

Effect of the Waste Heat Recovery System to Buoyancy and Momentum Flux of Combustion Stack in the Cement Industry

Jutarat Keawboonchu^{1,2}, Wissawa Malakan^{1,2}, Wisit Thongkum³ and Sarawut Thepanondh^{1,2*}

¹Department of Sanitary Engineering, Faculty of Public health, Mahidol University, Bangkok 10400, Thailand

²Center of Excellence on Environmental Health and Toxicology (EHT), Bangkok 10400, Thailand

³Faculty of Public Health, Mahasarakham University, Mahasarakham 44150, Thailand

ARTICLE INFO

Received: 9 Apr 2018
Received in revised:
5 Jul 2018
Accepted: 17 Jul 2018
Published online:
4 Oct 2018
DOI: 10.32526/ennrj.17.1.2019.02

Keywords:

Buoyancy flux/ Momentum flux/ PM-10/ Waste heat recovery

* Corresponding author:

E-mail:
thepanondh@gmail.com

ABSTRACT

Buoyancy and momentum fluxes are important parameters to determine the plume rise which is related to the ability to dilute air pollutants emitted from combustion stack sources. The change of temperature due to waste heat recovery directly affects these fluxes. This study analyzed buoyancy and momentum fluxes and evaluated the ground level concentration of PM-10 prior and after implementation of waste heat recovery in the area surrounding one of the largest cement production plants in Thailand. The results showed that the ambient temperature was the significant parameter affecting buoyancy and momentum fluxes. The buoyancy flux was found to be the dominant force to the rise of plume for both scenarios. There were no differences in the predicted PM-10 ground level concentrations at receptors around the cement plant for the model simulation under two scenarios. Therefore, it was concluded that decreasing of stack gas exit temperature does not affect the dispersion of air pollutants in the cement industry.

1. INTRODUCTION

Nowadays, a large number of pollutants emitted from various anthropogenic sources into the atmosphere cause damage to human health and the environment in the world (Liu et al., 2017; Cao et al., 2011; Kampa and Castanas, 2008; Brook et al., 2010). Approaches to manage and control air pollution problems in order to reduce ground level concentrations of pollutants can be classified into three general approaches. Firstly, increase the opportunity for air pollution to diffuse from emission sources. Secondly, modification of raw materials and production processes to reduce emissions of air pollutants from the source, and thirdly, by applying technology to the control and treatment of air pollutants. (Vallero, 2014; Dimmick and Wehe, 1999)

Under the first approach, increasing the chances of diffusion of air pollutants from the source leads to an increase of the volume of air dilution. Therefore, the ground level concentrations of pollutants at the receptor sites are reduced. The industry has applied this approach using tall stacks. Theoretically, increasing the vertical displacement of

pollutants from ground level will contribute to the reduction of ground level concentrations and result in a lower intake fraction (Bhargava, 2016; Parvez et al., 2017).

It is well recognized that the diffusion of air pollutants from stack sources is not at the constant height as the physical stack height (h_s) but the pollutants can travel in the vertical direction. The distance from the top of the stack to the center of the plume is described as a plume rise (Δh) (Hoven, 1975), while, the distance from the ground level to the center of the plume (include the physical stack height) is the effective stack height (H). It is an important factor in atmospheric dispersion modeling and may have a significant influence on modeled concentration values (Essa et al., 2006; Masters, G.M., 1997; Turner, D.B., 1970) as shown in Figure 1.

Plumes can move downwind of a source and expand by diffusion in both horizontal and vertical dimensions. From Figure 1, the increasing of plume rise (Δh) value leads to an increase in vertical distance before pollutants spread in the horizontal dimension. Therefore, the rising of plume induces

the reduction of ground level concentrations. Stack plume rise is a phenomenon which is mainly dependent on two factors. Firstly, thermal buoyancy or buoyancy flux dominated by temperature difference between the stack and ambient air at discharge point. Secondly, mechanical momentum or momentum flux dominated by difference of stack exit gas velocity and wind velocity at discharge point. Both of these data are specific in each stack and area.

