

# INVESTIGATION OF THE DIFFUSION FLAME

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## Abstract

In this paper, the analysed problem is how to explain the geometrical structure of flames in the combustion chamber, and how to establish the relationship between geometrical characteristics and flow parameters at the burner orifice. On the basis of our experimental data we have made a regression analysis to present numerical equation for practical use.

## Introduction

The heat release and utilization from burning fuel takes place in the combustion chamber, with the simultaneous interaction of chemical, heat transfer and flow processes. From a firing technical point of view in a combustion chamber the following requirements must be met:

- effective and safe ignition of the fuel,
- the flame should not impinge on the combustion chamber wall,
- complete burning of fuel up till the end of the combustion chamber,
- the load of the combustion chamber in the burner zone is to prevent pollution and scorification in a particularly dangerous range.

Ensuring the most important conditions with some mean values based on empirical data give information on the loads related to volume, cross section, cooling surface, cross section and surface around the burner zone.

The quantitative and qualitative characteristics of the processes taking place in the combustion chamber depend on the construction and characteristics of the flame shape in it.

However the geometrical characteristics of flame as well as the physical and chemical ones are very important in a firing technical study, because we can calculate the above-mentioned characteristics based only on the determination of the length, volume and surface of the flame. But these geometrical characteristics of flame can not be calculated based only on theory, since only experimental results are available.

There are many methods to determine the size, volume of the simple or combined flame based on different experimental views, thus:

*Visual observation:* the size of flame is established by the eye,

*Photographical:* the size of flame is photographed,

*Ionization, ion conductivity:* the limit of the reaction zone, i.e. the "edge of flame" is determined by the signal ( $e \rightarrow 0$ ) of the electric conductivity.

*CO component measurement:* it is the limit of the chemical reaction, where no CO component is found. Of course, we can say that there is limit of flame, where the value of the CO component is less than 20 ppm,

*Schlieren:* the limit of the flame is determined where the refractivity of the flame is equal with the refractivity of the surrounding (air).

### Fundamental theory

The fundamental equations of the flame discussed as aerothermochemical system are represented by those related to mass, impulse and energy. The system of the fundamental equations forms so very complex equations, that writing them, but especially their solution needs certain simplifying reductions. Approximations used to be considered of the source functions, space-time dependenc of state determination, interaction of different substances during flow.

For the mass of the different components, impulse and energy, the general form of continuity equation can be used as

$$\frac{\partial \rho}{\partial \tau} + \text{div } I = q.$$

Using the general equation of the flow its differential equation can be set up.

For the mass of the chemical component  $k$ : if the mass density of the chemical component  $k$  is  $\rho_k$ , flow density is  $I_k$ , source density is  $W_k$ , which means the reaction velocity in case of flame, the system flows with velocity  $w$ , diffusion coefficient of the component is  $D_k$ , concentration is  $C_k$ , then the differential equation related to the mass of component  $k$ :

$$\frac{\partial \rho_k}{\partial \tau} + \text{div } (\rho_k w - D_k \text{ grad } C_k) = W_k.$$

#### Concerning the impulse

Disregarding the external forces, the impulse generated in the unit volume is given by the divergence of the tension tensor. In case of velocity  $w$  with components of directions  $u, v, w, x, y, z$  the general equation for impulse:

$$\frac{\partial \rho}{\partial \tau} [\rho w] + \text{div } [\rho w \cdot \sigma w] = \text{div } P.$$

The usual form of the tensor gives the fundamental equation of hydrodynamics, Navier—Stokes' equation in a general form:

$$D \frac{w}{\varrho} \Delta C + \frac{\partial w}{\partial \tau} + [w, \text{grad}] w = -\frac{q}{\varrho} \text{grad} + \frac{u}{\varrho} \Delta w.$$

