Numerical Study of Radioactive Pollutants dispersion in Radioactive "Dirty Bomb" Events

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ABSTRACT

The simulation of radioactive pollutants dispersion is critical for emergency response of the nuclear terrorism. The radioactive "dirty bomb", also called radiological dispersion device (RDD), produced and used by the terrorist to make fearful and radioactive pollution in general, has a great risk on humans. Numerical investigation of the impact of different configurations on radioactive pollution release and dispersion in urban buildings is made in this paper. The numerical simulations used the OpenFOAM, a free and open source software for computational fluid dynamics (CFD), and the simulations can be implanted to the information system of the nuclear terrorism emergency decision support system(EDSS) as the consequence assessment subsystem conveniently. The study showed that the configurations of building canyon and the position relationship of the source item and the buildings both affect the concentration distributions around the buildings.

Keywords

atmospheric dispersion, radioactive "dirty bomb", configurations of building, concentration distribution, emergency response

INTRODUCTION

The radioactive "dirty bomb" event is a very likely nuclear terrorism. First, the distribution and application of radioactive materials and sources is so extensive that terrorists can obtain easily. Second, the technology to manufacture a "dirty bomb" is much easier than the nuclear weapon or the simple nuclear device. And detonating radioactive "dirty bomb" in a highly crowded area of the urban street is much simpler than attacking a nuclear facility. The investigate of the release and dispersion of "dirty bomb" event mainly focuses on the consequence and the mechanism of action. In this type of nuclear terrorism event, the forecast and monitor of the radioactive pollutants release and dispersion has a great importance for the emergency response and management to mitigate damages. Also, for the influenced people, the investigate is helpful for the evacuation and elude (Medalia, J.2011).

The main purpose of the "dirty bomb" event is making radioactive contamination to harm to human and causing social panic. The radioactive material is the core of the "dirty bomb" and some kinds of radioactive material used in the "dirty bomb" can make great harm to the human health. Based on these reasons, the urban street is the appropriate place for terrorists to detonate a "dirty bomb" (Rosoff, H. and D. Von Winterfeldt.2007). The release and dispersion of radioactive substances would be the consequence of a "dirty bomb" event. And the radioactive gases may be highly toxic for humans and the environment. The radioactive "dirty bomb" is a nuclear terrorist attack emergency which has a serious consequence on environments and economies, that means the release of radioactive substances by the "dirty bomb" event happened suddenly, the radioactive substances dispersion may occur instantaneously. So the release and dispersion of radioactive pollutants is always a potentially threatening to public safety. (Regens, J.L., et al.2007).

The numerical simulation of the radioactive material release and dispersion estimates the distribution of radioactive pollutants concentrations according to the different urban buildings configurations and the source items of radioactive "dirty bomb". The simulation of the radioactive "dirty bomb" consequence can be a function part of the information system for nuclear terrorist crisis response and management to improve the early warning and the consequence assessment ability. As mentioned, the estimation process needs the buildings configurations and the source items. Although there is no radioactive "dirty bomb" event happened ever, it is really a great risk to the public safety and social stability. By the atmospheric dispersion model, the consequence information can be given to support the emergency response and decision support.

In this paper, the investigate focuses on the influence of different urban configurations and different positions of "dirty bomb" source items to the distribution of radioactive pollutants concentrations. This investigation aimed to numerically analyzing the influence of different urban building configurations on the diffusion of radioactive pollutants in an urban area.

NUMERICAL SIMULATION METHODS AND MODELS

The usual methods used to study the atmospheric diffusion in urban street include three kinds and suit different conditions. For field measurements, this method can give researchers direct data and information of the pollutant concentration distribution in the real urban area, so it is suitable for basic verification research. However, the field measurements need huge and complicated experiment field and the meteorological conditions are uncertain, the high cost and the influence of the toxic gas on environment and human beings makes this method inconvenient. The second method is wind tunnel experiments, which are proceeded in physics laboratory, have also been extensively applied to understand the complex flow and pollutant distribution patterns within street canyons (Delaunay, D., et al.1997). Meroney et al. 1996 and Rafailidis. 1997 did the wind tunnel research and obtained wind tunnel experimental dataset to make open validation. But in wind tunnel experiments, the observation and measurement is based on the discrete measurement points in the model of the wind tunnel. Due to the number of measurement points is limited, the data provided by the experiments is discontinuous.

Expect these two methods, the numerical simulation based on the computer calculation, has many advantages. First, it is the most economic method which only needs a computer. Through the numerical simulation, computer can present the pictorial release and diffusion process of the pollutants and the airflow is also available for researchers to investigate. By this method, data of the pollutant release and dispersion is continuous, with higher spatial and temporal resolutions than the other two methods mentioned above. (Launder, B.E. and D.B.1974). The most important, the numerical simulation is much safer and more convenient than the other two methods.

