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Construction Network Ventilation System for Underground LPG Storage Cavern

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Abstract

Construction ventilation system is divided into two stages based on completion status of shafts in the underground petroleum storage project in Jinzhou, China. With the help of theoretical analysis and numerical simulations by using FLUENT software, in the first stage, reasonable construction ventilation is designed and cases with different outside temperature are discussed to investigate the effect of ventilation performance. It is found that with temperature difference increases, peak value of CO concentration, exhausting time of dirty air and required time to meet the CO concentration qualification decrease, but the influence degree is quite limited. Gallery-type network ventilation technique (GNVT) refined from theories of operation ventilation for road tunnel and mining ventilation network, is proposed to conduct the second stage construction ventilation. Ventilation performance of different ventilation schemes with various shafts' states and diverse arrangements of fans are also analyzed in this study. It turns out that Axial-GNVT with shafts taking in fresh air and access tunnel ejecting dirty air has much better performance than traditional forced ventilation from access tunnel. Improved energy saving scheme is finally adopted to guide the construction. In addition, it is worth mentioning that there is no need to build middle ventilation shafts and construct shafts as large and long as possible. Field test of wind speed, dust, poisonous gas, atmospheric pressure, temperature are performed to detect ventilation effectiveness. Reduction coefficient ξ_{bs} =0.69is obtained from the test results in consideration of super-large section and it also indicates that there is no difference if the axial fan is at the shaft mouth or in the bottom.

Keywords: Underground Petroleum Storage Caverns; Construction Ventilation System; Computational Fluid Dynamics; Ventilation Network.

1. Introduction

At present, water sealed underground petroleum storage caverns in rock, located in coastal regions where granite, welded stuff and other stable lithological rocks are widely distributed, is no doubt a project with better comprehensive economic effect and is also the main way used for strategic petroleum reserve [1-8]. It has been reported to have many advantages in construction cost, environmental protection, and operation safety [9-15]. Ventilation technique during the construction period in the large-scale underground engineering, related to construction conditions, cost and progress, still remains in exploration stage and there is no one systematic approach to solve this complex issue. Jurani [16] has discussed the main construction task for high-level nuclear waste disposal in a geologic repository and how ventilation design requirements were established and satisfied based upon current criteria. Rezaei et al. [17] have proposed and popularized reliability evaluation method of mine ventilation. Cornel et al. [18] have focused on multi cross tunnels in one underground coal mine project and performed ventilation network numerical simulation by using Canvent

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programme to optimize ventilating arrangements. Li [19] has identified the construction ventilation air safety and health standards combining with the ventilation in the similar engineering construction experience, propane caverns ventilation calculation model was established to determine whether the ventilation program was reasonable based on the theory of three-dimensional numerical simulation and the application of network ventilation via FLUENT software. Zhang [20] has researched forced ventilation technology supplemented jet ventilation in branch tunnel and the jet technology used in operation ventilation was firstly introduced to construction ventilation. Zeng [21] has studied on construction ventilation system of hydropower station underground caverns; influences among each ventilation area, the ventilation effect of different fan's position have been simulated to put forward a reasonable layout scheme of fans and the fan control scheme for different construction conditions. As above research, most researchers [12], [22-24] focused on forced construction ventilation in underground cavern group or ventilation network theory in the mine ventilation.

Furthermore, middle ventilation shafts are added in most cases [25-27], which is, actually, not only adding more construction cost especially that auxiliary shafts need to be blocked after the whole underground facility finished completely, but also causing flow traffic chaos. Stage excavation has been adopted in such underground storage caverns project with large-section and forced ventilation is the preferred alternative method in the first stage. While, pollution of the left stages is much more serious than the first one with working faces and excavated volume increase, which starves for larger air ducts and supply amount to sustain forced ventilation as the first stage. However, restricted to size of access tunnel and power of ventilation equipment, it's unreasonable to increase ducts and the quantity of supplying air. In a word, dust, carbon oxides and nitrogen oxides heap up after tunnel blasting, especially in the case of multi working faces being constructed simultaneously in the underground cavern group engineering. Therefore, advisable and economic construction ventilation method is an urgent problem requiring discussion and resolution. In this study, construction ventilation system technique of an underground petroleum storage project in Jingzhou China is discussed by using FLUENT software and proposed ventilation theory GNVT. Different ventilation schemes are developed to determine the ventilation design for the whole excavation period. The best ventilation network direction is investigated. Other cases with different locations, diameters and lengths of shaft, various fan's locations and diverse temperature difference between outside and inside storage caverns are also discussed on the effect of ventilation performance. Meanwhile, field air quality tests (wind speed, dust, poisonous gas (methane, CO, SO2, H2S), atmospheric pressure, temperature) with the optimal ventilation scheme developed from above research results are conducted in the constructed tunnels every day to inspect ventilation performance.

2. Project Overview

The Jinzhou project is located in Liaoning province, the northeast area of China. The rock in the study area consists primarily of Proterozoic and Cretaceous granite. Based on cores obtained from drill holes in the area, the predominant rock types are granite. Other minor rock types include diorite and amphibolite, which comprise less than 10% of the overall rock mass. The rock mass was classified based on the Q-system. More than 80% of the Q-values correspond to rock of fair to very good rock mass quality. According to geological advanced exploration drilling test, we found most of rocks were micro-weathered granites with developed closed joint fissures. Tunnel face was wet with a high self-stabilization, without chipping in close jointed area. Groundwater in the site is mainly in the form of pore water in the incompact rock mass and fracture water in the bedrock. The complement of the groundwater is mainly from the precipitation. The average annual precipitation in the area over the past 20 years has been 532.7 mm, and heavy rains tend to occur between June and September, when more than 76% of the annual precipitation occurs. Wind direction is N-NW in winter and S-SW in summer, predominant direction is SSW, average wind velocity is 3.8 m/s throughout the year.

The underground facility at this site will consist of eight storage caverns, eight shafts, two construction tunnels, seven access tunnels and five water curtain tunnels. Figure 1 shows the layout of the underground structures. Eight east-to-west storage caverns, which are to be left unlined aside from a layer of shotcrete, are aligned parallel to one another. Every two storage caverns form a storage group, which includes one petroleum inlet shaft and one petroleum outlet shaft. Every storage group is sealed by a set of water curtain system consists of two sets of horizontal water curtain holes and two sets of vertical water curtain holes drilled from the water curtain galleries. The water curtain tunnels are parallel to the storage caverns. The two storage caverns in the same storage group are connected by an access tunnel. The total storage capacity of the project is 3×106 m^3. Each of the storage caverns is 19 m wide at the base, 24 m tall and 934 m long. The access tunnels, which are also arched, are 8m wide and 8m tall. Their elevations vary from El. 0m at the entrance to El. -80 m at the floor level of the storage caverns. The water curtain tunnels, which are also arched, are 6.5 m wide, 6 m tall and 974 m long. The water curtain tunnels are at an elevation of El. -32 m which is 24 m above the storage caverns. The radiuses of outlet shaft and inlet shaft are 3 and 1.5 m respectively, and both of them are 80 m high.

The tunnels and caverns are being excavated using the tri-bench (8+12+8 m) excavation method. Access and water curtain tunnels are constructed first, and shafts are built completely after first bench is finished. Construction ventilation in this underground facility contains two stages, the first one is first bench without shafts and the second one is the second and third bench with shafts finished. This study is based on two storage groups, dashed part in Figure 1.

