MEASUREMENT 3

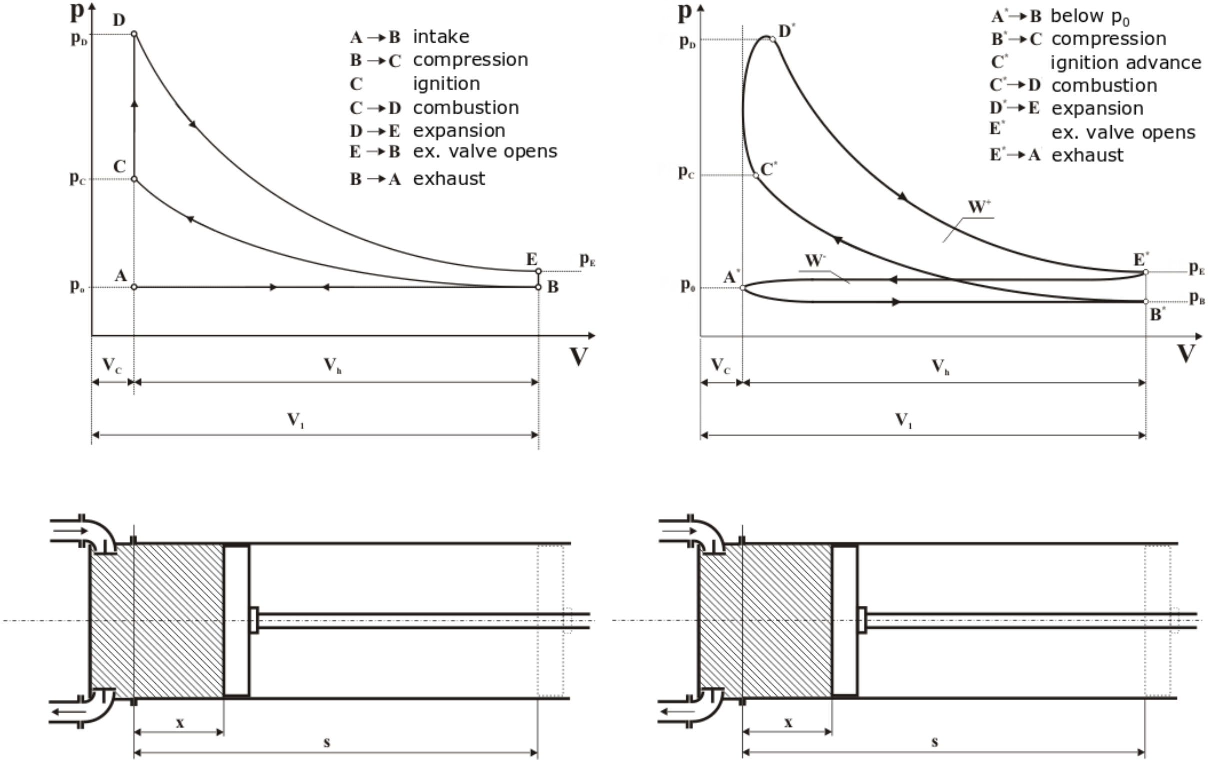
MEASUREMENT OF A MOBILE GENERATOR

Aim of the measurement:

A mobile generator consists of an internal combustion engine (in this case, a single-cylinder four-stroke engine) and a generator. The aim of this measurement is to determine the characteristic curve(s) of the unit; the specific fuel consumption and the efficiency are determined while varying the load factor. Furthermore, the average load and efficiency are calculated for a specific time interval.

Operation of a four-stroke Otto-cycle internal combustion engine (ICE):

In internal combustion engines, the fuel enters the cylinder together with the air. In the case of gaseous fuels (e.g., natural gas), the air and the fuel can be simply mixed, while in the case of liquid fuels (e.g., petrol) the liquid must be mixed properly first via the carburettor. Then, the mixture is compressed in the cylinder such that the temperature at the end of the process is lower than the ignition temperature. The mixture is then ignited by an electric spark at the last phase of the compression. (In the case of diesel engines, no spark is needed as the compression ratio is so high that the fuel auto-ignites.) The next step is the expansion, where useful work is done, and finally, the exhaust gases leave the cylinder via the exhaust port.



