

Evaluation of Emissions by Different Analysis Method at Hot Mix Asphalt Plant Combustion Source

Farahiyah Abdul Rahman^{1*}, Nur Anira Asyikin Hashim¹, Thanwa Filza Nashruddin²

¹Faculty of Civil Engineering and Technology,
Universiti Malaysia Perlis, 02600 Arau, Perlis, MALAYSIA

²Faculty of Civil Engineering,
Universiti Teknologi Malaysia, 81310 Skudai, Johor, MALAYSIA

*Corresponding Author

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Abstract: The combustion process for the asphalt mixing in hot mix asphalt (HMA) plant can produce harmful flue gases emission into the atmosphere. Combustion activities produce heat for industrial usage when fuel reacts with oxygen in the air under suitable conditions. High concentrations of undesirable emissions can be formed if the combustion is not properly controlled during the reaction. This paper gives an overview on the method and measurement of these emissions in combustion analysis by focusing on the three types of analysis methods which are laboratory testing analysis, on-site emission analysis, and theoretical analysis. Three types of data were prepared in order to achieve the objective of the study, which are literature study, site visit, and laboratory analysis. The result shows that there are slightly different emission results even though they came from the same source. Clearly, the analysis shows that the air-fuel ratio during combustion can have a significant effect on the emission result. The excess air supplied can cause dilution to the emission and leads to a low emission value.

Keywords: Emission analysis, combustion, hot mix asphalt plant

1. Introduction

The typical process in hot mix asphalt (HMA) plants includes aggregate stacking, aggregate supply, bitumen heating, aggregate heating, and mixture mixing [1]. This activity consists of the combustion process and is capable of producing greenhouse gas (GHG) emissions consisting of carbon dioxide (CO₂), nitrogen oxides (NO_x), hydrocarbons, carbon monoxide (CO), particulate matter, and sulfur dioxide (SO₂) [2], [3]. These emissions are capable of adversely affecting human health, ecosystem diversity, agricultural crops, forest species, and the environment as a whole if emissions from industrial activities are not properly monitored and controlled [4], [5]. Emission monitoring and enforcement will be needed to ensure that countermeasures are properly installed, maintained, and continually operated [6]. Thus, the Kyoto Protocol first commitment period (2008-12) to reduce harmful emissions has been set to counter this problem [7].

1.1 Combustion

Combustion is the process where CO₂ from fuel reacts with oxygen (O₂) in the air to produce heat. Fossil fuels are natural gas, fuel oil, coal, or gasoline. Heat is a useful product used for many conditions such as industrial processes, environmental heating, or for engine operation. It is therefore undeniable that boilers, furnaces and engines are important consumers of fossil fuels [8], [9]. Fossil fuels are mainly composed of carbon and hydrogen, so they are a

*Corresponding author: farahiyahrahman@unimap.edu.my

type of hydrocarbon. The main chemical products formed from the reactants of carbon and hydrogen in the fuel with the presence of oxygen (O₂) when they are burned in the air are carbon dioxide (CO₂) and water (H₂O). The purpose of combustion is to release energy in the form of heat [8], as shown in Eq. (1).



The reaction of methane (CH₄), which is the main component of natural gas, with O₂ in the air is the simplest example of hydrocarbon fuel combustion. When this reaction is under stoichiometric condition (balance), each molecule of methane reacts with two molecules of O₂ to produce one molecule of CO₂ and two molecules of H₂O in the reaction process. However, in actual combustion processes, other products are usually formed, which is the typical condition in the industrial process especially during the asphalt mixing process in hot mix asphalt (HMA) plant. A typical example of an actual industrial combustion process is shown in Fig. 1.

