Research on a Sudden Explosion and its Environmental Impact

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Abstract: A sudden blast was chosen as the studied topic. Also, one computer based virtual experimentation was used to estimate the dimensional impact of initial pollutant plume from blasts. Self-made method using Mathcad code was used to generate the output for the period of the first tenth of a second (1deci-second) to 1minute (60s) of the blast at the point source. It also depicted long-range air pollution travel within the first 1 to 10 minutes. In the case study, it assumed an average directional diffusivity of 1720 m²s⁻¹ which is about 25 per cent of the average generated speed of common explosives. The newly developed model revealed a plume cloud impact of 6.8×10⁷µgm⁻³ in the first 1millisecond (0.01s) which decayed suddenly to a value of 1.7×10⁷µgm⁻³ in the first 1decisecond (0.1s). The impact concentration at the point source by the end of the first second (1.0s) was 3.2×10⁵µgm⁻³ which implied a 99.5% sudden decay when compared to 0.01s concentration value at the emission point source. Computerized experiments observed that air pollutants release from explosives/blasts were dispersed into the atmosphere in the first few seconds by forceful injection instead of by gradual dispersion as is the case with normal air pollutants plume releases.

1. Introduction

Explosion is a hazard, and, besides the many services it provides to humankind, it may cause nuisance, damage to property and to people (injury and loss of life). Damage may be ranked in top-down severity order as: a) loss of life, i.e. mortality; b) loss of health, i.e. morbidity; c) loss of property and d) loss of activity.

Besides damage caused by the explosion process itself, there is also damage associated to the environment nearby. In 1997, Magurchara gas field caught fire and then caused huge damage of life and property over the whole area. The Magurchara gas field explosion damaged about 60 hectares of natural forest and 300 hectares of land were burnt. A large part of wild life (deer, birds, foxes, monkeys etc.) was destroyed or displaced to other places. Around 3000 people were affected because 31 hectares of tea garden was completely damaged during explosion (EPCT, 1997). This was a typical industrial accidental explosion which imitated follow-up negative environmental impact.

Also, the sudden explosions like volcanic eruptions will affect the environment, even human health. The 15 June 1991 eruption of Mt Pinatubo on the island of Luzon in the Republic of Philippines forced the evacuation of more than 200,000 people and caused the immediate deaths of more than 300, many from the collapse of homes due to the combination of heavy ashfall and rain from the nearly simultaneous passage of Typhoon Yunya(Hansen et al. 1992;McCormick et al. 1995). Actually there are three major areas of potential chronic human health impacts from volcanic activity which include respiratory problems, particularly silicosis (Buist et al. 1986; Baxter et al. 1999; Allen et al. 2000),
psychological stress (e.g., Shore et al. 1986), and chemical impacts of gas or ash (e.g., Giammanco et al. 1998). So, the overall environment nearby and people's health can be highly affected by volcanic eruptions.

In the natural environment, magma contains dissolved gases that are released into the atmosphere during eruptions. At high pressures deep beneath the earth's surface, volcanic gases are dissolved in molten rock (Sigurdsson, 1999). But as magma rises toward the surface where the pressure is lower, gases held in the melt begin to form tiny bubbles. The increasing volume taken up by gas bubbles makes the magma less dense than the surrounding rock, which may allow the magma to continue its upward journey (Heiken et al. 1991). Closer to the surface, the bubbles are increasing in number and size, so the gas volume may exceed the melt volume in the magma and create foams (Settle et al. 1978). The rapidly expanding gas bubbles of the foam can lead to explosive eruptions in which the melt is fragmented into pieces of volcanic rock, known as tephra. If the molten rock is not fragmented by explosive activity, a lava flow will be generated (Durand et al. 2001). Together with the tephra and entrained air, volcanic gases can rise tens of kilometers into Earth's atmosphere during large explosive eruptions. Once airborne, the prevailing winds may blow the eruption cloud hundreds to thousands of kilometers from a volcano (Makhviladze et al. 1995).

Air pollution can be defined as an atmospheric condition in which substances are present at concentrations higher than their normal ambient levels due to certain natural or anthropogenic activities. The environmental impact of specific air pollutant depends on its ability to produce adverse effects/hazards on lives. In a broader sense, gaseous air pollutants include all the gases that are found in the atmosphere above their normal ambient levels. Here, airborne particulates include both solid and liquid particles have similar environmental impacts (Seinfeld, 1986; Hopke, 2009; DiGiovanni et al., 2006; Smodos, 2007; Smith et al., 2001).

