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Study on Robot Search Gas Leakage Source by Entropy and Its Simulation

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Abstract: In this study, a new search strategy of robot for the gas leakage source is proposed. The searching algorithm based on information entropy and upwind information, is established by analyzing the link between the gas leakage source searching and obtaining information. This search strategy can improve the efficiency of global search by changing entropy mode and upwind search mode adaptively. The structure of the information entropy search algorithm is analyzed. The flow field distribution and concentration information is got by CFD simulation. The robot search gas leakage source simulation platform is established by combining the CFD with Matlab. The proposed search algorithms are simulated with different search conditions. The results of simulation indicate that information entropy combined with the upwind search strategy can improve the search efficiency and can be used in the actual gas leakage source search by robot.

Key words: Information entropy, gas leakage, localization, simulation

INTRODUCTION

With the development of the petrochemical industry, the leak detection and repair of the various types of chemical reaction vessel and pipeline have become an important guarantee of the petrochemical industry to avoid accidents. There are two kinds of detection and localization of the gas leakage source by traditional methods, one is to detect by person with a handheld portable detector to find the gas leakage source and the other is to detect the leakage gas by installing the distributed gas sensors or fixed gas detectors network. However, traditional detecting methods have some disadvantages, such as personal security risks, complicated wiring, higher network maintenance cost and so on. The mobile robot has fast scheduling arrangement, easy maintenance and long working hours (Zhang, 2009). Considering the characteristics of the mobile robot, robot can achieve the chemical industry gas detection.

The localization of gas leakage source by robot is interested by many researchers. Rozas *et al.* (1991) used the artificial nose to study the olfactory navigation. Lilienthal *et al.* (2003) and Lilienthal and Duckett (2003) proposed an odor source localization method by a gas concentration raster map. Ishida *et al.* (1994, 2006) studied a localization method by integrating the visual and olfactory information. Farrell *et al.* (2003, 2005 and Pang and Farrell, 2006) carried out the odor source localization by multi-robot systems within the non-wind environment. Kowadlo *et al.* (2006) used visual information of leakage crack as secondary information, to localize the gas leakage source by olfactory information. Meng *et al.* (2008) proposed an evolution gradient search algorithm for multi-robot and validated it by simulation and the result indicated the algorithm can be used to localize the odor source in time-varying gaseous fluid environment.

In this study, a new search strategy of robot for the gas leakage source is proposed. The searching algorithm based on the entropy is established by analyzing the link between the gas source searching and obtaining information. A search strategy for gas leakage source, which combine the information entropy and upwind information, is proposed. The simulation platform is established by combining the CFD with Matlab. The search strategy is simulated and the efficiency of strategy is studied in this study.

ROBOT'S INFORMATION ENTROPY SEARCH STRATEGY

Information entropy is used to describe the amount of information, which can be calculated as follows:

$$S = -\int P(x)\log P(x)dx \quad (1)$$

where, p (x) is the probability distribution function of the gas leakage source position and S is the size of the information entropy. The Eq. 1 illustrates the information entropy is a variables function of probability and indicates that higher uncertainty of the variables and greater the information entropy.

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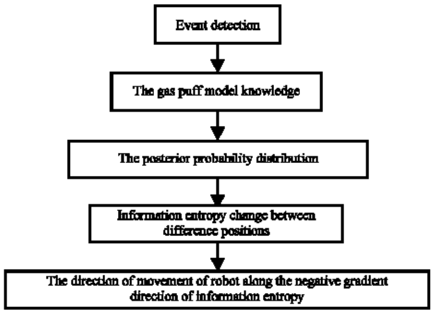

Fig. 1: Structure of information entropy searching algorithm

Information entropy algorithm: Robot detected information will be changed, when it is in different positions, so the size of the information entropy should be changed. Therefore, the direction of movement of robot can be determined by the gradient of the information entropy.

The basic structure of information entropy algorithm is shown as Fig. 1. The first step is to detect the gas information in environment and this step is called 'Event Detection'; the second step is get the gas puff model knowledge; the third step is to establish the posterior probability distribution of the gas leakage source by using of Bayesian reasoning method; With the information accumulation, the probability map is renewed and information entropy should be changed, therefore, the fourth step is to calculate information entropy change between different positions; The final step is to determine the movement direction of robot.

The amount of information is the maximum and the value of information entropy is the minimum, in the gas leakage source position. Therefore, the direction of movement of robot should along the negative gradient direction of information entropy.

In robot local search, the robot tracks the puff, predicts the detect trends and the direction of robot motion by updated information. The local search process is as shown in Fig. 2, robot moves according to the path, which has around the four cardinal points from the current position. By comparing information entropy of current position and the other four positions, to find the maximum reduction of the information entropy position and let robot move to the position.

Mesh the search environment: The robot working environment can be meshed as limited grids, each grid, which stored the existence of the gas leakage source information, represent part of the environment. The definition of the search space is a rectangular area, which is meshed into m*n grids, shown in Fig. 3. The dimension

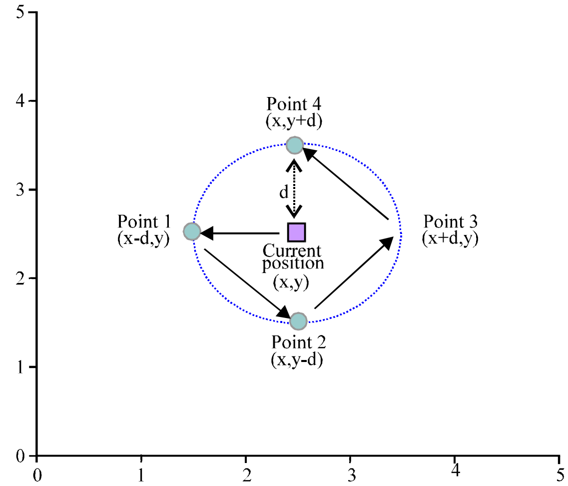

Fig. 2: Traversal sequence of local search

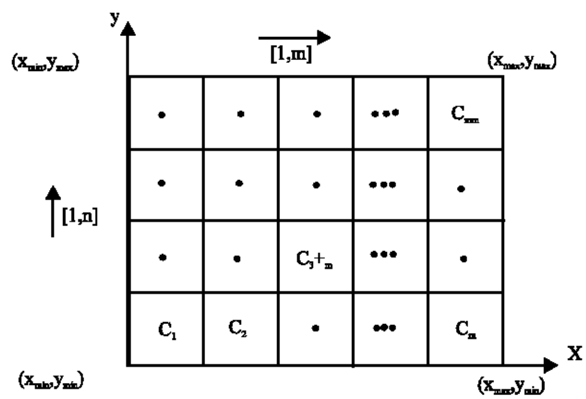

Fig. 3: Grid division of region to be searched

of grid is expressed as d*d and the size of the robot local search can be adjusted by changing the value of d to improve the search efficiency.