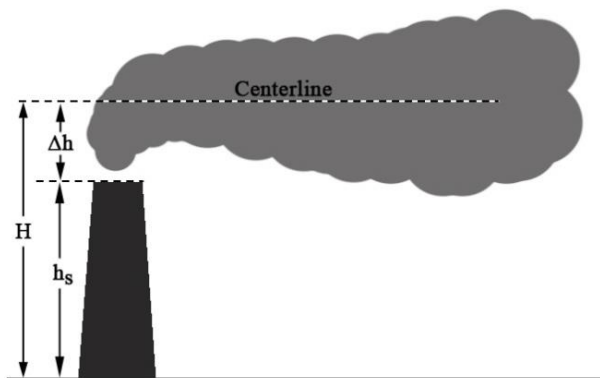


Figure 1. A Gaussian plume model

The cement industry is one of the world's largest energy consumers. Massive energy consumption for cement production occurs in the calcination process and clinker production process (Madloul et al., 2011; Madloul et al., 2013). Under the business as usual (BAU) for this type of industry, a large amount of heat is vented to the atmosphere passing through a combustion stack without utilization. Therefore, many cement plants have installed Waste heat recovery (WHR) systems to return escaping heat within processes and across the industry (Fang et al., 2013; United States Department of Energy, 2008; Demirkaya et al., 2013). WHR system may lead to a decreasing in the temperature of the discharged gas. The heat or temperature reduction will directly affect the buoyancy flux of gas, and may result in a decrease in the plume rise value. As a result, the ability to disperse and dilute air pollutants into atmosphere will drop off. Hence, ground level concentrations of air pollutants may be increased due to lower dilution ability caused by decreasing of stack plume rise. This research aims to analyze the effect of temperature changes in waste heat recovery system on buoyancy and momentum fluxes of the combustion plume from stacks in the cement

industry. Results are further analyzed and illustrated for their impact on ground level concentrations of PM-10 prior and after implementing of the WHR system. Findings from this study will be very useful to elaborate whether there are any demerits of process modification (installation of WHR system) to pollution control and management of the cement industry or not.

2. METHODOLOGY

2.1 Study area

This study is conducted at a cement plant located in Saraburi, Thailand as shown in Figure 2. The area is classified as a complex terrain (mountainous area) with mountain peak elevations of about 800 to 1,300 m above mean sea level. This area is the home of the cement industry in Thailand (TCMA, 2016). The selected cement plant is located about 110 km northeast of Bangkok.

2.2 Meteorology

Thailand is located in the tropical area between latitudes 5°37'N to 20°27'N and longitude 97°22'E to 105°37'E. The climate is under the influence of the monsoon wind of seasonal character as southwest monsoon and northeast monsoon. The climate of Thailand can be divided into three seasons: summer from mid-February to mid-May, winter from mid-October to mid-February, and rainy season from mid-May to mid-October (TMD, 2018). The study area is located in the central part of Thailand that usually encounters a long period of warm weather. The surface meteorological data were derived from the Na-Pha-Lan ambient air monitoring station operated by the Pollution Control Department (PCD). This station is about 22 km away from the reference point. In this study, meteorological characteristics over five years (1st January 2012 to 31st December 2016) were used for the analysis. Analyzed data is as presented in Table 1. Measured meteorological data indicated that the area is arid with little rain in winter. The warmest period of the year is from March to May. Average monthly temperature is about 24.4-34.3°C. These values for daytime and nighttime are about 29.4-34.3°C and 24.4-28.8°C, respectively. April is the hottest month of the year, while February is the coldest month. High wind speed is observed during winter with the highest average of 6.4 m/s in February. Average wind speeds during daytime and nighttime are

around 1.5-2.6 m/s and 0.6-1.1 m/s respectively. Figure 3 depicts the wind rose diagram of the study

area. Most of the wind prevails from the south direction as illustrated in Figure 3.

