

## Laminar flame speed (burning velocity)

### Introduction

One of the most important parameters, influencing both, the combustion system design and combustion process control, is the flame speed. The flame speed is strictly connected to the rate at which the oxidizer and the fuel are consumed and converted into products. The consumption rate is seen as the propagation of flame through combustible mixture. In Fig. 1 a tube filled with stationary combustible mixture is presented.

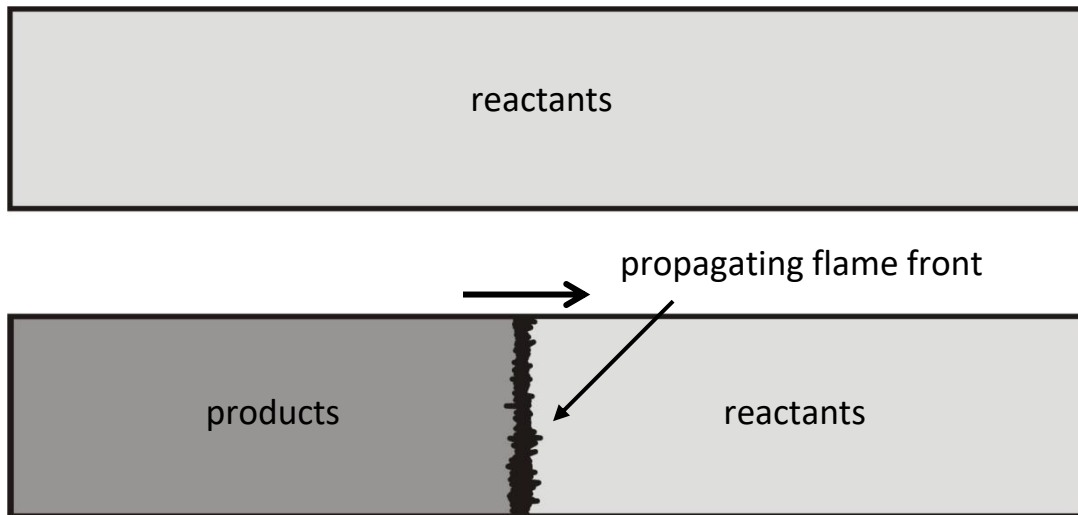


Fig. 1. Propagating flame front in a tube of stationary combustible mixture

The speed at which the flame propagates through the tube while ignited at one end is the laminar flame speed. For complex flows, the direction of flame propagation depends on local flow parameters and, as in the simple flow, the vector of the flame velocity is normal to the local flame front. Therefore the flame speed is often called the normal flame speed. Since the flame speed is strictly connected to the consumption of fuel and oxidizer, it affects the stabilization of flames [1]. In Fig. 2 a flame front propagating in a combustible mixture flowing in a duct with an average velocity  $w$ . In his case the flame front is not moving relative to the duct and is moving with the local effective velocity  $w_e$  relative to the mixture. The local effective velocity is equal to the local flow velocity of the mixture but with an opposite direction. Because the normal flame speed  $w_n$  is the component of the effective velocity, perpendicular to the flame front, its relationship to the effective velocity  $w_e$  can be written as:

$$w_n = w_e \cos \varphi \quad (1)$$

At various positions on the flame front, both the effective velocity  $w_e$  and the angle  $\varphi$  are changing due to the velocity distribution in the tube, however the product of  $w_e$  and  $\cos \varphi$ , equal to the normal flame speed, remains constant [2].

Theoretical considerations on laminar flames lead to conclusions that the laminar flame speed depends on initial temperature of reactants, system pressure, and mixture composition ( $\Phi$  or  $\lambda$ ). The flame speed

depends also on the final temperature of products, however this influence can be understood as the dependence of this temperature on the mixture composition. Maximum values of  $w_n$  are obtained for slightly rich flames as are the highest adiabatic flame temperatures of the products. This is the result of maximum reaction rates occurring at this compositions. Minimum values are obtained at the lower and upper flammability limits. The flame speed does not depend on the burner design and power. For most combustible mixtures the flame speeds range from 5 to 300 cm/s, usually being of the order of tens cm/s [3].