Currently, there are air pollution models which are mainly used to analyze the amount of smoke generated in the fire. They have different experimental basis and the applicable conditions, the results of the models for the same problem are often different. The plume flow values predicted by the model of Thomas and the model of McCaffrey were both a little big, which caused a lower calculated smoke temperature than the experimental values, so they are inapplicable to large power fires. The plume flow value predicted by the model of Zukoski was a little smaller and the calculated smoke temperature was bigger than the experimental value, so it is applicable to small power fires. The plume flow value predicted by the model of Heskestad was steady, and the result of the zone simulation agreed well with the experimental value, so it could be used to predict large power fires.

Another plume model is the Gaussian plume diffusion model which is widely used in the study of air pollution dispersion and the field of atmospheric environment quality prediction (Arystanbekova, 2004). It is a model used to describe the distribution of the mass concentration of atmospheric pollutants or toxicants in the atmospheric diffusion process. But this model did not involve the role of explosion on the pollutant diffusion. Besides, there was some error between the result from the model and the measured one. This model only applied to analyze the diffusion of continuous point source.

There are also some other air pollution models. TAPM is a PC-based, nestable, prognostic meteorological and air pollution model (with photochemistry) driven by a Graphical User Interface, and is a viable tool for year-long simulations (Hurley et al, 2005). Barsotti et al. (2008) presented a new modeling tool, named VOL-CALPUFF, that is able to simulate the transient and three-dimensional transport and deposition of volcanic ash under the action of realistic meteorological and volcanological conditions throughout eruption duration. Karamchandani et al. (2009) used a sub-grid scale modeling approach to simulate the transport and fate of toxic air pollutants. Molnar et al. (2010) studied about air pollution modeling using a Graphics Processing Unit with CUDA. Tominaga et al. (2011) have presented CFD modeling using RANS and LES of pollutant dispersion in a three-dimensional street canyon which is investigated by comparison with measurements. But these models can not reflect a sudden explosion and its environmental impact.
2. Theories
Here, an explosion can be defined as a sudden release of energy that produces a sudden volume expansion (dV) of the conveying material due to large changes in pressure dP within the shortest possible time (dt). This causes high pressure waves in the local medium in which they occur. These shock waves can either be subsonic or supersonic, natural or anthropogenic (Basarov et al., 1991, Slotnick, 2008). The intensity of an explosion (I\text{exp}) therefore is proportional to the magnitude of $\frac{dP}{dt}$ and $\frac{dV}{dt}$

$$I_{\text{exp}} \propto \frac{dP}{dt}$$  \hfill (1) \\
$$I_{\text{exp}} \propto \frac{dV}{dt}$$  \hfill (2)

As we know, parts of the natural largest sources of sudden explosions are volcanic explosive eruptions. The sudden volcanic eruption occurs as a result of high pressure build-up in the volcano’s magma chamber, which pushes up the magma with great force out of the chamber in the same way a warm soda drink will spray out vigorously out of its bottle when its CO\text{2} or H\text{2}S bubbles have a higher pressure when the bottle is violently shaken and the lid opened suddenly (HVO, 2011). Major volcanic eruptions eject large amounts of particulate matter in form of volcano ashes. Also, gases in volcanic eruptions mainly include carbon diode, sulphur dioxide, hydrogen sulfide and other gases into the ambient air. Part of these pyroclastic materials gets transported to high enough altitudes and stays there for months or several years to impact on the global climate system (Neff, 1998). Volcanic pyroclastic have been observed at very high altitudes, 25,000m and above. This implies that materials from volcanic eruptions easily transcend the lowest portion of atmosphere which is the troposphere into the stratosphere (Groisman, 1998; Kane, 1998). The stratosphere is the region of the atmosphere where the ozone layer is found within the altitudinal range of 18,000m and 32000m.