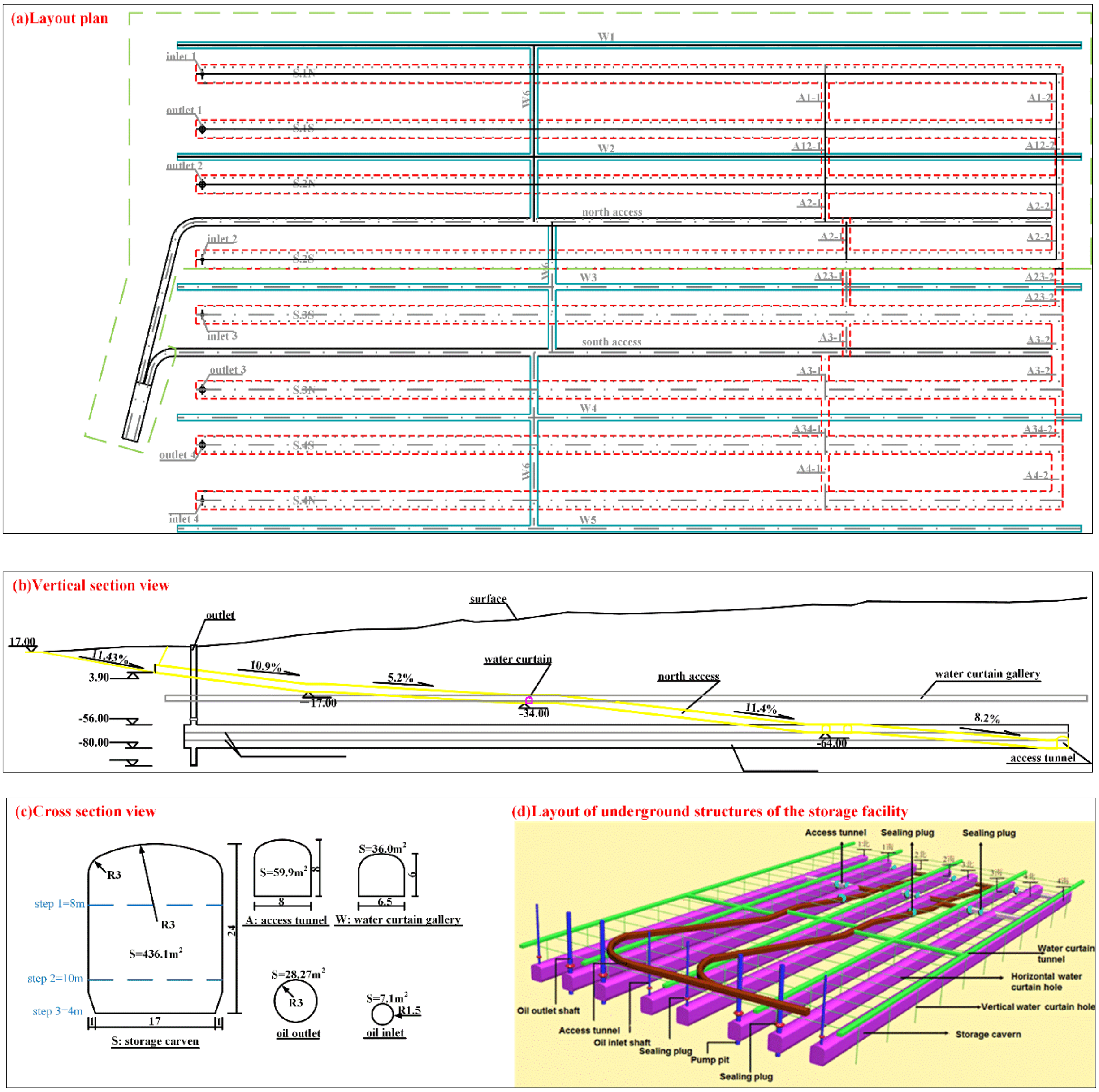

Figure 1. Overview of underground structures of the storage facility

3. Materials and Methods

3.1. Gallery-Type Network Ventilation Technique

3.1.1. Process Principle

Taking advantage of oil outlet and inlet shafts, Gallery-type network ventilation technique (GNVT) unites storage caverns and access tunnels to form ventilation network, as shown in Figure 2(a). Depending on rational arrangement of fans, fresh air taking in from the shaft drives through this network in good order, whilst dirty wind exhausts through the access tunnel, thereby building up one effective air circulation system.

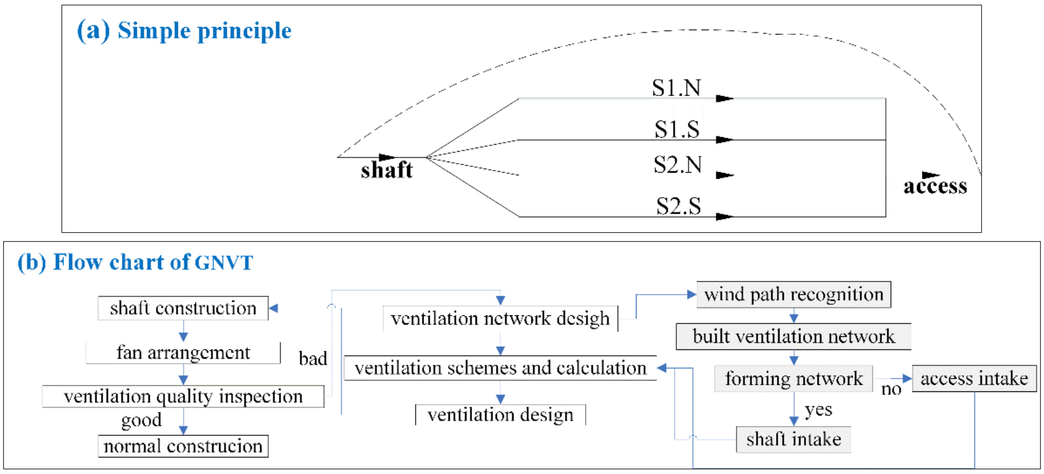

Figure 2. Simple principle and flow chart of gallery-type network ventilation technique for underground petroleum storage facility

For simplicity, we make the following assumptions: a. the air is incompressible; b. the temperatures in all branches are identical. Under assumptions a and b, each branch of the GNVT network is described with the following Equations 1-3:

$$Q = \sum Q_i \tag{1}$$

$$P = \Delta P_i \tag{2}$$

$$R = \frac{1}{\left(\frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \cdots + \frac{1}{\sqrt{R_i}}\right)} \tag{3}$$

Where Q is total air rate, P is overall wind pressure, R is total wind resistance, Q_i, Δp_i and R_i are air rate, wind pressure and wind resistance of each branch respectively, i is the number of network branch.

At each note, the air flow meet air volume and pressure balance, as follows:

$$\sum_{j=1}^{n} Q_{ij} = 0 \tag{4}$$

With ventilation power:

$$\sum_{j=1}^{n} \Delta P_{ij} = 0 \tag{5}$$

Without ventilation power:

$$\sum_{i=1}^{n} \Delta P_{ij} - \sum_{i=1}^{n} H_{ij} = 0 \tag{6}$$

Where Q_{ij} denotes air rate of branch j connected to node i, and it is taken as positive value when air flow into node i, or else it is assigned as negative value, n is the numbers of branches, Δp_{ij} and H_{ij} are wind pressure and ventilation forces (natural wind pressure, traffic ventilation power and fan power) respectively of branch j connected to node i. In addition, each branch complies with resistance law, as listed below:

$$\Delta P_i = R_i Q_i^2 \tag{7}$$

$$P = RQ^2 \tag{8}$$

3.1.2. Key operation

Figure 2(b) presents process stream of GNVT, detailed key steps are as follows.

a. Oil outlet and inlet shafts should be constructed timely after first step has been finished.

b. Ventilation network should guarantee airflow has the same direction as slag wagons' and fresh air arrives at working face in the first place. That is, shaft mouth plays the role as the intake gate of fresh air and the dirty wind discharges from the entrance of access tunnel, one construction transport tunnel connected ground surface and underground facility.

c. Low-loss and high-power fans and are recommended and fewer fans are arranged in inlet air region and large section; more are needed in pollution discharge region and small section. In addition, fans should not be neglected in where the wind direction varies.

d. Two ventilation schemes, jet and axial flow gallery-type network ventilation methods, are proposed in GNVT.

Jet-GNVT

Firstly, calculate required air quantity according to the environmental factors slag wagons and workers and simultaneous explosive amounts in the working face by using Equation 9 and 10 respectively, and then work out required minimum wind speed with Equation 11.

Slag wagons and workers:

$$Q_r = k\Sigma_{i=1}^{N} N_i + 4n \tag{9}$$

Where, Q_r is required air quantity, k is coefficient of ventilation calculation, set as 2.8-3 m^3/s, n is the numbers of workers, N_i is engine power.

Simultaneous explosive amounts:

$$Q_r = P\frac{5Ab}{t} \tag{10}$$

Where, P is safety factor, set as 1.1, t and b are ventilation time and generated CO volume after explosive explosion per kilogram respectively, 45 min and 40 L are recommended in underground storage caverns, A denotes simultaneous explosive consumption, kg, here, A=I1×S×I2;I1 is specific explosive consumption, 1.2, 1.0, 0.8 kg/m^3 are set for the first-step underground storage cavern, access and water curtain tunnel and second and third storage caverns respectively, S is blasting surface area, I2, the length of excavation footage cycle, is taken as 3m in this paper.

Minimum wind speed:

$$Q_r = V \times A_r \tag{11}$$

Where V, representing allowable minimum wind speed in the underground facility, is considered as 0.15 m/s, A_r is the headroom area of the tunnel.

Then choose the highest value as required airflow. Equation 12-14, simplification based on operation ventilation design of <specification for design of ventilation and lighting of highway tunnel>(TJT026.1—1999), are proposed to arrange jet fans.

$$\Delta P_r = \left(\Sigma\varsigma + \Sigma\lambda_i \frac{L_i}{d_i}\right) \bullet \frac{\rho}{2} \bullet V_i^2 \tag{12}$$

$$\Delta P_j = \rho \bullet V_j^2 \bullet \phi \bullet (1-\psi) \bullet K \tag{13}$$

$$n = \frac{\Delta P_r}{\Delta P_j} \tag{14}$$

Where n is numbers of fans; ρ is air density; ΔP_r is ventilating resistance, Pa; ΔP_j represents boosting capacity of jet fan; V_i is the designed wind speed and V_j is outlet wind speed, m/s; $\Sigma\varsigma$ is the sum of tunnel entrance resistance coefficient $\Sigma\varsigma_{in}$, tunnel exit resistance coefficient $\Sigma\varsigma_{out}$ and local resistance coefficient; $\Sigma\lambda_i$ is frictional resistant coefficient, $\lambda_i = \frac{1}{(1.1138-2\log\frac{\Delta}{d_i})^2}$, here, Δ is wall roughness, d_i is hydraulic diameter, $d_i = \frac{4\times A_r}{C}$; $\phi = F_j / F_s$, here, F_j is outlet area and F_s is the area of the cross-section of tunnel; $\psi = V_i / V_j$.

When the shaft is located in the end of the storage cavern, jet fans are assigned in the bottom of the shaft to introduce fresh air, as shown in Figure 3(a); shaft mouth is also a choice if there are no places at the bottom. When the shaft lies in the middle, one axial fan is set at the base to guide fresh air flow into storage carven by air duct and with the help of added jet fans to pull the air low, the fresh air could arrive at working face finally, as pictured in Figure 3(b). Jet-GNVT is much more suitable to whose ventilation distance is above 2 km.

