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REVIEW

Atmospheric Dispersion of Radioactive Material in Radiological Risk Assessment and Emergency Response

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The purpose of a consequence assessment system is to assess the consequences of specific hazards on people and the environment. In this paper, the studies on technique and method of atmospheric dispersion modeling of radioactive material in radiological risk assessment and emergency response are reviewed in brief. Some current statuses of nuclear accident consequences assessment in China were introduced. In the future, extending the dispersion modeling scales such as urban building scale, establishing high quality experiment dataset and method of model evaluation, improved methods of real-time modeling using limited inputs, and so on, should be promoted with high priority of doing much more work.

KEY WORDS: atmospheric model, risk assessment, emergency response, nuclear accident

I. Introduction

The studies and developments of techniques and methods of atmospheric dispersion modeling of radioactive material in radiological risk assessment and emergency response have evolved over the past 50-60 years. The three marked types of dispersion models, which may depict the development of dispersion modeling technique for the application in radiological risk assessment and emergency response, are Gaussian plume models in the 1960s and 1970s, Lagrangian-puff models and particle random walk models in the 1980s - 1990s, and developing CFD (Computational Fluid Dynamics) models in the 2000s. Current available atmospheric dispersion models range from the relatively simple to the highly complex. In order to determine how dispersion models can be applied most effectively, it is important to identify the needs in radiological risk assessment and emergency response.

Up to now, Gaussian plume models are applied to risk assessment and emergence response, typically, such as MACCS[1)] and COSYMA[2)] for probabilistic risk assessment and RASCAL/InterRAS[3,4)] and HOTSPOT[5,6)] for emergence response. The Gaussian plume model approximately depicts the distribution of time-averaged concentrations over a period of time such as one hour. Because of some insuperable inherent vices, new knowledge and processing methods cannot be taken into account though empirical corrections have been applied to model, for instance, terrain modified factor. Such models will face the challenge in the case of complex topographies, urban environments and buildings, low wind speed or calm conditions, and so on. For the purposes of actual emergency response and real-time consequence assessment, Lagrangian puff and particle models are currently used in many advanced emergency response system such as NARAC[7,8)] from U.S. DOE/LLNL, RODOS[9)] from EC, HYSPLIT[10)] from U.S. NOAA, and SPEEDI/WSPEEDI[11)] from Japan/JAERI. However, the needs of emergency management may not be well satisfied by existing models which are not well designed and confronted with difficulty in detailed constructions of local wind and turbulence fields, validity of empirical parameterization, and testing of confidence-level estimates. It should usually by difficult to obtain a dataset of field experiments to test atmospheric dispersion models including meteorological observations and tracer samplings of good quality and high-resolution. Some typical experiments considered to be of greatest potential value for testing models are Kincaid[12)] tracer experiment for plat terrain, MADONA[13)] field study for complex terrain, URBAN 2000[14)] and Joint Urban 2003[15)] for urban-scale and building-scale, and ETEX[16)] for long-range transport.

The studies and developments in China have made great progress in the functions and techniques of atmospheric dispersion modeling and real-time consequence systems for over a decade. The models applied to emergency response are currently involved in with mass consistent diagnostic wind field model, quasi-hydrostatic numerical prognostic model, Lagrangian puff model and particle random walk model. In fact, the same issues mentioned above should be resolved though the existing dispersion models can meet some needs of the emergency managements.

In this paper, a brief review of the needs of atmospheric dispersion models in radiological risk assessment and emergency response was given. Then the studies on nuclear accident consequences assessment in China were introduced. Finally, some issues calling for attentions in atmospheric dispersion modeling are discussed.

II. Needs of Atmospheric Dispersion Models in Radiological Risk Assessment and Emergency Response

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1. Consequence Assessment and Atmospheric Dispersion

There are three types of nuclear accident consequence assessment in the light of purposes of assessment:

(1) Probabilistic Risk Assessment (PRA). The assessment on the risk from the potential accident would be based upon probabilistic analysis considering the occurring probability and consequence spectrum of each accident.

