Catalytic purification of automobile exhaust gases

Aims of the experiment

- To learn about the function of vehicle catalytic converters
- To learn about exhaust gas analysis
- To work with testing tubes
- To learn about various detection reactions

Principles

Various substances harmful to the air and the environment form when fossil fuels such as coal, crude oil and natural gas are burned. These include, for example, carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and various hydrocarbons. These substances also form when burning fuel in petrol and diesel engines and are also toxic to humans.

Catalytic converters have been built into vehicles since the 1990s to reduce emissions of these harmful substances. They are made from a heat-resistant ceramic material in the form of a cylinder, which is traversed by numerous parallel channels in the direction of flow. This cylinder is coated with aluminium oxide and oxygen storage components, such as cerium(IV) oxide. Embedded in the coating are precious metals such as platinum, which are catalytically active. The reactions that take place are redox reactions and proceed as follows:

$$2\ CO + O_2 \rightarrow 2\ CO_2$$

$$2\ C_2H_6 + 7\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$$

$$2\ NO + 2\ CO \rightarrow N_2 + 2\ CO_2$$

As three reactions take place in parallel in this catalytic converter, it is also referred to as a three-way catalytic converter. Although only non-toxic CO_2 is created here, this is primarily jointly responsible for the greenhouse effect. This leads to a warming of the Earth's atmosphere.

In this experiment, three different substances or substance groups will be detected in the exhaust gas of a vehicle following the use of a catalytic converter: carbon monoxide (CO), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). CO binds to haemoglobin in the blood and blocks the absorption of oxygen from the blood. The nitrogen oxides are members of a group of irritative substances. They are strong respiratory poisons and are jointly responsible for the formation of the atmospheric poison ozone. SO_2 also damages respiratory organs, as it is also a strong respiratory poison. Apart from this, it is mainly responsible for the formation of acid rain.

In this experiment, the exhaust gas is firstly purified using the catalytic converter and then analysed with the help of testing tubes. In these tubes, a colour reaction takes place in the

