Nuclear Engineering and Design 416 (2024) 112769

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Autonomous search investigation for radioactive leaked source based on an updated infotaxis method during nuclear emergency rescue

Liwei Chen [a], Cong Zhou [a], Yu Wang [c], Yiran Zong [d], Tingting Lu [c,*], Chunhua Chen [b,*]

[a] School of Computer and Artificial Intelligence, Hefei Normal University, Hefei, Anhui 230601, China
[b] Institute of Nuclear Energy Safety Technology, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei, Anhui 230031, China
[c] Key Laboratory for the Application and Transformation of Traditional Chinese Medicine in the Prevention and Treatment of Major Pulmonary Diseases, Anhui Province, Anhui University of Chinese Medicine, Hefei, Anhui 230012, China
[d] Department of Computer Science, Hong Kong Baptist University, Hong Kong 999077, China

ARTICLE INFO

Keywords:
Off-site decision
Radioactive residues
Autonomous search
Nuclear emergency rescue

ABSTRACT

Identifying leakage locations is one of the key issues for off-site decision workers in nuclear accident conditions, especially for performing early emergency rescue. To rapidly reduce the environmental radiation level of serious accidents in nuclear facilities caused by external events and identify radioactive residues outside containment, an autonomous search method for residue leakage source in nuclear emergency rescue based on the updated Infotaxis method was proposed. It takes into account radioactive decay and wet settlement caused by high-pressure sprinkling or precipitation. The sampling rate function was updated by the radioactive decay term and washing factor in the Infotaxis method, which improves the dilution effect of environmental radiation and provides more accurate entropy information. The search trajectories were investigated under multiple scenarios, such as different source emission rates and wet deposition due to high-pressure sprinklers or precipitation. The results showed that the proposed method could improve search efficiency by adding a washing term, especially for improvement of the success rate in search of leakage source under higher source emission rates, and it helps nuclear emergency decision-makers trace the location of leakage source accurately during the rescue process to provide more scientific information for early emergency response and consequence assessment.

1. Introduction

Radioactive pollutants in airborne form leak from a leakage location and disperse to the environment under nuclear accident conditions, which contaminate the surrounding environment and do harm to human beings (Ghaemi far et al., 2019). Due to unstable radioactive concentrations affected by turbulent effects in the atmospheric environment, many scenarios of radioactive leakage, such as area control of environmental pollutants (Ruan et al., 2021) and postaccident disposal (Chen et al., 2021; Srinivas et al., 2012), have diluted characteristics, making it difficult to identify leakage locations (Vergassola et al., 2007).

To date, two patterns for the release types of radionuclides under nuclear accident conditions, continuous release and instantaneous release, have always been of concern to researchers (Chen et al., 2022). Identifying the location strategies of leakage sources includes static search and mobile search (Hutchinson et al., 2017). Static search is the leakage location of radioactive pollutants estimated by readings of monitors (Kovalets et al., 2018). Some work has been conducted on inversion models based on static search in a ventilated room under nuclear accident conditions (Chen et al., 2022; Hutchinson et al., 2017). The mobile search would sample concentration-related information of radioactive particles while moving to the leakage source location and gradually reach near location of leakage, and it aims to identify leakage location by mobile detectors through analysing sampling information. Compared with static search, mobile search has the characteristics of flexibility, accuracy and lower cost (Ji et al., 2022).

Bioinspired methods are used to identify source locations through mobile search strategies, and they have been widely applied in various engineering fields, such as information biology (Mafra-Neto and Cardé, 1994) and chemical engineering (Hutchinson et al., 2017). Hazardous gas leakage causes environmental damage in the chemical industry, and emergency decision-makers need to quickly estimate the source through mobile detectors based on these methods to assist decision-making (An et al., 2022; Park et al., 2022; Zhao et al., 2020). Bioinspired methods

* Corresponding authors.
E-mail addresses: liwei.chen@hfnu.edu.cn (L. Chen), tingting.lu@ahtcm.edu.cn (T. Lu), chunhua.chen@inest.cas.cn (C. Chen).

https://doi.org/10.1016/j.nucengdes.2023.112769
Received 14 August 2023; Received in revised form 7 November 2023; Accepted 13 November 2023
Available online 20 November 2023
0029-5493/

such as chemotaxis theory are inspired by the behaviour of courtship and foraging of organisms, for instance, the silkworm algorithm (Russell et al., 2003) and zigzag algorithm (Hutchinson et al., 2017). The effectiveness of odorant source identification has been verified by some researchers through experiments and simulations (Vergassola et al., 2007), especially for the stability of the infotaxis algorithm (Siqi et al., 2013). The Infotaxis algorithm based on the information trend uses a detector to identify a leakage location by obtaining uncertainty information in turbulent environments, and this search strategy was adopted in which the number of particle encounters corresponded to a concentration reading (Vergassola et al., 2007), which can update the sampling rate of the source location gradually to effectively prevent local optimization. It can solve the balance between source location search and algorithm solving (Siqi et al., 2013). Some researchers used the infotaxis algorithm to solve engineering problems through updated strategies, such as local probabilistic reliability (Cheng et al., 2016), cognitive differences (Cheng et al., 2018), reward function optimization (Fan et al., 2020), and changing the search path (Sidan et al., 2022), and the advantages of the updated Infotaxis algorithm were validated under different scenarios.