(2) Real-time consequence assessment. The aim is to provide an input for emergence response through assessing or predicting and to provide support for emergency response managers before accident releases. In detailed, the real-time consequence assessment is divided into early, intermediate and latent phases.

(3) Over-event or past accident consequence assessment. That means consequence assessment studies through retracing the transport of radioactive material for the historical releases.

Atmospheric dispersion modeling represents one of the valuable tools of effective emergency response for its technical support on environment and health prediction and decision-making. Thus, it is important to make models as accurate as possible. The present numerical modeling methods focus on providing various best prediction results not too conservative.

Errors in numerical modeling are mainly emerged from uncertainties in both the discrete process of transportation equation and the data input. To reduce uncertainties and develop most realistic atmospheric dispersion model, many details should be validated through meticulous studies. Field experiment should be the most traditional and reliable way for the validation and evaluation of atmospheric dispersion models.

2. Consideration for the Needs of Risk Assessment and Emergency Response

In fact different modeling methodologies are required in the risk assessment and different stages of emergency response. For the risk assessment and the preparedness and latent stages, an model capable of providing confidence-level estimates is desired, but model execution time is not important. For the response stage, especially for the immediate first response before releases, tradeoff and compromises will be needed between model accuracy and timely predictions.

In the wake of the terrorist attacks of September 11, 2001, the U.S. National Academies launched a major new initiative to provide guidance to the federal government on scientific and technical matters related to counterterrorism and homeland security. To address these issues, a steering committee was convened that included several members of the Board on Atmospheric Sciences and Climate (BASC) and a number of additional people chosen to augment the group's expertise and organized a workshop that addressed the following tasks[17)]:

- Review the current suite of atmospheric models that used in characterizing atmospheric dispersion and examine how these models are applied operationally for emergency response efforts.
- Identify deficiencies in the models that limit their effectiveness and breadth of application; assess the research and development needed to enhance the effectiveness and operational use of these models in emergency situations.
- Determine the observational data needed to initialize, test, and use these models effectively, and identify the ways in which other environmental measurements can complement these models to provide additional and more accurate information.

As for emergency response, it is very important to let emergency responders understand that there are limits to atmospheric dispersion modeling capabilities. Conversely, dispersion modelers and meteorologists would be aware of how nowcasts and forecasts are used in emergency response situations.

3. Types of Atmospheric Dispersion Model and Selection

Models of environmental processes are approximate representations of reality. Each model involves a set of tradeoffs, taking into account objectives such as whether it will be used to aid understanding, to estimate changes that might occur, or to determine which areas might be affected if a release were to occur. Now there are six general model types (as shown in **Table 1**), which are compartmentalized in the light of model principle and theory and complexity.

Table 1 General types of atmospheric dispersion model

Level	Type	Representative models
6	CFD, LES	FEM3MP(LLNL, US)
5	Three-dimensional Eulerian grid model	ADREA-DIFF(Demokritos, Greece) TRAVELLING(KfK/Univ. Karlsruhe, Germany)
4	Lagrangian particle model or Monte-Carlo particle model	MC31(CEA, France) ARCO(ENEA, Italy)
3	Lagrange puff model	RIMPUFF(Riso, Denmark) MESODIFF-II(SRC, US) RAPTAD(Los Alamos, US) SPADE(ENEA, Italy) HARM(EPA-ATDD, US) PG&E-Puff Model(PG&E, US)
2	Segmented plume model	ATSTEP(KfK, Germany) COSYMA(EC)
1	Gaussian plume model	RASCAL(NRC, US)

Part of the problem of model selection is to know the horizontal scale of the various transport and diffusion processes of concern. Another part of the model selection problem is to understand which transformations and removal processes are of concern. In fact not all processes are of interest in all scales. Taking the needs of risk assessment and emergency response as well as modeling horizontal scale and dispersion processes under consideration, one can conclude that the appropriate choice of an atmospheric dispersion model depends on the following selection parameters:

- A definition (or redefinition) of the information to be gained or the decision to be made;
- The selection of the scale of interest;
- A knowledge of the physical processes that likely should be treated for the intended purpose;
- An appreciation of the uncertainty associated with the tradeoffs made in the model's construction; and
- The limits of predictability associated with any modeling system for the scale of interest.

