Optimization of sampling structure on UAV for gas leakage monitoring in the atmosphere

Denglong Ma (✉ denglong.ma@xjtu.edu.cn)

Xi'an Jiaotong University School of Mechanical Engineering <https://orcid.org/0000-0001-9342-626X>

Guo SICHENG

Xi'an Jiaotong University

Yuxiang ZHOU

Xi'an Jiaotong University

Zezhou AO

Xi'an Jiaotong University

Yuhang QIU

Xi'an Jiaotong University

Jianmin GAO

Xi'an Jiaotong University

Research Article

Keywords: Quad-rotor UAV, CFD simulation, Gas sampling, Leakage identification, Gas leakage

Posted Date: March 7th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1262894/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Optimization of sampling structure on UAV for gas leakage monitoring in the atmosphere

Denglong MA* ^{1,2} Sicheng GUO ¹ Yuxiang ZHOU ¹ Zezhou AO ¹ Yuhang QIU ¹ Jianmin GAO ^{1,2}

1. School of Mechanical Engineering, Xi'an Jiao tong University, Shaanxi Xi'an 710049;

2. State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiao tong University, Shaanxi Xi'an 710049

*Corresponding author: denglong.ma@xjtu.edu.cn (denglong.ma@xjtu.edu.cn)

Abstract: In order to make a fast and accurate response for gas leakage event, e.g. gas leakage in hydrogen storage station, it is very important to identify and locate the leakage source accurately and quickly. Due to the flexibility and the adaptability of robot to harsh environment, leakage source tracing based on mobile robot has attracted more and more attention. However, the existing ground robots are limited by the ground environment and thus it is difficult to trace and locate the leakage in the complex environment with ground robot. Although UAV (Unmanned aerial vehicle) can overcome the limitation of ground obstacles, there are still some problems in the accuracy and reliability of gas sampling due to the interference of flow field caused by UAV rotors to the surrounding gases. Based on CFD (Computational fluid dynamic) simulation, a simulation model of UAV with four rotors was established. Combined with test experiments, the influence of flow field around UAV on gas sampling under different UAV speeds, rotors assembly structures, leakage and sampling conditions was analyzed and investigated. The optimized UAV assembly structure and gas sensor installation position were determined and verified by the simulations and experiments. The results showed that the sensor was less affected by the rotor airflow when the UAV rotor was reversely assembled and the gases were sampled above the UAV. This research can provide a guidance of gas sampling for emission source tracing with UAV for process safety management of energy gas storage.

Key words: Quad-rotor UAV; CFD simulation; Gas sampling; Leakage identification; Gas leakage;

0 Introduction

The leakage of hazardous chemicals, e.g. hydrogen and other energy gases, in the process of production, transportation or storage is one of the main issues faced by process safety management ^[1-6]. The leakage of toxic and hazardous chemicals will cause great losses to the environment, personnel and society. Therefore, it is very important to identify the hazard source in the atmosphere. Hence, an accurate and fast source tracing method for the release of hazardous chemicals is crucial to deal with the leakage event. On the other hand, it is also of significance to identify the emission source of contaminant gases for pollution control in the atmospheric environment.

Currently, there are two important source tracing methods. One is the source parameter estimation method based on sensor network and inversion algorithm ^[7-14]. The inverse solution model is built combined with measurement data and forward dispersion model with this method. Optimization and stochastic approximation are always utilized to estimate the source term. Another source tracing method is based on mobile sensor which is equipped on the robot ^[15-18]. Compared with the source identification method with static sensor network, mobile robot has higher ability in mobility and flexibility, and it is taking more and more attention on leakage tracing research. In this case, the concentrations are captured during the movement of the robot, and the source term is estimated with source tracing algorithm, which is guided with both gas concentrations and wind information. At present, there have been some researches on leakage source tracing based on ground mobile robot ^[15]. However, the complex terrain environment will limit the mobility of the ground robot. Hence, it is not suitable to patrol and trace emission gases for long distance and complex environment with ground robot. Compared with the ground robot, UAV (Unmanned aerial

vehicle) has the advantages of avoiding ground obstacles and rapid searching in a large-scale space. UAV can be used to sample and monitor the gas concentrations in the atmosphere to find the gas leakage source based on the tracing algorithm in a large space. At present, UAV detection methods have been preliminary applied in different fields. However, the concentrations captured by UAV are disturbed by the air flow of rotors and the errors will be brought into the measurement, thus multi-rotor UAV has not been widely used in gas leakage source tracing applications due to the uncertainty of the measured concentrations with UAV.