(a) (b)

Figure 1.
Ideal (a) and real (b) indicator diagram of a four-stroke Otto-engine

The workflow of an Otto-engine is best illustrated with its indicator diagram. The indicator diagram displays the pressure in the cylinder as the function of its volume. In theory, the piston compresses a combustible mixture which is ignited instantaneously everywhere in the cylinder volume, when the piston reaches its highest point in the cylinder volume (maximum compression). Based on this, in **Figure 1.**, the left-hand side shows the **ideal indicator diagram**. However, in reality, the flame front needs time to spread all over the cylinder volume, therefore the process is not instantaneous, so the sharp edges of the diagram become rounded, see the right-hand side of **Figure 1.,** depicting the **real indicator diagram**.

During the **Intake** (I. step; A^* – B^* line) the combustible mixture is sucked in the cylinder by the piston through the intake valve. The carburettor is responsible for producing the mixture, in which the liquid fuel and air are mixed in an accelerated airstream. (In newer engines the fuel is directly injected in the cylinder during the compression.)
The p_B pressure of the mixture in the cylinder is lower than the p_o ambient pressure due to the losses (vacuum). Because of this, in the indicator diagram the A^* - B^* intake line in case of a fully opened butterfly valve is lower by 0.1 bar compared to the p_o pressure line. In case of a throttled flow the vaccuum may be tripled.

In **Figure 2.** the sktech of the **carburator** is shown. The air is sucked in by the piston through the confusor-diffusor pipe. A nozzle is placed in the Venturi-tube. The level of the liquid fuel is controlled by a float directed valve. The small droplets are taken in the cylinder by the airflow in the form of partly fog partly evaporated liquid. The aforementioned principle of operation of the carburetor, which is still used in smaller engines, was worked out in 1893 by Donát Bánki, who was a professor in BME. (*His portrait can be seen on the Dean's necklace, he was the founder of the Department of Hydromachines which is the predecessor of our Department, and his bust is placed in the main hall.*) The carburetor demonstrated by this simple sketch cannot maintain a constant composition, because in case of increasing air velocity the amount of evaporated fuel also increases (the mixture enriches).

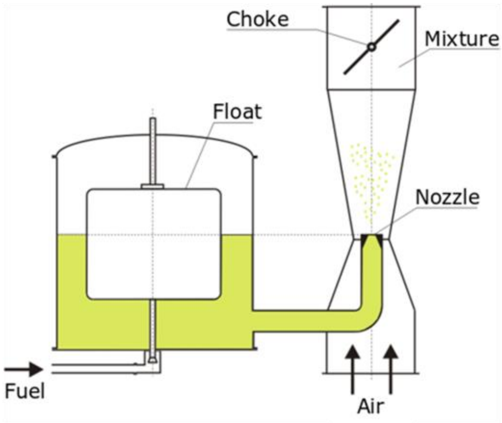


Figure 2.
The sketch of the carburetor

During the **Compression** (II. step; B* – C* line) the mixture is compressed from p_B to p_C pressure, while its volume is decreased from V_1 to V_C. The V_1/V_C ratio is called compression ratio (ε), the efficiency of the engine is greatly affected by this ratio.

The next phase is the **Ignition**. The compressed mixture is ignited by an electric spark near the end of the stroke. The spark is generated by the electrode of the spark plug built into the cylinder as a result of the high voltage coming from a transformer. In the ideal case, the combustion is considered infinitely fast, so the volume of the mixture is constant and only the pressure increases from p_C to p_D (C – D line in the diagram). The final temperature and pressure of the process can be calculated from the composition of the mixture and the heating value.