Volcanic explosion can be in the form of sudden eruption of hot lava and thick smoke unto the surface, sudden release of hot spring of water and steam also known as Geysers, and violent vibration of the earth crust to a certain depth also known as the earth quake. The depth of the vibration determines the magnitude of the earth quake (Robock, 2003; Devine et al., 1984; Arya, 1999). These effects can be summarized by the following mathematical expression, which gives the discharge rate Q at which magma is ejected out of a volcano conduit of average radius R and length L as:

$$Q = \frac{\pi R^4 P}{8\mu L}$$  \hfill (3)

*Here, \(\mu\) is the viscosity of the magma;\n\(P\) is the pressure inside the magma chamber.*

Under the explosive blast, a shock wave will be produced when the rate of combustion of the explosive substances generates a sharp pressure gradient. Chemical potential energy has been converted to kinetic and heat energy during the process of an explosion. For example, trinitrotoluene (TNT) is characterized by a large amount of chemical potential energy that is nearly instantaneously converted to kinetic and heat energy. The resulting generated speed in the medium is approximately 6900ms\textsuperscript{-1} for TNT. This results in very high kinetic energy of approximate value 4.7 kJg\textsuperscript{-1} or 4.7 MJkg\textsuperscript{-1}. According to Neff, (1998) the chemical reaction in an average TNT explosive is typically ninety percent complete in between 10\textsuperscript{-9} and 10\textsuperscript{-6} second (1nanosecond to 1microsecond), and as the energy of the blast dissipates with increasing distance from the blast, the wave dissipates into a sound wave resulting in the loud blast.
In industrial circles, Environmental Impact Assessment (EIA) for all petroleum projects will allow the planners and implementers to understand the environmental impacts and con-sequences of their projects (NEAB, 1998; DoE, 2001). The EIA process is thought to consist of six main components: basics; impact identification; description of the affected environment; prediction and assessment of impacts; selection of proposed action and documentation in accordance with extant guidelines (Canter LW, 1997).

3. Methods
PTC Mathcad is the industry standard software for solving, analyzing, and sharing most vital engineering calculations. Its live mathematical notation, units intelligence, and powerful calculation capabilities, presented within an easy-to-use interface, allows engineers and design teams to capture and communicate their critical design and engineering knowledge. Here, it was used for the simulation of sudden air pollutants release.

For the scenarios setting, it considered different area spread. Further, it was defined as a sudden plume cloud release. It has to exclude a continuous smoke release situation. Momentum and kinetic energy variations are the prominent factors for detonations, whereas transport and dispersion processes are more relevant for the air pollution generated. The self-similarity of the solution at different scales was an important characteristic of the plume wave profile generated by the model.

In the study, the explosive blast waves were hypothesized as identical to volcanic eruption except for scaling in magnitude and duration. The activation of the model was made to be proportional to the mass and the initial velocity, which also implies the embedding of the initial kinetic energy of the blast into the model.

4. Results and Discussions
Empirically, air pollutants generated under a normal gradual circumstance get dispersed depending on the prevalent atmospheric conditions such as local wind speed, wind direction, humidity, at the time of release. The composition and chemistry of the atmosphere is of importance for several reasons, but primarily because of the interactions between the atmosphere and living organisms. Atmospheric physicists attempt to model Earth’s atmosphere and the atmospheres of the other planets using fluid flow equations, chemical models, radiation balancing, and energy transfer processes in the atmosphere and underlying oceans.

Atmospheric stability, mixing height and atmospheric ventilation index are the primary influencing factors of the atmospheric conditions, which is categorized into five sections (A-E). A stable atmosphere is one that is strongly resistant to change, while atmospheric turbulence results in significant displacement of air parcels both in horizontal and vertical directions and vice versa. In order to model weather systems, atmospheric physicists employ elements of scattering theory, wave propagation models, cloud physics, statistical mechanics and spatial statistics, each of which incorporate high levels of mathematics and physics.

The numerical simulation revealed that air pollutants generated from sudden explosion/blast get dispersed very fast from emission point source due to the large forces and pressures which accompany the air pollutants at the moment of release.

In the simulation, it assumed an average directional diffusivity of 1720 m²s⁻¹. It is about 25% of the average generated speed of common explosives. The outcome put forward a plume cloud impact of 6.8×10³ µgm⁻³ at the emission point source in the first millisecond (0.01s) decayed suddenly to a value of 1.7×10³ µgm⁻³ in the first 1decisecond (0.1s) (Figure1a). Further, by the end of the first one second (1.0s), the plume concentration at the emission point source was 3.2×10³ µgm⁻³. This result implied a 99.5% sudden dispersion of the matters released by the eruption within the shortest possible time. Please see Figures 1(a-f).

