = 0.55$		
ρ_a	3.1120	--	11.50	23.50	0.270	--
0.9 ρ_a	2.8000	0.271	7.00	19.50	0.190	1.38 ρ_a^2
0.8 ρ_a	2.4896	0.488	3.30	16.80	0.160	2.2 ρ_a^2
0.7 ρ_a	2.1784	0.657	+0.50	14.80	9.140	2.94 ρ_a^2
0.6 ρ_a	1.8672	0.784	-1.80	13.00	0.120	3.81 ρ_a^2
0.5 ρ_a	1.5560	0.875	-3.20	12.20	0.110	4.42 ρ_a^2
0.4 ρ_a	1.2448	0.936	-4.30	11.50	0.100	4.67 ρ_a^2
0.3 ρ_a	0.9336	0.973	-5.00	11.00	0.100	4.8 ρ_a^2
0.2 ρ_a	0.6224	0.992	-5.20	19.80	0.100	4.87 ρ_a^2
0.1 ρ_a	0.3112	0.999	-5.30	10.70	0.100	4.9 ρ_a^2
--	--	--	-5.30	10.70	0.100	4.9 ρ_a^2

Table XVIII (Cont.)

Gasoline.

$c_1 = 0.238$; $m = 16.35$; $\nu_t = 74.9$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 4.2$

ρ_o cm	$\alpha\ \rho_o$	g_3	t °C	p_3 mm Hg	k cm²/s	z sec.
	Limiting Case $m' = m$; $t_a = 10.8$°C.					
ρ_a	3.140	--	10.80	22.50	0.270	--
$0.9\ \rho_a$	2.826	0.271	6.40	19.00	0.240	$0.82\ \rho_a^2$
$0.85\rho_a$	2.669	0.386	4.30	17.50	0.220	$1.47\ \rho_a^2$
$0.8\ \rho_a$	2.512	0.488	2.60	16.00	0.210	$2.29\ \rho_a^2$
$0.7\ \rho_a$	2.198	0.657	-0.30	14.00	0.200	$4.12\ \rho_a^2$
$0.5\ \rho_a$	1.570	0.875	-0.40	11.50	0.180	$11.17\ \rho_a^2$
$0.2\ \rho_a$	0.628	0.992	-5.90	10.50	0.170	$59.3\ \rho_a^2$
$0.1\ \rho_a$	0.314	0.999	-6.00	10.40	0.170	$158.3\ \rho_a^2$
$0.05\rho_a$	0.157	0.9998	-6.00	10.40	0.170	$407.00\ \rho_a^2$
--	--	1.000	-6.00	10.40	0.170	∞
		g_3 $t_a = 8$°C; $c_2 = 0.547$				
--		--	8.00	20.00	0.250	--
$0.965\ \rho_a$		0.100	6.30	19.00	0.240	$0.48\ \rho_a^2$
$0.928\ \rho_a$		0.200	3.40	17.00	0.230	$1.638\rho_a^2$
$0.888\ \rho_a$		0.300	2.90	16.50	0.220	$2.38\ \rho_a^2$
$0.843\ \rho_a$		0.400	1.10	15.00	0.210	$4.17\ \rho_a^2$
$0.793\ \rho_a$		0.500	-0.50	14.00	0.200	$6.46\ \rho_a^2$
$0.7368\rho_a$		0.600	-2.10	13.00	0.190	$10.32\ \rho_a^2$
$0.669\ \rho_a$		0.700	-3.80	11.60	0.180	$16.9\ \rho_a^2$
$0.531\ \rho_a$		0.850	-5.50	10.50	0.170	$40.0\ \rho_a^2$
$0.448\ \rho_a$		0.910	-7.40	9.75	0.160	$299.6\ \rho_a^2$
$0.434\ \rho_a$		0.918	-7.70	9.50	0.160	∞

Table XIX.

Kerosene.

$c_1 = 0.238$; $m = 16.3$; $\nu_t = 75.6$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 4.8$

		$t_a = 100^\circ C$; $c_2 = 0.65$				
ρ_a cm	g_3	$\alpha\ \rho_a$	t °C	p_3 mm Hg	k cm²/s	z sec
ρ_a	--	2.530	100.00	38.00	0.580	--
0.9 ρ_a	0.271	2.277	95.50	33.50	0.560	0.143 ρ_a^2
0.7 ρ_a	0.657	1.771	89.00	28.00	0.530	0.352 ρ_a^2
0.5 ρ_a	0.875	1.265	85.30	25.00	0.515	0.4915 ρ_a^2
0.2 ρ_a	0.992	0.506	83.40	24.00	0.510	0.558 ρ_a^2
0.1 ρ_a	0.999	0.253	83.30	23.80	0.508	0.596 ρ_a^2
--	1.000	--	83.20	23.70	0.506	0.602 ρ_a^2
		$t_a = 80^\circ C$; $c = 0.62$				
a	--	2.955	80.00	21.50	0.500	--
0.9 ρ_a	0.271	2.659	75.50	19.00	0.480	0.275 ρ_a^2
0.7 ρ_a	0.657	2.068	69.00	15.00	0.470	0.498 ρ_a^2
0.5 ρ_a	0.875	1.477	65.30	13.30	0.465	0.698 ρ_a^2
0.2 ρ_a	0.992	0.951	83.40	12.30	0.463	0.803 ρ_a^2
0.1 ρ_a	0.999	0.295	63.30	12.20	0.463	0.814 ρ_a^2
--	1.000	--	63.20	12.20	0.461	0.815 ρ_a^2
ρ_a cm	$\alpha\ \rho_o$	g_3	t °C	p mm Hg	k cm²/s	z sec.
	Limiting Case		$t_a = 71.8^\circ C$; $c_2 = 0.62$			
ρ_a	--	3.140	71.80	16.80	0.470	--
0.9 ρ_a	0.271	2.826	67.20	14.30	0.468	0.409 ρ_a^2
0.7 ρ_a	0.657	2.198	60.80	11.50	0.460	1.500 ρ_a^2
0.5 ρ_a	0.875	1.570	57.10	10.00	0.455	3.680 ρ_a^2
0.2 ρ_a	0.992	0.628	54.10	8.80	0.454	20.860 ρ_a^2
0.15 ρ_a	0.999	0.314	54.10	8.70	0.453	59.100 ρ_a^2
0.05 ρ_a	0.99987	0.157	54.00	8.70	0.453	177.600 ρ_a^2
--	1.000	--	54.00	8.70	0.453	∞

Table XIX (Cont.)