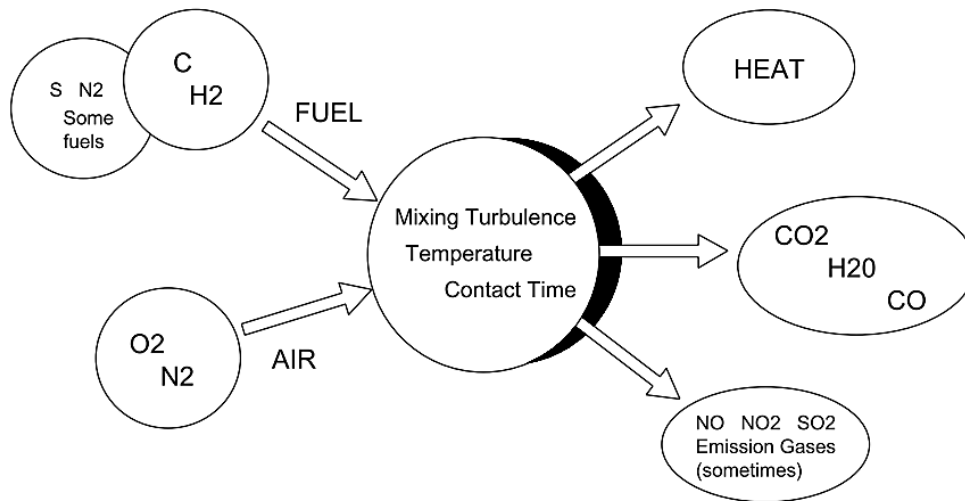


Fig. 1 - Combustion diagram [8]

This situation is because the combination of oxygen in the air and carbon in the fuel to produce heat and subsequently emissions is a complex process. It requires the right mixture ratio, sufficient activation temperature and enough time for the material to react in contact and combine [8].

1.2 Combustion Analysis

Combustion analysis is the process that usually consists of the measurement of flue emissions proportion, temperature, and may include the measurement of pressure and soot level [10]. If properly implemented, combustion analysis is able to reduce undesirable flue emissions, improve fuel efficiency and fuel economy, as well as improve the safety of fuel burning equipment. During the analysis, a probe is inserted into the exhaust flue to measure gas concentration, and a gas sample is measured on site or drawn out as a sample for further analysis. Once these measurements are made, the data is interpreted using combustion parameters such as combustion efficiency and excess air rate. A more in-depth analysis is required when studies are required to examine the content of unwanted emissions from combustion [11], [8].

1.2.1 Oxygen, Carbon Monoxide and Carbon Dioxide

Basic combustion involves the reaction of oxygen in the air with carbon and hydrogen in the fuel to produce energy in terms of heat. Besides that, it emits carbon dioxide (CO₂) and water vapour as the main combustion product and some other gases as minor combustion product. Theoretically, under stoichiometric combustion, the only gases from the combustion reaction are CO₂, water vapor and nitrogen [8].

There is the case that oxygen (O₂) appears together in the flue emissions. When this happens, it means that more air was supplied than was needed for complete combustion to occur, to the extent that some O₂ was not being used and leftover. To be noted, atmospheres consist of about 20.9 % of O₂ in the ambient air [12]. Theoretically, the presence of O₂ gas in the flue indicates that more than enough combustion air was supplied to the combustion reaction [13].

On the other hand, when an inadequate amount of air is supplied to the burner, it can cause the oxygen to be insufficient to react with the carbon in the fuel to form CO₂ completely during the reaction. Instead, too little oxygen combines with carbon leads to carbon monoxide (CO) formation. Hence, CO is the product of incomplete combustion

of fuel [12]. Some efforts must be made to minimize its formation because it is known as one of the toxic gas if it is released into the atmosphere [8], [14].

