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

By Fritz Heinlein

PART III

From "Der Motorwagen," June 30, 1926

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 384.

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

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PART III.

Experimental Apparatus.

Fig. 17 is a diagrammatic representation of the experimental apparatus, in which a is the calorimeter already used in the calorimetric measurements. It has a double bottom for heating and was used in these experiments as a vaporization vessel. It was made air-tight by means of the cover provided with two tubes (b and c) with packing boxes. The cover was screwed on tightly with the interposition of "Kingerit" packing. Another packing box d in the cover enabled the introduction of a small glass tube, which was drawn out to a capillary and had a glass stop-cock. This tube served to regulate the vaporization and the negative pressure in the vessel by the admission of outside air. The packing box b tightens the glass tube e with the two branches f and g for conducting the vapors to the manometer. The tube e was so modified that it could be made tight

\* From "Der Motorwagen," June 30, 1926, pp. 395-402. For Parts I and II, see N.A.C.A. Technical Memorandums Nos. 362 and 363.

with a copper plate, which rendered possible the air-tight introduction of the two thermo-electric wires of a glass float. The boiling point of the oil (by which is meant the temperature of the liquid at which, at the prevailing pressure, it changes to vapor at the same temperature) was measured by means of a thermo-electric couple, whose wires were attached to a glass bulb floating on the oil. Due to the spirals in the wires, the glass float could follow the surface of the liquid as it sank from the evaporation during the experiment. Thus, at every position of the surface of the liquid during the whole process of vaporization, the temperature of the upper layers of the liquid was taken, this temperature being identical with that of the vapor.

The vaporization vessel was heated by an electric current supplied by a battery, which current could be regulated by a rheostat and could be measured directly at both binding posts of the heating wires by inserted ammeters and precision voltmeters.

The assembled vaporization vessel was set into a Dewar vessel and the intervening space filled with glass wool, as in the specific heat determination, in order to prevent the loss of heat as much as possible. The Dewar vessel itself was then set in a sheet-iron jacket containing rape oil as the heating liquid and heated externally by means of electricity. The cover of the vaporization vessel was also covered externally with a layer of glass wool.

The whole apparatus thus assembled, was then placed on a balance, which had a sensitivity of 0.5 g (0.0176 oz.) when fully loaded. The rubber connections of the glass tube b of the vaporization vessel somewhat impaired the sensitivity of the balance which, when unloaded, gave easily readable deflections on the addition of 0.1 g (0.0035 oz.) to one of the pans. Only by passing the rubber tubes through a stationary halter, could the connections be so made as to prevent their interfering appreciably with the motion of the balance. The sensitivity of the balance was thus sufficiently preserved.

The rubber tube f led from the vaporization vessel to a Woolff's bottle h which was about one-third full of oil at the temperature of the room. Another rubber tube led to a water-jet air pump, used for drawing off the vapors, which were collected in the bottle as a condensate. The strength of the suction was indicated by the air bubbles rising in the condensing bottle and could be regulated by the cock in the water pipe leading to the jet-pump and by the cock in the capillary tube d.

The rubber connection g led to a mercury barometer, which was filled with purified mercury and which indicated the negative pressure. The U-shaped manometer tube was fastened by pipe clips to a vertical board. A millimeter scale was placed behind the manometer tube, thus enabling the direct reading of the negative pressure.

Before the beginning of each experiment, the vaporization

vessel was about three-fourths filled with the oil to be tested and this oil was heated to its lowest boiling point. Then the heating current was switched on and the air pump started. The very first resulting evaporation of the very volatile constituents was too irregular and had to be disregarded in determining the heat of vaporization. After about thirty seconds, however, the evaporation proceeded smoothly and the temperatures of the liquid and of the base-plate became constant. After this condition had been attained, enough weights were removed from the scale pan to bring the balance pointer near zero. Then, just as the pointer was passing through the zero point, a stop watch was started and a 20 g (0.7 oz.) weight was removed from the scale pan. After this weight of oil had evaporated, the pointer returned to zero and the time interval was read on the stop watch.

The temperatures of the liquid and of the base-plate were measured with the thermo-electric elements and were kept constant throughout the vaporization test, slight variations being eliminated by regulating the air pump. After several successive vaporization experiments, the boiling point rose so much, due to the evaporation of the lighter hydrocarbons, that the temperature of the liquid could no longer be kept constant by regulating the negative pressure. A transition then had to be made to a higher vaporization temperature.