If the compression is considered as an adiabatic process (without heat transfer), and without losses, the end pressure and temperature of the compression can be calculated as

$$p_c = p_S\left(\frac{V_1}{V_C}\right)^{\kappa} \text{ and } T_c = T_S\left(\frac{V_1}{V_C}\right)^{\kappa-1}$$

In the formulae above: V_C is the compression volume; $V_1 = V_C + V_S$ is the sum of the compression and the stroke volume. The V_S stroke volume is the multiplication of the s stroke and the $A = D_2\pi/4$ cylinder area; κ exponent is specific for the compressed gas, in case of air, it is 1.4.
The maximum value for $p_c$end pressure is specified by the auto ignition point of the mixture, so it is regulated by the temperature at which the mixture ignites by itself.
The V_1/V_C is called the compression ratio (ε).

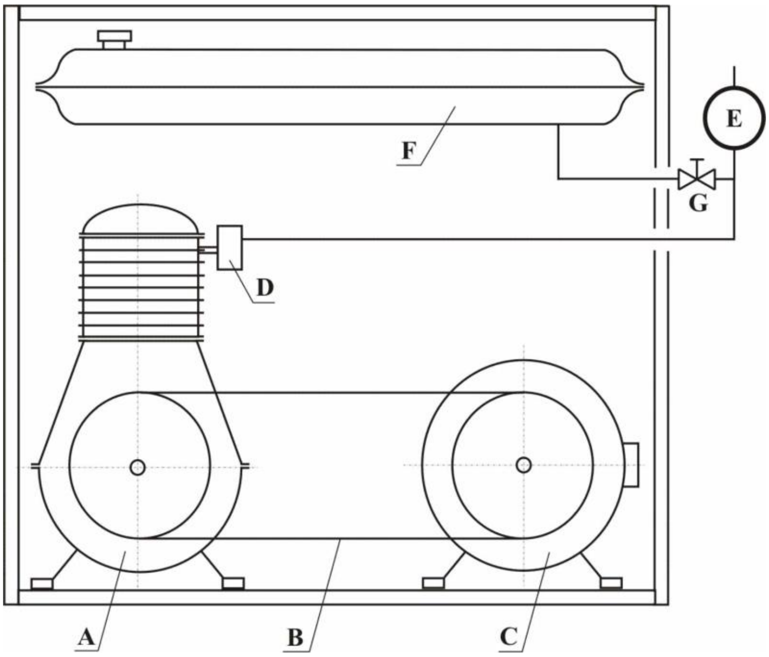
In reality the combustion is called favourable when the flame spreads from the spark plug fast but gradually. In unfavourable conditions the mixture in some places ignites by itself, this is called auto ignition. This phenomenon limits p_C end pressure of the process.
Since the speed of the ignition is finite, the ignition spark should take place before the piston reaches the end of the stroke (Figure 1. C*). The favourable ignition advance – which is expressed by the angle of the crank at the ignition – depends on the construction of the engine, RPM, load, and the type and quality of the fuel.

During the **Combustion** (III. step; D* – E* line in the diagram) the flue (waste) gas expands. In this step the pressure decreases from p_D to p_E, and after opening the Exhaust Valve it decreases a bit further.

During the **Exhaust** (IV. step; E* – A* line) the piston pushes out the flue gas through the Exhaust Valve. The exhaust pressure is higher by 10-100 kPa than the p_o ambient pressure because of the losses. At the end of the Exhaust step the Exhaust Valve closes and the cycle repeats itself.

The measurement rig:

In the measurement rig, a four-stroke Otto-engine drives a generator. The sketch of the rig can be seen in **Figure 3.**, while photos can be seen in the **Appendix**.



A – Otto-engine
B – drive
C – generator
D – carburettor
E – metering bowl
F – fuel tank
G – ball-valve

Figure 3.
The sketch of the measurement rig

Measurement rig specification:

Engine type: Einhell TC-PG 25/1/E5; four-stroke, air-cooled, single cylinder Otto-engine
Fuel: unleaded, 100 octane petrol
Output of the aggregator: U = 220 V; f = 50 Hz; P_N=2.1 kW

Measurement of the fuel consumption:

The fuel tank of the rig was modified in a way that measuring the average fuel consumption is possible (shown in **Figure 4.**). The built-in metering bowl (Figure 3. E) is located below the fuel level, therefore by opening the ball-valve G, the metering bowl is filled (communicating vessels). During the start of the metering, the ball-valve G is closed, thus the fuel is consumed from the metering bowl. The time it takes for the fuel level to decrease between two marks on the glass tube is measured. After the measurement the ball-valve should be opened in order to let the engine use the fuel from the tank.

