# DEVELOPMENT OF AIR POLLUTANTS DISPERSION ALGORITHM IN URBAN INDUSTRIAL PARK FOR AIR POLLUTION SIMULATION

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### **DEDICATION**

This thesis is dedicated to Umi and Abi, Mak and Ayah, and all my family members who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my beloved wife and children, Nur Amira, Maryam Hannah, Muhammad Yusuf Faris who taught me that even the largest task can be accomplished if it is done one step at a time.

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### ABSTRACT

Environmental Impact Assessment analysis is generally restricted to neighbourhood scale air pollution simulation using the Gaussian Plume model (GPM). This approach expected to enhance the resolution of ground level concentration in the conventional GPM based software up to building scale by using Computational Fluid Dynamics (CFD) model alongside the GPM. The aim of this study was to develop an air pollution prediction algorithm for air pollutants release from industrial stacks. It was used to estimate, simulate and control air pollution in urban industrial park using integrated GPM and CFD model. The GPM was used for regional air pollutant level prediction to find high pollutant concentration zones. Whereas, CFD model was used for detailed simulation on respective polluted areas. In order to achieve this, a building detection algorithm from satellite image based on building footprint detection and height estimation from shadow thickness has been proposed to reduce pre-processing effort of the present CFD solver. The present CFD algorithm were based on Fractional Step Method for efficient steady state solver and Prandtl Mixing Length turbulence model for low cost turbulence calculation. The accuracy of the CFD algorithm has been tested and verified against benchmark problems (less than 3% error for lid-driven cavity problem, less than 8% for flow over isolated cube). It was discovered that CFD algorithm developed in this study is sufficiently accurate as other wind flow models with slight over prediction in wind speed by 1.04 m/s (15.6% are below 10% error) and able to predict the wind direction correctly within  $60^{\circ}$  angle (37.5% are within  $15^{\circ}$ angle) compared to measurement data. Air pollutant release from major stacks in Pasir Gudang Industrial Park was studied using GPM and high NO<sub>2</sub> concentration zone  $(1800 \ \mu g/m^3)$  was found in Taman Air Biru. Results suggest that 24-hour averaged SO<sub>2</sub> and PM<sub>10</sub> maximum ground level concentration are well within Ambient Air Quality Standard (AAQS) limits with 8.9  $\mu$ g/m<sup>3</sup> (8.4%) and 11.4  $\mu$ g/m<sup>3</sup> (7.6%) respectively. Meanwhile, 24-hour averaged NO2 concentration exceed AAOS limit with 270.3  $\mu$ g/m<sup>3</sup> (360%). The detailed CFD simulation of wind distribution and pollutant dispersion process within the area was presented. Present CFD model (1800  $\mu g/m^3$ ) over predicted 1-hour averaged NO<sub>2</sub> ground concentrations by a factor of 3 compared to the present GPM (700  $\mu$ g/m<sup>3</sup>) but it provides more information on wind distribution as well as pollutant dispersion process. A new atmospheric dispersion solver has been developed that is able to simulate pollutant dispersion on both regional scale using GPM and building scale using CFD model.

### ABSTRAK

Analisis Penilaian Kesan Alam Sekitar umumnya terhad kepada skala kejiranan bagi simulasi bahan pencemar udara menggunakan model Gaussian Plume (GPM). Kaedah ini menambahbaik resolusi simulasi kepekatan bahan pencemar atas tanah dalam perisian konvensional GPM kepada skala bangunan dengan menggabungkannya bersama model Dinamik Bendalir Berkomputer (CFD). Kajian ini bertujuan untuk membangunkan algoritma ramalan pencemaran udara bagi pelepasan bahan pencemar daripada cerobong asap industri. Ia digunakan untuk meramal, mensimulasi dan mengawal pencemaran udara di kawasan perindustrian bandar dengan menggunakan GPM dan model CFD yang disatukan dalam satu algoritma. GPM digunakan untuk meramal tahap pencemaran udara secara kasar bagi mencari kawasan berkepekatan tinggi. Model CFD pula digunakan untuk simulasi terperinci di kawasan berkepekatan tinggi tersebut. Algoritma pengesanan bangunan dari imej satelit menggunakan teknik pengesanan tapak bangunan dan anggaran ketinggian bangunan berdasarkan ketebalan bayang telah dibangunkan untuk meringkaskan prapemprosesan model CFD. Dalam tesis ini, algoritma CFD menggunakan kaedah fractional step untuk penyelesaian secara efisien dan model pergolakan Prandtl Mixing Length untuk pengiraan yang pantas. Ketepatan algoritma ini telah diuji dan disahkan menggunakan data eksperimen piawai dan kajian eksperimen secara berperingkat (kurang 3% untuk kaviti, kurang 8% untuk pergerakan udara merentasi kiub). Hasil kajian menunjukkan algoritma CFD yang dibangunkan adalah cukup tepat kerana model pergerakan angin meramal sebanyak 1.04 m/s (15.6% mempunyai sisihan kurang 10%) lebih tinggi daripada dapatan eksperimen dan dapat meramalkan arah angin dengan betul dalam lingkungan sudut 60° (37.5% mempunyai sisihan kurang 15°) berbanding dengan data piawai. Pencemaran udara dari cerobong asap utama di Taman Perindustrian Pasir Gudang telah dikaji menggunakan GPM dan zon kepekatan NO<sub>2</sub> yang tinggi terdapat di Taman Air Biru. Keputusan mencadangkan bahawa kepekatan purata 24-jam SO2 dan PM10 adalah di bawah had kualiti udara (AAQS) iaitu sebanyak 8.9  $\mu$ g/m<sup>3</sup> (8.4%) dan 11.4  $\mu$ g/m<sup>3</sup> (7.6%). Sementara itu, kepekatan purata 24-jam NO<sub>2</sub> melebihi had AAQS sebanyak 270.3  $\mu$ g/m<sup>3</sup> (360%). Simulasi CFD yang terperinci terhadap pergerakan angin dan proses penyebaran pencemar di kawasan ini telah dibentangkan. Model CFD dalam kajian ini (1800  $\mu g/m^3$ ) terlebih anggar kepekatan purata 1-jam NO<sub>2</sub> dengan faktor 3 berbanding GPM  $(700 \ \mu g/m^3)$  tetapi ia mempunyai data yang lebih lengkap mengenai taburan angin dan juga proses pergerakan bahan pencemar udara. Algoritma penyebaran bahan pencemar udara yang baru telah dibangunkan bagi mensimulasikan penyebaran bahan pencemar udara pada kedua-dua skala serantau menggunakan GPM dan skala bangunan menggunakan model CFD.