The most common used model of numerical simulation is Computational Fluid Dynamics (CFD) models, which simulate the pollutant airflow based on hydromechanics (de Sampaio, P.A. et al. 2008). There are many investigations about the release and dispersion of the pollutant gas in the street canyons using the CFD simulation. Street canyons is a kind of common configurations in the urban areas. The numerical simulation of pollutants dispersion in the street canyons mainly use the CFD models, and then the data obtained by wind tunnel experiments was compared with the simulation data to demonstrate the CFD models can be used to simulate the actual situation.

Emphasis in this investigate is about the release and dispersion of radioactive substance, which is the consequence of a "dirty bomb" event. The impact range of a "dirty bomb" in urban street is only about hundred meters. So the main influence factors of the model are wind and configurations of buildings as the geographical condition is almost invariant in the model domain. The drift direction of radioactive pollutant depends on the wind direction. Due to the simulation of radioactive pollutant in urban area is very complicated and the condition of simulation area needs to be fine, the process using semi-empirical classical formula from the mesoscale atmospheric diffusion model is no longer available to small-scale atmospheric diffusion model. To solve the problem, we use the most basic fluid dynamics equations which use the Navier-Stokes (RANS) equations as the core.

In the small-scale atmospheric diffusion model, atmosphere is thought to be incompressible, adhesive turbulent fluid. So the model is set to solve the equation set consists of the hydromechanics equations and diffusion equations. The equation set includes continuity equation, Reynolds-averaged Navier-Stokes (RANS) equations and pollutant convection diffusion equations (Daly, B.J. and F.H. Harlow.1970). To solve the RANS equations, the Standard $k-\varepsilon$ turbulence model (Launder, B. E. & Spalding, D. B. 1974)was used. The integrated equation set can be described as follows:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \mu \frac{\partial}{\partial x_j}\left[\left(\nu + \nu_t\right)\frac{\partial \overline{u_i}}{\partial x_j}\right]$$

$$-\rho\overline{u_i' u_j'} = -A\delta_{ij} + \mu_t\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) \qquad A = \frac{2}{3}\rho k$$

$$\nu_t = \frac{\mu_t}{\rho} = C_\mu \frac{k^2}{\varepsilon} \qquad \mathrm{P} = \nu_t \frac{\partial \overline{u_i}}{\partial x_j}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

$$\frac{\partial k}{\partial t} + \overline{u_i}\frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + C_k\frac{k^2}{\varepsilon}\right)\frac{\partial k}{\partial x_i}\right] + \mathrm{P} - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} + \overline{u_i}\frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + C_\varepsilon\frac{k^2}{\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}\mathrm{P} - C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

$$\frac{DC}{Dt} = -\overline{u_i}\frac{\partial C}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\left(D + \frac{\nu_t}{Sc_t}\right)\frac{\partial C}{\partial x_i}\right] + S_C$$

where x_i is the i th Cartesian coordinate, $\overline{u_i}$ is the mean velocity in the x, y, z direction, u_i' is the fluctuating velocity, ρ is the air density, P is the mean pressure, μ is the fluid kinematic viscosity, k is the turbulent kinetic energy, ν_t is the kinematic eddy viscosity, ε is the turbulent dissipation rate, δ_{ij} is the Kronecker delta, $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ are model constants, S is the scalar concentration of mean source, D is the diffusivity coefficient and $Sc_t = 0.7$ is the turbulent Schmidt number.

In this investigation, the Open Source Field Operation and Manipulation (OpenFOAM) software was used. There are many CFD models in OpenFOAM adapt to different fluid situations. In the small-scale atmospheric diffusion model, atmosphere is thought to be incompressible, adhesive turbulent fluid. So the standard solver simpleFoam was modified to contain passive scalar turbulent transport equations to solve the equation sets put forward above.

NUMERICAL EXPERIMENTS

In the numerical experiment, the settings of buildings configurations are imitated from the wind-tunnel experiment mentioned above. According to the wind-tunnel experiment, the numerical experiments area is a 468m long, 150m high and 200m wide cuboid. The buildings in the urban street were simplified to cuboids. Five different kinds of experiment were considered in this study. The wind field is the perpendicular approaching flow.

In Exp.1, the amount of buildings in the downwind direction was set to examine the influence of building amount on the dispersion of radioactive pollutant. Exp.2,3,4 focused on the influence of the length, width and height of buildings in the urban area. In Exp.5, the "dirty bomb" source item position was differed to study the effect of the position relationship of source items with buildings.