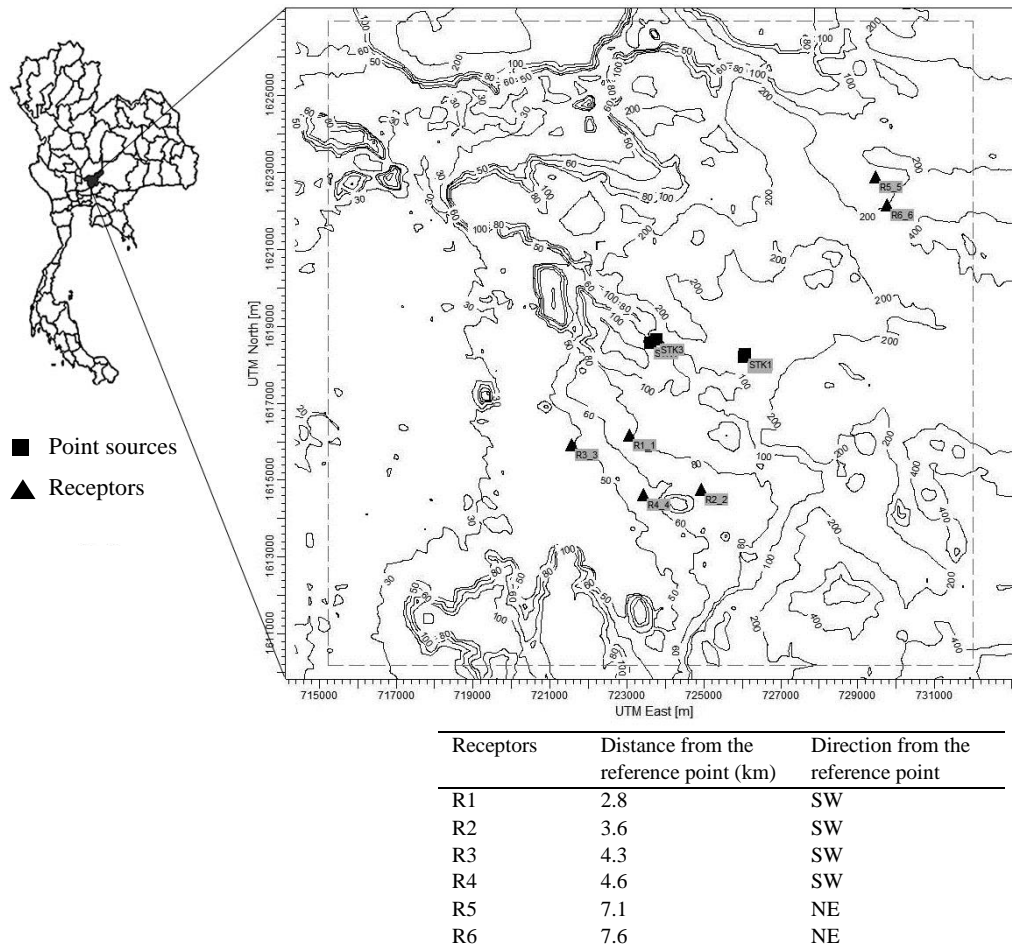


Figure 2. Location of emission sources and receptors in the modeling area

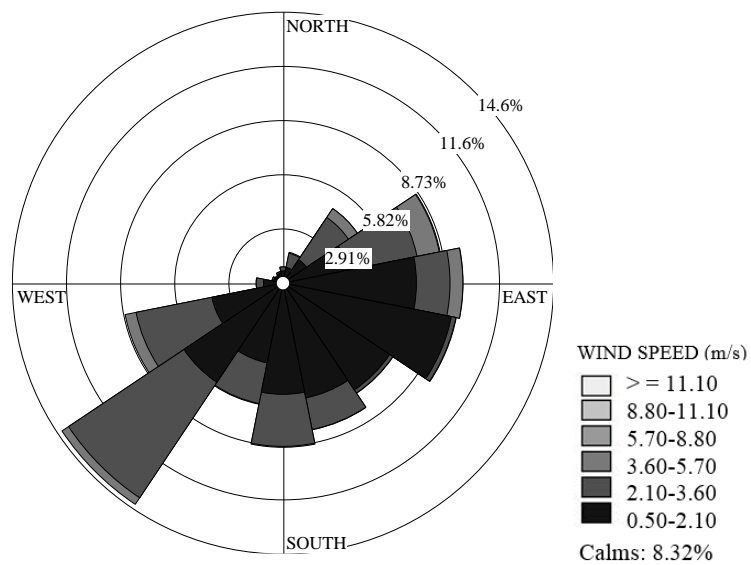


Figure 3. Wind rose of the study area (2012-2016)

Table 1. Summary of meteorological characteristics of the study area (data from 2012-2016)

Months	Relative humidity (%)	Average wind speed in day time ¹ (m/s)	Average wind speed in night time ² (m/s)	Average temperature in day time (°C)	Average temperature in night time (°C)	Minimum temperature (°C)	Maximum temperature (°C)
January	59.0	2.2	1.1	29.8	24.4	14.2	36.5
February	60.8	2.3	0.7	31.8	26.2	11.6	27.8
March	62.4	2.5	1.0	33.3	27.7	21.8	39.9
April	60.3	2.5	1.0	34.4	28.8	22.8	41.2
May	63.1	2.5	0.9	33.7	28.7	22.3	41.0
June	71.4	2.3	0.7	31.8	27.2	23.3	39.2
July	74.2	2.1	0.7	31.2	27.0	22.6	38.8
August	76.5	1.9	0.7	30.9	26.2	14.3	37.9
September	80.7	1.5	0.6	30.1	25.8	16.3	36.7
October	75.4	1.6	0.6	30.6	25.8	22.5	36.5
November	68.8	2.0	0.7	31.0	25.9	14.5	37.1
December	58.6	2.6	1.0	29.4	24.8	16.0	36.1

¹ Daytime is defined when the global radiation is less than or equal to 5 w/m²

² Nighttime is defined when the global radiation is greater than 5 w/m²

2.3 Evaluation of Buoyancy and Momentum fluxes

Screen View model (Lakes Environmental, 2011), a Window interface for the U.S. Environmental Protection Agency screening model SCREEN3 (USEPA, 1995a), provides a simple method of estimating contaminant concentrations. It is capable of measuring the worst-case dispersion (maximum concentration) of various pollutants. However, in this study, Screen View model is only used to estimate Buoyancy and momentum fluxes of combustion stack in the cement plant. For most plume rise situations, the value of the Briggs buoyancy flux parameter (F_b (m⁴/s³)) given by (1) and the momentum flux parameter (F_m (m⁴/s²)) given by (2) are needed.