We can found that the instant dispersion of air pollutants and displacement of air parcel in the immediate vicinity of the emission point source is directly resulted in the extreme forces and pressures generated by the blast. This aided the propagation of the air pollutants emitted both horizontally and
vertically at shortest time frame. The model simulation revealed that the rate of dispersion of the air pollutants depended directly on the associated mass of the pollutants, the speed and the momentum generated by the explosive blast. Thus the kinetic energy associated with the blast played more significant role in the almost instant dispersion from the point source than the prevalent atmospheric conditions. It would have been the case for normal emissions. The simulation outcome revealed that within an infinitesimal fraction of a second of the explosion was very significant as the result has shown in Figures (2a and 2b). From these figures, the sharp variation of concentration impact at the source from $1.7 \times 10^7 \, \mu g m^{-3}$ in the first decisecond (0.1s) to $3.2 \times 10^5 \, \mu g m^{-3}$ by the end of the first one second (1.0s) and to just $300 \, \mu g m^{-3}$ by the end of the first one minute (60.0s) was an index to the rapid decay which might not be easy to observe under real physical conditions but only in virtual experimentation as performed in this study. Here, we can see the significance of numerical experimentation in the reveal of potential physical process.

Clearly, this can thus be suggested that air pollutants emitted from sudden explosion is more of forceful injection into the atmosphere than gradual dispersion in the very few seconds of the blast occurrence. And like air pollutants from volcanic eruption, it also has capacity to penetrate higher altitude of the atmosphere at shorter time than normally released air pollutants would do.

The obvious example can be found in the eruption of Mt. Pinatubo in June, 1991. It was found to have made significant chemical perturbation to the ozone layer and the resulting observed depletion in the ozone concentration for that period (Groisman, 1998). Likewise, Kane, (1998) noted the occurrence of a spectacular quasi biennial oscillation (QBO) wave between 1991 and 1993 with a range of about ±10% which is associated partly with the volcanic eruptions of Mt. Pinatubo in June 1991. Similarly, Morris et al., (2003) observed significant increase in stratospheric chlorine, which was linked with the El Chichon eruption in 1982.

Figure 3 revealed that the long range air pollutant dispersion from sudden explosion. Air pollutant has the ability to reach a distance of 1.2km within the first minute of the explosion, and could be propagated as far as 4km within the first ten to fifteen minutes of the release.
Figures 1(a-f): Shockwaves of air pollution concentration (µgm⁻³) at the point source vicinity at various moments in the first one second of blast.

Figure 2(a-b): Variation of Concentration Impact at emission point source in the first one minute (60s) of blast.

Figure 3(a-d): Long range Air pollution Dispersion (kgm⁻³) in 1min, 3mins, 5mins and 10mins of blast respectively.
5. Conclusions
This paper used computerized method to make a virtual experimentation to explain how the rate of dispersion of air pollutants changes in certain time and make a model to reveal what is relating with plume cloud impact. The gaseous products created by a volcanic eruption and by an explosive blast follow a similar injection pattern, but this study revealed that like volcanic eruptions, air pollution from sudden blast is more of forceful injection into the atmosphere than gradual dispersion in the first few seconds of the explosion. The length and time scales involved are orders of magnitude different. In the study, it obtained a sudden decay of the concentration dimensional impact at source point from $1.7 \times 10^7 \mu \text{gm}^{-3}$ to $300 \mu \text{gm}^{-3}$ in the first 60s. Sudden injection of air pollutants into the ambient air is enhanced by the huge pressure and momentum generated by the blast. The ability of air pollutants from sudden explosion to reach higher altitudes within a short period of time made it to have both immediate and long term adverse effect on the environment and the life form. It also implies a further complication of the already existing air pollution challenge confronting the environment.

