**Gas Flow**

The problem was formulated as follows: *Measure the speed distribution of the gas flow in and around the flame of a candle. What conclusions can be drawn from the measurements?*

Flame is the result of a slow combustion and is usually associated with light accompanying it. The flame of a candle is a typical heterogeneous diffusion flame because, at first, the initial substances and products of combustion are in different phases and, at second, a fuel is evaporated and is mixed with an oxidant in the process of diffusion.

Structure of a flame is schematically shown on Figure 1. One may separate a flame on three zones:
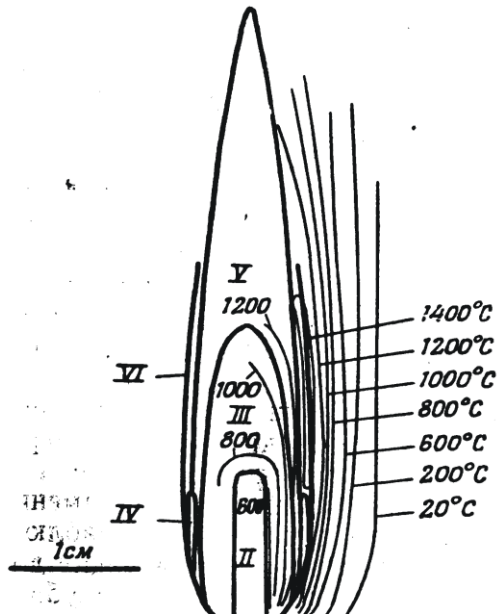
reaction zone, *dark* or *heating zone* and *luminescent zone*. Reaction takes place in external layers of a flame. In narrow sense, properly reaction zone is called by flame. In dark zone reactions do not take place because the air does not penetrate into internal layers of a flame. In this zone the heat transfer goes due to convection and the heat spend to melt and evaporate paraffin. Convection transfer paraffin into reaction zone. Luminescent zone emit light due to carbon particles which are intensively radiated while heated. The carbon is appeared because of condensation of $\tilde{N}_2$ produced in reactions of pyrolysis, polymerisation and condensation of hydrocarbons. Specialists consider pyrolysis to be dominated.

Convective movement up the surface of a flame is generated and supported due to non-uniform heating in external gravitation field. Convective hot gas flows outward to reaction zone form streams carried products of oxidation and surrounding air. In some cases the whirl structures may be produced.

The major problem considered and solved in literature is experimental measurement and theoretical calculation of the flame speed. Flame speed is the speed of the flame front movement relatively to the non-burned gas. This speed does not depend on the speed of gaseous flows in a flame but is defined by heat transfer and diffusion of reagents in reaction zone. In stationary front of flame case, fixed in laboratory frame of reference speed of flame is equal to magnitude of gas flow near to reaction zone.

Prevalent methods of shadow and shliren photographing and analogous methods of filming are applied only to measure the flame speed. But tracing method gives a possibility to measure speed distribution of gas flows.

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The tracing method consists of introduction of magnesium oxide particles into gas flows around of flame. Magnesium oxide powder is refractory, its melting temperature is 2825 °C. It is not oxidized. Therefore powder particles do not obtain the additional velocity, which can appear due to recoiling of reaction product. In hot flows of gas MgO is quickly heated and become luminous. This give the possibility to record its motion on film. But it is difficult to identify tracks of particles in luminescent zone, because brightness of its luminescence do non exceed brightness of carbon luminescence.

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In our investigation the candle was situated in front of rulers. For measuring speeds of particles in the flame a powder was penetrated into wick, for measuring out - was strewn over the flame. Tracks were photographed. Thus determine the track length during one shot the speed of gas flow can be calculated. Demonstration of the tracing method is represented on Figure 2.

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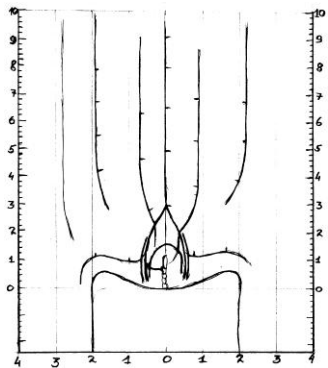

Figure 3. Stream lines.

As you can see ascendant streams are formed. Near to the flame speed is 0.6 m/sec on the axis and 0.4 m/sec on distance of 2 cm from the axis. Speed of gas flow decreases above the flame. Stream lines situated in the lower part of flame is the stream lines of air. Its speed is 0.2 m/sec.

There is a following way to estimate the gas temperature in a flame by the distribution of stream speeds around it. Speeds of gas streams are not high so the Mach number for different points of flow is low. On one hand, it leads to small pressure changing (according Lewis's to estimations it equal to 1 millimetre of mercury

column). On the other hand, gas can be considered incompressible, at least on the distance of flame sizes. From the continuity equation

$$\rho_1 u_1 = \rho_1 u_1$$

it follows that the ratio of speeds is inversely proportional to ratio of gas densities. It can be rewritten using the state equation for ideal gas and condition that the pressure is almost constant in different points of the flow:

$$\frac{u_1}{u_2} = \frac{\rho_2}{\rho_1} = \frac{\mu_2 T_1}{\mu_1 T_2} \quad \quad (1)$$

where μ_1 and μ_2 are average molecular masses of gaseous situated in point 1 and 2. If point 1 is taken into reaction zone, and point 2 is taken out of it, then μ_1 is average molecular mass of combustion product, and μ_2 is average molecular mass of air. Measuring $\grave{O}_1$ and $\grave{O}_2$, it can be estimated average molecular mass of combustion product. So we can estimate the degree of combustion

For example, when paraffin $C_{20}H_{42}$ is burned in full way average molecular mass of combustion product is equal to 33 kg/kmol. Temperature of reaction zone was measured by thermocouple to be of 960 Ê. On the distance of 1 cm from a flame temperature $\grave{O}_2$ was 740 Ê. It can be calculated that μ_1 is 33,8 kg/kmol. This result shows that combustion is almost full.

