

## Ignition temperature of solid fuels

### Introduction

Combustion of solid fuels is a complex phenomenon where various stages of the process can be distinguished. A solid fuel when heated up is drying out first and then releases volatiles that are burned. Thus, combustion occurs mainly in the gaseous phase at the early stages of the process where homogeneous reactions occur. At the last stages of the process combustion occurs at the solid/fluid interface where heterogeneous reactions occur. Since the ignition occurs at the beginning of the combustion we will limit our considerations to the analysis of gaseous phase combustion.

Every flammable substance while in contact with an oxidizer undergoes oxidation. According to the Arrhenius equation, the heat transfer rate generated by reaction is related to the temperature of the reacting substance [1] in the following way:

$$\dot{Q}_r \sim \exp\left(-\frac{E}{(MR)T}\right) \quad (1)$$

where:

$T$  - fuel (volatiles) temperature, K

$E$  - activation energy of the combustion global reaction, kJ/(kmolK)

$(MR)$  – is the universal gas constant,  $(MR) = 8.314$  kJ/(kmolK)

Consider a dish containing solid fuel at temperature  $T$  realising combustible volatiles also at  $T$ . It is assumed that at the beginning the walls of the dish and the volatiles are at thermal equilibrium thus they are at the same temperature  $T = T_w$ . If heat is supplied to the fuel, warming it up, the temperature of the fuel and the volatiles will rise and heat transfer to the dish walls will occur. The heat transfer rate according to the Newton's law of cooling is proportional to the temperature difference  $(T - T_w)$  and can be written as:

$$\dot{Q}_\alpha \sim \alpha(T - T_w) \quad (2)$$

Where  $T$  is the current temperature of the volatiles,  $T_w$  is the temperature of the dish walls, and  $\alpha$ , W/(m<sup>2</sup>K) is the convective heat transfer coefficient. Both, heat released due to reaction and heat lost to the surroundings can be shown on a graph as presented in Fig. 1. The straight lines are the heat lost to the dish walls corresponding to various dish wall temperatures ( $T_{w1}, T_{w2}, T_{w3}$ ). These are straight lines since for constant  $\alpha$  the heat transfer rate is linear with respect to the wall's temperature (cf. Eq. (2)). The curved line is the heat released due to reaction (nonlinear with respect to volatiles temperature, cf. Eq. (1)).

Point 1 represents an equilibrium state where a little increase or decrease of temperature moves the system automatically back to point 1. This is due to the fact that an increase in temperature causes

higher heat loss than heat generation which in turn decreases the temperature and moves the system to point 1 (cf. Fig. 1). A decrease of fuel temperature is the reason of higher heat generation than heat losses, which in turn increases the temperature of the system until heat losses prevail, namely to point 1. Thus point 1 is a stable equilibrium state of the system.