Published leakage tracing algorithms based on mobile sensor can be divided into two type of forms. One is bio-inspired algorithms based on the behavior of animal or microbes, such as *E.coli* algorithm, Zigzag, Silkworm et al. [16-17]. Another category of source location with mobile sensor is that based on inverse model and information driven process [18-20], where the next movement is predicted with captured concentrations, forward model and acquired information. All above researches were always based on ground robot and supposed that concentrations monitored by the mobile sensor are accurate. However, due to the flow field caused by the fuselage during the movement process for multi-rotor UAV, the gas sensing process will be disturbed by the flow from the surrounding gases, which will have impact on the accuracy of gas sampling and detection, and eventually affect the accuracy of source tracing. The researches on how to effectively reduce the interference of outflow field on the accuracy of gas sensing with UAV are still not enough. Therefore, it is of significance to optimize the gas sampling structure of multi-rotor UAV.

Compared with the fixed-wing UAV, the cruise speed of the rotary-wing UAV is relatively low, but the ability of manual control and fixed-point hovering are relatively enhanced, which makes the rotary-wing UAV more fitted for stable operation in small-area. The stable structure of the centrosymmetric provides good wind resistance for rotor UAV. Although the motors increase energy consumption, multi-rotor UAV has advantages of high stability, low operation difficulty and low requirement in taking off and landing, which has been used in the fields of industrial pollution inspection and fixed-point monitoring [21-22]. Niu et al.[23] used the six-rotor UAV equipped with PM2.5 sensor to collect data in the vertical direction near the ground to investigate the distribution law of PM2.5 near the ground. Rossi et al.[24-26] designed a set of embedded gas monitoring platform, which was equipped with UAV for environmental monitoring experiment and pollutant mapping. Norsuzila et al.[27] developed an environmental monitoring system based on UAV, which can collect relatively accurate environmental data around the fuselage, including environmental temperature and humidity data. Daniele et al.[28] used multiple UAVs to establish a joint monitoring system and designed a variety of algorithms to detect the distribution of fluid plume accurately. Malaver et al.[29] designed a UAV air monitoring system powered with solar to measure the content of air pollutants in the troposphere for a long time. Kent et al.[30] designed a micro UAV to establish a detection platform to sample and detect the chemical vapor cloud. Mehmet et al.[31] used the vision system on the UAV system to monitor the forest fire in real time. Yuan et al.[32-33] introduced the UAV gas detection system into the search and rescue work in the remote areas to find the persons in complex landforms by analyzing the gas residue in the environment. They also introduced UAV gas detection technology into marine ship emission measurement in complex sea and atmospheric conditions by combining vector tracking algorithm. Raphael et al.[34] utilized UAV to accurately detect vehicle exhaust emissions. In order to correct the influence of UAV on detection, rotor speed was set as the correction factor so as to improve the detection accuracy. Kersnovski et al.[35] loaded on-board cameras and gas sensors on the UAV platform to accurately detect the large-scale environment, and used the vision system to guide the path for the UAV. Shi et al.[36] introduced UAV system into hazardous gas detection in hazardous environment. Accordingly, the application of UAV gas detection system in complex environment such as underground mine and chemical park, can effectively protect the personnel safety. However, few researches can be found on the impact of UAV movement on the surrounding gases with low concentration. Most of the objects measured in above researches are the environmental gases with obviously high concentration, and thus the motion interference of UAV on the gas sampling could be ignored although there are still some errors in measurement. But the

signals from the cases with low concentration due to leakage may be more important for early warning in actual emergency response. Therefore, the disturbance of propellers should be considered and investigated for UAV to detect leaking gases with low concentration.

Because the flow field caused by multi rotors is not a simple geometric overlapped result of single rotors, there will be interaction between the wind field and fuselage during the sampling process with multi rotor UAV. Li^[37-38] compared and analyzed the airflow velocity models in three directions below the UAV. They found that there was mutual interference between the lateral airflows of the multi rotor UAV. Zheng^[39] found that the increase of hovering height will lead to the uniform flow field due to the attenuation of ground effect, and its turbulent flow will be gradually stable for multi-rotor UAV. They studied the downwash flow of six-rotor UAV with turbulence models respectively, and discussed its ground effect at different hovering heights. Xue^[40] and Li et al.^[41] simulated the fuselage turbulence of hovering twin rotor UAV. Ryu et al.^[42] analyzed the turbulence effect of UAV in crosswind environment, and Seong^[43] analyzed the fuselage flow field distribution of four rotor UAV in forward flight attitude. The downwash flow field generated by multi-rotor UAV is more complex than that by a single rotor, and the flow field of multi-rotors will induce and affect with each other, resulting in aggregation flow. However, there are few studies on the gas sampling effect and the optimal layout of gas sensors under the condition of rotor movement.

Therefore, this research will focus on quantitative research on the parameters of the flow field in and outside the fuselage under different conditions. The gas sampling structure of UAV was optimized by simulation scenarios to improve the gas detection accuracy. Finally, the experiments will be carried out to verify the performance of the optimal sampling structure.

1 CFD simulation model of UAV

The three-dimensional scanning method was used to obtain the surface information of the blade, and the scatter cloud image was inversely processed to generate the blade model data that can be used for CFD simulation calculation. The complete blade model was obtained by arraying the blade near the central circular axis.