The set of grids is defined as $C = [C_1,..., C_M]$ $(M = mn)$ and the set can include the entire search environment. Aϵ is the coordinates of the sequence number in x axial direction and aϵ[1, m] is the coordinates of the sequence number in y axial direction.

The exact position of robot can be determined by calculating the subscript of the grid. The number of the grids can also be calculated by $i = a+(b-1)^m$ and the mapping relationship between I and (a, b) are as follows:

$$a\,(i) = \mathrm{rem}\,(i-1, m)+1 \tag{2}$$

$$b\,(i) = \mathrm{int}\,(i-1, m)+1 \tag{3}$$

The probability of the gas leakage source in grid C_i can be expressed as $0 \le \pi_i \le 1$ and the vector $\pi = [\pi_1,...,\pi_M]$

is an unknown constant. If assuming to only exist a gas leakage source in the search area, then:

$$\sum_{i=1}^{M}\pi_i = 1$$

If there is no priori information about the gas leakage source, each grid has the equal probability of the gas leakage source and the initialized vector π should be a uniform value π_i = 1/M; If there is priori information of the gas leakage source in grid C_i, M can be transformed into a matrix of n*m according to the initialized vector π and priori information. This matrix can be considered as the probability map of the gas leakage source.

Probability map of the gas leakage source position: The puff, which is composed together by countless puff, is affected by the turbulent diffusion and convection, therefore, the movement of the puff can be considered as a random fluctuation with downstream movement superimposed. In two dimension environment, the plume movement formula can be expressed as Eq. 8:

$$\dot{X}(t) = U(X, t) + N(t) \tag{4}$$

where, X is the position of the plume, U = (u_x, u_y) is the average velocity of the plume, N = (n_x, n_y) is a random process, the expectation is (0, 0) and the variance is (σ^2_x, σ^2_y).

Single puff analysis: Suppose that in t_l moment, the gas leakage source located in X_s = (x_s, y_s) only release a puff and at t_k = (t_k, t_t) moment, the position of puff on the spatial and temporal distribution can be got by integrating Eq. 4:

$$X(t_1, t_k) = \int_{t_1}^{t_k} U(X(\tau))d\tau + \int_{t_1}^{t_k} N(\tau)d\tau + X_S \tag{5}$$

The average position of the plume in t_k moment is

$$\bar{X}(t_1, t_k) = \int_{t_1}^{t_k} U(X(\tau))d\tau + X_S$$

Assume the random process is Gaussian type and to definite as follow:

$$W(t_1, t_k) = \int_{t_1}^{t_k} N(\tau)d\tau \tag{6}$$

where, the expectation is (0, 0) and the variance is $[(t_k - t_1)\sigma_x^2, (t_k - t_1)\sigma_y^2]$, wherein the variance and t_k-t_t is a linear relationship.

Therefore, at t_k moment, the expectation of X (t_t-t_k) position of the puff is $\bar{X}(t_1, t_k)$ and the variance is:

$$[(t_k - t_1)\sigma_x^2, (t_k - t_1)\sigma_y^2]$$

The robot search gas leakage source process is an inverse problem comparing with above described in this study. Considering the mounting position of the gas sensors in robot is fixed, therefore, at t_t moment, when the gas sensors detect the puff, the position of puff (X (t_t, t_t)) can be represented by the position of robot (X_v (t_t)). And the position of the gas leakage source can be deduced by Eq. 5:

$$X_S(t_1, t_k) = X_v(t_k) - \int_{t_1}^{t_k} U(X(\tau))d\tau - \int_{t_1}^{t_k} N(\tau)d\tau \tag{7}$$

Using the center of the grid X_j is to represent the position of the grid V (t_t, t_k). When the robot is located in grid W (t_t, t_k), then the position of robot can be described as (0, 0).

Taking into account delay of the gas sensor, the robot can only collected at discrete time points $\{t_i\}_{i=0}^{k}$, so the approximate considering:

$$\int_{t_1}^{t_k} U(X(\tau))d\tau \approx \sum_{i=1}^{k-1} U(X_v(t_i))dt$$

Make: $V(t_1, t_k) = (v_x(t_1, t_k), v_y(t_1, t_k)) = \sum_{i=1}^{k-1} U(X_v(t_i))dt$ and then substitute into Eq. 6:

$$X_S(t_1, t_k) = X_j - V(t_1, t_k) - W(t_1, t_k) \tag{8}$$

where, X_j-V (t_1, t_k) is a calculated variable, X_j can be got by calculating the robot's current position V (t_1, t_k) can be got by calculating the velocity data, W(t_1, t_k) is a Gaussian random variable and its expectations for (0, 0).

Therefore, X_s (t_1, t_k) is a Gaussian random variable and its expectation for X_s-V(t_1, t_k) and its variance for (t_{kl}, t_t))σ^2.

The probability density distribution function of W(t_1, t_k) can be obtained as follows:

$$f(w_y(t_1, t_k)) = \frac{e^{-\frac{w_y^2}{2(t_k - t_1)\sigma_y^2}}}{\sqrt{2\pi(t_k - t_1)\sigma_y^2}} \tag{9}$$

$$f(w_x(t_1, t_k)) = \frac{e^{-\frac{w_x^2}{2(t_k - t_1)\sigma_x^2}}}{\sqrt{2\pi(t_k - t_1)\sigma_x^2}} \tag{10}$$

Respectively, the useful information can be obtained by "detected event" and "not detected event "during establishing the probability map of the gas leakage source:

- **"Detected event" means the robot obtains the leakage gas information:** If robot locates inside the grid C_j and detects the gas leakage source release a single puff at t_t moment, then, the probability of gas leakage source locating in grid C_j can be expressed as P_{ij} (t_l, t_k), which is obtained by Eq. 6-8, as follows:

$$\begin{aligned}P_{ij}(t_l,t_k) &= \int_{x\in C_i} \frac{e^{-\frac{(x_j-v_x(t_l,t_k)-x)^2}{2(t_k-t_l)\sigma_x^2}}}{\sqrt{2\pi(t_k-t_l)\sigma_x^2}}dx \times \int_{y\in C_i} \frac{e^{-\frac{(y_j-v_y(t_l,t_k)-y)^2}{2(t_k-t_l)\sigma_y^2}}}{\sqrt{2\pi(t_k-t_l)\sigma_y^2}}dy \\ &= \int_{x_i-\frac{d}{2}}^{x_i+\frac{d}{2}} \frac{e^{-\frac{(x_j-v_x(t_l,t_k)-x)^2}{2(t_k-t_l)\sigma_x^2}}}{\sqrt{2\pi(t_k-t_l)\sigma_x^2}}dx \times \int_{y_i-\frac{d}{2}}^{y_i+\frac{d}{2}} \frac{e^{-\frac{(y_j-v_y(t_l,t_k)-y)^2}{2(t_k-t_l)\sigma_y^2}}}{\sqrt{2\pi(t_k-t_l)\sigma_y^2}}dy \\ &= \frac{1}{2\pi(t_k-t_l)\sigma_x\sigma_y}\int_{-\frac{d}{2}}^{\frac{d}{2}} e^{-\frac{(x_j-x_i-v_x(t_l,t_k)-x)^2}{2(t_k-t_l)\sigma_x^2}}dx \times \int_{-\frac{d}{2}}^{\frac{d}{2}} e^{-\frac{(y_j-y_i-v_y(t_l,t_k)-y)^2}{2(t_k-t_l)\sigma_y^2}}dy\end{aligned} \tag{11}$$

where, P_{ij} (t_l, t_j) is a function about grid C_i and C_j.