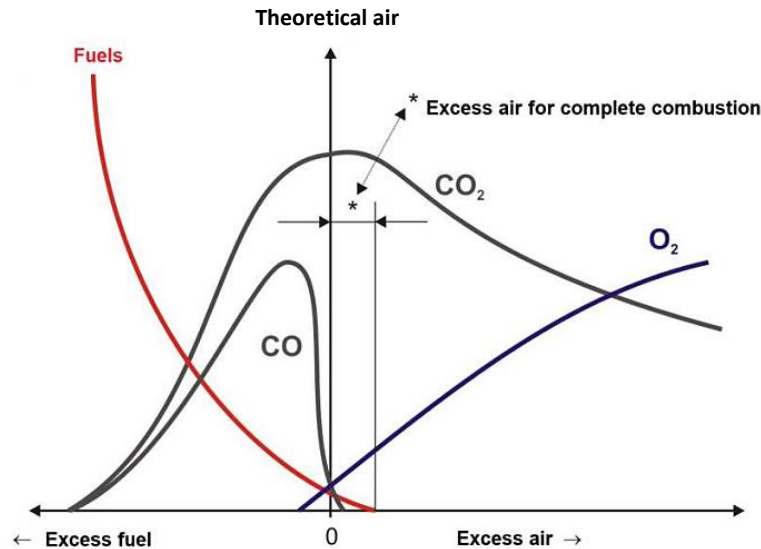


Fig. 2 - Combustion gas concentration of theoretical combustion air [15]

Fig. 2 illustrates the general relationship between the O_2 supplied for the reaction with the concentration of CO_2 and CO emission in the exhaust. The CO concentration decreases rapidly as the air level approaches the theoretical air condition. This condition occurs when CO selects additional O_2 atoms to form CO_2 . After the theoretical air limit, O_2 begins to increase, but CO_2 concentration drops gradually. It is because O_2 concentration starts to dilute the exhaust gases containing CO_2 . The maximum value of the CO_2 peak depends on the type of fuel used for the combustion.

When the concentration of CO_2 is maximum during the reaction, it means that the use of fuel is the most efficient and cost-effective at that time. In theory, this condition occurs when the optimum amount of O_2 in the supplied air reacts with all the carbon in the supplied fuel. The condition where the optimum quantity of air is supplied is usually referred to as theoretical air or stoichiometric air conditions. The fuel consumption rate plays the most important role in the theoretical quantity of air required for the combustion reaction [16].

1.2.2 Nitrogen Oxides (NO_x) and Hydrocarbon (HCs)

Nitrogen oxides occur when oxygen combines with nitrogen in the air or in the fuel during the combustion process. In order to form, firstly, nitric oxide (NO) is generated at high temperatures flame. This is followed by the formation of nitrogen dioxide (NO_2) in the stack at cooler temperatures as the result of the oxidization process [17]. Nitrogen oxides (NO_x), principally NO and NO_2 are pollutant gases that contribute to the formation of acid rain and smog [18]. Hydrocarbons (HCs) are usually present in the combustion products because of incomplete combustion [19]. The emission can be reduced by maintaining the proper air/fuel mixture during the combustion process or proper burner maintenance of combustion equipment.

1.2.3 Sulphur Dioxide (SO₂)

The SO_2 emission levels are directly related to the amount of sulphur in the fuel used for the combustion process. During the reaction, sulfuric acid mist could be formed when SO_2 combines with water vapor in the exhaust. Sulphur dioxide itself is corrosive and harmful to the environment [20]. The most cost-effective way to reduce SO_2 emissions is to select a low-sulphur or de-sulphured fuel.

1.2.4 Air to Fuel Ratio (AFR)

The air to fuel ratio (AFR) is defined as the amount of air required to burn a given fuel. The best combustion efficiency occurs at optimum or stoichiometric AFR, so to control the highest efficiency, the AFR needs to be controlled during the combustion process [21]. It is because during fuel combustion heating process, the largest source of energy loss is through the exhaust stack. The loss of energy into the atmosphere happens when there is the condition of unnecessary high excess air is supplied during combustion. This condition also led to the reduction of the temperature of hot flue emissions.

For any combustion process there is a balance sought between wasting fuel from running it too richly and losing energy from using too much air. However, with an inadequate amount of air supplied, it led to some combustible fuel

components remain unburned. This means a balance is needed between reducing efficiency and reducing air pollution by controlling the unburned components from escaping into the atmosphere.

2. Methodology

Three types of data were prepared in order to achieve the objective of study, which are literature study, site visit, and laboratory analysis. There are three numbers of hot mix asphalt plants around Kulai, Johor which is one of the Malaysia's states that have been chosen for this study. The data collected from the site visit are the emission sources, the proportion of flue gas emissions, fuel type for combustion, and HMA's operation time. For the proportion of flue gas emission, data were analyzed in three parts, which are laboratory analysis after gas sampling, on-site gas analysis using portable equipment and theoretical analysis.

