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Identification of the CH_4 Emission Factor and Emission Characteristics for a Wood-Fired Boiler

Song, Garam* · Jeong, Sunhee** · Kang, Sungmin*** and Jeon, Eui-Chan****†

*Ph.D. student, Department of Climate and Environment, Sejong University, Seoul, Korea
**Ph.D. student, Cooperate Course for Climate Change, Sejong University, Seoul, Korea
***Senior Researcher, Department of Climate and Environment Research Center, Sejong University, Seoul, Korea
****Professor, Dept. of Climate and Environment, Sejong University, Seoul, Korea

ABSTRACT

In this study, the emission characteristics of residential wood-fired boilers were identified and the CH_4 emission factor was developed. We conducted field surveys of exhaust gas from stacks of wood-fired boilers over a four-day period. The CH_4 and CO levels of the exhaust gases were analyzed in the laboratory, as were those of the firewood used in the wood-fired boilers. Regarding emission characteristics, CH_4 concentration was low with the fan turned on because of the amount of combustion air being added to the furnace. Spearman's rho correlation analyses were performed to investigate the correlations between CH_4 concentration and CO according to exhaust gas and temperature in the furnace. The analysis showed that the higher was the concentration of CO in the exhaust gases, the higher was the concentration of CH_4. However, the higher was the temperature in the furnace, the lower was the concentration of CH_4.

The CH_4 emission factor was 130.15 $kgCH_4/TJ$, as estimated and compared to the Intergovernmental Panel on Climate Change (IPCC) default values. A comparison between wood stoves and wood-fired boilers showed lower CH_4 emission factors for the boilers. The difference between CH_4 emission factors in this study and those of the IPCC were likely because of the specific combustion technologies and the total moisture content of the fuel used.

Key words: Wood-fired Boiler, Greenhouse Gas, CH_4 Emission Factor, Woody Biomass, Firewood

1. Introduction

Korea has set a target to reduce the total GHG emissions measured in 2018 by 40% by 2050. In 2018, the total GHG emissions from Korea were 727.6 million tons CO_2eq, of which 627.9 million tons CO_2eq were emitted from fuel combustion. CH_4 accounts for 3.8% of Korea's GHG emissions, which is considerably less than its CO_2 emissions at 91.4%. However, the global warming potential (GWP) of CH_4 is 21 times higher than the GWP of CO_2. Major agencies, including the World Resources Institute, the World Business Council for Sustainable Development (WRI/WBCSD), and the Intergovernmental Panel on Climate Change (IPCC) have determined that emission factors and emissions characteristics of non-CO_2 GHG are important indicators.

The amount of CO_2 emitted from fuel combustion depends on the carbon content of fuels, but non-CO_2 emission factors are affected combustion conditions and technology which, in general, are not well-known.

The emissions from combustion of biomass were not included in national totals and the sectoral to avoid double counting. However, the emissions of CH_4 and N_2O are included and estimated in the national totals because their effect is in addition to the stock changes estimated in the AFOLU sector (IPCC). Local governments and the Korea Forest Service have therefore offered firewood to rural households that have installed wood-fired boilers (Korea Forest Service).

†**Corresponding author** : ecjeon@sejong.ac.kr (05006, 209, Neungdong-ro, Gwangjin-gu, Seoul, Korea. Tel. +82-2-3408-4353)

ORCID Song, Garam 0000-0002-9111-8922 Kang, Sungmin 0000-0001-8628-8241
Jeong, Sunhee 0000-0001-5242-4479 Jeon, Eui-Chan 0000-0003-2783-4550

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According to the Korean Statistical Information Service, wood-fired boilers were operating in approximately 111,128 households in Korea in 2020. Unlike other combustion facilities, wood-fired boilers have incomplete combustion conditions because of the non-uniformity of the fuel and intermittent fuel supplies. As a result, there should be a difference between the emission characteristics of wood-fired boilers and those of other types of boilers. The amount of CH_4 emitted during fuel combustion depends on the combustion conditions. It is thus necessary to determine the CH_4 emission factor for wood-fired boilers because the CH_4 emitted from burning firewood cannot be considered carbon neutral. In this study, we identified the emission characteristics of wood-fired boilers and then developed the CH_4 emission factors of the same. The emission factors developed in this study were compared with the IPCC default values for similar combustion facilities.

2. Method

2.1. Sampling and analysis of exhaust gases

2.1.1. Sampling method of exhaust gases

Field surveys were conducted to collect exhaust gases from the stack of wood-fired boiler. The exhaust gases were sampled using EPA method 18 (US EPA, 2001) which is one of the intermittent collection.