Kerosene.

$c_1 = 0.238$; $m = 16.3$; $\nu_t = 75.6$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 4.8$.

ρ_o cm	g_3	t °C	p_3 mm Hg	k cm²/s	z sec
		$t_a = 50°C$;	$c_2 = 0.59$		
ρ_a	--	50.00	7.00	0.455	--
0.983 ρ_a	0.050	49.15	6.80	0.454	$0.461 \rho_a^2$
0.865 ρ_a	0.100	48.30	6.50	0.453	$1.26 \rho_a^2$
0.928 ρ_a	0.200	46.60	6.00	0.453	$1.25 \rho_a^2$
0.8879 ρ_a	0.300	44.90	5.50	0.452	$8.03 \rho_a^2$
0.843 ρ_a	0.400	43.20	5.00	0.450	$28.9 \rho_a^2$
0.819 ρ_a	0.450	42.40	4.80	0.449	$58.2 \rho_a^2$
0.7979 ρ_a	0.492	41.70	4.70	0.448	∞
		$t_a = 30°C$;	$c_2 = 0.59$		
ρ_a	--	30.00	3.00	0.400	--
0.983 ρ_a	0.050	29.20	2.95	0.398	$0.773 \rho_a^2$
0.965 ρ_a	0.100	28.50	2.90	0.390	$2.94 \rho_a^2$
0.928 ρ_a	0.200	26.60	2.70	0.385	$11.3 \rho_a^2$
0.892 ρ_a	0.290	25.10	2.60	0.375	$26.1 \rho_a^2$
0.89 ρ_a	0.295	25.00	2.60	0.375	∞

Table XX.

Gas Oil.

$c_1 = 0.238$; $m = 16.0$; $r = 63.8$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 9.74$

$t_a = 160°C$; $c_2 = 0.63$

ρ_a cm	$\alpha\ \rho_a$	g_3	t °C	p mm Hg	k cm²/s	z sec
ρ_a	1.847	--	160.00	50.00	1.250	--
0.98 ρ_a	1.622	0.271	156.10	49.00	1.220	$0.0374 \rho_a^2$
0.59 ρ_a	1.925	0.875	147.50	46.00	1.160	$0.1467 \rho_a^2$
0.2 ρ_a	0.369	0.992	145.80	45.00	1.150	$0.185 \rho_a^2$
0.1 ρ_a	0.1847	0.999	145.70	45.00	1.150	$0.189 \rho_a^2$
--	--	1.000	145.60	45.00	1.150	$0.191 \rho_a^2$

Table XX (Cont.)

Gas Oil.

$c_1 = 0.238$; $m = 16.0$; $r = 63.8$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 9.74$

ρ_o cm	$\alpha\,\rho_o$	g_3	t °C	p_3 mm Hg	k cm²/s	z sec.
			$t_a = 120°C$;	$c_2 = 0.62$		
ρ_a	2.500	--	120.00	28.50	0.980	--
0.9 ρ_a	2.250	0.271	116.50	25.50	0.960	$0.0778\rho_a^2$
0.5 ρ_a	1.250	0.875	107.40	17.50	0.890	$0.297\ \rho_a^2$
0.2 ρ_a	0.500	0.992	105.70	16.00	0.880	$0.357\ \rho_a^2$
0.1 ρ_a	0.250	0.999	105.60	16.00	0.880	$0.363\ \rho_a^2$
--	--	1.000	105.50	16.00	0.880	$0.364\ \rho_a^2$
			$t_a = 90°C$;	$c_2 = 0.6$		
ρ_a	3.060	--	90.00	7.00	0.780	--
0.9 ρ_a	2.754	0.271	86.10	6.00	0.750	$0.25448\rho_a^2$
0.5 ρ_a	1.530	0.875	77.30	5.00	0.700	$0.536\ \rho_a^2$
0.2 ρ_a	0.612	0.992	75.60	4.90	0.690	$0.599\ \rho_a^2$
0.1 ρ_a	0.306	0.999	75.50	4.80	0.690	$0.6045\ \rho_a^2$
--	--	1.000	75.40	4.80	0.690	$0.605\ \rho_a^2$
			Gas Oil			
	Limiting Case		$t_a = 82.5°C$;		$c_2 = 0.57$	
ρ_a	3.140	--	82.50	5.20	0.720	--
0.9 ρ_a	2.726	0.271	78.55	5.00	0.700	$0.378\rho_a^2$
0.7 ρ_a	2.198	0.657	72.90	4.80	0.680	$0.387\rho_a^2$
0.5 ρ_a	1.570	0.875	69.75	4.70	0.670	$1.327\rho_a^2$
0.2 ρ_a	0.628	0.992	68.09	4.60	0.670	$10.43\ \rho_a^2$
0.1 ρ_a	0.314	0.999	67.90	4.59	0.670	$32.0\ \rho_a^2$
0.05 ρ_a	0.157	0.999375	67.90	4.59	0.670	$87.2\ \rho_a^2$
--	--	1.000	67.90	4.59	0.670	∞

Table XX (Cont.)

Gas Oil

$c_1 = 0.238$; $m = 16.0$; $r = 63.8$; $b = 720$; $\frac{\gamma_3}{\gamma_1} = 9.74$.