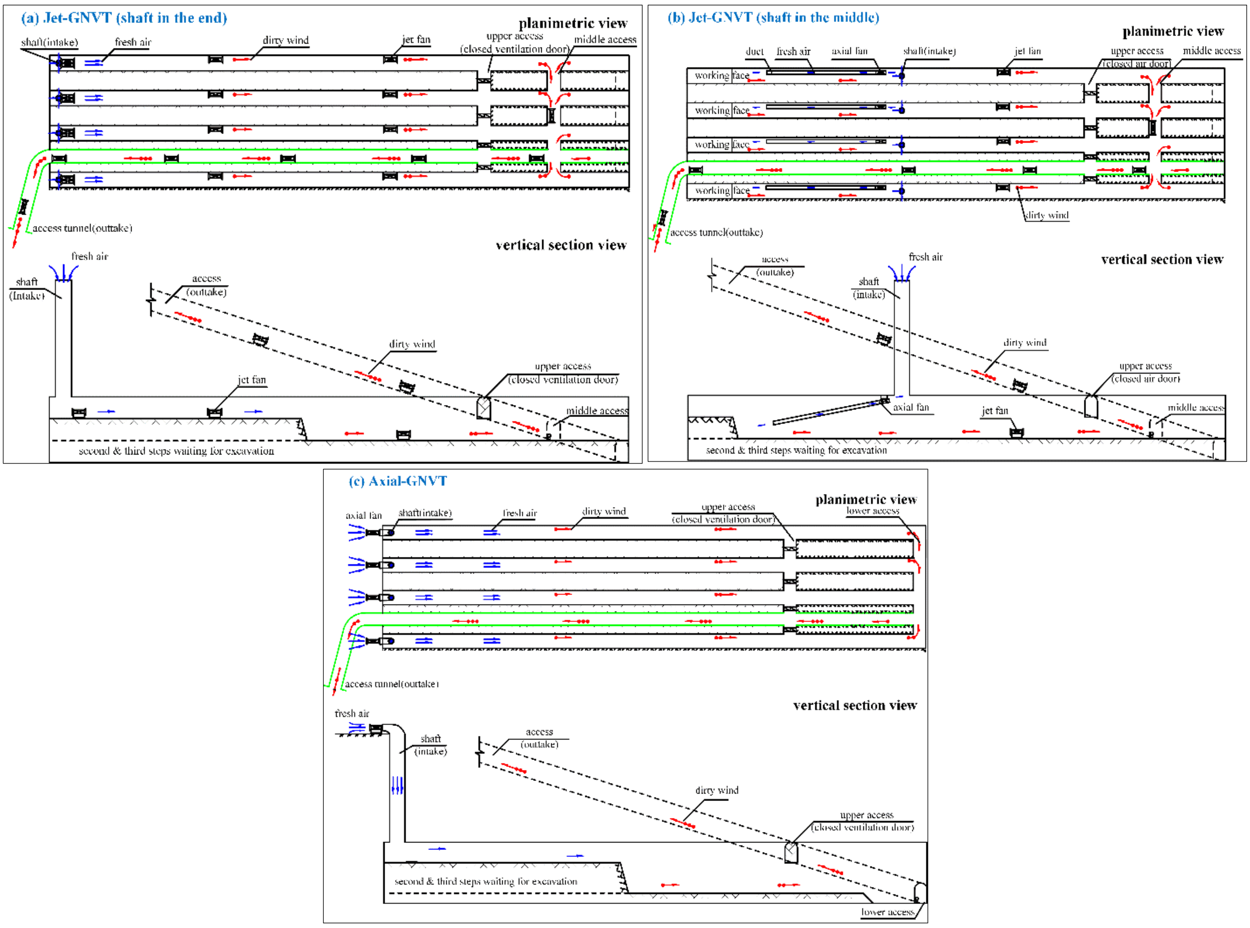

Figure 3. Schematic diagram of Jet-GNVT and Axial-GNVT

Axial-GNVT

At first, calculate required air quantity in the same way as Jet-style. Then determine wind pressure of axial fan by using Equation 15:

$$h = 1.2 \times 0.0013 \frac{L}{d^5} Q_r^{\ 2} \tag{15}$$

Where h represents frictional resistance, Pa; L is the length of the duct, m; d is the diameter of the duct. Actually, the shaft and tunnel are considered as ventilation duct, whose frictional resistance is much less than ventilating pipe. Therefore, the calculated h is regarded as a reference factor not the governing factor to conduct axial fans arrangement.

Next, choose proper axial fan in consideration of required air quantity, fan performance curve and power parameters of axial flow fan (see the Equation 16 and 17).

Shaft power:

$$S_{kw} = \frac{Q_a \cdot p_{tot}}{1000\eta} \cdot \left(\frac{273 + t_0}{273 + t_1}\right) \cdot \frac{p_1}{p_0} \tag{16}$$

Where S_{kw} represents shaft power, kW; Q_a is fan delivery, m^3/s; P_{tot} is full air pressure of fan, N/m^2; η indicates fan efficiency, 80% is accepted value; t_0 is standard temperature, 20℃ is adopted; t_1 is ambient temperature of fan; p_0 is standard atmosphere, $101.325 N/m^2$; p_1 is ambient temperature, N/m^2.

Motor power of axial fan:

$$M = \frac{S_{kw}}{\eta_m} \cdot k \tag{17}$$

Where M is power of motor, kW; η_m indicates motor efficiency, 90%~95% is recommended; k is safety factor of electromotor capacity, here, 1.15 is accepted value.

Finally, the axial fan is set firmly in the bottom of shaft or shaft mouth, as shown in Figure 3(c).

e. In order to avoid blasting effect, special cables for fans are accessed from shaft if the fans are located in the frond of working face, which are accessed from access tunnel if the fans are lied in the behind of working face.

f. Close upper access tunnel, which is also designed to be blocked after storage caverns excavation finished, before second and third steps excavation, which helps to form GNVT network.

g. Detect wind speed, temperature, humidness and air pollution load inside the storage caverns regularly to inspect ventilation quality, which contributes to optimize ventilation design.

h. Adjust fan assignment and operation state timely according to specific construction situation to satisfy air quality requirements in the cavern.

3.2. Simulation Method

Considering air flow of underground oil storage caverns as steady turbulent flow, and picking high Renold number k-ε model as mathematical model, computational fluid dynamics software FLUENT is adopted to conduct numerical simulation calculation in this paper.

3.2.1. Boundary and Initial Conditions

Based on the actual situation, boundary conditions are set as follows:

a. Walls of tunnels and shaft are set as wall surface and wall-parameters are adopted according to practical roughness.

b. Fan outlet is taken as constant-speed boundary condition.

c. Outtake of storage cavern is set as pressure boundary condition.

d. When the fans are fixed inside the caverns, fan inlet, set as flux boundary, is taken the wind quantity of fans as the value; fan outlet, set as constant-speed boundary, is taken outlet speed as the value and wall of the fan is delimited as solid boundary.

Initial CO concentration can be determined in Equation 18:

$$c = \frac{Gb}{LA} \tag{18}$$

Where c denotes CO concentration, ppm; G is explosive amounts, kg; b, produced toxic gases per kilogram, m^3/kg, is considered as 0.04; A is excavated cross-sectional area, m^2; L, length of tunnel polluted by blasting smoke, can be calculated by empirical formula $L = 15 + G/5$, m.

3.2.2. Simulation Cases

Figure 4 presents different cases of construction ventilation system for underground oil storage facility during the whole excavation period. Before shafts have been finished - the first-stage construction ventilation, three cases (access tunnel, water curtain tunnel and storage cavern under construction) are analyzed to determine the ventilation design for the first-step excavation. And seven cases are studied under different outside temperature to discuss the effect on ventilation performance. After the shafts completed, i.e., storage caverns have been connected to the ground surface through more than access tunnel, the second-stage construction ventilation, shafts could also help air circulation, four main study schemes have been investigated to improve ventilation effectiveness for the second and third steps: a) Effect of different locations, diameters and lengths of shaft on ventilation performance. b) The best network direction of GNVT. c) Best fan's locations around shaft (at the shaft mouth or at the bottom), and nine more cases are studied to discuss the best position in the bottom of shaft. d) Two natural ventilation with shaft schemes simulation (shaft intake air when outside temperature is lower and shaft outtake air when outside temperature is higher).

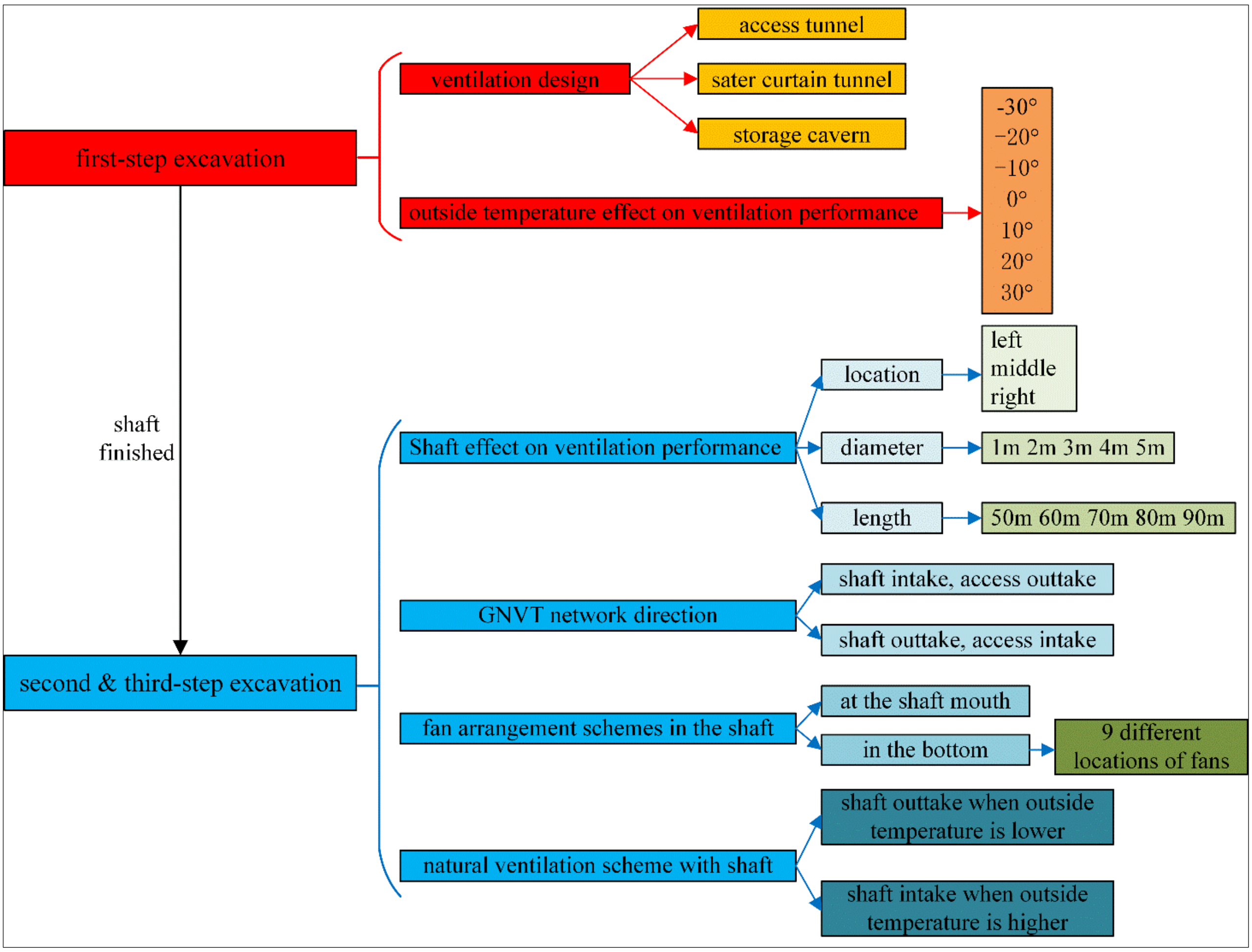

Figure 4. Different cases of construction ventilation system for underground LPG storage cavern