The probability map of the gas leakage source can be established by calculating the probability of all the grids, as $\{P_{ij}(t_l,t_k)\}_{i=1}^{M}$:

- **"undetected event" means the robot does not obtain the leakage gas information:** If robot locates inside the grid C_j and doesn't detect the puff at t_k moment, then, the probability of the gas leakage source reduces in adjacent positions. Here, μ presents the gas sensor detecting puff's probability, which determined by the sensor's inherent characteristics. At time t_k, the gas leakage source releases a puff; the detecting probability is μP_{ij} (t_l, t_k) at grid C_j, while the undetected probability is 1 μ P_{ij} (t_l, t_k) . Therefore, $\{1-\mu P_{ij}(t_l,t_k)\}_{j=1}^{M}$ can be established the undetected probability map

Continuous leaking puff analysis: The gas leakage source does not only release a single gas puff but a continuous leaking puff. In this study, the probability map with continuous leaking puff condition is established according to single leaking puff.

If the gas leakage source releases the continuous puff within t∈ $[t_0, t_k)$, then, F = N $(t_{k-1}-t_0)$ (while N is the releasing rate of the gas leakage source) puff exists in air. The gas leakage source releasing time is unknown but the releasing time should be earlier than the robot searching time, the detected puff can't be known the releasing time, when the robot detects it at t_k moment in grid C_j. However, the gas leakage source probability map still can be established by detected event and undetected event.

- **Detected event:** To assume the gas leakage source releases continuous puff at t_0. Considering all the possible releasing time t_l, the robot detects puff at t_k in grid C_j, the probability of gas leakage source in grid C_j can be expressed as β_{ij} (t_0, t_k), as following:

$$\beta_{ij}(t_0,t_k) = \frac{1}{k}\sum_{l=0}^{k-1} P_{ij}(t_l,t_k) \tag{12}$$

The probability map of the gas leakage source can be got by calculating $\{\beta_{ij}(t_0,t_k)\}_{i=1}^{M}$:

- **Undetected event:** When the gas leakage source at C_i grid releases the puff continuously, Considering all releasing time t_l∈$[t_0, t_k)$, the undetected probability at t_k in grid C_j can be calculated as following:

$$\gamma_{ij}(t_0,t_k) = \prod_{l=0}^{k-1}[1-\mu P_{ij}(t_l,t_k)] \tag{13}$$

By calculating $\{\gamma_{ij}(t_0,t_k)\}_{j=1}^{M}$, the undetected probability map of robot at t_k in grid C_j can be got.

The search path of robot can be constructed by detecting information at different time and position. This search path, which contains the gas leakage source information, will be regard as the signal to send robot from the gas leakage source. This signal is input to the Bayesian criteria, by information decoding and posterior probability of gas leakage source can be established.

Assuming the continuous detection is mutually independent in time, while the random detection is Poisson distribution. The robot's search path at grids $\{C_1,..., C_n\}$ during $\{t_1,..., t_n, t\}$ is T_t, then, the posterior probability distribution at t is following:

$$P_t(C_r) = \frac{L_{C_r}(\Gamma_t)}{\int L_x(\Gamma_t)dx} = \frac{e^{-\int_0^t \beta_{rj}(t')dt'}\prod_{n=1}^{H}\beta_{rj}(t_n)}{\int e^{-\int_0^t \beta_{ij}(t')dt'}dx\prod_{n=1}^{H}\beta_{ij}(t_n)} \tag{14}$$

where, H is the robot detecting times; t_n is the corresponding detecting time; L_{C_r} is the possibility of obtain path C_r, when the gas leakage source is at Γ_t.The path C_r and the probability Γ_t are variable and updated with time.

Actually:

$$P_{t+\delta t}(C_r) = P_t(C_r)e^{-\beta_{rj}^{\eta}(t+\delta t)\delta t}\beta_{rj}^{\eta}(t+\delta t)\Big/Z_{t+\delta t}$$

where, η is the detecting times in interval δ_t; $Z_{t+\delta t}$ is with regard to parameter C_r.

Combining the information entropy search with the upwind search strategy for the gas leakage source: The information entropy search strategy: When the robot finds the gas leakage source at j point, information entropy of this point is $S = -\Sigma p_j \ln P_j$, where, $\Sigma p_j = 1$, the expectations of search time is $T = \Sigma P_j \ln P_j$. If the robot finds the gas leakage source at the first point, then it will stop searching, otherwise, the robot has to consider other information, such as $P_1 \mapsto 0, P_{j\neq 1} \mapsto P_{j\neq 1}/(1-P_1)$ to update the probability map and the robot uses the same process to repeat in each search position.

Assuming the robot reaches C_r point at time t, the distribution function of posterior probability is $P_t(C_r)$ and information entropy is S. When the robot moves to next adjacent positions around C_f, the change amount of information entropy is:

$$\overline{\Delta S}(C_r \to C_f) = P_t(C_f)(0-S) + (1-P_t(C_f))\left[\sum_{k=0}^{\infty}\rho_k(C_f)\Delta S_k\right] \tag{15}$$

The first item is "detect gas leakage source event" around C_f and if the robot found the gas leakage source, $P_{t+\delta t}$ will change as a unit impulse function δ and the information entropy is reduced to zero; and the second item is "undetected gas leakage source", in right side of the Eq. 15.

The probability of the gas leakage source is unknown and the posteriori probability is only estimated value, therefore, it has to balance the information detection and utilization behavior to improve the robot searching efficiency. The first item of the equation 15 accords with the maximum likelihood criterion, information entropy S reflects the uncertainty of the current state; the second item, which considers the additional information and not includes the gas leakage source probability, contains information using behavior and detecting trends. Therefore, the equation 15 shows the information search process can balance the detecting and utilizing information behavior.