III. Progresses in Studies on Nuclear Accident Consequences Assessment in China

The development of the assessment of nuclear accident consequences and decision support system in China stared at the end of 1980s and was divided into two phases. The representative systems of the first phase were the Real-time Dose Assessment System for Qinshan Nuclear Power Plant[18,19] finished in 1991 and the consequence assessment system for Daya Bay Nuclear Power Plant also finished in 1991. The relatively simple atmospheric dispersion models, such as Gaussian plume model and puff model, were adopted because of the limit of computer capability and financing. These systems have not met the needs of current emergency response management and were not used.

A summary of consequence assessment systems developed in the second phase is presented in **Table 2**. A quasi-hydrostatic numerical prognostic model and diagnostic wind field model were used to simulate airflow over complex underlay and provide the wind fields during the future 24 hours with 1 hour duration in the early system of the second phase such as QS-NUCAS[20] and TW-NAOCAS[21]. In recent years the products of Numerical Weather Prediction (NWP) from meteorological department or community were used to provide a series of forecasting wind fields with coarse grid resolution. The atmospheric dispersion modeling mainly adopted the Lagrangian puff models and particle random walk models. Existing dispersion models can meet the general needs of the emergency response community.

Table 2 Development status and characteristics of the representative nuclear accident consequence assessment systems in China.

Sponsoring Agency	Model Acronymus	Developer[a]	Wind Field Methodology	Atmospheric Dispersion Model	Dose	Counter-measure	Display of Information
Emergency Committee Office of Guangdong Province for Nuclear Power Accident	GNARD	TU	Statistic Forecasting +Dynamical equation and diagnostic	Lagrangian Particle dispersion model	Yes	No	GIS platform
Qinshan Nuclear Power Base	QS-NUCAS	TU	Quasi-hydrostatic numerical prognostic model + diagnostic	Particle dispersion + puff model	Yes	No	GIS platform
Tian Wan NPP	TW-NAOCAS	CIRP	Quasi-hydrostatic numerical prognostic model + diagnostic	Lagrangian puff model	Yes	No	GIS COM with real-time display
National Nuclear Accident Emergency Office, Daya Bay NPP	RODOS3.0-C	CIAE, CIRP, TU, CAINI	NWP + diagnostic	Lagrangian puff model, Segmented plume model	Yes	No	Special GIS
Ministry of Environment Protection	NACPADS	TU	NWP + diagnostic	Lagrangian puff model	Yes	Yes	GIS platform
	RADCON (long-range)	CIRP	NWP (National Meteorological Center)	Particle dispersion model	Yes	No	GIS COM with real-time display

[a] TU stands for Tsinghua University; CIRP for China Institute for Radiation Protection; CIAE for China Institute of Atomic Energy; CAINI for Computer Application Institute of Nuclear Industry.

In addition, RODOS Version 3.0 was introduced into our country from 1997 to 2001 and was redeveloped as the platform for the development of the Chinese decision support system for nuclear emergency management. It should be noted that the introduction of RODOS played an important role to develop the techniques of nuclear accident consequence assessment and decision support in China.

In recent years, on the one hand, the modeling capabilities should be strengthened because the needs of emergency management may not be well satisfied by existing models in the case of actual emergencies. In particular, current models are not well designed for complex natural topographies or built urban environments. On the other hand, expanding modeling scales is paid attention in order to meet the challenges of future threats and a long-range atmospheric transport modeling system for Ministry of Environment Protection, RADCON, will be established in 2009. Endeavor for development of CFD models applicable to urban environments is under way.

The enhanced research needs also include methodology of model evaluation, such as validation of models, parameter uncertainty and sensitivity analysis and criteria of model evaluation. It will be useful to establish benchmarks to validate wind field models and atmospheric dispersion models.

IV. Researches on Current Issues of Atmospheric Dispersion Modeling

1. Atmospheric Dispersion Modeling for Complex Environments

The accuracy of a dispersion model will depend on the quality of model input, the model's analytical methodology, and the inherent random nature of turbulent processes.