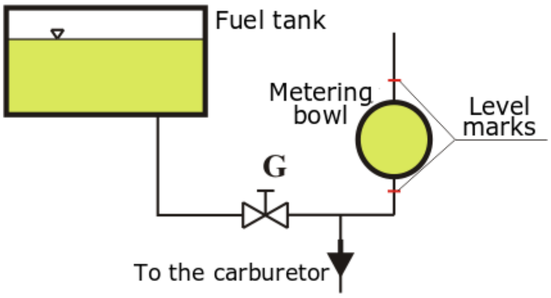


Figure 4.
Measurement of the fuel consumption

Volume of the metering bowl	$V_K = 22{,}1\ \text{cm}^3 = 22{,}1\cdot 10^{-6}\ \text{m}^3$
Time of the metering	t (seconds)
Flow rate of the consumed fuel	$q_b = \dfrac{V_K}{t}$
Density of the fuel	$\rho_b = 740\ \text{kg/m}^3$
Mass flow rate of the consumed fuel	$\dot{m}_b = q_b \rho_b$ (kg/s)

The adjustment of the useful power of the aggregator (and the load of the whole group of machines) is via the built-in ohmic resistances and a light bulb (**Figure 5.**).

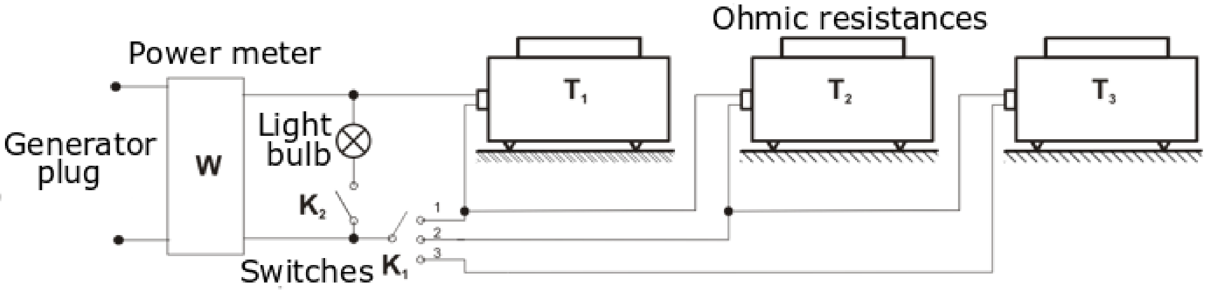


Figure 5.
Built-in resistances for varying the load

The specific fuel consumption is the mass flow rate for unit useful power, that is $b = \frac{\dot{m}_b}{P_u}$ (kg of fuel consumed to produce 1 Watt of useful electric power). The load factor is the ratio of the instantaneous useful power and the machine's nominal useful power, so $x = \frac{P_u}{P_N}$. (The nominal useful power is the output power for which the machine was designed.)
The heating value of the petrol is $H_b = 43.6\frac{MJ}{kg}$. (MJ of power gained by burning 1 kg of fuel.)
With this, the input power becomes $P_{in} = \dot{m}_b\, H_b$.
The efficiency of the unit (ICE + generator) is the ratio of the useful power and the input power: $\eta = \frac{P_u}{P_{in}}$.

Average efficiency and load:

The above quantities are instantaneous values, since the power is work done per unit time, the fuel consumption is the fuel consumed in unit time, etc. In reality, machines work with loads therefore calculating the average efficiency can be relevant. (For example, the load of a car driving in the city is continuously changing depending on the actual traffic.)