Exp.number	Parameter	(a)	(b)	(c)
1	Amount of Buildings	1	2	3
2	Length	30	60	120
3	Width	9	18	36
4	Height	9	18	36
5	release position*	84	54	24

*the value of release position is the distance between the source and the buildings

Table 1. Description of the Numerical Experiments

RESULTS AND DISCUSSION

Influence of the Amount of Buildings

In this part, the amount of downwind buildings was set to one, two and three to compare the difference of the distributions of radioactive pollutant concentration. The distributions of pollutant concentration in vertical plane are given in Fig.1. In the middle of y-direction(y=150m), it is obvious to see the plume formed by the release and dispersion of radioactive pollutants. From the Fig.1(a) and 1(b), compared with the concentration in the leeward side of the building in Fig.1(a), the concentration in the leeward side of the downstream building in Fig.1(b) is smaller as building has block function to the dispersion of radioactive pollutants. However, for the situation of three buildings showed in the Fig.1(c), the dispersion range of same concentration is longer than the other two situations. As the radioactive pollutants can stride the buildings from the top, each building can cause an effect like lifting the plume and finally makes the dispersion range longer. In the left interval, the radioactive pollutants concentrate more in the windward side of downstream building as there is a vortex, which can drive the radioactive pollutants transport away through the leeward side of upstream building.

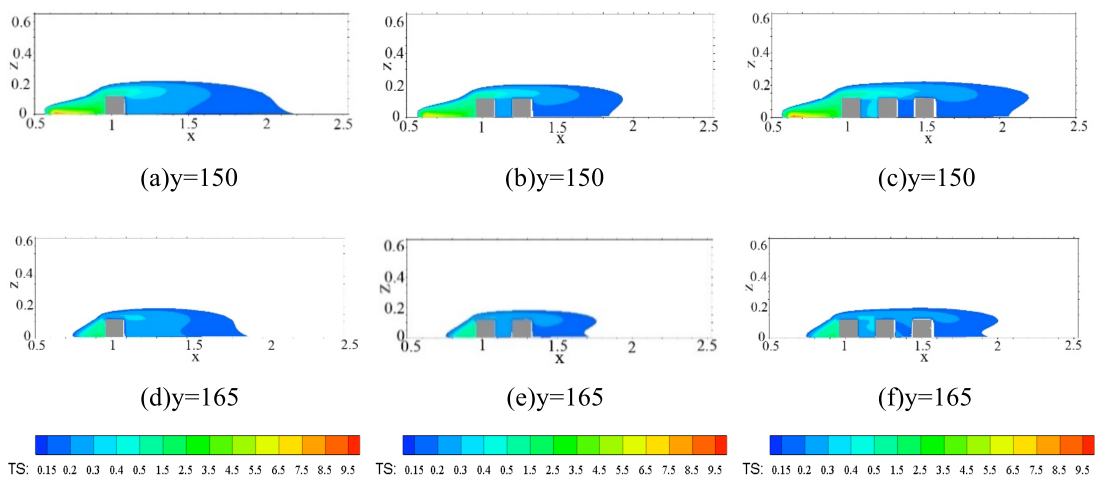


Figure 1. The normalized concentration of different amounts of buildings in vertical plane, Experiment 1. (a),(d),(g)a

building;(b),(e),(h)two buildings;(c),(f),(i)three buildings

The horizontal distribution of radioactive pollutants concentration is showed in Fig.2. From the Fig.2, we can see as the amount of buildings increases from one to three, the pollutants concentrate more in the first and second interval formed in downwind direction. It is found that the three buildings configuration is the most polluted configuration. In this configuration, the radioactive pollutants area is the biggest and the concentration in the intervals is higher than the value in the same position of other configurations.

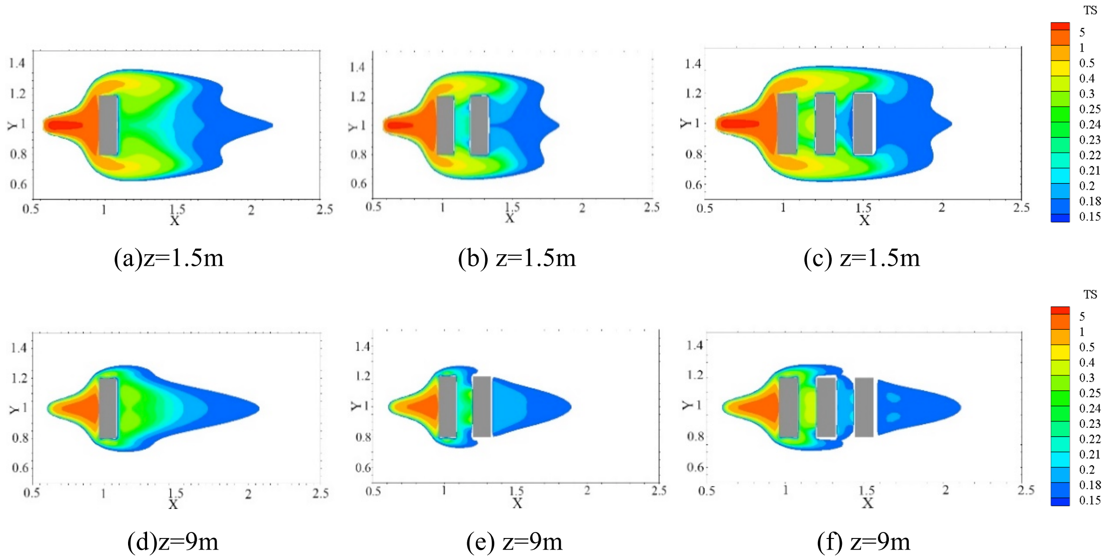


Figure 2: The normalized concentration of different amounts of buildings in horizontal section, Experiment 1. (a),(d) a building;(b),(e) two buildings;(c),(f) three buildings