The electrical energy consumed during the evaporation was measured and the amount of oil evaporated was found by weighing. The ratio of these two quantities gave the vaporization heat in electric units. For conversion into heat energy, the following relation was used:

1 watt-second = 0.2389 lesser calories, so that the vaporization heat is computed to

$$r = \frac{0.2389 \times e \times i \times z}{G}$$
 lesser calories, in which  $z$  = the vaporization time in seconds and  $G$  = the weight in grams of the evaporated oil.

In order that the heat exchange with the surrounding media should not have to be introduced into the calculation as a disturbing correction factor, there were determined, for a series of temperatures of the liquid in the vaporization vessel, the same temperatures of the outer heating liquid, which enabled the keeping of the liquid in the vaporization vessel at a constant temperature. Thus it was brought about that the heat lost by the vaporization vessel through radiation and conduction was offset by heat received from the external heating liquid.

The current strength was measured by an ammeter directly connected with the ends of the heating wires, while the electric tension was measured by a precision voltmeter of very high resistance introduced into a shunt.

As soon as a uniform rate of evaporation was obtained by

regulating the exhaust, and the temperature difference between the bottom heating plate and the fuel liquid became constant, the experiment was begun. Toward the close of the evaporation, when nearly all the fuel liquid had been evaporated, the temperature differences between the bottom plate and the liquid could no longer be kept constant. The heat stored up in the bottom plate would then have affected the vaporization heat without being measurable and would have given too low values for the heat of vaporization. Hence no correct values could be given for the latter at the close of the evaporation.

The vaporization heats obtained in the experiments are given in Table XV, the last column containing the mean values used in subsequent computations.







## Vaporization Speed and Diffusion Coefficient.

Along with the hitherto tested properties which affect the vaporization of the fuels, the vaporization speed is of decisive importance, because of the extremely short vaporization time available in engine functioning. The vaporization speed first raises the question of how well the carburetor performs its task of producing an ignitable fuel mixture for a given temperature of the outside air.

The vaporization of a liquid is essentially a process of diffusion of the vapor through the gas in which the vaporization takes place. Thereby we assume that, at any given temperature, there is continually formed, on the surface of the liquid, enough vapor to keep the liquid in equilibrium with the vapor, and that there is a saturation pressure on the surface of the liquid corresponding to the temperature. This saturated layer above the liquid is surrounded by atmospheric air with which the vapor must be diffused. Thereby, in the steady condition of the vaporization, there is a vapor-pressure fall normal to the surface, on which the vaporization speed depends. Fundamental researches were carried out by J. Stefan on the vaporization of liquids with the establishment of the factors which determine the vaporization speed. These experiments had to do with the vaporization of liquids in narrow tubes. The vaporization speed was defined by Stefan as the quantity of vapor formed per unit of time and cross section at a given temperature.

$b$  = barometer stand in mm Hg.

$p$  = partial pressure of vapor in mixture of vapor and air at any point in the diffusion chamber, in mm Hg.

$h$  = diffusion distance in cm from open end of tube computed as distance between level of liquid and end of tube.

$k$  = diffusion coefficient which shows how many  $\text{cm}^3$  vapor per second passes through one  $\text{cm}^2$  of cross section perpendicular to the direction of diffusion, when the decrease in vapor pressure in this direction is 1 mm Hg per cm. The laws discovered by Stefan can then be written in the form

$$v = \frac{k}{h} \ln \frac{b}{b-p} \text{ cm}^3/\text{sec.}, \text{ i.e.:}$$

1. The vaporization speed depends on a constant  $k$ , which itself depends on the nature of the gases to be diffused;
2. It is inversely proportional to the diffusion distance  $h$ ;
3. It is proportional to the expression  $\ln \frac{b}{b-p}$ .

The Stefan laws have been confirmed by a very large number of researches of other investigators, so that the determination of the vaporization speed of liquids can be undertaken in accordance with them. A few preliminary remarks must be made, however, as regards the evaluation of the results expected from this method.

The determination of the vaporization speed by the method of vaporization in narrow tubes applies to a quiet level surface,

It can not be unconditionally assumed that the absolute value of the vaporization speed is equal to the vaporization speed of curved surfaces as exhibited by a liquid in the form of drops. In this case the vaporization speed is higher. Likewise the vaporization speed is increased by a current of air across the surface of the liquid.