*Concerning energy transport*

The energy density consists of the kinetic energy  $\frac{1}{2} \varrho w^2$  and the specific internal energy denoted with  $e$ :

$$\varrho_e = \left[ \frac{1}{2} m w^2 + e \right] \varrho$$

taking into account the thermal conductivity  $\lambda$  and the reaction heat related the unit mol weight,  $q_k$ , the generated thermal energy is

$$\sum_k w_k q_k$$

and the differential equation related to the energy:

$$\frac{\partial}{\partial \tau} \left[ \varrho \left[ \frac{w^2}{2} + e \right] \right] + \text{div} \left[ \varrho \left[ \frac{w^2}{2} + e \right] w - \lambda \text{grad} T \right] = \sum_k w_k q_k.$$

Application of the general differential equation for hydrogen and oxygen turbulent free-jet flames, is done by using some reduction.

In order to estimate the process in technical flames it is necessary to know the local gas conditions of the reaction zone, first of all temperature and mass distribution. These distributions are the results of complex interactions between the flow, elementary chemical kinetics, as well as the energy and mass transport processes. The regularities of the individual processes taking place in the flames are theoretically well founded for laminar flows, however, the analysis of the turbulent fields is possible only with semiempirical correlations, that have to reckon with local fluctuations and their effects, first of all on the transport processes.

The velocity distributions at the cross section of the free-jet along the length of the jet, after H. Eickhoff and B. Lenze [6] as follows:

$$u = u_0 \frac{6,4}{x:d_0} \sqrt{\frac{\varrho_0}{\varrho}} e^{-82(y:x)^2}$$

where

- $x$  — component of the mean flow
- $y$  — perpendicular component of flow
- $d_0$  — diameter of the burner mouth.

The mass concentration distributions at the cross section of the free-jet:

$$C = C_0 \frac{5,26}{x:d_0} \sqrt{\frac{\varrho_0}{\varrho_k}} e^{-54(y:x^2)}$$

where:

$\varrho_k$  — density of the surrounding.

The closing angle of the free-jet is often  $19^\circ$ .

Because of the difference of mass-densities a buoyancy force exists in the jet, however the impulse flow is not constant along the jet and increases quickly within it. Along the length of flame the admixture is larger if the impulse flow is larger. As a matter of course the buoyancy force has brought about the mixing rapidly and because of it the length of flame is shorter, too.

It can be concluded that in case if Froude's number is larger than  $10^5$  the effects of the buoyancy force on the length of flame have not been considered.

*Concerning the turbulent flame:* the impulse flow at the optional cross-section along the jet length is equal with the initial cross-section of the jet:

$$I = 2\pi \int_0^r \varrho u^2 y dy = I_0$$

and mass flow:

$$M = 2\pi \int_0^r \varrho c u y dy = M_0.$$

After H. Eick and B. Lenze [6] the velocity distributions along the axis of the jet:

$$u_m = \frac{1}{x} \sqrt{\frac{I_0}{\varrho k_1}}.$$

The concentration distributions along the axis of jet:

$$C_m = \frac{1}{x} \frac{M_0}{\sqrt{I_0 \varrho}} k_2$$

of course

$$\frac{C_m}{C_0} = k_3 \frac{d_0}{x} \sqrt{\frac{\varrho_0}{\varrho}}$$

if the fuel flow (with density  $\varrho_0$  and with a density  $\varrho_k$  of the air flow) takes place in the mixture:

$$\frac{C_m}{C_0} = k_3 \frac{d_0}{x} \sqrt{\frac{\varrho_0}{\varrho_k}}.$$

In case of the reaction zone  $\varrho_k$  changes to  $\varrho_f$

$$\frac{C_m}{C_0} = k_3 \frac{d_0}{x} \sqrt{\frac{\varrho_0}{\varrho_f}}.$$

We may thus say, that the end of flame is to be found where the concentration along the axis of the jet is equal with the theoretical stoichiometric concentration ( $C_m = C_{st}$ ). Of course the length of flame is calculated as follows:

$$\frac{x_f}{d_0} = k_4 \frac{C_0}{C_{st}} \sqrt{\frac{Q_0}{Q_f}}$$

where:

$$I_0 = [\rho u^2]_0 \frac{\pi d_0^2}{4}$$

$$M_0 = [\rho C u]_0 \frac{\pi d_0^2}{4}$$

$x_f$  — the distance from the beginning until the end of the flame.