1.2 Simulation Parameters

Relevant parameters such as the size of UAV, rotor and calculation zone are shown in Table 1:

Table 1 The Simulation Parameters of CAD model

Rotor diameter	153mm
Rotor center distance	212.1mm
Diagonal length of UAV frame	300mm
Simulated space size	Cuboid, 1800mm in length and width, 3000mm in height
Height above ground	900mm

The propeller scanning model used in the experiment is shown in Fig. 1:

Fig.1 propeller scanning model

1.2 Calculation Conditions

The calculation conditions and governing equations used in CFD simulation are shown in Table 2:

Table 2 The Calculation Conditions of CFD model

Inlet	Velocity-inlet, $v = 0 \text{ m} \cdot \text{s}^{-1}$
Outlet	Pressure-outlet, $P = 0 \text{ pa}$
Wall	No-slip boundary condition
Mathematical model	Realizable $k - \varepsilon$ model
Discrete format	Second order upwind
Discrete equation	SIMPLC

1.3 Governing Equation

The continuity equation of incompressible fluid is mainly based on the law of mass conservation [44]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_i}{\partial x_i} = 0 \quad (1)$$

The momentum equation in Navier-Stokes equation is mainly based on the law of momentum conservation:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial \rho U_i U_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} [(\mu + \mu_t) (\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i})] \quad (2)$$

Where ρ representative density; t is the time; U_i is the speed; x_i and x_j are coordinates; p is the pressure; μ and μ_t stand for molecular viscosity and turbulent viscosity, respectively.

The standard $k - \varepsilon$ model mainly uses two transfer equations to describe turbulence. One is the turbulent kinetic energy equation used to determine the turbulent energy, and the other is the turbulent dissipation equation expressing the dissipation rate of turbulent flow energy:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k U_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu_1 + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \mu_t \frac{\partial U_j}{\partial x_i} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho \varepsilon \quad (3)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon U_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu_1 + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \mu_t \frac{\partial U_j}{\partial x_i} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (4)$$

Where k represents turbulent kinetic energy; ε represents the dissipation rate of turbulent kinetic energy; μ_1 is the laminar eddy viscosity coefficient; σ_k , $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the model constants.

Realizable $k - \varepsilon$ model introduces a more reasonable turbulent viscosity formula and uses a new energy dissipation rate transfer equation, which is derived from an accurate eddy current pulsation transfer equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k U_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu_1 + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k + P_b - \rho \varepsilon - Y_M + S_k \quad (5)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon U_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu_1 + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_{1\varepsilon} S_\varepsilon - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} P_b + S_\varepsilon \quad (6)$$

Where P_k represents the turbulent kinetic energy generated by the velocity gradient; P_b represents turbulent kinetic energy generated by buoyancy; Y_M is the fluctuation due to the diffusion; S_k and S_ε are source term parameters; $C_{3\varepsilon}$ is a model constant.

1.4 Grid Independence

Before the numerical simulation of UAV outflow field, it is necessary to mesh the geometric entities and verify the grid independence. With the rotor speed of 5000 rpm, the pressure under the UAV was taken as the comparison parameter. The results under different grid sizes were compared, as shown in Fig. 2. It

was finally found that the parameter of pressure kept stable with the grid size larger than 35 mm. Therefore, the best grid size was selected as 35 mm in this case.

Fig. 2 The results of grid independence variation

2 Simulation Results

2.1 Effects of different assembly structures

The external flow field of common four rotor UAV structure at 5000 rpm was numerically simulated and analyzed. The flow field is shown in Fig. 3.

Fig. 3 The flow field of common four-rotor UAV at 5000 rpm

The interference of the UAV cantilever makes the air flow below the rotor unstable, resulting in strong vortex clusters. Therefore, the rotor mounting structure should be further adjusted. The new scheme is shown in Fig. 4.

Fig. 4 Improved assembly structure of UAV

In this scheme, the fuselage originally installed below was moved above the rotor to avoid the influence of the fuselage on the air flow as much as possible to obtain a relatively stable surrounding flow field for gas sampling.

2.2 Flow field effects at different speeds

With the structure of reverse assembly, the flow fields of the UAV at the speed of 3000 rpm, 4000 rpm and 5000 rpm under the condition of no wind were simulated, as shown in Fig. 5.

Fig. 5 The velocity distribution of ZY section with different speeds

It is noticed from the velocity distribution of the flow field on ZY section in Fig. 5, the interference of the cantilever to the air flow is significantly reduced compared with the results with traditional rotor assembly structure (Fig. 3a). In this case, the flow field does not generate many vortices due to the drainage and interference of the fuselage at the upper inlet point, and thus the velocity distribution is relatively stable. The flow velocity under the UAV increases while the aggregation effect between the downwash flows decreases with an increase in rotating speed.

2.3 Effects of different atmospheric wind fields

The scenarios of UAV with the rotor speed of 5000 rpm under an external wind field was simulated. The wind speed was set as $0.5 \text{ m}\cdot\text{s}^{-1}$ and $1.0 \text{ m}\cdot\text{s}^{-1}$, respectively. In this case, the wind direction is in the negative direction along Z axis. In order to clearly demonstrate the impact of transverse wind speed on the whole flow field, the velocity trajectory on the ZY plane was intercepted, as shown in Fig. 6.