		$t_a = 60^\circ C$;	$c_2 = 0.56$		
ρ_o cm	g_3	t °C	p mm Hg	k cm^2/s	z sec
--	--	60.00	4.20	0.670	--
0.928 ρ_a	0.200	57.10	4.15	0.665	0.235 ρ_a^2
0.888 ρ_a	0.300	55.70	4.10	0.663	0.289 ρ_a^2
0.794 ρ_a	0.500	52.70	4.10	0.662	0.74 ρ_a^2
0.736 ρ_a	0.600	51.20	4.00	0.661	1.49 ρ_a^2
0.669 ρ_a	0.700	49.80	4.00	0.660	4.71 ρ_a^2
0.584 ρ_a	0.800	84.30	3.90	0.660	9.59 ρ_a^2
0.506 ρ_a	0.870	47.00	3.90	0.660	∞
		$t_a = 30^\circ C$;	$c_2 = 0.52$		
--	--	30.00	3.20	0.642	--
0.928 ρ_a	0.200	27.10	3.10	0.640	0.506 ρ_a^2
0.888 ρ_a	0.300	25.70	3.05	0.635	1.049 ρ_a^2
0.794 ρ_a	0.500	22.70	3.00	0.630	4.03 ρ_a^2
0.736 ρ_a	0.600	21.20	3.00	0.628	15.65 ρ_a^2
0.7046 ρ_a	0.650	20.40	3.00	0.626	10.58 ρ_a^2
0.704 ρ_a	0.651	20.00	3.00	0.625	∞

We will now represent graphically on the basis of Tables XVIII-XX, the vanishing of the drop radius with advancing vaporization time for a series of temperatures of the air in which the vaporization occurs for the individual fuels. Thereby the drop radii will be plotted as ordinates and the computed vaporization times in their dependence on the initial radius of the atomized fuels in the function $z = \alpha \rho_a^2$ as abscissas.

Results of the Theoretical Investigation

Before drawing any conclusions on the basis of these graphs, we must understand that the vaporization times, as computed on the basis of formulas 18b and 20, represent no definitive values embracing the whole process of vaporization. According to the formulas given, the vaporization time is essentially a function of the diffusion coefficient k and the initial radius ρ_a of the atomized fuels.

The diffusion coefficients, however, which are calculated from the experimentally determined vaporization speeds, correspond only to the initial stage of the vaporization in which the volatile components of the fuel are still present. With the prolongation of the experiment, the diffusion coefficients decreased further, corresponding to the more slowly evaporating residual heavy-liquid components. The vaporization times yielded, however, very small values, when we used the correct value for ρ_a^2, notwithstanding which I could not obtain an entirely satisfactory value for the whole vaporization process.

I restricted myself, therefore, to the obtention of comparable values, on the assumption that, in the determination of the vaporization speed, the duration of the vaporization for all the fuels was nearly the same in all the experiments. Moreover, I apply the conclusions only to gasoline, kerosene and gas oil, because the vaporization curves (Part I, Fig. 1) of these three fuels, in the region of their initial vaporization, indicate an approximately equal ascent of the boiling curves and hence approximately equal vaporization. From this we may also conclude that the vaporization times and speeds must be approximately equal, of course, with correspondingly higher temperatures for the heavier fuels. The graphs accordingly show approximately equal vaporization times for the same conditions of the vaporized drop for the three compared fuels, gasoline, kerosene and gas oil.

Although no definite experimental data are yet available on the size of the fuel drops after atomization in an ordinary carburetor, the probable sizes of the drops are estimated in several publications at 0.1 - 0.01 mm (0.004 - 0.0004 in.) and smaller. For the different fuels, a drop radius of 0.05 mm (0.002 in.) gives the following vaporization times:

$z = 1.2 \times 0.000025$ s. $= 0.000030$ s. for gasoline at $t = 30°C$

$z = 0.9 \times$ " $= 0.000022$ " " kerosene " $t = 80°C$

$z = 1.0 \times$ " $= 0.000025$ " " gas oil " $t = 90°C$

which may be regarded as approximately equal.

When, at these temperatures, the graph of the drop radius indicates its complete disappearance (i.e., complete vaporization), we must understand that this occurred only because the heavier liquid components were given too little weight in the diffusion coefficient. The only conclusion drawn from the graph was that, in the approximately equal vaporization time for the three fuels at the coordinated temperatures, the shortening of the drop radii (i.e., the vaporization) was equally far advanced.

We will now inquire as to the relation of the shrinking drop radius to the vaporization time beyond the initial vaporization. In the preliminary assumption of equal initial radii of the fuel drops for all the fuels, the vaporization time is generally deduced from the vaporization speed or from the diffusion coefficient. It follows from the less-steep ascent of the vaporization curves of kerosene and gas oil in comparison with the gasoline curve (Part I, Fig. 1), that the decrease in the vaporization speed and consequently in the diffusion coefficient will be considerably greater for these fuels as compared with gasoline. Hence, the vaporization time increases more rapidly for the heavier fuels than for gasoline.

In order to assimilate the vaporization time and the shrinking of the drops of the heavier fuels to the corresponding phenomena of the more volatile gasoline, there remain two ways: either to increase the temperature, thereby increasing the diffusion coefficient, or to increase the fineness of the atomization, thereby decreasing the initial radius of the drops of the heavier fuels. The effect of increasing the fineness of the atomization is much greater than that of increasing the temperature, as follows, from equation 18b, in which ρ_a occurs in the second power, while the diffusion coefficient is only in the first power.

If, with the aid of the diagrams, we follow up the behavior of gasoline and the two heavier oils at lower temperatures, we come first to a limiting region, in which the complete vaporization of the fuel drop will only be accomplished in infinite time.