Compared with other environmental disasters, radioactive source leakage under nuclear accident conditions would have impact on human beings environment over a long period of time, such as the Fukushima accidents (Yasutaka and Naito, 2016) and Chernobyl accidents (Steinhauser et al., 2014). In this work, considering radioactive decay and wet deposition due to a high-pressure sprinkler or precipitation (washing effect) during nuclear emergency rescue, an autonomous search based on the Infotaxis algorithm was used to identify the radioactive leakage location caused by an external event, and the sampling rate function was updated by the radioactive decay term and washing term in Infotaxis, which improves the dilution effect of the radiation environment and provides more accurate entropy information. The search trajectories were investigated under multiple scenarios, such as different source emission rate conditions and washing effects. In addition, full trajectories were analysed in detail under no washing and washing, which could intuitively describe the radiation level decrease and search efficiency improvement with the washing effect.

2. Scenario hypothesis

A containment melt-through accident caused by external events was assumed, where the surrounding monitoring equipment failed under the serious nuclear accident due to irradiation damage, and radioactive leakage from a containment was blocked by a blocking suppression team. However, radioactive residues would migrate from containment to the external environment under serious accidents, and the specific source location cannot be identified within a short time, which would still result in continuous emission of radioactive pollutants, as shown in

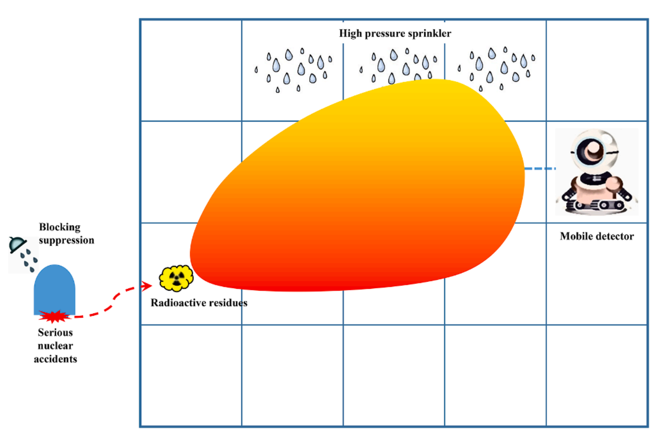

Fig. 1. Description of scenario hypothesis.

Fig. 1. To control radiation levels, nuclear emergency teams would identify leakage source locations by a mobile detector and differentiate contaminated regions accurately as soon as possible under nuclear accident conditions, and decontamination through high-pressure sprinklers would be carried out. Leaked radionuclides, as airborne pollutants, are released into the atmospheric environment and disperse to the surrounding environment. In addition, radioactive residues as the type of point source were assumed in this work, radionuclides would be affected by stable wind direction and airflow, and air was considered incompressible at room temperature. A 2-dimensional mean stationary concentration field was considered, and radioactive decay and deposition were considered to occur during the radionuclide transportation process. To control radiation, which would harm humans, nuclear emergency rescue teams would identify leakage source locations as soon as possible through readings of detectors under accident conditions (as shown in Fig. 1). A source blocking suppression team would use a high pressure sprinkler with resin to decrease radiation levels (Cheng et al., 2022; Ruan et al., 2021) to help the mobile detector search for leakage source based on emission of radioactive residues and block them. In this work, an autonomous search strategy for radioactive leakage location was investigated through a mobile search coupled with washing conditions.

3. Methodology

In this work, an autonomous search method for radioactive leakage source outside of the containment in an atmospheric environment consists of posterior probability modelling and an autonomous search strategy (as shown in Fig. 2), which can help nuclear emergency workers identify leakage source as soon as possible. First, posterior probability modelling is mainly composed of a sampling rate map of radioactive pollutants establishing and calculating the posterior probability of the leakage source. The sampling rate map is updated by the radioactive decay factor and washing factor under accident conditions, which provide more accurate information for calculating the posterior probability of the leakage source. Second, entropy decline for each sample based on calculating the posterior probability of the leakage source is a key point of the autonomous search strategy, and it is an important reference for choosing the next moving position until the search over.

3.1. Posterior probability modelling

Posterior probability modelling is composed of turbulent dispersion modelling, sampling rate updating and posterior probability estimation in an atmospheric environment, which is a key input for an autonomous search strategy.

3.1.1. Turbulent dispersion modelling

Advection-diffusion Eq. (3.1) is adopted to simulate the turbulent dispersion of radionuclides in this work (Vergassola et al., 2007).

$$0 = \boldsymbol{U}\nabla_y C(\boldsymbol{r}|\boldsymbol{r}_0) + \Gamma \Delta C(\boldsymbol{r}|\boldsymbol{r}_0) - \frac{1}{\tau} C(\boldsymbol{r}|\boldsymbol{r}_0) + Q\delta(\boldsymbol{r} - \boldsymbol{r}_0) \quad (3.1)$$

where $\boldsymbol{U}$ (m/s) is the mean wind velocity, $C(\boldsymbol{r}|\boldsymbol{r}_0)$ (kBq/m^2) is the radionuclide concentration at position $\boldsymbol{r}$ when a leakage source is located at $\boldsymbol{r}_0$, Γ is the diffusion coefficient (the sum of the turbulent diffusion term and molecular diffusion term), τ (s^{-1}) is the radioactive particle lifetime, Q (kBq s^{-1}) is the source term at position $\boldsymbol{r}_0$, and δ is an impulse function. In addition, the radioactive particle lifetime is mainly affected by radioactive decay, and it can be equivalent to the radioactive decay factor (Chen et al., 2018).

