Validated method for trace impurities analysis in bulk gas using Gas Chromatography with Pulse Discharge Helium Ionization Detection

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Abstract. Pulse discharge helium ionization detector (PDHID) is developed to respond the need of many applications in the area of chromatographic quantitative analysis. The PDHID is a general type of detector with very high detectability property covering a wide range of chemical compounds. Based on ISO/IEC 17025, a reliable and accurate of measurement result can be obtained by applying a validated method. This paper reports a validation study with regard to the application of GC-PDHID for trace impurity analysis in bulk gases. An optimized operating condition of GC was used to evaluate the method performance with parameters including precision (repeatability and reproducibility), linearity, limit of detection (LoD), and limit of quantification (LoQ). In this study, six trace compounds (CO₂, H₂, Ar, O₂, CH₄, and CO) in bulk gas were analyzed. The results show that the validated of the GC-PDHID method was repeatable and reproducible for the analysis of trace impurities in bulk gas. The %RSD of repeatability and reproducibility were found to be < 3.00% and < 10.50%, respectively. Good linearity of the validated method was obtained with the correlation coefficient (R²) higher than 0.99 for all six trace compounds. In addition, the calculated LOD and LOQ of the GC-PDHID were found to be < 0.60 and < 2.00 μmol mol⁻¹ respectively. In conclusion, validated method of the GC-PDHID for the measurement of the six trace compounds in bulk gas is reliable and fit for its purpose, implying that the validated method can be used in daily measurement in the testing laboratory.

1. Introduction
The purity of bulk gases is an indication of the gas quality and commonly expressed in the percentage. The usage of the high purity of bulk gases in certain applications have a significant impact to the quality result of measurement and cost of good production [1]. Different level of purity gas has used in many fields of applications. For example, 98 - 99.5% purity of nitrogen (N₂) used in food and beverages industries, 97 - 99.99% purity of N₂ used in pharmaceutical and 95 - 99.999% purity of N₂ used in the electronics assembly [2]. The 6.0 (99.9999%) means that 1 μmol mol⁻¹ of impurities gas are present in the bulk gases. The impurities of the gas, such as carbon dioxide (CO₂), hydrogen (H₂), argon (Ar), oxygen (O₂), methane (CH₄) and carbon monoxide (CO) might be a presence in trace...
level. Therefore, accurate and reliable methods for determination of trace impurities in bulk gas are tremendously needed to assure the quality of bulk gas.

In general, gas chromatography (GC) has been used widely as the preferred method for trace impurities analysis [3]. During the last decade, GC has become a reliable analytical method that can be configured using different detectors. For trace impurities analysis, the widely used detector today is the Pulsed Discharge Helium Ionization Detector (PDHID) because it can detect impurities in the level of \(10^{-9}\) mol mol\(^{-1}\) concentration range [4]. Besides that, PDHID is proved to be universally sensitive to permanent gases at trace level and it has an advantage over flame ionization detector (FID), where permanent gases like \(O_2\) give little or no response and it was more sensitive than thermal conductivity detection (TCD) [1, 4].

The validation of the methods is one of the essential components in the procedures of analysis and measurements to obtain an accurate and reliable result [5]. Based on ISO/IEC 17025, the testing laboratories shall validate their methods to meet the needs of the given application or field of application [6]. The validation method is a process to confirming that the method under consideration has capabilities with to the required application [7]. In this paper, method validation for six trace compounds (\(CO_2\), \(H_2\), \(Ar\), \(O_2\), \(CH_4\), and \(CO\)) in bulk gas using GC-PDHID were carried out by investigating several parameters, such as precision (repeatability and reproducibility), linearity, limit of detection (LoD), and limit of quantification (LoQ). The result from this study can be used in daily measurement in testing laboratories as a practical example for their method validation of trace impurities analysis and to judge the quality, reliability, and consistency of their analytical results [8].

2. Method

2.1 Material

The certified standard gas mixtures containing \(CO_2\), \(H_2\), \(Ar\), \(O_2\), \(CH_4\), and \(CO\) in Helium (He) matrix was purchased from Air Liquid Indonesia and NIM (National Metrology Institute) China and used in all experimental runs.

2.2 Equipment

A GC (7890B, Agilent Technologies, USA) with software OpenLAB CDS Chemstation Edition Rev. C.01.01, Agilent Technologies, USA) equipped with Pulsed Discharge Helium Ionization Detector (PDHID) was used for trace impurities (\(CO_2\), \(H_2\), \(Ar\), \(O_2\), \(CH_4\), and \(CO\)) analysis in bulk gas. The procedure was similar with literature [9], except PDHID detector was used. Analysis of gas sample was conducted under optimum operating condition. The gas mixture sample was injected into GC system through mass flow controller Brooks 0254 (Brooks Instrument, USA) that was installed before the injection line of GC system in order to maintain a constant of the sample flow rate. The flow rate of the sample was set at 40 mL min\(^{-1}\). The sample of the gas mixture from the injection line was flown through 1 mL of sample loop. The valve box temperature was maintained at 100 °C and two columns were used in the GC system are Pora PLOT Q column (50 m x 530 µm x 20µm) and Molsieve 5A column (50m x 530µm x 20µm).