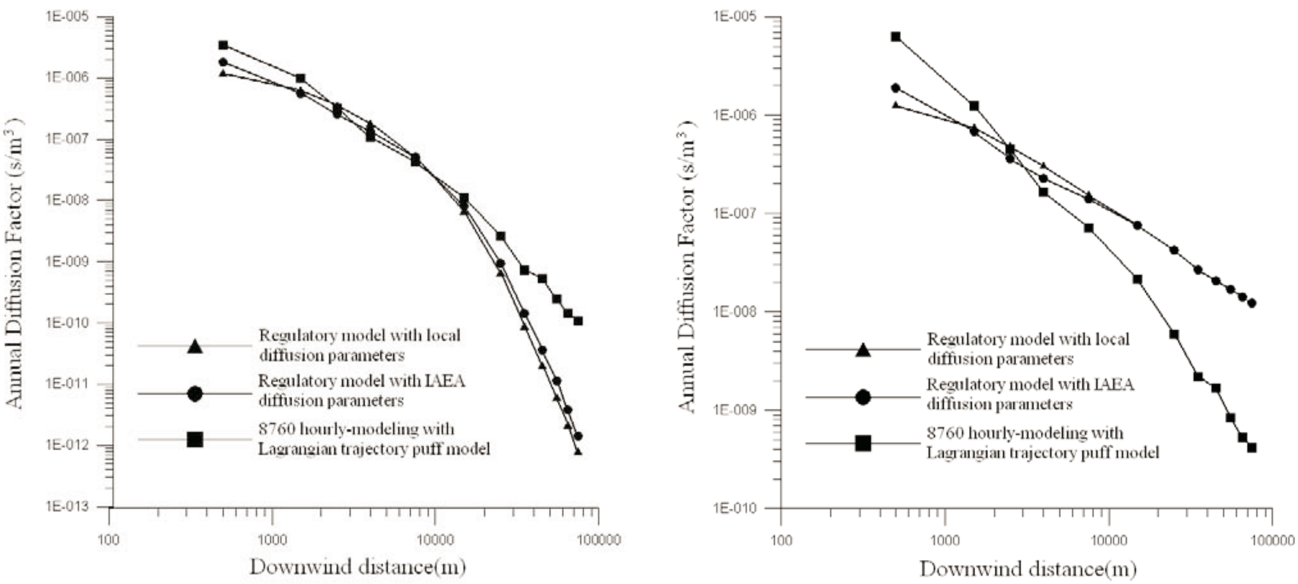
Diagnostic meteorological models derive mean wind, turbulence, and other variables at specified times from observational data and land-surface characteristics via a combination of interpolation, extrapolation, and similarity-theory parameterizations. Such models are commonly used for emergency response applications, due to their capabilities for ingesting real-time observational data and their computational speed. Thus, for most of the release situations with short period, diagnostic meteorological models can meet the needs of emergency response, especially for the early phase.

No matter what the simple models or complex models, an important factor which affects the quality of atmospheric dispersion modeling is the density of the wind measurements and the quality of the meteorological observation data. Observational technologies have been evolving rapidly in recent decades. Model operators and developers would benefit from broader interaction with the meteorological community to take advantage of leading-edge research in data assimilation, quantitative precipitation forecasting, short-range numerical weather prediction, and high-resolution forecasting initialized with radar data.

Of course, considering that the period of releases is long or there may be long-range transport effects, most current emergency response modeling system drive dispersion models with weather forecast model output, rather than directly integrating dispersion processes into NWP models. This allows relatively rapid hazard predictions to be made for multiple scenarios based on the same meteorology.

The fundamental problem in any existing dispersion models is that the turbulence must somehow be parameterized. For Lagrangian puff model or particle random walk model, research will be considered to better parameterization methods of mean flow vectors and turbulence for all time periods and surface types, improved methods of real-time modeling using limited inputs, and optimization of methods to use new meteorological observation system.

