University of Salford
MANCHESTER

A laboratory report on

FUNDAMENTAL OF NATURAL GAS PRODUCTION SYSTEMS AND DESIGN

By

Idoko Job John
@00512412

Submitted to

Dr Martin Burby

Petroleum and Gas Engineering Division, School of Computing Science and Engineering, University of Salford, Manchester

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ABSTRACT

This document presents the report of three laboratory sessions: Gas Relative Density Measurement, Determination of the Calorific Value (CV) of natural gas and Analysis of Natural Gas Combustion Products. It, therefore, consists of three chapters covering the three sessions respectively.

The aim of the first experiment (Gas Relative Density Measurement) is to demonstrate laboratory estimation of the Specific Gravity of Natural Gas using the 'Simmance' bell method. To do this, the effusion time of Methane and Butane were related to the effusion time of air, under the same conditions using Graham's law of effusion. The test revealed that the relative density of the Natural Gas sample is 0.66 for the wet gas basis and corrected to 0.657 for the dry gas basis at 15°C and 1.021bar. Also, Butane, which was used as the control experiment, was found to have a specific gravity of 2.014 at 15°C and 1.021bar. This agrees with the standard value of the Specific Gravity (SG) of methane and establishes the credibility of the experiment.

In the Determination of the Calorific Value of Natural Gas experiment, Natural gas heating value was determined using the Boys Apparatus at the same conditions of temperature and pressure stated in the second paragraph above. The Calorific value of the sample Gas was obtained as $975.45 \frac{BTU}{sft^3}$. The CV value obtained is in the range of published figures for the lower and higher heating values of natural gas at the prevailing conditions, within acceptable error margin.

The third experiment was aimed at investigating the main products of natural gas combustion. The test showed that the Oxygen content in the combustion product ranges from 12% to 20% with the maximum obtained when the air shutter was opened. Also, maximum $CO:CO_2$ ratio of 9.3×10^{-3} was obtained when the shutter was closed.

An error analysis was carried out and precautions taken to minimize errors were given for each experiment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

GAS RELATIVE DENSITY (SPECIFIC GRAVITY) MEASUREMENT

1.1 The Aim of the Experiment

This experiment was aimed at demonstrating laboratory estimation of the Specific Gravity of Natural Gas using the 'Simmance' bell method.

1.2 Objectives of the Experiment

To achieve the above aim, requisite objectives include:

- To obtain an average value of the time of effusion of Methane.
- To obtain an average value of the time of effusion of air.
- To estimate an uncorrected value of the SG of Methane with the results of the above two objectives.
- To repeat the above three objectives for Butane.
- To obtain a corrected value for the SG of Methane using the appropriate correlation or correction factors

1.3 Theory

The specific gravity (SG) or relative density of a gas, at a given condition of temperature and pressure, is the ratio of the density of that gas to that of air under the same conditions of temperature and pressure.

The 'Simmance' bell method of determining the SG of gas relates the time taken for a volume of the test gas to effuse through an orifice with the time taken by the same volume of air under the same conditions. The SG of the test gas is then calculated using Graham's law of effusion which states that "the rate of effusion of a gas through an orifice is inversely proportional to the square root of its density" (Mason & Kronstadt, 1967).

Equation 1 relates the time of effusion of a gas through an orifice and the time of effusion of air through the same orifice, under the same conditions, with the relative density of the gas.

$$Gas\ Specific\ Gravity\ (SG) = \left(\frac{Gas\ time}{Air\ time}\right)^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\text{ Equation 1.1}$$

Equation 1.1 gives the value of the uncorrected relative density of natural gas (or values obtained on the wet basis). To obtain the values on the dry basis, the correction factor in Table 1.1.

Table 1.1: Dry Basis to Wet Basis Methane Relative Factor Correction Factors at 15°C