2.3 Validation method

Several parameters on method performance in validation method, such as precision (repeatability and reproducibility), linearity, LoD, and LoQ were investigated using optimized operating condition of the GC-PDHID. The optimization process was conducted by injecting the sample while varying the instrument conditions such as oven temperature, detector temperature, and flow rate of carrier gas. Subsequently, the optimized operating of GC-PDHID was used to evaluate the method performance for each trace compounds (\(CO_2\), \(H_2\), \(Ar\), \(O_2\), \(CH_4\), and \(CO\)). The assessment of validation method procedure was adopted from literatures [7, 9-12].

Precision of the method was evaluated in term of repeatability (intra-day precision) and reproducibility (inter-day precision). Repeatability was determined by measuring the standard of impurities gas
mixtures for seven replication and expressed as the percentage relative standard deviation (%RSD) in the same day using Eq. 1 [11].

\[
\%RSD = \frac{100}{\bar{y}} \sqrt{\frac{\sum (y_i - \bar{y})^2}{(n-1)}}
\]

Where \(y_i\) is an individual GC measurement expressed as a peak area, \(\bar{y}\) is the mean of the peak area value of seven replicates injections and \(n\) is a number of injection replication. The repeatability of the method is acceptable if %RSD value of measurement is less than 0.67 of the coefficient of variability Horwitz (0.67 x CV-Horwitz) [9-12]. Eq. 2 was used to calculate the CV-Horwitz.

\[
CV - Hotwitz (\%) = 2^{(1-0.5logc)}
\]

Where \(c\) is the concentration of trace compound in a decimal fraction. Then reproducibility was determined by similar procedure to repeatability but in different days. The acceptance criteria is %RSD value is below the CV-Horwitz [11].

The linearity of the method was assessed using the calibration curve of a series concentration for each trace target compound and for LoD and LoQ were establish at a signal to noise (S/N) ratio of 3 and 10, respectively [11, 13].

3. Results and Discussion

3.1 Optimized operating condition of GC-PDHID

Optimizing operating condition of a GC-PDHID system is crucial to improve the efficiencies and analytical performance. The parameters such as flow rate, temperature oven and temperature detector must be optimized in order to separate the trace compounds (CO₂, H₂, Ar, O₂, CH₄, and CO) in bulk gas at good resolution and sharp peak [14]. The optimized operating condition that used in a GC-PDHID system for trace impurities analysis was shown in Table 1. These optimized operating conditions were used in all experiment runs.

3.2 Precision

Precision is a measure of how close the results of one to another measurement [7]. Repeatability (intra-day precision) was conducted to assess the closeness between a measured value of number measurements using the same equipment, same condition, and same operator in a short period [12, 15]. Repeatability precision was determined by comparing %RSD of the measurements with CV-Horwitz (Eq. 1). The result of the method repeatability evaluation was shown in Table 2. As it can be seen in Table 2, %RSD of the method repeatability for six traces of component gas were found lower than 0.67 x CV-Horwitz. Therefore, the method was categorized as excellent repeatability for the measurement of trace impurities in bulk gases using GC-PDHID.

The reproducibility (inter-day precision) is an analytical parameter that measures the variability of the measurement results in different day [7]. Seven replicates measurement at different days for evaluation of reproducibility were conducted and the results are described in Table 3. It can be found that the %RSD value from the trace impurities analysis is less than CV-Horwitz and it means that the method used is reproducible.
Table 1. Optimized operating condition of GC PDHID for trace impurities analysis in bulk gases

| Parameters                     | Conditions                                                                 |
|--------------------------------|-----------------------------------------------------------------------------|
| Front SS Inlet He Temperature  | 250 °C                                                                      |
| Pressure                       | 21.046 psi                                                                  |
| Total Flow                     | 23 mL min⁻¹                                                                  |
| Septum Purge Flow              | 3 mL min⁻¹                                                                  |
| Split Ratio                    | 1:1                                                                         |
| Split Flow                     | 10 mL min⁻¹                                                                 |
| Column/Oven temperature        | Temperature programmed, Initial 40 °C (hold for 6.5 min), Ramp #1 down 100 °C min⁻¹ to 30 °C (hold for 8.4 min), Ramp #2 up 6 °C min⁻¹ to 75 °C (hold for 0 min), Ramp #3 up 12 °C min⁻¹ to 160 °C (hold for 0 min) |
| Running time                   | 29.5 min                                                                    |
| Carrier gas                    | Helium GCMS 99.999% grade (Air Liquide, Singapore)                           |
| Carrier gas flow rate          | Flow rate programmed, Initial 10 ml min⁻¹ (hold for 11.5 min), Ramp #1 down 60 ml min⁻¹ by each minute to 5 ml min⁻¹ (hold for 3.4 min), Ramp #2 up 60 ml min⁻¹ by each minute to 10 ml min⁻¹ (hold for 0 min) |
| Detector PDHID temperature     | 220 °C                                                                      |
| Electrometer                   | On                                                                          |