## TABLE OF CONTENTS

## TITLE

DEC	CLARATION	ii
DEI	DICATION	iii
ACI	KNOWLEDGEMENT	iv
ABS	STRACT	v
ABS	STRAK	vi
TAI	BLE OF CONTENTS	vii
LIS	Г OF TABLES	xi
LIS	Γ OF FIGURES	xiii
LIS	Γ OF ABBREVIATIONS	xix
LIS	Γ OF SYMBOLS	xxi
LIS	Γ OF APPENDICES	xxiii
CHAPTER 1	INTRODUCTION	1
1.1	Research Background	1
1.2	Problem Statement	5
1.3	Research Objectives	6
1.4	Significance of Study	7
1.5	Scope of Study	7
CHAPTER 2	LITERATURE REVIEW	9
2.1	Overview of Air Pollution Models	9
	2.1.1 Gaussian-type models	9
	2.1.2 Langrangian-type models	11
	2.1.3 Eulerian-type models	12
	2.1.4 Models Integration	14
2.2	Computational Fluid Dynamics in Urban Air Pollutant Simulation	15

2.2.1 Effects of Building Dimension and Configuration 16

		2.2.2	Effects of Trees and Vehicles	17
		2.2.3	CFD on Urban Industrial Stacks	20
		2.2.4	Simulation Scale	22
		2.2.5	CFD on Urban Design	23
	2.3	Geosp	atial Data in Air Pollution Software	24
		2.3.1	Geo Information System (GIS)	25
		2.3.2	Satellite Image	28
	2.4	Integr	ation of Spatial Data and CFD solver	29
		2.4.1	Limitations of Existing Commercial Software	32
		2.4.2	Satellite Image Building Extractor	34
	2.5	Air Po	ollution in Pasir Gudang	37
		2.5.1	Field Measurements and Air Pollutants Sampling	38
		2.5.2	Air Pollutant Modelling	39
		2.5.3	Climate and Wind Data	39
	2.6	Summ	ary of Literature Review	40
СНАРТЕ	ER 3	MET	HODOLOGY	45
СНАРТЕ	E <b>R 3</b> 3.1		HODOLOGY uction	<b>45</b> 45
СНАРТЕ		Introd		
СНАРТЕ	3.1	Introd Gauss	uction	45
СНАРТЕ	3.1 3.2	Introd Gauss Comp	uction ian Plume Model	45 45
СНАРТЕ	3.1 3.2	Introd Gauss Comp	uction ian Plume Model utational Fluid Dynamics Model	45 45 47
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS)	45 45 47 47
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1 3.3.2	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS) Equation	45 45 47 47 48
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1 3.3.2 3.3.3	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS) Equation Turbulence Model (Prandtl Mixing Length)	45 45 47 47 48 49
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1 3.3.2 3.3.3	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS) Equation Turbulence Model (Prandtl Mixing Length) Numerical Implementation	45 45 47 47 47 48 49 51
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1 3.3.2 3.3.3	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS) Equation Turbulence Model (Prandtl Mixing Length) Numerical Implementation 3.3.4.1 Fractional Step Method	45 45 47 47 47 48 49 51 51
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1 3.3.2 3.3.3	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS) Equation Turbulence Model (Prandtl Mixing Length) Numerical Implementation 3.3.4.1 Fractional Step Method 3.3.4.2 Air Pollutant Dispersion 3.3.4.3 Boundary Conditions and Near Wall	45 45 47 47 48 49 51 51 53
CHAPTE	3.1 3.2	Introd Gauss Comp 3.3.1 3.3.2 3.3.3 3.3.4 3.3.4	uction ian Plume Model utational Fluid Dynamics Model Governing Equations Reynolds Averaged Navier-Stokes (RANS) Equation Turbulence Model (Prandtl Mixing Length) Numerical Implementation 3.3.4.1 Fractional Step Method 3.3.4.2 Air Pollutant Dispersion 3.3.4.3 Boundary Conditions and Near Wall Treatment	45 45 47 47 48 49 51 51 53 54