Fig. 6 Velocity of different wind speed ZY sections

It is observed that the characteristics of velocity distribution in the face of cross wind are as follows: when the wind speed is small, the air flow near the surface suppresses the wind to form a large vortex cluster; When the wind speed becomes high, the influence of wind speed is much stronger than that of air flow generated by the rotors near the ground and there will not vortex clusters near the ground surface. On the leeward side, the flow field presents different variations. When the wind speed is low, the velocity trajectories on the leeward side of the UAV are distorted greatly, and vortices are formed on the leeward side (Fig. 6a). However, the trajectories on the leeward become smooth and the gas flow is relative stable under condition with higher wind speed (Fig. 6b).

3 Optimization of the sensors position

3.1 Relationship between concentration and velocity

In order to demonstrate the concentration variations in the atmosphere near the UAV, ammonia with the mass fraction of 10% was added into the calculation domain. The concentration distribution of ammonia in space is shown in Fig. 7a compared with the velocity distribution in Fig. 7b.

Fig. 7 Ammonia distribution in the calculation domain

It is noted from Fig. 7 that the area with low concentration of ammonia is basically consistent with that with high flow velocity distribution of gas flow. Hence, the variation trend of ammonia concentration distribution is opposite to that of gas flow velocity distribution in the field caused by the rotors.

3.2 Velocity distribution above the UAV

In order to analyze the stability of the airflow in the UAV's external flow field and find a suitable installation position for the gas sensor, the velocity distributions at different heights of the flow field above the UAV at 5000rpm were quantitatively compared.

The sampling interval is established along the vertical direction at 0.01m, 0.02m, 0.1m, 0.2m and 0.5m above the UAV. Then the corresponding variations of velocity distribution are shown in Fig. 8.

Fig. 8 Velocity distribution at different altitudes above a 5000 rpm UAV

At the height of 0.5 m, the air flow is hardly affected by the UAV. However, the total length of UAV fuselage in this case is 0.3 m, thus the installation height of 0.5 m may have great impact on the attitude of UAV during the flight. Therefore, this position is only set as the reference and is not considered to be actual installation.

It is noted that the variation of air flow fluctuation gradually slows down with an increase of installation height. At the height of 0.01m, the vortex effect could be observed at the center of four rotor, which is the gas inlet. However, the effect of vortex can be ignored at the height of 0.2 m. Therefore, the sampling position at the height of 0.2 m above UAV can be considered as a potential good position to install the gas sensor.

When the external wind field exerts on the flow field generated by the rotors, overall space flux changes greatly. The same slice at the height of 0.2 m above the UAV was selected under the conditions with wind velocity of $0.5 \text{ m}\cdot\text{s}^{-1}$ and $1.0 \text{ m}\cdot\text{s}^{-1}$. The velocity distributions at different wind speeds were compared in Fig. 9.

Fig. 9 Comparison of velocity distribution at 0.2 m above UAV

In the cases with the interference of wind fields under different wind speeds, the variation of velocity distribution at the height of 0.2 m demonstrates a relatively stable state, and has a relatively similar law for the cases with different wind speeds. Therefore, it can be inferred that the flow field at the height of 0.2 m is influenced slightly by both rotor and external wind. Hence, the position at the height of 0.2 m above the UAV can be viewed as a potential good installation for gas sensor.

3.3 Gas velocity distribution below UAV

The slices with the sampling interval along the direction of axis Y at -0.75 m, -1.0 m, -1.25 m, -1.33 m and -1.4 m below the UAV were selected. The velocities along the axis Z were drawn for different slices, as shown in Fig. 10.

Fig. 10 Velocity distribution at different altitudes below the 5000 rpm UAV

It is obvious that it is difficult to find a completely stable area under the UAV. Therefore, only a relatively stable range of air flow can be determined through quantitative comparison of velocity distributions at different heights.

With an increase in height below UAV, the variations of velocity at different heights slow down first and then increases. The reasons may be that the downwash air flow under the UAV rotor gradually weakens with the distance far away from the fuselage below the UAV, and the variation of velocity gradually becomes flat. Then, the downwash air diffuses along the ground to the surrounding area with the further distance from the fuselage, and the overall flux area expands. Thus, the velocity tends to be an unstable state once more.

When there is a transverse wind along the reverse Z axis in the environment, the flow field in overall space changes greatly. The flow field are also different with different wind speeds. The results of the velocity at the height from -0.6 to -1 m with the wind speed of $0.5 \text{ m}\cdot\text{s}^{-1}$ is shown in Fig. 11.

Fig. 11 Velocity distribution at different heights under UAV with wind speed of $0.5 \text{ m}\cdot\text{s}^{-1}$

In the case of scenarios with the interference from the wind field in the environment, the velocity distribution below the UAV changes more sharply than that in the cases without external wind fields. The transverse wind makes the downwash flow field of UAV deviate along the wind direction. Therefore, the effect of the external wind on the area right below the UAV is weakened.