$$\text{Buoyancy flux, } F_b = g v_s d_s^2 \left(\frac{T_s - T_a}{T_s} \right) \quad (1)$$

$$\text{Momentum flux, } F_m = \left(\frac{T_a}{T_s} \right) v_s^2 d_s^2 \quad (2)$$

where, T_s is the stack gas temperature (K), T_a is ambient temperature (K), g is gravity, 9.8 m/s², v_s is

stack exit velocity (m/s), and d is top inside stack diameter (m)

The effects of buoyancy and momentum fluxes on plume rise are analyzed by using two data sets, meteorological data and stack characteristics. Meteorological data measured over the year 2012-2016 from the Na-Pha-Lan station are used to represent the meteorological conditions occurring in each month separated for daytime and nighttime data (Table 1). Information on the stack characteristics such as emission rate, stack height, stack diameter, stack gas exit velocity, stack gas exit temperature (designed data from the plant) are obtained from the factory (Table 2). The influences of implementing the waste heat recovery program in the factory on stack plume rise are evaluated under two scenarios.

Scenarios I. No waste heat recovery installation (No WHR) and

Scenarios II. Waste heat recovery installation (WHR)

Table 2. Input data

Cases	Emission rate (g/s)	Stack height (m)	Stack diameter (m)	Velocity (m/s)	Gas temperature (K)	Ambient temperature (K)	Wind speed (m/s)
I	43.94	120	5.2	17.85	598	Using measured meteorological data	Using measured meteorological data
II	43.94	120	5.2	17.85	413	Using measured meteorological data	Using measured meteorological data

2.4 PM-10 ground level concentrations

The AERMOD air quality dispersion model (version 9.4.0) is used to predict the concentrations of PM-10 at receptor points located in the vicinity of the factory in this study. AERMOD is recommended and designed as a regulatory model by U.S. EPA. The model performs under the Gaussian plume theory for the vertical and horizontal distributions. The model is composed of three components: AERMOD Meteorological Pre-processor (AERMET), AERMOD Terrain Pre-processor (AERMAP), and the control module and modeling preprocessor (AERMOD). The AERMET processes the hourly surface data and a profile data file. The AERMAP is used to process the terrain data in conjunction with a layout of receptor and sources for AERMOD control files. The AERMOD is a dispersion model (USEPA, 2018).

The study domain covered an area of 16 x 16 km² with a finest grid resolution of 250 x 250 m² grid resolution. One stack emission source is set as a

reference point (UTM 723618E and 1618563N). The hourly surface and upper air meteorological data from the year 2015 were used. The upper meteorological data were derived from the measurement in Bangkok (about 120 km in the southwestern direction of the plant).

Ground level concentrations of PM-10 are predicted for 6 receptor points located within community areas. Affected communities were selected based on their location along the prevailing winds of the study area (Figure 2). The nearest receptor to the reference point is about 2.8 km. Data of amount of dust (total Suspended Particulate, TSP) emitted from combustion stacks in cement plant are obtained from direct measurement. About 88% of them are estimated as PM-10 (Gupta et al., 2012) with 60 µg/m³ of background concentration. The background concentration of PM-10 in this area was obtained from Department of Primary Industries and Mines, Thailand. Emission characteristics of each stack source are summarized in Table 3.

Table 3. Emission characteristics of four stacks in the cement plant

Stack number	Height (m)	Diameter (m)	Gas temp. (K)		Gas velocity (m/s)	PM-10 (g/s)
			No WHR	WHR		
S1	102	4	598	413	20	19.22
S2	102	4	598	413	16.5	19.49
S3	120	5.2	598	413	18	25.64
S4	120	5.2	598	413	17.9	43.94

3. RESULTS AND DISCUSSION

The effects of implementing waste heat recovery system in the factory to the alteration of plume rise were estimated under two difference scenarios. In the first scenario, plume rise was calculated under the condition with no waste heat recovery system were utilized in the factory. The hot gas was released directly to the atmosphere with the same temperature after exiting the combustion activity. Implementing of waste heat recovery system in the target industry which could be affected in decreasing of stack exit temperature of the exhaust gas was evaluated under the second scenario. Results are presented and discussed as follows:

3.1 Contribution of momentum and buoyancy fluxes to the plume rise

Many research studies have reported that buoyancy and momentum fluxes are associated

factors affecting plume rise and ground level concentration of pollutants. In an unstable condition, the buoyancy of the plume increases as it rises, increasing the plume height. (Bhargava, 2016; Ilaboya et al., 2011). The business as usual (BAU) of the cement factory which the exhaust gas were released directly to the atmosphere (scenario I) was used to evaluate the contribution of buoyancy and momentum fluxes to the plume rise. Calculated results are presented in Table 4 and Table 5. The lowest buoyancy flux was predicted to occur during daytime in April while the highest value occurred during the nighttime in January. These findings could be resulted from the fact that buoyancy flux is mainly driven by the difference between stack exhausted gas and ambient temperature. April is the warmest month in Thailand (Average daytime temperature=34.4°C), which leads to a smaller calculated buoyancy flux as compared with the

nighttime in January, which is the coldest period (Average nighttime temperature=24.4°C). The buoyancy flux was predicted to be highest during the nighttime periods. Average buoyancy flux during the day and nighttime were estimated as about 581.0 and 590.81 m⁴/s², respectively. There were slight differences between the values of each month as indicated by low standard deviations (S.D.). However, buoyancy and momentum fluxes of daytime and nighttime are significantly different with statistically highly significant p-value<0.001 (Independent t-test)