6. References
[1] Allen, A.G., Baxter, P.J. and Ottley, C.J. (2000) Gas and particle emissions from Soufriere Hills Volcano, Montserrat, West Indies: characterization and health hazard assessment. Bull. Volcano. 62, 8–19.
[2] Arystanbekova, N. K. (2004). Application of Gaussian plume models for air pollution simulation at instantaneous emissions. Mathematics and Computers in Simulation, 67(4), 451-458.
[3] Arya P, (1999). Air Pollution, Meteorology and Dispersion. Oxford University Press, New York, 310pp.
[4] Bazarov SB, Bazhenova V, Bulat OV, Golub VV, ShulmeisteR AM, (1991). Three dimensional diffraction of shock wave. In K. Takayama, editor, Shock Waves Proceedings of Sendai Japan Springer-Verlag, 1: 251.
[5] Baxter, P.J., Baubron, J.C. and Countinho, R. (1999) Health hazards and disaster potential of groundgas emissions at Furnas volcano, Sao Miguel, Azores. J. Volcanol. Geotherm. Res. 92, 95–106.
[6] Barsotti, S., Neri, A., & Scire, J. S. (2008). The VOL—CALPUFF model for atmospheric ash dispersal: I. Approach and physical formulation. Journal of Geophysical Research: Solid Earth (1978–2012), 113(B3).
[7] BUET, (2003). Workshop in Oil and Gas Sector”, organized by Bangladesh University of Engineering and Technology, Dhaka.
[8] Buist, A.S., Vollmer, W.M., Johnson, L.R., Bernstein, R.S. and McCamanat, L.E., (1986) A four-year prospective study of the respiratory effects of volcanic ash from Mt. St. Helens. Am. Rev. Respir. Dis. 133, 526–534.
[9] Canter LW, (1997). “Environmental impact assessment”, 2nd edition, Mcgraw-hill Inc., p. 640.
[10] DoE, (2001). “EIA Guidelines”, Department of Environment, Ministry of Environment and Forest, Govt. of Bangladesh.
[11] Devine, J.D., Sigurdsson, H., Davis, A.N., Self, S, (1984). Estimates of sulfur and chlorine yield to the Atmosphere from volcanic eruptions and potential climatic effects. J. Geophysical Research 89: 6309.
[12] DiGiovanni F, Fellin P, (2006). Trans-boundary air pollution, in Environmental Monitoring, [Eds.Hilary I. Inyang, John L. Daniels], in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK, [http://www.eolss.net]
[13] Durand, M., & Grattan, J. (2001). Effects of volcanic air pollution on health. The Lancet, 357(9251), 164.
[14] EPCT, (1997). “Draft Report - Environmental Impact Assessment in Oil and Gas Sector”, survey work conducted by Engineering Planning Consultancy Team, Sylhet.
[15] Fire Research Station, & Thomas, P. H. (1963). *Investigations into the flow of hot gases in roof venting*. HM Stationery Office.

[16] Groisman, P. Y. (1992). Possible regional climate consequences of the Pinatubo eruption: an empirical approach. *Geophysical Research Letters* **19**(15):1603.

[17] Giammanco, S., Ottaviani, M., Valenza, M., Veschetti, E., Principio, E., Giammanco, G. and Pignato, S. (1998) Major and trace elements geochemistry in the ground waters of a volcanic area: Mount Etna (Sickly, Italy). *Water Res.* **32**, 19–30.

[18] Kato N, Akimoto H, (1992). Anthropogenic Emissions of SO2 and NOx in Asia: Emission Inventories. *Atmospheric Environment*, **26A**: 2997-3017.

[19] Kane RP, (1998). Ozone depletion, related UV-B increase and increase skin cancer incidences. *International J. Climatology* **18**: 457.

[20] Karamchandani, P., Lohman, K., & Seigneur, C. (2009). Using a sub-grid scale modeling approach to simulate the transport and fate of toxic air pollutants. *Environmental fluid mechanics*, **9**(1), 59-71.

[21] Hawaii Volcano Observatory, (HVO), (2011). Volcanic Air Pollution- A Hazard in Hawaii. [http://hvo.wr.usgs.gov/](http://hvo.wr.usgs.gov/).

[22] Hansen, J., Lacic, A., Ruedy, R., & Sato, M. (1992). Potential climate impact of Mount Pinatubo eruption. *Geophysical Research Letters*, **19**(2), 215-218.