The detection time is divided into several time intervals δt and ΔS_k is the change mount of information entropy between $P_{t+\delta t}$ and P_t. $\rho_k(C_f)$ is the probability of detecting puff k times within time interval δt.

The detection event is the Poisson distribution model, therefore:

$$\rho_k = h^k \exp(-h)/k! \tag{16}$$

$$S_k = -\int dx \rho_k(x) \log \rho_k(x) \tag{17}$$

were, H is the expectation of detecting puff's number and can be estimated as:

$$h(C_f) = \delta t \int P_t(C_r)\beta_{rj} dC_r \tag{18}$$

The calculation of polynomial $\rho_k(C_f)\Delta S_k$ is large to affect the real-time search. Therefore, according to Eq. 16-18, to regard the detection time t as a whole:

$$\begin{aligned}\sum_{k=0}^{\infty}\rho_k(C_f)\Delta S_k &= \rho_0\Delta S_0 + \rho_1\Delta S_1 + \rho_2\Delta S_2 + \cdots \\ &= \rho_0(S_0 - S) + \rho_1(S_1 - S) + \rho_2(S_2 - S) + \cdots \\ &= \rho_0 S_0 + \rho_1 S_1 + \rho_2 S_2 + \cdots + (-S) \\ &= S_h - S\end{aligned} \tag{19}$$

Equation 19 into Eq. 15, the amount of change of the information entropy can be simplified as follow:

$$\begin{aligned}\overline{\Delta S}(C_r \to C_f) &= P_t(C_f)(0-S) + (1-P_t(C_f))(S_h - S) \\ &= (1-P_t(C_f))S_h - S\end{aligned} \tag{20}$$

The robot chooses the moving direction by calculating the maximum reducing amount of change of the information entropy to the adjacent position in each time step, after determining the appropriate amount to balance the relationship between use and detection information. In this way, the search efficiency and accuracy can be improved.

Combining the upwind search strategy with information entropy: In a windy environment, the leakage gas must spread along the downwind direction; therefore, the wind also can be an important clue as the puff tracking. When the robot is into the puff zone, the upwind search method can track the puff effect (Spears *et al*., 2009), the simulation results from Iacono and Reynolds (2008) show the upwind search efficiency can be improved by increasing the wind speed information. In this study, as localization strategy of the gas leakage source, which is upwind search strategy combined information entropy, is proposed. And the proposed strategy contains found puff, tracking puff and confirming gas leakage source three sub processes:

- **Sub process 1 finding puff:** One of the important conditions of localization the gas leakage source by obot is finding the leakage gas by robot's olfactory

Therefore, when starting the search task, the robot searches the work environment by exhumation route to collect the gas concentration and wind information by switching on all the gas sensors. The robot random search in the global scope, in this way, the robot can find the leakage puff and into the gas puff

- **Sub process 2 tracking puff:** The robot began the local search, when the robot continued detected gas concentration information, which implies the robot has entered into the gas puff. If the gas concentration is less than or equal to the certain threshold, it implies this zone is far from the gas leakage source and the robot will use information entropy search strategy, which is higher search accuracy, to gradually approach the suspected target. If the gas concentration is greater than the certain threshold, it implies this zone is the vicinity of the gas leakage source or a gas concentration in the dense region. At this time, the search strategy should be divided by the wind speed information, if the wind speed is greater than the threshold value, which indicates the leakage gas waft from the gas leakage source and the possibility of the gas leakage source located on up-site. Therefore, the robot will use the upwind search and adjust the search direction in accordance with the change of the gas concentration gradient, to approach quickly the suspected gas leakage source target. If the wind speed is less than or equal to the threshold value, in order to reduce the number of the detection and iteration, the robot will use the information entropy strategy with increased search step to gradually move the vicinity of the suspected gas leakage source
- **Sub process 3 confirming gas leakage source:** The ultimate goal of the search and locate the gas leakage source is to find the exact location of the gas leakage source by robot, therefore, all the identified targets should be regarded as suspected targets before the gas leakage source confirming process. Confirming the gas leakage source is to judge and identify. One of the remarkable features is that near the gas leakage source the gas concentration is higher than any other position, accordingly, a gas leakage source confirming method is proposed, if the suspected target meet the following three conditions at the same time, then the suspected target can be confirmed as the gas leakage source. The three conditions are as follow:

  - The distance between the robots with a suspected target itself is less than the set distance threshold
  - The gas concentration detected by robot is greater than the set concentration threshold;
  - The robot detects continuously the gas concentration higher than the concentration threshold, meantime, the maintain time is higher the set time threshold

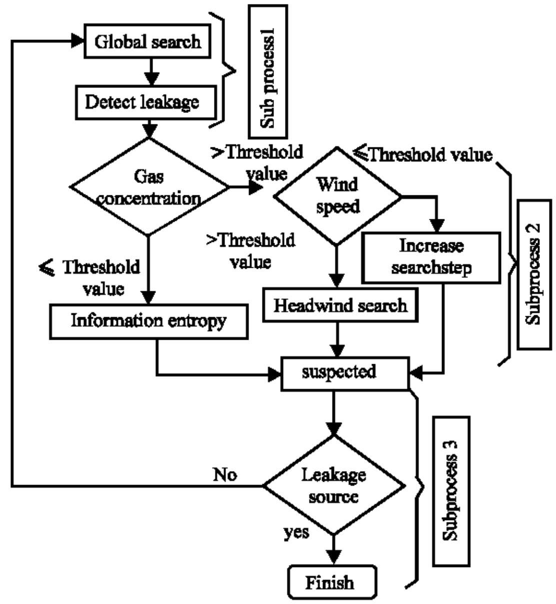

Fig. 4: Gas leakage source localization strategy based on information entropy combined with upwind search

If the robot detects the gas concentration can be prolonged to maintain a relatively higher value and the distance from suspected target is within 60 cm, at this time, it is determined that the robot approaches the gas leakage source and the search task is completed. Otherwise, the robot will reenter the global random search stage to look for the new suspected target. This gas leakage source localization strategy can reduce the local search calculation amount to improve the search efficiency and real-time and its control structure as shown in Fig. 4.

SIMULATION RESEARCH ON THE GAS LEAKAGE SOURCE LOCALIZATION BY INFORMATION ENTROPY SEARCH STRATEGY

Taking into account the risk of the actual environmental conditions, as well as the established cost of the real experimental environment, simulation experiments can provide a unified platform to verify the search algorithm, therefore, the simulation experiments is an effective method in initial stage.