The **average efficiency** over a time interval t is the ratio of the *useful work* and the *input work* during that interval:

$$\eta_{ave} = \frac{W_u}{W_{in}} = \frac{\int_0^t P_u \, dt}{\int_0^t P_{in} \, dt}.$$

If we assume that there were no idle time intervals (when the load was 0, for example standing at red light with a car while running the engine), and use the fact that the nominal power is constant, we can write that

$$\eta_{ave} = \frac{W_u}{W_{in}} = \frac{\int_0^t P_u \, dt}{\int_0^t P_{in} \, dt} = \frac{\sum_{i=1}^n P_{u\,i} \, t_i}{\sum_{i=1}^n \frac{P_{u\,i} \, t_i}{\eta_i}} = \frac{\sum_{i=1}^n x_i \, t_i}{\sum_{i=1}^n \frac{x_i \, t_i}{\eta_i}},$$

where

n – number of loading periods for the whole interval
t_i – time of the i-th loading period
x_i - load of the i-th loading period
η_i - efficiency of the i-th loading period.

The **average load** for the whole time interval:

$$x_{ave} = \frac{W_u}{W_N} = \frac{\int_0^t P_u \, dt}{\int_0^t P_N \, dt} = \frac{\sum_{i=1}^n x_i \, t_i}{\sum_{i=1}^n t_i}.$$

It is worth noting that even though the average load is simply the weighted average of the subsequent load values (weighted by the length of time interval), the average efficiency is not the time-weighted average of the subsequent efficiency values!

Calculation task:

Utilize the measurement results to calculate the average efficiency and average load for the measured aggregator in the following case:

- running for 10 minutes with useful power of 250 W,
- running for 20 minutes with useful power of 800 W,
- running for 30 minutes with useful power of 1400 W.

Determine the fuel needed for the 1-hour long work cycle described above. For the calculation read the b_i and η_i values from the diagram after calculating x_i for each load. This calculation should be done in the measurement report after the measurement.

Steps of starting the measurement rig:

1. Start of the ventilation system.
2. Open the petrol tap and wait until the metering bowl fills up.
3. Turn on the ignition switch.
4. Pull out the manual choke.
5. Start the engine by pulling the kick-starter.
6. Push in the choke.
7. Start the device for measuring the useful power.

Setting the measurement points:

1. Idle operation. No resistance is connected in the system.
2. Switchboard is in position No1.
3. Switchboard is in position No2.
4. Switchboard is in position No3.
5. Switchboard is in position No3 + Light bulb (250 W) is on.
6. Switchboard is in position No2 + Light bulb (250 W) is on.
7. Switchboard is in position No1 + Light bulb (250 W) is on.
8. Switchboard is turned off + Light bulb (250 W) is on.

The measured data should be collected in the following table (this is included in the blank measurement report)**:**

No. of meas.	t	P_u	q_b	$\dot{m}_b$	b	x	P_{in}	η
	[s]	[W]	[cm^3/s]	[kg/s]	[kg/kWh]	[-]	[kW]	[-]
1.								
…								
8.								

Steps of turning off the measurement rig:

1. Switch of the resistances and the light bulb.
2. Close the petrol tap.
3. Wait until the metering bowl becomes empty.
4. Switch off the ignition switch.
5. Turn off the ventilation system after around 15 minutes.

After the measurement the following diagrams should be prepared in a common A4 graph paper:

1. $b = f(x)$ the specific fuel consumption as the function of the load factor
2. $\eta = f(x)$ the efficiency of the aggregator as the function of the load factor.

Choose an appropriate scale for the diagram. The title, date, angular speed at which the measurement was made, and the name and Neptun code of the student(s) performing the measurement should be indicated on the diagram.

THE PREPARATION FOR THE MEASUREMENT

- Bring 1 sheet of A4 graph paper[1], pencil, ruler, calculator.
- Before the measurement the knowledge about the aim and method of the measurement and the formulae will be checked by a short theoretical and calculation task (for example, see the sample questions on the web page, but please note that these are only sample questions different questions may arise).
- The blank measurement report should be filled in from sections 1 to 4. Sections 5-8 will be filled during the measurement.

Comments about the measurement description should be sent to dgyurki@hds.bme.hu.