With the aid of the theory of heat conduction, whose fundamental equation is analogous to Stefan's formula, experiments have been undertaken by various investigators, in order to find the laws, according to which the vaporization speed of a liquid changes for different surface shapes and under different conditions of motion of the air in contact with these surfaces. The results of these researches conform to very definite experimental arrangements and confirm, in the observation of the special cases, the above-mentioned increase in the vaporization speed of chemically homogeneous liquids.

The differences which occur in these special cases (in contrast with the fundamental determinations of Stefan, Winkelmann and others) are less important, however, for the determination of the vaporization speed of fuels, because the nature of the fuels, on account of their varying composition, prevents any absolute evaluation of their vaporization speeds. Hence we can only hope to obtain in these experiments, comparative values for the vaporization speeds of the individual fuels under very similar experimental conditions.

I therefore decided to undertake the determination of the vaporization heat of fuels in connection with the methods instituted by Stefan and improved by Winkelmann, Wuppermann and others.

### Experimental Arrangement

The system of vaporization tubes, as shown in Fig. 19, was set into a thermostat for heating to the desired vaporization temperature. The thermostat was filled with rape-seed oil which was heated internally by electricity and provided with an electric stirrer.

A copper tube I, which was about 30 cm (11.8 in.) long and about 5 cm (1.18 in.) in diameter and was closed at the bottom, was surrounded by a spiral copper tube about 2.8 m (9.2 ft.) long, the lower end of which opened into tube I about 15 mm (0.6 in.) from the bottom of the latter. The upper end of the spiral tube extended above tube I, in order to enable connection with the air supply. The real vaporization tube III, which contained the fuel, was set into tube I. Thereby, because tube I already had the thermostat temperature while tube III still had the room temperature when set into tube I, the heating of tube III proceeded upward from the bottom of tube I and the already evaporated liquid, which rose from the surface of the liquid up to the upper, still cooler wall of tube III, might have been precipitated again on this cooler wall. Hence only a thin-walled copper tube II, with a flat bottom, was placed between

the tubes I and III. Tube II rested directly on the bottom of tube I where it was held by a copper collar-step bearing. The top of tube II was widened into a conical shape, on which rested the similarly shaped top of tube III, leaving an air space between the two throughout the whole length of the latter, 17 cm (6.7 in.). Thus the vaporization tube III was heated from above downward, so that no precipitation of the vapors could occur inside the tube above the fuel. The copper vaporization tube III had an inner diameter of 6.05 mm (0.238 in.) and wall thickness of 0.5 mm (0.02 in.).

In order to measure the temperature of the fuel, a thermoelectric couple was soldered to the vaporization tube III at a height of 3 cm (0.79 in.) from the open end, because the surface of the liquid remained at this height with variations of only a few millimeters. Moreover, the vaporization process was disturbed less by this arrangement, than by immersing the wires in the liquid.

A is the entrance point of an air stream dried by passing through a long calcium chloride tube which, after passing through the 2.8 m (3.2 ft.) thin-walled copper spiral, had taken on the temperature of the thermostat. The air was drawn through by means of a water-jet air pump. Pressure variations of the air stream were prevented by the introduction of two glass bottles. The air-exhaust pipe B extended through a rubber stopper in tube I to within about 3 cm (1.2 in.) of the vaporization tube III and was

connected with the air pump.

The tube III was filled with fuel to a certain height and a determination was made of the amount of fuel evaporated in a given time at a given temperature. When an air stream is led past the top of the vaporization tube, it carries away the vapors coming out of the tube, thus reducing the vapor pressure at the open end of the tube practically to zero while, at the surface of the liquid in the vaporization tube, there is the saturation pressure corresponding to the vaporization temperature at the time.

The diffusion height is then the distance between the level of the liquid and the open end of the vaporization tube.

According to this arrangement, the vaporization process can be formulated as follows:

$$\frac{dx}{dZ} = \frac{k O}{h} f(p, b) \quad (1)$$

in which

$x$  = quantity of fuel evaporated in the time  $Z$ ;

$Z$  = time in seconds of the vaporization;

$k$  = coefficient of diffusion;

$q$  = cross section of inside of tube III = the surface area  $O$  of the liquid in  $\text{cm}^2$ ;

$h$  = height of diffusion space in cm;

$b$  = barometer stand;

$p$  = vapor pressure in mm Hg at the experimental temperature  $t$ .