Laboratory gases analysis was done by using a residual gas analyzer (RGA). RGA is commonly used for contamination monitoring, leak detection and analysis of gases within the vacuum chamber. So, in general, RGA is used to detect small impurity effects in low-pressure gas environments because it can monitor vacuum quality on a small scale. It can easily measure up to 10-14 Torr gas level. Meanwhile, the on-site flue gas analysis was conducted by using a portable gas analyzer. The equipment used is EMS Model 5002 with accurate reading and reliability with small dimensions and low weight.

The laboratory and on-site gas analysis are compared with the theoretical combustion analysis. In the HMA plant, fuel oil was used for combustion, which consisted of 85.5% of carbon (C), 11.5% of hydrogen (H), and 3.0% sulphur (S) [11]. The emission ratio can be found by calculating the mass of a particular substance or by the number of moles produced by each substance in the fuel. A mole is defined as the mass of a substance equal to its molecular weight. This data is important and is often used to determine the theoretical combustion analysis.

3. Results

3.1 Laboratory Gas Analysis

The analysis equipment used was Residual Gas Analyzer (RGA). Table 1 shows the proportion of gases at each site. The result shows that there is significant difference of flue gases proportion by different HMA plants. The nitrogen (N₂) and nitrogen dioxide (NO₂) value are about the same for different plants. However, for carbon dioxide (CO₂), oxygen (O₂), and sulfur dioxide (SO₂), the difference in value is very significant.

Argon (Ar) and helium (He) is not the combustion product. However, the presence of these gases might be due to the air supplied during the gas sampling. This is because the ambient air contains 78.08% N₂, 20.95% O₂, 0.04% CO₂, 0.93% Argon (Ar), and a very small amount of Neon (Ne), Helium (He), Methane (CH₄), Krypton (Kr) and Hydrogen (H₂) [22].

Table 1 - The proportion of gases of a different HMA plant

| Type of gases | HMA Plant A | HMA Plant B | HMA Plant C |
|-----------------|-------------|-------------|-------------|
| N ₂ | 77.49% | 78.41% | 78.02% |
| CO ₂ | 15.55% | 4.95% | 13.15% |
| O ₂ | 2.38% | 11.11% | 6.63% |
| Ar | 2.03% | 1.89% | 1.73% |
| SO ₂ | 10 ppm | 25 ppm | 14 ppm |
| NO ₂ | 146 ppm | 157 ppm | 151 ppm |
| He | 36 ppm | 4 ppm | 44 ppm |

3.2 On-site Gas Analysis

On-site gas analysis was conducted as the gas analyzer probe was inserted into the exhaust flue. These results were compared with the theoretical value and the value analyzed in the laboratory. The result of on-site gas analyzer reading of HMA Plant A is shown in Fig. 3. The value shows that at the beginning of combustion, the amount of O₂ was higher than the amount of CO₂. This means that enough air was supplied for combustion to occur [9]. It also indicated that extra combustion air (or excess air) was supplied to the combustion reaction by observing the high value of the air-fuel ratio (AFR) in the graph. Then the percentage of O₂ decreased and CO₂ gradually increased. This pattern showed that O₂ was consumed to produce CO₂ during the combustion process. This continued until the combustion reached thirty-sixth minutes. After that, the O₂ and CO₂ levels stabilized at 10.1% and 13.1%, respectively, with proportional values.

