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Effects of CH_4 and CO_2 on Intrinsic Instability of Synthetic Thai Natural Gas Flames

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Abstract

Natural Gas (NG) is widely applied in many sectors of Thailand such as industrial and transportation sectors. There are many sources of NG in Thailand which were categorized locally as eastern and western sources. The main components of NG are 84.1% of methane (CH_4), 15.9% of Carbon dioxide (CO_2) and 76.0% of CH_4, 24.0% of CO_2, for eastern and western sources, respectively. As the difference of NG composition between two main sources, this study focused on the effects of CH_4 and CO_2 on synthetic Thai NG flames. In order to investigate the effects of CH_4 and CO_2, the lean combustion was applied to observe the change of cellular premixed Thai synthetic NG flames due to reduction of emission. The variation of CH_4 was varied between 74.4-76.6% and 80.0-83.7% for western and eastern NG sources, respectively. The variation of CO_2 was varied between 19.5-37.7% and 15.9-36.0% for western and eastern NG sources, respectively. These variations affected to sharp peak frequency, cell size and attractor of cellular flames. For the same CH_4 composition, greater cell size was obtained from western NG source compared with eastern NG source. Moreover, the 1% decrease of CH_4 composition affected to 1.4% and 1.5% increase of cell size from eastern and western NG sources, respectively. As the same CO_2 composition, the greater cell size was obtained from western NG source compared with eastern NG source. Moreover, the 10.0% increase of CO_2 composition affected to increase of cell size about 59.9% and 35.9% for eastern and western NG source, respectively. The results showed decrease of CH_4 and increase of CO_2 induced higher sharp peak frequency, greater cell size and attractor due to higher instability intensity. At same CH_4 composition, more stable flame was obtained from eastern NG source compared to western NG source, and it had no effect difference on decreasing of CH_4 for both sources. At same CO_2 composition, more unstable flame was observed from eastern NG source compared to western NG source, and it had more effects on decreasing of CO_2 for eastern NG sources.

***Keywords**:* Cellular flame, CH_4, CO_2, Synthetic Natural Gas, Diffusive-thermal instability, Cell size, Attractor

1. Introduction

Generally, the combustion was derived from fossil fuel which emitted the greenhouse gases such as carbon dioxide (CO_2) and nitrogen oxide (NO_x). In order to reduce the emission the low-carbon fuel such as liquefied petroleum gas (LPG) and natural gas (NG), were applied instead of conventional fossil fuel. The study of global energy trend [1] was shown that NG was used highly and trended to apply increasingly in the future due to low price and high heating value. For Thailand [2], NG was imported (19%) and produced (81%) which was consumed widely in transportation (6%), industrial (14%) and power plant (21%] sectors. As the NG in Thailand, it was produced from western source such as Banthong, Ratchaburi, southern Bangkok and Sainoi and from eastern sources such as Mabtaput, Nongkae, Bangpakong, Navanakorn and Kangkoi [3]. Moreover, the data from gas supply station operated in Thailand was shown that the main compositions of NG such as methane (CH_4) and carbon dioxide (CO_2) from eastern and western of Thailand were different. As the above states, NG was used widely in the part of power plant especially in gas turbine, thus it was interesting to study the composition effects of different NG combustion. Normally, gas turbine was focused on the lean combustion which helped for the reduction of emission with unstable flame such as cellular flame due to intrinsic instability [4].

There are three basic instinct of intrinsic instability as diffusive-thermal instability, hydrodynamic instability and body-force instability. In the past, the lean combustion of CH_4/air and CH_4/CO_2/air was investigated with cellular flame analysis which was the comparison of cellular flame range (unstable range), cell size and reconstructed attractor [5]. The previous study [6-7], Liquefied Petroleum Gas (LPG) and $CH_4/O_2/CO_2$ combustion was experimented on ceramic porous board which the light emission was detected and cellular flame range was obtained at ϕ=0.88-0.95. Moreover, the CO_2 effects of H_2/O_2 on flat burner was investigated and cell size, power spectral density and reconstructed attractor were analyzed to compare the intrinsic instability [8-9]. In order to investigate the effects of CH_4 and CO_2 as main compositions with lean combustion of synthetic NG between eastern and western sources, thus, this study focuses on the analyze of cell size, emission light and reconstructed attractor of cellular flame due to intrinsic instability.