In environment impact assessment and risk assessment for the sites in complex terrain, the usual models and methods may be also faced with proof. For example, the annual and accident atmospheric dispersion factors calculated with the regulatory models are significantly different from those through modeling of 8760 hourly releases with Lagrangian trajectory puff model, as shown in **Figure 1**. Therefore, care should be paid to apply the usual models to the site in complex terrain and also to analyze the validity of the models and parameters.



(a) I-131 (b) Kr-85

Fig. 1 The comparison of annual atmospheric dispersion factors among different dispersion models and parameters for the Fuling site in Chongqing, China.

2. Field Experiment and Model Evaluation

(1) Field experiment

The best way to evaluate the accuracy of atmospheric dispersion models is to compare their predictions with concentration measurements taken downwind from actual releases. But verification is still hampered by the lack of suitable experimental data. The previous field experiments may be suitable to the models predicting only the ensemble-averaged concentration (that is, the average over a large number of realizations of a given dispersion situation). In addition, existing many experimental data sets are often incomplete and lacking of information mainly because they have been usually programmed for scopes different from complex terrain flow and dispersion model validation. A huge amount of work is generally needed just to clean, validate the data and make them finally suitable for model evaluation.

Local topography and the built environment will lead to local wind patterns that can carry contaminants in unexpected directions. A high-quality experimental data set should be involved:

- High-quality meteorological observation data including high temporal and spatial resolution, surface energy balance measurements, extensive vertical measurements of turbulence and flow structure, etc. In a word, observational networks must represent local flows as faithfully as possible.
- High-quality tracer sampling data. The sampling duration can be done with fast-response (such as 1 Hz) measurements of tracers. Arcs are generally used for long-range and grids generally for small-scale.

There were some better field experiments in recent years such as URBAN 2000[14] and Joint Urban 2003[15] for urban-scale and building-scale.

(2) Methods of testing model validity

In fact, the “true” concentration field of a specific release cannot be predicted. Tennekes (1990)[22] challenged the atmospheric modeling and measurement communities with three requirements:

- No observation is complete without an appropriately sampled estimate of the variance of the properties observed.
- No forecast is complete without a preceding estimate of forecast skill.
- No model calculation is complete without a calculation of its variance.

The field measurements represent the actual distributions and characteristics of concentrations in space and time whether or not. The statistical methodology is used for most of the coefficients in the sense that data are coupled in space and time; therefore the pair measured/predicted concentration refers to the same location at the same time. For the meso- and micro-scale transport, the common statistical indexes are bias, NMSE, Pearson’s correlation coefficient, geometric mean bias, geometric mean variance, scatter diagram (FOEX and FA), etc. For the evaluation of long-range dispersion models, the indexes, Figure of Merit in Space (FMS) and Figure of Merit in Time (FMT)[23], should be taken into account. A focused research need is to develop criteria for synthetically assessing agreement of model predictions with observations.

3. Data Assimilation

Data assimilation aims at accurate re-analysis, estimation and prediction of an unknown, true state by merging observed information into a model. This issue arises in all scientific areas that enjoy a profusion of data. The problem is fundamental yet challenging as it does not naturally afford a clean solution.

As mentioned above, the development of data assimilation of meteorological data will offer help to improving dispersion modeling capabilities. The Ensemble Kalman filter has been applied successfully to improve the model predictions of radioactive contamination on the ground by means of measured data in RODOS[24]. Zheng et al. (2007)[25] also applied the same method to improve a Monte Carlo atmospheric dispersion model (MCADM). The results indicate that about 80% of error caused by the uncertainty in the source term is reduced and the value for that caused by uncertainty in the turbulence intensity is about 50%.

For the evaluation of long range dispersion modes using tracer experimental data, the FMS is a valuable statistical index and is defined as the percentage of overlapping of the measured and predicted areas above the significant level. Concentration distributions are often drawn from an interpolation of each data set. For this reason, the FMS is sensitive to the type of interpolation adopted which, in fact, belongs to an issue of 2-D static-state data assimilation. However, no special investigation was carried out on the space distribution of concentration, and each concentration sampler was assumed to represent a large area and a geometrical logarithmic interpolation was used. The result also depends on the type of projection adopted. The same questions were met for data processing of the meso- and micro-scale tracer experiments.

