Investigation: Determine the identity of gas based on the calculated molar mass [$gmol^{-1}$]

Results and analysis

Raw Data table

Table 1: Raw data for initial and final mass[g] of reagents $CuCO_3$ and product CuO, initial and final volume of gas in the eudiometer[cm^3], room pressure[kPa] and room temperature[K] for 20 trials and their respective uncertainties. The highlights are the outliers that will be excluded from calculations because of the unreasonably small final volume of gas.

	Initial mass of $CuCO_3$+test tube[g] ±(0.01g)	Final Mass of CuO+test tube[g]±(0.01g)	Initial Volume of gas [cm^3]+(0.05cm^3)	Final volume of gas [cm^3]+(0.05cm^3)	Room pressure[kPa]±(0.01 kPa)	Room temperature[K]±(0.01K)
Trial 1	130.05	129.97	0.00	10.50	100.28	296.6
Trial 2	41.97	41.9	0.00	11.30	100.28	296.6
Trial 3	42.36	42.27	1.21	40.35	100.28	296.6
Trial 4	126.47	126.26	2.20	44.00	100.28	296.6
Trial 5	44.15	44.07	0.98	43.25	100.28	296.6
Trial 6	44.34	44.27	0.00	36.50	100.28	296.6
Trial 7	44.43	44.36	1.50	42.80	100.28	296.6
Trial 8	33.57	33.53	1.00	32.70	100.28	296.6
Trial 9	41.90	41.86	2.10	35.50	100.28	296.6
Trial 10	41.93	41.87	1.50	35.50	100.28	296.6
Trial 11	42.00	41.92	1.68	34.91	100.33	297.0
Trial 12	44.66	44.6	7.91	43.64	100.33	297.0
Trial 13	42.41	42.35	0.00	44.85	100.33	297.0
Trial 14	42.52	42.44	0.05	44.00	100.33	297.0
Trial 15	41.81	41.75	9.50	44.82	100.33	297.0
Trial 16	42.01	41.98	1.40	49.91	100.33	297.0
Trial 17	42.72	42.64	3.02	47.32	100.33	297.0
Trial 18	42.52	42.48	2.45	45.58	100.33	297.0
Trial 19	42.10	42.03	1.00	32.25	100.33	297.0
Trial 20	41.86	41.79	1.00	49.00	100.33	297.0

Processed data table:

Table 2: Processed data table for mass of CO_2 [g], volume of CO_2 gas [dm^3], room pressure[kPa], room temperature[K], molar mass constant (R) [$dm^3 kPaK^{-1} mol^{-1}$] with their uncertainties for 20 trials with two trials excluded because they are outlier. The molar mass [$gmol^{-1}$] for 20 trials with 2 trials excluded is calculated through ideal gas equations and molar mass Uncertainty (±$gmol^{-1}$). The calculated molar mass is two significant figures while their uncertainties are one significant figure.

CO_2 Mass(±0.02g)	CO_2 Volume (±0.0001dm^3)	Pressure (±0.01kPa)	Temperature (±0.01K)	Molar mass constant (R) [$dm^3 kPaK^{-1} mol^{-1}$]	Molar mass [$gmol^{-1}$]	Molar mass Uncertainty [$gmol^{-1}$]
0.09	0.03914	100.28	296.6	8.314	57	10
0.21	0.04180	100.28	296.6	8.314	120	10
0.08	0.04227	100.28	296.6	8.314	47	10
0.07	0.03650	100.28	296.6	8.314	47	10
0.07	0.04130	100.28	296.6	8.314	42	10
0.04	0.03170	100.28	296.6	8.314	31	20
0.04	0.03340	100.28	296.6	8.314	29	20
0.06	0.03400	100.28	296.6	8.314	43	20
0.08	0.03323	100.33	297.0	8.314	59	20
0.06	0.03573	100.33	297.0	8.314	41	10
0.06	0.04485	100.33	297.0	8.314	33	10
0.08	0.04395	100.33	297.0	8.314	45	10
0.06	0.03532	100.33	297.0	8.314	42	10
0.03	0.04851	100.33	297.0	8.314	15	10
0.08	0.04430	100.33	297.0	8.314	44	10
0.04	0.04313	100.33	297.0	8.314	23	10
0.07	0.03125	100.33	297.0	8.314	55	20
0.07	0.04800	100.33	297.0	8.314	36	10
Average					45	10

Qualitative data table:

Type of qualitative observation	Before the experiment	After the experiment
Colour (of $CuCO_3$)	The Copper carbonate was a green powdery like substance.	The Copper carbonate powder turned from green to black after getting burnt in the test tube because it transformed into Copper (II) oxide
Gas/reaction (in the eudiometer)	The water was still and there were no air bubbles inside the eudiometer.	When there was flame on the Benson burner, the gas bubbles entered the eudiometer and rose up to the top.
Smell	It was odourless	Throughout the combustion, there was a smell of burning.
Temperature/touc h	The test tube was cold.	The test tube felt extremely hot right after being taken away from the benson burner.