3.3. Field Test

In order to inspect air quality and ventilation performance in the constructed tunnels, wind speed, dust, poisonous gas (methane, CO, SO_2, H_2S), atmospheric pressure, and temperature are tested in different positions every day, as shown in Figure 5. Test method is as follows: a) Wind speed test - tested cross sections, at interval of about 100 m, of storage cavern and access tunnel are divided into 9 and 4 parts respectively in consideration of different tested value at various height in large underground cavern, as presented in Figure 5 (e). b) Poisonous gas and O_2 test is performed in the same position as wind speed test. c) Dust must be measured immediately after blasting of excavated face every 5 min near working face and tunnel lining trolley. Finally, weighted average tested value of every cross section is adopted to investigate ventilation performance and Table 1 indicates control value of every air quality index and test instrument.

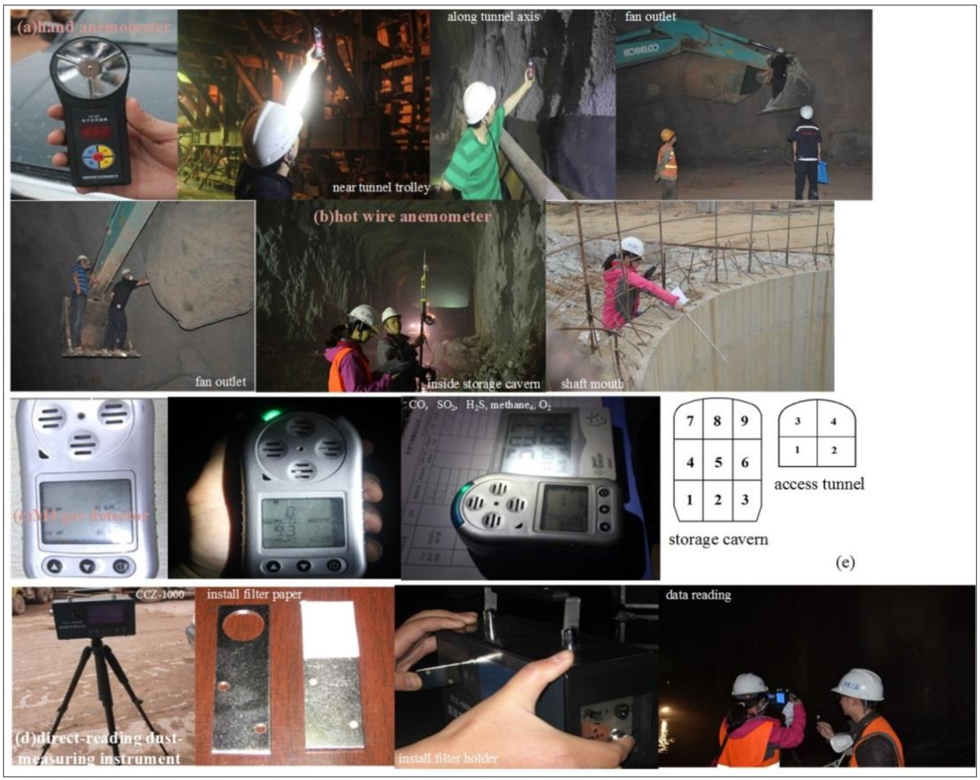

Figure 5. Field wind speed measurement and air quality test

Table 1. Control value of air quality indexes in the tunnel

Air index	Allowable value	Instrument
above 10% free SiO_2 dust	≤2 mg/m³	CCZ-1000 direct reading dust measuring instrument
below 10% free SiO_2 dust	≤4 mg/m³	CCZ-1000 direct reading dust measuring instrument
CO	≤30 mg/m³	M4 gas detector
H_2S	≤10 mg/m³	M4 gas detector
SO_2	≤14.3 mg/m³	M4 gas detector
temperature	≤28℃	hand and hot wire anemometer
wind speed	-	hand and hot wire anemometer
O_2	≥20%	M4 gas detector

4. Optimal Ventilation Design for First-Step Excavation

4.1. Ventilation Design

The first-stage construction ventilation contains three parts: a) Access tunnel construction-the primary step to construct this underground facility. b) Water curtain tunnel driving-must be finished before storage cavern digging. c) The first step storage cavern excavation. Forced ventilation with axial fans is one preferred alternative design for digging tunnel with only one opening to the ground surface, here are the processes. Firstly, maximum ventilation length of each part is determined, as shown in Figure 6(a). Afterwards, maximum required airflow and maximum pressure loss of each part are calculated in Equation 9-11 and 15. Finally, suitable type of fans and ventilation duct are picked according to the calculation results. Table 2 presents ventilation calculation results for first-step excavation; it also shows ventilation design for this stage. Zippered vinylon duct with major diameter 1.8 m and low friction loss is used, and, four fans (SDZ-12.5, performance parameters are listed in Table 3), one fan and three fans are set to supply fresh air for storage cavern, access tunnel and water curtain tunnel construction stages respectively. Daily power consumption is obtained in Table 2 as well. Figure 6(b) plots ventilation scheme for the first stage in the worst situation, when multiple working faces work simultaneously, four jet fans are put in four storage cavern and three more are set in access tunnel to help exhaust dirty air.

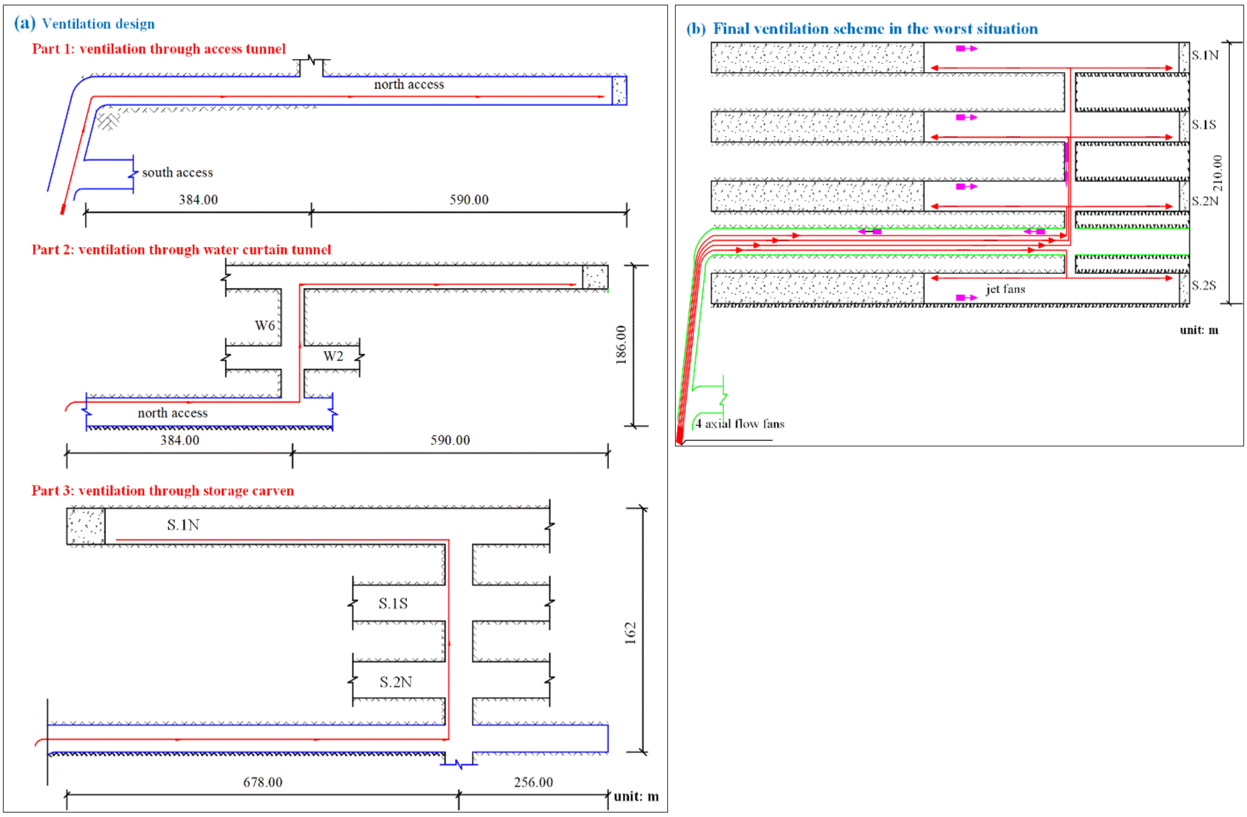

Figure 6. Ventilation design for first step excavation of storage carven

Table 2. Ventilation calculation results for first-step excavation

Part	Construction region	Maximum ventilation length (m)	Maximum required airflow (m^3/min)	Maximum pressure loss (Pa)	Duct diameter (m)
part 1	north access	1069	1581	613	1.8
part2	water curtain	1236	1350	2366	1.8
part 3	storage cavern	2165	1980	1946	1.8
fan assignment	access tunnel: 1fan, water curtain gallery: 3 fans, storage caverns: 4 fans				
power consumption	total power =2×135×4=1080kW, daily electrical usage=1080×7=7560kwh				

Table 3. Parameters of axial-flow fan

Fan type	Velocity	Air volume (m^3/min)	Air pressure (Pa)	Power (kW)	High efficient air volume (m^3/min)	Efficiency (%)
SDZ-12.5	high	1650-2800	5000-1500	135×2	2400	81%
	medium	1200-1900	2600-700	47×2	1600	81%

One numerical simulation model with four axial fans assigned at the entrance of access tunnel is built to detect ventilation effect in the first stage. Pollution source is set in the left of S.1N, furthest away from access entrance. Figure 7(a) displays seven moments (initial state, ventilation for 5, 10, 15, 20, 25 and 30 min) of CO concentration after blasting. From this figure, you can see that CO concentration pushes along access tunnel with time and reaches to national safety standard 24 ppm basically after ventilation for 20 min. After 30 min, the whole tunnels meet safety standard, and then follow-up construction can be performed. Figure 7(b) indicates that CO concentrations in 100 and 300 m front of working face appears one peak with time and drop down below 24 ppm after 20 min. There results do help to construction opportunity selection and avoid worker injury.