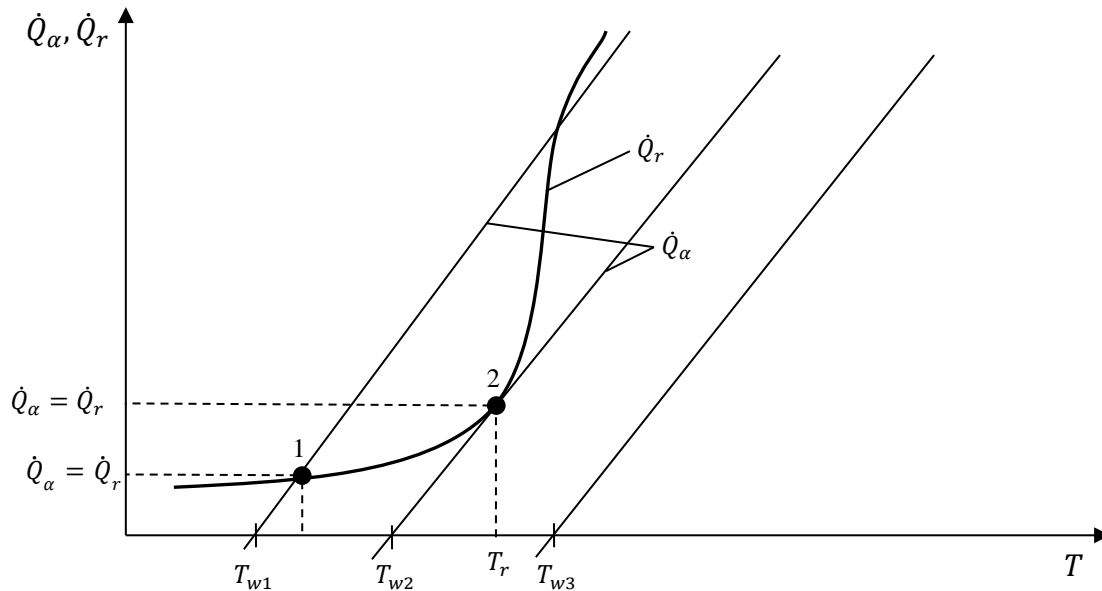


Fig. 1. Heat transfer rates generated by reaction and lost to the dish walls versus fuel (volatiles) temperature

At point 2 a similar balance is established when moving from the left (lower wall temperatures) to the temperature at point 2. However, this state is unstable, since even a slight increase of temperature causes the reaction heat release to be greater than the heat losses. This slight imbalance is then the reason of a violent temperature increase and propagation of the reaction. The critical temperature  $T_r$  can be recognized as the temperature of the autoignition.

The slope of the curve of heat generation due to reaction (Eq. (1)) depends on the way the fuel sample is prepared, the intensity the fuel is mixed with the oxidizer and other similar conditions related to the experiment. The slope of the straight lines representing the heat losses (Eq. (2)) depend on the heat transfer coefficient  $\alpha$  which in turn depends on the experimental setup. During the experiment the fuel is placed in a dish. The temperature of the walls of the dish  $T_w = T_{w2}$  in which the autoignition occurs is called the ignition temperature. Both, the temperature of the dish walls  $T_{w2}$  and the critical temperature  $T_r$  are not characteristics of a given fuel, but depend on the test rig used and measurement procedure.

## The measurement method

Autoignition temperature is a quantity important for stability of combustion and safety considerations regarding proper use and storage of fuels. Therefore, the comparison of ignition temperatures of different fuels are tested in technical laboratories, where standardized conditions and equipment are used to determine it. One of the most commonly used methods is the Kreulen method [2]. In this procedure, a properly prepared sample of fuel is placed in a metal container heated by an external source of heat. Oxygen of constant flow rate is passed through the sample. In the course of the measurement the sample temperature  $T_1$  and container walls  $T_2$  are controlled. In the initial period of heating the temperature of the container walls is higher than that of the sample, which is the result of the direction of heat flow. As the heat flow increases the rate of the reaction, the sample temperature gets closer to the temperature of the container and finally exceeds it. The solid fuel ignition temperature is determined graphically by finding a point where the sample temperature is 6 K higher than the wall's temperature as shown in Fig. 2.

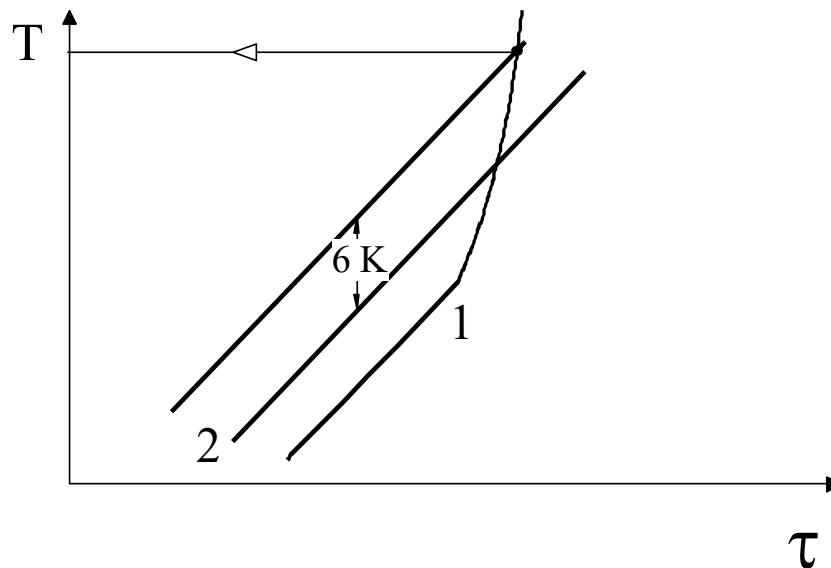


Fig. 2. Temperature changes observed during the measurements using Kreulen device; 1. temperature of reacting fuel, 2. temperature of container walls

## Aim of the exercise

The aim of this exercise is to familiarize with the Kreulen method. This method is used to determine ignition temperature of the solid fuel and the effect of fuel type including volatile content.