It is remarkable that usually the beginning of the flame is not at the outlet orifice of the burner. Based on different experiments the following may be considered:

— in case of a little number  $Re$  the beginning of the flame is at the outlet orifice of the burner,

— in case of the double concentric burner: because of the relativ velocity between two jetflows is minished, as well as turbulent exchange the beginning of the flame is displaced from the initial of the jet into flow.

#### *Concerning the rotation jets*

In case of a simple rotation-jet, the decrease of the concentration is as follows:

$$\frac{C_m}{C_0} = k_3 \frac{d_0}{x + kD} \sqrt{\frac{Q_0}{Q}}$$

However the length of flame may be written as follows:

$$\frac{x_f}{d_0} = k_4 \frac{C_0}{C_{st}} \sqrt{\frac{Q_0}{Q_f}} - k\theta$$

where

$k$  — constant established by experiments

$D$  or  $[D:d_0 = \theta]$  — rotation parameter.

#### **Experimental method**

The experimental apparatus is shown in Fig. 1.

According to experiences the burner block is made up with 3 kinds: Benson diffusive, preparative mixture rotative and injector burners. The orifice of the burners is variable to determine the size of flame at different flow conditions and dif-

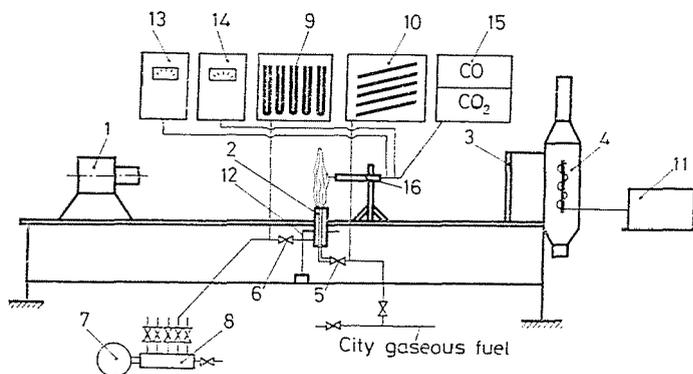


Fig. 1. The experimental apparatus

1. Schlieren's head; 2. Burner block; 3. Normal light source; 4. Impulse light source; 5. Gas-closing valve; 6. Closing valve; 7. Electric fan; 8. Distribution valve; 9. Manometer; 10. Manometer; 11. Unit of supplement; 12. The support of the burner; 13. Unit of temperature; measuring 14. Unit of measuring electric conduction; 15. Unit of measuring CO, CO<sub>2</sub>; 16. Probes (T, E, CO, CO<sub>2</sub>)

ferent geometrical parameters. In each experiment there are five burners in the block. They are aggregated that their axes are parallel together. The burner is shown in Fig. 2. We can see that the outlet orifice of the burner is varied by change the orifice diameter from 2 mm to 3,5 mm. The gas comes from the main system, flows into the distribution chamber and then flows through the closing valve and the mass measurement, and last flows into the burner. The velocity of the gas and air streams is oppositely varied by a change in the flow pressure of the gas or air stream after the closing valve. In our experiments the velocity of the gas stream is varied from 5 m/s to 50 m/s and for the air flow from 2 m/s to 30 m/s.