The human body becomes irradiated due to radioactive pollutant dispersion in the atmospheric environment (Tao et al., 2021). To analyse detailed differences in external irradiation from radioactive plumes with no washing or washing during the nuclear emergency rescue process,

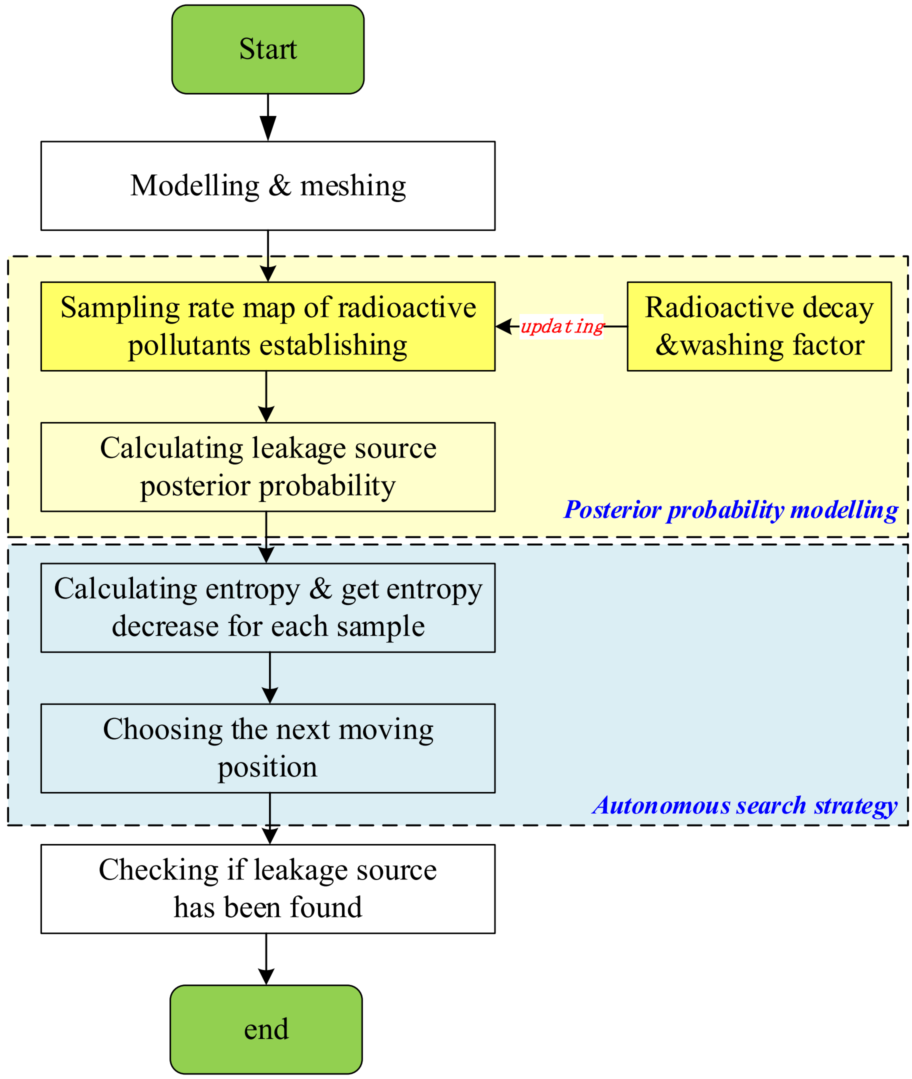

Fig. 2. Simulation procedure of radioactive leakage location identified in atmospheric environment.

the estimation of the dose rate $H_{p\gamma}$ (Sv) can be considered as Eq. (3.2) (Regulation, 2018):

$$H_{p\gamma} = C(\boldsymbol{r}|\boldsymbol{r}_0) \times DCF_{p\gamma} \times SF_{p\gamma} \tag{3.2}$$

where $DCF_{p\gamma}$ ((Sv/Bq·s·m^{-3})$^{-1}$) is the dose conversation coefficient and $SF_{p\gamma}$ (is 1) is the shielding factor.

3.1.2. Radioactive decay effect

Radioactive pollutants decay under nuclear accident conditions during transportation in the atmospheric environment, and the source term Q can be updated in exponential form as follows (Qiang et al., 2014).

$$Q(x) = Q \bullet \exp(-\frac{\lambda x}{U}) \tag{3.3}$$

where λ (s^{-1}) is the radioactive decay.