2. Experimental Apparatus

Fig.1 shows the experimental apparatus which composes of 60 mm in diameter of McKenna burner, digital camera (Nikon d800e), photo-diode (Hamamatsu S1223-01) for 320-1100 nm of wavelengths, data logger, air compressor, mixing chamber, digital mass flow controller (Azbil), CH_4 gas and CO_2 gas. The study of synthetic Thai NG combustion was experimented by mixing of CH_4/CO_2/air at 45 L/min of total gas flow rate which were measured by digital mass flow controller. The CH_4/CO_2/air mixtures were ignited to obtain cellular flame which was taken by digital camera and detected by photo-diode for reconstructed attractor.

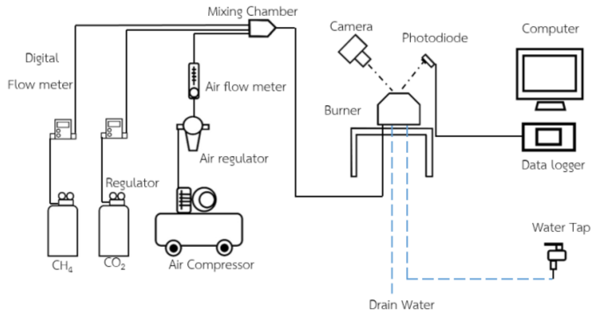

Fig. 1 Experimental apparatus.

3. Methodology

In this experiment, the Thai synthetic NG/air combustion shown in Eq.(1) was treated with variation of CH_4 and CO_2 for eastern and western NG compositions as shown in Table.1. Following the difference between eastern and western NG composition, the effects of CH_4 and CO_2 were investigated. The flow rate of CH_4 was varied from 2.9-3.3 L/min and 2.74-3.0 L/min for western and eastern NG sources, respectively. Moreover, the flow rate of CO_2 was treated from 0.8-2.0 L/min and 0.6-1.8 L/min for western and eastern NG sources, respectively. The experimental conditions with different gas flow rates of both CH_4 and CO_2 are illustrated in Table. 2-5. The photographs the cellular flame were taken directly by digital camera to obtain the cell size. The intensity of light emission was measured by photo-diode to analyze for power spectral density and create reconstructed attractor.

Table. 1 Gas composition of eastern and western natural gas sources.

Natural Gas Source	*CH_4 [%]*	*CO_2 [%]*
Eastern source	*84.1*	*15.9*
Western source	*76.0*	*24.0*

$$aCH_4 + bCO_2 + 2a(O_2+3.76N_2) \rightarrow (a+b)CO_2 + 2aH_2O + 7.52aN_2 \quad (1)$$

Table. 2 Variation of CH_4 from western NG source.

CH_4 [%]	*CH_4 [L/min]*	*CO_2 [L/min]*	*Air [L/min]*	*Total [L/min]*
76.6	*3.3*	*1.0*	*40.7*	*45.0*
75.6	*3.1*	*1.0*	*40.9*	*45.0*
74.4	*2.9*	*1.0*	*41.1*	*45.0*

Table. 3 Variation of CH_4 from eastern NG source.

CH_4 [%]	*CH_4 [L/min]*	*CO_2 [L/min]*	*Air [L/min]*	*Total [L/min]*
83.7	*3.0*	*0.6*	*41.4*	*45.0*
82.4	*2.8*	*0.6*	*41.6*	*45.0*
81.3	*2.7*	*0.6*	*41.8*	*45.0*
80.0	*2.4*	*0.6*	*42.0*	*45.0*

Table. 4 Variation of CO_2 from western NG source.

CO_2 [%]	*CH_4 [L/min]*	*CO_2 [L/min]*	*Air [L/min]*	*Total [L/min]*
19.5	*3.3*	*0.8*	*40.9*	*45.0*
26.7	*3.3*	*1.2*	*40.5*	*45.0*
32.7	*3.3*	*1.6*	*40.1*	*45.0*
37.7	*3.3*	*2.0*	*39.7*	*45.0*

Table. 5 Variation of CO_2 from eastern NG source.