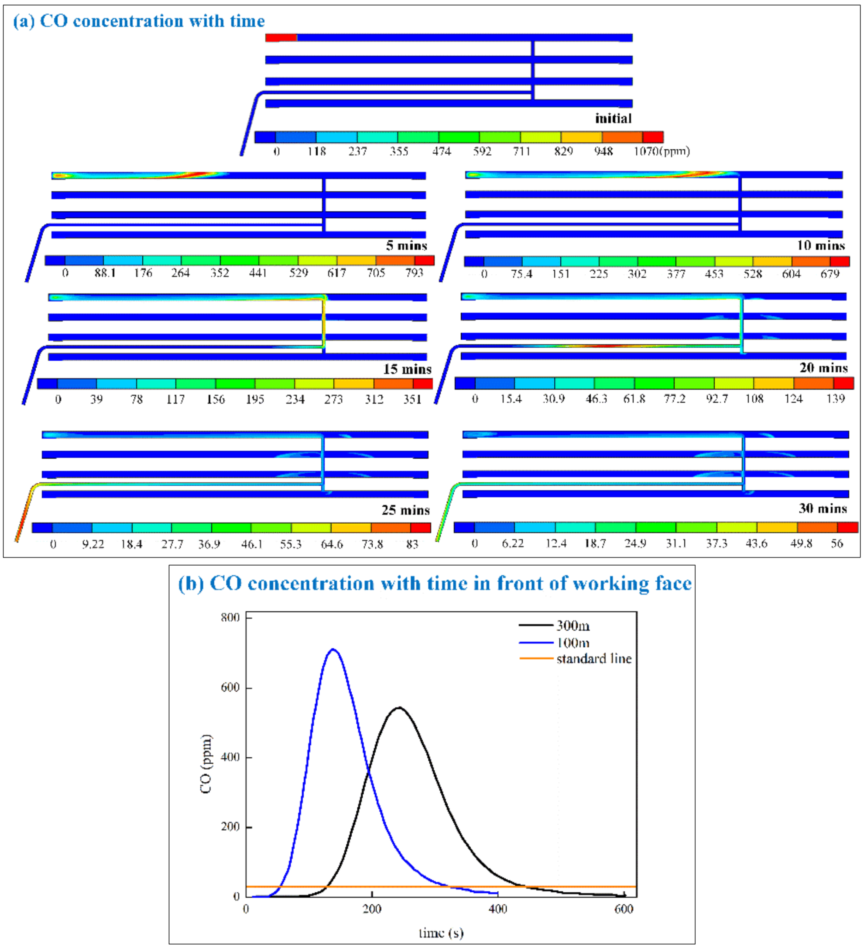

Figure 7. CO concentration with time of first step excavation

4.2. Outside Temperature Effect on Ventilation Performance

Seven cases with different outside temperature are analyzed to investigate ventilation performance, here, inside temperature is 15℃. Figure 8(a) and 8(b) depict CO concentration with time and required time to meet the CO concentration qualification in different outside temperature in front of working face for 500 m respectively, as can be seen that with temperature difference increases, peak value of CO concentration and required time to below 24 ppm decrease and exhausting time of dirty air shortens, but the influence degree is quite limited.

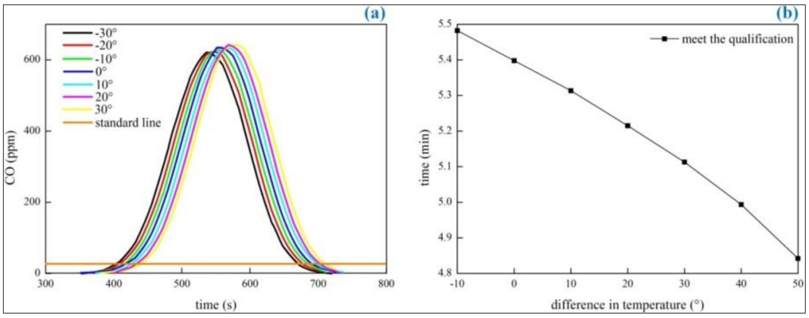

Figure 8. CO concentration versus time and required time to meet the qualification in different outside temperature in front of working face for 500 m

5. Optimal Ventilation Network for Second and Third-Steps Excavation

5.1. Shaft Effect on Ventilation Performance

After the first-step excavation has been finished, the outlet and inlet shafts also have been completed, which means the whole underground storage facility can be connected to the ground not only from access tunnel but also from the shafts. 13 models with the same geometry as first-step cavern, whose fans are assigned at the access entrance, are built in this paper to study the ventilation effectiveness of different locations, diameters and lengths of shafts.

5.1.1. Location

Two working faces, i.e. two pollution sources, at both ends of storage caverns are set in cases of different shaft's locations (left, right, middle) respectively. It can be seen from Figure 9(a), when shaft is set on the left side, most CO on the left can be discharged after ventilation for 5 minutes, and they are all out after 10 minutes. Then CO produced on the right working face move to the left and exhaust through the shaft. The movement route is totally opposite of the case with shaft on the right, as shown in Figure 9(b). When shaft is installed in the middle, CO from both left and right working faces drive to the middle shaft and there is no CO detained in the access tunnel during the whole ventilation period, as presented in Figure 9(c). Figure 9(d) describes CO concentration along S.1N tunnel axis after ventilation for 30 minutes, as can be observed that CO gathers in the side where the shaft located with highest concentration, whilst there is also lower CO concentration existed in the other side, as a result of two pollution sources and forward motion of air flow produced of two ventilation ducts in both ends, when the shafts are set on both ends. Basically, expect a small amount of CO concentration in both ends is a little higher than 24 ppm, ventilation effect works very well in the storage cavern. Whereas there is no CO gathered in the storage cavern after ventilation for 30 minutes, and the highest concentration is 14ppm, lower than 24 ppm. Thus it can be seen that installing shaft in the middle is the most beneficial to CO discharge, but the tiny advantage can be neglected over ventilation time with a limited budget and construction conditions.

5.1.2. Diameter

Working faces and shafts are set at the left side of storage caverns in cases of different shaft's diameters (1, 2, 3, 4, 5 m). The results show that CO concentration curves with different diameters are almost exactly the same in front of working face for 500 m, which means diameter does not affect CO distribution when dirty air doesn't pass the shaft; case with diameter as 1m has the highest CO concentration at the shaft mouth and case with diameter as 2 m has the lowest peak value at the shaft mouth, which has the same highest and lowest cases 100 m below shaft mouth, and the peak value decreases with shaft diameter increases only among cases with diameters as 3, 4, 5 m that is, increasing shaft's diameter to improve ventilation performance has only limited effect, as shown in Figure 9(e).