3.1.3. Washing effect

A radioactive plume is cleaned by a high-pressure sprinkler during source blocking suppression, and the wash coefficient Λ (s^{-1}) is used to express the cleaning capability for radioactive contamination by a high-pressure sprinkler. The source term Q is updated by the wash coefficient under the washing condition as follows (Qiang et al., 2014).

$$Q(x) = Q \bullet \exp(-\frac{\Lambda x}{U}) \tag{3.4}$$

3.1.4. Sampling rate updating

During the sampling process by a detector, the sampling rate $R(\boldsymbol{r}|\boldsymbol{r}_0)$ given by Smoluchowski's arguments (Cheng et al., 2016; Smoluchowski, 1918; Vergassola et al., 2007) expresses the probability of the detector meeting radioactive particles, which is the rate of encounters between a detector and radioactive aerosols. The detector with a spherical shape of radius a was assumed, and the sampling rate equation is as follows (Vergassola et al., 2007).

$$R(\boldsymbol{r}|\boldsymbol{r}_0) = \frac{Q}{ln\frac{L}{a}} e^{\frac{-(y-y_0)U}{2\Gamma}} K_0\left(\frac{|\boldsymbol{r}-\boldsymbol{r}_0|}{L}\right) \tag{3.5}$$

where a is the radius of the detector, K_0 is the modified Bessel function of order zero (Vergassola et al., 2007), $L(=\sqrt{\frac{\Gamma\lambda}{1+\frac{U^2\lambda}{4\Gamma}}})$ is the characteristic length, and λ is the radioactive decay, considered as the airborne radioactive particle lifetime.

Considering radioactive decay and washing effects, the sampling rate Eq. (3.5) can be updated as follows.

$$R_u(\boldsymbol{r}|\boldsymbol{r}_0) = \frac{Q \bullet \exp(-\frac{(\lambda+\Lambda)x}{U})}{ln\frac{L}{a}} e^{\frac{-(y-y_0)U}{2\Gamma}} K_0\left(\frac{|\boldsymbol{r}-\boldsymbol{r}_0|}{L}\right) \tag{3.6}$$

Due to the sampling rate of the radioactive leakage source depending on the distance between the detector and leakage location, the radioactive particles sampled by the detector contain the information of the radioactive source location at $\boldsymbol{r}(t_k)$ along with the trajectories $t = t_k$. Bayesian inference is used to decode information by the detector because of the radionuclide dispersion randomness during transportation in the atmospheric environment. Therefore, the probability graph of the leakage source is established by the posterior probability $P_{t=t_k}(\boldsymbol{r}_0)$ corresponding to the unknown leakage position $\boldsymbol{r}_0$.

3.1.5. Posterior probability estimation

The possibility ($p_{r_0}(T_t)$) of the trajectories T_t at leakage position $\boldsymbol{r}_0$ can be calculated by Eq. (3.7).

$$p_{r_0}(T_t) = \exp\left(-\int_0^t R_u(\boldsymbol{r}(t')|\boldsymbol{r}_0)dt'\right)\prod_{k=1}^{H} R_u(\boldsymbol{r}(t_k)|\boldsymbol{r}_0) \tag{3.7}$$

where H is the number of samples by the detector.

The posterior probability distribution along with the trajectories T_t can be estimated by Eq. (3.8).

$$P_t(\boldsymbol{r}_0) = \frac{p_{r_0}(T_t)}{\int p_x(T_t)dx} = \frac{\exp\left(-\int_0^t R_u(\boldsymbol{r}(t')|\boldsymbol{r}_0)dt'\right)\prod_{k=1}^{H} R_u(\boldsymbol{r}(t_k)|\boldsymbol{r}_0)}{\int \exp\left(-\int_0^t R_u(\boldsymbol{r}(t')|x)dt'\right)\prod_{k=1}^{H} R_u(\boldsymbol{r}(t_k)|x)dx} \tag{3.8}$$

The probability graph at every time step Δt will be updated by Eq. (3.9).

$$P_{t+\Delta t}(\boldsymbol{r}_0) = \frac{P_t(\boldsymbol{r}_0)\exp(-R_u(\boldsymbol{r}(t+\Delta t)|\boldsymbol{r}_0)\Delta t)R_u^N(\boldsymbol{r}(t+\Delta t)|\boldsymbol{r}_0)}{Z_{t+\Delta t}} \tag{3.9}$$

where N is the number of samples by the detector within Δt and $Z_{t+\Delta t}$ is the normalization constant of $P_{t+\Delta t}(\boldsymbol{r}_0)$. In addition, the m-time sampling at position $\boldsymbol{r}$ can be modelled by a Poisson distribution as Eq. (3.10).

$$p_m = \frac{h^m}{m!}e^{-h} \tag{3.10}$$

where the mathematical expectation of sampling numbers is defined by Eq. (3.11).

$$h(\boldsymbol{r}_k) = \Delta t \int P_t(\boldsymbol{r}_0)R_u(\boldsymbol{r}(t_k)|\boldsymbol{r}_0)d\boldsymbol{r}_0 \tag{3.11}$$

In this work, the sensor model of radioactive pollutants was adopted as a binary sensor model (Park et al., 2022).

3.2. Autonomous search strategy

In this work, the level of entropy decline is mainly considered by the autonomous search method based on the information trend strategy, and it selects the next moving location based on the decline level of entropy.