The samples were collected using a Lung sampler, which creates a vacuum that uses negative pressure as a pump. The lung sampler was connected to a 10L Tedlar bag (SKC, US). Separate samples were collected when the wood-fired boiler fan was on and when it was off. The sampling was carried out for 60-70 minutes, with samples taken every 5 minutes. The sampling was collected at least two times. The specification of wood-fired boiler is shown in <Table 1>.

The temperature in the furnace was measured using a K-type electronic thermometer (RS-232 Thermolog, Taiwan) and the flow rate was measured whenever samples were collected as shown in <Fig. 1>.

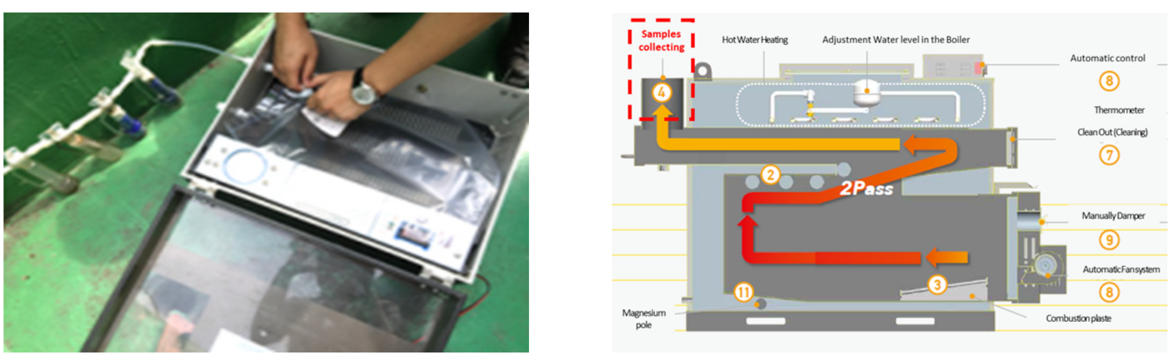
Table 1. Specification of wood-fired boiler

Classification	Unit	Capacity
Heating	kW/h (kcal/h)	22.2 (19,000)
Hot-water supply	kW/h (kcal/h)	22.2 (19,000)
Irrigation	L	150
Combustion chamber	mm	431 × 441 × 875
Input the fuel (Max)	kg	45

2.1.2. Analysis of exhaust gases

CH_4 concentrations were analyzed by Gas Chromatography-Flame Ionization Detector (GC-FID). The CH_4 analysis used 1 m stainless steel columns and a 3.175 mm outer diameter mesh column with packed Q 80/100.

The calibration curve was derived from the average value of three repeated analyses using standard gas. The concentration of the sample would be within the calibration curve. The analysis conditions for the GC-FID are shown in <Table 2>.



(a) Field survey (b) Sampling of the exhaust gas

Fig. 1. Sampling of the exhaust gas (The manufacturer of wood-fired boiler)

Table 2. Analysis condition of GC for CH_4

Classification		Analysis condition
Column		Porapack Q 80/100 Mesh
Carrier gas		N_2 (99.999%)
Flow	N_2	25 mL/min
	H_2	30 mL/min
	Air	300 mL/min
Temperature	Oven	70°C
	Injector	120°C
	Detector	250°C

In order to draw the calibration curves, CH_4 concentrations were set at 50, 100, 250, and 500 ppm, in standard conditions. When a high concentration of sample was analyzed, it was diluted. The result indicates excellent linearity, as shown in <Fig. 2>.

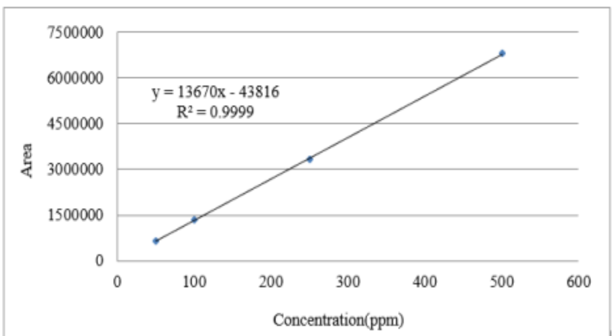


Fig. 2. Calibration curve with CH_4

In order to quantify and identify CO, the exhaust gases were sent through an in-line micro-Gas Chromatography (micro-GC). The micro-GC was equipped with a capillary column. The conditions for the micro-GC are detailed in <Table 3>.