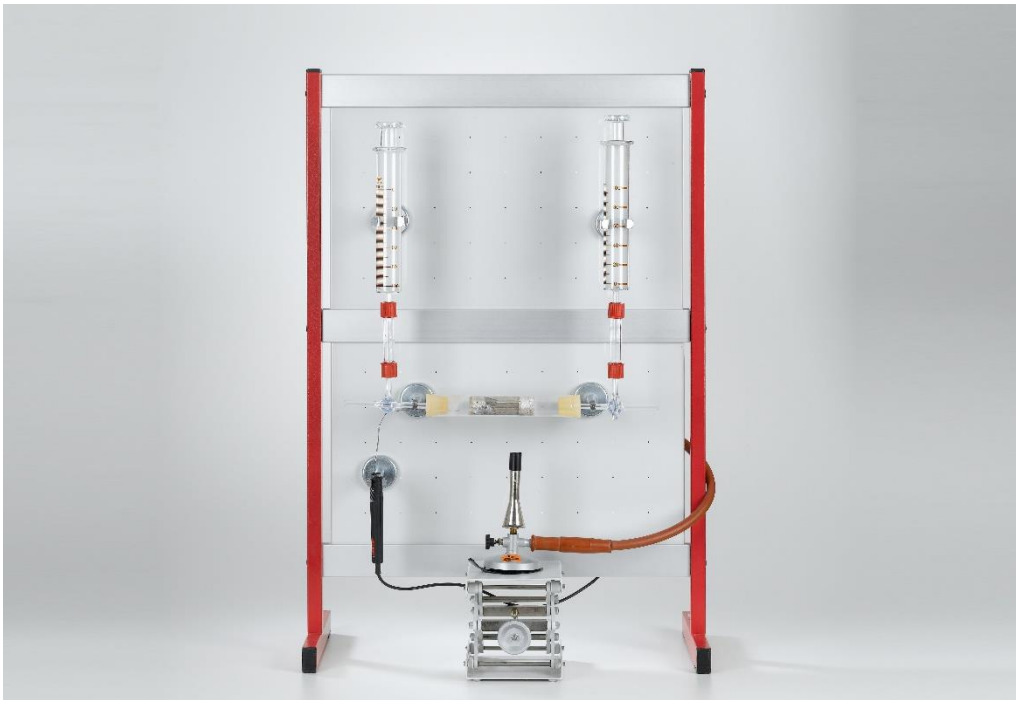

Fig. 1 Set-up of the experiment

presence of the respective analytes, which can be read directly off the tube. The individual reactions are explained more precisely in experiment C5.3.1.1.

Risk assessment

The substances investigated in the experiment, carbon monoxide, nitrogen oxides and sulphur dioxide, form in such small amounts that they do not represent a hazard. Nevertheless, the experiment should be performed in the fume cupboard owing to this exhaust gas.

CO testing tube	
	Hazard statements R20/21/22 Harmful on inhalation, in contact with skin and if swallowed. R35 Causes severe burns. R37 Irritating to respiratory system. **Precautionary statements** P102 Keep out of reach of children. P260 Do not breathe dust/fume/gas/ mist/vapours/spray. P262 Do not get in eyes, on skin, or on clothing. P305+P351+P338 IF IN EYES: Rinse continuously with water for several minutes. Remove contact lenses if present and easy to do. Continue rinsing. P313 Get medical advice/attention. P302+P352 IF ON SKIN: Wash with soap and water.
NO_x testing tube	
	Hazard statements R21/22 Harmful in contact with skin and if swallowed. R34 Causes burns. R43 May cause sensitisation by skin contact. **Precautionary statements** P102 Keep out of reach of children. P262 Do not get in eyes, on skin, or on clothing. P305+P351+P338 IF IN EYES: Rinse continuously with water for several minutes. Remove contact lenses if present and easy to do. Continue rinsing. P313 Get medical advice/attention. P302+P352 IF ON SKIN: Wash with soap and water.
SO_2 testing tube	
	Hazard statements R20/21/22 Harmful on inhalation, in contact with skin and if swallowed. R35 Causes severe burns. **Precautionary statements** P102 Keep out of reach of children. P260 Do not breathe dust/fume/gas/ mist/vapours/spray. P262 Do not get in eyes, on skin, or on clothing.

Equipment and chemicals

1	Catalytic converter	666 360
2	Gas syringe, 100 ml with three-way stopcock	665 914
3	Glass connector, 2 x GL 18	667 312
1	Mobile-CASSY 2	524 005
1	Temperature probe, NiCr-Ni, 1.5 mm, type K	529 676
1	Panel frame C50, two-level, for CPS	666 425
2	Adhesive magnetic board 500 mm	666 4659
2	Holder, magnetic, size 1, 9...11 mm	666 4661
1	Holder, magnetic, size 2, 11...14 mm	666 4662
2	Holder, magnetic, size 5, 30...32 mm	666 4665
1	Bunsen burner, universal	656 016
1	Safety gas hose with clamp, 0.5 m	607 020
1	Laboratory stand 16 cm x 13 cm	300 76
1	Silicone gasket, GL 18	667 296
1	Testing tube NO_x 0.5 … 50 ppm, set of 10	666 313
1	Testing tube CO 0.5 … 7.0%, set of 10	666 319
1	Testing tube SO_2 1 … 25 ppm, set of 10	666 314
1	Glass file	667 015
1	Hand-held stopwatch	313 07
1	Air bag, set of 30	662 302
1	Funnel, PP. 75 mm Ø	665 009

Also required:
Car exhaust gas or a home-made exhaust gas mixture of nitrogen dioxide and methane or carbon monoxide, rubber band, if required