### *Schlieren's block*

The twin-lens Toeplitz-type Schlieren apparatus is shown in Fig. 3. The essential part of the apparatus is the collecting lens  $K$ , the so-called Schlieren head, which transilluminates the object  $S$  with a convergent beam of rays. Spark gap is used to study the light source  $L$  phenomenon, projected to knife-edge aperture  $B$  through the condenser. In respect of an uniform illumination of the field of vision it is essential that the light cone should illuminate completely the Schlieren head  $K$  which projects the aperture  $B$  directly in front of camera  $K_a$ . Here we find the knife-edge aperture "B". The suitable adjustment of the two knife-edge apertures enables, in case of a Schlieren-free object, the uniform illumination of the image plane  $S'$  with a corresponding slight aperture displacement. The Schlieren head consists of a Tessar—4,5/300 object and a knife-edge aperture, whose constant is  $e=2$  mm. The size of the first knife-edge aperture is  $30 \times 40$  cm<sup>2</sup> and its negative is  $6,5 \times 9$  cm<sup>2</sup>. The object is in the middle of the distance between the first- and the negative knife-



edge aperture. The size of visualization of the object is  $15 \times 20 \text{ cm}^2$ . So the photographic relation of the object is  $N=0.5$ , however the refractivity is

$$\varepsilon_{\min} = \frac{e}{40f} \cdot \frac{N}{N+1} \quad (\text{rad})$$

The light source consists of a normal and an impulse source.

The normal light source is made up by a matrix of 30 spherical lamps (with a power of 60 W).

The impulse light source is made up by 6 spherical lamps (their power is 60 W) and 3 electronic tubes filled with "argon" gas with a pressure of 400 torr. Of course, we have to have a supplement consisting of a transformer (max. pressure 15 kV) and 3 condensers in 250 mF.

#### *Ionization measurement*

It consists of an electric conductivity sensor and electric circuitry. The electric conductivity probe is made up by a cylindrical tube with a length of 3 mm and an internal diameter of 2 mm. One rod (external diameter of 1 mm) is placed in the centre of the cylindrical tube thus it is a condenser with a capacitance of 1—2 PF. Two electrodes are matched parallel to the impedometer. Of course, we have to have an amplifier for the use. The measurements are carried out spot wise in the axial cross section of the flame and the mean time values of the variables were determined from signals registered by an oscillograph.

The flame temperature is measured by Ni—CrNi thermocouples. They are used with a ceramic protective tube, which is made up by a 0.5 mm internal diameter double wall tube. The probe is set on the oscillator. The probes are shown in Fig. 4.

#### *Gas analyser*

Gas analysis was performed by "URAS" complex CO and CO<sub>2</sub> analyser. It works on the basis of the theory of infrared heat radiation displacement. The probe is a 1.0/0.2 mm diameter ceramic tube. The probe is shown in Fig. 4.

### **Results**

Diffusion flame is a flame where the fuel and the oxidant meet in a reaction zone by molecular and turbulent diffusion. The distinctive characteristics of a diffusion flame is that the burning (or consumption) rate is determined by the rate at which the fuel and oxidant are brought together in a proportion suitable for reaction.

Between the extremes in which the chemical reaction rate on the one hand, and the mixing on the other control the burning rate, there is the region in which chemistry and mixing have similar rates and must be considered together.