		3.4.1.1	Color Band Thresholding	60
		3.4.1.2	Building Footprint Segmentation	62
		3.4.1.3	Vegetation and Shadow Removal	63
		3.4.1.4	Building Delineation	63
	3.4.2	Building Thicknes	Height Estimation from Shadow s	64
3.5	Algor	ithms Flov	vchart	66
3.6	Algor	ithm Valid	ation and Performance Evaluation	71
3.7	Pasir	Gudang Ai	r Pollutant Prediction and Simulation	77
CHAPTER 4	RESU	JLTS ANI	D DISCUSSION	81
4.1	Introd	luction		81
4.2	Case S Evalu	•	Algorithm Validation and Performance	81
	4.2.1	Gaussian	Plume Algorithm	81
	4.2.2	Satellite	Image Building Generator	87
		4.2.2.1	Building Footprint Detection Algorithm	87
		4.2.2.2	Height Estimation Algorithm	94
		4.2.2.3	Integration of Building Footprint Detection and Height Estimation	98
	4.2.3	CFD Sol	ver	103
		4.2.3.1	Lid Driven Cavity Benchmark Problem	103
		4.2.3.2	Comparison with Flow over Isolated Cube Benchmark Problem	108
		4.2.3.3	Comparison with Joint Urban 2003 Field Experiment	113
4.3		Study II – imulation	Pasir Gudang Air Pollutant Prediction	122
	4.3.1	Regional Plume m	Scale Estimation using Gaussian odel	123
		4.3.1.1	Comparison with Atmospheric Dispersion Model	123
		4.3.1.2	Comparison with Field Measurement	132

APPENDIX B	Publi	cations		177
APPENDIX A Software)	Detai	led Gauss	sian Plume Model (IMMDADS	169
LIST OF PUBL	ICATIO	ONS		167
REFERENCES				155
5.3	Future	e Works		153
5.2	Contr	ibutions to	o Knowledge	153
5.1	Resea	rch Concl	usion	151
CHAPTER 5	CON	CLUSIO	N AND RECOMMENDATIONS	151
		4.3.2.4	Pollutant Dispersion and Ground Concentration	144
		4.3.2.3	Wind Flow Distribution	140
		4.3.2.2	Urban Structures Generation Using Present Satellite Image Building Extractor	139
		4.3.2.1	Predicted High Concentration Zone	138
	4.3.2	-	g Scale Simulation using CFD Model at oncentration Zone	135

Table 4. 14	Comparison of Ground-Level Concentration	131
Table 4. 15	$PM_{10}$ concentration of 4 residential areas (Rozana <i>et al.</i> , 2009) and present study (24-hour averaged)	133
Table 4. 16	Measured and predicted GLC for all pollutants in Pasir Gudang monitoring station	134

### LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 1. 1	(a) Location of Pasir Gudang Industrial Park (b) Neighbourhood scale $(10^4 \text{ m or } 10 \text{ km } x10 \text{ km } using Gaussian Plume model})$ (c) Building scale $(10^3 \text{ m or } 1 \text{ km } x \text{ 1 km } using CFD model})$ (Google Maps, 2019).	4
Figure 2. 1	Conical plume assumption used in Gaussian Plume model (Beychok, 2005).	10
Figure 2. 2	Ground concentration output from Gaussian models (P1, P2, P3 and P4 as the source) (Tartakovsky et. al., 2016)	11
Figure 2. 3	Puff particles in Langrangian Particle Tracking models (Szabo, 2016)	11
Figure 2. 4	Cumulated number of puffs converted as ground concentration in Langrangian models (Tang et. al., 2018)	12
Figure 2. 5	Wind varies locally and disperse within buildings in CFD model (Boppana et. al., 2019)	13
Figure 2. 6	Calculated concentration contours at 1.6 m compared with measured concentration contour at 1 ppm for field scale scenario (Antonioni <i>et al.</i> , 2012).	14
Figure 2. 7	Velocity magnitude contours and vectors of multiple urban street canyons with buildings (black) (a) normal buildings (b) buildings with ventilation on ground floor (Chew and Norford, 2018).	16
Figure 2. 8	Recirculation region (dark colour) that hinder pollutant removal (Bijad, 2016)	17
Figure 2. 9	Schematic of vehicle movement study (a) Schematics of vehicle passing urban street canyon (b) Common pedestrian and vehicle lanes (Li <i>et al.</i> , 2017)	18
Figure 2. 10	Comparison of CFD and Gaussian model (a) Ground concentration (CFD) (b) Ground concentration (Gaussian) (c) CO concentration for Gaussian and CFD (d) NO concentration for Gaussian and CFD (Bady, 2017)	20
Figure 2. 11	Detailed simulation results of Carbon concentration (ppm) (Toja-Silva <i>et al.</i> , 2017)	21