According to the previous conclusions from the vaporization curves, the graphic presentation shows the most favorable case, because it was obtained on the basis of the initial vaporization speeds. Due to the heavier components of the liquids, the rate of decrease of the radii of the drops of the heavier oils is slower than for gasoline, and the temperature differences, as found for the different fuels, are very much to the disadvantage of the heavy fuels. In order, therefore, to vaporize the heavy fuels as rapidly as gasoline, it is necessary to change the initial temperatures of 10.8, 71.2 and 82.5°C (51.4, 160.2 and 180.5°F) much to the disadvantage ~~o~~f the heavier fuels, without being able to calculate on complete vaporization in finite time.

The asymptotic assimilation of the ρ_a z curves to the axis of the abscissas precludes the complete vaporization of all the fuels in any given vaporization time for the engine process before the cylinder. This is still more manifest in the diagrams, when we consider the ρ_a z curves of the heavier fuels (Figs. 23-24) for temperatures below those of the limiting curves. In the latter case, the asymptote lies in a parallel to the axis of the abscissas and is mathematically determined by means of the radius at the end of the vaporization, which is always greater than zero.

If, by way of illustration, we take for gasoline the limiting curve $t = 10.8^\circ C$ ($51.4^\circ F$) and compare it with the curves for kerosene at $t = 50^\circ C$ ($122^\circ F$) and gas oil at $t = 60^\circ C$ ($140^\circ F$), whereby the values of z are introduced into Fig. 25 in their actual magnitude by using the initial radius $\rho_a = 0.05$ mm (0.002 in.), we can follow the shrinking of the fuel drops for the different oils and refer it to the time available in the engine process.

The available time for the vaporization, from the carburetor to the engine cylinder, was calculated, on the basis of an intake pipe about 0.4 m (1.31 ft.) long and an air velocity of about 30 m (98.4 ft.) per second, as 0.4/30 = 0.013 second. For this vaporization time, we obtain a decrease:

For gasoline, of about 5% of the initial radius for $t_a = 10.8^\circ C$;
" kerosene, " " 80% " " " " " $t_a = 50^\circ C$;
" gas oil, " " 50% " " " " " $t_a = 60^\circ C$.

In order to effect, at these temperatures for the heavier fuels, a diminution of the initial radius of the fuel drops equal to that for gasoline, the initial radius must be diminished 16-fold for kerosene and 10-fold for gas oil, i.e., the atomization must be correspondingly finer.

Thereby, however, it must always be remembered that the graphs apply only to the lighter liquid components and that the evaluation magnitudes for the heavier liquid components are very unfavorable to the heavier fuels and require a still finer atomization or so strong heating that the temperatures are inadmissible. In order that less preliminary heating of the intake air may suffice for the heavier oils, the fineness of the atomization must be still further increased, as is manifest from a comparison of the curves for $t = 30^\circ C$ ($86^\circ F$).

Since these considerations plainly indicate that the heavy fuels require a better atomization than gasoline, if the atomized fuel drops are to be reduced to the same size as in gasoline for the same vaporization period, but that the heating of the intake air seems adapted to produce the same result, we will briefly discuss the disadvantages connected with high heating in engine operation.

It is known that preliminary heating of the intake air lessens the amount of air delivered and thereby reduces the power of the engine. If V = the volume in cubic meters of the mixture actually taken in, as measured under standard conditions ($0^\circ C$ and 760 mm Hg); if V_h = the stroke volume in cubic meters; and if $\eta l = V/V_h$, the ratio of the quantity of air delivered, to what it would be under standard conditions; then the delivery efficiency ηl varies at different temperatures according to the formula

$$\eta l = \frac{V}{V_h} = \frac{G}{\gamma_t \, V_h} = \frac{G}{\frac{\gamma_o \, , \, 760}{1 + \alpha \, t} \, V_h}$$

The following Table XXI shows the decrease in the delivery efficiency with increase in temperature.

Table XXI.

t =	0°	10°	20°	30°	40°	50°	60° C
$\eta l_t =$	ηl_o	$0.96 \eta l_o$	$0.92 \eta l_o$	$0.9 \eta l_o$	$0.86 \eta l_o$	$0.84 \eta l_o$	$0.81 \eta l_o$
t =	70°	80°	90°	100°	110°	120°	130°C
$\eta l_t =$	$0.79 \eta l_o$	$0.77 \eta l_o$	$0.75 \eta l_o$	$0.73 \eta l_o$	$0.71 \eta l_o$	$0.69 \eta l_o$	$0.68 \eta l_o$

Güldner gives an accurate formula for the delivery efficiency ηl with regard to the exhaust gases remaining in the cylinder,

$$\eta l = \left(\frac{E \, P_a}{T_a} - \frac{P_r}{T_r} \right) \frac{T_g}{10333} , \quad \text{in which}$$

E = the compression ratio = $v : v_c$ = cylinder volume to compression volume,

P_a = tension of residual gases at end of intake stroke,

P_r = tension of residual gases at beginning of intake stroke,

T_a = temperature of charge at end of intake stroke,

T_r = temperature of residual gases at end of compression,

T_g = temperature of intake air.

Even this more accurate formula brings only a change in the delivery efficiency with T_g the absolute temperature of the outer air and T_a the temperature of the mixture of the outer air with the residual gases, since E is assumed to be unchanged and P_a and P_r depend only on the intake and exhaust resistances and T_r is a function of the temperatures of the exhaust gases and cooling water. The more accurate formula also causes no substantial change in the values of ηl at different temperatures.

Table XXI accordingly shows a decrease in the delivery efficiency of the engine: of 12% at 50°C (122°F), 15% at 60°C (140°F), 19% at 80°C (176°F), 21% at 90°C (194°F), 23% at 100°C (212°F), and 27% at 120°C (248°F), as compared with operation at a temperature of 10°C (50°F), of the intake air, at which temperature the engine functions perfectly with gasoline. The power decreases in the same ratio, according to the formula

$$N_e = \frac{V_h \, H \eta_w \, n \, \eta l}{21.1 \, b}$$

for explosion engines.