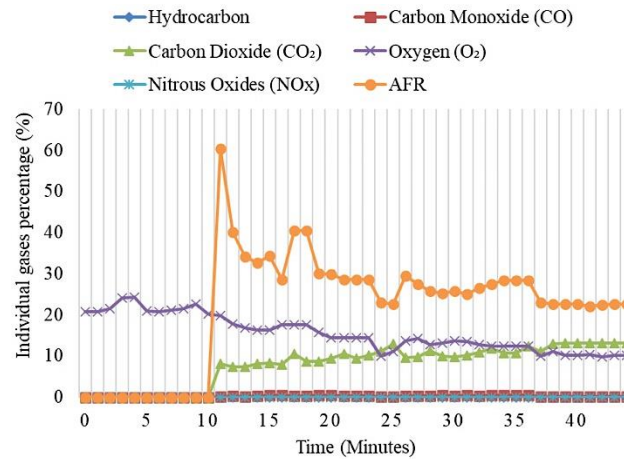


Fig. 3 - On-site gas analyzer reading for HMA Plant A

The results of the on-site gas analyzer of HMA Plant B in Fig. 4 show that at the beginning, the amount of O₂ is higher than the amount of CO₂, which means that enough air was supplied for combustion to occur [9]. This also indicates that extra combustion air (or excess air) was supplied to the combustion reaction, and then just after the combustion, the percentage of O₂ starts to decrease while CO₂ gradually increases. This pattern shows that O₂ is consumed to produce CO₂ during the combustion process. After the fourth minute, the O₂ and CO₂ are stable at 18.0% and 6.3%, respectively, with proportion value.

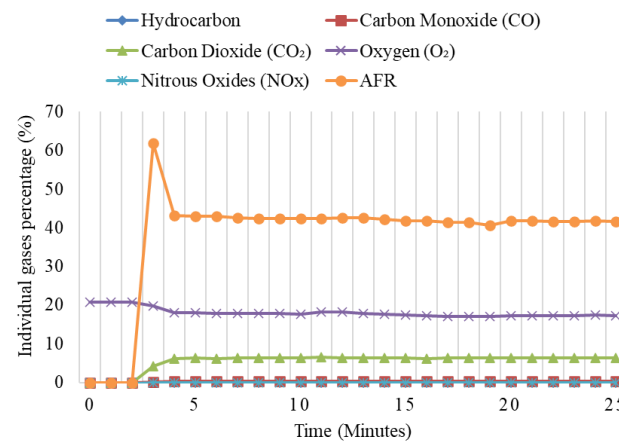


Fig. 4 - On-site gas analyzer reading for HMA Plant B

The results of HMA Plant C for on-site gas analysis in Fig. 5 show that at the beginning, the amount of O₂ is higher than the amount of CO₂. This means that enough air was supplied for combustion to occur [9]. After that, the percentage of O₂ starts to decrease, and CO₂ is gradually increased. This pattern shows that O₂ is consumed to produce CO₂ during the combustion process. After the twenty-first minute the O₂ and CO₂ are stable at 11.60% and 13.50%, respectively, with the proportion value. These values have been compared with the laboratory analysis using Residual Gas Analyzer (RGA).

3.3 Theoretical Gas Analysis

The theoretical measurement is based on the fuel used for the combustion. In this study, all HMA plants used light fuel oil (LFO) for the combustion of bitumen storage tank system. The fuel contains 85.5% of carbon (C), 11.5% of hydrogen (H), and 3.0% sulphur (S) [23], [24]. From the value of LFO compositions, the theoretical air-fuel ratio (AFR), carbon dioxide (CO₂), nitrogen (N₂) and sulphur dioxide (SO₂) emissions are calculated based on the theory suggested by United Nation Environment Program (UNEP) in their publication for the Energy Efficiency Guide for Industry in Asia [25]–[27]. The air to fuel ratio (AFR) is the ratio of the mixture between fuel and air during the combustion process, while the stoichiometric/theoretical air-fuel ratio is the ratio at which exactly all the available oxygen is used to burn the fuel completely or at least to the best possible value [28]. The percentage of gases obtained from the theoretical calculation are 15.54% of CO₂, 84.25% of N₂, and 0.20% of SO₂, while stoichiometric AFR is 14.06. Because all the evaluated HMA plants in the study used the same combustion fuel, the theoretical value of the flue gases emission is the same for all the HMA plants evaluated by this study.