4. Source Term Estimation Using Meteorological Field and Environmental Monitoring Data

For nuclear power plant accidents, it may be possible to make credible estimates of the source term based on plant conditions, inventories, or data from a monitored stack. However, refinement of these estimates requires additional data. But the past real accidental releases of radioactivity showed that it was hard to acquire the release condition in the early stage of the accidents. For terrorist scenario or other unexpected radiological release events, on the other hand, little may be known about the characteristics of the dispersed and airborne material. In this case, an idealized gas or aerosol source with a unit amount of material can be used to initially predict the downwind area in which to focus air- or ground monitoring activities.

JAERI has been engaged in a research project to develop technology in the source term estimation on the release point, time and amount by coupling monitoring data with atmospheric simulations[26, 27]. NARAC has developed a flexible and robust data-driven event reconstruction capability which approach couples data and predictive models with Bayesian inference and stochastic sampling to provide backward analyses to determine unknown source characteristics, optimal forward predictions for consequence assessment, and dynamic reduction in uncertainty as additional data become available[28, 29].

5. CFD Model

A CFD model is based on the three fundamental principles that govern the physical aspects of any fluid flow:

- Mass is conserved;
- Energy is conserved;
- Newton's second law (the acceleration of an object is a function of the net force acting upon the object and the mass of the object).

CFD models solve the full 3-dimensional Navier-Stokes fluid dynamics equations together with appropriate physics submodels, for turbulence, radiation, surface heat budgets and other processes affecting the airflow. The resulting meteorological fields are used to drive solutions to the conservation-of-species equation using either steady-state conditions based on the Reynolds-Averaged Navier-Stokes (RANS) approach or via a coupled system using the time-dependent large-eddy simulation (LES) approach.

Many researches have made clear that LES is viable for urban type flows at high Reynolds number. The 'typical' small-scale inlet features are required for special situations. Thus, to date the data requirements, problem definition, and time required to generate results have limited the use of CFD models to studies of special situations.

Although CFD models are computationally expensive compared to Gaussian or Lagrangian models, the cost is repaid by the generation of significantly more detailed outcomes. CFD models are able to capture transient phenomena, such as plume arrival and departure times and peak concentrations.

NARAC has developed a CFD code called FEM3MP[30, 31] which has been extensively tested against data obtained from wind-tunnel and field experiments, such as Urban 2000 and Joint Urban 2003. A major roadblock to using FEM3MP and similar CFD codes in an emergency situation is the time required to generate the grids used in calculations. To address this problem, NARAC is incorporating FEM3MP's capabilities into the Adaptive Urban Dispersion Model (AUDIM)[32]. AUDIM uses adaptive mesh refinement to automate and integrate the steps in simulating dispersion in an urban environment, from grid generation to flow and transport prediction. AUDIM's grid-generation program can use raw lidar data from aerial surveys as well as "shape files" of building footprints and heights to generate 3D surface meshes in minutes.

IV. Concluding Remarks

Perfect prediction of the smallest motions in the atmosphere is not possible. Some of the motions involved must be described stochastically or as nonlinear dynamic processes. Consequently, getting useful results from an atmospheric dispersion model is always a compromise between timeliness and completeness in portraying how the atmosphere acts on the released material.

Intensive research activity related to different aspects of wind field and dispersion modeling over complex terrain is still needed. An important topic for harmonization purposes is the adequate evaluation and validation of atmospheric flow models, including a better assessment of the uncertainty of their results.

In order to improve atmospheric dispersion modeling capabilities, priorities should be considered as follow: (a) to enhance the temporal and spatial resolution and quality of meteorological observations; (b) to extend the modeling scales, especially the development of CFD and LES for urban environments and complex topographies; (c) to learn how to more effectively assimilate into models an appropriate range of meteorological data and contaminant monitoring data; (d) to estimate the source terms including the time, location and magnitude of releases by using meteorological field and environmental monitoring data; and (e) to develop and establish experiment dataset and evaluation method to be used to allow quantitative evaluation of models.

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