CO_2 [%]	*CH_4 [L/min]*	*CO_2 [L/min]*	*Air [L/min]*	*Total [L/min]*
15.9	*3.2*	*0.6*	*41.2*	*45.0*
23.8	*3.2*	*1.0*	*40.8*	*45.0*
30.4	*3.2*	*1.4*	*40.4*	*45.0*
36.0	*3.2*	*1.8*	*40.0*	*45.0*

3.1 Cell size analysis

In this study, the cell size was investigated to perform the instability intensity. Fig. 2 shows the definition of cell size which is the distance between cusps of cellular flame fronts.

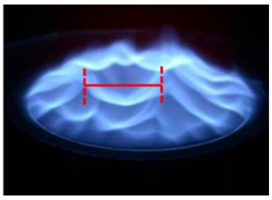

Fig. 2 Cell size analysis.

3.2 Power Spectrum Density

The power spectrum density was obtained by signal data detected by photo-diode and analyzed by Fast Fourier Transform (FFT) then the typical oscillation frequency, f_1, called "sharp peak frequency" was shown from in Eq. (2).

$$\tau = \frac{1}{4 f_1} \qquad (2)$$

3.3 Chaos behavior analysis

The sharp peak frequency was analyzed by Eq. (3) to obtain time delay and applied for the reconstructed attractor created by Takens' embedding theorem as chaos behavior analysis. The vector $\vec{V}(t)$ in the time-delayed coordinate was shown in Eq. (2), indicating the vector in reconstructed phase space as shown in Fig. 3.

$$\vec{V}(t) = [y(t), y(t+\tau), y(t+2\tau), \cdots, y(t+(m-1)\tau)] \qquad (3)$$

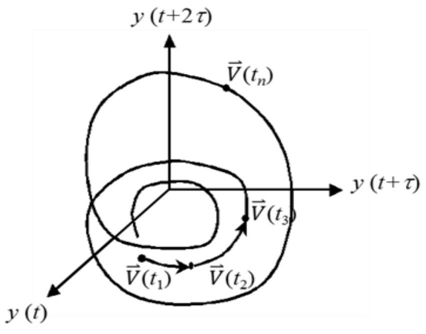

Fig. 3 Reconstructed attractor by Takens' embedding theorem [10].

4. Results

4.1 Effects of methane (CH_4)

The variation of CH_4 as the hydrocarbon fuel, was treated and the cell size of cellular flame, power spectrum density and reconstructed attractor were obtained for comparison between western and eastern NG sources.

Table. 6 Cell size with variation of CH_4 from western NG source.

CH_4 [%]	CH_4 [L/min]	CO_2 [L/min]	Air [L/min]	Cell size [mm]
76.7	3.3	1.0	40.7	5.8
75.6	3.1	1.0	40.9	7.1
74.4	2.9	1.0	41.1	8.8

Table. 7 Cell size with variation of CH_4 from eastern NG source.

CH_4 [%]	CH_4 [L/min]	CO_2 [L/min]	Air [L/min]	Cell size [mm]
83.7	3.0	0.6	41.4	3.5
82.1	2.8	0.6	41.6	6.8
81.1	2.7	0.6	41.8	9.4
80.0	2.4	0.6	42.0	11.8

4.1.1 Cell size

The photos of cellular flames varied by CH_4 both NG sources, were taken by digital camera to analyze cell size of cellular flames. Table. 6-7 show the cell size with variation of CH_4 from western and eastern NG sources. When the composition of CH_4 decreased by decreasing of gas flow rate, the cell size became larger and closed to the blown-off flame as shown in Fig. 4. In the same way for eastern NG source, the cell size was greater when the composition of CH_4 was lowered due to diffusive-thermal instability.

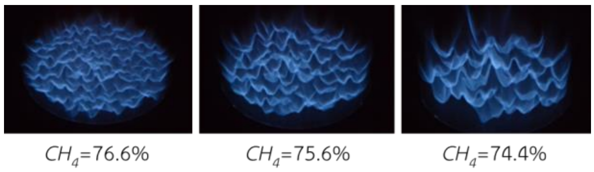

Fig. 4 Photos of cellular flames with variation of CH_4 from western NG source.