By comprehensively comparing the results of velocity distribution at -1.0 m , -0.8 m and -0.6 m , it is noted that the variation of velocity distribution at -1.0 m is relatively stable. Therefore, the gas detection can be carried out at this position with less interference of vortex clusters near the ground. In order to detect the gas below the UAV accurately, the installation position of the gas sensor should be set within -1.0 m to -1.33 m by considering the conditions with both windy and windless environment.

3.4 Velocity distribution at different rotor speeds

The velocities at the position of $y = 0.2 \text{ m}$ (above the UAV) and $y = -1.15 \text{ m}$ (below the UAV) with the rotor speed of 3000, 4000 and 5000 rpm were captured. The results along Z axis is shown in Fig. 12.

Fig. 12 Velocity distribution above and below the model at different speeds: (a) is the velocity distribution at 0.2 m above the model, (b) is the velocity distribution at 1.15 m below the model

The results showed that the variation law of flow field velocity at 0.2 m above the UAV is more stable than that at -1.15m. with different rotor speeds. Therefore, it can be considered that the samples will be impacted less by the rotor flow field when the gas sensor is installed at 0.2 m above the UAV discussed in this research.

4 Verification with the Experiments

Three MQ-2 gas sensors were installed at three positions including 0.2 m above the rotor, 1.15 m below the model and 3 m far from the end of the rotor model (reference point). The concentrations of the gases were measured by MQ-2 sensor, whose response was in the form of voltage. The higher the voltage, the greater the concentration. The automatic fogger filled with the liquid of ethanol was used to simulate the gas leakage release. The experimental environment and its schematic diagram are shown in Fig. 13.

Fig. 13 Experimental environment

First, the rotor was closed. The concentrations of the emission gases near the rotor were measured. After three sensors at different positions on the rotor reached to stable, the fogger was started at 5 s and then stopped at 30 s. The responses of the sensors in one minute were recorded. The process was repeated three times.

Afterwards, above process was repeated under the condition of opening the rotor with the speed of 5000 rpm. The rotor was started at 30s. Then, the propeller and fogger were both turned off at 40 s. The responses of three sensors within one minute were observed, as shown in Fig. 14.

Fig. 14 The response values of the sensor at different positions: (a) is the response curve when the rotor was closed, (b) is the response curve of the rotor rotated at 5000 rpm

Due to the heavy density of the ethanol, it is easier to accumulate near the ground. Therefore, the sensor under the rotor model detected the ethanol first, and the response values of the sensor at the lowest position increased faster than that of above sensors. Moreover, the peak value measured by the sensor at lowered position was higher than that by the sensor above the rotor, and thus the response curve decreased more slowly due to the accumulation of near the ground after the fogger was closed.

After the rotor started to rotate, the response signals collected by the gas sensor decreased, indicating that the rotor rotation increased the gas diffusion and diluted the gas concentration. After the rotor was turned on, the ethanol concentration detected by the sensors above and below the UAV decreased sharply. However, the response value of the sensor at 0.2 m above the rotor model decreased by 27% (from 78 mV to 57 mV) while the response value at 1.15 m below the model decreased by nearly 50%(from 91 mV to 46 mV) after the rotor startup. Hence, the degree of reduction for the sensor at 0.2 m above the model was significantly less than that for the sensor at 1.15 m below the model. After the fogger and propeller both terminated, the responses at 0.2 m above the model decreased continuously, but the responses at 1.15 m below the model increased first and then dropped down. It was caused by the existence of the downwash flow field of the model, due to the low-pressure area below the model during the running of the propeller. Therefore, the transient pressure difference between the center and the surrounding will help the ethanol gas to reflux briefly after stopping the rotation, which resulted in that the ethanol concentration at this position did not fall down but rose up in a short time. Hence, the results showed that the variation law of concentration at 0.2 m above the model was closer to that when the rotor is at rest. Therefore, the position at 0.2 m above the model is deemed as a better installation position than that at 1.15 m below the mode.

In order to find a better detection points above the model, the responses at 0.1 m above the model was compared with that at 0.2 m. The same operation process as above was repeated. The results are shown in Fig. 15, where the rotor stated at 30 s with the speed of 5000 rpm, and then shut down the system at 40 s.

Fig. 15 The response values of the sensor at 0.2m and 0.1 m above: (a) is the response curve when the model was off, (b) is the results when the rotor with speed of 5000 rpm

When the model was in motionless, the variation law of responses measured at 0.2 m above the model was nearly the same as that at 0.1 m above the model. The only difference lied in that the response peak measured by the sensor at 0.1 m above the model is slightly higher than that measured at 0.2 m above the model because the diffusion of the ethanol in vertical direction from the ground.