Table 3. Analysis condition of micro-GC

Classification	Analysis condition	
Channel A, Column	Molsieve, 10 m × 0.32 mm × 30 μm	
Channel B, Column	PLOTU, 8 m × 0.32 mm × 30 μm	
Oven and GC setting	Channel A	Channel B
Sample inlet	100℃	100℃
Injector	100℃	80℃
Column	80℃, 25 psi	70℃, 25 psi
Run time	3 min	3 min

In order to evaluate the relative standard deviation (RSD), the standard deviation of CO, CO_2 and O_2 was measured three times. The result of the repeatability test is shown in <Table 4>.

Table 4. Repeatability test for CO, CO_2, O_2

Number of analysis	CO (%)	CO_2 (%)	O_2 (%)
1	0.05	0.1	20.99
2	0.05	0.12	20.98
3	0.07	0.14	21.03
4	0.05	0.14	21.01
5	0.04	0.12	21
6	0.04	0.1	21.09
7	0.06	0.08	21.05
Mean	0.05	0.11	21.02
SD	0.01	0.02	0.04

2.2 Analysis of fuel

2.2.1. Calorific value analyzing method

The calorific value was analyzed using a calorimeter. The quantification value for a standard sample was measured using an electronic scale with 0.0001 g sensitivity.

In order to analyze calorific value, the temperature of the cooling water was set at 25°C using a water temperature controller. The cooling water was pure water. The repeatability test for calorific value was conducted using benzoic acid. The gross calorific value of benzoic acid was analyzed five times. As shown in <Table 5>, the relative standard deviation (RSD) was 0.13% that indicates excellent repeatability.

Table 5. Repetition test of calorific value analysis using standard sample

Sample	Mass of standard (g)	Gross calorific value (cal/g)
1	0.4884	6,544
2	0.5012	6,598
3	0.4792	6,535
4	0.4823	6,555
5	0.4983	6,531
Mean		6,541
Standard deviation (SD)		8.36
Relative standard deviation (RSD, %)		0.13

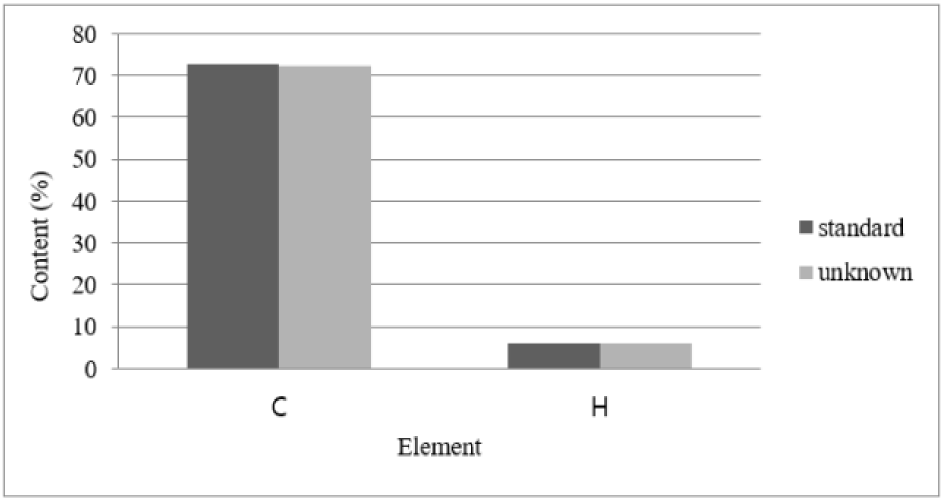


Fig. 3. Repetition test of elemental analysis for carbon and hydrogen

2.2.2. Element analyzing method

The samples were analyzed using an automatic element analyzer 12 for carbon and hydrogen. The flow rate of oxygen, carrier gas and reference gas were respectively set at 140, 240, and 100 mL/min. TCD oven and the furnace temperatures were set at 70°C and 900°C. A 2 m column was used.

The repeatability test for element analysis was conducted using BBOT (2,5-bis(5-tert-butyl-benzoxazolyl) thiophene: C = 72.52%, H = 6.06%, N = 6.54%, S = 7.43%, O = 7.42%). It was estimated by analyzing between standard and unknown. The absolute value of the difference was 0.32% for carbon and 0.02% for hydrogen. As shown in <Fig. 3>, this result indicated excellent repeatability.

2.3. Method of development of CH_4 emission factor

Emission factors were calculated using the calorific value analysis result, elemental analysis of fuel, and the measured CH_4 concentration from the wood-fired boilers.