3.2.1. Information trend strategy

In information theory, entropy is used to measure uncertainty of information. The level of entropy decline at each time step is used to determine the direction of the leakage source in this work, and the entropy corresponding to $P_t(\boldsymbol{r}_0)$ at time t can be expressed as follows.

$$S(P_t) = -\sum_r P_t(\boldsymbol{r}_0)logP_t(\boldsymbol{r}_0) \tag{3.12}$$

3.2.2. Decision-making for mobile control

The next moving direction of the detector was controlled by choosing the maximum level of entropy decline, and the move action set of the detector included forward, back, left, right, and stay.

The level of entropy decline can be calculated by Eq. (3.13) when the detector moves from $\boldsymbol{r}$ to $\boldsymbol{r}_s$.

$$\overline{\Delta S}(\boldsymbol{r}\rightarrow\boldsymbol{r}_s)) = P_t(\boldsymbol{r}_s)[-S(P_t)] + (1-P_t(\boldsymbol{r}_s))\sum_{m=0}^{\infty} p_m(\boldsymbol{r}_s)\Delta S_m \tag{3.13}$$

The first term ($P_t(\boldsymbol{r}_s)[-S(P_t)]$) on the right side of Eq. (3.13) indicates that the leakage source has been found, the posterior probability $P_t(\boldsymbol{r}_s)$ has been obtained and $P_{t+\Delta t}$ at the next shift position would be an impulse function at the next time step, so the entropy $S(P_t) = 0$.

The second term ($(1-P_t(\boldsymbol{r}_s))\sum_{m=0}^{\infty}p_m(\boldsymbol{r}_s)\Delta S_m$) of the right side of Eq. (3.13) indicates that the level of entropy decline would be estimated under the leakage source not found. ΔS_m is the difference in the entropy between $P_{t+\Delta t}$ and P_t.

4. Analysis of the accuracy and reliability of the proposed method

Due to harmfulness of radiation, it is difficult to validate the proposed method experimentally. The dispersion of airborne radionuclides has similar characteristics to other airborne pollutant dispersions in the atmospheric environment. Moreover, the original Infotaxis algorithm has been widely developed and validated through other engineering fields, such as chemical engineering, biological engineering, and environmental engineering. For example, the accuracy and reliability of odorant source identification has been verified by Vergassola et al.'s work by both experiments and simulations (Vergassola et al., 2007). An RRT-Infotaxis method as an updated Infotaxis method was developed and validated by Seulbi An's work, which was used to simulate hazardous gas leakage location estimation (An et al., 2022).

Based on the original Infotaxis algorithm, in the sampling rate Eq. (3.5), L as the characteristic length is considered as the dispersion distance of the airborne radioactive particles from the source leakage location to disappear, which is an important factor for establishing the sampling rate map (Siqi et al., 2013). In Eq. (3.6), the sampling rate Eq. (3.5) is updated by radioactive decay and washing factors to enhance the average dilution effect of the sampling rate map and improve search efficiency, especially for higher source emission rates. In addition, even though the sampling rate Eq. (3.5) was updated by radioactive decay and washing factors in Infotaxis, the search strategy in Section 3.2 is not changed in the proposed method to ensure reliability. To validate the performance of the proposed method, various scenario descriptions are simulated in Section 5.

5. Numerical simulation

5.1. Simulation configuration

Some preparatory work must be illustrated and explained before the simulation is performed. The code of Infotaxis was updated based on Vergassola's work with the Python 3.7 platform (Vergassola et al., 2007), and a module of radioactive decay and washing factor was added and compiled. A 2000 m × 1000 m area was modelled and meshed uniformly by approximately 5000 grids in this work (as shown in Fig. 3). The continuous and stable leakage source of ^{131}I was assumed at the coordinates of (100, 200) corresponding to the black star, and the dose conversion coefficient and radioactive decay factor of ^{131}I were 1.6 × 10^{-14} and 8.02d, respectively. Considering different leakage accident levels, the different source emission rates were assumed to be 1 kBq·s^{-1}, 5 kBq·s^{-1}, 10 kBq·s^{-1}, 25 kBq·s^{-1}, 35 kBq·s^{-1} and 40 kBq·s^{-1}. Searching by a gamma detector, sampling radioactive aerosols (Marques et al., 2021), initiated at the point (1900, 900), corresponding to the brown circle, and the speed of the detector was 10 m·s^{-1}. Considering the early phase of accident (Regulation, 2018), the maximum search time of 3600 s was considered as the search source failure, and the time step was set to 1 s. The wind speed is 1 m·s^{-1}, and the diffusion coefficient for radioactive pollutants in the atmospheric environment was assumed to be 50 (m^2·s^{-1}).