Influence of the Length of Buildings.

The distributions of radioactive pollutant concentration in the two buildings street canyon with different length are studied in this part. The effect of the length of buildings mainly reflected in the edge of buildings. The Fig.3(a) and (d) show the different y-direction sections when the buildings length is 30m. The comparison of y=150m and y=165m section reflects that the concentrations increase with the y-axis values. As for the distributions of radioactive pollutant concentration in the buildings canyon, it is easily to find the influence of the vortex which formed in the canyon of length=60m.

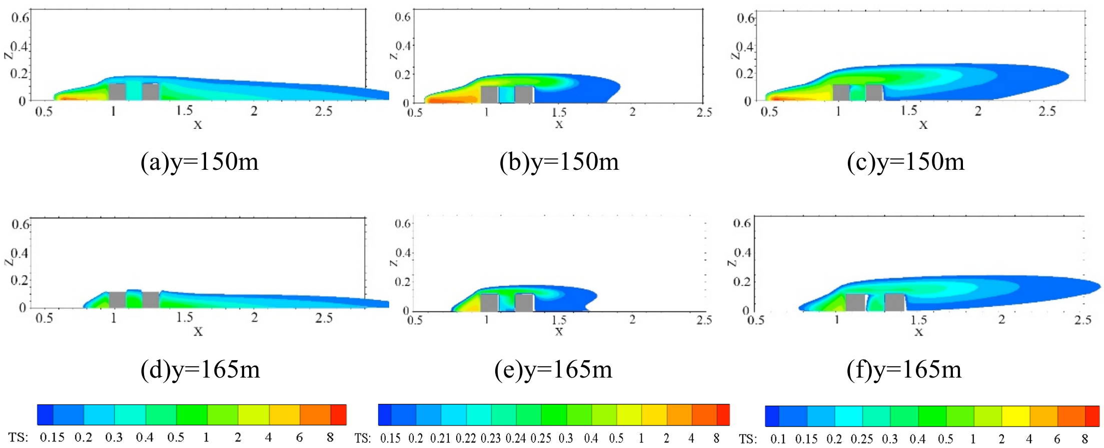
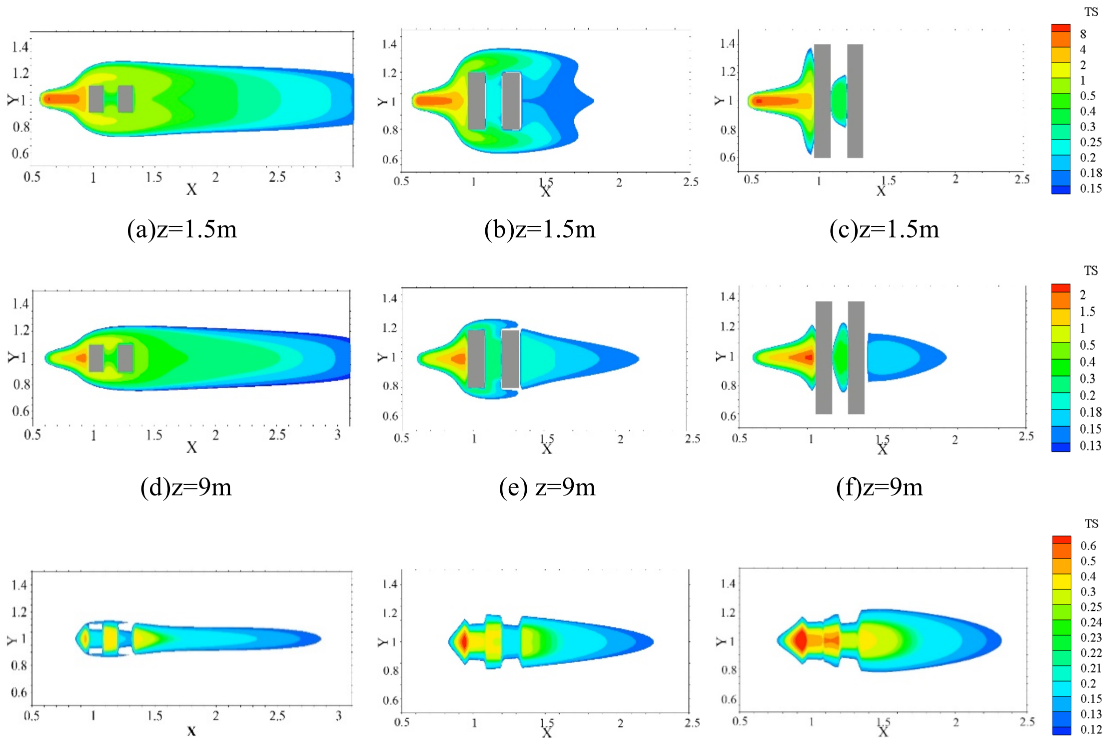