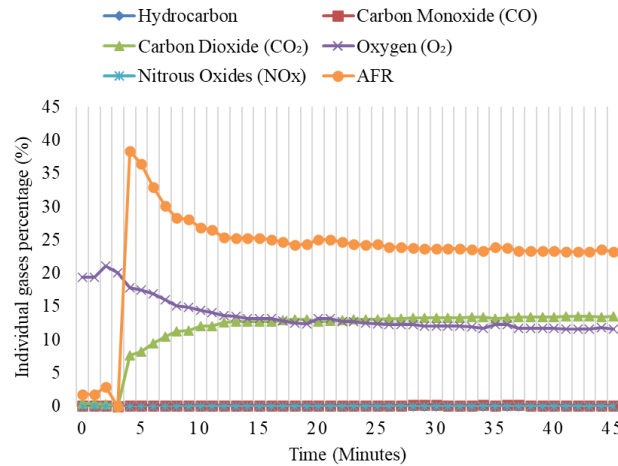


Fig. 5 - On-site gas analyzer reading for HMA Plant C

3.4 Comparison Between Analysis Methods

The value of theoretical, on-site reading and laboratory analysis results of flue gases are shown in Table 2. The results show that the stoichiometric/theoretical AFR for the fuel is 14.06%. This value is based on the calculation of the proportion of carbon (C), hydrogen (H), and sulphur (S) content in fuel. However, AFR collected from the on-site gas analyzer shows a higher value at 22.63%, which means that 22.63 kg of air is supplied to burn 1.0 kg of fuel for the combustion in the real site. Hence, in reality, combustion requires a greater amount of air than theoretically calculated. It has been reported that, sufficient oxygen was needed for the combustion to occur as complete combustion. However, if excess air supplied is more than is required for complete combustion, additional heat would be lost, making the equipment less efficient [29]. Meanwhile, insufficient air would lead to incomplete combustion and the formation of smoke and carbon monoxide (CO) [27].

The values of on-site theoretical readings and laboratory results for flue gas emission are shown in Table 3. The result shows that the stoichiometric/theoretical air-fuel ratio (AFR) for the fuel is 14.06%. However, AFR collected from the on-site gas analyzer show a higher value which is 42.48%, and this means that 42.48 kg of air is supplied to burn 1.0 kg of fuel for the combustion. Hence in reality, combustion requires much more air than theoretically calculated.

In general, there are differences in the values between the methods of analysis. For the CO₂ value, 15.54% was obtained from theoretical, 6.30% from on-site analysis, and 4.95% from laboratory analysis. For the N₂ value, 84.25% obtained from the theoretical, while 78.42% was obtained from laboratory analysis which is lower than the theoretical. The O₂ value is not included in the theoretical value because it is assumed that the combustion occurred in the stoichiometric condition in which all the O₂ is consumed during the combustion process. For SO₂ emission, 0.20% (2000 ppm) was obtained from theoretical, while the laboratory value is much lower, which is 20 ppm (0.0020%). Moreover, the value of NO₂ was also different between on-site analysis and laboratory value when 42 ppm (0.0042%) and 160 ppm (0.016%) were obtained from on-site and laboratory, respectively. The value of CO emission is 0.22% and obtained only from the on-site gas analysis. Meanwhile, a minimal amount of hydrocarbon is obtained, which is 10 ppm (0.0010%) that might occur due to unburn hydrocarbon in fuel [30].

Table 2 - The proportion of flue gases in percentage (%) and part per million (ppm) with a different analysis method for HMA Plant A

| Type of gas | Theoretical | On-site Gas Analyser | Residual Gas Analyser (RGA) |
|-----------------|-------------|----------------------|-----------------------------|
| AFR | 14.06% | 22.63% | - |
| CO ₂ | 15.54% | 13.10% | 15.55% |
| N ₂ | 84.25% | - | 77.48% |
| O ₂ | - | 10.10% | 2.38% |
| SO ₂ | 0.20% | - | 10 ppm |
| NO ₂ | - | 21 ppm | 146 ppm |
| CO | - | 0.17% | - |
| Hydrocarbon | - | 14 ppm | - |