Figure 2. 12	Multiple scale urban air pollutant problems (Cui et al., 2016)	22
Figure 2. 13	Multi-layer of information in geospatial database (US GAO, 2017).	24
Figure 2. 14	Walking activities distribution in Glasgow, UK (Sun et al., 2017)	26
Figure 2. 15	Spatial distribution of NO <sub>x</sub> in roundabouts (Sanchez <i>et al.</i> , 2017)	27
Figure 2. 16	Projected simulation results and damage distribution onto satellite image (Pontiggia <i>et al.</i> , 2011)	29
Figure 2. 17	Footprints traced using AC3D software (Houda et al., 2017)	30
Figure 2. 18	Generated discrete domain of Tokyo city. The isosurface (yellow) corresponds to pollutant release (Toja-Silva <i>et al.</i> , 2018a)	30
Figure 2. 19	CFD solver novel feature available in present algorithm (a) (Google Maps, 2019) (b) (Gowardhan et. al., 2011) (c) (Dominik B., 2017)	32
Figure 2. 20	Features detection of buildings and street networks (Grinias et al., 2016)	35
Figure 2. 21	Height estimation from SAR image (Wang et al., 2018)	36
Figure 3. 1	2D flow over square-shaped building	54
Figure 3. 2	Staggered grid used in present study	58
Figure 3. 3	Sample satellite image (left) and resulting colour band thresholding process (right)	62
Figure 3. 4	Output of centroid identification algorithm	62
Figure 3. 5	Output of building delineation algorithm	64
Figure 3. 6	Shadow regions after shadow detection algorithm	64
Figure 3. 7	Pixel counting direction (red) for height estimation from shadow thickness (bottom left building)	65
Figure 3. 8	Algorithm flowcharts (a) Building Detection (b) Height Estimation	67
Figure 3. 9	Algorithm flowcharts (a) Building Generator (b) Fluid Solver Pre-processing.	68
Figure 3. 10	Flowcharts of Solver Time Iteration	69

Figure 3. 11	Flowcharts of Pollutant Transport and Post processing	70
Figure 3. 12	Boundary conditions for lid-driven cavity flow (Ghia et. al., 1982)	74
Figure 3. 13	Satellite image of Oklahoma City (Google Maps, 2019)	75
Figure 3. 14	Building footprints of Oklahoma City (Gowardhan et. al., 2011)	76
Figure 3. 15	Wind rose of Senai Monitoring Station for year 2009	78
Figure 4. 1	Comparison of maximum GLC for ISC and IMMDADS (present) for CASE 1	84
Figure 4. 2	Comparison of maximum GLC for ISC and IMMDADS (present) for CASE 2	84
Figure 4. 3	Comparison of maximum GLC for ISC and IMMDADS (present) for CASE 3	85
Figure 4. 4	Comparison of maximum GLC for ISC and IMMDADS (present) for CASE 4	85
Figure 4. 5	Building detection output of (a) Tested satellite image (b) (Benedek et al., 2015) (c) (Sumer and Turker, 2013) and (d) present algorithm	88
Figure 4. 6	Comparison chart of performance parameters	90
Figure 4. 7	Resulting images from algorithm (a) Satellite image (b) Building footprints and centroids (c) Building Edges (d) Building delineation (e) Finalized footprint without delineation	91
Figure 4. 8	a) Original image and (b) resulting detected buildings in NIT, Japan	93
Figure 4. 9	Test image for height estimation algorithm (Manno-Kovacs and Sziranyi, 2015)	94
Figure 4. 10	(a) Buildings centroid and (b) detected shadow. Red boxes show Segment 17-22)	94
Figure 4. 11	Detected shadow region (Image 1) (a) Satellite image (b) Gregoris et. al. (2016) (c) Present algorithm	96
Figure 4. 12	Detected shadow region (Image 2) (a) Satellite image (b) Gregoris et. al. (2016) (c) Present algorithm	96
Figure 4. 13	Comparison Chart for calculated height between Gregoris et. al., 2016 and present study (Segment 1-7 for Image 1 and Segment 1-2 for Image 2).	97

