Development of Gaussian dispersion computer code enhanced with building downwash parameter

Nurlyana Omar$^1$ and Meng Hock-Koh$^{1,2}$

$^1$Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
$^2$UTM Centre for Industrial Applied Mathematics, 81310 Skudai, Johor, Malaysia

Nurlyana3@live.utm.my

Abstract. Atmospheric dispersion has been well known in environmental risk assessment. However, one parameter in atmospheric dispersion which is the building downwash was always neglected when calculating the dispersion of radioactive effluent using basic Gaussian dispersion model. In the Gaussian model, this parameter usually replaces by a value which is far from being accurate. The results of can differ almost to half of the actual result. Thus, the building downwash must be included in the calculation for more accurate dispersion results. This work focusses on the development of computer code to calculate the dispersion of radionuclide effluent which emphasis on the building downwash parameters. There are two parts of this work, the first is the basic Gaussian dispersion model computer code, named GD-Nx$^3$ and the second part is the Gaussian dispersion model enhanced with building downwash which called GDb-Nx$^3$. Both computer codes were build using Fortran computer language.

1. Introduction
During normal operating hours, radionuclide effluent was released from a nuclear power plant (NPP). However, these released complied to the standard and regulations from International Atomic Energy Agency (IAEA) [1][2][3] and it does not pose a danger to human since the concentration of radionuclide effluent is below the permissible limit.

However, when an accident happens, the radionuclide effluent released is beyond the permissible limit and can travel hundreds and thousands of kilometers away. This happened in early 2011 when the world was shocked by the serious multiple-reactor accident occurred in Japan. A huge amount of radioactive substance was released into the atmosphere from March 12 to the end of April and dispersed across the northern hemisphere due to the fast transport atmospheric system [4][5][6][7].

Many studies have been performed to simulate the dispersion of radionuclide effluents [8][9][10][11]. This is important to study the dispersion of the radionuclide effluent as it can be a potential health risk to the public. However, these simulation studies did not account for building downwash.

Measurement technique for atmospheric analysis has been improved in recent year. Gaussian atmospheric dispersion model was used to analyze the dispersion from a point source within 100 km radius. It is a simple model that needs few input data. However, it can only be used in an open space area and does not include building downwash. Thus, it is important to incorporate Gaussian
atmospheric model with building downwash due to the possibility that radionuclide effluent can travel in the city area after release from the point source.

It is important to note that the simulations model need to have a high degree of accuracy and must be achieved faster than real-time detection for effective decision support tools. As stated by [12][13], atmospheric dispersion tools can contribute as good decision support tools in making a prevention action in an emergency.

According to [14] the concentration of radionuclide before and after a building can differ up to 90 per cent of initial reading. Most of the software in the market only focus on the open-air analysis and does not include building a washout parameter.

In this paper, we are working towards producing our very own dispersion computer code analysis by using Gaussian atmospheric dispersion model enhanced with building downwash parameter to assess the radioactive effluent dispersion released in an emergency such as in the Fukushima accident.

There are two parts of this research, there is the basic Gaussian atmospheric model (GD-Nx3) and the second is enhanced with building downwash parameter (GDb-Nx3).

Our GD-Nx3 computer code is benchmarked to the HotSpot Health Physics code (hereafter referred as HotSpot) developed by Steven et al. in Lawrence Livemore National Laboratory’s National Atmospheric Release Advisory Center (NARAC) [15]. Whereas our GDb-Nx3 is based on the technical paper by [16]. Using Fortran computer language, these analysis codes were developed.

2. Methodologies

2.1. Gaussian plume model

The transport of radionuclide effluent is given by the expression [17][18]:

$$\frac{\partial C}{\partial t} + \nabla \cdot \mathbf{J} = S$$

where \(C\) refers to the mass [kg/m³], \(S\) the source function [kg/m³s] and \(J\) being the mass flux [kg/m²s] with the combinations of diffusion and advection effects. Following the Fick’s law, the three-dimension advection-diffusion equation to be solved is in the form:

$$\frac{\partial C}{\partial t} + \nabla (C \mathbf{u}) - \nabla (-K \nabla C) - S = 0$$

where:

- \(K\) is the diffusion coefficients [m²/s] and \(\mathbf{u}\) is the wind velocity [m/s].

In our code, few Gaussian assumptions were made to solve the eq.2 namely:

- i. The wind velocity in the y-direction or also known as the crosswind direction is negligible.
- ii. The wind velocity in the z-direction is negligible.
- iii. Radioactive effluent is released at a constant rate, \(Q\) from a single point source which located at a height, \(H\) from the ground. The source term may be written as

$$S (\mathbf{x}) = Q \delta(x) \delta(y) \delta(z - H)$$

- i. The solution takes place in a steady state condition.
- ii. The diffusion due to advection in \(x\)-direction is overwhelming large compared to the diffusion because of turbulent in the \(x\)-direction.
- iii. The radioactive effluent does not penetrate the ground.