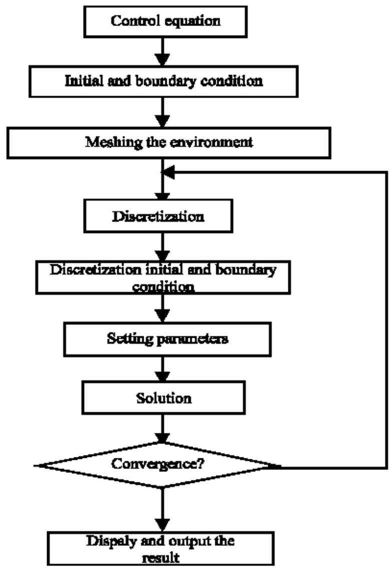

Fig. 5: Work flow chart of CFD

3When the leakage hole is small, the leak is often in the form of injection, considering the tank and pipeline with a certain pressure. Most of the expansion of the leakage gas is converted into kinetic energy, according to the energy conservation law; the gas mass rate model of the leakage gas through the small holes can be obtained:

$$Q_m = C_0 A P_0 \sqrt{\frac{2rM}{R_g T_0 (r-1)}\left[\left(\frac{P}{P_0}\right)^{2/r} - \left(\frac{P}{P_0}\right)^{(r+1)/r}\right]} \quad (21)$$

where, Q_m is the mass leak rate; C_0 is the leak coefficient; P_0 is the area of the leakage hole;M is the pressure of the tank; P is the gas molar mass;R_g is the ideal gas constant; T_0 is the gas leakage source temperature; P is the pressure of gas leakage source; r is the heat capacity ratio.

The mass leak rate is maximum, when the leakage process exists the critical state, then, the maximum mass leak rate is calculated as follows:

$$(Q_m)_{choked} = C_0 A P_0 \sqrt{\frac{rM}{R_g T_0}\left(\frac{2}{r+1}\right)^{r+1/r-1}} \quad (22)$$

The leak coefficient effects directly the calculation of the gas mass leak rate. Generally, C_0 is set between 0.6 and 1.

Simulation of the leakage gas puff based on CFD: CFD (Computational Fluid Dynamics) plume model is based on computational fluid dynamics; the leakage gas distribution can be simulated by CFD. The solution process of CFD includes defining the correct mathematical model for physical model, determining the initial and boundary conditions, using numerical discretization method, solution and so on, as shown in Fig.5. The simulation results can reflect the gas flow field distribution trends, such as velocity field, concentration field, pressure field and temperature field.

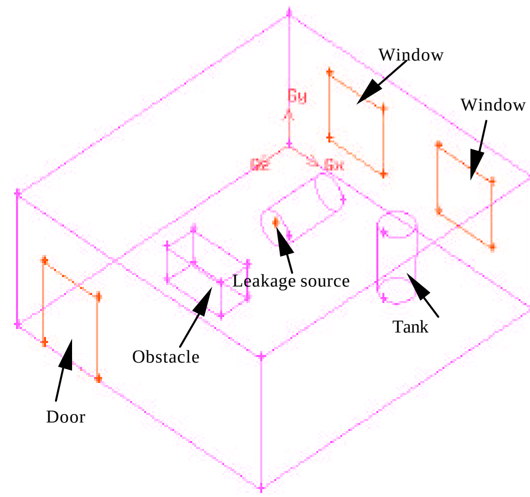

Fig. 6: Physical model of robot's search environment

Established the physical model Define the robot's search zone as a rectangular area, length 9 m, width 10 m high 4 m and the cylindrical gas tank diameter is 1 m and its' high is 2 m, the windows size is 2×2 m, door size is 2×2.5 m and define the gas leakage source is circular hole with diameter of 0.02 m in the bottom or side of the tank, meanwhile, the obstacles are placed in other zone, the physical model is shown as Fig. 6.

After establishing the geometric model, it is to be meshed by using quadrilateral element. The leakage gas is leaked in form of injection, therefore, the boundaries of the two inlets is defined, one is for the leakage gas 's inlet, the other is for the wind's inlet and to define an outlet for the door. Then to set the boundary conditions, the leakage hole is the inlet of the leakage gas and its' velocity is 2 m sec^{-1}, the windows is the inlet of the wind and its' velocity is 0.5 m sec^{-1}, the door is the outlet, the others use the default settings. To check the meshed model, then, the turbulence k-ε equations is chosen according to the turbulence situation and calculation amount and SIMPLEC solution is used to solve the couple of velocity and pressure. The solution of flow of in the robot search zone carried on the Fluent.

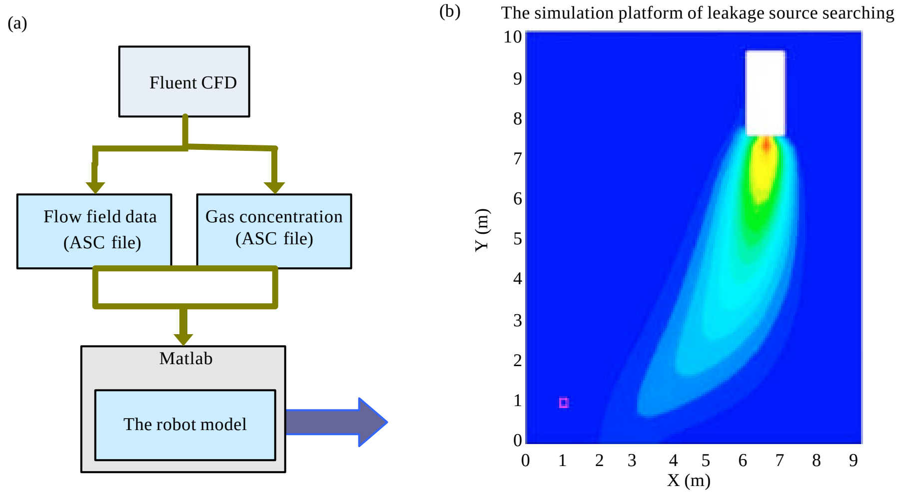

Fig. 7: Simulation platform framework

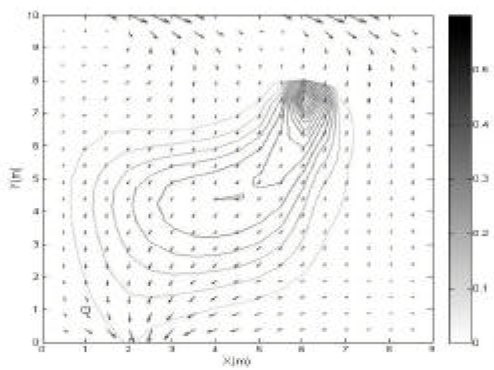

Fig. 8: Simulation environment of the gas leakage source search

Simulation platform of the robot search leakage gas: The fluid dynamics software fluent can simulate accurately the leakage gas's puff distribution in flow field. However, the robot's motion cannot be simulated in CFD simulation environment, therefore, to simulate the mobile robot search the gas leakage source process, the simulated fluid field, puff distribution and other data are output into ASCII file, then input in the Matlab programming environment to combine the robot's model, in this way, the simulation platform of the robot search leakage gas can be established and the framework of this simulation is shown in Fig. 7.