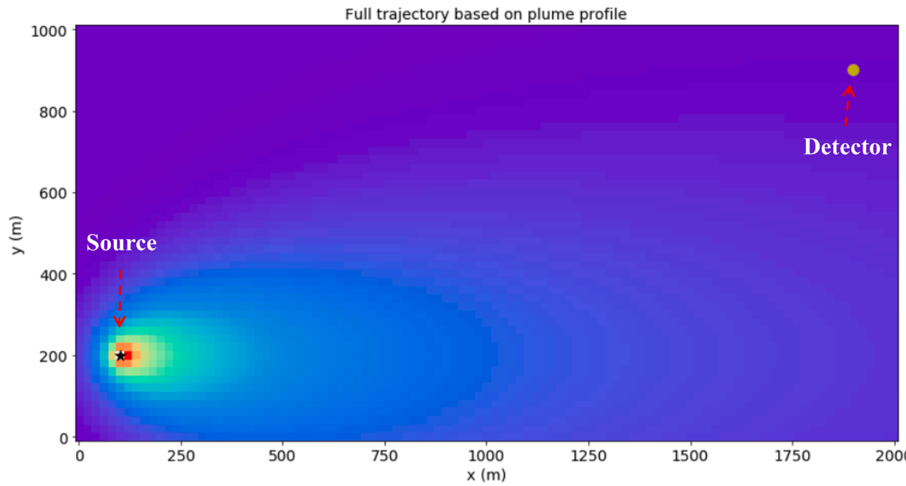

Fig. 3. ^{131}I dispersion in an atmospheric environment under leakage accident conditions.

5.2. Results and discussion

5.2.1. Moving trajectory based on radioactive plume profile considering decay

Fig. 4 shows the moving trajectory of the detector for searching leakage source considering decay with no washing effect based on the radioactive plume profile at 6 time intervals under $Q = 1$ kBq·s^{-1}. The probability graph of the leakage source was visualized as a 'rainbow' of colours, where red and blue indicate maximum and minimum probabilities, respectively. The black star is the radioactive leakage source, the brown circle is the detector, and the blue points on the white line indicate records for the moving trajectory for each sampling. The same probabilities for each grid were set based on a uniform distribution at the start of the search in the calculated domain (as shown in Fig. 4(a)), and the detector moved from the starting position to the next moving position by choosing the direction with the maximum level of entropy decline, which means that most information about radioactive aerosols can be obtained by sampling at the next moving position. From Fig. 4 (b)

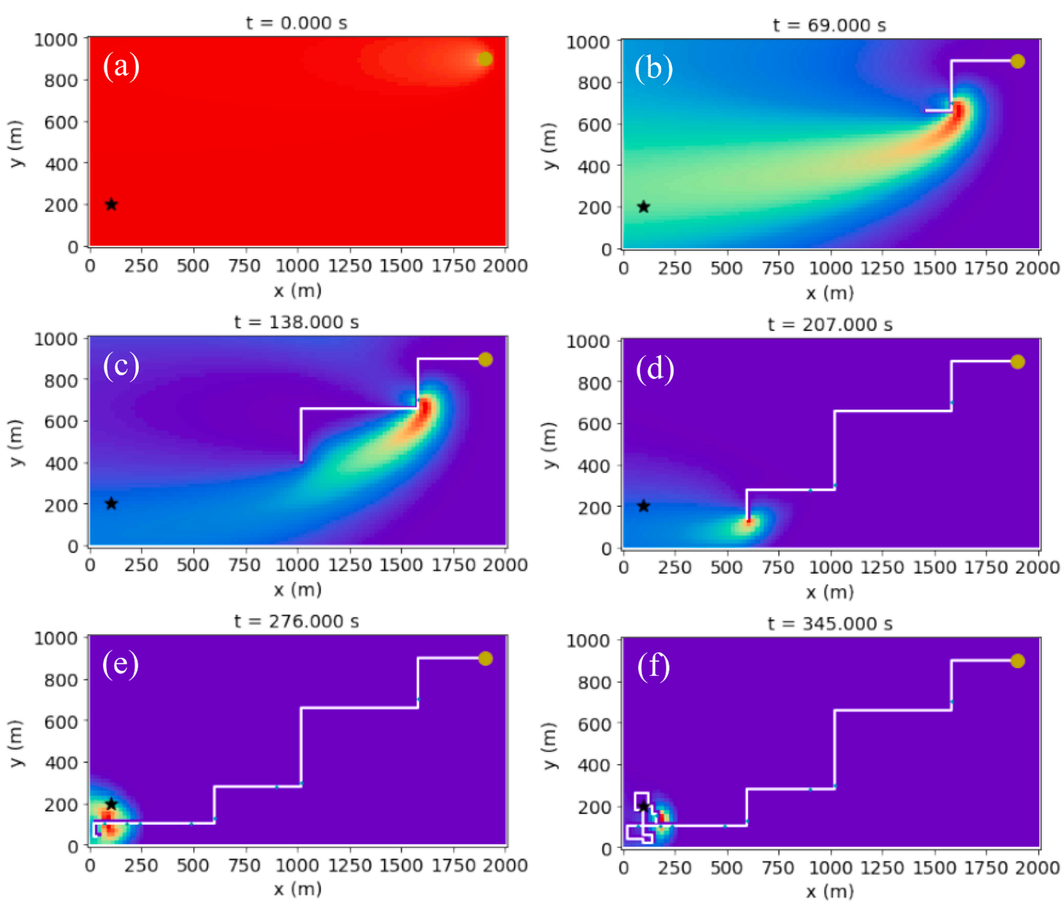

Fig. 4. Moving trajectory considering decay with no washing conditions at 6 time intervals under $Q = 1$ kBq·s^{-1}. (a) $t = 0$ s; (b) $t = 69$ s; (c) $t = 138$ s; (d) $t = 207$ s; (e) $t = 276$ s; (f) $t = 345$ s.

to Fig. 4 (f), the detector moves to the position of higher probability for each sampling corresponding to the red region and gradually approaches the leakage source until the source has been found.