In this study, the CH_4 emission factor was developed using measured CH_4 concentrations, calculated combustion exhaust emissions, and theoretical air. In equation (1), EF is the emission factor of CH_4 (kg/TJ), C_{CH_4} (ppm) is the CH_4 concentration, G_{0d} (Sm^3/kg) is the theoretical dry exhaust emissions of the combusted fuel, and A_0 (Sm^3/kg) is the theoretical air of the combusted fuel. As in equation (2), the O_2 in the exhaust gas was used for m, the excess air ratio.

$$EF = [C_{CH_4} \times G_0 + (m-1) \times A_0 \times \frac{16}{22.4}]/NCV \quad (1)$$

$$m = 21/(21 - C_{O_2}) \quad (2)$$

EF : CH_4 emission factors ($kgCH_4$/TJ)
C_{CH_4} : CH_4 Concentration (ppm)
G_0 : Amount of theoretical dried combustion gas (Nm^3/kg)
m : Excess air ratio
A_0 : Theoretical air (Nm^3/kg)
NCV : Net calorific value (MJ/kg)

In order to develop the CH_4 emission factor of wood-fired boilers, we need to the Net Caloric Value (NCV), measured in MJ/fuel. The calculation of NCV is shown in equation (3).

$$NCV = GCV - [6 \times (Moisture(\%) + 9 \times Hydrogen(\%))] \quad (3)$$

3. Result

3.1. Result of CH_4 concentration for wood-fired boiler

To identify the emission characteristics, the experimental condition was varied by operating the fan. The results of the analysis of CH_4 concentrations are shown in <Table 6>.

Table 6. CH_4 concentration analysis of wood-fired boiler

No	Number of samples	Configuration	CH_4 (ppm)	Mean (ppm)	SD (ppm)
1	14	Fan off	547.56	521.02	26.54
2	13		494.47		
3	12	Fan on	254.10	280.19	26.09
4	15		306.28		

The CH_4 concentrations with the fan turned off were relatively high, ranging from 271.13 ppm to 676.91 ppm. The average CH_4 emission concentration was 521.02 ppm. The CH_4 concentrations with the fan turned on were relatively low, ranging from 111.28 ppm to 466.49 ppm. The average CH_4 emission concentration was 280.19 ppm. The CH_4 concentration with the fan on was lower than the CH_4 concentration with the fan off. It is concluded that the CH_4 concentration appears to be low when the fan was on because of the amount of combustion air being added into the furnace.

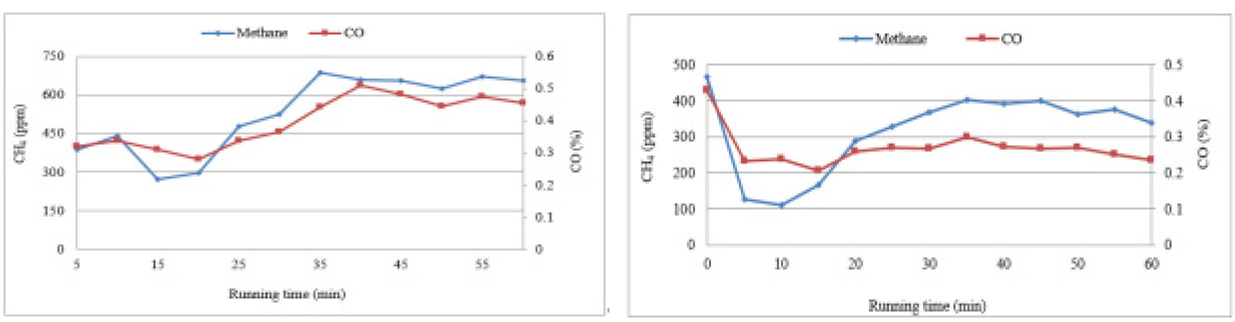
3.2. Characteristics of CH_4 emissions for wood-fired boiler

The CH_4 concentrations in exhaust gas were measured for 60 minutes, with samples taken every 5 minutes. The CH_4 concentration in exhaust gas with the fan turned off was relatively high, ranging from 271.13 ppm to 676.91 ppm. In case of the fan turned on, CH_4 concentrations ranged from 111.28 ppm to 466.49 ppm. The CH_4 concentration with the fan turned on was relatively lower than it was with the fan turned off. This suggests that CH_4 concentration increased under conditions of incomplete combustion with insufficient air and a combustion temperature (Kim, 2013).

