

# Hess's law with Cobra SMARTsense



For spontaneous and quantitative formation reactions, e.g. the conversion of carbon and oxygen to CO<sub>2</sub>, standard enthalpies of formation can be measured directly using calorimetry. Alternatively, they can be calculated from known enthalpies of reaction using Hess's law.

Chemistry

Physical chemistry

Thermochemistry, calorimetry



Difficulty level

hard



Group size

2



Preparation time

30 minutes



Execution time

45+ minutes

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## General information

## Application

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The Hess's law states that the total enthalpy change is the same, no matter of the route by which the chemical change happens, under condition the initial and final condition are the same.

Industries that research the different methods in production use this law to determine if their method is the most effective one to produce the products based on the energy needed or released. Car companies must see how much energy the car engine uses or produces when it burns gasoline. The industry can measure how much energy each process releases when it is performed, so that they can make effective energy choices. When we work- out we often say that we burn calories. In reality, the food goes through a series of oxidation processes and is converted to products like carbon dioxide and water.

Hess' Law shows that the energy change is independent of the pathway, this means that the same amount of energy is released through burning food. Our body breaks down carbohydrates to simple sugars so they can be used for cellular respiration. This law is the chemistry behind the calorie counting apps.

## Other information (1/2)

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### Prior knowledge



In order to carry out this experiment certain keywords and definitions should be clear. The Students should know the first law of thermodynamics. It states that energy is always conserved, it cannot be created or destroyed. Energy can be converted from one form into another. Another keyword is calorimetry which is the science of measuring the heat of chemical reactions or physical changes as well as heat capacity.

### Scientific principle



The standard molar enthalpies of formation are important compiled thermodynamic tabulation quantities for calculating standard enthalpies of reaction for any arbitrary reaction. They are defined as the heat of reaction occurring in the direct formation of one mole of the pertinent pure substance from the stable pure elements at constant pressure. For spontaneous and quantitative formation reactions, standard enthalpies of formation can be measured directly using calorimetry. Alternatively, they can be calculated from known enthalpies of reaction using Hess's law.

## Other information (2/2)

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### Learning objective



The aim of this experiment is that the students gain a better knowledge of the first law of thermodynamics and calorimetry. They will learn more about the enthalpy of formation and the enthalpy of reaction, their differences and how are they used. The students will be able to use calorimetry and Hess's law in order to determine the standard molar enthalpies of formation.

### Tasks



In this experiment students should determine the enthalpies of reaction for the combustion of carbon and carbon monoxide calorimetrically. They should use the experimentally determined enthalpies and Hess's law to calculate the enthalpies of formation of carbon monoxide and carbon dioxide.

## Safety instructions

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- When handling chemicals, you should wear suitable protective gloves, safety goggles and suitable clothing.
- For this experiment the general instructions for safe experimentation in science lessons apply.
- For H- and P-phrases please consult the safety data sheet of the respective chemical.

## Theory (1/2)

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Hess's law of constant heat summation (or simply Hess's law) is understood as an expression of the principle of conservation of energy, which is also expressed in the first law of thermodynamics. The enthalpy of a chemical process is independent of the path taken from the initial to the final state; the total enthalpy change for a reaction is the sum of all changes. This law is a manifestation that enthalpy is a state function.

Molar enthalpies of reaction  $\Delta_R H$  characterise the heat balance of substance transformations. They are defined as the heat of reaction  $Q_P = \Delta h$  occurring per mole formula conversion  $\Delta \xi$  at constant pressure  $p$  and constant temperature  $T$ .

$$\Delta_R H = (\Delta h / \Delta \xi)_{p, T}$$

For spontaneous and quantitative conversions, the molar enthalpies of reaction can be determined directly using calorimetry. Otherwise, they can also be calculated using Hess's law of constant heat summation (the additivity of reaction enthalpies).

## Theory (2/2)

The molar formation enthalpy  $\Delta_B H$  corresponds to the molar enthalpy of reaction in the direct formation of 1 mole of the respective compound from the elements in stable modification (for which the enthalpy of formation is zero by definition). The formation enthalpies of most substances at  $p = 1013hPa$  and  $T = 298K$  are listed in tables.