Literature:

http://en.wikipedia.org/wiki/Otto_engine
http://en.wikipedia.org/wiki/Carburetor
http://en.wikipedia.org/wiki/Indicator_diagram

---

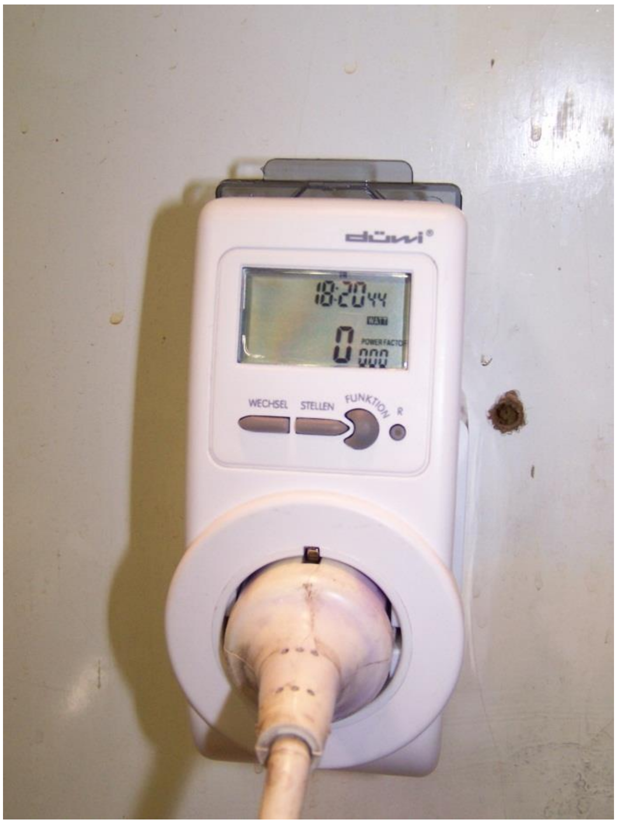
[1] „Milliméter papír” in Hungarian

Appendix

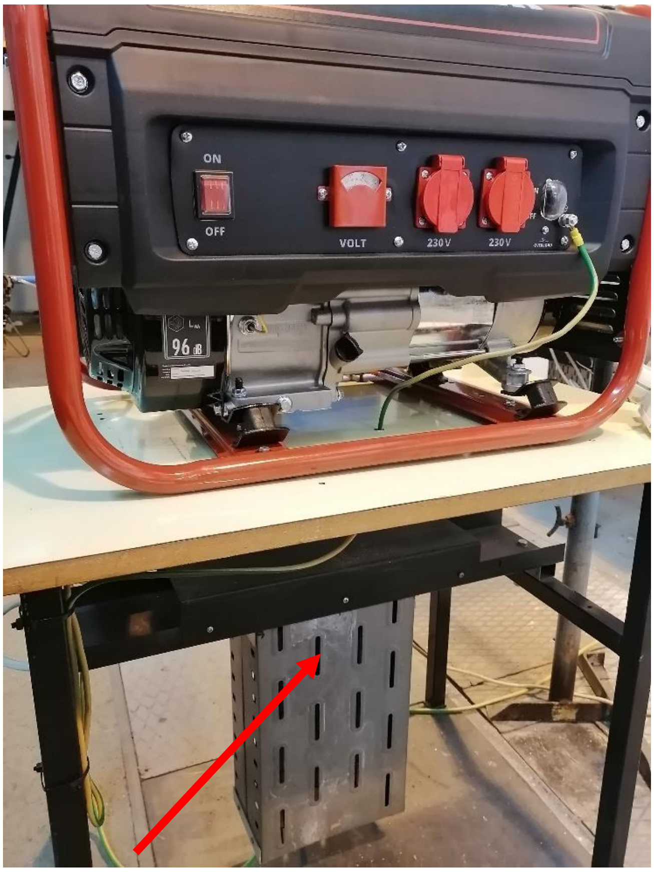
Measurement device, front view

Measurement device, rear view

Metering bowl for measuring fuel consumption



Device for measuring the useful power of the generator



Electric resistances for varying the load