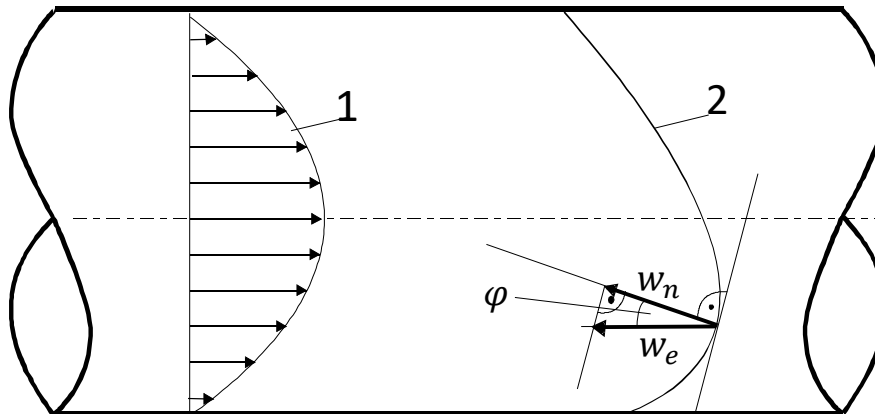


Fig. 2. Normal flame speed as the component of the local effective velocity;  
1, radial velocity distribution; 2, flame front

The flame speeds can be calculated, however they are usually obtained experimentally based on measurements of shape of the flame front or velocity of its propagation. Therefore the experimental methods can be divided into stationary and non-stationary methods:

- In the stationary methods the flame front is not moving relative to the burner and the burning mixture is flowing. The Bunsen burner method or the flat flame method belong to this group.
- In the non-stationary methods the combustible mixture is not moving and the flame is propagating in the volume of reactants. A constant pressure or constant volume combustion bomb method belong to this group of methods. Another way to measure the speed is to photograph the flame propagating in a tube filled with combustible mixture [4].

Within this exercise the Bunsen burner method will be used to measure the normal flame speed. In the Bunsen burner the luminous flowing mixture is burned forming a stable light blue inner cone and an outer diffusive front. The method is based on the following simplifying assumptions:

- It is assumed that the thickness of the flame is infinitely small, thus it is treated as a thin sheet dividing the reactants and products.

- The inner cone of the flame is geometrically an ideal solid of revolution.
- The effective velocity of the flame is constant along the flame sheet.
- The mixture is not warming up prior to burning.

In Fig. 3 a schematic of the cross-section of the real (left) and the idealized (right) inner cone is presented.