The standard enthalpy of reaction  $\Delta_R H^\ominus$  of any arbitrary reaction is equal to the stoichiometric sum of the standard enthalpies of formation  $\Delta_B H^\ominus$  of the participating educts and products, whereby the original substances are entered with negative stoichiometric values  $v_i$ .

$$\Delta_R H^\ominus = \sum v_i \Delta_B H_i^\ominus$$

Hess' law can be used to determine the overall energy required for a chemical reaction, when it can be divided into synthetic steps that are individually easier to characterize. The principle underlying Hess's law does not only apply to enthalpy but can be used to calculate other state functions such as changes in Gibbs' energy and entropy.

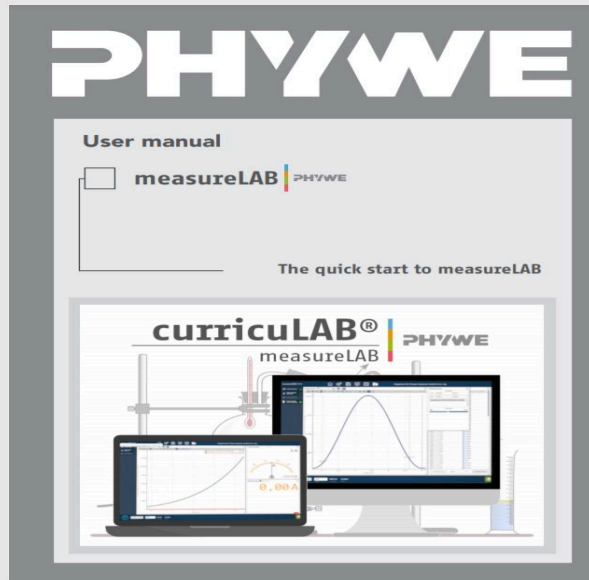
## Equipment (1/2)

Position	Material	Item No.	Quantity
1	Glass jacket	02615-00	1
2	Calorimeter insert for glass jacket	02615-01	1
3	Combustion lance for gases	02613-00	1
4	Gasometer 1000 ml	40461-00	1
5	Cobra SMARTsense - Thermocouple, -200 ... +1200 °C (Bluetooth + USB)	12938-01	2
6	Immersion probe NiCr-Ni, teflon, 300 °C	13615-05	2
7	measureLAB, multi-user license	14580-61	1
8	Stopcock,3-way,t-shaped, glass	36731-00	1
9	Retort stand, h = 750 mm	37694-00	2
10	Support base DEMO	02007-55	1
11	Support rod, stainless steel, l = 250 mm, d = 10 mm	02031-00	2
12	Barrel base expert	02004-00	1
13	Right angle boss-head clamp	37697-00	6
14	Universal clamp	37715-01	7
15	Magnetic stirring bar 30 mm, cylindrical	46299-02	1
16	Magnet, d = 10 mm, l = 200 mm	06311-00	1
17	Techn. magnifier, 10x, d:23mm	64598-00	1
18	Funnel, glass, top dia. 50 mm	34457-00	1
19	Graduated beaker with handle, 1000 ml, plastic (PP)	36640-00	1
20	Paper,ceram.fibre,1.0x500x2000mm	38750-01	1
21	Commercial weight, 500 g	44096-50	1
22	Test tube GL25/8, w.hose connec.	36330-15	1
23	Glass tubes,right-angled, 10	36701-59	1
24	Pinchcock, width 15 mm	43631-15	1
25	Funnel for gas generator, 50 ml, GL18	35854-15	1
26	Round bottom flask, 100ml, GL 25/12	35841-15	1
27	U-tube with lateral connector, GL 25	MAU-27229500	1
28	Test tube,180x20 mm, PN19	36293-00	1
29	Rubber stopper, d=22/17 mm, without hole	39255-00	1
30	Rub.stop.d=38/31mm,1 hole 15mm	39260-19	1
31	Test tube holder, up to d 22mm	38823-00	1
32	Teclu burner, DIN, natural gas	32171-05	1
33	Safety gas tubing, DVGW, sold by metre	39281-10	1
34	Hose clip f.12-20 diameter tube	40995-00	2
35	Lighter f.natural/liquified gases	38874-00	1
36	Steel cylinder oxygen, 2 l, filled	41778-00	1
37	Reducing valve f.oxygen	33482-00	1
38	Wrench for steel cylinders	40322-00	1
39	Table stand for 2 l steel cylinders	41774-00	1
40	Hose clip, diam. 8-16 mm, 1 pc.	40996-02	4
41	Weather monitor, 6 lines LCD	87997-10	1
42	Mortar with pestle, 150 ml, porcelain	32604-00	1
43	Scissors,straight,blunt,l 140mm	64625-00	1
44	Tweezers,straight,blunt, 200 mm	40955-00	1
45	Water jet pump, plastic	02728-00	1
46	Rubber tubing, i.d. 6 mm	39282-00	5
47	Protective glasses, green	39317-00	1
48	Glass wool 10 g	31773-03	1
49	Charcoal,small pieces 250 g	30088-30	1
50	Formic acid 75% 250 ml	30023-25	1
51	Sulfuric acid 95-97% 500 ml	30010-50	1
52	Hydrochloric acid 37% 500 ml	30010-50	1
53	Sodium hydroxide 50% 500 ml	30010-50	1
54	Glycerol, 250 ml	30084-25	1