Figure 4. 14	Satellite image used in Feng Qi et. al. (2016) (a) Zone A (b) Zone B (c) Zone C	98
Figure 4. 15	Images acquired used in present study (a) Zone A (b) Zone B (c) Zone C	99
Figure 4. 16	Detected building foot prints for Zone A (a) and Zone B (b)	99
Figure 4. 17	Shadow detection in present algorithm (a) Zone A (b) Zone B (c) Zone C	100
Figure 4. 18	Building detection with height estimation (a) Satellite image (b) Footprints and centroids (c) Shadow estimation	101
Figure 4. 19	Comparison charts of calculated height of Feng Qi et. al., 2016 and present study	102
Figure 4. 20	Velocity vectors (a) and streamlines (b) of $Re = 100$ with 30 x 30 mesh (present study)	104
Figure 4. 21	Velocity vectors (a) and streamlines (b) of $Re = 400$ with 60 x 60 mesh (present study)	104
Figure 4. 22	Velocity vectors (a) and streamlines (b) of $Re = 1000$ with 90 x 90 mesh (present study)	104
Figure 4. 23	Horizontal U-velocity across geometric centre, $Re = 100, 400, 1000$ between Ghia (1982) and present study	107
Figure 4. 24	Vertical V-velocity across geometric centre, Re = 100, 400, 1000 between Ghia (1982) and present study	107
Figure 4. 25	Velocity vectors of wind tunnel data (black) and CFD results by Gowardhan et. al. (2011) (grey). (Side view)	108
Figure 4. 26	Velocity vectors from present algorithm (Side view)	109
Figure 4. 27	Velocity vectors of wind tunnel data (black) and CFD results by Gowardhan et. al. (2011) (grey). (Top view)	110
Figure 4. 28	Velocity vectors of present algorithm. (Top view)	110
Figure 4. 29	Present algorithm profiles (line) overlapped with wind tunnel data (dot)	112
Figure 4. 30	Contours of $u'w'$ in the x-z plane for Gowardhan et. al. (2011)	112
Figure 4. 31	Contours of $u'w'$ in the x-z plane for present study	113

Figure 4. 32	Detected building footprints (a) and shadows (b) using present algorithm	114
Figure 4. 33	Buildings isosurface generated in present algorithm	114
Figure 4. 34	Velocity vectors generated using present algorithm (buildings are rotated inside whereas boundary is fixed in present algorithm)	115
Figure 4. 35	Velocity vectors at centre region (red box) (a) field measurement (black arrow) and Gowardhan (2011) (grey arrow) (b) present algorithm	116
Figure 4. 36	Horizontal velocity vectors overlapped with velocity magnitudes (a) Gowardhan et. al. (2011) (b) present algorithm	118
Figure 4. 37	Vertical velocity vectors overlapped with velocity magnitudes (a) Gowardhan et. al. (2011) (b) present algorithm	119
Figure 4. 38	Computed and observed wind direction of present study	121
Figure 4. 39	Computed and observed wind speed of present study	122
Figure 4. 40	24-hour SO <sub>2</sub> GLC distribution (a) maximum location (red) (b) areas exceeded allowable limits (90 $\mu$ g/m <sup>3</sup> )	124
Figure 4. 41	Annual SO <sub>2</sub> GLC distribution (a) maximum location (red) (b) areas exceeded allowable limits (50 $\mu$ g/m <sup>3</sup> )	125
Figure 4. 42	24-hour NO <sub>2</sub> GLC distribution (a) maximum location (red) (b) areas exceeded allowable limits (75 $\mu$ g/m <sup>3</sup> )	126
Figure 4. 43	Annual NO <sub>2</sub> GLC distribution (a) maximum location (red) (b) areas exceeded allowable limits $(40 \ \mu g/m^3)$	127
Figure 4. 44	24-hour PM <sub>10</sub> GLC distribution (a) maximum location (red) (b) areas exceeded allowable limits (150 $\mu$ g/m <sup>3</sup> )	128
Figure 4. 45	Annual PM <sub>10</sub> GLC distribution (a) maximum location (red) (b) areas exceeded allowable limits (50 $\mu$ g/m <sup>3</sup> )	129
Figure 4. 46	24-hour $PM_{10}$ concentration.	132
Figure 4. 47	1-hour ground concentration of $NO_2$ for northwest to southeast wind (1.5 m/s) (a) and regions exceeded limits (b) using present algorithm	136
Figure 4. 48	1-hour ground concentration of $NO_2$ for south to north wind (1.5 m/s) (a) and regions exceeded limits (b) using present algorithm	137

Figure 4. 49	Predicted high NO <sub>2</sub> region in Taman Air Biru (red circle) located at northern Stack 35 (red dot)	138
Figure 4. 50	Enlarged view (a) and detected footprints (b) using present algorithm	139
Figure 4. 51	Mesh generated by present algorithm of respective area after height estimation process	140
Figure 4. 52	Velocity magnitudes overlapped with horizontal velocity at 6.5 m height (A - B Plane is the plume cross section)	141
Figure 4. 53	Horizontal velocity magnitudes at plume cross section (A-B Plane)	142
Figure 4. 54	Velocity streamlines at 6.5 m height	143
Figure 4. 55	Turbulent eddy viscosity, $v_t$ at 6.5 m height	144
Figure 4. 56	1-hour concentration of $NO_2$ at ground-level at 6.5 m height	145
Figure 4. 57	1-hour concentration of NO <sub>2</sub> at plume cross section (A-B Plane)	146
Figure 4. 58	NO <sub>2</sub> GLC for first 10 minutes at 6.5 m height (a) 2 minutes (b) 4 minutes (c) 6 minutes (d) 8 minutes (e) 10 minutes	147
Figure 4. 59	NO <sub>2</sub> GLC for first 10 minutes at plume cross section (a) 2 minutes (b) 4 minutes (c) 6 minutes (d) 8 minutes (e) 10 minutes	149