Simultaneously with the decrease in the delivery efficiency of the engine at high temperatures, there arises the necessity of reducing the compression ratio ϵ, because the hotter mixture of fuel and air produces self-ignition before the end of the compression stroke. Thereby the thermal efficiency ηt and the power of the explosion engine are, however, decreased. The thermal efficiency of an explosion engine is expressed by the formula

$$\eta t = 1 - \left(\frac{V_c}{V}\right)^{k-1}$$

If, for example, with gasoline for fuel and a temperature of the intake air up to 10°C (50°F), $\epsilon = 5$, and with a heavy oil at 80°C (176°F), the compression ratio must be reduced to $\epsilon = 4$, we then have in these two cases, if k is assumed to equal 1.35,

$$\eta t = 1 - \left(\frac{1}{5}\right) 0.35 = 0.431 \quad \text{at} \quad t = 10^\circ C \quad \text{and}$$

$$\eta t = 1 - \left(\frac{1}{4}\right) 0.35 = 0.384 \quad \text{at} \quad t = 80^\circ C.$$

hence a decrease of 11% in thermal efficiency.

The total loss in the power of an engine, operated at high temperatures of the intake air, therefore increases considerably, so that one will employ high intake temperatures of the combustion air only when compelled to do so. This leads us again to the conclusion that only moderate heating of the intake air is admissible when using heavy oils in explosion engines, but that the atomization must be as fine as possible. The results of this investigation can, moreover, be stated as follows.

In the functioning of an engine, the time available for vaporization, before the mixture reaches the cylinder, does not suffice, even with a preliminary heating of the combustion air to 60°C (140°F), to bring the heavy-oil vapors formed in the carburetor even approximately to the same stage of vaporization as with gasoline under normal atmospheric conditions of the intake air. It must therefore be endeavored to attain, with a moderate preliminary heating of the intake air, the same degree of fineness of atomization of the fuel cloud for heavy oils, as obtained with gasoline by vaporization alone.

Since the results of the investigation, which were mostly obtained from the lighter components of the heavy fuels, require a 10- or 16-fold vaporization in comparison with gasoline, we must attain a still finer degree of atomization, in order to include the heavier components. This brings us to a problem which is surely solvable, though difficult, because the atomizing force must be obtained entirely from the suction and is therefore limited, and the composition of the fuel must correspond to the suction force of the engine. Carburetor manufacturers first adapted the design of the modern carburetor to the light fuels, which are continually becoming heavier and which already require a finer degree of atomization, and they will also endeavor to adjust the atomization to the heavy fuels, whenever high-speed medium and heavy-pressure engines begin to replace carburetor engines on motor vehicles. In the more recent carburetors with improved atomization (Zenith three-step carburetor and Pallas intensive carburetor), the fuel is no longer introduced into the carburetor in the form of a single closed jet, but is divided so that the largest possible amount of air can participate in the atomization. If we succeed in separating the fuel into a fine spray before its atomization, or in producing a preliminary atomization by using a portion of the combustion air, and in then applying the whole of the combustion air to the further atomization, we will come much nearer to the requisite degree of fineness for heavy oils.

Translation by Dwight M. Miner,
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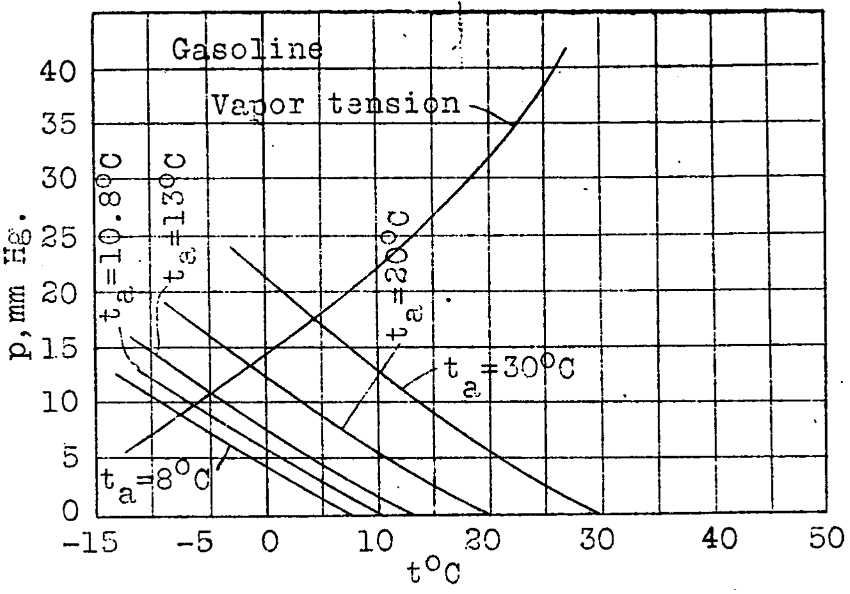
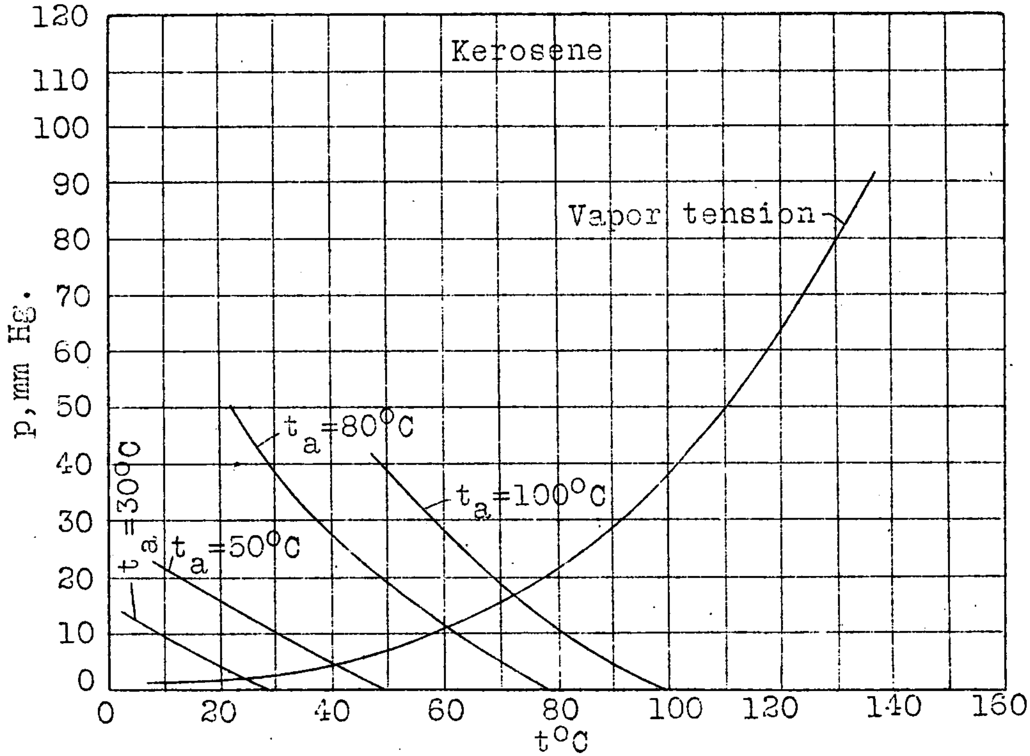