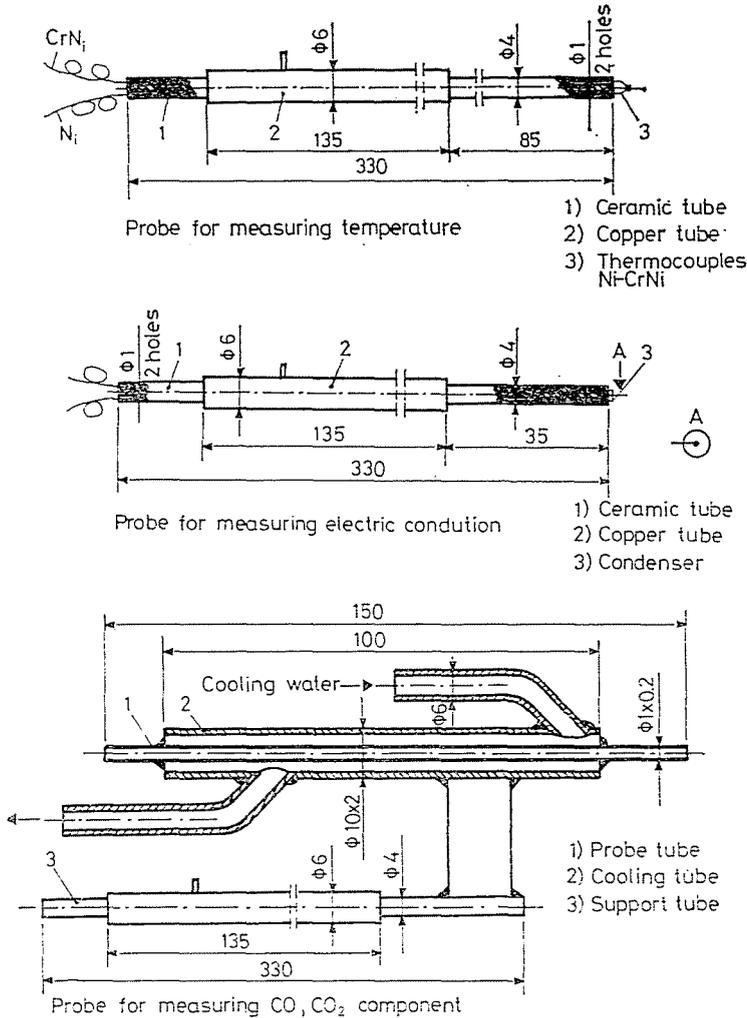


Fig. 4. Experimental probes

The diffusion flame has a wide region over which the composition of the gases changes. These changes are principally due to the interdiffusion of reactants and products since the actual reaction apparently takes place in a narrow zone.

The concentration of fuel and oxidizer is minimal at the flame front where the product concentration is maximal. These conditions arise, of course, due to diffusion.

Based on the previous theory we undertook a lot of experiments with our experimental apparatus.

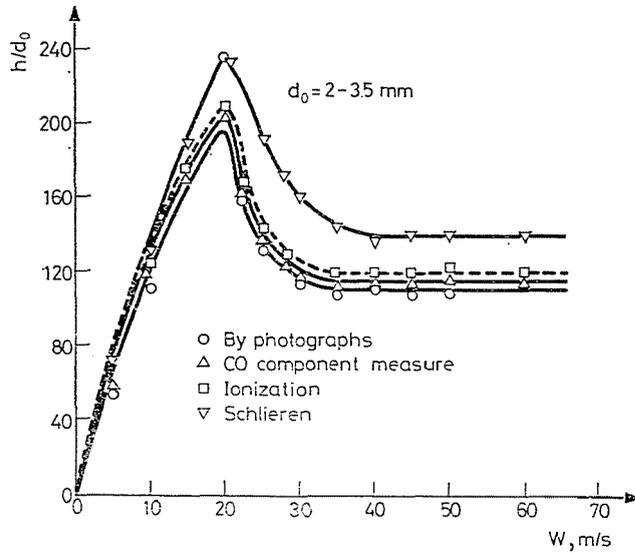


Fig. 5. The relationship between the length of flame and outward velocity flowing

Based on our experimental results, the relationships between the geometrical characteristics of flame and the size of burners and physical chemical characteristics of gas were introduced as follows:

#### Flame length

The length of flame is a function of the diameter of the burner orifice and the outward flow velocity, as shown in Fig. 5.

It is clear that there are differences in diffusion flames: such as laminar, transition and turbulent diffusion flames.