## LIST OF ABBREVIATIONS

AAQG	-	Ambient Air Quality Guidelines
AAQS	-	Ambient Air Quality Standard
ADMS	-	Atmospheric Dispersion Modelling System
AECOPD	-	Acute Exacerbations Of Chronic Obstructive Pulmonary
		Disease
AGREE	-	Accidental Gas Release
AMR	-	AMR Environmental Pte. Ltd.
AMS	-	American Meteorological Society
CALINE	-	California Line Source Model
CALPUFF	-	California Puff Modelling System
CFD	-	Computational Fluid Dynamics
CTDMPLUS	-	Complex Terrain Dispersion Model
GIS	-	Geo Information System
GLC	-	Ground-Level Concentration
IAQ	-	Indoor Air Quality
IOP	-	Intensive Observational Periods
IMMDADS	-	Integrated Malaysian Meteorological Data Atmospheric
		Dispersion Software
ISC	-	Industrial Source Complex
JU2003	-	Joint Urban 2003 Field Measurement
EIA	-	Environmental Impact Assessment
EPA	-	Environmental Protection Agency
ESRI	-	Environmental Systems Research
GPU	-	Graphics Processing Unit
KAMI	-	Kualiti Alam Modularized Incinerator
LES	-	Large Eddy Simulation
LIDAR	-	Light Detection and Ranging
LPG	-	Liquefied Petroleum Gas
NAME	-	Numerical Atmospheric-dispersion Modelling Environment
NOx	-	Oxides of Nitrogen

O <sub>3</sub>	-	Ozone
$PM_{10}$	-	Particulate Matter 10 Micrometer in Size
PM <sub>2.5</sub>	-	Particulate Matter 2.5 Micrometer in Size
RAM	-	Random Access Memory
RANS	-	Reynolds Averaged Navier-Stokes
RGB	-	Red Green Blue
RMG	-	Recommended Malaysian Guidelines
SAR	-	Synthetic-Aperture Radar
$SF_6$	-	Sulfur Hexaflouride
SRTM	-	Shuttle Radar Topography Mission
TDMA	-	Tri-Diagonal Matrix Algorithm

## LIST OF SYMBOLS

β	-	Artificial Compressibility
С	-	Pollutant Concentration
D	-	Molecular Diffusivity
Н	-	Height of Cube
$h_e$	-	Effective Stack Height
$h_s$	-	Stack Height
$h'_s$	-	Effective Stack Height
k	-	Karman Constant
K <sub>c</sub>	-	Turbulent Diffusivities of Scalar Variables
l <sub>mix</sub>	-	Mixing Length
μ	-	Kinematic Viscosity
n	-	Normal to Boundary
ρ	-	Fluid/Air Density
р	-	Power Law Exponents
Р	-	Deviation of Pressure
Q	-	Stack Volumetric Flow Rate
S <sub>c</sub>	-	Source/Sink Term of Pollutants
SF <sub>6</sub>	-	Sulphur Hexafluoride
$T_a$	-	Ambient Air Temperature
$T_s$	-	Stack Gas Temperature
t	-	Time
$ au_{ij}$	-	Reynolds Stress Tensor
τ	-	Artificial Time
u	-	Wind Velocity
U <sub>c</sub>	-	Velocity Independent of Outlet Plane
Ui	-	ith Mean Velocity Component
u <sub>s</sub>	-	Wind Velocity at Stack Height
$U_t$	-	Friction Velocity
U, V, W	-	Velocity in X, Y and Z Directions

### **CHAPTER 1**

### **INTRODUCTION**

### 1.1 Research Background

Air pollutant release from transportation and industries have been major threat to human health and wellness in rural and urban areas (Tian *et al.*, 2019). Air pollutants are the early origin of respiratory diseases (Kim *et al.*, 2018) that need to be constantly monitored to preserve air quality and environment. One of the methods to control air pollution is by regulating law to limit permissible amount of harmful gases into the atmosphere. In order to do so, air pollution dispersion simulation is needed to estimate the allowable release amount and assess the impact of unhealthy chemical releases to the surrounding ambient atmosphere.

In environmental town planning, air pollutant prediction and simulation in urban industrial park is important to identify critical areas where pollutant entrapments are taken place due to vehicle emissions, industrial release, agricultural waste and construction dusts. They are used by urban planners for long-term air pollution risk and health assessments, evacuation plan during accidents and assists in smart city design with good ventilation resulting in effective natural pollutant removal process. Besides, the analysis prevents failed urban design such as developing residential areas around polluted areas as well as evade late warnings of severe pollution levels that adversely affect health of citizen in the long run. In addition, detailed simulation can also be used to locate strategic station for air cleaning devices in urban areas.

