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V. A. MIKHELSON THE FOUNDER OF THE PHYSICS OF COMBUSTION IN RUSSIA

TO CELEBRATE THE OCCASION OF HIS HUNDREDTH BIRTHDAY

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THE HUNDREDTH birthday of the prominent Russian scientist V. A. Mikhelson was celebrated on 27 June. His most outstanding investigation was the study of the inflammation of detonating gas mixtures. In spite of the fact that this problem was the object of numerous investigations before V. A. Mikhelson, nevertheless it is true to state that this is the work which made him very famous, and made him the founder of a vast branch of science in Russia known as the physics of combustion and explosions.

Mikhelson's works on the physics of combustion and explosions were compiled into an extensive monograph which was submitted to the Moscow University as a thesis for a master's degree. Numerous explosions in coal pits, with their attendant heavy toll on humanity, initiated the investigation of processes of combustion and explosions. This monograph is full of ideas which still preserve their freshness. Some of Mikhelson's ideas may be easily developed and are capable of expansion into forms of considerable use nowadays; this is the aim of the present work.

The classical memoirs of Mallyar and Le Chatelier published in 1883 open the history of this problem. However, besides the works of these scientists there were important investigations carried out by Davy, Bunsen, Schlesing and Fonseca, as a result of which the so-called heat theory of fire travel was outlined. Proceeding from the equation of energy balance in a combustion process, Mallyar and Le Chatelier for the first time made an attempt to give a formula for the rate of fire travel in a combustible mixture. The problem investigated by Mallyar and Le Chatelier was the determination of a functional relationship between the propagation rate of a front, physical properties of a gas mixture, and chemical kinetics of combustion. Mallyar and Le Chatelier did not completely manage to achieve their objective, but they described the qualitative aspect of the phenomenon correctly.

The historical memoirs of Mallyar and Le Chatelier had already been published five years when Mikhelson's works on the physics of combustion appeared. An experimental part of his work was carried out at the Physical Institute of the Berlin University, where Mikhelson had been sent in order to expand his scientific education. Investigations were sanctioned by Helmholtz and Kundt.

In his thesis, besides giving striking experimental results on the rate of propagation of a combustion front in various combustible gas mixtures, Mikhelson gave a theoretical statement of the problem in the form which is still believed to be the only true one.

Even now the problem of fire propagation is one of great controversy, and, approaching this question quite objectively, one may confirm that the theories of all the investigations carried out in the Soviet Union and abroad do not possess any advantages over the statement of the problem proposed by Mikhelson.

Mikhelson as well as Mallyar and Le Chatelier

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considered that fire propagation over a combustible mixture should be investigated in relation to the heat propagation over a non-combustible gas mixture. This means that the conduction equation should be used as the basis of the theory, but this is not all; the heat conduction equation differs in its character from the wave equation, which in its differential form contains the idea of a wave being propagated at a definite rate. As is known, the solutions of the wave equation are always as follows:

$$\Phi = \Phi(\mathbf{r} \pm \mathbf{g}t)$$

Here, the direction of the ray is designated through $\mathbf{r}$ and the velocity of wave propagation through $\mathbf{g}$.

The differential heat conduction equation by itself does not have such solutions. The question of why the front propagates with a definite rate is in fact the case with combustion.

Mikhelson understood quite clearly that such a possibility may appear in all cases where there are conjugated processes similar to heat distribution in chemically reacting media. The joint consideration of the differential heat conduction equation with the equation of kinetics of chemical reactions may yield solutions similar to those of the wave equation. That is the reason why, when searching for the functional relationship between the rate of fire travel and that of a chemical reaction, he transformed the one-dimensional heat conduction equation to a variable:

$$\xi = x - gt.$$

As a result of such a transformation and the solution of the heat conduction equation he gets the following formula for the rate of displacement of a flat combustion front:

$$g = -\frac{a}{\xi} \lg \frac{T - T_0}{T_1 - T_0} \qquad (1)$$

where T_0 is the initial gas temperature; T_1 is the inflammation temperature; a is the so-called thermal diffusivity of the gas mixture.

In order not to have indefinite values of the variables ξ and T in the formula mentioned, we relate it to that surface behind the front where the temperature reaches its limiting value, designated by T_f. If the origin and time reading are connected with the front head, then in this case the co-ordinate ξ by its absolute value, will be equal to the front thickness d and will have the inverse sign. Thus, Mikhelson's formula for the rate of front motion may be written as follows:

$$g = \frac{a}{d} \lg \frac{T_f - T_0}{T_1 - T_0}.$$

But, on the other hand, the quantity of a burnt gas in a combustion zone is equal to some finite value $\mathscr{M}$. Consequently, the mass flow through the front surface required for combustion is:

$$q = \mathscr{M} g.$$

This flow should be equal to the following value if the rate of a chemical reaction is designated through $\mathrm{d}y/\mathrm{d}t$:

$$q = \int_0^d \frac{\mathrm{d}y}{\mathrm{d}t}\, \mathrm{d}\xi = \bar{\dot{y}} d$$