On the other hand, the maximum momentum flux (1106.8 m⁴/s²) was estimated to occur during the

daytime in April and the lowest value (1071.2 m⁴/s²) was predicted during the nighttime in January. Average momentum flux was 1096.7 and 1078.9 m⁴/s³ for day and nighttime, respectively. The values were not much difference among each month.

After implementing the waste heat recovery system in the factory (2nd Scenario), the results shows that decreasing of stack temperature lead to reduction of buoyancy flux while the momentum flux had the same tendency to the first scenario. The lowest and highest buoyancy fluxes occurred during daytime in April and nighttime in January, respectively.

Table 4. Temporal variation of buoyancy and momentum fluxes on a monthly basis in case of no waste heat recovery installation

Month	Buoyancy flux (m ⁴ /s ³)		Momentum flux (m ⁴ /s ²)	
	Daytime	Nighttime	Daytime	Nighttime
January	584.3	595.0	1090.6	1071.2
February	580.4	591.5	1097.8	1077.7
March	577.4	588.5	1103.2	1083.1
April	575.4	586.4	1106.8	1086.8
May	576.6	586.5	1104.7	1086.7
June	580.4	589.5	1097.8	1081.3
July	581.6	589.9	1095.7	1080.5
August	582.2	591.5	1094.6	1077.7
September	583.8	592.3	1091.7	1076.2
October	582.8	592.3	1093.5	1076.2
November	582.0	592.1	1095.0	1076.6
December	585.1	594.2	1089.2	1072.6
Average ¹	581.0	590.8	1096.7	1078.9
S.D.	2.9	2.5	5.2	4.6

¹ p-value<0.001 (Independent t-test)

In most EPA dispersion models, in order to calculate the plume rise, the buoyancy flux and momentum flux parameters are required. For cases of unstable condition with stack gas temperature greater than or equal to ambient temperature, it must be determined whether the plume rise is dominated by momentum or buoyancy forces. The dominant flux can be determined following the procedure of Briggs as showed in the ISC Users' Guide, Section 1.1.4.3 (USEPA, 1995b).

For $F_b < 55$,

$$(\Delta T)_c = 0.00297 T_s \frac{v_s^{1/3}}{d_s^{2/3}} \quad (3)$$

and for $F_b \geq 55$,

$$(\Delta T)_c = 0.00575 T_s \frac{v_s^{2/3}}{d_s^{1/3}} \quad (4)$$

If the difference between the stack gas and ambient temperature (ΔT) is greater than or equal to the crossover temperature difference $(\Delta T)_c$ as shown in (3 and 4), then the plume rise is assumed to be buoyancy dominated. Using the stack and meteorological data in this study, we found that buoyancy is the dominant flux over the calculated plume rise. Even though in the case of implementing waste heat utilization, in which the temperature of exhausted gas decreased from their business as usual, the buoyancy flux still plays the key factor in controlling the plume rise. Results are as summarized in Table 6.

Table 5. Temporal variation of buoyancy and momentum fluxes on a monthly basis in case of waste heat recovery installation

Month	Buoyancy (m^4/s^3)		Momentum (m^4/s^2)	
	Daytime	Nighttime	Daytime	Nighttime
January	315.9	331.3	1579.2	1551.0
February	310.1	326.2	1589.6	1560.4
March	305.8	321.9	1597.4	1568.2
April	303.0	318.9	1602.6	1573.7
May	304.7	319.0	1599.5	1573.4
June	310.1	323.3	1589.6	1565.6
July	311.8	323.9	1586.5	1564.6
August	312.7	326.2	1584.9	1560.4
September	315.0	327.3	1580.7	1558.3
October	313.6	327.3	1583.3	1558.3
November	312.4	327.0	1585.4	1558.8
December	317.0	330.2	1577.1	1553.1
Average ¹	311.0	325.2	1588.0	1562.2
S.D.	4.3	3.8	7.8	6.9

¹ p-value<0.001 (Independent t-test)**Table 6.** Dominated flux over the plume rise