The gas concentration distribution can be re-built according to puff concentration distribution and flow field information in ASCII files and different concentration value can be expressed as different color. The square represents the robot model and the robot can read puff concentration value, wind direction and wind speed in the current grid, then to determine next step's motion by according to the search strategy.

The information collection is to get the data of each grid position in data file, if the effect by robot's size, motion and sensor's model is neglected. The simulation environment for the gas leakage source search is shown in Fig.8. The closed curve represents the contour line of the concentration, the gray of curve represents the value of the gas concentration and the size and direction of arrows represent the size and wind direction relevantly.

SIMULATION RESULTS AND ANALYSIS

Simulation result of information entropy search strategy: The simulation experiments are carried out in wind and non-wind environments, the gas leakage source position coordinates are (6, 8), the starting position of the robot coordinates are (0.5, 0.5), the motion of the robot step length is 0.25 m. The robot has forward, backward, left, right and stationary five kinds of motion behavior. The robot calculates and compares the current position's information entropy with adjacent positions' information entropy to choose motion direction by according to information entropy reducing maximum direction:

- **Simulation in non-wind environment:** Setting the boundary conditions are as non-wind from the window and the gas leakage source as continuous bleed inlet. The triangle represents the robot and the

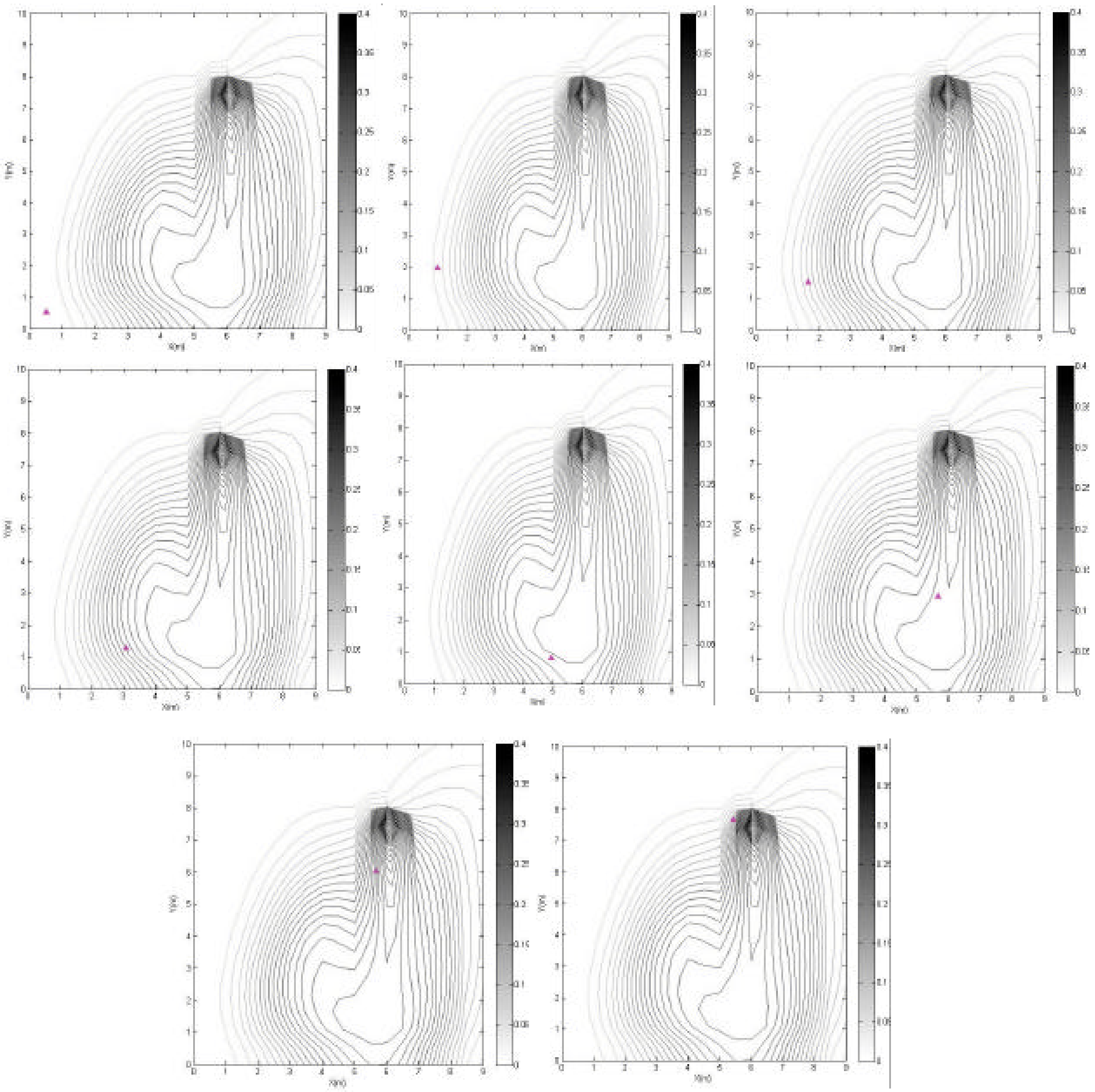

Fig. 9: Robot searching process in non-wind environment

search process in non-wind environment is shown in Fig. 9. Search path the information entropy

The robot detects the leakage gas concentration information until step 8 from the initial position, then, the robot moves gradually to the high gas concentration direction, meantime, to the gas puff center. The gas concentration gradient in the leakage puff center line is obvious. With the gas concentration increasing, the robot is closer to the gas leakage source and after 63 steps, the robot moves to the gas leakage source, the whole search process is shown in Fig .9. The information entropy search strategy in non-wind environment is similar to the concentration gradient algorithm, that the gas concentration information reflects the gas leakage source position information. The gas leakage source position is