Speed distribution data can be used to estimate the flame speed S_u. Because the flame is stationary, the magnitude of flame speed is the magnitude of gas speed near the flame. So $S_u = 0.5$ m/sec. The thickness of reaction zone can be estimated using S_u value. The thickness value much higher then molecular free running length λ, and much lower then characteristic sizes of the flame l,

$$\lambda << \delta << l, \quad \quad (2)$$

If it relationship is true for the flame that statement made above about the flame is stationary and laminar is valid.

Estimation formula for thickness of reaction zone can be calculated from the behaviour of solutions for diffusion and thermoconductivity with point sources. It is wellknown that these solutions can be described [2] as

$$T(t,r) = \frac{const}{8(\pi \ \chi \ t)^{3/2}} e^{-r^2/4\chi t}$$

$$C(t,r) = \frac{const}{8(\pi \ D \ t)^{3/2}} e^{-r^2/4Dt} \qquad \qquad \qquad \text{oo}(3)$$

Where

$$\chi = \frac{\kappa}{\rho \ c_p} \quad \text{} \quad (4)$$

coefficient of temperatureconductivity, κ - coefficient of thermoconductivity, $\rho - gas \ density$, $\tilde{n}_{D}$ - special isobaric thermal capacity, $\tilde{N}$ - *relative concentration of reagent (oxidant)*, D - diffusion coefficient of reagent (*oxidant*).

Estimation of reaction zone thickness is determined by one of following relationship

$$\delta_1 \approx \sqrt{\chi \ \tau} \quad \text{}(5)$$

$$\delta_2 \approx \sqrt{D\tau} \quad \text{ooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooo}(6)$$

where τ is time of reaction. Reaction goes only when temperature is high and there are reagents in reaction zone. Therefore reaction zone thickness can be estimate as the least of relationships (5) and (6):

$$\delta = \min(\delta_1, \delta_2). \tag{7}$$

The gases can be looked as ideal. For estimation (4) - (7) it can be considered

$$\kappa = \frac{1}{3} c_v \rho \lambda \bar{v} \quad ,°$$

where c_v is special thermal isohoric capacity of gas, $\bar{v}$ - mean squared speed of molecules. Thus

$$\chi = \frac{1}{3} \frac{\lambda \bar{v}}{\gamma}, \quad \gamma = \frac{c_p}{c_v}, \quad D = \frac{1}{3} \lambda \bar{v} , \tag{8}$$

where γ – Poisson coefficient. As $\gamma \geq 1$, then $D \leq \chi$. Thereby

$$\delta \approx \sqrt{\chi \tau} \tag{9}$$

The combustion front velocity S_u is directed perpendicularly to front and can be estimated as

$$S_u \approx \frac{\delta}{\tau} \approx \sqrt{\frac{\chi}{\tau}} \tag{10}$$

According to (8)

$$S_u \approx \sqrt{\frac{\lambda \bar{v}}{\tau}} = \bar{v} \sqrt{\frac{\tau_{c\theta}}{\tau}}$$

where $\tau_{\tilde{n}\hat{a}}$ - average time of free running. Sonic speed in the air in order of magnitude coincide with mean squared speed of molecules v. So $\quad \dfrac{S_u}{c} = \sqrt{\dfrac{\tau_{c\theta}}{\tau}}$

For slow combustion $S_u \ll c$. Therefore $\tau_{\tilde{n}\hat{a}} \ll \tau$.

Knowing S_u, the reaction zone thickness can be estimated by the following equation

$$\delta \approx \frac{\chi}{S_u} \approx \frac{\lambda \bar{v}}{S_u} \tag{11}$$

Hence, the condition of slow combustion must be $\delta \gg \lambda$.

Thermal coefficient for air in temperature about 1000 K is $5 \cdot 10^{-2}$ Wt/(m·K). In this case the temperature coefficient is 10^{-5} m²/sec. So $\delta \square 10^{-4}$ m. The length of free running is 10^{-8} m. The visible size of the flame is 10^{-2} m. Therefore, relationship (2) is fulfilled. It means that the flame of a candle is stationary and laminar, and gas flow can be described hydrodynamically [2]. Hence, the mapping of gas velocities like represented above is of real sense.

Conclusions:
The results of measurements of gas velocities around a flame yield:
1) to estimate the degree of paraffins combustion and give approximate prediction about content of paraffin's in simple cases;
2) to estimate the flame speed;
3) to estimate the thickness of burning zone and on this base
4) to prove that hydrodynamical model can be applied to the gaseous flows around the flame of a candle.