This formula would, with the differential  $dx/dZ$ , comprehend

the true vaporization condition of the fuel and take into account the fact that the vaporization speed diminishes, at constant temperature, from a maximum at the beginning of the vaporization.

After a constant vaporization rate has been established by the condition that, at the mouth of the small tube during the vaporization process, the vapor pressure is zero, the experiment can be extended for considerable time periods  $Z$ . Some changes in the vaporization speed are due to the nature of the fuel. The results of the experiments give vaporization speeds which can be regarded only as comparative values. In the experiments, we must take into consideration the fact that we can compare only such values as are obtained at the same time.

For the constant rate of vaporization, at which the vapor pressure at the mouth of tube III can be maintained at zero, the formula changes to

$$\frac{x}{Z} = \frac{k \cdot O}{h} f(p, b) \quad (2)$$

and is simplified, when  $O$  remains constant and when the barometer and vapor pressure can also be assumed to remain constant during the experiment, to

$$\frac{x}{Z} = \frac{k'}{h} \quad (3)$$

$k'$  is therefore a measure for the vaporization speed and can be expressed by measurable quantities.

If we define, as the unit vaporization speed  $k''$ , the quan-



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tity of fuel evaporated in one hour, with a surface area of 1 cm<sup>2</sup>, a height of 1 cm for the diffusion space and a barometer stand of 760 mm, the vaporization speed, according to equation (3), is then reduced to

$$k'' = \frac{x_{760} h 60}{q z} \quad (4)$$

in which

$x_{760}$  = amount in grams evaporated in the experiment time of Z minutes, converted from the barometric pressure of the experiment to 760 mm, by using the gas equation for the vapor formed;

h = mean height of diffusion space;

q = cross sectional area of tube III in cm<sup>2</sup>;

z = vaporization period in minutes.

The quantities determining the vaporization speed in equation (4) were then found with the above-described apparatus.

For this purpose, we filled tube III with fuel up to within about 2 cm (0.8 in.) of its open end, being careful not to get any on the walls of the diffusion chamber above the surface of the fuel liquid, which would exert a disturbing effect on the vaporization. The fuel was introduced with a glass pipette, which was drawn out to a capillary and which extended just 2 cm into the tube III, at which point the pipette rested on the tube. The tube was then filled just to the tip of the pipette without wetting the wall above the liquid. Before filling with a different fuel, the tube III was brought to a red heat and then cooled

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in a desiccator.

The quantity  $x$  of the evaporated fuel was determined by weighing the filled vaporization tube III before and after the experiment. The vaporization period  $Z$ , from the insertion to the removal of the tube III, was measured by a stop watch. Before inserting tube III, the apparatus was heated to the experiment temperature  $t$ , but the tube III and its contents still had the room temperature of about  $15^{\circ}\text{C}$  ( $59^{\circ}\text{F}$ ). Had the liquid been chemically homogeneous, it would have been necessary, for an accurate result, to determine, by a preliminary experiment, the quantity of liquid vaporized up to the instant when the tube III, with its contents, had reached the vaporization temperature  $t$ . The time and the quantity of the vaporized liquid would have had to be subtracted, as a correction, from the values of the main experiment, since they corresponded to a lower variable vaporization temperature. In my experiments with fuels, I attempted to make this correction, but found that with this correction, the vaporized fuel gave considerably lower values than really corresponded to the fuel, because the light liquid components, which evaporated quickly, were not taken into consideration. I did not therefore undertake any correction of the vaporized quantity, as regards the time and weight, and accordingly obtained somewhat lower values than the actual ones, because the first vaporization period was at too low a temperature, but I came nearer to the reality than with the correction

and the values found are at least accurate enough for purposes of comparison.

The mean height of the diffusion space had still to be determined. This was found as the difference between the known inner height  $H = 19$  cm of the vaporization tube III and the mean height  $h'$  of the fuel surface above the bottom of the tube. The height  $h'$  was found by weighing, from the formula

$$\frac{g_1 + g_2}{2} = q h' s,$$

in which  $g_1$  and  $g_2$  = the weights of the filled tube in grams before and after the vaporization.

$q$  = cross section of tube III in  $\text{cm}^2$ .

$s$  = specific weight of fuel at the vaporization temperature as determined with a specific-gravity bottle.

The vaporization speeds were determined for all the fuels at different temperatures (Table XVI) and were plotted against the temperature in Fig. 19a.