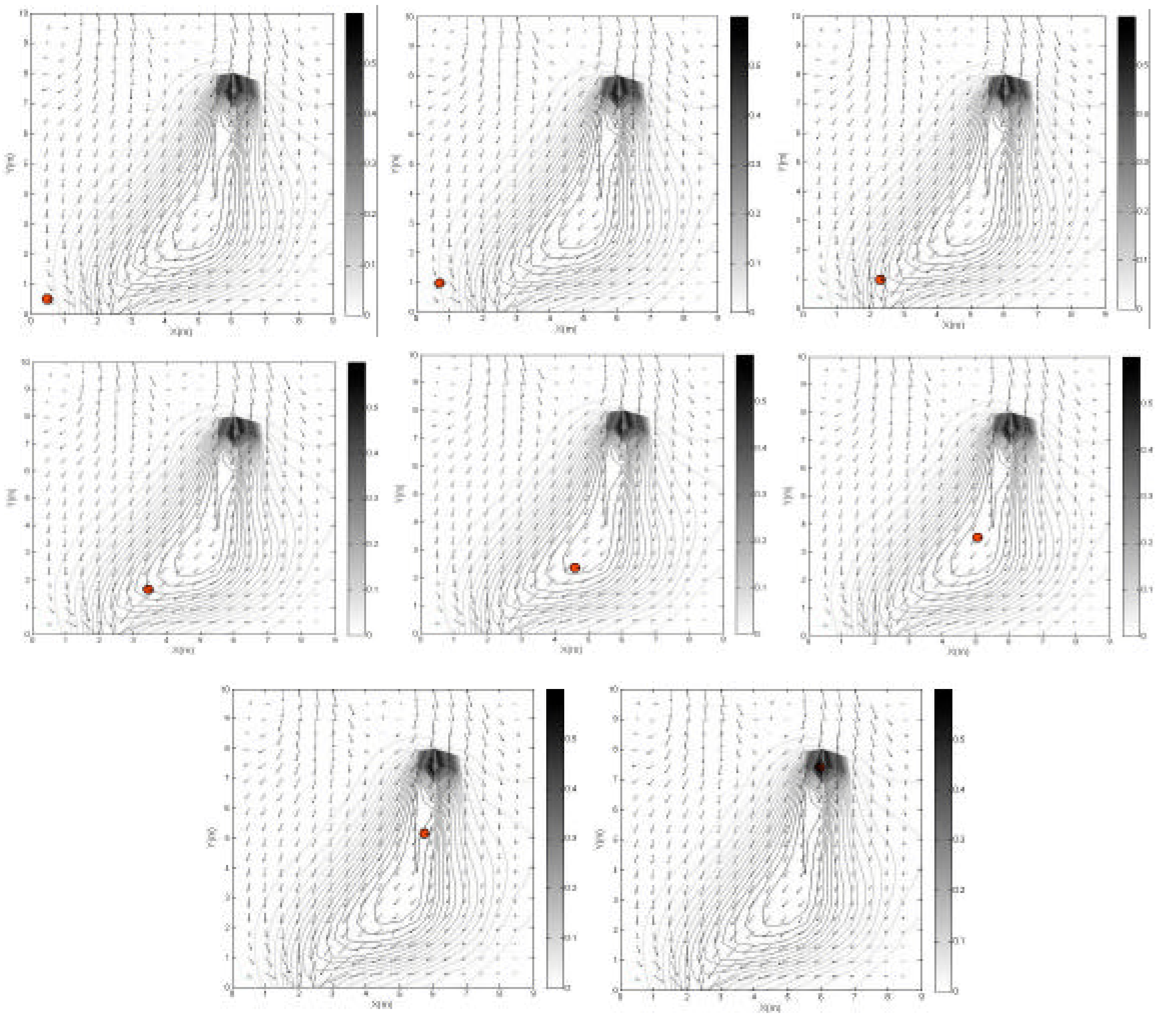

Fig. 10: Robot search path and information entropy in non-wind environment

more obvious with gas concentration increasing and information accumulation.

The whole search path of the robot and the change of the information entropy in non-wind environment are shown in Fig.10. The robot moves along the information entropy reducing direction during the search process. After 63 steps iteration, the value of the information entropy is 1.36 and the robot reaches the gas leakage source position:

- Simulation in wind environment. Setting the boundary conditions are as wind from the window, the direction of the wind is along the y-axis negative direction and the gas leakage source as continuous bleed inlet. The triangle represents the robot and the search process in wind environment is shown in Fig. 11

The robot detects the leakage gas concentration information until step 3 from the initial position, then, it is similar with in non-wind environment, the robot moves gradually to the high gas concentration direction, meantime, to the gas puff center. After 54 steps, the robot moves to the gas leakage source, the whole search process is shown in Fig.11. The leakage gas is along the wind direction, so the leakage gas puff distribution is also