Scenarios	$(\Delta T)_c$	$T_s - T_a$		Dominated flux
		Daytime	Nighttime	
No waste heat recovery				
January	13.56	295.2	300.6	Buoyancy flux
February		293.2	298.8	
March		291.7	297.3	
April		290.7	296.3	
May		291.3	296.3	
June		293.2	297.8	
July		293.8	298	
August		294.1	298.8	
September		294.9	299.2	
October		294.4	299.2	
November		294.0	299.1	
December		295.6	300.2	
Waste heat recovery				
January	9.36	110.2	115.6	Buoyancy flux
February		108.2	113.8	
March		106.7	112.3	
April		105.7	111.3	
May		106.3	111.3	
June		108.2	112.8	
July		108.8	113.0	
August		109.1	113.8	
September		109.9	114.2	
October		109.4	114.2	
November		109.0	114.1	
December		110.6	115.2	

3.2 PM-10 spatial distributions

Predicted 24-hour concentrations of PM-10 were calculated using AERMOD. Results are presented in Table 7. It was found that predicted PM-10 concentrations at every receptor were within the Thailand's ambient standard of 120 $\mu\text{g}/\text{m}^3$. There were no differences between predicted concentrations at receptors prior and after installation of the waste heat recovery system. However, the predicted maximum concentration of the second scenario over the modeling domain was found higher than its base line value. The predicted maximum concentration of 129 $\mu\text{g}/\text{m}^3$ under the utilization of waste heat recovery scenario was higher than the ambient PM-10 standard. High concentrations were predicted to occur in January

which is the dry season with low humidity (Chaurasia et al., 2014). Predicted ground level concentrations of PM-10 in this study agree well with the results reported in other studies. It confirmed that increasing the stack gas temperature will increase the value of the effective stack height and lead to lower ground level concentrations (Ahmed, 2013). Differences between the temperature of ambient and emission sources affected the rise of plumes and played an important role in the dilution ability of air and ground level concentrations of air pollutants (El-Gazar and Tawfik, 2013). The pollution maps of predicted 24-hour average PM-10 concentration over the modeling domain for each scenario are illustrated in Figure 4 and Figure 5.

Table 7. Maximum 24-hour predicted concentration for PM-10

Stack temperature	Receptor no.	Max. concentration	Occurred duration	Thai Std. PM-10 ($\mu\text{g}/\text{m}^3$)
598 K (No WHR)	Maximum	115	January	120
	R1	64	January	
	R2	63	April	
	R3	66	January	
	R4	63	April	
	R5	62	September	
	R6	62	July	
413 K (WHR)	Maximum	129	January	120
	R1	65	December	
	R2	63	April	
	R3	66	January	
	R4	63	April	
	R5	62	September	
	R6	62	September	

4. CONCLUSIONS

The effect of utilizing waste heat recovery systems on the rise of plumes from combustion stacks in the cement industry was evaluated in this study. The results revealed that the buoyancy flux played a more dominant force than momentum flux on the rise of plumes. Decreases in the stack exit temperature due to implementation of waste heat recovery did not much affect the value of plume rise. Low ambient temperature is found to be a key factor influencing the increase of the plume rise. Spatial distribution of PM-10 concentrations were simulated under two different scenarios (with and without installation of waste heat recovery) in order to evaluate the effect of changing of stack gas exit temperature on the dispersion of an air pollutant

emitted by the cement industry. Results indicated that there were no differences of the predicted PM-10 ground level concentrations at the receptors prior and after utilization of waste heat recovery. However, it should be noted that the maximum predicted concentration within the modeling domain in the scenario of using waste heat recovery was increased. This value was also higher than the ambient PM-10 concentration standard ($>120 \mu\text{g}/\text{m}^3$, daily average). Results, derived from this study can confirm that the implementation of waste heat recovery in this cement plant is not only a valuable energy source but also, in general, does not cause air pollution problems to the surrounding area of the factory.