Figure 3. The normalized concentration of different length in horizontal section, Experiment 2. (a),(d),(g)length=30m;(b),(e),(h) length=60m;(c),(f),(i) length=120m

Fig.4 shows the distributions of pollutants concentration of horizontal section at different height. At the low height (z=1.5m) of the 120m length building canyon, the pollutant plume flows across the upstream building and concentrates in the windward side of downstream building. But the situation is quite different in the cases of length=30m and 60m, the plume strides through the edge of the building but not only the top. And the pollutants concentrate more in the leeward of upstream building. To have a better realize of the radioactive pollutants diffusion of different length, the horizontal section at a high height(z=18m) is showed in the Fig.4(g),(h),(i). From the section, in the axis of y=150m, the concentration of length=120m is higher than the other two and it means when the length of building increases to 120m, the radioactive pollutants would mainly stride through the top of the buildings. At the horizontal section of z=9m, it is found that as the length increases, the pollutants concentrate less in the leeward of the downstream buildings.



(a)z=1.5m (b)z=1.5m (c)z=1.5m

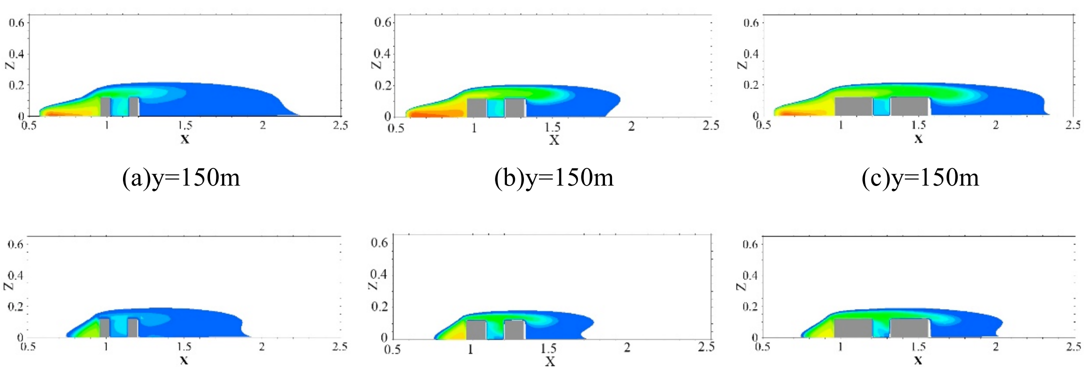
(d)z=9m (e) z=9m (f)z=9m

(g)z=18m (h)z=18m (i)z=18m

Figure 4. The normalized concentration of different length of buildings in horizontal section, Experiment 2. (a),(d),(g)length=30m;(b),(e),(h) length=60m;(c),(f),(i) length=120m

Influence of the Width of Buildings

To examine the effect of different widths, three different kinds of building canyons widths were set as 9m,18m and 36m in the experiment. In Fig.5(a),(b),(c), we can find the cambered concentration distribution curves in the building canyons. The cambered curves are formed by clockwise vortex in the canyon and the pollutants are gathered along the windward side of the downstream building as the pollutants along the leeward side of upstream building are transported by the vortex.