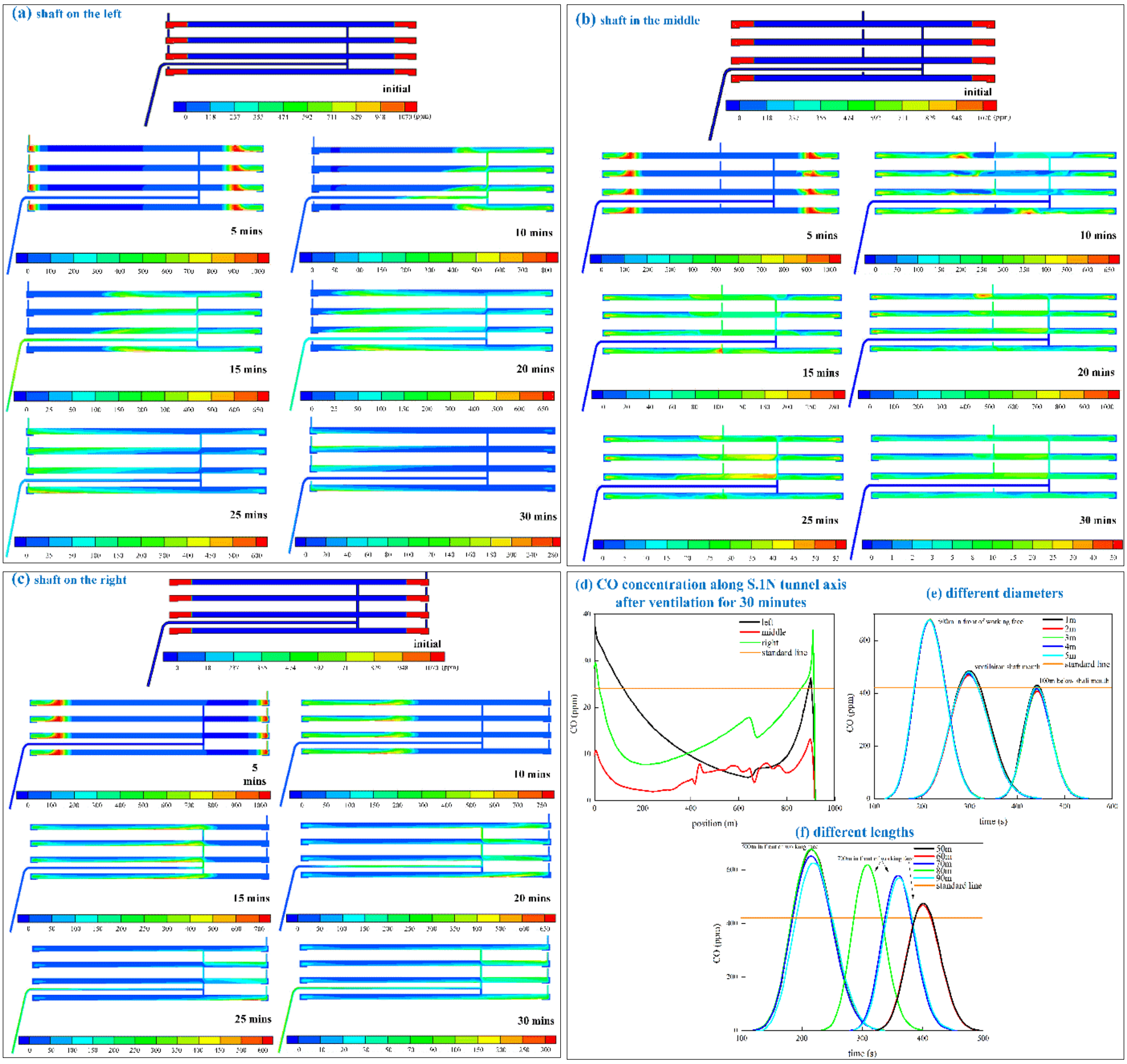

Figure 9. CO concentration versus ventilation time with different locations, diameters and lengths of shaft

5.1.3. Length

Cases of different shafts' lengths have the same pollution sources and geometric model as cases of different shafts' diameters. From Figure 9(f) we can see length as 50, 60 and 80 m have the highest peak value and 90 m has the lowest in front of working face for 500, 80 m gets the first place and 60 m is the last one on the peak value in front of working face for 700 m. However 80 m is the first one to calm down to the standard line in front of working face for both 500 and 700 m, especially in 700 m part, it can be recognized obviously. In other words, 80 m has the least time to exhaust dirty air and ventilation of such length performs the best.

5.2. Best Ventilation Network Selection

GNVT network has two airflow directions – fresh air take-in from the access tunnel and take-out through the shaft, and air take-in from the shaft and take-out through the access tunnel. Also, network is simplified with only two nodes and four parallel airflow lines, as shown in Figure 10(a). Figure 10(c) and (d) plot CO concentration with time of second and third excavation in two airflow directions, here, and pollution source is set in the left of S.1N. The simulation results show that CO produced in the working face flow inside the storage cavern and a small quantity gather in the other end, whose concentration become lower than 12 ppm after ventilation for 30 minutes, when fresh air is taken in from the shaft. CO only exist near the working face, however, still remain higher than 24 ppm even after ventilation for 30 minutes, when shaft is used to eject dirty air, which proves that case of shaft taking in fresh air is better than shaft take-out and it has a better working condition after ventilation.

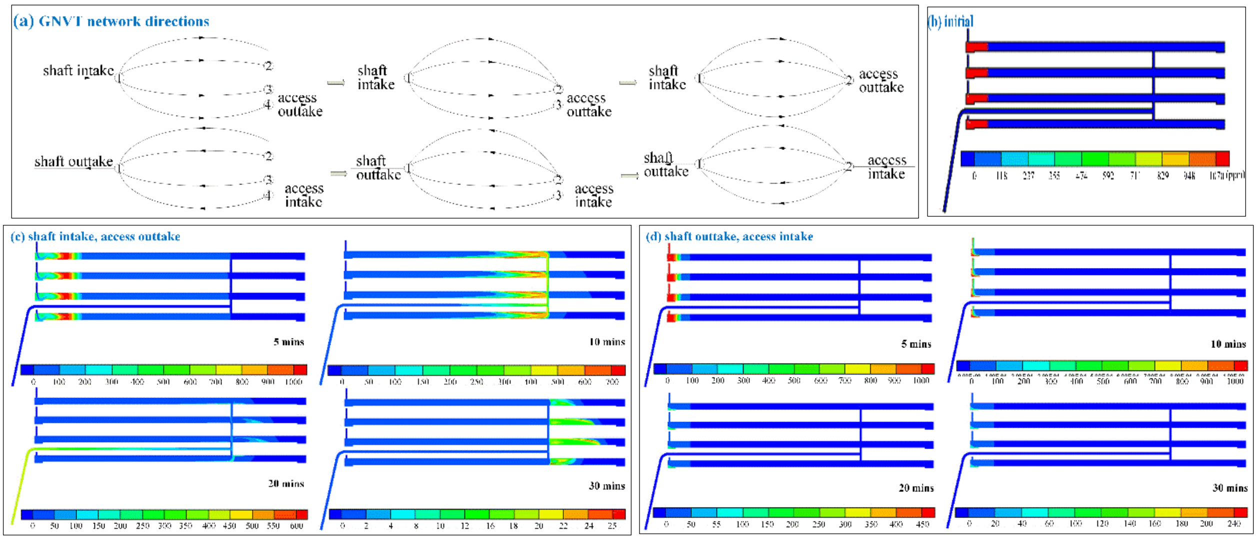

Figure 10. GNVT network directions for second and third steps excavation

5.3. Fan Arrangement Schemes in the Shaft

Two models - fans assigned on the top (Scheme 1) and in the bottom (Scheme 2) of the shaft are built to investigate a preferable fan's position for fresh air intake from the shaft, as shown in Figure 11(a). The result indicates that CO have been dropped below 24 ppm even in front of working face for 500 m after ventilation for 450s and 390s in Scheme 1 and 2 respectively, in addition, CO move to the access tunnel and peak value of CO concentration decrease with time in both schemes, as presented in Figure 11(b)-(e). It also shows that peak value of CO concentration in scheme 2 is a slightly higher, but each curve of Scheme 2 reaches the standard line firstly. Figure 11(f) plots required time to meet the CO concentration qualification with different distances in front of working face under Scheme 1 and 2, as we can see that less time is needed to be reduced to 24 ppm in Scheme 2, thereby proceeding next working procedure much more quickly. Partial model (storage cavern is 100m in length) of scheme 1 is developed to detect ventilation performance in Figure 11(g), as can be seen that one vortex region is produced in the left wall of the shaft, which causes big flow loss and less air flow is introduced into storage cavern, although wind speed could come to 4 m/s. Therefore, placing fan in the bottom of the shaft is propitious to CO ejection.

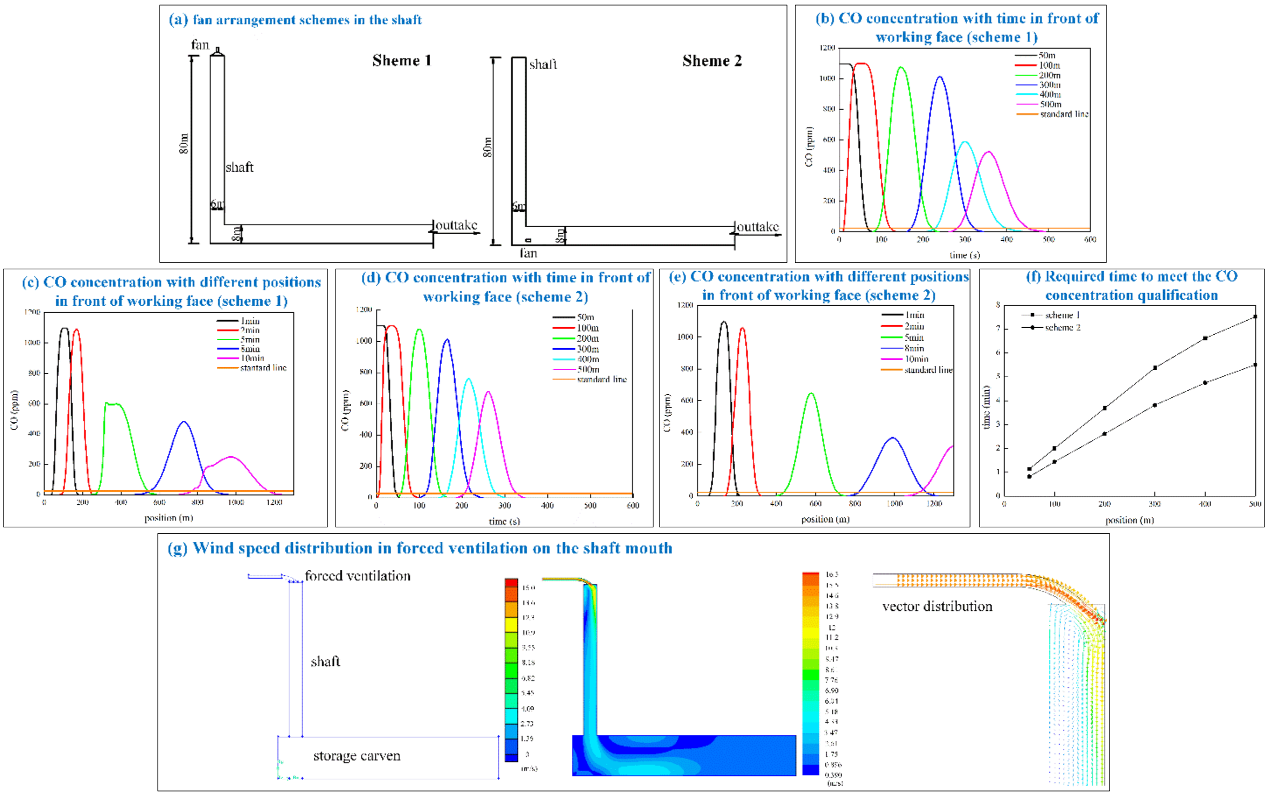

Figure 11. Fan arrangement schemes in the shaft

Nine models are developed to study a best and feasible position of fan in the bottom of the shaft, as shown in Figure 12. It turns out that positions 7, 8 and 9 have a bigger entrainment room while 1, 2 and 3 have the least. For example, wind speed at inlet cone of fan can come to 11.28 m/s in position 5 and only 4.92 m/s in position 3. What's worse, positons 1, 2 and 3 cause vortex regions, it goes against taking in fresh air. Position 5 has a best drainage effect of fan obviously as you can see from the last picture in Figure 12.