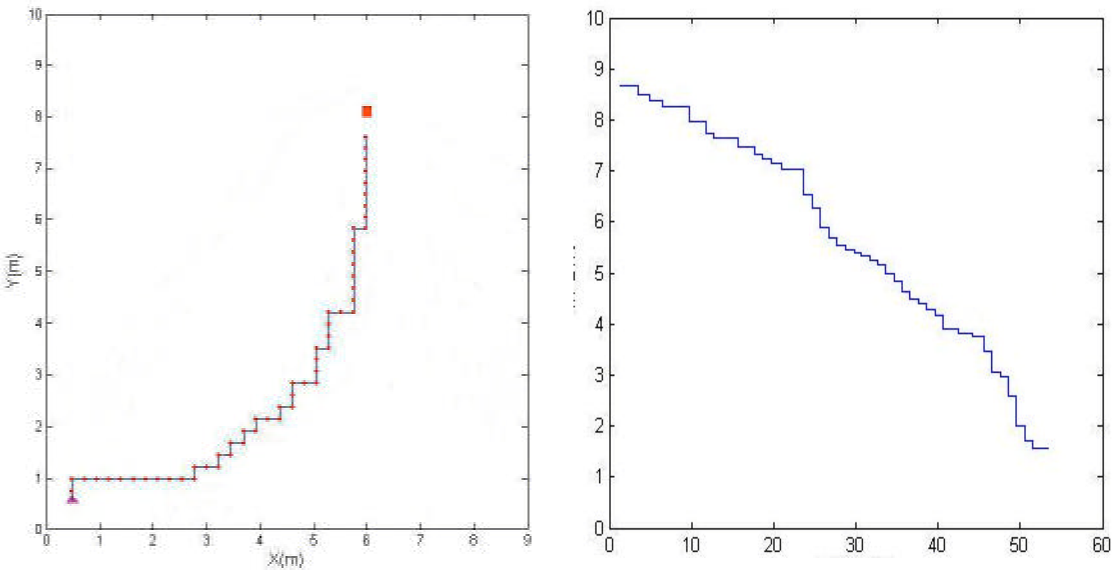

Fig. 11: Robot searching process in wind environment

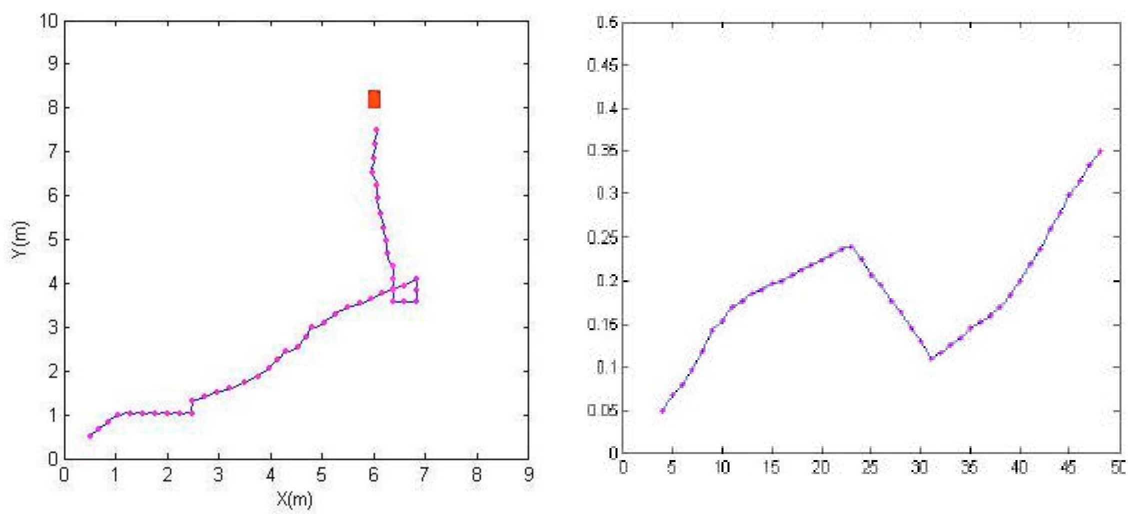

Fig. 12: Robot search path and the information entropy in wind environment

determined by the leakage gas flow field distribution. Therefore, the wind information is an important clue for search the gas leakage source and the robot based on the information entropy strategy is similar to the upwind search algorithm, that the upwind can lead the robot to the gas leakage source position.

The whole search path of the robot and the change of the information entropy in wind environment are shown in Fig. 12. With robot search ongoing, the information entropy gradually decreases and the robot's motion is "z" type. The robot moves along the information entropy reducing direction during the search process and after 55 steps, the value of the information entropy is 1.62 and the robot reaches the gas leakage source position. It is can be seen in Fig.12that the robot also search the gas leakage source by using the upwind strategy.

- Simulation result of the combined the upwind search strategy based on information entropy: The gas leakage source position coordinates are (6, 8), the starting position of the robot coordinates are (0.5, 0.5), the motion of the robot step length is

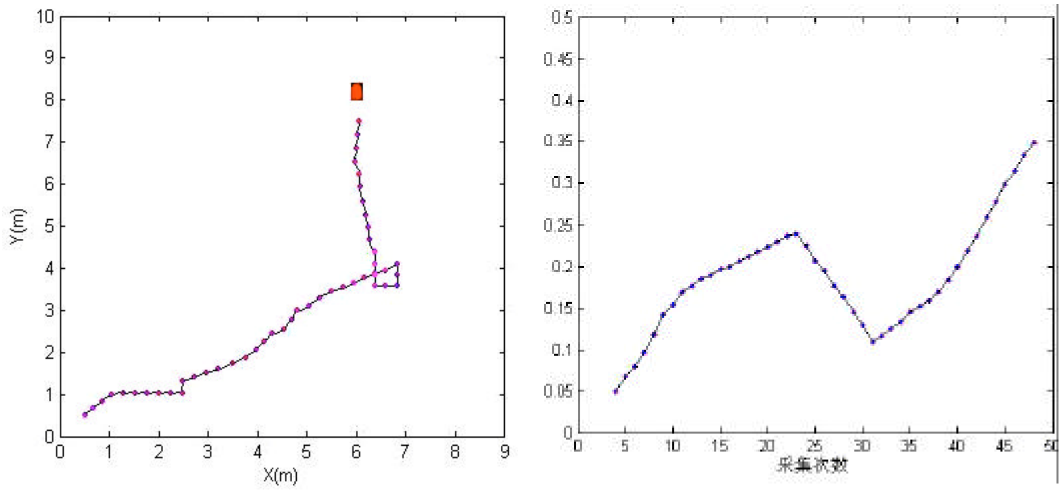

Fig. 13: The robot searching path and collected gas concentration

0.25 m. The robot has forward, backward, left, right and stationary five kinds of motion behavior. The gas concentration threshold value is 0.16 kg m^{-3}, the wind speed is 0.2 m sec^{-1}. The simulation is carried out by the combined the upwind search strategy based on information entropy, after simulating, the robot's search path and the leakage gas concentration information on each position are shown in Fig. 13

The robot begins random search from the position coordinates (0.5, 0.5) and moves along the direction of 45°, with reference to Fig. 12. When the robot is in the third search step, the gas concentration is 0.05 kg m^{-3}, which is less than the gas concentration threshold, then, the robot begins to search along the information entropy reducing direction by using of information entropy search strategy and the robot approaches the gas puff center, the detected gas concentration is increased. When the robot is in the 10th search step, the gas concentration is 17 kg m^{-3}, which is larger than the gas concentration threshold, meantime, the robot is close to the door, the airflow is larger than others, so the robot moves to the gas leakage source along the upwind direction by using of the upwind search strategy. The gas concentration during the upwind search path is larger and larger. At 22th search step, the gas concentration approaches a maximum value, then, begins to reduce, in the upwind search strategy stage, as shown in Fig.13. That is because the robot gradually leaves the puff centerline, even run out of the puff region during the upwind search strategy stage and the robot still uses the upwind search because the gas concentration at this step is still larger than the gas concentration threshold. When the robot is in the 30^{th} step, the gas concentration increases as 0.11 kg m^{-3}, which is less than the gas concentration threshold, the robot begins to search by i nformation entropy strategy. So the robot begins search the adjacent area and reentry into the puff center line. When the robot is in the 37th step, the gas concentration increased to 1.67 kg m^{-3}, which is larger than the gas concentration threshold value and the robot uses again the upwind search until approaching the gas leakage source position.

The simulation results indicate that the search strategy, which is combined the upwind search strategy with information entropy search strategy, is feasibility to use in actual working conditions. The robot can choose the optimum search direction according to the information entropy change in low concentration puff environment, in this way; the robot can avoid repeating search for the puff information's intermittent. The robot can use the information entropy combined the upwind search strategy in the high concentration puff environment. Comparing with other search strategy, the proposed search strategy has more advantages, such as higher efficiency, save time, higher real-time.

CONCLUSION

In this study, a new gas leakage source search strategy, which is combined information entropy with upwind search strategy, is proposed. The structure of the information entropy search algorithm is analyzed by analyzing the relationship between the gas leakage source search and information usage. The flow field distribution and concentration information is got by CFD simulation. And using the simulation results from CFD, the robot search gas leakage source simulation platform is established by using Matlab. In the simulation environment, the proposed search algorithms are simulated with different search conditions. The results of simulation indicate that the information entropy combined with the upwind search strategy can improve the search efficiency and can be used in the actual gas leakage source search by robot.

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