Sample Calculations

1. **CO_2 Mass [g]**

   Data used for the sample calculations: (raw data table trial 3, Initial mass, final mass)

Trial 3	42.36	42.27

$$M_{CO_2}[g] = m_{initial}[g] - m_{final}[g]$$

$$M_{CO_2}[g] = 42.36 - 42.27 = 0.09\,g$$

2. **CO_2 volume[dm^3]**

   Data used for the sample calculations: (trial 3, Initial volume, final volume)

Trial 3	1.21	40.35

$$V_{CO2}[dm^3] = (V_{final}[cm^3] - V_{initial}[cm^3]) \div 1000$$

$$V_{CO2}[dm^3] = (40.35 - 1.21) \div 1000 = 0.03914\,dm^3$$

3. **Molar mass $[gmol^{-1}]$ and average molar mass $[gmol^{-1}]$**

   Data used for molar mass $[gmol^{-1}]$ sample calculations: (All factors in processed data table, row 1)

CO_2 Mass(±0.02g)	CO_2 Volume (±0.0001dm^3)	Pressure (±0.01kPa)	Temperature (±0.01K)	Molar mass constant (R) $[dm^3kPaK^{-1}mol^{-1}]$	Molar mass $[gmol^{-1}]$
0.09	0.03914	100.28	296.6	8.314	57

Data used for average molar mass$[gmol^{-1}]$ sample calculations: All data in Molar mass$[gmol^{-1}]$ column.

Molar mass $[gmol^{-1}]$
57
…
36

$$Mr\ [gmol^{-1}]\ =\ \frac{m[g] * R\ [dm^3kPaK^{-1}mol^{-1}] * T[K]}{P[kPa] * V[dm^3]}$$

Mr $[gmol^{-1}]$ is Molar mass, m[g] is CO_2 Mass, R $[dm^3kPaK^{-1}mol^{-1}]$ is Molar mass constant , T [K] is temperature, P [kPa] is pressure and V $[dm^3]$ is CO_2 volume.

$$Mr\ [gmol^{-1}]\ =\ \frac{0.09g * 8.314\ dm^3kPaK^{-1}mol^{-1} * 296.6K}{100.28kPa * 0.03914dm^3} \approx 57\ [gmol^{-1}]$$

$$Average\ molar\ mass(amm)[gmol^{-1}]\ =\ \frac{\sum_{i=1}^{18} Mr_i}{18}$$

i is the number of trials. $Mr_i\ [gmol^{-1}]$ is the molar mass $[gmol^{-1}]$ calculated for each trial.

$$amm\ [gmol^{-1}]\ =\ \frac{57+120+...+36}{18}\ \approx\ 45\ gmol^{-1}$$

4. **CO2 molar mass uncertainty[±gmol^-1]**

Data used for sample calculation: Processed data table, row one.

CO_2 Mass(±0.02g)	CO_2 Volume (±0.0001dm^3)	Pressure (±0.01kPa)	Temperature (±0.01K)	Molar mass constant (R) $[dm^3kPaK^{-1}mol^{-1}]$	Molar mass $[gmol^{-1}]$	Molar mass Uncertainty $[gmol^{-1}]$
0.09	0.03914	100.28	296.6	8.314	57	10

$$CO_2\ molar\ mass\ uncertainty[\pm gmol^{-1}]\ =\ \pm\ (\frac{|\pm m[g]|}{m[g]} + \frac{|\pm V[dm^3]|}{V[dm^3]} + \frac{|\pm P[kPa]|}{P[kPa]} + \frac{|\pm T[K]|}{T[K]})\ *\ Mr\ [gmol^{-1}]$$

±m[g] is the uncertainty of CO_2 mass, m[g] is CO_2 mass, $\pm V[dm^3]$ is uncertainty of CO_2 volume, V$[dm^3]$ is CO_2 volume, ±P[kPa] is uncertainty of pressure, P[kPa] is pressure, ±T[K] is uncertainty of temperature, T[K] is temperature, Mr $[gmol^{-1}]$ is the molar mass.