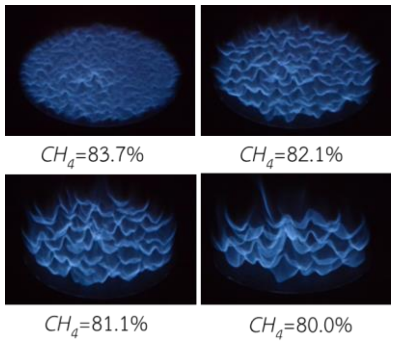

Fig. 5 Photos of cellular flames with variation of CH_4 from eastern NG source.

4.1.2 Power spectrum density

The emission lighting was detected by photo-diode with voltage signal and was analyzed by FFT to obtain the power spectrum density. The analyzed power spectrum density showed the sharp peak, f_1 which was corresponding to the typical oscillation frequency. Figure 6-7 shows the decrease of CH_4 composition from 76.6% to 74.4% affected to lower f_1 from 10.558 to 8.905 Hz for western NG source. For eastern NG source in Fig. 8-9, the CH_4 composition was decreased from 83.7% to 80.0%, the f_1 was lower from 11.830 to 8.786 Hz.

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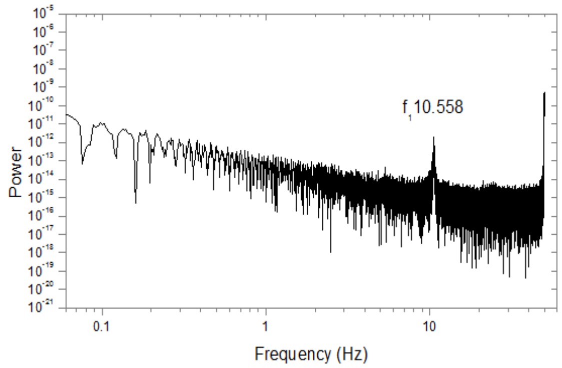

Fig. 6 Power spectral density at CH_4=76.6% from western NG source.

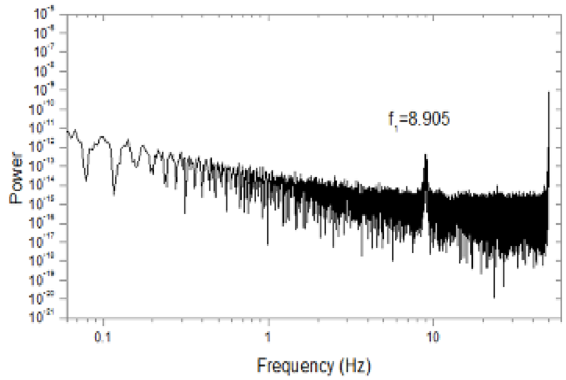

Fig. 7 Power spectral density at CH_4=74.4% from western NG source.

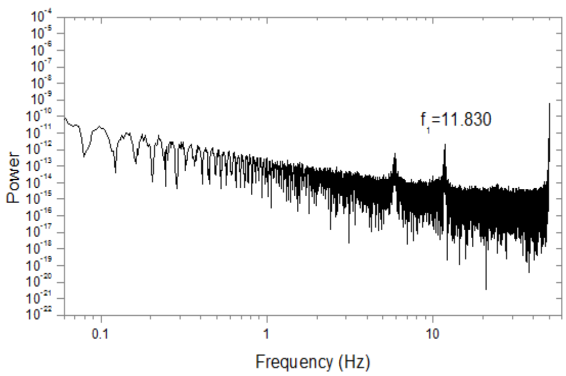

Fig. 8 Power spectral density at CH_4=83.7% from eastern NG source.

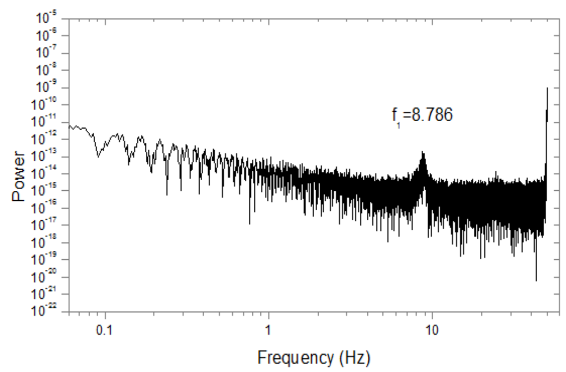

Fig. 9 Power spectral density at CH_4=80.0% from eastern NG source.