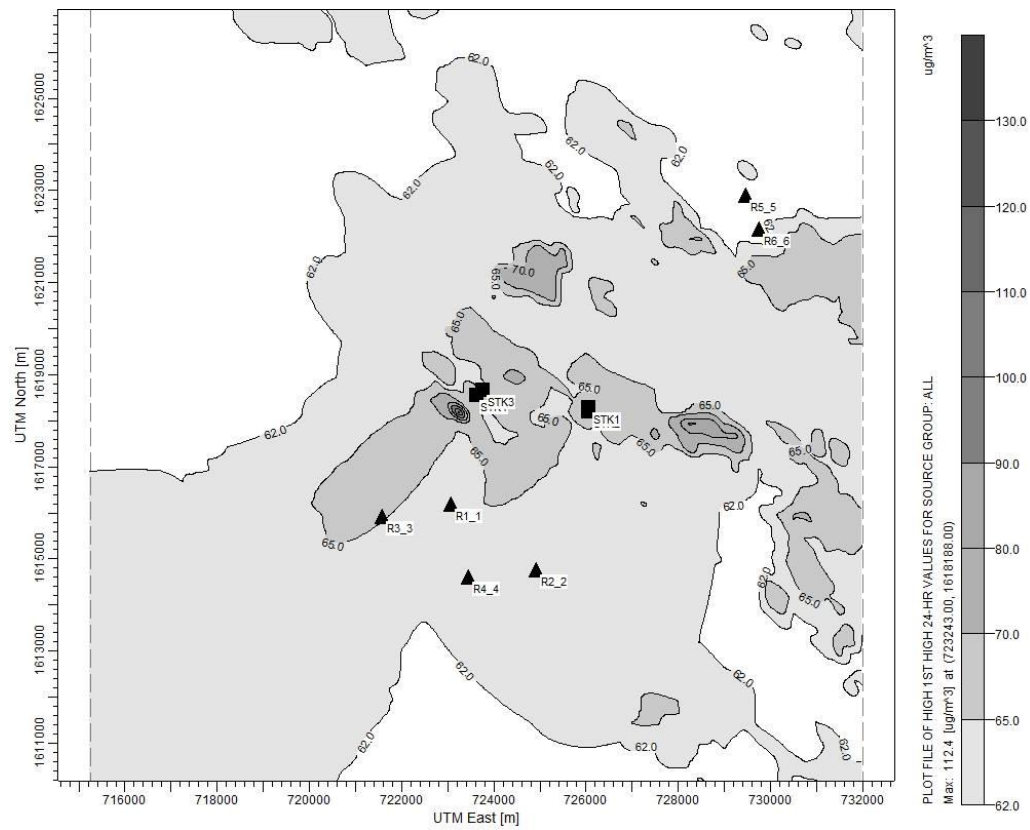


Figure 4. Daily simulation results of PM-10 spatial distribution (no waste heat recovery installation)

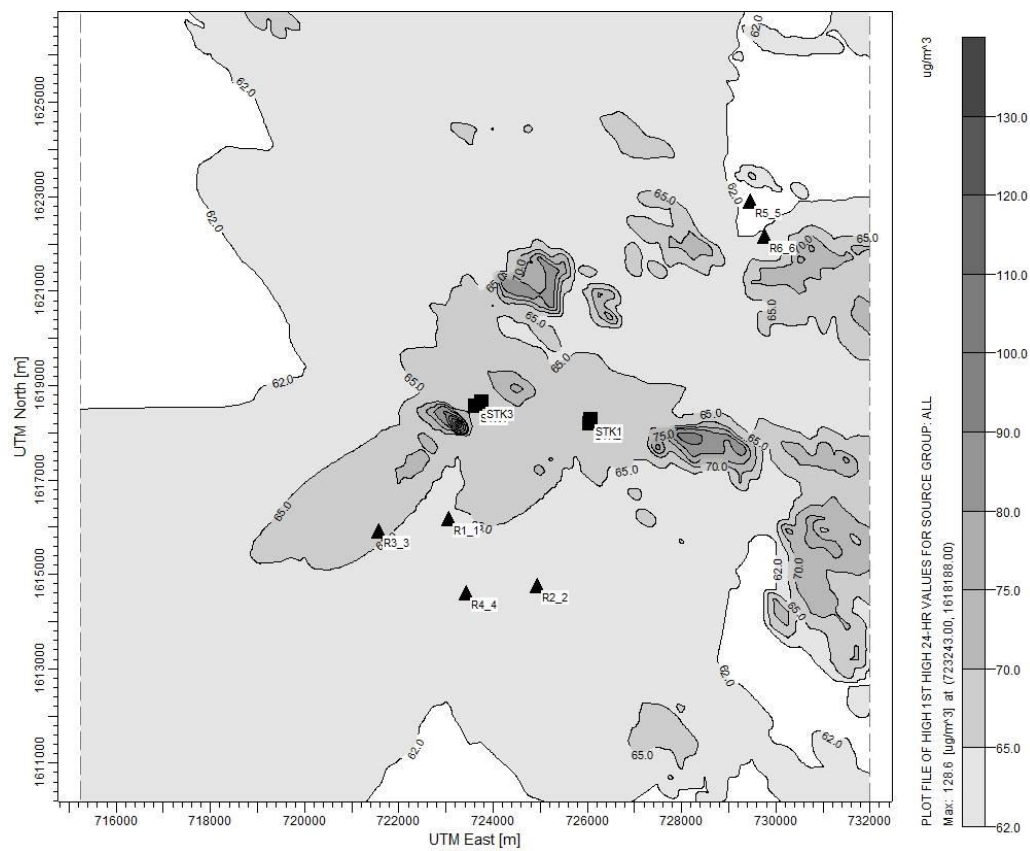


Figure 5. Daily simulation results of PM-10 spatial distribution (waste heat recovery installation)

ACKNOWLEDGEMENTS

The authors sincerely thank the Pollution Control Department and the cement plant for providing input data used in this study. This study was partially supported for the Center of Excellence on Environmental Health and Toxicology (EHT), Faculty of Public Health Mahidol University, Thailand. This study was partially supported for publication by the China Medical Board (CMB).