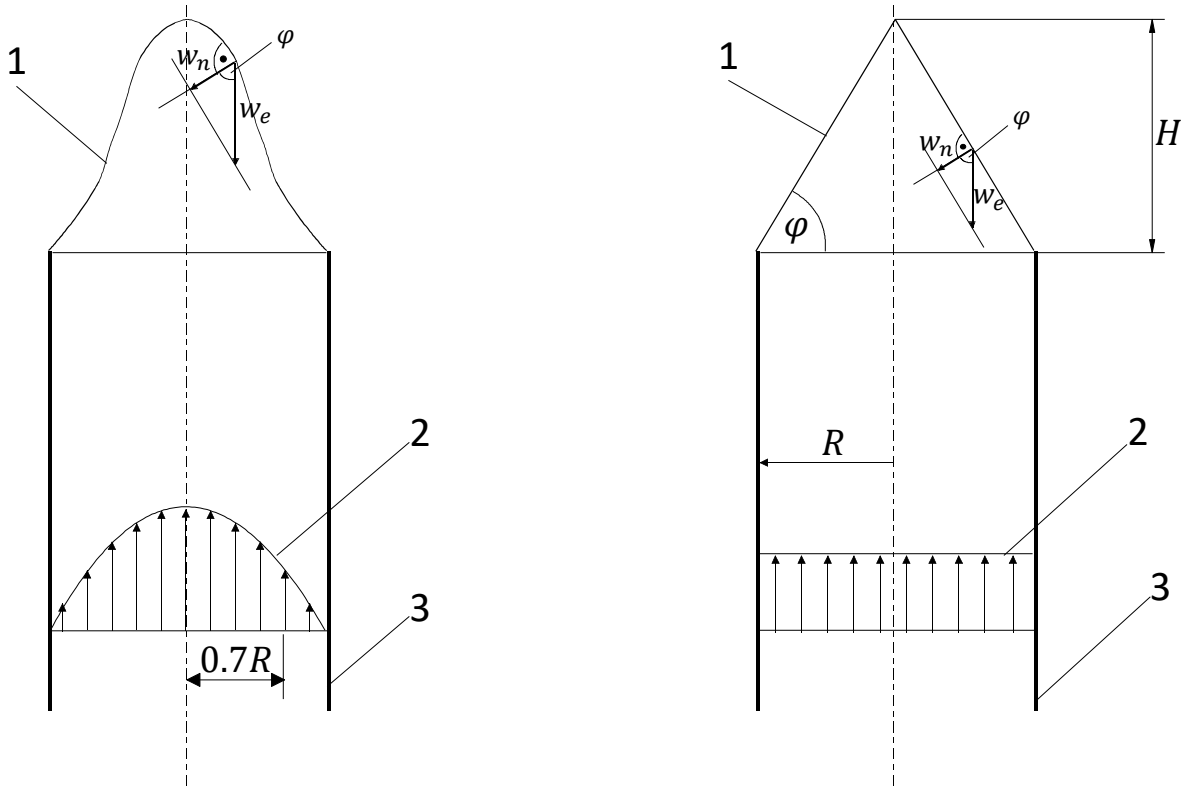


Fig. 3. The inner cone of the flame front of the real (left) and idealized (right) Bunsen burner; 1, flame front; 2, mixture velocity distribution; 3, burner

It can be seen from Fig. 3 that the angle  $\varphi$  between  $w_n$  and  $w_e$  is the same as the angle between the burner radius  $R$  and the cone slant  $l$  (from similarity of the triangles). Using this fact, the normal flame speed can be calculated as:

$$w_n = w_e \cos \varphi = \frac{\dot{V}_g + \dot{V}_p}{\pi R^2} \cos \varphi \tag{2}$$

where the angle  $\varphi$  can be determined from:

$$\varphi = \text{arctg} \frac{H}{R} \tag{3}$$

Thus, in order to determine the normal flame speed, one needs to measure the volumetric flow rates of the oxidizer and the fuel, the burner diameter (radius) and the inner cone height. A method based on photographing the flame front and determining the angle from the image can also be applied. The angle is measured at  $0.7R$  because at his radial distance the local effective velocity  $w_e$  is equal to the average velocity  $w$  (this is the result of the parabolic velocity profile of the laminar flow).

## The aim of the exercise

The aim of the exercise is to acquaint the students with the structure of the Bunsen burner flames and the method of determining normal (laminar) flame speed as a function the excess air coefficients  $\lambda$  (or equivalence ratio  $\Phi = 1/\lambda$ ) for different gases.

## Experimental setup

Scheme of the test rig used to measure the normal laminar flame speed using the Bunsen burner method is shown in Fig. 4.