Table XVI.

Barometer mm Hg	Temp. in °C	Height dif. h cm	Min- utes z	g/hr. x	g/hr. x760	k"
Gas oil. $q = 0.2873 \text{ cm}^2$ ; $H = 19 \text{ cm}$						
721	20	2.80	60	0.004	0.00379	0.0369
721	38	2.65	60	0.0051	0.00475	0.0436
721	55	2.44	60	0.007	0.00653	0.0557
722	70	2.33	60	0.075	0.01657	0.1347
722	92	2.25	60	0.026	0.0246	0.2795
Paraffine oil. $q = 0.2873$ ; $H = 19 \text{ cm}$						
724	22	2.78	60	0.029	0.0276	0.267
724	50	2.64	60	0.051	0.0486	0.525
724	70	2.39	60	0.0879	0.0837	0.685
724	90	2.33	60	0.2008	0.1918	1.550
Coal-tar oil I. $q = 0.2875$ ; $H = 19 \text{ cm}$						
722	22	2.52	60	0.023	0.0218	0.191
722	40	2.54	90	0.080	0.076	0.448
724	52	2.40	74	0.0876	0.0826	0.568
724	70	2.08	60	0.123	0.1173	0.849
724	90	2.26	60	0.219	0.2088	1.642
Kerosene. $q = 0.2873$ ; $H = 19 \text{ cm}$						
724	18	2.90	60	0.002	0.0019	0.0197
724	32	2.77	70	0.005	0.00476	0.0393
724	56	2.47	70	0.015	0.0143	0.105
724	70	2.36	70	0.028	0.0267	0.11
Gasoline. $q = 0.2873$ ; $H = 19 \text{ cm}$						
719	17	2.95	60	0.024	0.02276	0.2337
720	28	2.85	60	0.040	0.0379	0.376
720	35	2.88	60	0.054	0.0512	0.513
720	43	2.33	70	0.71	0.0675	0.662
720	50	2.77	60	0.093	0.0881	0.849
720	74	2.78	60	0.116	0.110	1.065
Benzol. $q = 0.2873$ ; $H = 19 \text{ cm}$						
720	30	2.74	60	0.028	0.0265	0.253
720	42	2.74	60	0.048	0.0455	0.438
720	50	2.66	60	0.067	0.0635	0.638
720	70	2.58	60	0.257	0.2434	2.187

The representation of the vaporization speeds in Fig. 19a shows remarkably large values for paraffine oil and coal-tar oil I in comparison with gas oil and kerosene, which is probably due to the fact that in these two fuels, the percentage of volatile constituents, which evaporate at the experiment temperatures, is larger than in the two other fuels which are of uniform composition and evaporate more uniformly. In the first two fuels, the lack of experimental facilities for measuring the vaporization time and quantity at very small intervals, is more manifest and allow the values found for the vaporization speeds of these two fuels to be used only with caution, even for comparison.

If we compare the values of the vaporization speeds of gasoline, as a volatile fuel, with the values of kerosene and gas oil, we find, for example, at  $t = 20^{\circ}\text{C}$  ( $68^{\circ}\text{F}$ ), a vaporization speed for gasoline respectively 12 and 10 times as great as for kerosene and gas oil. The ratio for the heavier fuels is still more unfavorable at higher experiment temperatures. A subsequent chapter will contain a theoretical discussion of the subject as to how much the smaller vaporization speed of the heavy fuels impairs their utility in carburetor explosion engines and necessitates the use of other means for obtaining an ignitable mixture of fuel and air. Such theoretical computations, however, require the diffusion coefficients of the fuels, which can be determined from the experimentally found vaporization speeds.

Calculation of the Diffusion Coefficients from  
the Vaporization Speeds

If we start with the formula

$$\frac{x}{Z} = \frac{k}{h} f(p, b)$$

for the determination of the vaporization speeds, it leads (in combination with Stefan's theoretically derived formula, according to which the vaporization speed is proportional to the logarithm of a fraction whose numerator is the air pressure  $b$  and whose denominator is the difference between the air pressure  $b$  and the maximum vapor pressure  $p$ ) to the formula for determining the diffusion coefficient  $k$ .