6/16

## Equipment (2/2)

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### Usage of measureLAB

- The usage of the software is extensively described in the "User Manual"
- You will find this manual by pressing the following button within the measureLAB software



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## Setup and procedure

## Setup (1/5)

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This experiment needs the software measureLAB. You can download the measureLAB-Software at the PHYWE website or using following QR-Codes to download the software.



measureLAB  
for Windows



measureLAB  
for macOS

## Setup (2/5)

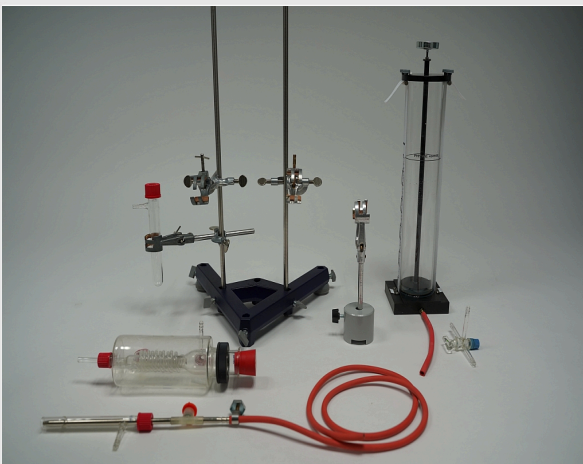
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figure 1: parts of the experiment

- Prepare the experiment setup as shown in the figure 1.
- Take the support base and put 2 support rods in it.
- Take 3 Right angle boss-head clamp and plug them on the support rods (as shown in figure 1).
- Fit the calorimeter insert into the glass jacket as described in the instruction manual.
- Fill the graduated vessel with approximately 500 g of water and determine the mass of it on the balance ( $= m_1$ )



## Setup (3/5)

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figure 2: Glass Jacket

- Place the calorimeter insert for glass jacket inside the glass jacket. Follow the handbook for the glass jacket
- Fit the glass jacket as shown in figure 3.
- Carefully pour the water into the glass jacket through one of the vertical tubular sleeves (using a funnel) and weigh the vessel again ( $= m_2$ ).
- Calculate the mass of the water ( $m(H_2O) = m_2 - m_1$ )
- Put a magnetic stirrer bar into the glass jacket.

## Setup (4/5)

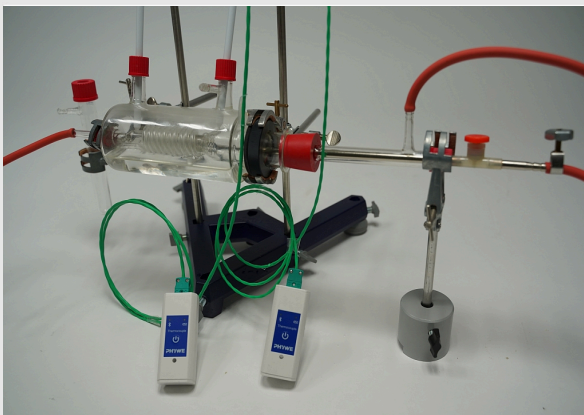
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figure 3: Fit in the Glass jacket in the experiment setup

- Immerse the temperature probes through the vertical tubular sleeves into the water.
- Prepare and connect the bubble counter as follows: Fill a little water into the test tube with hose connector, fit the right-angled tube on and connect it to the outlet of the calorimeter. Connect the hose connector to the water jet pump.
- Fill the gasometer with 300 to 400 ml of some flammable gas (natural gas, propane or a similar gas which is used to produce a very small pilot flame) and connect it to the combustion lance via a rubber tube.