In case of the laminar region the length of flame is increased by increasing the jet velocity and the burner diameter, calculated by an experimental approximate equation:

$$h = k_1(1 + L_{\min})w^{n_1}d_0$$

where:

- $h$  — flame length  $m$
- $d_0$  — diameter of the burner orifice  $m$
- $L_{\min}$  — theoretically necessary amount of air  $m^3/m^3$
- $w$  — gas velocity flowing out from burner orifice  $m/s$  (outward flow velocity)
- $k_1$  — constants were established experimentally, as follows
  - $k_1=2,58$  by photographs
  - $k_1=2,81$  by CO component measurement
  - $k_1=2,98$  by ionization
  - $k_1=3,5$  by Schlieren.

$n_1$  — exponent was established experimentally, as follows:

- $n_1=0,94$  by photographs
- $n_1=0,923$  by CO component measurement
- $n_1=0,915$  by ionization
- $n_1=0,89$  by Schlieren.

It is remarkable that the length of flame obtained by photography is the shortest and is the longest by Schlieren's method, other methods resulting in between values.

*In case of a turbulent region* the length of flame is thus independent of the outward flow velocity and proportional to the diameter of the burner orifice only, as shown in Fig. 5. Based on our experimental data an equation may be obtained to calculate the length of turbulent flame, as follows:

$$h = k_2(1 + L_{\min})d_0$$

where:

$k_2$  — constant was established experimentally as follows

- $k_2=18$  by photographs
- $k_2=20$  by CO component measurement
- $k_2=21$  by ionization
- $k_2=24$  by Schlieren.

*In case of a transition region* the length of flame is thus inverse proportional to the outward flow velocity and may be written as follows:

$$h = k_3(1 + L_{\min})w^{n_3}d_0$$

where:

$k_3$  — constant was established experimentally as follows:

- $k_3=1895$  by photographs
- $k_3=1982$  by CO component measurement
- $k_3=1892$  by ionization
- $k_3=1864$  by Schlieren.

$n_3$  — exponent was established by experiments too,

- $n_3=-1,31$  by photographs
- $n_3=-1,29$  by CO component measurement
- $n_3=-1,26$  by ionization
- $n_3=-1,22$  by Schlieren.

It is important to note that the above equations and diagrams can be applied in case of diffusion flames at a free flow state.

### *Flame diameter*

Based on our experimental results it is known that the diameter of the diffusion flame is a function of the outward flow velocity and the burner orifice diameter. Figure 6 shows the relationship between the maximum flame diameter and outward flow velocity and orifice diameter.

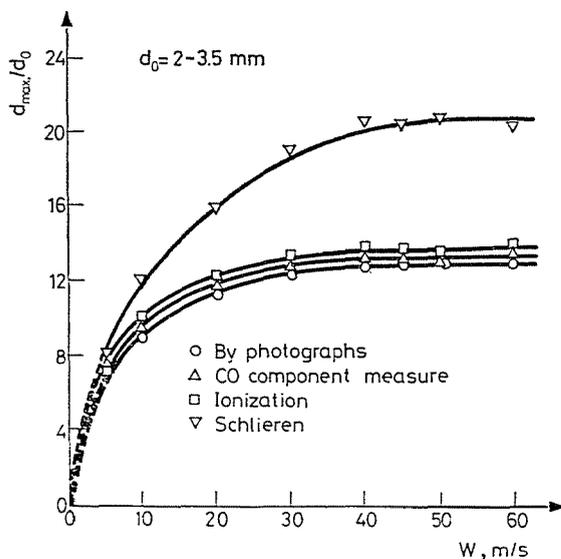


Fig. 6. The relationship between the max. diameter of flame and outward flowing velocity

As with the length of flame there are different formations and calculation equations concerning the flame diameter for different combustion states.

*In case of a laminar region*, the flame diameter is increased by the increase of the outward flow velocity and the diameter of the burner orifice. Thus *in case of a transition region*, the flame diameter is increased too, when the flame length is decreased through the velocity increase. Using an approximating method, the equation for calculation of the maximum diameter of flame may be established as follows:

$$d_{\max} = k_4(1 + L_{\min})w^{n_4}d_0$$

where:

$k_4$  — constant depended on experiments

$k_4=0.8$  by photographs

$k_4=0.86$  by CO component measurement

$k_4=0.94$  by ionization

$k_4=0.79$  by Schlieren.