(a)y=150m (b)y=150m (c)y=150m

(d)y=165m (e)y=165m (f)y=165m

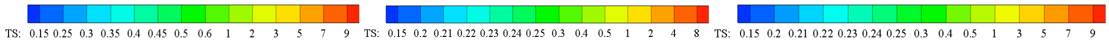
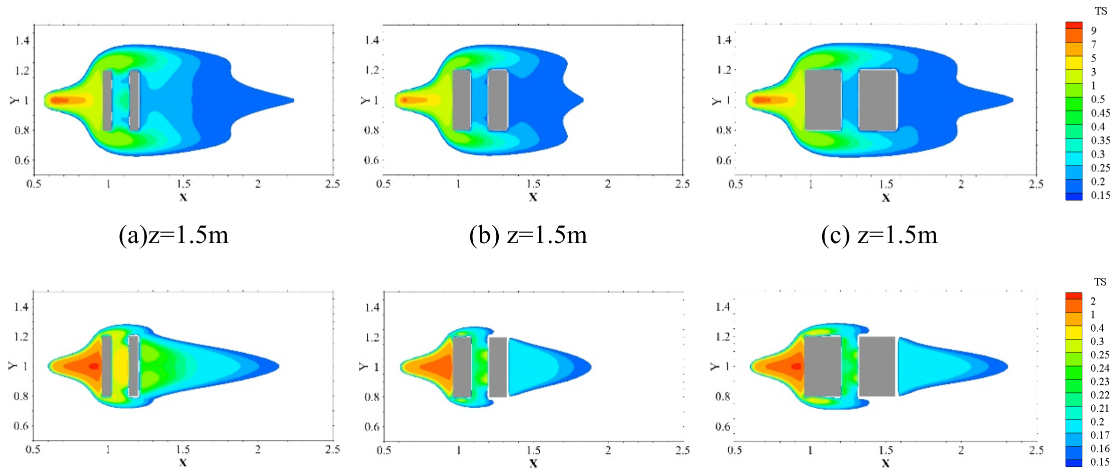


Figure 5. The normalized concentration of different width in horizontal section, Experiment 3. (a),(d) width=9m;(b),(e) width=18m;(c),(f) width=36m

The horizontal distributions of radioactive pollutants concentration are showed in the Fig.6. At the pedestrian breath height level(height=1.5m), the pollutants concentrate around the source position of the width=36m situation while the pollutants disperse along the streams direction of the other two situation. In the building canyon, as the width increases from 9m to 36m, the concentration has a decrease and the biggest concentration level appears in the situation of width=9m. At the level of height=9m, showed in Fig.6(d),(e),(f), it is easily to find the radioactive pollutants concentrate more in the leeward side of downstream building and there formed two independent high concentration range clinging the building. The "twin peaks" shape can be found in the Fig.6 (d),(e),(f). And it can be concluded that the longer the width, the heavier the pollution would happen in the street canyon at pedestrian height level.



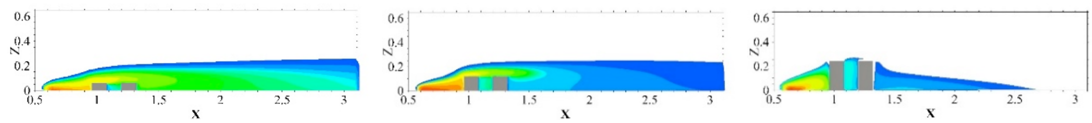
(a)z=1.5m (b) z=1.5m (c) z=1.5m

(d)z=9m (e) z=9m (f) z=9m

Figure 6. The normalized concentration of different width of buildings in horizontal section, Experiment 3. (a),(d) width=9m;(b),(e) width=18m;(c),(f) width=36m

Influence of the Height of Buildings

In this study, the buildings height was set to three different values (9m,18m, and 36m). For the situations of 9m and 18m height, the distribution patterns both have a vortex in the canyon which makes the concentration of the leeward side of upstream building smaller than the concentration near the downstream building. However, the situation of the 36m height is different. From Fig.7(c),(f),(i), the pollutants are trapped in the leeward side of upstream building. That means there is no vortex formed in the canyon to drive the pollutants out of the canyon. For the building height is 36m, the concentration near the ground in the vertical section of y=165m and 180m is higher than the concentration in the y=150m vertical section. But for the situation which buildings height is 18m, the concentration close to the ground in y=150m vertical section is higher than the y=165m section and lower than the y=180m. When the buildings height decrease to 9m, the condition is different again. The concentration of radioactive pollutant near the ground decreases with the increase of the y-direction. The different variation trends of the concentration near the ground depend on the different length-height ratios. When the height is much larger than the length, the pollutant gathered close to the ground in canyon mainly through the gap in the length-direction. On the other hand, when the length is much larger than the height of the buildings, the main way is the pollutant across the buildings in the height-direction.