## Setup (5/5)

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figure 4: complete experiment setup

- Connect the steel cylinder with oxygen to the combustion lance and secure all hose connections with hose clips.
- Put the SMARTsense Thermocouple on
- Start the PC and start the software "measureLAB".
- Boot the experiment "Hess's Law with Cobra SMARTsense" (experiment > open experiment). The measurement parameters for this experiment are loaded now.

## Procedure - Burning of carbon (1/4)

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Fig. 4: Preparation of coal

- Prepare very strongly heated and completely degassed charcoal. ( The heat value of this charcoal is only negligibly different from that of graphite).
- It is prepared as follows: Use a mortar and pestle to slightly crush a solid piece of charcoal to give some pieces of between 0.4 and 0.7 g in size. Place the pieces in a test tube and heat them strongly with the Teclu burner until all humidity, all tar residues and all residual gases have been driven off. Allow it to cool in a closed vessel.
- Weigh one of the pre-treated pieces of carbon and place it in the combustion chamber on a strip of ceramic paper.

## Procedure - Burning of carbon (2/4)

- Turn on the water jet pump and adjust it so that a moderate flow of air is drawn through the calorimeter (use the pinchcock on the test tube between the pump and the bubble counter). The current of air ensures that all of the hot gas generated is drawn through the calorimeter. Move the stirring bar with the magnet to mix the water within the glass jacket until the thermo-elements indicate the same temperature (=starting temperature  $\vartheta_1$ ).
- Start the measurement. Wear dark protective glasses during the subsequent combustion of carbon in a flow of oxygen to avoid being dazzled.
- Place a weight of approximately 500 g on the plunger of the gasometer to achieve a sufficient speed of the gas outflow.
- Open the precision control valve of the combustion lance, ignite the outflowing gas, and adjust the flame to a length of 1 to 2 cm.

## Procedure - Burning of carbon (3/4)



figure 5: insert a flame

- Supply oxygen, adjust the length to approximately 0.5 cm, and then move the barrel base to quickly insert this pilot flame into the glass jacket calorimeter so that the charcoal ignites.
- Close the precision control valve on the gasometer.
- The charcoal burns in the flow of oxygen with an extremely bright flame to form carbon dioxide.
- Stir the water in the calorimeter during combustion with a magnet in order to achieve a maximum transfer of the reaction heat to the liquid.

## Procedure - Burning of carbon (4/4)

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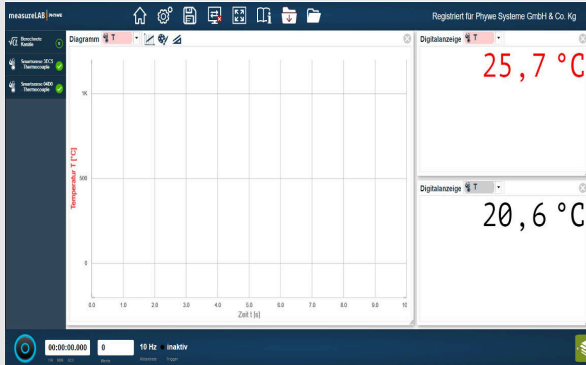
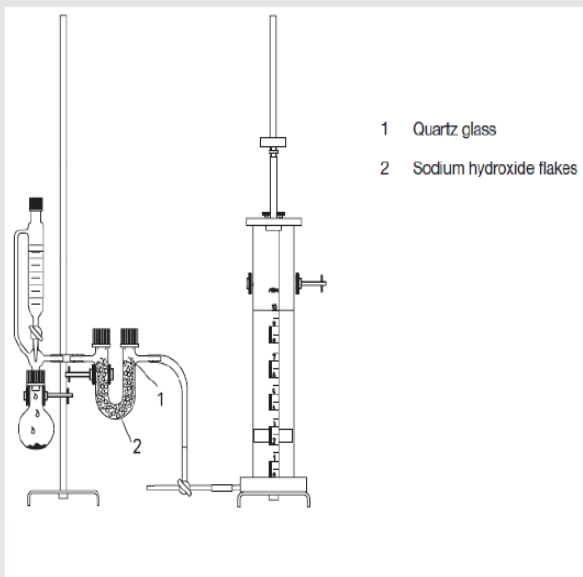


figure 6: programme measureLAB

- When combustion is complete, shut off the air flow and the oxygen supply, but continue mixing until thermal equilibrium has re-established.
- Stop the measurement by pressing.
- Save your project by clicking on the button in the top bar.