Since two measuring points were located above the model, the variation laws of the response values measured by two sensors were roughly the same after the model started to rotate. However, the concentrations detected by the sensor at 0.1m above the model were lower than that at 0.2 m after the rotor rotated. Hence, the rotor movement has less impact on the position at 0.2 m above the model, and it is a fitted position to install the gas sensor for the rotor UAV.

5 Conclusion

In this research, CFD simulation method based on ANSYS fluent was used to study the gas flow field of four rotor UAV under different conditions to find a potential good insulation position for gas sensor. The results showed that the structure of common UAV will lead to the instability of the downwash flow field during its movement, which has impact on the gas sampling. Moreover, the atmospheric conditions and the speed of UAV also affect the sampling process.

Based on the simulation results, the form of reverse assembling the rotor was better than common rotor structure. The influence of the rotor on the flow field around the rotor structure could be reduced significantly with reverse assembling structure, which provides a feasible area for gas sampling. The quantitative results under different atmospheric conditions and rotor speeds showed that the variations of the flow velocity above the model of UAV is relatively stable than that below the model. Moreover, the flow velocity above the UAV is relatively low, thus it is more suitable for gas sampling.

The experimental results of gas sampling based on reverse assembled rotor showed that the collected data at 0.2 m above the UAV model performed better than that at other installation positions, which can meet the sampling requirements.

Accordingly, though there still some problems such as for larger UAV device and more complex atmospheric conditions, the gas sampling optimization discussed in this research can provide good data support for the gas sensing structure with UAV, which is helpful to build an accurate and effect source tracing algorithm based on UAV. It can be applied in the fields of monitoring and identifying the leakage of hazardous gases as well as the emission of contaminant gases in the atmosphere.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests.

Funding

Financial support was provided by the National Natural Science Foundation of China (21808181), China Postdoctoral Science Foundation (2019M653651, 2021T140544), Basic research project of natural science in Shaanxi province (2020JM-021).

Authors' Contributions

DM is the supervisor and designed the research method. SG was in charge of the whole analyses and wrote the initial manuscript; YZ, ZA and YQ assisted with simulation analyses; JM is the supervisor. All authors read and approved the final manuscript.

Acknowledgements

Not applicable

Authors' Information

Denglong Ma was born in Gansu, China, in 1984. He received the Ph.D. degree in power engineering and engineering thermophysics from Xi'an Jiaotong University, where he is currently an Associate Professor with the School of Mechanic Engineering. His research interests include process safety, gas leakage

measurement and monitoring technology, gas source identification, and other issues about safety and computation.

Sicheng Guo, Yuxiang Zhou, Zezhou Ao and Yuhang Qiu are the candidates of master student in the school of Mechanic Engineering in Xi'an Jiaotong University.

Jianmin Gao was born in Shaanxi, China, in 1957. He received Master and Ph.D. degrees in mechanic engineering, in 1989 and 2000, respectively. He is currently the Leader of the Institute of Quality Science and Technology, Xi'an Jiaotong University. He has done many works about reliability, risk, and safety in complex systems. His researches have been applied in many equipment systems successfully

Reference

- [1] Tomaso V., Marco P., Bruno F.. (2021) Critical aspects of natural gas pipelines risk assessments. A case-study application on buried layout. *Process Safety and Environmental Protection* 149, 258-268. <https://doi.org/10.1016/j.psep.2020.10.050>
- [2] Cai J., Wu J., Yuan S. et al. (2021) Numerical analysis of multi-factors effects on the leakage and gas diffusion of gas drainage pipeline in underground coal mines. *Process Safety and Environmental Protection* 151, 166-181. <https://doi.org/10.1016/j.psep.2021.05.017>
- [3] Liu C., Liao Y., Liang J. et al. (2021) Quantifying methane release and dispersion estimations for buried natural gas pipeline leakages. *Process Safety and Environmental Protection* 146, 552-563. <https://doi.org/10.1016/j.psep.2020.11.031>
- [4] Liu T., Lin B., Fu X. et al. (2020) Modeling air leakage around gas extraction boreholes in mining-disturbed coal seams. *Process Safety and Environmental Protection* 141, 202-214. <https://doi.org/10.1016/j.psep.2020.05.037>
- [5] Hisham A. B., Kumar P., Dhinesh T. et al. (2021) Experimental study of accidental leakage behaviour of liquid CO₂ under shipping conditions. *Process Safety and Environmental Protection* 153, 439-451. <https://doi.org/10.1016/j.psep.2021.07.038>
- [6] Wang D., Huang P., Qian X. et al. (2021) Study on the natural gas diffusion behavior in sewage pipeline by a new outdoor full-scale water cycling experimental pipeline system. *Process Safety and Environmental Protection* 146, 599-609. <https://doi.org/10.1016/j.psep.2020.11.049>
- [7] Wang Y., Chen B., Zhu Z. et al. (2020) A hybrid strategy on combining different optimization algorithms for hazardous gas source term estimation in field cases. *Process Safety and Environmental Protection* 138, 27-38. <https://doi.org/10.1016/j.psep.2020.02.029>
- [8] Ma D., Tan W., Wang Q. et al. (2018) Location of contaminant emission source in atmosphere based on optimal correlated matching of concentration distribution. *Process Safety and Environmental Protection* 117, 498-510. <https://doi.org/10.1016/j.psep.2018.05.028>
- [9] Zhang S., Yan Y., Shi L. et al. (2021) A semi-empirical model for underground gas storage injection-production string time series remaining useful life analysis in process safety operation. *Process Safety and Environmental Protection* 154, 1-17. <https://doi.org/10.1016/j.psep.2021.08.003>
- [10] Zhao X., Cheng K., Zhou W. et al. (2022) Source term estimation with deficient sensors: A temporal augment approach. *Process Safety and Environmental Protection* 157, 131-139. <https://doi.org/10.1016/j.psep.2021.10.042>
- [11] Zhang C., Jing D., Wu C. et al. (2021) Integrating Chemical Mass Balance and the Community Multiscale Air Quality models for source identification and apportionment of PM_{2.5}. *Process Safety and Environmental Protection* 149, 665-675. <https://doi.org/10.1016/j.psep.2021.03.033>
- [12] Yang J. C., Chang P. E., Chie W. C. et al. (2016) Large-scale search method for locating and identifying fugitive emission sources in petrochemical processing areas. *Process Safety and Environmental Protection* 104, 382-394. <https://doi.org/10.1016/j.psep.2016.09.015>
- [13] Ma D., Gao J., Zhang Z. et al. (2021) Identifying atmospheric pollutant sources using a machine learning dispersion model and Markov chain Monte Carlo methods. *Stoch Environ Res Risk Assess* 35, 271-286. <https://doi.org/10.1007/s00477-021-01973-7>