Table 2. Evaluation results for the repeatability of the method

| Parameter                  | Trace target compounds | CO₂ | H₂  | O₂   | Ar   | CH₄  | CO  |
|----------------------------|------------------------|-----|-----|------|------|------|-----|
| %RSD                       |                        | 0.73| 2.12| 2.83 | 1.48 | 0.69 | 1.24|
| CV-Horwitz                 |                        | 11.98| 12.97| 12.85| 13.04| 12.97| 12.04|
| 0.67 x CV-Horwitz          |                        | 8.02| 8.69| 8.61 | 8.74 | 8.69 | 8.06|
| Criteria:                  |                        |     |     |      |      |      |     |
| %RSD < 0.67 x CV-Horwitz   | OK                     | OK  | OK  | OK   | OK   | OK   | OK  |

Table 3. Evaluation results for the reproducibility of the method

| Parameter                  | Trace target compounds | CO₂ | H₂  | O₂   | Ar   | CH₄  | CO  |
|----------------------------|------------------------|-----|-----|------|------|------|-----|
| %RSD                       |                        | 8.40| 0.68| 10.38| 1.66 | 2.56 | 2.77|
| CV-Hotwitz                 |                        | 11.98| 12.97| 12.85| 13.04| 12.97| 12.04|
| Criteria:                  |                        |     |     |      |      |      |     |
| %RSD < CV-Hotwitz          | OK                     | OK  | OK  | OK   | OK   | OK   | OK  |

3.3 Linearity

Linearity of the method is directly proportional to the concentration of an analyte in the sample [8]. The linearity of the GC-PDHID was evaluated by a calibration curve using a series of certified standard gas mixtures having different concentration. Each concentration was analyzed in seven replication. As it can be seen in Table 4, good linearity was obtained for six trace target compounds with the correlation coefficient (R²) higher than 0.99.
Table 4. Data indicating the linearity of the method for trace target compounds in impurities analysis using GC-PDHID

| Parameter                  | Trace target compounds |
|---------------------------|------------------------|
|                           | CO₂  | H₂   | O₂   | Ar   | CH₄   | CO   |
| Slope                     | 296.73 | 53.677 | 85.512 | 167.98 | 420.27 | 195.18 |
| Intercept                 | -3.5672 | -11.398 | +465.54 | +119.98 | +230.68 | -23.585 |
| Range concentration       | 2.36 – 8.63 | 2.28 – 3.88 | 1.22 – 4.08 | 1.14 – 3.83 | 1.16 – 3.88 | 2.36 – 8.68 |
| Correlation coefficient   | 0.9936 | 0.9996 | 0.9992 | 0.9967 | 0.9997 | 0.9962 |

3.4 Limit of Detection (LoD) and Limit of Quantification (LoQ)

In Chromatography, LoD and LoQ was determined using a signal to noise (S/N) ratio method which 3:1 for LoD and 10:1 for LoQ that quantified according to the comparison S/N ratio with the response from the lowest of standard gas mixtures for impurities gas analysis which the value are 2.36 μmol mol⁻¹ for CO₂, 2.28 μmol mol⁻¹ for H₂, 1.14 μmol mol⁻¹ for Ar, 1.22 μmol mol⁻¹ for O₂, 1.16 μmol mol⁻¹ for CH₄, and 2.36 μmol mol⁻¹ for CO) [11, 13]. The calculation of LoD and LoQ were tabulated in Table 5.

Table 5. LoD and LoQ of the trace level of target compounds using GC-PDHID

| Trace target compounds | LoD (μmol mol⁻¹) | LoQ (μmol mol⁻¹) |
|------------------------|-----------------|-----------------|
| CO₂                   | 0.04            | 0.14            |
| H₂                    | 0.53            | 1.77            |
| Ar                    | 0.21            | 0.71            |
| O₂                    | 0.20            | 0.66            |
| CH₄                   | 0.18            | 0.60            |
| CO                    | 0.24            | 0.78            |

4. Conclusion

From the result of the study, it can be concluded that the GC-PDHID under the experimental condition is reliable and fit for the trace target compounds of impurities analysis, such as CO₂, H₂, Ar, O₂, CH₄ and CO in bulk gas. Subsequently, this method can be applied for routine analysis of trace impurities gas analysis in bulk gas, such as nitrogen.

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