Particle lifetime is a key factor in establishing a probability graph for sampling, and it means that the shorter the particle lifetime is, the more significant the dilution effect. Due to the long lifetime of ^{131}I, the radioactive decay factor is very small (approximately $1x10^{-6}$ s), and it is not significant for improving the dilution effect of the probability graph for sampling and identifying the location of radioactive radiation when only considering radioactive decay. However, the radioactive decay effect cannot be ignored during the dispersion process. Therefore, a combination effect of washing and radioactive decay was considered in Sections 5.2.2 and 5.2.3.

5.2.2. External exposure dose rate under the different source emission rates between no washing and washing considering decay

Considering the external exposure dose rate difference under the different source emission rates between no washing and washing considering decay during radioactive source suppression. Fig. 5 illustrates the radiation dose rate difference of ^{131}I for the public between no washing and washing considering decay. The differences in the mean dose rate and maximum dose rate are described by the red line and blue line, respectively. The differences in the dose rates of the mean dose rate and maximum dose rate obviously increase as the radioactive source emission rate increases by washing, which means that the radioactive concentration in the calculated domain is diluted by the washing effect. This means that the ^{131}I concentration in the calculated domain was diluted by the washing effect. In addition, the greater the release rate is, the better the dilution effect, which would improve the dilution effect of the probability graph for sampling to help a detector trace the radioactive source location, as described in Section 5.2.3.

5.2.3. Full trajectories under the different source emission rates between no washing and washing considering decay

To describe in detail the difference in the search efficiency of the detector between no washing and washing considering decay, full trajectories of the detector under the different source emission rates are illustrated in Fig. 6, which is composed of 12 subfigures. The left side and the right side of Fig. 6 show ^{131}I release from the leakage point to the environment with no washing or washing considering decay, respectively.

From Fig. 6, compared with no washing, the area of the radioactive plume was weakened by washing, and the dilution effect of the radioactive concentration improved, especially for the source emission rate, which increased gradually. Due to the autonomous search strategy based on the information trend sensitive to the dilution environment, the leakage point would be easier to identify by the detector near the radioactive leakage location under the washing effect to reduce the redundancy of the search paths, which means that the dilution effect would be improved by the washing effect, with the source emission rate increasing gradually under nuclear accident conditions, which could improve the search efficiency. Therefore, radioactive leakage location can be identified through a mobile detector coupled with washing measures during nuclear emergency rescue.

To intuitively analyse the search efficiency with the washing effect, Table 1 shows a quantitative assessment of the search efficiency corresponding to different source emission rates. The search efficiency was obviously improved by the washing effect, with the source emission rate increasing gradually, especially for $Q = 35$ kBq·s^{-1} and $Q = 40$ kBq·s^{-1}. In addition, compared with the search success rate under the washing effect, the leakage location was not found by searching the detector under no washing effect within 3600 s at $Q = 40$ kBqs$^{-1,}$ corresponding to Fig. 6(f-1) and the last line in Table 1, which means that the washing effect could help emergency rescue teams improve leakage source searching under nuclear accident conditions.

From Fig. 5, Fig. 6 and Table 1, the autonomous search strategy based on the Infotaxis method coupled with the washing factor not only reduces the radiation dose rate but also improves the search efficiency and search success rate of the leakage source under source suppression conditions.

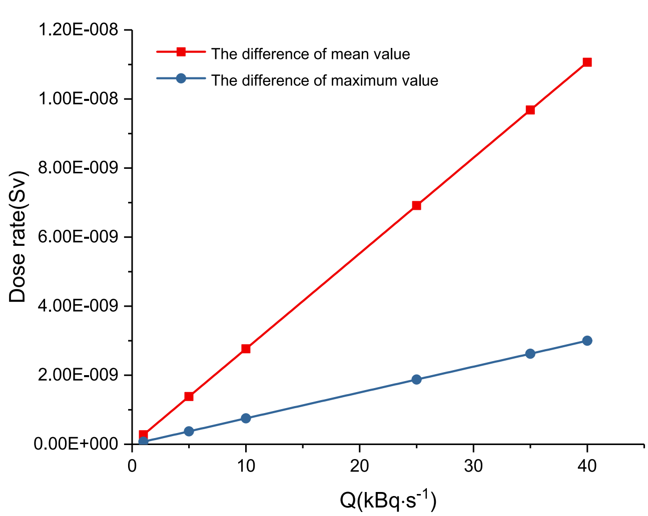

Fig. 5. Dose rate differences of ^{131}I under the different source emission rates between no washing and washing considering decay.

6. Conclusions

In this work, an autonomous search method based on Infotaxis coupled with a washing factor considering decay was established outside of the containment in an atmospheric environment under nuclear accident conditions. The radioactive leakage source location could be identified using the entropy decline trend of radioactive particle sampling based on the updated Infotaxis method. Three patterns are observed: (1) the detector moves from the start position to the leakage source gradually based on the entropy decline strategy until the source has been found; (2) the dilution effect is improved by the washing effect, with the source emission rate increasing gradually during nuclear emergency rescue, which could improve the search efficiency; and (3) the Infotaxis method updated by the washing factor improves the success rate of leakage source search under nuclear accident conditions, which means that radioactive residues can be identified more accurately through the Infotaxis method coupled with a high-pressure sprinkler.