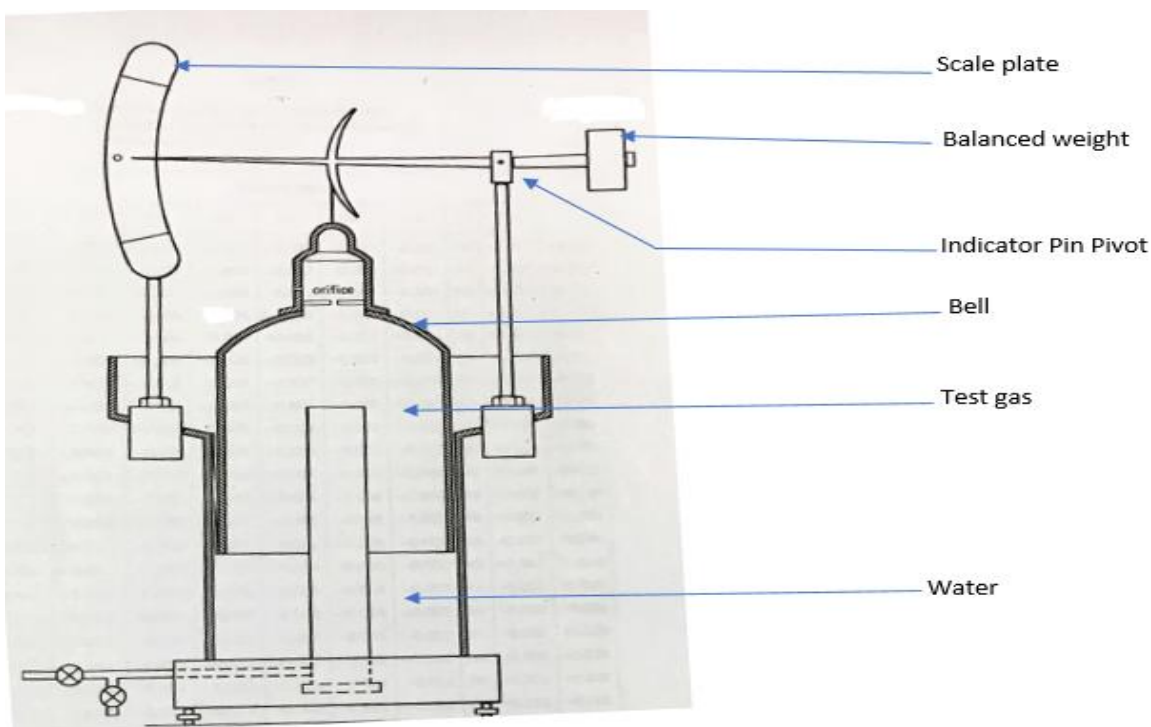| Relative Density	Correction factor
0.3	-0.007
0.4	-0.006
0.5	-0.005
0.6	-0.004
0.7	-0.003
0.8	-0.002
0.9	-0.001
1	Nil
1.1	0.001
1.2	0.002

1.4 Description of Experimental Setup

Figure 1.1.4: Schematic of Simmance Specific Gravity Bell

The apparatus used for this experiment are:

- 'Simmance' Specific Gravity Bell.
- Electronic stopwatch.

A schematic of the experimental set up is shown in Figure 1.1.

1.5 Experimental Procedure

i. The apparatus for the experiment was set up as shown in Figure 1.1.

ii. One, out of two gas feed cocks was connected to the test gas supply while the second was left open so that air can enter without restriction.

iii. To purge the system of any unintroduced, unintended gases, the gas cock was closed and filled with air by slowly depressing the free end of the beam until the pointer is well above the upper mark on the scale and then, allowing the bell to descend until water covers its crown.

iv. Step (iii) was repeated until the system was sufficiently cleansed of any other gases but air.

v. With air as the test gas, the bell was refilled with air as described in Step (iii).

vi. The air cock was closed when the bell was at its highest point.

vii. Using a stopwatch, the time taken for the pointer to pass between the upper and lower marks on the scale was measured as the air outlet was opened and the bell descended.

viii. The experiment was repeated, and successive observations were made until two readings with no more than ±2 seconds variation were obtained.

ix. The average of the two close readings was taken and used to compute the relative density of the gas using Equation 1.1 and Table 1.1.

x. The experiment was repeated with methane and butane as the test gas.

xi. Prior to the commencement of the testing for another gas, the intended test gas was used to recirculate the entire system until the previous gas was sufficiently purged.

xii. Results are reported to the nearest 0.001.

1.6 Experimental Data

Ambient Temperature: **15°C.**

The temperature of the water = **17°C**

Barometric pressure reading: **21mbarg. Therefore, Atmospheric pressure =** 1.021bar.

Table 1.2 shows the data obtained from the experiment. The two highlighted cells, in each column, indicate **the two readings with no more than ±2 seconds difference** that will be used to estimate the relative density of the gas.