## Procedure - Burning of carbon monoxide (1/3)

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- The experimental set-up is analogous to that of the first experiment.
- Prepare carbon monoxide by dehydrating formic acid with concentrated sulphuric acid. To do this you have to work under an extractor hood.
- Drop formic acid from the graduated funnel into the round flask containing sulphuric acid.
- Clean and dry the carbon monoxide that evolves with sodium hydroxide flakes held in a U- tube between two balls of quartz glass.

## Procedure - Burning of carbon monoxide (2/3)

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- Fill the gasometer with 1000 ml of carbon monoxide and again connect it to the combustion lance, which is furthermore connected to the oxygen cylinder.
- Adjust the airflow with the water jet pump.
- Subsequently, adjust a weak flow of carbon monoxide and ignite the gas at the tip of the combustion lance.
- Set the flame length to approximately 2 cm and add oxygen in order to guarantee complete combustion.
- Start the measurement.

## Procedure - Burning of carbon monoxide (3/3)

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figure 7: Experiment setup

- Wait until the sinking piston of the gasometer touches a certain mark on the scale (e.g. 900 ml) and then move the lance to a position deep inside the combustion chamber of the calorimeter by moving the barrel base.
- Continuously but gently stir the water in the calorimeter, combust exactly 500 ml of carbon monoxide, then turn off the air flow and the oxygen supply.
- Wait until thermal equilibrium has established.
- Stop the measurement by pressing.
- Save your project.
- Measure the room temperature and the atmospheric pressure.

## Evaluation (1/5)

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The reaction enthalpy C to  $CO_2$  is calculated as follows:

- $\Delta_H = (m_w \cdot c_w + C_{Cal}) \cdot \Delta T \cdot \frac{M}{m}$
- $m_w = m_2 - m_1$
- $c_w = 4.1798 \frac{J}{g \cdot K}$
- $C_{(Cal)} \approx 410 J/K$
- $M = 12.01 \frac{g}{mol}$
- $m$ : mass of carbon

## Evaluation (2/5)

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The reaction enthalpy CO to  $CO_2$  is calculated as follows:

$$\Delta_H = (m_w \cdot c_w + C_{Cal}) \cdot \Delta T \cdot \frac{V_{mol}}{V}$$

$$m_w = m_2 - m_1$$

$$c_{(w)} = 4.1798 \frac{J}{g \cdot K}$$

$$C_{(Cal)} \approx 410 J/K$$

$$V_{mol} = 22.41 \frac{l}{mol}$$

$V$  : volume of carbon monoxide



## Evaluation (3/5)



- The combustion of 0.644 g of carbon increased the temperature of the 500 g water in the filled glass jacket calorimeter by  $\Delta T = 8.4K$ .
- $\Delta H = -391.6KJ/mol$ (lit. -393.2 kJ/mol)
- The oxidation of 460 ml  $CO$  at  $T= 291 K$  and  $p= 993 hPa$  caused a temperature increase of  $\Delta T = 2.3K$ .
- $\Delta H = -280.1KJ/mol$ (lit. -282.6 kJ/mol)
- $\Delta H_R = -391.6KJ/mol - (-280.1KJ/mol)$
- $\Delta H_R = -111.5KJ/mol$ (lit. -110.6 kJ/mol)

## Evaluation (4/5)

Complete the correct molar enthalpies of reaction that were calculated during the experiment.

$$\Delta_R H_1 = \Delta_B H(CO_2) = \text{[input field]}$$

  $-110.6kJ \cdot 1/mol$ 

$$\Delta_R H_2 = \text{[input field]}$$

  $-393.2kJ \cdot 1/mol$ 
  $-282.6kJ \cdot 1/mol$ 

$$\Delta_R H_3 = \Delta_B H(CO) = \text{[input field]}$$

## Evaluation (5/5)

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What does the first law of thermodynamics state?

Energy is always conserved and it can be converted from one form to the other.

Energy can be created or destroyed.



Slide

Score/Total

Slide 26: Molar enthalpies

0/3

Slide 27: Basic in thermodynamics

0/3

Total Score

0/6

Show solutions

Retry