Further explanation on Gaussian model that was used in GD-Nx³ and GDb-Nx³ can be referred to [19]. The equation to be computed is as per Eq.4:
where \( x \) is the downwind distance, \( y \) is the crosswind distance from the centre line of the plume and \( z \) is the height above the ground for which the concentration is calculated (all in units of \( m \)). The parameters \( Q \), \( u \) and \( h \) are the release rate \([\text{Bq/s}]\), mean wind speed \([\text{m/s}]\) and the effective release height \([\text{m}]\), respectively.

Further explanation on GD-NX\(^3\) and GDb-NX\(^3\) can be referred to [19] as it explains more details on how the equation of Gaussian atmospheric dispersion model works which is the basic of our computer code.

2.2 Building downwash parameter

Radionuclide effluent example from Fukushima accident can travel far into the city area and encounter high rise building [8]. Therefore, it is crucial to incorporate the building downwash effect into the main atmospheric dispersion calculation as the concentration of radionuclide effluent can differ by 90\% [20] from its real reading.

By understanding the building downwash effect, it can help in preventing the dangerous situation such as a high concentration of harmful effluent in one local area. For example, ‘Good Practice Guide for Atmospheric Dispersion Modelling’ prepared by the National Institute of Water and Atmospheric Research, AURORA, New Zealand was published to advise the best building dimension to avoid downwash effect as airflow around a building are often a complicated process [21].

Based on [16], there are four crucial part in incorporating building downwash with Gaussian atmospheric dispersion model (Figure 1). Segment A of the figure shows that the streamline slope is equal to zero which is the same as the Gaussian atmospheric dispersion model in an open space area. The segment, B, C and D will have a different calculation of the streamline slope. This calculation will be embedded into the Gaussian atmospheric dispersion model as part of the building downwash parameter.

![Figure 1](image-url)

Figure 1. The building downwash effect due to the windward side.
Table 1. Table shows the streamline slope used to calculate the movement of the radionuclide effluent in building downwash.

- **Segment** | **Streamline slope** | **Downwind distance from the windward**
- A | $\frac{\delta z}{\delta x} = 0$ | $(x < -R)$
- B | $\frac{\delta z}{\delta x} = \frac{2(H_R - H)(x - R)}{R^2}$ | $(-R \leq x \leq 0)$
- C | $\frac{\delta z}{\delta x} = \frac{(-4(H_R - H)(x^2 - 1))}{R^2}$ | $(0 \leq x \leq 0.55R)$
- D | $\frac{\delta z}{\delta x} = \frac{(H_R - H)(R - 2x)}{(L + L_R - R^2)} + \left( \frac{z}{H} \right)^{0.3}$ | $(0.5 \leq x \leq L + L_R)$

The notation of $H$ refer to the building height, $H_R$ is the maximum building height, $R$ is the building length scale, $L$ is the projected building length along with the flow and $L_R$ is the downwind recirculation cavity. This streamline slope will be calculated depending on the building dimension and in segment B onwards, the assumption is that the effluent plume is consider moving as particle thus the streamline slope is to calculate the $z$-direction.