Table 1.2: Experimental Observations of the Time of Effusion of Air, Methane and Butane

RUNS	TIME(seconds)		
	Air	Methane	Butane
1	54.74	45.04	78.31
2	55.33	44.78	78.83
3	55.13	44.66	78.14
4	55.12	44.79	78.49

1.7 Data Analysis

The highlighted **two readings, of effusion time, with no more than ±2 seconds difference**, of Table 1.2 are imported into Columns 2 and 3 of Table 1.3 and the average for each is given in Column 4 of Table 1.3.

The Relative Density for each gas (Column 4, Table 1.3) is obtained using Equation 1.1

Using Table 1.1, the SG of methane is corrected to the dry gas bases as the sum of the correction factor in Table 1.1 and the SG of 0.660 obtained in Table 1.3 below. The correction factor for an SG of 0.66 was obtained using linear interpolation between the columns of Table 1.1 shown in Table 1.4.

Table 1.3: Relative Density of Gases obtained from the Experiment

TEST GAS	TIME OF EFFUSION(SECONDS)			RELATIVE DENSITY	
	R1	R2	Average	Wet Gas Basis	Dry Gas Basis
Air	55.130	55.120	55.125	1.000	N/A
Methane	44.780	44.790	44.785	0.660	0.657
Butane	78.310	78.140	78.225	2.014	N/A

Table 1.4: Linear interpolation to Obtain Correction Factor for Natural Gas SG of 0.66 at 15°C

Relative Density	Correction factor
0.6	-0.004
0.66	-0.0034
0.7	-0.003

4

1.7.1 Sources of Errors and Precautions Taken to Minimize Errors

i. Gas effusion from the bell causes cooling as pressure is reduced due to Joule-Thompsons Effect; which can lead to condensation of water across the orifice (Figure 1.1) and a consequent undue increase in the time of effusion of the gases. To prevent this, weight was balanced such that the time of effusion was less than 80 seconds for all experimental runs.

ii. Besides condensed water, other restrictions to gas effusion through the orifice was prevented by periodic removal of the cap on the orifice to clean out dust, fluff or moisture with a soft brush.

iii. To eliminate parallax error, the scale plate was polished for a clear determination of the time of intersection of the pointer and its reflector, and the upper and lower indicator lines of the plate. Also, the beam and bell were aligned to prevent the indicator pointer from touching or gliding on the scale.

iv. The system was initially purged with air prior to the start of the experiment, when the air was the test gas, and subsequently, with the next test gas; recirculating it for a period sufficient enough to rid the system of any remnant gas but the gas to be tested.

v. Contact between the bell and the wall will introduce error due to friction and reduce the time of effusion. This was avoided by properly aligning the bell in the water-filled wall to just float in the water and not touch the wall during the experiments.

vi. Bell was also stabilized and not wobbling during each experiment.

vii. Proper division of labour and housekeeping were implemented.

1.8 Conclusions

- Natural Gas relative density was obtained as 0.66 for the wet gas basis and corrected to 0657 for the dry gas basis at 15℃ and 1.021bar.

- Butane, which was used as the control experiment, was found to have a specific gravity of 2.014 at 15℃ and 1.021bar. This agrees with the standard value of the SG of methane and establishes the credibility of the experiment.

- As expected, Butane gave a higher reading for SG since it has more carbon and hydrogen atoms than Natural gas and is thus, denser than both natural gas and air.

1.9 Chapter Reference

Mason, E. A. (University of M., & Kronstadt, B. (University of M. (1967). Graham's Laws of Diffusion and Effusion. *Journal of Chemical Education*, 740–744. Retrieved from https://pubs.acs.org/doi/pdf/10.1021/ed044p740

CHAPTER TWO

DETERMINATION OF THE CALORIFIC VALUE OF NATURAL GAS

2.1 The Aim of the Experiment

This experiment was aimed at measuring the Calorific Value (CV) of natural gas.

2.2 Theory

The Calorific Value (CV) of a fuel is a measure of its heating value. For liquid fuels, it is the amount of energy that can be derived from the combustion of a unit volume of the fuel (Nasr & Connor, 2014). The CV can, therefore, be expressed in ratios of Energy to volume such as $MJ/_{(st)m^3}$ and $BTU/_{sft^3}$.

$$26.34 \left(MJ/_{(st)m^3} \right) = 1 \left(BTU/_{sft^3} \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{ Equation 2.1}$$

In this experiment, the CV of natural gas was determined by relating the amount of expansion caused by heating water through the combustion of Methane as given shown in Equation 2.2.

$$CV = \frac{\Delta T \times W \times S \times F}{V} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{ Equation 2.2}$$

Where:

$\Delta T = Temperature\ rise\ (°C)$

$W = Amount\ of\ water\ displaced\ (Kg)$

$S = Specific\ heat\ capacity\ of\ water\ (MJ/Kg°C)$

$CV = Calorific\ value\ of\ the\ gas \left(MJ/_{(st)m^3} \right)$

$F = Conversion\ factor\ for\ converting\ CV\ from\ MJ/_{(st)m^3}\ to\ BTU/_{sft^3}\ and\ vice\ versa.$

$V = Volume\ of\ gas\ burnt\ in\ (st)m^3$

2.3 Description of Experimental Setup

The apparatus for this experiment is called Boys Calorimeter. Figure 2.1 shows a cross-section of it and a schematic of how it works.
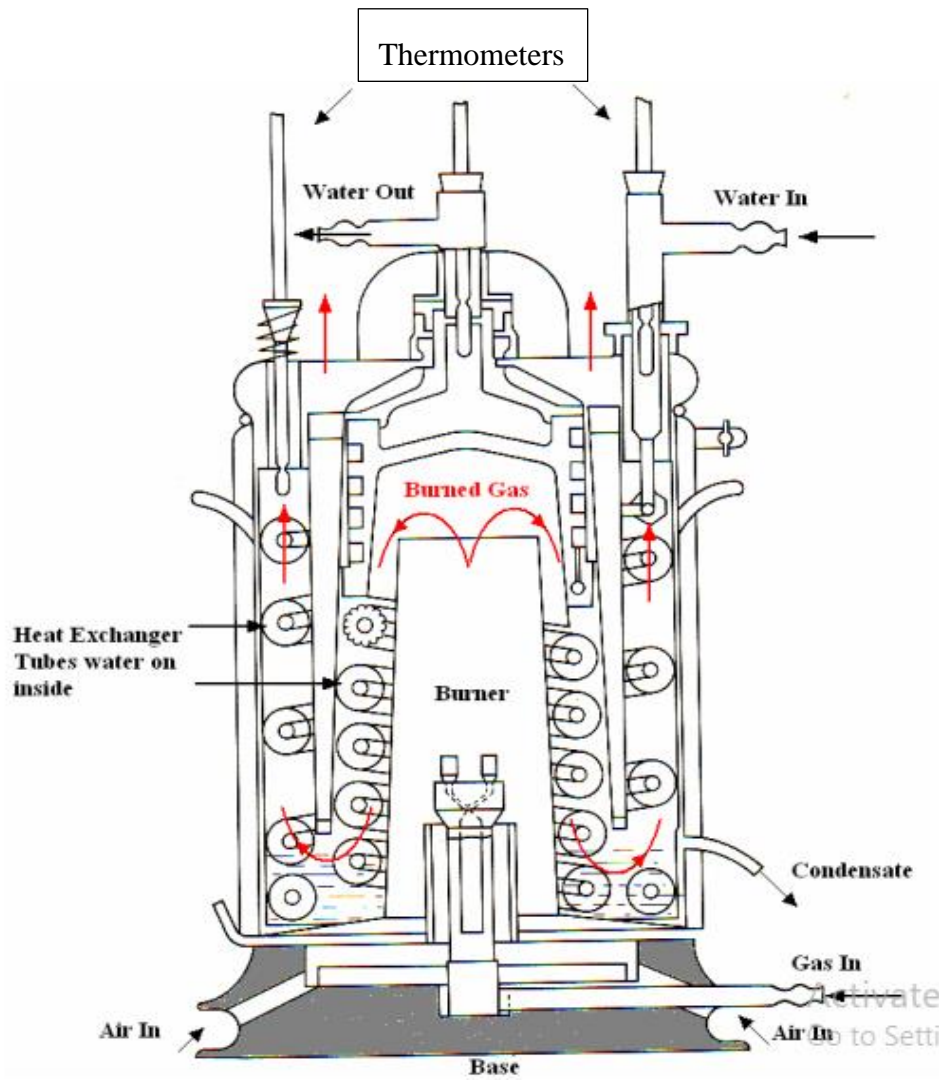
Figure 2.1: Cross-section and schematic of the Boys Calorimeter (Edexcel National Certificate., N.D.)