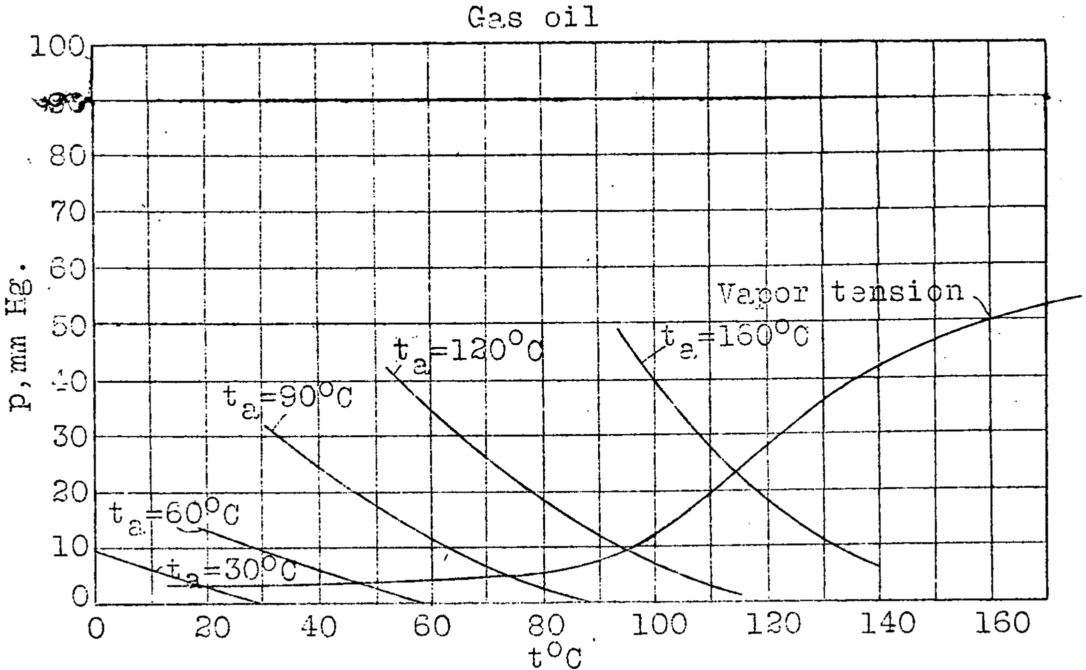
$t_a=30^{\circ}C$; $p_3e=17.0$ $t_e=4.5^{\circ}C$
$t_a=20^{\circ}C$; $p_3e=13.5$ $t_e=1.3^{\circ}C$
$t_a=13^{\circ}C$; $p_3e=11.1$ $t_e=-5^{\circ}C$
$t_a=11.5^{\circ}C$; $p_3e=10.6$ $t_e=-5.8^{\circ}C$
$t_a=10.8^{\circ}C$; $p_3e=10.33$ $t_e=-6^{\circ}C$
$t_a=8^{\circ}C$; $p_3e=9.5$ $t_e=-7.5^{\circ}C$

Fig.19



$t_a=100^{\circ}C$; $p_3e=17$ $t_e=72^{\circ}C$
$t_a=80^{\circ}C$; $p_3e=11.1$ $t_e=60^{\circ}C$
$t_a=50^{\circ}C$; $p_3e=4.5$ $t_e=41.5^{\circ}C$
$t_a=30^{\circ}C$; $p_3e=2.7$ $t_e=25^{\circ}C$

Fig.20



t_a = 160°C; p_3e = 23 t_e =113.5°C
t_a = 120°C; p_3e = 9 t_e = 94.5°C
t_a = 90°C; p_3e = 5 t_e = 75.0°C
t_a = 60°C; p_3e = 4 t_e = 47.0°C
t_a = 30°C; p_3e = 3 t_e = 20.0°C