$n_4$  — exponent also depended on experiments:

$n_4=0.328$  by photographs

$n_4=0.315$  by CO component measurement

$n_4=0.299$  by ionization

$n_4=0.447$  by Schlieren.

*In case of a turbulent region*, the flame diameter does not depend on the outward flow velocity, which is written as follows:

$$d_{\max} = k_5(1 + L_{\min})d_0$$

where:

$k_5$  — constant was obtained experimentally, as follows:

$k_5=2,25$  by photographs

$k_5=2,33$  by CO component measurement

$k_5=2,38$  by ionization

$k_5=3,97$  by Schlieren.

*Flame surface*

The surface of a flame can be obtained directly by experimental data. Figure 7 shows the variation of the dimensionless surface of flame at different gas-flow velocities and the diameter of the burner orifice. It is interesting to see that the surface of the flame depends only on its length of flame but also on its diameter. Owing to this the dimensionless surface of the flame increases in case of a laminar region, and does not change in case of a turbulent region with the increase of the outward flow velocity, but it is then intricate in case of a transition region.

Based on our experimental data, the equation for calculating the flame surface is as follows:

$$\frac{F}{F_0} = k_6(1 + L_{min}) w^{n_6}$$

where:

$F$  — the flame surface

$F_0$  — the surface of the burner orifice

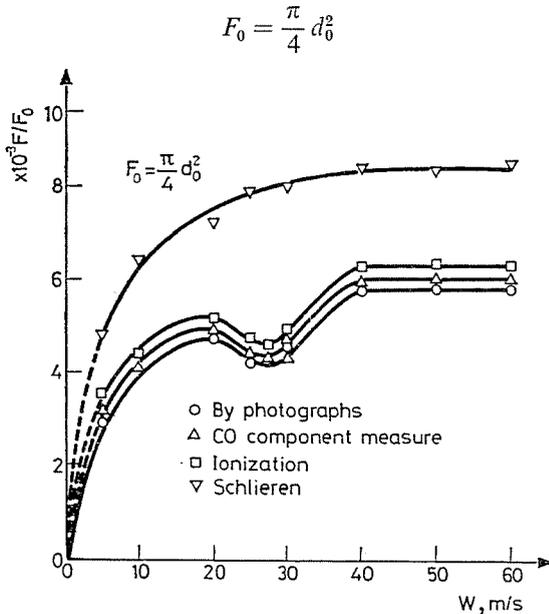


Fig. 7. The relationship between the surface of flame and outward flowing velocity

$k_6$  — constant depended on experiments  
 $k_6=297$  by photographs  
 $k_6=333$  by CO component measurement  
 $k_6=399$  by ionization  
 $k_6=501$  by Schlieren.

$n_6$  — exponent also depended on experiments:  
 $n_6=0.352$  by photographs  
 $n_6=0.326$  by CO component measurement  
 $n_6=0.278$  by ionization  
 $n_6=0.537$  by Schlieren.

*In case of a turbulent region*, the flame surface can be calculated as follows:

$$\frac{F}{F_0} = k_7(1 + L_{\min})$$

where:

$k_7$  — constant was established by experiments:  
 $k_7=1000$  by photographs  
 $k_7=1040$  by CO component measurement  
 $k_7=1090$  by ionization  
 $k_7=1450$  by Schlieren.

#### *Flame volume*

Knowing the length and the diameter of the flame we can calculate the flame volume, but on the other hand the flame volume may be established directly by experimental data. Based on our experimental results, Fig. 8 demonstrates the variation of dimensionless volume of the flame with the outward flow velocity and the diameter of the burner orifice. From the diagrams it can be seen as follows:

*In case of a laminar region*, the flame volume increases with the velocity increase and orifice diameter. With the approximation method an equation may be established to calculate the flame volume as follows:

$$v = k_8(1 + L_{\min})w^{n_8}d_0^3$$

where:

$k_8$  — constant was established by experiments  
 $k_8=332$  by photographs  
 $k_8=406$  by CO component measurement  
 $k_8=478$  by ionization  
 $k_8=555$  by Schlieren.