2.4 Experimental Procedure

i.   The Boys calorimeter was set up as shown in Figure 2.1.

ii. Gas was turned on and ignited

iii. The water source was also turned on and the calorimeter was placed on its base.

iv. The flow of gas to the calorimeter was adjusted so that the time for one revolution of the meter hand falls within a set time obtained from the Equation below:

$$t_{min} = \frac{3CV}{100} \ and \ t_{max} = \frac{3CV}{100} + 5$$

Where: $CV = Expectected \ Calorific \ value \ in \ \frac{Btu}{cu.ft}$

$$t = time \ in \ seconds$$

v. The water flow rate was also adjusted so that the amount of water collected over for revolutions of the meter hand is within $50mL$ of the numerical value of CV.

vi. Water was then poured through one of the effluent gas holes until it began to run out of the condensate outlet pipe.

vii. The calorimeter was then allowed to settle down until steady temperature readings were observed at the water inlet and outlet.

viii. The following observations were then made and recorded.

    a. When the meter hand was at 3 o'clock, the inlet thermometer was read. When the meter hand reaches 12 o'clock, the changeover funnel was moved to direct the water into the container.

    b. When the meter hand reaches 3 o'clock again, the first reading of the outlet thermometer was taken, and this reading was repeated at every succeeding quarter turn until four readings have been taken.

    c. Steps (a) and (b) are repeated three times and a total of four readings of the inlet temperatures and sixteen readings of the outlet temperatures were obtained and tabulated.

    d. When the meter hand reaches 12 o'clock the final time, after the last reading of the outlet thermometer, the funnel was moved to direct the outlet water to waste.

ix. Barometer reading was taken, and the ambient temperature was also recorded.

x. The water collected is measured in the cylinder and the volume was recorded.

2.5 Experimental Data

Ambient Temperature: **15°C.**

The temperature of the water = **17°C**

Barometric pressure reading: **21mbarg. Therefore, Atmospheric pressure =** 1.021bar.

Table 2.1 shows the data obtained from the experiment.

Revolutions	T$_{in}$(°C)	T$_{out}$(°C)
1st	16.4	51.5
		51.8
		52.0
		52.0
2nd	16.4	52.2
		52.4
		52.6
		52.3
3rd		53.1
		53.1
		53.2
		53.3
4th	16.4	53.4
		53.5
		53.6
		53.7
Average temperature reading	**16.4**	**52.73**
VOLUME OF WATER = 540ml		

2.6 Data Analysis

The weight of water volume collected and the change in temperature have been earlier related to the calorific value using Equation 2.2 which can be modified to obtain the CV in BTU/sft^3 as shown in Equation 2.3; which can be converted to SI units using Equation 2.1.

$$\boldsymbol{CV = 49.72 \times \Delta T \times W} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{Equation 2.63}$$

$Where$:

$49.72 = conversion\ factor$

$\Delta T = Avg.T_{out} - Avg.T_{in} = 52.73 - 16.4 = 36.33°C$

$W = Weight\ of\ water\ (Kg)$

$CV = Calorific\ value\ of\ the\ gas\ in\ BTU/sft^3$

The weight of water, W, can be obtained from the volume of water obtained using as shown below:

$$W\ (kg) = \rho_{water}\left(\frac{Kg}{m^3}\right) \times Water\ volume\ (m^3)$$

$$\therefore \qquad W = 1000\left(\frac{Kg}{m^3}\right) \times 540(ml) \times \frac{1L}{1000ml} \times \frac{1m^3}{1000L} = 0.54Kg$$

9

Using Equation 2.3,

$$\therefore CV = 49.72 \times 0.54 \times 36.33 = 975.45 BTU/sft^3$$

$$or \quad CV = (975.45 BTU/sft^3) \times \frac{26.34 \left(MJ/_{(st)m^3} \right)}{1 \left(BTU/_{sft^3} \right)} = 25693.37 \left(MJ/_{(st)m^3} \right)$$

The CV value obtained above is reasonably close to the publication of The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), of the lower and higher heating values of natural gas at 32°F and 1atm, of 983 $BTU/_{sft^3}$ and 1089 $BTU/_{sft^3}$ respectively (GREET, 2010).

2.7 Conclusion

- The Calorific value of the natural gas was obtained as $975.45 BTU/sft^3$
- The CV value obtained is in the range of published values for the lower and higher heating values of natural gas at the prevailing conditions, within acceptable error margin.

2.7.1 Possible Sources of Error and Steps Taken to Minimize Them

i. Temperature and Pressure readings were taken, with the thermometer and barometer respectively, and meter hand revolutions were observed at eye level to avoid parallax error.

ii. To avoid fluctuations in the natural gas supply, a thick cylinder gas source was used and not the mains supply.

iii. Also, a bleed tube was incorporated into the system to sink any excess water.