Fig.21

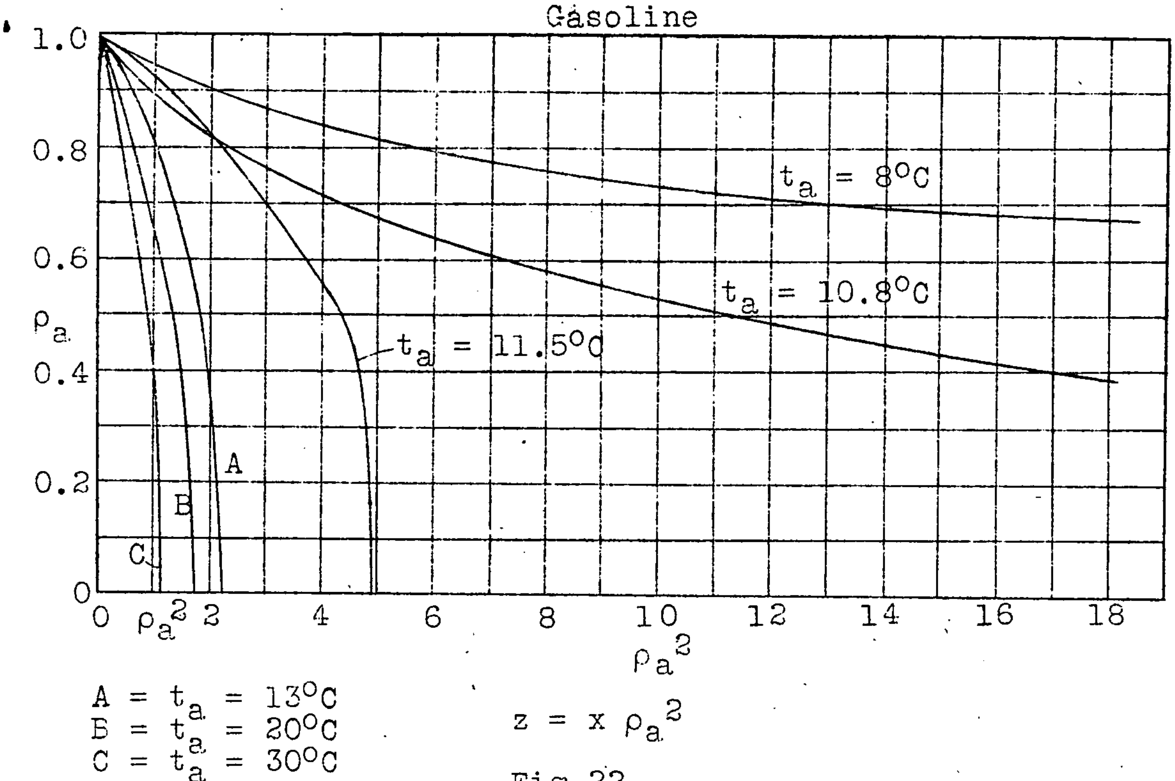

Gasoline
1.0
0.8
0.6
ρ_a
0.4
0.2
0
t_a = 8°C
t_a = 10.8°C
t_a = 11.5°C
A
B
C
0
ρ_a^2
2
4
6
8
10
12
14
16
18
ρ_a^2
A = t_a = 13°C
B = t_a = 20°C
C = t_a = 30°C
$z = x\,\rho_a^2$

Fig.22

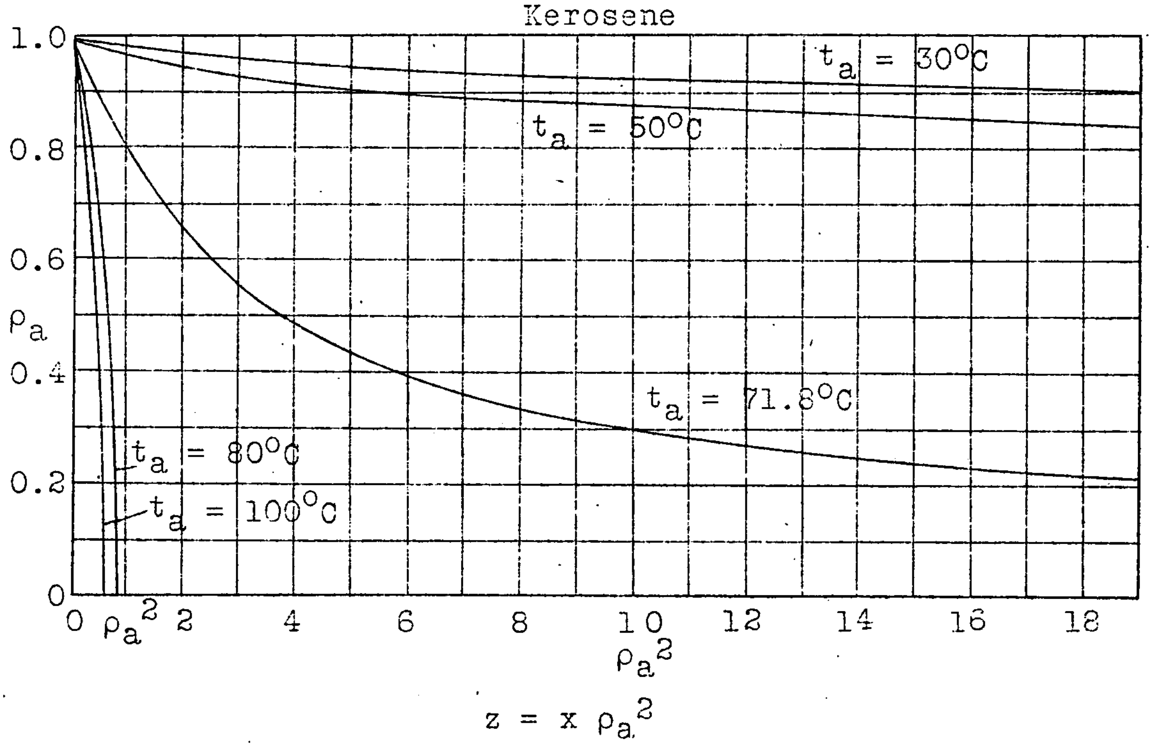

Kerosene
1.0
0.8
0.6
ρ_a
0.4
0.2
0
t_a = 30°C
t_a = 50°C
t_a = 71.8°C
t_a = 80°C
t_a = 100°C
0
ρ_a^2
2
4
6
8
10
12
14
16
18
ρ_a^2
$z = x\,\rho_a^2$

Fig.23.