Table 3 - The proportion of flue gases in percentage (%) and part per million (ppm) with a different method of analysis for HMA Plant B

| Type of gas | Theoretical | On-site Gas Analyser | Residual Gas Analyser (RGA) |
|-----------------|-------------|----------------------|-----------------------------|
| AFR | 14.06% | 42.48% | - |
| CO ₂ | 15.54% | 6.30% | 4.95% |
| N ₂ | 84.25% | - | 78.42% |
| O ₂ | - | 18.00% | 11.11% |
| SO ₂ | 0.20% | - | 20 ppm |
| NO ₂ | - | 42 ppm | 160 ppm |
| CO | - | 0.22% | - |
| Hydrocarbon | - | 10 ppm | - |

The value of theoretical, on-site reading and laboratory results of flue gas emissions are shown in Table 4. The result shows that the stoichiometric/theoretical air-fuel ratio (AFR) for the fuel is 14.06; however, AFR collected from on-site gas analyser shows a higher value at 23.07. This means 23.07 kg of air is supplied to burn 1.0 kg of fuel in combustion. Hence, in reality, combustion requires a more significant amount of air than theoretically calculated.

Table 4 - The proportion of flue gases in percentage (%) and part per million (ppm) with a different method of analysis for HMA Plant C

| Type of gas | Theoretical | On-site Gas Analyser | Residual Gas Analyser (RGA) |
|-----------------|-------------|----------------------|-----------------------------|
| AFR | 14.06% | 23.07% | - |
| CO ₂ | 15.54% | 13.50% | 13.15% |
| N ₂ | 84.25% | - | 78.02% |
| O ₂ | - | 11.60% | 6.63% |
| SO ₂ | 0.20% | - | 10 ppm |
| NO ₂ | - | 23 ppm | 150 ppm |
| CO | - | 0.10% | - |
| Hydrocarbon | - | 45 ppm | - |

In general, there are differences in the values between the methods of analysis. For the CO₂ value, 15.54% was obtained from theoretical, while 13.50% was obtained from the on-site analysis, and 13.15% was obtained from laboratory analysis. For the N₂ value, 84.25% was obtained from the theoretical, while 78.02% was obtained from laboratory analysis which is lower than the theoretical. The O₂ value is not included in the theoretical value because it is assumed that the combustion occurred in stoichiometric condition which all the O₂ is consumed during the combustion process. For SO₂ emission, 0.20% (2000 ppm) was obtained from theoretical, while the laboratory value is much lower, which is 10 ppm (0.0010%). Moreover, the value of NO₂ is also different between on-site analysis and laboratory value when 23 ppm (0.0023%) and 150 ppm (0.015%) were obtained from on-site and laboratory, respectively. The value of CO emission is 0.10% and obtained only from the on-site gas analysis. Meanwhile, minimal amount of hydrocarbon is obtained, which is 45 ppm (0.0045%) that might occur due to unburn hydrocarbon in fuel [30].

4. Conclusion

Results obtained from the combustion products from all plants include CO₂, SO₂, NO₂, CO and hydrocarbons. From the flue gases analysis, the most significant emission due to the fuel combustion is CO₂ which is also one of the greenhouse gases (GHG) emissions. The CO₂ value is in a range between 4.95% to 15.55% from all values calculated despite of the same fuel used and the same type and size of HMA plant. The differences might be due to the different equipment conditions of the combustion system. Meanwhile, the SO₂ values range from 10 ppm to 20 ppm, NO₂ ranges from 21 ppm to 160 ppm, CO ranges from 0.10% to 0.22%, and hydrocarbon is within the range of 10 ppm and 45 ppm for all HMA plants.

The results also show that the combustion optimization has not been fully achieved as there are presence of CO and hydrocarbon in the flue gas. The presence of CO, SO₂, NO₂, and hydrocarbon might be due to the cooling of the flame temperature before combustion is completed, as the AFR obtained is more than enough of the required value. However, the presence of N₂ and O₂ is due to the excess air supplied during the combustion process, and thus, is not considered to be combustion products. The excess air supplied can cause dilution to the emitted flue gas from the chimney. The on-site gas analysis result-shows that the more significant AFR value can produce a lower amount of CO₂ as the combustion product.

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