-
-
- [14] Ma D., Tan W., Zhang Z. et al. (2017) Parameter identification for continuous point emission source based on Tikhonov regularization method coupled with particle swarm optimization algorithm. *Journal of Hazardous Materials* 325, 239–250. <https://doi.org/10.1016/j.jhazmat.2016.11.071>
 - [15] Ma D., Mao W., Tan W. et al. (2021) Emission source tracing based on bionic algorithm mobile sensors with artificial olfactory system. *Robotica*, 1–21. <https://doi.org/10.1017/S0263574721000904>
 - [16] Lilienthal A., Reimann D., Zell A. (2003) Gas Source Tracing with a Mobile Robot Using an Adapted Moth Strategy. *Autonome Mobile Systeme*, 150–160. https://doi.org/10.1007/978-3-642-18986-9_16
 - [17] Russell, R. Andrew. (2006) Tracking Chemical Plumes in 3-Dimensions. *2006 IEEE International Conference on Robotics and Biomimetics*, 31–36. <https://doi.org/10.1109/ROBIO.2006.340274>
 - [18] Michael H., Hyongdong O., Chen W. (2017) H. A review of source term estimation methods for atmospheric dispersion events using static or mobile sensors. *Information Fusion* 36, 130–148. <https://doi.org/10.1016/j.inffus.2016.11.010>
 - [19] Li J., Meng Q., Wang Y. et al. (2011) Odor source localization using a mobile robot in outdoor airflow environments with a particle filter algorithm. *Auton Robot* 30, 281–292. <https://doi.org/10.1007/s10514-011-9219-2>
 - [20] Branko R., Alex S., Ajith G. (2016) A study of cognitive strategies for an autonomous search. *Information Fusion* 28, 1–9. <https://doi.org/10.1016/j.inffus.2015.06.008>
 - [21] Deng C., Wang S., Huang Z. et al. (2014) Unmanned Aerial Vehicles for Power Line Inspection: A Cooperative Way in Platforms and Communications. *J. Commun.* 9, 687–692. <https://doi.org/10.12720/jcm.9.9.687-692>
 - [22] Carlo D. M., Francesco A., Daniele P. et al. (2016) Using a fixed-wing UAS to map snow depth distribution: an evaluation at peak accumulation. *The Cryosphere* 10, 511–522. <https://doi.org/10.5194/tc-10-511-2016>
 - [23] Niu J., Wang R.. (2014) PM2.5 Low Altitude Measurement System Based on Six-rotor UAV. *Sci. Technol. Eng* 14, 72–76
 - [24] Rossi M., Brunelli D.. (2017) "Gas Sensing on Unmanned Vehicles: Challenges and Opportunities," *2017 New Generation of CAS (NGCAS)*, 117–120. <https://doi.org/10.1109/NGCAS.2017.58>
 - [25] Rossi M., Brunelli D.. (2016) Autonomous Gas Detection and Mapping With Unmanned Aerial Vehicles. *IEEE Transactions on Instrumentation and Measurement* 65, 765–775. <https://doi.org/10.1109/TIM.2015.2506319>
 - [26] Rossi M., Brunelli D., Adami A. et al. (2014) Gas-Drone: Portable gas sensing system on UAVs for gas leakage localization. *SENSORS, 2014 IEEE*, 1431–1434. <https://doi.org/10.1109/ICSENS.2014.6985282>
 - [27] Ya'acob N., Zolkapli M., Johari J. et al. (2017) "UAV environment monitoring system," *2017 International Conference on Electrical, Electronics and System Engineering (ICEESE)*, 105–109. <https://doi.org/10.1109/ICEESE.2017.8298395>
 - [28] Facinelli D., Larcher M., Brunelli D. et al. (2019) "Cooperative UAVs Gas Monitoring using Distributed Consensus," *2019 IEEE 43rd Annual Computer Software and Applications Conference (COMPSAC)*, 463–468. <https://doi.org/10.1109/COMPSAC.2019.00072>
 - [29] Malaver R. J., Gonzalez F., Motta N. et al. (2012) "Towards the development of a gas sensor system for monitoring pollutant gases in the low troposphere using small unmanned aerial vehicles," *2012 Workshop on Robotics for Environmental Monitoring*. 1–3. <https://eprints.qut.edu.au/52042/>
 - [30] Rosser K., Pavey K., FitzGerald N. et al. (2015) Autonomous chemical vapour detection by micro UAV. *Remote Sensing* 7, 16865–16882. <https://doi.org/10.3390/rs71215858>
 - [31] Masat M., Saglam H. K., Ertugrul M. et al. (2021) The use of unmanned aerial vehicles in the detection of forest fires with a gas detection technique. *NanoEra* 1, 14–18.
 - [32] Yuan, H., Xiao, C., Zhan, W. et al. (2019) Target Detection, Positioning and Tracking Using New UAV Gas Sensor Systems: Simulation and Analysis. *J Intell Robot Syst* 94, 871–882. <https://doi.org/10.1007/s10846-018-0909-2>
 - [33] Yuan H., Xiao C., Wang Y. et al. (2020) Maritime vessel emission monitoring by an UAV gas sensor system. *Ocean Engineering* 218, 108206. <https://doi.org/10.1016/j.oceaneng.2020.108206>
 - [34] Mawrence R., Munniks S., Valente J.. (2020) Calibration of Electrochemical Sensors for Nitrogen Dioxide Gas Detection Using Unmanned Aerial Vehicles. *Sensors* 20, 7332. <https://doi.org/10.3390/s20247332>
 - [35] Kersnovski T., Gonzalez F., Morton K.. (2017) "A UAV system for autonomous target detection and gas sensing," *2017 IEEE Aerospace Conference*, 1–12. <https://doi.org/10.1109/AERO.2017.7943675>
 - [36] Shi L., Wang X., Zhang T. et al. (2016) "Hazardous gas detection four-rotor UAV system development," *2016 IEEE International Conference on Mechatronics and Automation*, 2461–2465. <https://doi.org/10.1109/ICMA.2016.7558952>