In practical use, air pollutants dispersion software are developed based on Gaussian Plume model. They are based on conical plume assumption in which the concentration across the plume cross-section has a Gaussian (normal) distribution. Those software are used to estimate the pollutant concentration on the ground around industrial stack such as the well-known U.S. Environmental Protection Agency (EPA) Regulatory Model (AERMOD). This model is widely used for Environmental Impact Assessment (EIA) because it is sufficiently accurate, relatively simple to run with short computing time and low computer requirement. On average computer, for 50 x 50 number of grids with 200m distance between each grid (10 km x 10 km simulation area), those software usually take seconds to calculate 1 hour ground-level pollutant concentration (GLC) and approximately 15 to 40 minutes to calculate 1 year GLC. The Random Access Memory (RAM) used is relatively low compared to other advanced models since Gaussian Plume model can be run effectively with lower than 5000 number of grid points. However, Gaussian Plume model falls short in complex built environment due to flat terrain assumptions that were used during model development.

For complex urban structures, Computational Fluid Dynamics (CFD) models are better in handling three-dimensional (3D) air flow and pollutant dispersion within building configurations but it is less popular among environmental modellers due to high computing load required, complexity of the setup and long simulation times (Antonioni *et al.*, 2012). In practice, CFD models are only able to conduct simulation on approximately 1 km x 1 km x 1 km computational domain with lower than 10 m in grid size (approximately 1 million grid points). Though, it may take more than 1 hour to complete the calculation for steady flow and up to days and months for unsteady and transient flow. Moreover, the simulation times might increase significantly for larger CFD mesh (discrete grid points to solve air/fluid equations). In common, such simulations can take more than 1 GB of RAM usage on average computer. For these reasons, CFD analysis are generally not included in EIA analysis. Although air pollutant prediction and simulation has been studied extensively, no attempt has been made to analyse detailed wind distribution and pollutant dispersion process on high concentration zones in urban industrial park (network of stacks with nearby residential areas) predicted from conventional Gaussian Plume model.

In this study, both models are developed together in a single algorithm to complement their limitations. Due to poles apart models' structure, fundamental equations, coding architectures and massive programming effort to integrate both models in a single algorithm, there is no effort found in the literature on integrating both models as one. The primary advantage acquired by integrating both models in the same algorithm is that it allows user to find the high concentration zones using Gaussian Plume model and further investigate pollutant dispersion process within the areas using CFD model. In this study, the code of both models are written from scratch to ensure unified programming structure in order to carry out the integration. The main difficulty of this study lies on figuring out coding implementation of collective governing equations and assuring accuracy, stability, efficiency and robustness of the algorithm. Integrated Gaussian and CFD model allow multiple scale air pollutant dispersion prediction commencing from regional/neighbourhood estimation of air pollution level using Gaussian Plume model in neighbourhood scale (10<sup>4</sup> m in computational domain size) up to detailed building scale simulation (10<sup>3</sup> m) using CFD model as shown in Figure 1.1 (residential area in Pasir Gudang) (Cui et al., 2016). Hence, ability of the present algorithm developed in this study ranging from conducting routine air pollution assessment for regional estimation of air pollution level to more detailed wind flow analysis within building structures in the urban industrial park.



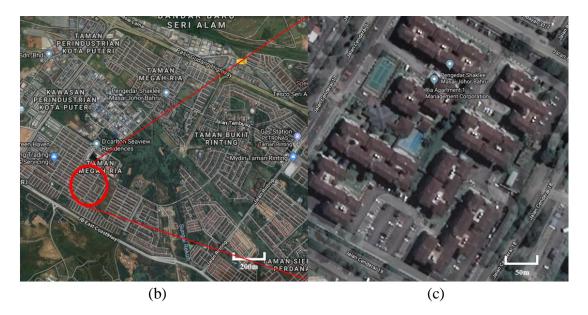


Figure 1. 1 (a) Location of Pasir Gudang Industrial Park (b) Neighbourhood scale  $(10^4 \text{ m or } 10 \text{ km x} 10 \text{ km using Gaussian Plume model})$  (c) Building scale  $(10^3 \text{ m or } 1 \text{ km x} 1 \text{ km using CFD model})$  (Google Maps, 2019).

Applying CFD models on complex urban structures requires extra task to remodel the buildings. Although accuracy of CFD models are satisfactory in recent years, generating urban 3D building models for CFD solvers still require manual effort especially in highly populated areas with multiple building configurations. In commercial software such as the well-known ANSYS Fluent software, users need to manually model the buildings using third-party software such as SOLIDWORKS (Bock, 2015). In the present CFD model, a smart function to automatically generate CFD mesh consisting urban buildings using image processing of satellite image is developed. Even though modellers are able to obtain the building data from Geographic Information System (GIS) data centre, several limitations of GIS approach restrict the convenience of the process. Those constrains include digitizing accuracy, incomplete data for rural and remote areas, costly and time consuming to obtain the data, manual update that causes human error and require good understanding on software architecture to extract available information before data manipulation (Schmit *et al.*, 2006).