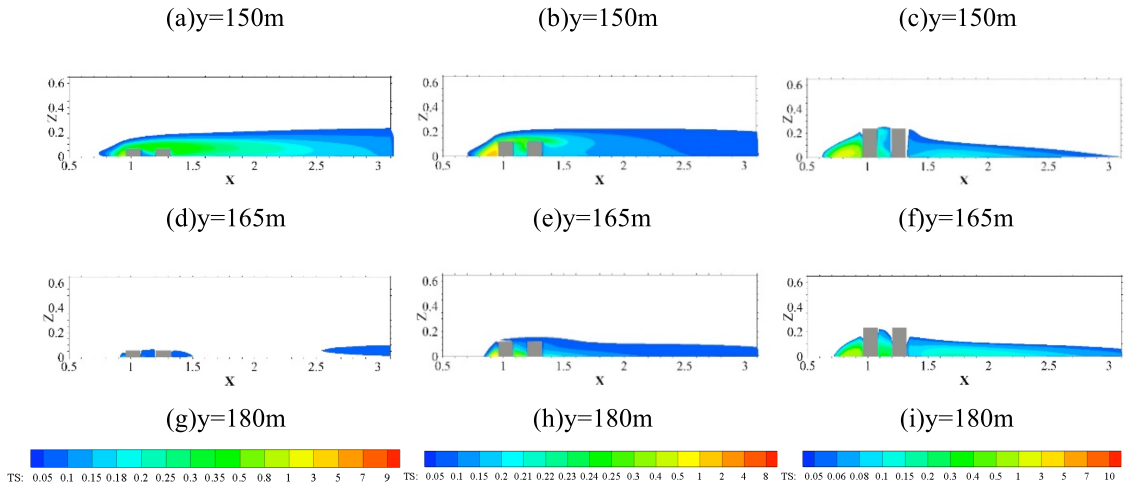


Figure 7. The normalized concentration of different height in horizontal section, Experiment 4. (a),(d),(g)height=9m;(b),(e),(h) height =18m;(c),(f),(i) height =36m

To have a better understand of the effect of buildings height, the horizontal distribution of pollutant concentration is showed in Fig.8. The height level of z=1.5m was chose to represent the breath height of humans. In the building canyon, as the buildings height increases, the radioactive pollutants concentrate less in the middle alone the leeward side of upstream building. And in the leeward side of downstream building, the concentration of the height=9m is much higher than the 36m and the pollutants can diffuse for a long distance with a considerable concentration level.

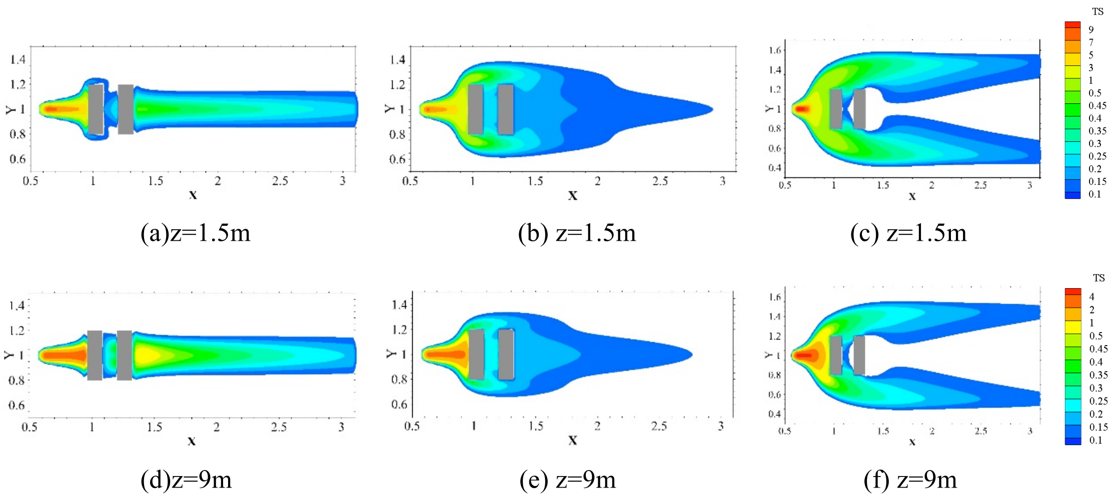
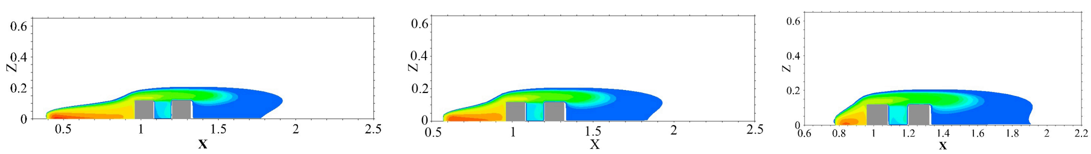


Figure 8. The normalized concentration of different width of buildings in horizontal section, Experiment 4. (a),(d) height=9m;(b),(e) height =18m;(c),(f) height =36m

Influence of the Release Position

The positional relationship of building canyon and release position of radioactive "dirty bomb" has a great effect on the distributions of pollutant concentration, which showed in Fig.9 and Fig.10. From the vertical distributions showed in Fig.9, we can find that no matter where the radioactive "dirty bomb" is, the flow field and the distribution trend is the same basically. There is a clockwise vortex formed in the building canyon and drive the pollutants in the leeward side of the upstream building out of the canyon.