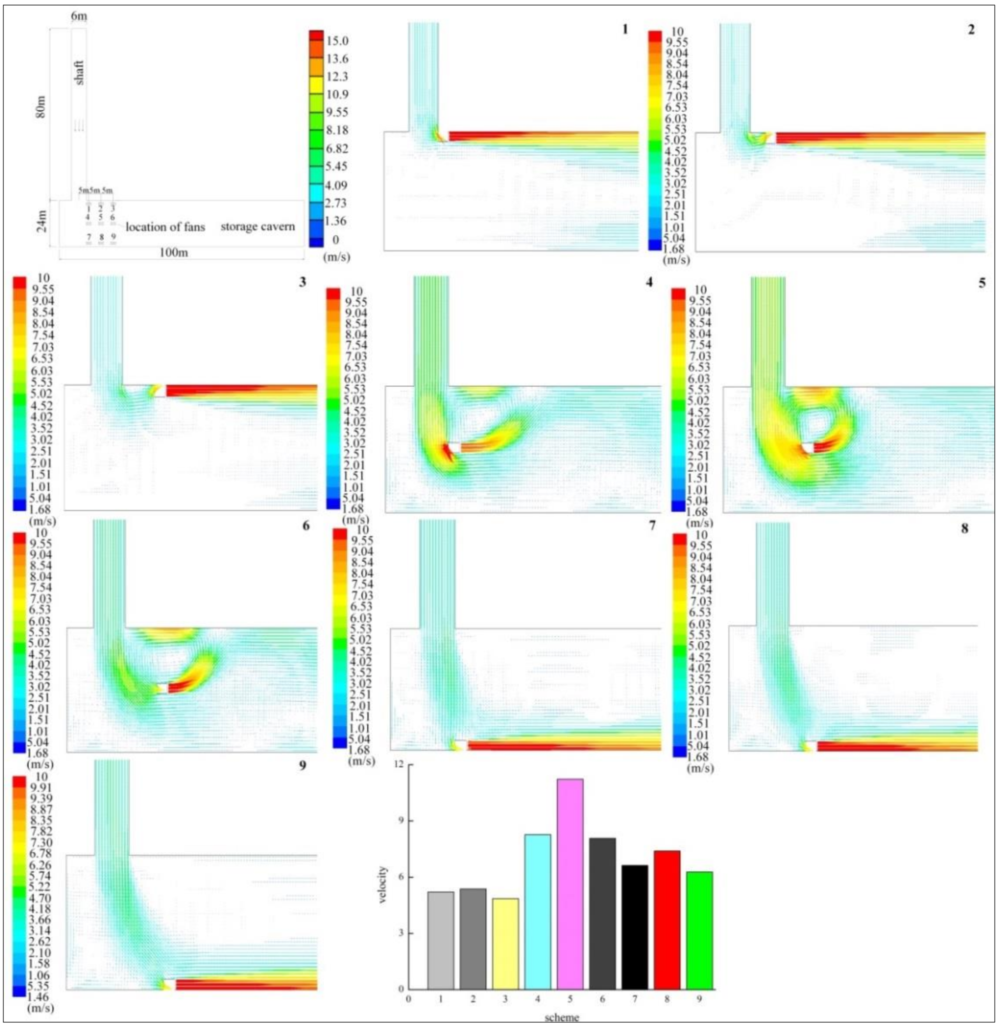

Figure 12. Air velocity distribution in 9 locations of fans

5.4. Natural Ventilation Scheme with Shaft

From the results of outside temperature effect on ventilation performance in ventilation Stage 1, we can see temperature difference between outside and inside does affect ventilation effectiveness. After shafts have been completed, models, with two working faces in the both ends, under different outside temperatures with inside temperature as 15℃ are created to investigate more economically rational natural ventilation scheme by the use the shaft. Natural ventilation scheme doesn't mean ventilation without any mechanical equipment in the underground storage facility; it means fewer fans are assigned in the caverns. Two schemes, shaft outtake airflow when outside temperature is lower (-10℃, -5℃, 0℃, 5℃ and 10℃) and shaft intake airflow when outside temperature is higher (20℃, 25℃and 30℃), are proposed to detect ventilation effectiveness.

5.4.1. Shaft Outtake Airflow when Outside Temperature is Low

As we can see from Figure 13(a), various temperature differences not only affect CO concentration distribution, but also ventilation time. When the outside temperature is 10℃, CO concentration is 39 ppm, higher than standard, in front of right working face, after ventilation for 30 minutes, as shown in Figure 13(c). However, CO concentration drops below 24 ppm after ventilation for 20 minutes, when outside temperature is -10℃. From Figure 13(c), it is also indicated that the highest CO concentration gathers in front of right working face at a distance as 50-150 m, and the higher the temperature different is, the lower the CO concentration.

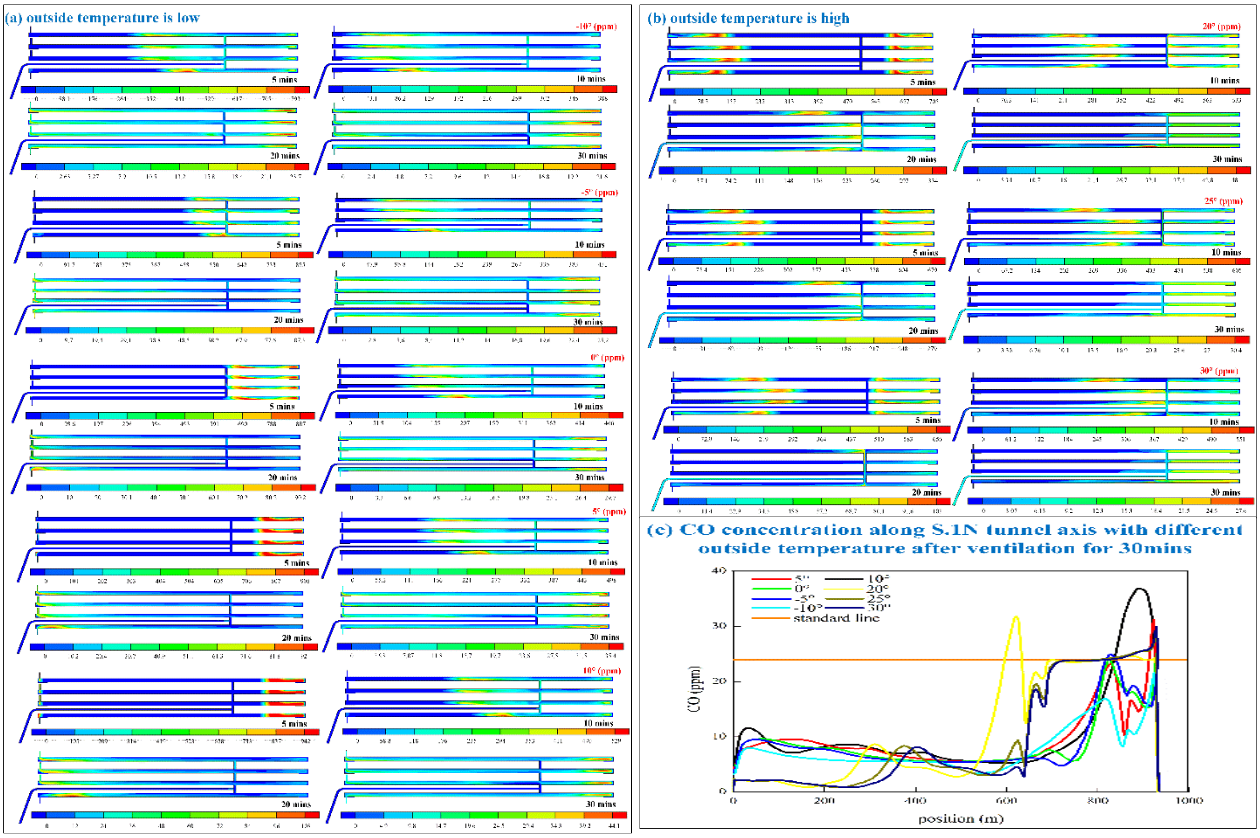

Figure 13. (a)CO concentration versus time with shaft outtake airflow when outside temperature is low, (b)CO concentration versus time with shaft intake airflow when outside temperature is high, (c) CO concentration versus different positions along S.1N tunnel axis with different outside temperature after ventilation for 30 min

5.4.2. Shaft Intake Airflow When Outside Temperature Is High

In Figure 13(b), the higher the temperature is, the lower the CO concentration and the better ventilation effectiveness, in the same ventilation time. After ventilation for 30 minutes, the average CO concentration catches down to the standard and the higher concentration get together in access tunnel and in front of right working face, as listed in Figure 13(b) and 13(c).

Therefore, compared with only mechanical forced ventilation scheme in Figure 10, combing mechanical and natural ventilation together makes a relatively good result, especially when the temperature different is high enough. Nevertheless, it has limitations with the outside higher or lower airflow entering into inside, which narrows the temperature difference, such a situation where heat producer is needed inside the cavern. That is, mechanical ventilation plays in the regular first-team to maintain air circulation.