$n_8$  — exponent also was established by experiments  
 $n_8=0.486$  by photographs  
 $n_8=0.425$  by CO component measurement  
 $n_8=0.384$  by ionization  
 $n_8=0.416$  by Schlieren.

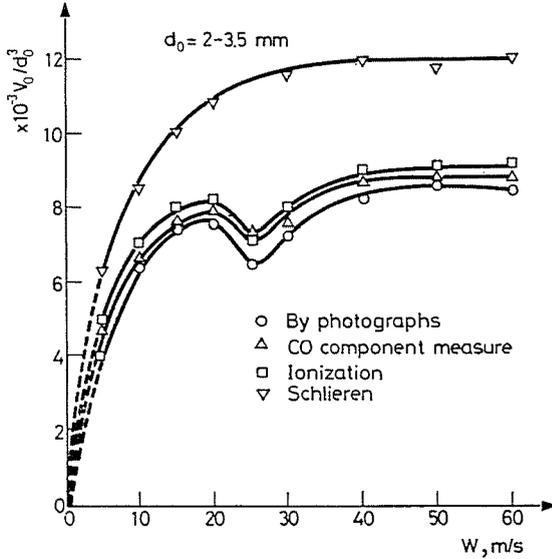


Fig. 8. The relationship between the volume of flame and outward flowing velocity

In case of a turbulent region, flame volume is likely that the same value, with a variation of the outward flow velocity, may be written as follows:

$$v = k_9(1 + L_{\min})d_0^3$$

where:

- $k_9$  — constant was established by experiments
- $k_9 = 1468$  by photographs
- $k_9 = 1520$  by CO component measurement
- $k_9 = 1563$  by ionization
- $k_9 = 2073$  by Schlieren.

### Conclusion and discussion

In combustion and heat transfer calculation, it is very important to reliably define the flame and establish its physical and geometrical characteristics more exactly.

From previous of view usually the flame is a space, in which the fuel and oxidant come together in a reaction zone. In the flame chemical and physical processes take place with heat transfer and photoradian phenomena. Of course, the flame structure (length, diameter, surface and volume) is established easily on basis of the photographic method, from our experimental data, it may be seen that the flame size is

smallest by photographs and largest by Schlieren's method. From a firing technical point of view we think it is more suitable to use the CO component measurement to calculate the combustion and heat transfer of the flame structure. Of course also Schlieren's flame structure may be used for the investigation of the intereffects of flame, specifically at a temperature distribution in intereffective zones. This will be discussed later on.

It is remarkable that previous diagrams and equations may be applied in case of a free-jet diffusion flame with city gaseous fuel. Owing to this reason, we have to apply corrections in these equations when calculating the flame size forming in the combustion chamber, as follows:

$$h_{c.f} = (1,1 - 1,3) h_{f.f}$$

$$F_{c.f} = (1,25 - 1,5) F_{f.f}$$

$$v_{c.f} = (1,3 - 1,6) v_{f.f}$$

where:

index  $c.f$  — flame forming in the combustion chamber  
 $f.f$  — free-jet diffusion flame.

*In case of a parallel stream burners*, owing to the mixing brought about by an impulse of the air stream, the flame will be shorter. By approximation the ratio of the flames is as follows

$$h_p = \frac{I_0}{I_0 + 0.5 I_1} h_d$$

where:

$h_p$  — the length of flame in case of a parallel stream

$h_d$  — the length of flame in case of a diffusion flame

$I_0, I_1$  — intensity of the gas flow in jet and impulse of the air stream surrounding the gas stream.

Of course, the flame surface and volume are changed, too.

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