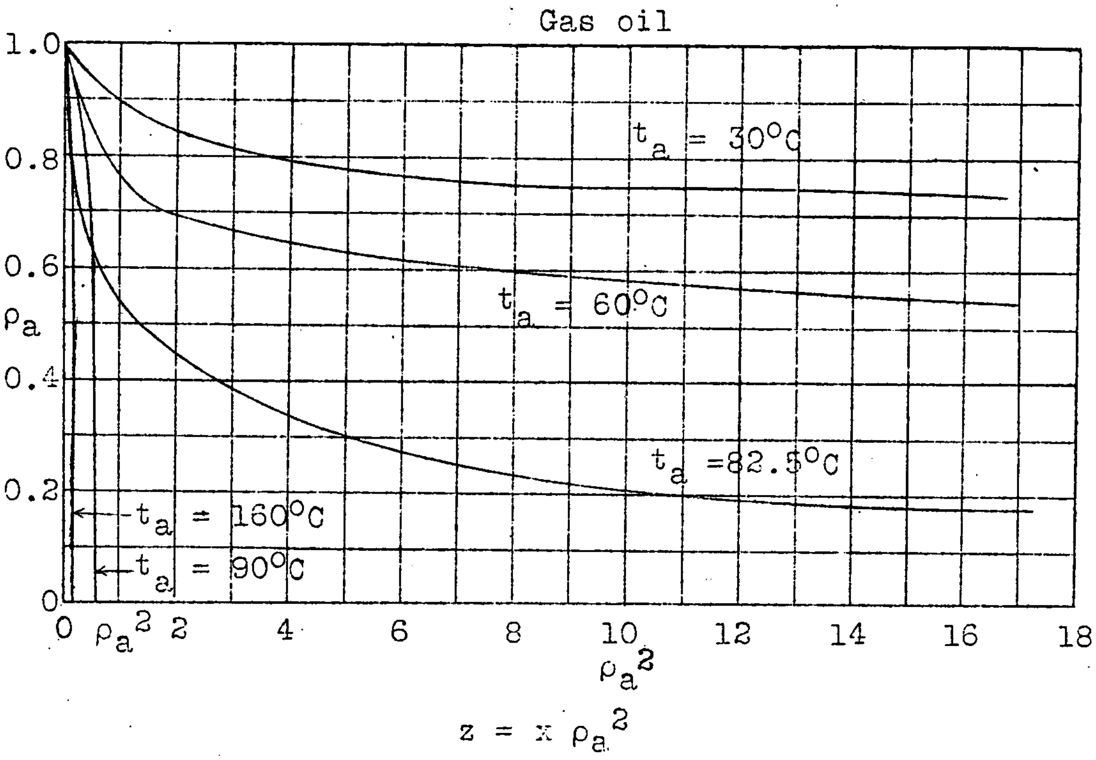

Gas oil
1.0
0.8
0.6
ρ_a
0.4
0.2
0
t_a = 30°C
t_a = 60°C
t_a =82.5°C
t_a = 160°C
t_a = 90°C
0
ρ_a^2
2
4
6
8
10
12
14
16
18
ρ_a^2
$z = x\,\rho_a^2$

Fig.24.

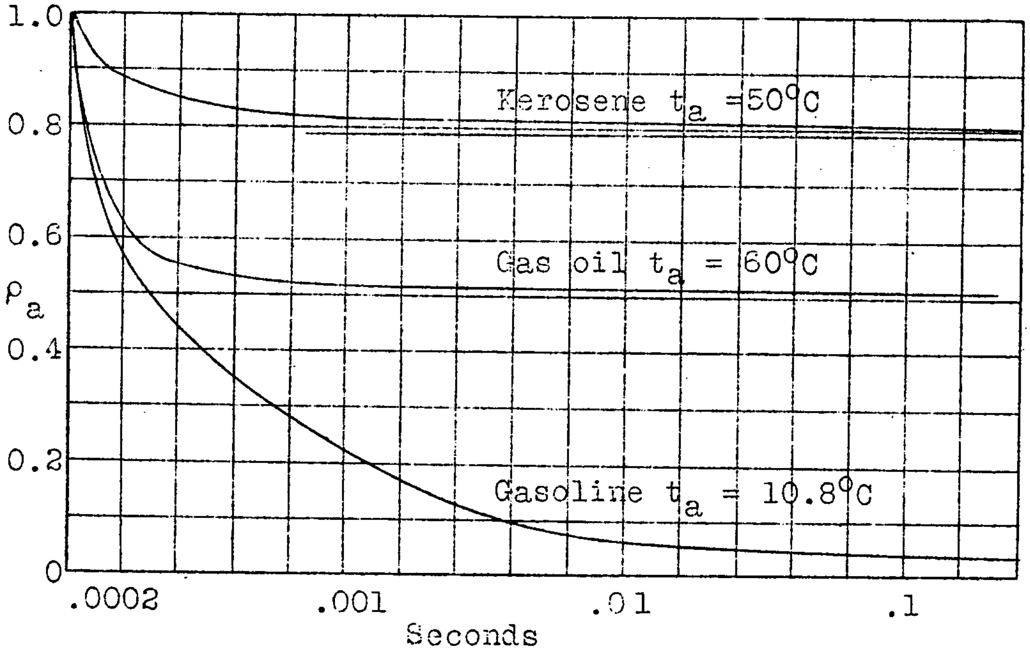

1.0
0.8
0.6
ρ_a
0.4
0.2
0
Kerosene t_a =50°C
Gas oil t_a = 60°C
Gasoline t_a = 10.8°C
.0002
.001
.01
.1
Seconds

Fig.25.