Because the radioactive leakage source identified is affected by multiple factors, such as the wind field, source emission rate, and detector moving speed, a reasonable selection of multiple parameters is one of the key technologies of the autonomous search method. Based on the updated Infotaxis method, different scenarios will be investigated in future work, such as the uncertain leakage height, multipoint radioactive leakage identification, source suppression during nuclear emergency rescue and searching for regional radioactive leakage source during postdisposal after nuclear accidents, especially with uncertain leakage height. For example, if the detector height is lower than the leakage height, the nearest location below the leakage point can be identified by the proposed method; then, whether it is possible to establish a sampling rate map on the vertical plane and identify leakage location gradually is the next key point of our work. This will provide more accurate information about radioactive leakage source locations under nuclear accident conditions and will help emergency decision-makers make reasonable decisions based on the autonomous search of leakage location.

CRediT authorship contribution statement

Liwei Chen: Investigation, Conceptualization, Methodology,

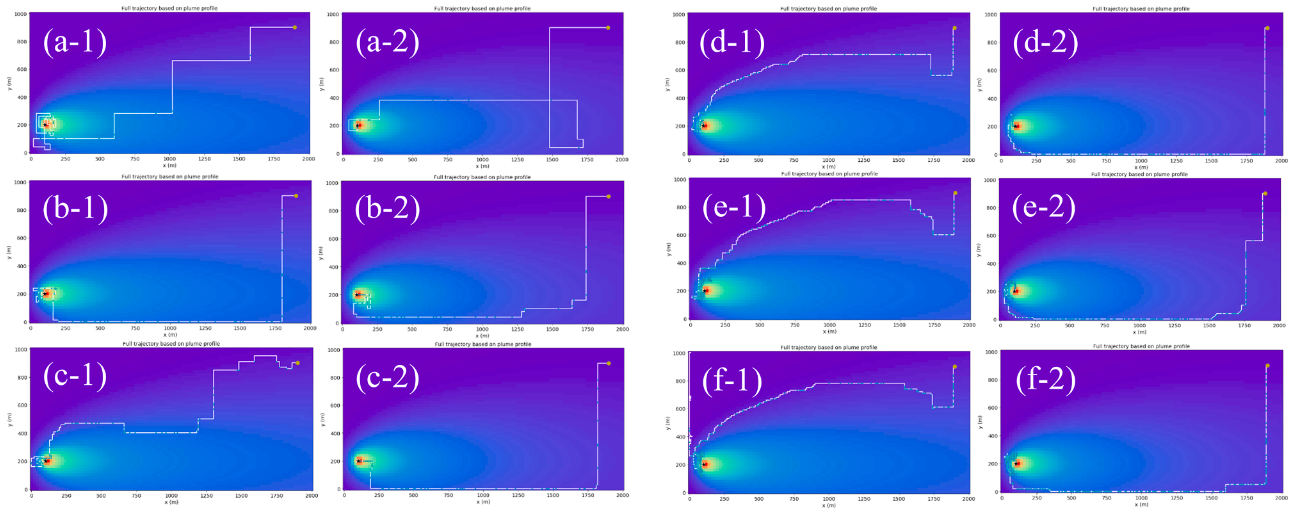

Fig. 6. Full trajectory at different emission rates between no washing and washing considering decay. (a) $Q = 1$ kBq·s^{-1}; (b) $Q = 5$ kBq·s^{-1}; (c) $Q = 10$ kBq·s^{-1}; (d) $Q = 25$ kBq·s^{-1}; (e)$Q = 35$ kBq·s^{-1}; (f)$Q = 40$ kBq·s^{-1}.

Table 1
Quantitative assessment of searching efficiency under the different source emission rates.

Source emission rate Q (kBq·s^{-1})	Search time with no washing (s)	Search time with washing (s)	Search efficiency improvement (s)
1	418	386	**32**
5	338	322	**16**
10	330	292	**38**
25	358	344	**14**
35	2289	993	**1296**
40	***Not found***	1959	∞

Software, Data curation, Writing – original draft, Funding acquisition. **Cong Zhou:** Software, Data curation. **Yu Wang:** Investigation. **Yiran Zong:** Investigation, Visualization. **Tingting Lu:** Project administration, Funding acquisition. **Chunhua Chen:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (82104454), Natural Science Foundation of Anhui Province (2108085QH376), Outstanding Talent Support Program in University of Anhui Province (gxyq2022060), Project of Hefei Normal University Student Innovation and Entrepreneurship Training Program (14098154), Anhui University of Chinese Medicine 2021 First Batch of High-level Talents Support Program (2021rcyb009), New Era Education Quality Project of Anhui Provincial Department of Education (Post-graduate Education) (2022xscx105), Anhui University Graduate Scientific Research Program (YJS20210482), and National Innovation and Entrepreneurship Training Program for College Students (202110369041).

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