4.1.3Chaos behavior

The chaos behavior was studied to analyze and create the reconstructed attractor by Takens' embedding theorem. Figure 10-11, when the composition of CH_4 composition decreases from 76.6% to 74.4%, the reconstructed attractor was greater for western NG source. For eastern NG source in Fig. 12-13, the CH_4 composition was lower from 83.7% to 80.0%, the reconstructed attractor was also greater and more complicated because of the higher instability intensity induced by lower CH_4. The results indicated that the instability intensity is higher because the decrease of CH_4 induced the diffusive-thermal instability.

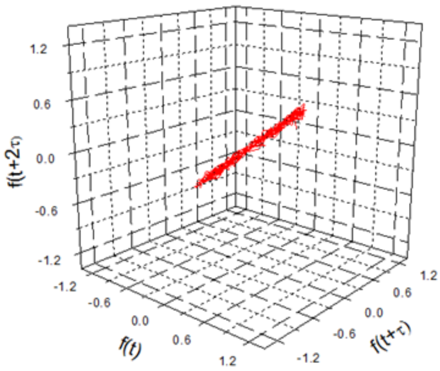

Fig. 10 Reconstructed attractor at CH_4=76.6% from western NG source.

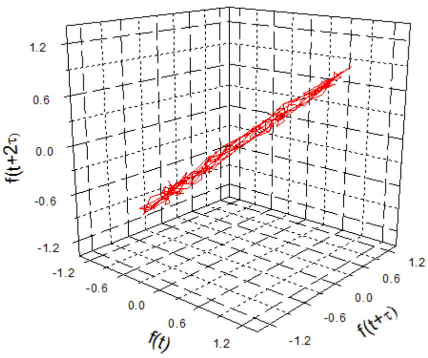

Fig. 11 Reconstructed attractor at CH_4=74.4% from western NG source.

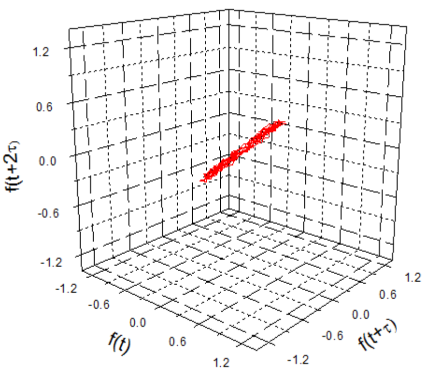

Fig. 12 Reconstructed attractor at CH_4=83.7% from eastern NG source.

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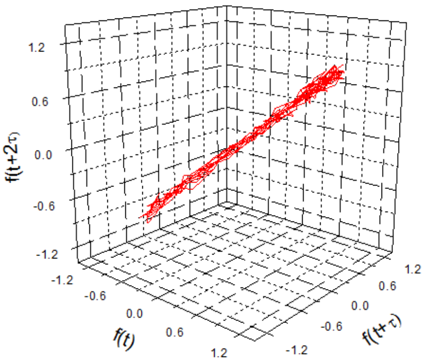

Fig. 13 Reconstructed attractor at CH_4=80.0% from eastern NG source.

4.2 Effects of carbon dioxide (CO_2)

The variation of CO_2 was experimented and the cell size of cellular flame, power spectrum density and reconstructed attractor were obtained for comparison between western and eastern NG sources.

Table. 8 Cell size with variation of CO_2 from western NG source.

CO_2 [%]	CH_4 [L/min]	CO_2 [L/min]	Air [L/min]	Cell size [mm]
19.5	3.3	0.8	40.9	5.9
26.7	3.3	1.2	40.5	7.1
32.7	3.3	1.6	40.1	8.4
37.7	3.3	2.0	39.7	8.8

Table. 9 Cell size with variation of CO_2 from eastern NG source.