As shown in <Fig. 4>, the CO concentration was similar to that of CH_4 when the boiler was operated. Both CH_4 and CO concentrations increased after 20 minutes. It can be seen that the higher the concentration of CO in the exhaust gases, the higher the concentration of CH_4.

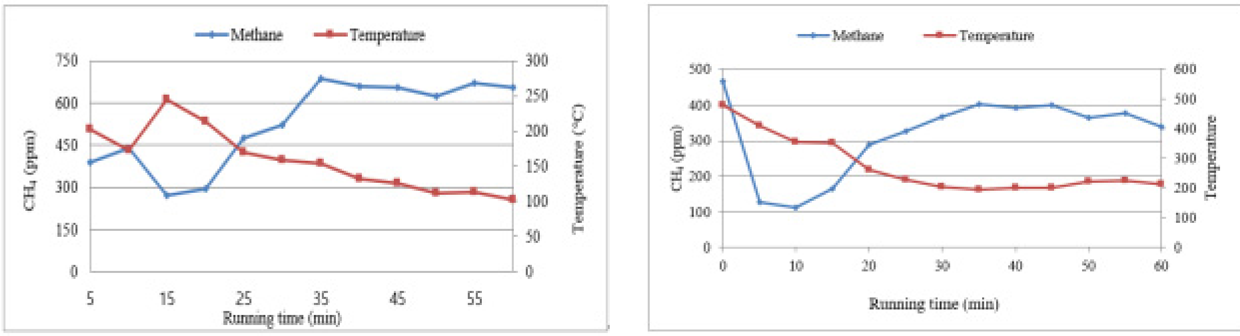
As shown in <Fig. 5>, the temperature and CH_4 concentration followed different trends while the boiler was operated. It can be seen that the lower the temperature, the higher the CH_4 concentration. This suggests that CH_4 concentration increased under conditions of incomplete combustion with insufficient air and a combustion temperature. The CH_4 concentration and temperature were different when the boiler was operated. The temperature with the fan turned on was higher than when it was off.

The changes in concentrations with the fan turned off were no different than with it turned on. CH_4 concentration was proportional to CO, but it was in inverse proportion to temperature.



(a) Turn off a fan (b) Turn on a fan

Fig. 4. CH_4 and CO concentration



(c) Turn off a fan (d) Turn on a fan

Fig. 5. CH_4 concentration and temperature

3.3. Analysis of correlations between flue gases

The correlations between CH_4 concentration and the CO in exhaust gases were examined using SPSS. Before the correlation analysis, normality tests were performed to understand the distribution of the results. According to the results of the normality tests of CO and CH_4 concentrations among exhaust gases, the significances of the test values were all lower than 0.05, indicating that the test values did not follow a normal distribution. Therefore, nonparametric Spearman's rho correlation analyses were performed to investigate the correlations between CH_4 concentrations and CO, as well as furnace temperatures. The results are shown in <Table 7>.

The significance (2-tailed) of the correlation between CH_4 and CO concentrations among the exhaust gases is less than 0.01, indicating that the correlation between them is statistically significant. The correlation coefficient of CH_4 and CO concentrations among the exhaust gases was 0.756, indicating a positive linear relationship. Therefore, it can be seen that the higher the CO concentration in the exhaust gases, the higher the CH_4 concentration. CH_4 is formed in an environment of incomplete combustion at a low combustion temperature.

CO concentration in exhaust gases is also associated with incomplete combustion. It is concluded that the higher the CO concentration was, the more CH_4 was emitted through incomplete combustion.

The significance (2-tailed) of the correlation between CH_4 concentration and in-furnace temperatures was lower than 0.05, indicating that the correlation between them is statistically significant. The correlation coefficient was -0.303, indicating a negative linear relationship. Therefore, it can be seen that the higher the temperature in the furnace, the lower the concentration of CH_4. Because CH_4 concentration tends to decrease steadily as combustion temperature increases, it is concluded that the CH_4 concentration is lower when the temperature is higher.

Table 7. Result of correlation analysis

Classification			CH_4	CO	Temperature
Spearman's rho	CH_4	Correlation Coefficient	1.00	.756**	-.303*
		Sig. (2-tailed)	.	.000	.020
		N	59	59	59

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

3.4. Results of fuel analysis for wood-fired boiler

The results of analysis of the firewood used in this study are shown in <Table 8>. In order to estimate the net calorific value from the total calorific value of a fuel, the total water content and the hydrogen content of the fuel must be known. The average calorific value as dry basis was 4,421 kcal/kg. The average of net calorific value as received basis was 3,494 kcal/kg.