Therefore, we have

$$\mathscr{M} g = \bar{\dot{y}} d$$

or

$$d = \mathscr{M} g / \bar{\dot{y}}. \qquad (2)$$

Substituting this expression for d into the Mikhelson formula, we obtain:

$$g^2 = \frac{a\bar{\dot{y}}}{\mathscr{M}} \lg \frac{T_f - T_0}{T_1 - T}. \qquad (3)$$

The equation given above essentially completes this problem. It is interesting to note that all the existing formulae obtained to date by Soviet and foreign scientists differ only slightly in form from that in which Mikhelson's formula was presented. No experiments carried out up to now have disproved Mikhelson's concept, or new definitions of it introduced anything essential. At present the object of discussions is only temperatures T_f and T_1, i.e. those conditions which should be assumed on the surfaces restricting the zone of the combustion front. But these conditions are highly restricted in their variety.

Proceeding from Mikhelson's concept it is also easy to obtain another type of the formula for the velocity of displacement of a normal combustion front. For this purpose it is assumed that the velocity of the temperature change at the moment of front formation has always a finite and constant value.

The integral of heat conduction equation (1) in a non-logarithmic form is written as follows:

$$T = (T_1 - T_0)\, e^{-(g/a)x}\, e^{(g^2/a)t} + T_0.$$

Determine the first-time derivative of the function T. It will be:

$$\frac{\partial T}{\partial t} = (T_1 - T_0)\, e^{-(g/a)x}\, e^{(g^2/a)t}\, \frac{g^2}{a}.$$

Upon referring this expression to the origin of co-ordinates and initial moment it will give:

$$\left(\frac{\partial T}{\partial t}\right)_{t=0} = \frac{g^2}{a}(T_1 - T_0). \tag{4}$$

The time required for the front formation is designated through τ. Let the maximum front temperature be equal to T_f. Therefore, the velocity of the temperature change at the front formation may be expressed in the following form:

$$(T_f - T_1)/\tau.$$

But according to the hypothesis given above this expression must be equal to relation (3). Consequently, such an equality may be written:

$$g^2(T_1 - T_0)/a = (T_f - T_1)/\eta.$$

Hence

$$g^2 = a\left(\frac{T_f - T_1}{T_1 - T_0}\right)\frac{1}{\tau}. \tag{5}$$

But from equation (2) which is also valid for the given conditions, we have:

$$\frac{d}{g} = \tau = \frac{\mathscr{M}}{\bar{\bar{y}}}.$$

Now formula (5) may be presented in the following form:

$$g^2 = a\,\frac{T_f - T_1}{T_1 - T_0}\,\frac{\bar{\bar{y}}}{\mathscr{M}}. \tag{5a}$$

The average reaction rate during the time necessary for the formation of a combustion zone may also be written in the form of the following integral:

$$\bar{\bar{y}} = \frac{1}{T_f - T_1}\int_{T_1}^{T_f}\frac{dy}{dt}\,dT.$$

Taking this into account, equation (5a) may be given in the form:

$$g = \sqrt{\left[\frac{a}{\mathscr{M}(T_1 - T_0)}\int_{T_1}^{T_f}\frac{dy}{dt}\,dT\right]}. \tag{6}$$

The formula obtained, as is easy to see, is very close in its physical content to the formula of Lewis and Elbe as well as to the formula obtained by our Soviet investigators Zeldovich and Frank–Kamenetsky.

Experimental results described by Mikhelson in his thesis are also excellent. He established two essential facts. The investigation on the dependence of the normal rate of front displacement upon the mixture composition led to the discovery of limiting points, i.e. the rate of front displacement does not become zero at any change of mixture concentration, it always has lower and upper limits.

It means that in Mikhelson's formula (3) for the thermal diffusivity coefficient the multiplier equal to

$$\frac{\bar{\bar{y}}}{\mathscr{M}}\lg\frac{T_f - T_0}{T_1 - T_0},$$

never becomes zero. From the relation mentioned above it is seen that at equalities $T_f = T$, $T_1 = T_0$ the logarithm of the relation becomes zero, but the value $\mathscr{M}$ is equal to zero as well.

Another phenomenon observed by Mikhelson and closely connected with the one described is, the rate of normal front displacement at its maximum is dependant on the mixture composition. Thus, the curve of the dependence of the front displacement rate on the composition has the form of a bell resting upon the limiting points. These facts are of paramount importance for an understanding of the true kinetics of the chemical substance conversion.

The last but one chapter of the thesis deals with the theory of the Bunsen burner. The author gave such thorough development of the problem that even now text-books and monographs contain it almost in the same form as Mikhelson gave it.

We see that Mikhelson's scientific achievements in the field of the physics of combustion are so considerable that we may consider him by right the founder of this teaching. Soviet scientists must strengthen and develop scientific concepts proposed by Mikhelson.