CO_2 [%]	CH_4 [L/min]	CO_2 [L/min]	Air [L/min]	Cell size [mm]
15.9	3.2	0.6	41.2	6.5
23.8	3.2	1.0	40.8	7.6
30.4	3.2	1.4	40.4	8.2
36.0	3.2	1.8	40.0	8.8

4.2.1 Cell size

The photos of cellular flames varied by CO_2 for both NG sources, the cell size of cellular flames were obtained. Table. 8-9 show the cell size with variation of CO_2 from western and eastern NG sources. For western NG source, when the composition of CO_2 was decreased from 37.7%-19.5%, the cell size became smaller as shown in Fig.14. In the same way for eastern NG source, the cell size was smaller when the composition of CO_2 was decreased from 36.0%-15.9%.

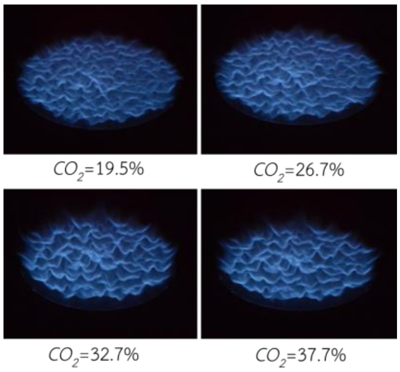

Fig. 14 Photos of cellular flames with variation of CO_2 from western NG source.

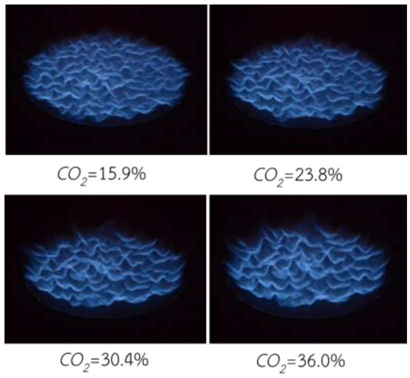

Fig. 15 Photos of cellular flames with variation of CO_2 from eastern NG source.

4.2.2 Power spectrum density

Figure 16-17 shows the increase of CO_2 composition from 19.5% to 37.7% affected to lower f_1 from 11.023 to 9.998 Hz for western NG source. For eastern NG source in Fig.18-19, the CO_2 composition was increased from 15.9% to 36.0%, the f_1 was lowered from 10.713 to 9.834 Hz.

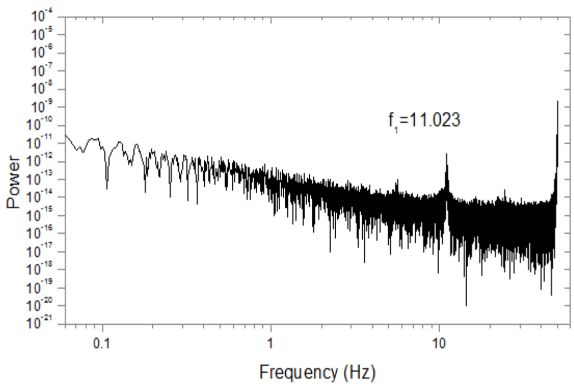

Fig. 16 Power spectral density at CO_2=19.5% from western NG source.

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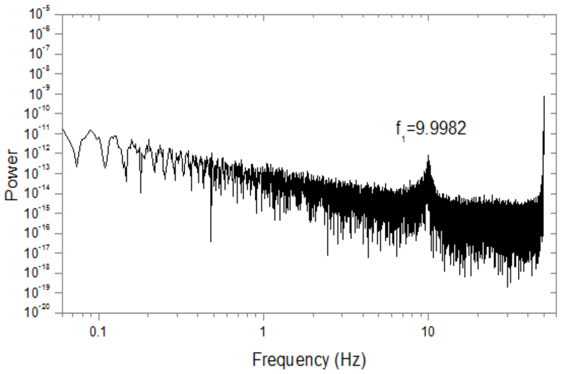

Fig. 17 Power spectral density at CO_2=37.7% from western NG source.

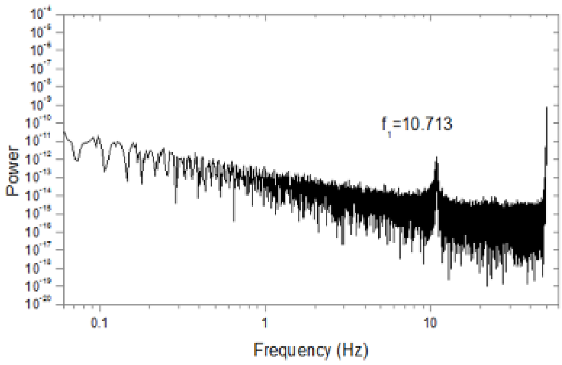

Fig. 18 Power spectral density at CO_2=15.9% from eastern NG source.