REFERENCES

- Ahmed OS. Assessment and modeling of the effective stack height for different types of atmospheric stability class. *Arab Journal of Nuclear Science and Applications* 2013;46(1):179-91.
- Bhargava A. Effect of wind speed and stack height on plume rise using different equations. *International Journal of Engineering Science and Computing* 2016;6(4):3228-34.
- Brook RD, Rajagopalan S, Pope CA III, Brook JR, Bhatnagar A, Diez-Roux AV, et al. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. *Circulation* 2010;121(21):2331-78.
- Cao J, Yang C, Li J, Chen R, Chen B, Gu D, Kan H. Association between long-term exposure to outdoor air pollution and mortality in China: a cohort study. *Journal of Hazardous Materials* 2011;186(2-3):1594-600.
- Chaurasia S, Ahmed I, Gupta AD, Kumar S. Assessment of air pollution emission from cement industries in Nimbahera, India. *International Journal of Current Microbiology and Applied Sciences* 2014;3(3):133-9.
- Demirkaya G, Padilla RV, Goswami DY. A review of combined power and cooling cycles. *Wiley Interdisciplinary Reviews: Energy and Environment* 2013;2(5):534-47.
- Dimmick WF, Wehe AH. 41 - Technology and costing of air pollution abatement1 A2 -Holgate. In: Maynard R, Holgate S, Koren H, Samet J, Maynard R, editors. *Air Pollution and Health*. London: Academic Press; 1999. p. 931-45.
- El-Gazar MM, Tawfik BBS. Analysis of the factors affecting the distribution of chimney emissions to the atmosphere - simulation approach. *International Journal of Computer Science Engineering and Information Technology Research* 2013;2(2):367-78.
- Essa KSM, Mubarak F, Elsaid SEM. Effect of the plume rise and wind speed on extreme value of air pollutant concentration. *Meteorology and Atmospheric Physics* 2006;93(3):247-53.
- Fang H, Xia J, Zhu K, Su Y, Jiang Y. Industrial waste heat utilization for low temperature district heating. *Energy Policy* 2013;62(Supplement C):236-46.
- Gupta RK, Majumdar D, Trivedi JV, Bhanarkar AD. Particulate matter and elemental emissions from a cement kiln. *Fuel Processing Technology* 2012;104 (Supplement C):343-51.
- Hoven IVD. Effects of time and height on behavior of emissions. *Environmental Health Perspectives* 1975;10:207-10.
- Ilaboya IR, Atikpo E, Umukoro L, Omufuma FE, Ezugwa MO. Analysis of the effects of mixing height and other associated factors on the effective dispersion of plume. *Iranica Journal of Energy and Environment* 2011;2(2):153-60.
- Kampa M, Castanas E. Human health effects of air pollution. *Environmental Pollution* 2008;151(2):362-7.
- Lakes Environmental. Screen View 4.0.0 edition. Ontario, Canada: Lakes Environmental Software; 2011.
- Liu H, Fang C, Zhang X, Wang Z, Bao C, Li F. The effect of natural and anthropogenic factors on haze pollution in Chinese cities: a spatial econometrics approach. *Journal of Cleaner Production* 2017;165(Supplement C):323-33.
- Madloul NA, Saidur R, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews* 2011;15(4):2042-60.
- Madloul NA, Saidur R, Rahim NA, Kamalisarvestani M. An overview of energy savings measures for cement industries. *Renewable and Sustainable Energy Reviews* 2013;19(Supplement C):18-29.
- Masters GM. *Introduction of Environmental Engineering and Science*. Prentice Hall, USA; 1997.
- Parvez F, Lamancusa C, Wagstrom K. Primary and secondary particulate matter intake fraction from different height emission sources. *Atmospheric Environment* 2017;165(Supplement C):1-11.
- Thai Cement Manufacturers Association (TCMA). TCMA 2016. Thailand: Thai Cement Manufacturers Association; 2016.
- Thai Meteorological Department (TMD). Season of Thailand [Internet]. 2018 [cited Jun 2018]. Available from: <https://www.tmd.go.th/info/info.php?FileID=23>
- Turner DB. *Workbook of Atmospheric Dispersion Estimates*. U.S. Environmental Protection Agency; USA; 1970.
- United States Department of Energy. *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. Industrial Technologies Program, U.S. Department of Energy. United State; 2008.
- United States Environmental Protection Agency (USEPA). *SCREEN3 model User's Guide*. EPA-454/B-95-004, U.S. Environmental Protection Agency; USA; 1995a.
- United State Environmental Protection Agency (USEPA). *User's Guide for the Industrial Source Complex (ISC3)*

- Dispersion Models. Volume II - Description of Model Algorithms. North Carolina; 1995b.
- United State Environmental Protection Agency (USEPA). User's Guide for the AMS/EPA Regulatory Model (AERMOD). Research Triangle Park, North Carolina; 2018.
- Vallero D. Air pollution control technologies. In: Vallero D, editor. Fundamentals of Air Pollution (5th edition). Boston: Academic Press; 2014. p. 829-79.