3.5. Estimation of CH_4 emission factors for wood-fired boiler

Previous studies on the development of CH_4 emission factors of wood-fired boilers were reviewed. However, most studies regarding CH_4 emission factors and emission characteristics of wood-pellet boilers have been conducted in Europe, and such studies were mainly conducted on air pollutants. This tendency applies in Korea as well, where only studies regarding the emission characteristics of air pollutants and black carbon were conducted (Yi et al, 2013; Kim et al. 2014; Park et al., 2015), and studies on CH_4 are insufficient.

The emission factors developed in this study were compared with the IPCC default values for the residential sector. However, emission factors for wood-fired boilers were not found in the residential sector of the 2006 IPCC guidelines. Therefore, the emission factors developed in this study were compared with the emission factors of similar firewood-burning facilities and wood/wood waste boilers which were in the industrial and commercial/ institutional sector.

In order to identify the emission characteristics of wood-fired boiler, samples were taken based on whether the fan was in operation. In general, the fan is turn on at the beginning of operation for the purpose of fuel combustion. After that, when the temperature of the wood-fired boiler is set, the fan automatically turns off depending on the temperature in the furnace. Based on these characteristics, In this study, the emission factor was developed using the average value of CH_4 concentration. The result of CH_4 emission factor was 130.15 kg CH_4/TJ. As shown in <Table 9>, the emission factors developed in this study were lower than the other emission factors without wood/wood waste boilers. These differences in CH_4 emissions could be due to the specific technology used and the total moisture content of the fuel.

Table 8. Fuel analysis of wood-fired boiler

No.	Total moisture (%)	Element content as dry basis (%)		Gross calorific value as dry basis (kcal/kg)	Net calorific value as received basis (kcal/kg)
		C	H		
1	16.21	51.73	5.78	4,417	3,342
2	11.68	50.01	5.99	4,448	3,573
3	11.28	49.15	5.76	4,313	3,483
4	12.11	49.73	5.82	4,469	3,579
Mean	12.82	50.16	5.84	4,412	3,494
SD	2.29	1.11	0.10	69	111
RSD (%)	17.83	2.21	1.79	2	3

Table 9. Comparison of CH_4 emission factors

Source	Technology	Configuration	CH_4 emission factor (kgCH$_4$/TJ)
This study	Wood-fired boiler	Fan on	88.31
		Fan off	171.98
		Mean	130.15
IPCC	Wood pits	-	200
	Wood stove in US	Conventional	932
	Wood stove in Asian countries	-	258 - 2190
	Wood fireplaces	-	275 - 386
	Agriculture wastes stoves	-	230 - 4190
Cho et al.	Biomass fired fluidized bed combustion	Fuel used of RDF, RPF	1.4
Jeong et al.	Wood chip fired fluidized bed combustion	Fuel used of wood chip	0.22
Kim	Coal briquette stove	Open the air inlet	11.28 ± 0.70
		Close the air inlet	18.14 ± 1.67

4. Conclusion

This study identified emission characteristics and developed the CH_4 emission factors for residential wood-fired boilers. Four surveys were conducted in order to collect exhaust gasses from the stacks of wood-fired boilers. The CH_4 and CO concentrations in the exhaust gases were analyzed in the laboratory, as were the fuels used in the wood-fired boilers.

As a result of identifying the CH_4 emission characteristics, we can see that CH_4 concentration appears to be lower when the fan is turned on due to the combustion air being added to the furnace. Spearman's rho analyses were performed to investigate the correlations between CH_4 concentrations and CO, as well as the temperatures in the furnace.

The Spearman's rho correlation analysis shows that the higher the CO concentrations in the exhaust gases, the higher the CH_4 concentration. However, the higher the temperature in the furnace, the lower the CH_4 concentration. CH_4 emission factors were estimated and were compared to the IPCC default values. CH_4 emission factors were found to be 130.15 kg CH_4/TJ. The emission factors developed in this study were different than the IPCC default values. The emission factor developed in this study was compared with the emission factors of similar firewood-burning facilities and wood/wood waste boilers which were in the industrial and commercial/institutional sector. The difference between the CH_4 emission factors found in this study and those of the IPCC are likely because of the specific combustion technology and the total moisture content of the fuel used. For future research, studies on the development of emission factors and inventories for wood-fired boilers should be continued, measuring N_2O as well as CH_4. Such studies should also be conducted for other facilities that use firewood as fuel.

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