According to Stefan, as already explained, the vaporization speed of a liquid is

$$v = \frac{k}{h} \ln \frac{b}{b - p}, \quad (5)$$

in which

$v$  = volume of vapor which passes in unit time through a unit cross section and is reduced to the pressure  $b$  and the temperature  $t$  of the experiment;

$k$  = diffusion coefficient of vapor at the pressure  $b$  and temperature  $t$  of the experiment;

$h$  = distance of fuel surface below open end of vaporization tube;

$b$  = atmospheric pressure;

$p$  = saturation pressure at the temperature  $t$  of the experiment.



Hence:

$$k = \frac{r h}{\ln b - \ln (b - p)} \quad (6)$$

Now the quantity of fuel vaporized per unit of time and cross section, which has already been defined as the vaporization speed, is equal to the quantity of vapor which is diffused per unit of time through a unit cross section.

If  $d$  denotes the vapor density of the fuel, as compared with air at  $0^{\circ}\text{C}$  and 760 mm;  $v$ , the quantity of vapor diffused through the unit cross section per second; and  $h$ , the height of the diffusion space in centimeters; we then have

$$\frac{k''}{k} = v d,$$

whereby we must remember that the quantity of liquid and of vapor can be put equal to one another, only when we refer  $v d$  to water at  $0^{\circ}\text{C}$  and 760 mm and convert the vapor density, which is universally referred to air at  $0^{\circ}\text{C}$  and 760 mm, to water. Accordingly, the right member of the equation must be multiplied by the specific gravity of the air:

$$\frac{k''}{k} = v d 0,001293.$$

Moreover, the density  $d$ , which is referred to  $0^{\circ}\text{C}$  and 760 mm, must be converted to the experiment temperature through multiplication by the factor  $\frac{273}{273 + t}$  and the vaporization speed  $k''$  be referred to the second as the unit of time.

The equation for calculating the diffusion coefficient accordingly reads

$$k = \frac{k''}{3600 \times 0.001293 \times d_1} \cdot \frac{l}{2.303 \log b - \log (l - p)},$$

in which  $k''$  is taken from Table XVI, as also the barometer stand  $b$ ;

$d_1 = d \frac{273}{273 + t}$  is computed from the vapor densities already known for the fuels;  $p$ , the vapor pressure of the fuel, is taken from the vapor-pressure curves in Fig. 12.

The diffusion coefficients  $k$  for the different fuels are plotted against the temperature in Fig. 19b. The results of the computation will be given in Table XVII of Part IV, which is yet to follow.

Translation by Dwight M. Miner,  
National Advisory Committee  
for Aeronautics.