[23] Heiken, G., & Wohletz, K. E. N. E. T. H. (1991). Fragmentation processes in explosive volcanic eruptions. *Sedimentation in volcanic settings*, **45**:86.

[24] Hopke PK (2009). Contemporary threats and air pollution. *Atmospheric Environ* **43**: 87.

[25] Hurley, P. J., Physick, W. L., & Luhar, A. K. (2005). TAPM: a practical approach to prognostic meteorological and air pollution modelling. *Environmental Modelling & Software*, **20**(6), 737-752.

[26] Heskestad, G. (1984). Engineering relations for fire plumes. *Fire Safety Journal*, **7**(1), 25-32.

[27] Leopold LB, Clarke FE, Manshaw BB, Balsley JR, (1971). A Procedure for Evaluating Environmental Impacts, U.S. Geological Survey Circular No. 645, Government Printing Office, Washington, D.C.

[28] Makhviladze, G. M., Roberts, J. P., & Yakush, S. E. (1995). Modelling of atmospheric pollution by explosions. *Environmental Software*, **10**(2), 105-112.

[29] McAdam M, (2008). Bangladesh Travel Guide, Lonely Planet, 6th Edition ISBN: 9781741045475, p. 153.

[30] McCaffrey, B. J. (1983). Momentum implications for buoyant diffusion flames. *Combustion and Flame*, **52**, 149-167.

[31] Morris G, Barbara G, Newman PA, Aikin A, Heaps W, Crum F, Larko D, Todaro RM, (2003). The Chemical, Thermal, and Dynamical Structure of Earth's Atmosphere [http://hyperion.gsfc.nasa.gov/](http://hyperion.gsfc.nasa.gov/) code 916.

[32] Molnar Jr, F., Szakaly, T., Meszaros, R., & Lagzi, I. (2010). Air pollution modelling using a graphics processing unit with CUDA. *Computer Physics Communications*, **181**(1), 105-112.

[33] Neff M, (1998). A Visual Model for Blast Waves and Fracture. PhD Thesis, University of Toronto pp11.

[34] NEAB, (1998). “EIA Manual”, National Environmental Association of Bangladesh.

[35] McCormick, M. P., Thomason, L. W., & Trepte, C. R. (1995). Atmospheric effects of the Mt Pinatubo eruption. *Nature*, **373**(6513), 399-404.

[36] Robock A, (2003). Volcanoes: Role in climate in Encyclopedia of Atmospheric Sciences, J. Holton, J. A. Curry, and J. Pyle, Eds., (Academic Press, London), 10.1006/rwas.2002.0169: 2494.

[37] Seinfeld JH, (1986). Atmospheric chemistry and physics of air pollution. John Wiley and Sons, New York, Toronto, pp77-91.

[38] Slotnick J, (2008). Explosive Forces of Improvised Explosive Devices, [http://www.securitydiver.com/aic/stories/article-114.html](http://www.securitydiver.com/aic/stories/article-114.html) (accessed August 2008).
[39] Smith SJ, Pitcher H, Wigley TML, (2001). Global and regional anthropogenic sulfur dioxide emissions. *Global and Planetary Change* 29: 99.

[40] Smodis B, (2007). Investigation of trace element atmospheric pollution by nuclear analytical techniques at a global scale: harmonized approaches supported by the IAEA. *Journal of Environmental Management* 85:121.

[41] Shore, J.H., Tatum, E.L. and Vollmer, W.M. (1986) Psychiatric reactions to disaster: the Mt. St. Helens experience. *Am. J. Psychiatry* 143, 590–598.

[42] Sigurdsson, H., Houghton, B., Rymer, H., Stix, J., & McNutt, S. (1999). *Encyclopedia of volcanoes*. Access Online via Elsevier.

[43] Settle, M. (1978). Volcanic eruption clouds and the thermal power output of explosive eruptions. *Journal of Volcanology and Geothermal Research*, 3(3), 309-324.

[44] Tominaga, Y., & Stathopulos, T. (2011). CFD modeling of pollution dispersion in a street canyon: Comparison between LES and RANS. *Journal of Wind Engineering and Industrial Aerodynamics*, 99(4), 340-348.

[45] Zukoski, E. E., Kubota, T., & Cetegen, B. (1981). Entrainment in fire plumes. *Fire Safety Journal*, 3(3), 107-121.