CO_2 molar mass uncertainty will be denoted as CO_2MMU

$$CO_2MMu[\pm gmol^{-1}] = \pm\left(\frac{|\pm 0.02g|}{0.09g} + \frac{|\pm 0.0001dm^3|}{0.03914dm^3} + \frac{|\pm 0.01kPa|}{100.28kPa} + \frac{|\pm 0.01K|}{296.6K}\right) * 57gmol^{-1} \approx 10$$

5. Percent uncertainty(%uncertainty) for molar mass $[gmol^{-1}]$

Data used for sample calculation: Entire processed data table

$$\%uncertainty = \sum_{i=1}^{n}\left(\frac{|\pm m_i[g]|}{m_i[g]} + \frac{|\pm V_i[dm^3]|}{V_i[dm^3]} + \frac{|\pm P_i[kPa]|}{P_i[kPa]} + \frac{|\pm T_i[K]|}{T_i[K]}\right) * 100\% \div n$$

$\pm m_i$[g] is the uncertainty of CO_2 mass for trial i, m_i [g] is CO_2 mass for trial i, $\pm V_i$ $[dm^3]$ is uncertainty of CO_2 volume for trial i, V_i $[dm^3]$ is CO_2 volume for trial i, $\pm P_i$ [kPa] is uncertainty of pressure for trial i, P_i [kPa] is pressure for trial i, $\pm T_i$ [K] is uncertainty of temperature for trial i, T_i [K] is temperature for trial i. n is the number of trials.

$$\%uncertainty = \pm\sum_{i=1}^{18}\left(\frac{|\pm m_i[g]|}{m_i[g]} + \frac{|\pm V_i[dm^3]|}{V_i[dm^3]} + \frac{|\pm P_i[kPa]|}{P_i[kPa]} + \frac{|\pm T_i[K]|}{T_i[K]}\right) \times 100\% \div 18$$

$$= \pm\frac{[(\frac{|\pm 0.02g|}{0.09g} + \frac{|\pm 0.0001dm^3|}{0.03914dm^3} + \frac{|\pm 0.01kPa|}{100.28kPa} + \frac{|\pm 0.01K|}{296.6K}) + (\frac{|\pm 0.02g|}{0.21g} + \frac{|\pm 0.0001dm^3|}{0.04180dm^3} + \frac{|\pm 0.01kPa|}{100.28kPa} + \frac{|\pm 0.01K|}{296.6K}) + ...] \times 100\%}{18}$$

$\approx \pm 30\%$

6. Percent error(%error) for molar mass$[gmol^{-1}]$

Data used for sample calculations:

Average molar mass $[gmol^{-1}]$	45 $gmol^{-1}$
Theoretical molar mass of CO_2 $[gmol^{-1}]$	44.1 $gmol^{-1}$

$$\pm Percent\ error = \pm\left|\frac{Actual - theoretical}{theoretical}\right| \times 100\% = \pm\left|\frac{Mr_{exp}[gmol^{-1}] - Mr_{theo}[gmol^{-1}]}{Mr_{theo}[gmol^{-1}]}\right| \times 100\%$$

$$\pm\%error = \pm\frac{45gmol^{-1} - 44.1gmol^{-1}}{44.1gmol^{-1}} \times 100\% \approx \pm 2.0\%$$

Conclusion and evaluation

Conclusion

According to the sample calculations and processed data table, the molar mass $[gmol^{-1}]$ for the unknown gas is 45±10 $gmol^{-1}$ by taking the average of all 18 molar masses obtained (with two outliers excluded.) More specifically, the value of 45 $gmol^{-1}$ was obtained by averaging the molar masses calculated by the ideal gas equation $Mr\ [gmol^{-1}] = \frac{m[g] * R\ [dm^3 kPaK^{-1} mol^{-1}] * T[K]}{P[kPa] * V[dm^3]}$. To determine the name of the unknown gas, it is necessary to compare the experimentally obtained value, 45±10 $gmol^{-1}$, with the actual molar mass of gases according to the periodic table. Since the molar mass of carbon dioxide(CO_2) is 44.1 $gmol^{-1}$, according to the *IB Chemistry Data Booklet*, and there are no other gases that have a closer value, it is reasonable to conclude that the gases obtained from this experiment is carbon dioxide. Additionally, the actual molar mass of CO_2, 44.1 $gmol^{-1}$, is within the range of the experimentally determined molar mass including its uncertainty 45±10 [$gmol^{-1}$]. Because the theoretical value is within the range, the result is accurate.

Another noticeable trend in the data collection can be revealed by conducting stoichiometry of $CuCO_3$(s) → CO_2(s) +CuO (g). Involving quantities are 0.20±0.01 g of $CuCO_3$, molar mass of $CuCO_3$ 123.56 $gmol^{-1}$, 0.07±0.02 g of CO_2 calculated by averaging the CO_2masses of 18 trials and the experimentally obtained CO_2 molar mass 45±10 $gmol^{-1}$. Theoretically, the number of moles(n) of $CuCO_3$ should be the same as that of CO_2 calculated using the formula $n = \frac{M}{Mr}$. In this way, the number of moles for $CuCO_3$ is $\frac{0.20g}{123.56gmol^{-1}} \approx 0.0016$; the number of moles for CO_2 is $\frac{0.07}{45.00} \approx 0.0016$. Thus, the molar mass of CO_2 obtained in this experiment is accurate.