### Description of the laboratory experimental setup

The test rig used to determine the ignition temperature using the Kreulen method is shown in Fig. 3. Oxygen is used as the oxidizer which is supplied from the gas cylinder. The oxygen flows through a flow meter to the inlet nozzle of the Kreulen device. The whole device is heated from the bottom using an electric heater. The wall and sample temperatures are measured using two thermocouples (NiCr-Ni). The chamber is built out of aluminum and its interior has drilled labyrinth like holes, which allow bringing the stream of oxygen to the bed of solid fuel. The inflowing gas temperature is close to the temperature of the cylinder.

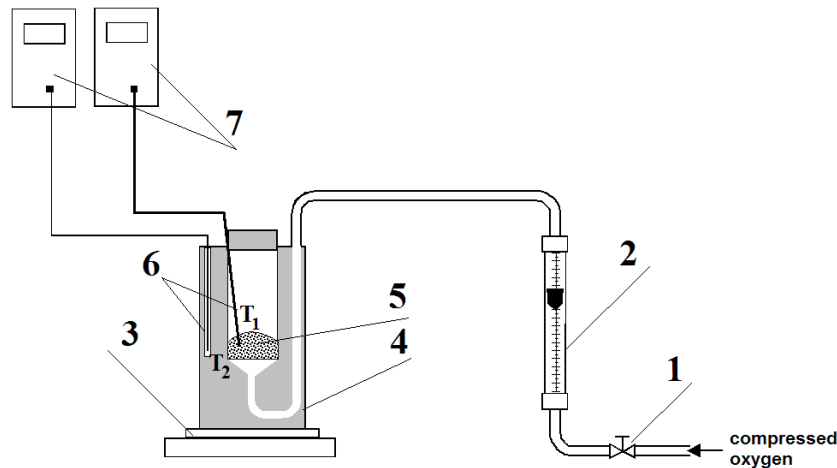


Fig. 3. Schematic of the ignition temperature experimental rig; 1. control valve, 2. flow meter, 3. electric heater, 4. steel cylinder, 5. sample of fuel, 6. thermocouples, 7. displays

### The measurement procedure

After inspection of the wiring connections and measuring devices, follow the steps below:

- 1) open the valve of oxygen on the gas cylinder in counter-clockwise direction
- 2) open the main valve cylinder and check the pressure
- 3) put the fuel sample inside the chamber, the sample must fill up half of the chamber
- 4) place the first thermocouple in the chamber and the second inside the sample, carefully open the flow meter valve to adjust the oxygen flow values to  $10 \text{ dm}^3/\text{h}$
- 5) turn on the electric heater and a stopwatch
- 6) note down sample and the chamber temperatures every two minutes
- 7) when the temperature will get greater than  $150 \text{ }^\circ\text{C}$  register the temperature every minute, but when any of the temperatures exceeds  $180 \text{ }^\circ\text{C}$  register them every half minute
- 8) stop recording the results when the sample temperature becomes  $20 \text{ }^\circ\text{C}$  larger than chamber temperature
- 9) close the valve of the reducer in clockwise direction, close the valve of the cylinder and turn off the electric heater

**Attention: during the measurement the whole device is hot, therefore you should not touch the elements of the test rig.**

Note the results of the measurements in the following table

	Time, min	Chamber temperature, K	Sample temperature, K
1			
2			

### Results and analysis

Students should make a plot of chamber and sample temperatures as a function of time starting from the point in which the temperature exceeded 150°C. After drawing the two curves, move the cylinder temperature curve at 6 °C vertically upwards. A point of intersection of the sample temperature curve and transferred chamber temperature is the ignition temperature of the sample.

The report should contain a short theoretical introduction with test rig description, the table of measurements, the plot and conclusions.

### Literature

- [1] Jarosiński J.: Techniki czystego spalania, WNT, Warszawa, 1996
- [2] Kreulen D.W., Schuyer J.: Węgiel, PWN, 1959