2.8 Chapter References

Edexcel National Certificate/Diploma Principles and Applications of Thermodynamics Nqf Level 3 Outcome 3-Combustion Content. (N.D.). Retrieved From Www.Freestudy.Co.Uk

GREET, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, GREET 1.8d.1, developed by Argonne National Laboratory, Argonne, IL, released August 26, 2010.

Nasr, G. G., & Connor, N. E. (2014). *Natural Gas Engineering And Safety Challenges: Downstream Process, Analysis, Utilization And Safety*. *Natural Gas Engineering And Safety Challenges: Downstream Process, Analysis, Utilization And Safety* (Vol. 9783319089). Https://Doi.Org/10.1007/978-3-319-08948-5

CHAPTER THREE

ANALYSIS OF NATURAL GAS COMBUSTION PRODUCTS

3.1 The Aim of the Experiment

This experiment aimed to investigate the main products of natural gas combustion.

3.2 The objective of the Experiment

To achieve the above aim, the objectives below were met:

i. To measure the oxygen contents of combustion products from a natural gas burner.

ii. To measure the carbon monoxide (CO) contents of combustion products from a natural gas burner.

iii. To measure the carbon dioxide (CO_2) contents of combustion products from a natural gas burner.

3.3 Theory

Combustion is an important exothermic reaction which releases the energy in a fuel (Penninger, L et al. n.d.). Three major elements are required for combustion to take place: fuel, heat and oxygen. The general combustion equation given below shows the major products of the combustion of saturated hydrocarbons of the alkane family.

$$C_xH_y + aO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O$$
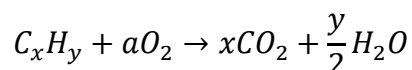
$$where: a = x + \frac{y}{4}$$

3.4 Description of Experimental Setup

The equipment used for the experiment comprises of the following:

i. Paramagnetic, Oxygen Analyser

ii. Fyrite Apparatus

iii. Draeger, Analysis tubes

iv. Infra-Red, CO/CO_2 analyser

v. Kane May, Portable Gas Analyser

3.5 Experimental Procedure

The Bunsen burner was placed beneath the sampling hood with its air shutter fully opened and the damper closed.

i. The oxygen analyser was zeroed by passing "white-spot" nitrogen through the instrument.

ii. Air was passed through the instrument and the "span" control was adjusted to 20.95%O_2.

iii. Keeping the sample rate equivalent to 70-80units, on the flowmeter, the oxygen analyser was used as indicated in the maker's manual.

iv. Also, the Fyrite apparatus and Draeger apparatus were utilized as instructed in the user's manual.

v. The experiment was repeated with the air shutter of the Bunsen burner fully closed and the sampling hood damper closed.

3.6 Experimental Data

	Air Shutter Open			Air shutter Closed		
	CO (ppm)	CO$_2$ (%)	O$_2$ (%)	CO (ppm)	CO$_2$ (%)	O$_2$ (%)
Bacharach Fyrite		1	20		4	12
Infra-red	0.0019	1.13		0.080	5	
Drager Tube	50	1		700	7.5	

3.7 Data Analysis

3.7.1 Air Shutter Open

- Infra-red $CO:CO_2 = \frac{0.0019\times10^{-6}}{0.0113} = 1.68 \times 10^{-7}$

- Drager Tube: $CO:CO_2 = \frac{50\times10^{-6}}{0.01} = 50 \times 10^{-8}$

3.7.2 Air Shutter Closed

- Infra-red $CO:CO_2 = \frac{0.08\times10^{-6}}{0.05} = 1.6 \times 10^{-6}$

- Drager Tube: $CO:CO_2 = \frac{700\times10^{-6}}{0.075} = 9.3 \times 10^{-3}$

3.8 Conclusion

- The experiment showed that Oxygen content in the combustion product ranges from 12% to 20% with the maximum obtained when the air shutter was opened.
- Also, maximum $CO:CO_2$ ratio of 9.3×10^{-3} was obtained when the shutter was closed.

3.9 Chapter Reference

Penninger, A., Lezsovits, F., Rohaly, J., & Wolff, V. (n.d.). *Combustion*. Budapest: Department of Energy Engineering, Budapest University of Technology and Engineering. Retrieved from ftp://ftp.energia.bme.hu/pub/Tananyagok-archivuma/BSc-kepzes/COMBUSTION.pdf