論 文 の 内 容 の 要 旨

論文題目　Study on Statistical Inference for Unknown Sources of Atmospheric Pollutants in Urban Environment
（都市環境における未知空気汚染発生源の確率的推定に関する研究）

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This dissertation studies the statistical inference method for an unknown source of atmospheric pollutants in the complicated urban environment based on Bayesian inference. To enable the inference method to handle the characteristics of the urban area, the main works of the dissertation include: extending the inference's ability to estimate the geometry of the unknown source; increasing the estimation accuracy by introducing a sophisticated dispersion model into the inference; proposing a sensor configuration optimization method to improve the quality of measurements and guide the sensor network design.

Nowadays, a high level of urbanization results in a considerable amount of people gathering in the urban area, where a safe and healthy atmospheric environment has never been more important. However, unexpected atmospheric pollution emitted from unknown sources sometimes occurred because of terrorism, nuclear accidents, illegal industrial emission, and other emergencies, which is a serious threat to humankind and the earth's environment. Therefore, it is important to identify the unknown source as soon as possible after these dispersion emergencies happened. Until now, intensive research has proposed various methods to realize source term estimation (STE). The basic framework of STE is using the estimation algorithm to find the true source based on the measurements obtained during the emergency and the source-receptor relationship (S-RR), which is the concentration prediction modeled in advance. However, the existing methods are still not capable enough of handling complex scenarios in the urban environment because of its unique features as follows.

First of all, possible sources of pollutants are diverse in the urban environment. Although the previous research has considered mobile sources and multiple sources, their estimation algorithm always assumed that the unknown source is an ideal point without geometry. Actually, some sources have non-negligible shapes or volumes, which may fail the estimation based on the point assumption. It is important to extend the STE method for geometry estimation.

Besides, the dispersion mechanism of atmospheric pollutants is extremely complicated in the urban environment. The transportation of pollutants involves complex turbulence caused by buildings, equipment, moving objects, and heat discontinuity. However, the existing simulation techniques for S-RR are still limited in steady models and cannot accurately predict turbulent dispersion. Since STE relies on S-RR as the prior prediction of pollution dispersion, it is necessary to introduce a precise modeling technique for the S-RR in order to promise the accuracy of STE.

What's more, ideal concentration measurements are difficult to acquire in cities because of the dense building distributions and land property limitations. Sensor configurations used in real life are nearly random or empirical, but their effectiveness to all possible sources has no promise. Because the performance of STE is highly dependent on the quality of measurements, it is meaningful to develop a sensor configuration optimization method to guide the sensor deployment and provide high-quality measurements.

Based on this research background, this dissertation aims to develop a statistical inference method for STE in the urban environment by dealing with 3 unsolved problems mentioned above. Because the complexity of real atmospheric pollution is out of the range of a single dissertation, the research subject is limited to one single source with constant emission strength and fixed location in a statistically steady turbulent flow field in a neighborhood-scaled urban area. The main research contents are summarized below.

As a beginning, a new method was proposed to estimate the geometry of unknown sources based on the super-Gaussian function. The coefficients of this function can control its distribution to approximate common shapes: line, rectangular, and ellipse. These coefficients are added into Bayesian inference to realize the geometry estimation. The applicability of the proposed method was first confirmed using a numerical experiment of an ideal boundary layer. The method successfully inferred that the source is line-like without any prior knowledge. Based on this case, the effects of different sensor configurations on the line source estimation were discussed. Because the line source contained more geometric information than point sources, the conventional sensor configuration for the point source may fail in the line source estimation. It was found that the requirements on the sensor configuration become higher. Both the sensors near the source and null-measurement sensors are indispensable.

To examine the robustness of the proposed method against measurement and modeling errors, the second case of a simplified urban square with wind tunnel experiment measurements was conducted. The line source was successfully identified by the proposed method again. By comparing to the conventional STE method with ideal point assumption, it is confirmed that the proposed method can not only provide the geometry estimation but also reduce the inference errors caused by the point source assumption. Hence, it is important to include the geometry estimation when the geometry of the source has unignorable effects on the dispersion.

Then, to improve the accuracy of STE in complex urban applications, large-eddy simulation (LES) was introduced to model the S-RR by unsteady adjoint equations. The LES of adjoint equations has rarely been conducted in the literature because the adjoint equation describes an inverse dispersion process. The time-series flow field data of the entire domain must be produced by forwarding simulation and stored in advance, thus the volume of data simulated with LES is too large for practical applications. This research proposed to use the wavelet-based compression method to mitigate the storage pressure. The LES flow field can be compressed into a portable database to make the simulation of unsteady adjoint equations easier.

As the first step, to evaluate the accuracy of compression and usefulness of the compressed database, a turbulent flow field in a block-arrayed building group model was simulated by LES and compressed into a database by the wavelet-based compression method. The influence of compression on the quality of the data was checked from the perspectives of a single snapshot and time series. It was confirmed that about 100 times compression can still satisfy the requirement of flow field visualization and afterward simulation. Large-scaled turbulent structures were well preserved after compression, and the dispersion simulation can be reliably reproduced with compression data. Therefore, it is reasonable to expect that the unsteady simulation of adjoint equations can be realized based on the compression database.

Afterward, the compression database above was used in the LES of adjoint equations to model S-RR, which was combined with Bayesian inference as a new STE method. The concentration measurements obtained from a wind tunnel experiment were applied to testify the performance of the proposed method. As a comparison, another STE was also conducted with a conventional method, where steady adjoint equations were simulated with the Reynolds-averaged Navier-Stokes (RANS) model. The results showed that the modeling of S-RR and the accuracy of STE were significantly improved by the LES of the adjoint equation. The complicated turbulent flows caused by buildings destroyed the reliability of the conventional RANS model. Although the proposed method needs more computational resources, to effectively perform STE in the complicated urban environment, it is valuable to apply LES for adjoint equation simulation.

At last, a sensor configuration optimization method for STE was proposed by the design of an objective function and application of the simulated annealing method. The objective function was set as the information entropy of the spatial distribution of the adjoint concentration field. Its ability to represent the measurement ability of sensor configurations was proved from the views of mathematics and physical meanings. Simulated annealing was applied to find the optimal configuration which owns the largest value of the objective function. The proposed method was utilized to design an optimal sensor configuration for the block-arrayed building group model. The performance of the optimal configuration in STE was compared to uniform and random configurations through estimations for 25 unknown sources. The results revealed that the accuracy of STE is related to the entropy contained in the adjoint concentration of the configuration such that the design of the objective function is reliable. The optimal configuration outperforms the other two in STEs. It is valuable to use the proposed method to guide the configuration design in real applications.