-
-
- [37] Li J., Zhou Z., Lan Y. et al. (2015) Distribution of canopy wind field produced by rotor unmanned aerial vehicle pollination operation. *Transactions of the Chinese Society of Agricultural Engineering* 31, 77–86.
 - [38] Li J., Zhou Z., Hu L. et al. (2014) Optimization of operation parameters for supplementary pollination in hybrid rice breeding using round multi-axis multi-rotor electric unmanned helicopter. *Transactions of the Chinese Society of Agricultural Engineering* 30, 1–9.
 - [39] Zheng Y., Yang S., Liu X. et al. (2018) The computational fluid dynamic modeling of downwash flow field for a six-rotor UAV. *Front. Agr. Sci. Eng.* 5, 159–167. <https://doi.org/10.15302/J-FASE-2018216>
 - [40] Xue X., Lan Y., Sun Z. et al. (2016) Develop an unmanned aerial vehicle based automatic aerial spraying system. *Computers and Electronics in Agriculture* 128, 58–66. <https://doi.org/10.1016/j.compag.2016.07.022>
 - [41] Li B., Zhou W., Sun J. et al. (2018) Development of Model Predictive Controller for a Tail-Sitter VTOL UAV in Hover Flight. *Sensors* 18, 1424–8220. <https://doi.org/10.3390/s18092859>
 - [42] Ryu M., Cho L., Cho J.. (2016) Aerodynamic Analysis of the Ducted Fan for a VTOL UAV in Crosswinds. *TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES* 59, 47–55. <https://doi.org/10.2322/tjsass.59.47>
 - [43] Lee S., Oh S., Choi S. et al. (2018) Numerical Analysis on Aerodynamic Performances and Characteristics of Quad Tilt Rotor during Forward Flight. *Journal of the Korean Society for Aeronautical & Space Sciences* 46, 197–209. <https://doi.org/10.5139/JKSAS.2018.46.3.197>
 - [44] Dai B., Chen Z., Zhou W.. (2018) Numerical simulation of flow field downstream of a submerged sluice gate based on the realizable k-epsilon model. *Journal of Water Resources and Architectural Engineering* 16, 176-180.