In contrast, this study proposes a more reliable and effective way to generate building geometries using satellite image for CFD simulation. This approach analyses building footprints information and estimates the height using shadow length to produce urban geometries by extruding the footprints detected beforehand. Furthermore, this technique only requires Red Green Blue (RGB) satellite image (.jpg, .jpeg, .png) to process which is much easier to obtained, low in cost, faster data acquisition, good availability, low memory requirement, efficient building generation process, partially automated and suitable for repetitive building extraction for entire city mapping application. From our observation, upcoming technological utilization that are predicted to be impacting environmental modelling study is CFD and automatic building generation from satellite image. This study attempts to merge unique capabilities of both research areas to produce a smart algorithm that ease modelling in environmental studies.

In short, this study emphases on integrating Gaussian Plume algorithm alongside air flow and pollutant dispersion solver based on CFD model. Additional unique features on CFD model mesh generation for automatic building construction from satellite image is developed using building footprint detection and height estimation technique.

### **1.2 Problem Statement**

In standard practice, Gaussian Plume model (regional estimation of air pollution level in EIA analysis) and CFD models (detailed air flow and pollutant dispersion simulations) are used in different applications and purposes. Gaussian Plume models generally applied in predicting ground concentration from industrial stack release in EIA analysis, whereas CFD models are used to attain detailed wind flow and pollutant simulation in urban areas. By having both models in the same algorithm, town planners will be able to find areas in urban industrial park with severe pollutant concentration and further investigate those regions using CFD model. In order to achieve this, a new algorithm are developed from scratch as both models are developed separately due to dissimilar approaches, assumptions, fundamental principles, governing equations and parameters used in the models. The present algorithm is not restricted to provide regional estimation of air pollution level (as in commercial software packages), but also able to present detailed wind distribution, pollutant dispersions and entrapment zones within respective areas that is crucial to monitor in the long run. Existing commercial atmospheric dispersion software is not capable to do so.

For air pollutant simulation across complex building structures, building data such as stored in GIS are hard to acquire, expensive in cost and usually less accurate for small cities and undeveloped areas. GIS data require manual update on regular basis to stay updated with newly developed areas and a large number of GIS personnel are needed to cover data for all cities. In addition, manual data update practice in GIS may cause human error as well as labour and time consuming. As for current CFD commercial software, users need to remodel buildings and obstacles which results in repetitive and tedious process for air pollutant mapping in town planning application. To our knowledge, an effective tool that is able to automatically produce CFD mesh from satellite image integrated with air pollutant simulation solver for urban planners is still unavailable. Besides, studies on CFD analysis on high concentration zones predicted by Gaussian Plume model within urban industrial park is lacking in the literature.

For that, present study integrates both Gaussian and CFD model with automated building generation algorithm from satellite image and apply the algorithm in high pollutant concentration zone in urban industrial park.

### **1.3** Research Objectives

The objectives of the present study are:

- (a) To integrate urban building generator from satellite image, Gaussian Plume and CFD model.
- (b) To evaluate performance of the developed satellite image urban building generator, Gaussian Plume and CFD algorithms.

(c) To analyse wind flow, air pollutant dispersion and critical zones at high ground-level concentration areas in urban industrial park.

#### 1.4 Significance of Study

This study improves conventional air pollutant regulatory model by providing detailed analysis of wind flow and pollutant dispersion process at high concentration zones predicted by the Gaussian plume model. It enhances usage of CFD model alongside Gaussian Plume model for air pollutant modellers by providing relatively accurate and fast CFD solver using the least expensive turbulence model coupled with automated CFD urban mesh generator from satellite image. As a result, an integrated Gaussian and CFD solver is produced that is practical for regulatory use united with additional capabilities to get detailed simulation on highly concentrated areas. This study encourages the use of CFD model in EIA analysis to complement data provided by Gaussian Plume model.

### 1.5 Scope of Study

In this study, Gaussian Plume and CFD model are used. In the CFD model, Fractional Step Method is used as the steady-state wind flow solver, Prandtl Mixing Length model is used for turbulence calculation. In urban building generator algorithm, colour separation technique is used for building detection process whereas shadow length estimation is used for building footprint height extrusion.

This study focuses on simulation of non-reactive air pollutants (SO<sub>2</sub>, NO<sub>2</sub> and PM<sub>10</sub>) released from major industrial stacks in Pasir Gudang Industrial Park, Johor towards nearby residential areas. In the simulation, only industrial stacks emissions are considered without background pollutant concentration (previous day, month and year concentration) and external pollutant sources such as vehicular emissions and

construction sites are not taken into account. In this study, the air pollutants are assumed to be released towards a completely clean ambient atmosphere thus the ground pollutant concentration exerted to the nearby residential areas in Pasir Gudang are only contributed by respective industrial stacks emissions.

It is assumed that all buildings are on flat terrain without elevation (hills and mountains), no trees and bushes are considered and all buildings have flat rooftops in which building geometries are dependent on their footprint shapes for building extrusion process.

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