Evaluation

To examine the accuracy and precision of data collection, the percent uncertainty and percent error were calculated. The percent uncertainty is 30%, which is very significant. Thus, it is reasonable to determine that the results are not precise because there is a large variation in the data for each trial. On the other hand, the percent error is 2.0%, which is very small. In addition, as stated in the conclusion, the theoretical molar mass $[gmol^{-1}]$ is 44.01, which is in the range of 45±10 $[gmol^{-1}]$. Thus, the result is accurate but imprecise. There are sources of uncertainties that caused these discrepancies.

Errors	Systematic or random	How significant(how big they are)	Improvements
Leak of air	Systematic	This source of error can be significant depending on how much air is leaked during the chemical reaction. Its impact on the result depends on how much air is leaked. This error can be caused by the fissure in the boiling rubber tube and the boiling rubber tube plug. In this way, the produced CO_2 gas can partially escape the transfer into the eudiometer into the room. As a result, the volume of gas collected in the eudiometer will be smaller. The calculated molar mass for the gas will be bigger due to the equation $Mr\ [gmol^{-1}] = \frac{m[g] * R\ [dm^3 kPaK^{-1} mol^{-1}] * T[K]}{P[kPa] * V[dm^3]}$, because as V $[dm^3]$ becomes smaller(the denominator becomes smaller), the left hand side will be bigger, causing a slightly larger molar mass. This discrepancy can both contribute to percent error and percent uncertainty.	To improve on the experiment's methodology, it is essential to eliminate the leak of air during the chemical reaction. Possible improvements on this can be using completely new rubber tube plug and boiling rubber tube to lower the possibility of employing problematic gas transfer devices. In this way, gas can be more successfully conducted into the eudiometer.
Mass measurement	Systematic	This source of error might not be very significant but can still have a slight influence on experimental results. Since the weighing of $CuCO_3$ is performed on open electronic balance, the flowing air in the room can have an effect on the number displayed. The air flow can make the mass appear larger but the actual amount is less. The smaller mass would lead to smaller molar mass due to the equation $Mr\ [gmol^{-1}] = \frac{m[g] * R\ [dm^3 kPaK^{-1} mol^{-1}] * T[K]}{P[kPa] * V[dm^3]}$. As m [g] becomes smaller, the value of molar mass also becomes smaller. This discrepancy can both contribute to percent error and percent uncertainty.	An improvement on this procedure to avoid discrepancies associated with mass measurement can be performing the experiment in a room without airflow, using a glass shield to isolate the balance with the outside, or in vacuum. For a high school lab environment, the first and third-a room without airflow and vacuum-are not realistic, but using a shield to exclude air fluctuations on the balance is effective.
Temperature and Pressure	Systematic	When deriving the molar mass $[gmol^{-1}]$ with $Mr\ [gmol^{-1}] = \frac{m[g] * R\ [dm^3 kPaK^{-1} mol^{-1}] * T[K]}{P[kPa] * V[dm^3]}$, the values of temperature [K] and pressure [kPa] are taken directly by reading the number on the electronic device in the room. As a result, the values are not relevant to the gas collected, but the air in the room. This source error can be the most significant because there can be a big difference between the temperature[K] and pressure[kPa] of room and that of CO_2 gas. Both T [K] and P [kPa] in numerator and denominator can increase or decrease the measurement of Mr $[gmol^{-1}]$. Their impact on the result can be big or small depending on what the actual values of pressure and temperature are.	An improvement for this methodological discrepancy can be applying a pressure sensor and a electronic thermometer to measure of the actual pressure [kPa] and determine the temperature [K] of CO_2. In this way, the value of temperature and pressure used in the equation to derive molar mass $[gmol^{-1}]$ will be more accurate, reducing the inaccuracy and imprecision of the measurement.

Extensions:

An extension to this experiment, determining the molar mass of an unknown gas, is changing the condition of temperature and pressure. Ideal gas law works best under high temperature and low pressure(Marie, 2020). In this case, to ensure the ideal gas equation is used most appropriately and ideally, experimenters can manipulate the experiment condition.

Reference:

Helmenstine, Anne Marie, Ph.D. (2020, August 25). What Is the Most Ideal Gas? Retrieved from https://www.thoughtco.com/what-is-the-most-ideal-gas-607548

International Baccalaureate Organization. (2017). Chemistry data booklet. In http://www.ibo.org/ (4th edition). https://www.iisjaipur.org/International_Wing/Chemistry_data_booklet.pdf