Table 2. Table shows the percentage of difference between GD-Nx$^3$ and HotSpot

| Distance (km) | GD-Nx$^3$ (Bq·sec/m$^3$) | HotSpot (Bq·sec/m$^3$) | Differences value |
|---------------|--------------------------|-------------------------|-------------------|
| 1.0           | $3.6 \times 10^{10}$     | $3.5 \times 10^{10}$    | $-0.1 \times 10^{10}$ |
| 5.0           | $3.0 \times 10^{9}$      | $3.0 \times 10^{9}$     | -                  |
| 10.0          | $8.8 \times 10^{8}$      | $8.8 \times 10^{8}$     | -                  |
| 15.0          | $4.4 \times 10^{8}$      | $4.4 \times 10^{8}$     | -                  |
| 20.0          | $2.7 \times 10^{8}$      | $2.7 \times 10^{8}$     | -                  |
| 25.0          | $1.8 \times 10^{8}$      | $1.8 \times 10^{8}$     | -                  |
| 30.0          | $1.4 \times 10^{8}$      | $1.4 \times 10^{8}$     | -                  |
| 35.0          | $1.1 \times 10^{8}$      | $1.1 \times 10^{8}$     | -                  |
| 40.0          | $8.8 \times 10^{7}$      | $8.8 \times 10^{7}$     | -                  |
| 45.0          | $7.3 \times 10^{7}$      | $7.2 \times 10^{7}$     | $-0.1 \times 10^{7}$ |
| 50.0          | $6.2 \times 10^{7}$      | $6.2 \times 10^{7}$     | -                  |
| 55.0          | $5.3 \times 10^{7}$      | $5.2 \times 10^{7}$     | $-0.1 \times 10^{7}$ |
| 60.0          | $4.7 \times 10^{7}$      | $4.6 \times 10^{7}$     | $-0.1 \times 10^{7}$ |
| 65.0          | $4.1 \times 10^{7}$      | $4.0 \times 10^{7}$     | $-0.1 \times 10^{7}$ |
| 70.0          | $3.6 \times 10^{7}$      | $3.6 \times 10^{7}$     | -                  |
| 75.0          | $3.2 \times 10^{7}$      | $3.2 \times 10^{7}$     | -                  |
| 80.0          | $2.9 \times 10^{7}$      | $2.9 \times 10^{7}$     | -                  |
| 85.0          | $2.7 \times 10^{7}$      | $2.7 \times 10^{7}$     | -                  |
| 90.0          | $2.4 \times 10^{7}$      | $2.4 \times 10^{7}$     | -                  |
| 95.0          | $2.2 \times 10^{7}$      | $2.2 \times 10^{7}$     | -                  |
| 75.0          | $3.2 \times 10^{7}$      | $3.2 \times 10^{7}$     | -                  |
| 80.0          | $2.9 \times 10^{7}$      | $2.9 \times 10^{7}$     | -                  |
3. Results and discussion

3.1. Benchmarking GD-Nx^3 computer code
We benchmark our GD-Nx^3 analysis computer code with the available software in the market which is HotSpot. We have utilized the data obtained from the Fukushima Dai-ichi accident in 2011 as the input data for this analysis. This analysis focus on the Cs-137 as it is one of the most emitted radionuclides during a nuclear accident. The half-life of Cs-137 is 30 years and assumed to exist longer in the air and can easily be used by selecting default settings in HotSpot software. Table 2 shows the concentration of Cs-137 in the distance of x km from the point source.

It shows that our GD-Nx3 analysis computer code is in line with HotSpot software with the percentage different of 75 per cent which consider good.

3.2. Complementing GDb-Nx^3 analysis computer code
The GD-Nx^3 and GDb-Nx^3 analysis computer code were developed using Fortran computer language. Fortran is the oldest computer language and does not need a Fortran Window, instead, it just needs a program to type it and can be saved using an editor which turned into an executable file by a Fortran compiler.

There are two stages in developing GDb-Nx^3 analysis computer code. The first stage is to develop GD-Nx^3 which is the open space dispersion analysis (Segment A) and then calculate the streamline slope for Segment B onwards for the GDb-Nx^3. This part of the work is still in progress. Up to now, the GDb-Nx^3 coding is still in Segment B, where the assumption needed such as the distance of the building from the point source and the dimension of the building is yet to finalized. Both parameters are crucial in developing the GDb-Nx^3 code since it will affect the total result of the concentration.

4. Conclusion
In this paper, we discussed the current progress of our GD-Nx^3 analysis computer code that has been benchmarked with the commercial HotSpot software for a hypothetical nuclear accident and also the current progress with GDb-Nx^3. It shows that our GD-Nx^3 analysis computer code in-line with HotSpot although there are some results underestimate the HotSpot results. We used the Fukushima Daiichi accident as the hypothetical nuclear accident for this study. From our analysis, it shows that if a nuclear accident to happen in Malaysia with the centre to be from Malaysia Nuclear Agency, the impact of radionuclide effluent can cover up to 95 km of radius. This prediction should cover an area such as Kuala Lumpur, Pahang, Negeri Sembilan and Melaka. However, the concentration would be different if the radionuclide to enter high-rise building area such as Kuala Lumpur and Selangor areas.