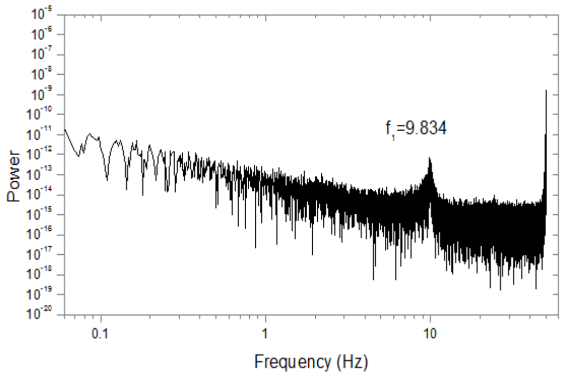

Fig. 19 Power spectral density at CO_2=36.0% from eastern NG source.

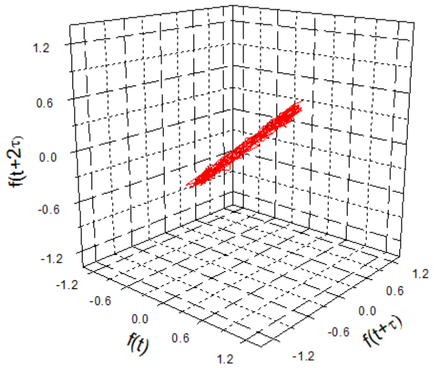

Fig. 20 Power spectral density at CO_2=19.5% from western NG source.

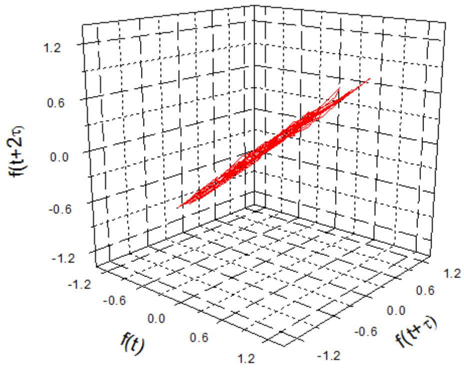

Fig. 21 Power spectral density at CO_2=37.7% from western NG source.

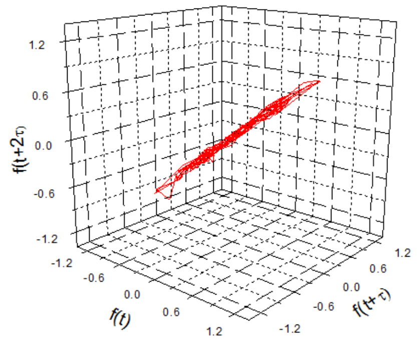

Fig. 22 Power spectral density at CO_2=15.9% from eastern NG source.

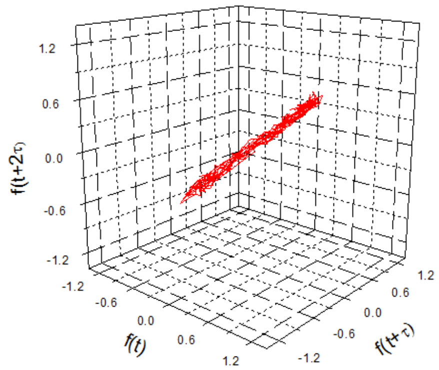

Fig. 23 Power spectral density at CO_2=36.0% from eastern NG source.

4.2.3 Chaos behavior

The chaos behavior was studied to analyze and create the reconstructed attractor by Takens' embedding theorem. Figure 20-21, when the composition of CO_2 composition increased, the reconstructed attractor was greater for western NG source. For eastern NG source in Fig. 22-23, the CO_2 composition was lowered, the reconstructed attractor was also smaller because of the lower instability intensity. The results indicated that the instability intensity increased because the higher ratio of CO_2 in the mixture.