Set-up and preparation of the experiment

Set-up of the apparatus

1. The apparatus is set up as shown in Fig. 1.
2. Insert adhesive magnetic boards into the CPS frame.
3. Attach the gas syringes to the right and left of the upper board using the magnetic holders (size 5).
4. Attach each gas syringe via a glass connector with a three-way stopcock.
5. Attach the catalytic converter midway between the two three-way stopcocks. Insert the end of the three-way stopcocks into the stoppers and stabilise with magnetic holders.
6. Insert the temperature probe also through the left stopper into the catalytic converter; connect this also to the board using a magnetic holder (size 2).
7. Connect the temperature probe to the Mobile-CASSY 2.
8. Place the Bunsen burner onto a laboratory stand beneath the catalytic converter.

Preparation of the experiment

1. Attach the detector tubes to the right-hand three-way stopcock at the outlet which is still free using a glass connector.

2. Two different gaskets in the screw caps are needed for this. The larger gasket is for the glass part of the three-way stopcock and the smaller one for the testing tube.

3. Insert the first testing tube for CO into the screw cap with the smaller gasket. Beforehand, break off both tips of the tube and smoothen the sharp edges with the help of the glass file.

4. Attach the testing tube in such a way that the arrow points in the direction of the gas flow.

5. The exhaust gas from a vehicle will be used for the analysis.

6. An air bag and a funnel will be used to collect the exhaust gas. The tube on the air bag should be cut down to a length of about 5 cm.

Note: It is necessary to cut the tube down, as the air bag would otherwise be difficult to fill.

7. Insert the funnel into the tube of the air bag and hold it against the exhaust pipe of a vehicle in order to collect the gas.

Note: The funnel must not be held too closely to the exhaust pipe and only briefly after starting. Also, the exhaust gas sample should be taken within 5 minutes of starting the vehicle, as the vehicle's catalytic converter is activated after this time. Press the accelerator to produce a higher pressure, if necessary.

8. When the air bag is filled, remove the funnel and seal the bag tightly.

Performing the experiment

1. Connect the air bag beneath the left gas syringe via the outlet of the three-way stopcock which is still free. Loosen the knot in the tube and push the tube over the glass part of the three-way stopcock. To ensure gas-tightness, hold the tube firmly in the fingers or fix with a rubber band.

2. Now set the three-way stopcock such that the air bag is connected to the gas syringe.

3. The apparatus must first be flushed out well for the analysis. To obtain this, slowly withdraw the piston of the gas syringe and press lightly on the air bag.

4. When the gas syringe is filled, close the three-way stopcock of the gas syringe such that no connection can result between the gas syringe and the atmosphere and the exhaust gas is enclosed in the left gas syringe. Then produce a connection between gas syringe and apparatus with the other three-way stopcock.

5. The air bag does not need to be removed as it is not connected to the apparatus.

6. Check that the right-hand gas syringe is only connected to the apparatus and not still connected to the testing tube.

7. Ignite the Bunsen burner and place under the catalytic converter.

8. The catalytic converter requires an operating temperature of 300-350 °C. When this is reached, the Bunsen burner can be extinguished. Follow the temperature rise on the Mobile-CASSY 2.

9. Now set the three-way stopcock of the left gas syringe such that a connection to the apparatus is created.

10. Pass the exhaust gas through the catalytic converter by lowering the piston of the left-hand gas syringe and by raising the piston of the right-hand gas syringe.

11. For the analysis, now produce a connection between the right-hand gas syringe and the glass connector and empty the gas syringe slowly and without exerting much pressure so that the exhaust gas passes into the testing tube. Start the stopwatch and read off the result on the testing tube after two minutes.

Repeat this experiment with the testing tubes for nitrogen oxides and SO_2. To do this, fill the left gas syringe with exhaust gas again and bring the catalytic converter up to operating temperature.

Note: Testing tubes in which a reaction turns out to be negative can be used again on the same day.