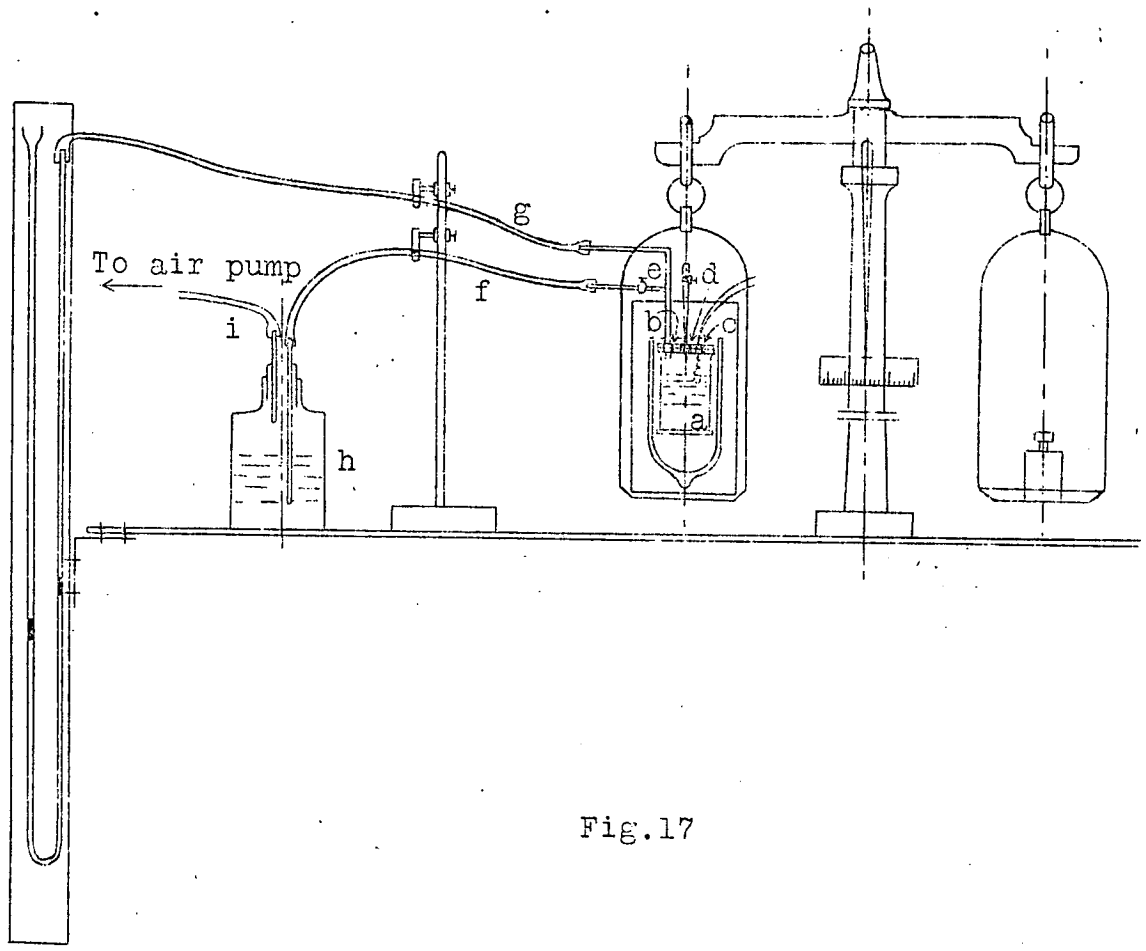


Fig.17

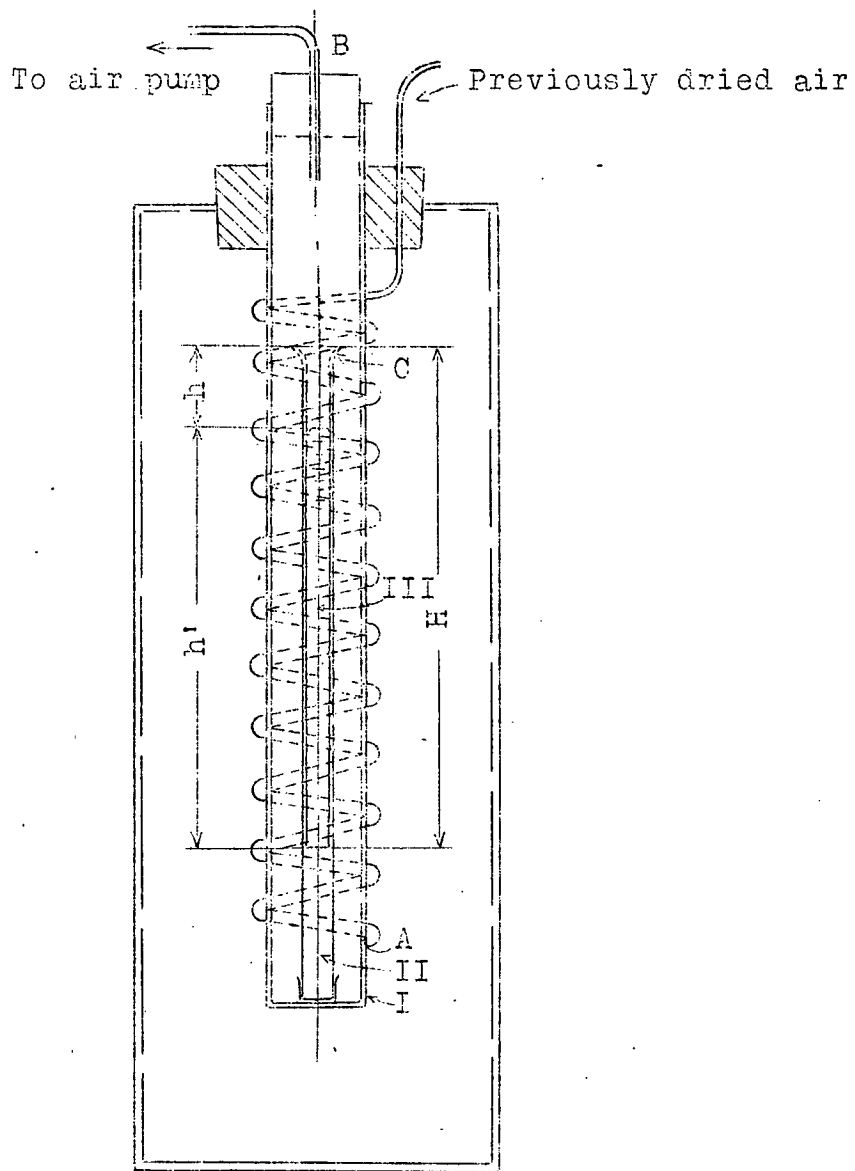