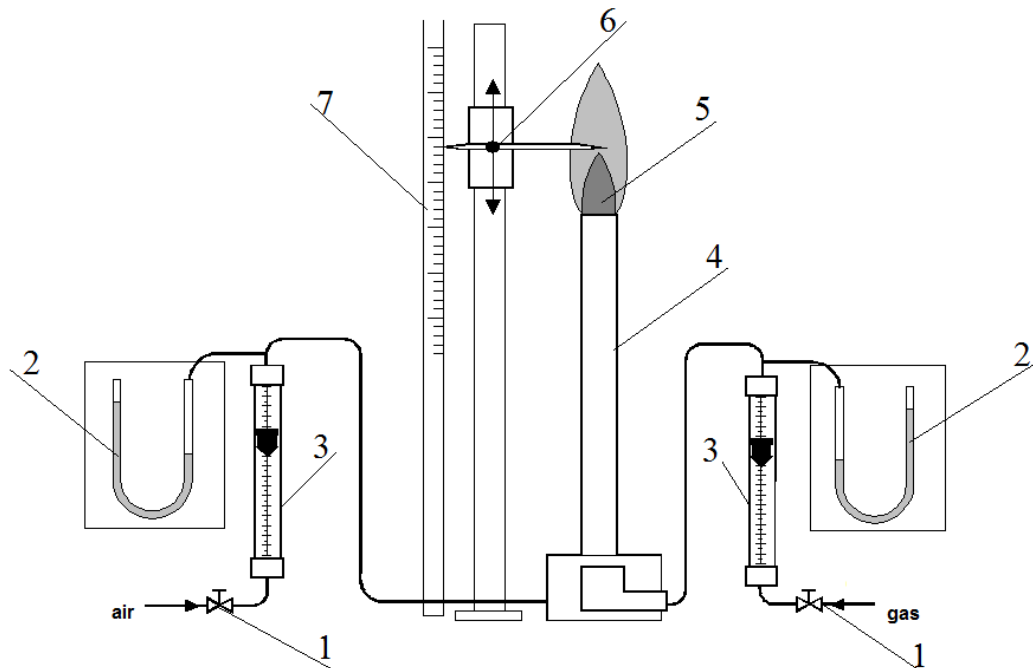


Fig. 4. Scheme the test rig to measure the normal burning velocity using the Bunsen burner method; 1, control valve; 2, manometer, 3, flow meter (rotameter); 4, removable burner; 5, inner combustion cone; 6, movable indicator with stand; 7, ruler

A fundamental element of the test rig is the burner whose mixing chambers can be replaced. This allows using mixing chambers of various diameters and changing composition of the air/fuel mixture. In order to generate a premixed flame the gas and the air are introduced by two separate tubes to the base of the mixing chamber. The burner tube is relatively long, so that the out flowing mixture is homogenously mixed. The flow rates of the gases are measured using the flow meters. In order to determine a correction factor, taking into account the thermal parameters of the gases, the gauge pressure of the gas and air are also measured. The height of the inner combustion cone is measured with the ruler, and the inner diameter of the burner with caliper.

## The experimental procedure

After revising the measurement system and checking its condition, follow the steps below:

- 1) Put on the mixing chamber and measure its inner diameter  $D$ . Because the length of the mixing chambers differ remember to reset the system of flame height measurement
- 2) Set the combustible gas flow rate given by the instructor. This flow rate should be constant for a single test series. Ignite the gas. The resulting flame is a diffusion flame.
- 3) Start increasing the air flow rate and keep observing the flame. The flame should become shorter, and at some point you will observe two fronts of the flame - premixed (inner cone) and diffusion (outer cone)
- 4) Start the measurement when the inner cone becomes visible. Note down the volumetric flow rates of the substrates ( $\dot{V}_g, \dot{V}_p$ ) and height of the inner cone  $H$ . Write down the gauge pressures of the flowing gases ( $p_g, p_p$ ). Write down the results in the measurement table.
- 5) Repeat the measurements for increased air flow rates so that each next reading of flame height will differ by about 1 cm. Note down the sets of parameters ( $H, \dot{V}_g, \dot{V}_p, p_g, p_p$ ) in the table for each air flow rate. Continue measurements until the flame is blown off. Remember to close the gas valve after this occurs.
- 6) Repeat steps 2 to 5 for other values of the combustible gas flow rate as given by the instructor.
- 7) Change the mixing chamber and repeat steps 1 to 6.
- 8) Note down the ambient air temperature and pressure.