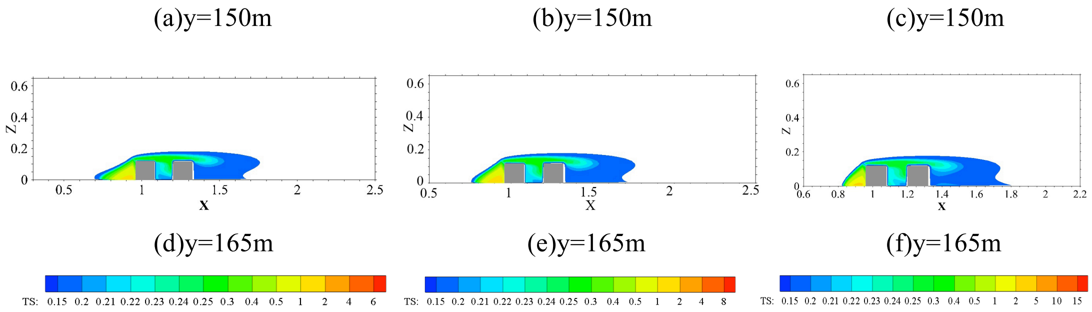


Figure 9. The normalized concentration of different release position in horizontal section, Experiment 4. (a),(d),(g)distance=84m;(b),(e),(h) distance=54m;(c),(f),(i) distance=24m

In the horizontal section at height=1.5m, the distribution trend in the x-y plane can be studied visualized. Between the two buildings, the pollutants concentrate more along the windward side of downstream building and form the “twin peaks” shape close to the downstream building.

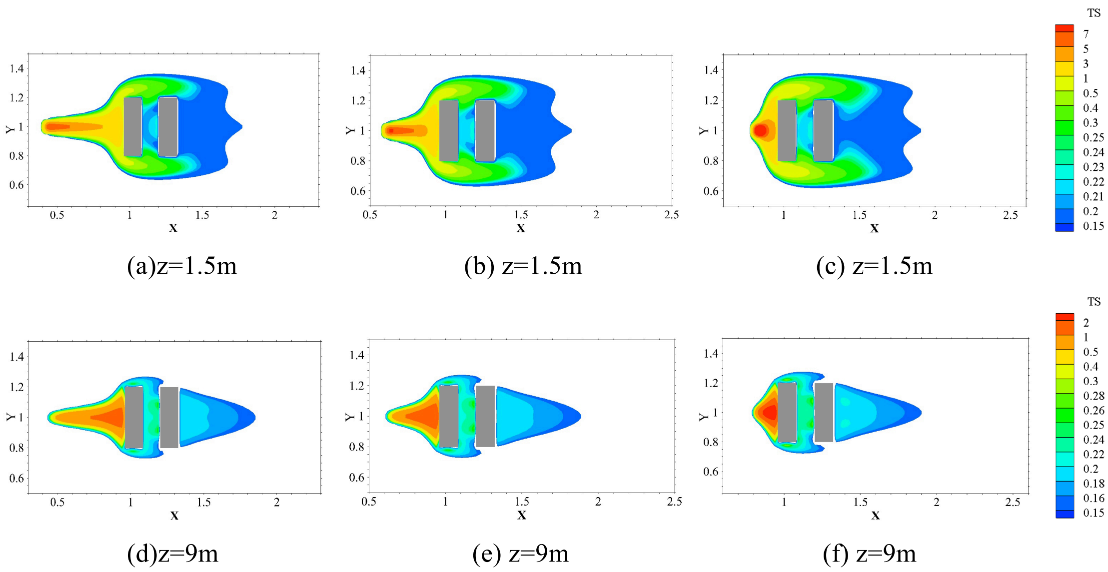


Figure 10. The normalized concentration of different release position in horizontal section, Experiment 5. (a),(d),(g)distance=84m;(b),(e),(h) distance=54m;(c),(f),(i) distance=24m

CONCLUSION

The study mainly investigates the distributions of radioactive pollutants concentration of different buildings configurations, aims to provide the emergency adapting and evasive strategy to ease the radiation effect. After radioactive “dirty bomb” events, under the perpendicular approaching flow, the dispersion of radioactive pollutants will cause a bad effect on human health. The length, width, height of building can signally influence the pollutants concentration level inside the building canyon or behind the canyon. In addition, the amount of buildings and the position relationship of buildings and the source position can also affect the distribution of the concentrations in different ways.

The influence on the dispersion and distributions of radioactive materials has a great importance on the crisis response and management of the nuclear emergency. The information provided by the numerical simulation can be offered for the emergency management to make reasonable evacuation and rescue plan. The experiments are supported by an open source software and can be used as the consequence assessment subsystem to support the emergency decision support system(EDSS).

The radioactive “dirty bomb” event is a small scale pollutants dispersion event, the OpenFOAM can be used as a dependable and convenient numerical computation tool. In further research, multi-scale and transient-state dispersion scenarios are to be investigated to better describe the consequence of the radioactive “dirty bomb” events. Analyzing the effect of the decay and sedimentation of various radionuclides is also a significative research for the crisis response and management of the nuclear terrorists.

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