Fig.18

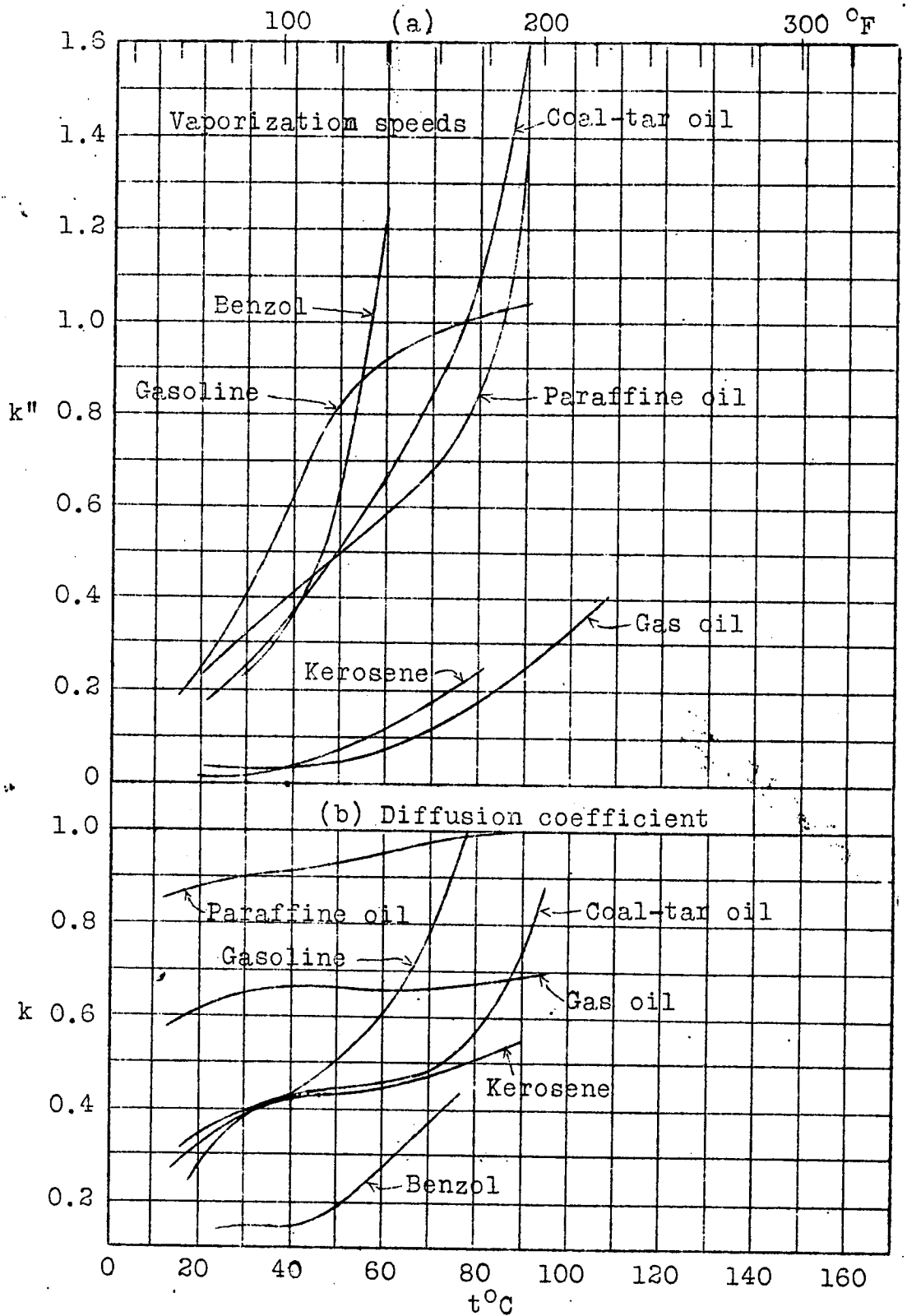


Fig.19