5. References
[1] International Atomic Energy Agency 2010 TECDOC-1638 Setting authorized limits for radioactive discharges: practical issues to consider (IAEA).
[2] International Atomic Energy Agency 2012 Generic models for use in assessing the impact of discharges of radioactive substances to the environment (IAEA).
[3] International Comission on Radiological Protection 2005 Draft For Consultation 2005 Recommendations Of The International Commission On Radiological Protection ICRP (ICRP).
[4] Masson O, Baeza A, Bieringer J, Brudecki K, Bucci S, Cappai M, Carvalho F P, Connan O, Cosma C, Dalheimer A, Depuydt G, De Geer L E, De Vismes A, Gini L, Groppi F,
Guonason K, Gurriaran R, Hainz D, Halldorsson O, Hammond D, Holy K, Homoki Z, Ioannidou R, Isahenko K, Jankovic M, Katziberger C, Kettunen M, Kierepko R, Kontro R, Kwakman P J M, Lecomte M, Vitro L, L. Leppane, A P, Lind, Lujaniene G, Mc Ginnity P, Me Mahon C, Mala H, Menenti S, Manalopoulou M, Mattila A, Mauring A, Mietelski JW, Moller B, Nielsen S P, Nikoli, J, Overwater R M W, Palsson S E, Papastefanou C, Penev I, Pham MK, Povinec P P, Rameback H, Reis MC, Ringer W, Rodrigues A, Rulik P, Saey PR J, Samsonov V, Schlosser C, Sgorbati G, Silobrieniene B V, Soderstrom C, Sogni R, Solier L, Sonck M, Steinhauser G, Steinkopff T, Steinnmann P, Stroulos S, Sykora I, Todorovic D, Tooloutalaie N, Tositti L, Tschiersch J, Urgon A, Vagena E, Vergas A, Wershofen H, Zhukoya O 2011 Tracking of airborne radionuclides from the damage Fukushima Daiichi nuclear power plant European Netw. Environ. Sci. and Technol. 45 7670-7677.

[5] Pittauerova D, Hettwig B, Fischer HW 2011 Fukushima Fallout In Northwest German Journal of Environmental Radioactivity 102 877-880.

[6] Pham MK, Eriksson M, Levy I, Nies H, Osvalt I, Betti M 2012 Detection of Fukushima Daiichi Nuclear Power Plant Accident Radioactive Traces in Monaco J. of Environ. Radioact. 114 131-137.

[7] Ioannidou A, Manenti S, Gini L, Groppi F 2012 Fukushima fallout at Milan, Italy Journal of Environmental Radioactivity 114 119-125.

[8] Man CK, Kwok YH 2001 Assessment of risk to Hong Kong due to accidental release of radionuclides from a nearby nuclear power plant J. of Radioanalyt. and Nucl. Chemi. 250(3): 485-490.

[9] Pirouzmand A, Dehghani P, Hadad K, Nematollahi M 2015 Dose assessment of radionuclides dispersion from Bushehr nuclear power plant stack under normal operation and accident conditions Int. J. of Hydrogram Ener. 40 15198-15205.

[10] Sahin S, Ali M 2016 Emergency planning zone estimation for Karachi-2 and Karachi-3 Nuclear power plant using Gaussian puff model Hindawi Pub. Corp. Sci. Technol. of Nucl. Instalation.

[11] Aliyu AS, Ramli A T, Saleh MA 2014 Environmental impact assessment of a new nuclear power plant (NPP) based on atmospheric dispersion modeling. Stoch Environ. Res Risk Assess. 28 1897-1911.

[12] Benamrane Y, Boustras G 2015 Atmospheric dispersion and impact modeling system: How are they perceived as support tools for nuclear crises management? Safety Sci. 71 48-55.

[13] Benamrane Y, Wybo JL, Armand P 2013 Chernobyl And Fukushima nuclear accidents: What has changed in the use of atmospheric dispersion modeling? J. of Environ. Radioact. 126 239-252.

[14] Capena E. 2004 An overview about the study of downwash effects on dispersion of airborne pollutants Environ. Modelling and Softw. 9 1077-1087.

[15] Homann SG, Aluzzi F 2013 HotSpot health physics codes version 3.0 user’s guide Nat. Atmosph. Release Adv. Cent. 3.

[16] Schulman LL, Strimaitis DG, Scire JS 2000 Development and evaluation of the PRIME Plume Rise and Building Downwash Model Air and Water Management Association 50 378-390.

[17] Stockle JM The Mathematical of Atmospheric Dispersion Modelling. SIAM REVIEW 2011 53(2) 349-372.

[18] Veigele WJ, Head JH 1978 Derivation of the Gaussian plume model J. of the Air Pollut. Contr. Assoc. 28(11) 1139-1141.

[19] Shamsuddin SD, Omar N, Meng-Hock K 2017 Development of radionuclide dispersion modeling software based in Gaussian plume model Matematika 23(2) 149-157.

[20] Schulze RH 1995 Balancing simplicity with accuracy in the use of dispersion modeling in the United States International Journal of Environment Pollutan 5 521-529.

[21] Bluett J and Gimson N, Fisher G, Heydenrych C, Freeman T and Gadfrey J 2004 Good
practise guide for atmospheric dispersion modelling *Minist. for the Environ.* (New Zealand).

**Acknowledgement**
This document is the results of the research project funded by the UTM Potential Academic Staff grant (Q.J130000.2726.02K70) UTM Research University Grant (Q.J130000.2626.15J74) and UTM ZAMALAH Scholarship.