### Analysis of the results

Note down in the Table 1 the measured quantities where:  $D$  – inner diameter of the burner,  $\dot{V}_g, \dot{V}_p$  - gas and air volumetric flow rates,  $H$  – height of the inner combustion cone,  $p_g, p_p$  – gauge pressure of the gas and air,  $\dot{V}_{g,r}, \dot{V}_{p,r}$  - corrected volumetric flow rate of the gas and air,  $\lambda$  – excess air coefficient,  $w_n$  – laminar (normal) flame speed. In order to calculate the corrected volumetric flow rates, the following formulae should be used

$$\dot{V}_c = \dot{V} \sqrt{\frac{\rho}{\rho_c}} \quad (4)$$

where:

$\dot{V}_c$  - corrected volumetric flow rate of the current fluid

$\rho_c$  - density of the current fluid

$\dot{V}$  - volumetric flow rate shown by the rotameter

$\rho$  - density of the fluid used to calibrate the rotameter

Table 1. Results of the measurements using Bunsen burner method

Gas:										
Minimum air requirement		$n_{a,min} =$								
Ambient air temperature		$t_{ot} =$								
Barometric pressure		$p_{ot} =$								
No.	$D$ mm	$\dot{V}_g$ $\text{m}_n^3/\text{h}$	$\dot{V}_p$ $\text{m}_n^3/\text{h}$	$H$ mm	$p_g$ mmH <sub>2</sub> O	$p_p$ mmH <sub>2</sub> O	$\dot{V}_{g,r}$ $\text{m}_n^3/\text{h}$	$\dot{V}_{p,r}$ $\text{m}_n^3/\text{h}$	$\lambda$	$w_n$ m/s
1										
2										

Calculate the effective velocity using equation the following relationship:

$$w_e = \frac{\dot{V}_{g,r} + \dot{V}_{p,r}}{\frac{\pi D^2}{4}} \quad (5)$$

Calculate the angle  $\Phi$  from Eq. (3), and then calculate the normal combustion velocity using Eq. (1).

Calculate the excess air ratio  $\lambda$  knowing the minimum air requirement  $n_{a,min}$  using the following equation:

$$\lambda = \frac{\dot{V}_{p,r}}{n_{a,min} \dot{V}_{g,r}} \quad (6)$$

Based on the obtained measurement results and calculated values of  $w_n$  and  $\lambda$  plot the relationship between the normal laminar flame speed as a function the excess air coefficient for the tested gasses. Approximate this relation using a quadratic polynomial. Determine the coefficients of this function, and check the correctness of the approximation calculating the correlation coefficient. Analyze the graph and try to characterize the changes of  $w_n$  as a function of  $\lambda$ . Describe the sources of possible measurement errors. Using the law of uncertainty (error) propagation calculate the uncertainty related to determining the excess air coefficient and the normal laminar flame speed. Assume that the class of the rotameters is 2.5 (maximum relative error) and the uncertainty in height measurement is 0.1 mm.

## Literature

- [1] Paliwa i ich spalanie. Część V Laboratorium (Petela R. - red.), Skrypt Politechniki Śląskiej Nr 1191, Gliwice, 1984
- [2] Lewis B., von Elbe G.: Combustion, Flames and Explosion of Gases, 3<sup>rd</sup> edition, Academic Press, New York, 1987
- [3] Chomiak J.: Combustion: A Study in Theory, Fact and Application, Abacus Press/Gordon&Breach Science Publishers, New York, 1990
- [4] Spalanie i paliwa (Kordylewski W. - red.), Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, 1993