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5. Conclusions

This study focused on the effects of CH_4 and CO_2 on intrinsic instability of synthetic Thai NG flames. The results showed variation of CH_4 and CO_2 affected to sharp peak frequency, cell size and attractor.

The relation between cell size with CH_4 variation between eastern and western NG sources are shown in Fig. 24-25. For the same CH_4 composition, the greater cell size was obtained from western NG source compared with eastern NG source. Moreover, the 1% decrease of CH_4 composition affected to 1.4% and 1.5% increase of cell size from eastern and western NG source, respectively.

The relation between cell size with CO_2 variation between eastern and western NG sources are shown in Fig. 26-27. At the same CO_2 composition, the greater cell size was obtained from western NG source compared with eastern NG source. Moreover, the 10% increase of CO_2 composition affected to 59.9% and 35.9% increase of cell size from eastern and western NG source, respectively.

The results showed decrease of CH_4 and increase of CO_2 induced higher sharp peak frequency, greater cell size and attractor due to higher instability intensity. At same CH_4 composition, more stable flame was obtained from eastern NG source compared to western NG source, and it had no effect difference on decreasing of CH_4 for both sources. At same CO_2 composition, more unstable flame was obtained from eastern NG source compared to western NG source, and it had more effects on decreasing of CO_2 for eastern NG sources.

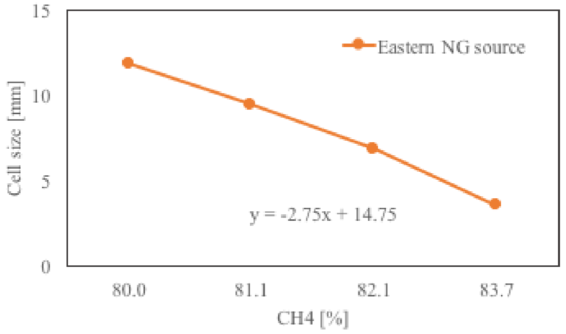

Fig. 24 Relation between cell size with CH_4 variation for eastern NG sources.

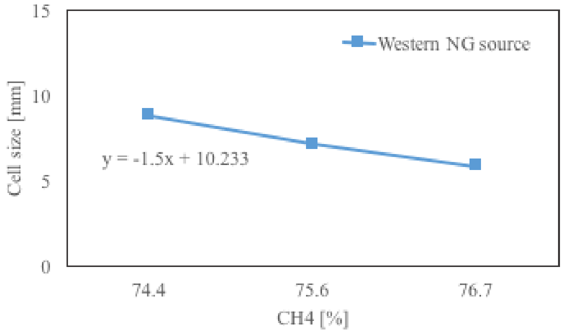

Fig. 25 Relation between cell size with CH_4 variation for western NG sources.

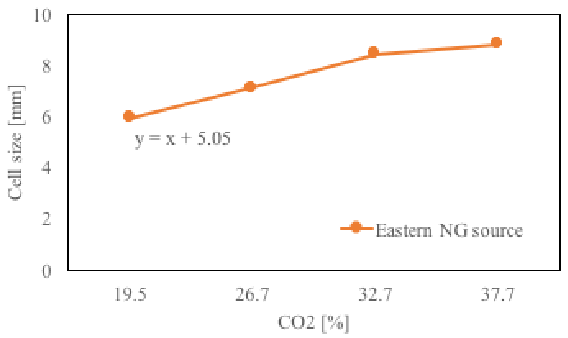

Fig. 26 Relation between cell size with CH_4 variation for eastern NG sources.

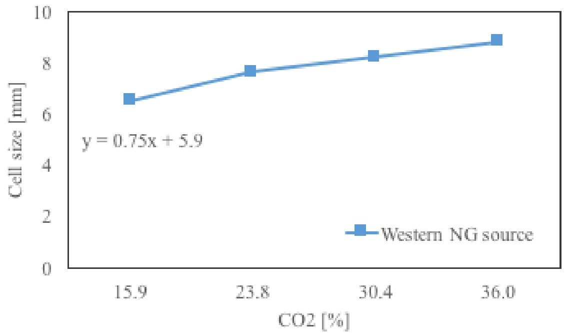

Fig. 27 Relation between cell size with CH_4 variation for western NG sources.

6. Acknowledgement

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7.1 Report

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