Observation

The gas syringe is filled by drawing in exhaust gas and the air bag empties at the same time. The exhaust gas being investigated originates from a Diesel vehicle. By passing the exhaust gas through the testing tube, a reaction takes place between the relevant analyte, when it is present, and the material in the testing tube. For the evaluation of the analyses, colour changes take place in the testing tubes. With CO, the colour changes from white/yellowish to brown in a positive reaction. With nitrogen oxides, NO_x, this changes from white or pale blue to dark blue. With SO_2, the colour changes from violet to white.

The result for the individual analysis can be read directly on the testing tube. It is worth noting that the test was positive for CO and NO_x. In contrast, the test for SO_2 was negative.

Evaluation

In this experiment, the exhaust gas of a vehicle without an active catalytic converter was investigated. The content of CO, NO_x and SO_2 in the exhaust gas was tested after treatment in a catalytic converter.

The analyses were evaluated using the calibrated scale on the testing tubes. The values need to be read off and noted and can be compared with the values in the literature.

Results

The results of the analyses of CO, NO_x and SO_2 in the exhaust gas of a Diesel vehicle after treatment in a catalytic converter are shown in Table 1.

Table 1: Results of the individual analyses after treatment with a catalytic converter.

Analyte	Results
CO (n = 1)	-
NO_x (n = 5)	0.5 ppm
SO_2 (n =3)	-

Depending on the information on the testing tube, the concentration value (e.g. in % or ppm) must be multiplied by the factor *n* stated in the package insert in order to arrive at the exact concentration of the analyte.

The literature values for the analytes in the exhaust gas of a petrol engine are shown in Table 2.

Table 2: Literature values for analytes in exhaust gas.

Analyte	Vol %
CO	0.2 - 5 (Diesel engine lower)
NO_x	0.005 - 0.4 (Diesel engine higher)
SO_2	0.006 (Diesel engine higher)

Exhaust gases with and without treatment (see Table 3) in a catalytic converter can also be compared. See experiment C5.3.1.1 for the analysis without treatment in a catalytic converter.

Table 3: Results of an analysis without treatment in a catalytic converter.

Analyte	Results
CO (n = 1)	0.3%
NO_x (n = 5)	3 ppm
SO_2 (n =3)	-

CO is present in the exhaust gas of Diesel engines only in small amounts (see Table 2). It forms through the incomplete combustion of hydrocarbons. After treating the exhaust gas in a catalytic converter, the CO is completely removed. The catalytic converter has completely oxidised the CO to CO_2 in accordance with the reaction described at the start.

Nitrogen oxides are formed during the combustion of petrol at high temperatures from the nitrogen and oxygen contained in the air. Up to more than 80% of nitrogen oxides are removed from the exhaust gas by the catalytic converter. The reaction equation is also described under Principles in this experiment.

SO_2 could not be detected as the concentration in the exhaust gas is too low. The sulphur contained in crude oil is removed to a very large extent during the manufacture of petrol. Removal is necessary, as the SO_2 resulting from the combustion would act as a poison for the catalytic converter and destroy it.

A further reaction which takes place in the catalytic converter is the complete combustion of hydrocarbons.

$$C_mH_n + \left(m + \frac{n}{4}\right) O_2 \rightarrow m\ CO_2 + \frac{n}{2}\ H_2O$$

However, this cannot be proven in this experiment, as here a mixture is present for which the testing tubes are not suitable.

Cleaning and disposal

The testing tubes must on no account be disposed of in the normal waste, as they contain small amounts of chemicals. The laws on waste disposal and on protection against hazardous substances must be observed.

The testing tubes for CO and SO_2 contain inorganic substance, they must therefore be disposed of in the waste for inorganic solids. In the testing tube for NO_x there is an organic amine as well as chromium(VI) oxide, which is highly poisonous. For this reason, these testing tubes must be collected in a specially labelled container for disposal.

The residual exhaust gas in the air bag can be emptied in the fume cupboard.