5.5. Ventilation Design

From the simulation results of various cases above, three GNVT ventilation schemes are proposed to investigate the economic and reasonable one: a) Take in air from the four shafts and dirty air discharge from the access tunnel with Jet-GNVT. b) Take in air from the four shafts and dirty air discharge from the access tunnel with Axial-GNVT. c) Take in air from access tunnel with axial fans assigned in the access entrance and dirty air exhaust from the shafts. Required air quantity and wind speed are calculated by use of Equation 9-11 in Table 4.

Table 4. Required air quantity and wind speed

region	required air quantity(m^3/s)	required wind speed(m/s)
storage cavern (first step)	39.63	0.15
storage cavern (second step)	48.75	0.15
storage cavern (third step)	65.4	0.15
R3 shaft	65.4	2.31
R1.5 shaft	65.4	9.21
north access	261.6	4.37

5.5.1. Scheme A

Ventilating resistance and boosting capacity of jet fans for each region, and total number of jet fans are calculated in Equation 12, 13 and 14, as listed in Table 5. Here, 23 75 kW jet fans are adopted to conduct construction ventilation under the ground. Dirty air can be easily diluted in the storage cavern with such a large cross section and only maintaining good air circulation in construction-level can meet air-quality limit, nevertheless, there is no need to calculate the required air quantity with the whole cross section. Therefore, 18 fans (3 for each storage cavern, 6 for north access tunnel) are assigned for normal ventilation and 5 more are considered for preparation in case of emergency. Daily power consumption is also obtained in Table 5.

Table 5. Ventilation design of scheme a

region	ΔP_r (Pa)	ΔP_t (Pa)	n
one storage cavern	0.17	4.25	0.04
oneR3 shaft	371.55	226.55	1.64
oneR1.5 shaft	351.53	1673.95	0.21
north access	13.68	1.10	12.43
total number of jet fans	N=4×1+13+2×2+1×2=23		
fan performance parameters	75kW jet fan		
fan assignment	each storage cavern: 3 fans north access tunnel: 6 fans 5 more for preparation		
power consumption	total power=18×75=1350kW, maximum power=23×75=1725kW, daily electrical usage=1350×10=13500kwh		

5.5.2. Scheme B

The longest ventilation distance and maximum pressure loss for each region are calculated in Equation 15, as listed in Table 6. SDZ-12.5 axil fan, which is set at the mouth of shaft of each storage cavern, is selected based on configuration principle of axial-fan and calculations. Daily power consumption is also obtained in Table 6.

Table 6. Ventilation design of scheme b

region	longest ventilation distance(m)	maximum pressure loss(Pa)	duct
one storage cavern	934	34	storage cavern
north access	1069	5757	access tunnel
fan performance parameters	SDZ-12.5, air volume: 2400 m^3/min, total pressure: 5000Pa, power: 2×135kW		
fan assignment	1 fan is set at the mouth of shaft of each storage cavern		
power consumption	total power=2×135×4=1080kW, maximum power=1080kW, daily electrical usage=1080×10=10800kwh		

5.5.3. Scheme C

The longest ventilation distance and maximum pressure loss for each region are calculated in Equation 15, as listed in Table 7. Considering multiple working faces being constructed simultaneously with only one entrance of access tunnel as air intake, 7 SDZ-12.5 axil fans are set at the access entrance. Daily power consumption is also obtained in Table 7.

Table 7. Ventilation design of scheme c

region	maximum ventilation length(m)	maximum pressure loss(Pa)	duct diameter(m)
S.1N Left	2165	764	1.8
S.1S Left	2108	744	1.8
S.2N Left	2051	724	1.8
S.2S Left	2086	737	1.8
access tunnel	1069	604	1.8
S.1N Right	1739	614	1.8
S.1S Right	1682	594	1.8
S.2N Right	1625	574	1.8
S.2S Right	1615	570	1.8
fan assignment	7 fans are set at the entrance of access tunnel		
power consumption	total power =2×135×7=1890kW,daily electrical usage=1890×10=18900kwh		

5.5.4. Scheme Comparison

Scheme c, with the opposite ventilation direction to Scheme a and b, has the highest power consumption. And fresh air around working face could be mixed with dirty wind produced by slag car, which has a much weaker ventilation performance than Scheme a and b with air intake from shaft and fresh air flowing through working face, storage cavern and access tunnel. Therefore, scheme b, with the lowest cost, is the optimal choice.

Table 8. Test results of wind flow and air quality

position	wind speed m/s	CO mg/m^3	SO2 mg/m^3	Dust (%)	O2(%)	H2S mg/m^3	ventilation distance(m)	power	fan location
1 S.1N	0.1	22.89	8.25	0.29	20.6	1.46	570	low	mouth
2 S.1N	0.7	15.65	8.25	0.19	20.7	1.46	710	high	mouth
3 S.1N	0.15	1.20	4.12	0.29	20.6	0	660	low	bottom
4 S.1N	0.75	6.02	4.12	0.04	20.7	0	420	high	bottom
5 S.1N	1.22	21.66	4.12	0.33	20.6	0	730	high	bottom
6 S.1N	0.55	1.0	0	0	20.7	0	330	low	mouth
7 S.1N	0.35	1.3	0	0	20.6	0	700	low	bottom
8 S.1N	0.23	1.1	4.0	0	20.6	0	300	low	bottom
9 S.1S	0.45	7.02	6.6	0.14	20.6	1.3	300	low	mouth
10 S.1S	0.1	19.23	8.4	0.30	20.6	1.47	550	low	mouth
11 S.1S	0.55	1.3	0	0	20.6	0	600	low	bottom
12 S.1S	0.3	0	0	0	20.6	0	400	low	bottom
13 S.1S	0.75	1.1	0	0	20.6	0	700	high	bottom
14 S.1S	0.1	1.01	0	0	20.6	0	450	low	mouth
15 S.1S	0.9	0	0	0	20.6	0	680	high	bottom
16 S.1S	1.1	0	0	0	20.6	0	710	high	bottom
17 S.1S	1.0	0	0	0	20.7	0	730	high	mouth
18 S.2N	0.4	20.9	8.25	0.28	20.6	1.46	600	low	bottom
19 S.2N	0.3	19.8	6.02	0.13	20.6	1.02	300	low	bottom
20 S.2N	0.15	16.7	6.02	0.20	20.6	1.46	350	low	mouth
21 S.2N	0.9	0	0	0	20.6	0	700	high	bottom
22 S.2N	0.55	0	0	0	20.6	0	680	low	mouth
23 S.2N	0.6	0	0	0	20.6	0	650	high	mouth
24 S.2N	0.1	20.9	8.25	0.29	20.6	1.46	550	low	mouth
25 S.2N	0.15	1.4	0	0	20.6	0	500	low	mouth
26 S.2S	1.23	0	0	0	20.6	0	730	high	mouth
27 S.2S	1.0	0	0	0	20.6	0	700	high	bottom
28 S.2S	0.6	1.02	0	0	20.7	0	600	low	mouth
29 S.2S	0.55	19.6	6.02	0.17	20.6	1.02	200	low	mouth
30 S.2S	0.3	1.4	0	0	20.6	0	300	low	bottom
31 S.2S	0.15	20	6.02	0.2	20.6	1.43	530	low	bottom
32 S.2S	0.1	20.8	8.25	0.29	20.6	1.46	550	low	mouth
33 north access	2.7	0	0	0	20.7	0	430	low	bottom
34 north access	3.3	0	0	0	20.6	0	600	low	mouth
35 north access	4.0	0	0	0	20.6	0	800	low	bottom
36 north access	3.1	0	0	0	20.7	0	700	low	mouth
37 north access	3.2	0	0	0	20.6	0	900	low	mouth
38 north access	3.7	0	0	0	20.6	0	1000	low	mouth

Calculated wind speed of access tunnel can come to 4.37 m/s, a larger theory value, when 0.15 m/s is the minimum wind speed. Tested weighted average wind speeds on the spot in storage cavern and access tunnel are 0.98 and 3.0 m/s respectively, as presented in Table 8. Here, position 1, 2, 5, 9, 10, 18-20, 24, 29, 31-32 are tested in the region of blasting influence, and field tested wind speed is larger than calculated values. Thus it can be seen that calculated required airflow and wind speed should be revised by reduction coefficient in consideration of super-large section. Reduction coefficient ζ_{bs} =0.69 is obtained according to tested wind speed and anti-calculated required airflow, and then final required air quantity and calculated wind speed are determined, as shown in Table 9. Furthermore, there is no difference if the axial fan is at the shaft mouth or in the bottom.

Table 9. Optimal ventilation scheme for second & third steps

Region	Required air quantity(m^3/s)	Required wind speed(m/s)
storage cavern (first step)	27.34	0.10
storage cavern (second step)	33.64	0.10
storage cavern (third step)	45.13	0.10
R3 shaft	45.13	1.59
R1.5 shaft	45.13	6.35
north access	180.50	3.01
fan assignment	1 axial fan is set at the mouth of shaft of each storage cavern to supply fresh air to every storage cavern	
note: turn to high power after blasting and after a while; turn to low power when temperature difference between inside and outside underground facility increases		

Therefore, in view of installation convenience of fans optimum fan assignment, 1 axial fan is set at the mouth of shaft of each storage cavern to supply fresh air to every storage cavern, as listed in Table 9. It is noteworthy that energy saving scheme is developed to save construction costs, which is, turning to high power after blasting and after a while, turning to low power when temperature difference between inside and outside underground facility increases.

6. Conclusions

The construction network ventilation system for Jinzhou project of petroleum underground storage is studied through field test, theoretical calculation and numerical modelling by using computational fluid dynamics method to identify optimal ventilation design in complicated groups of tunnels with only access entrance in the first ventilation stage and shafts added in the second ventilation stage connected to the ground for air interchange. Gallery-type network ventilation technique (GNVT) refined from theories of operation ventilation for road tunnel and mining ventilation network, is proposed to conduct construction ventilation for underground tunnels originally. Ventilation performance of different ventilation schemes with various outside temperature, different shafts' states and diverse arrangements of fans are also discussed in this study. Field test of wind speed, dust, poisonous gas, atmospheric pressure, temperature are performed to detect ventilation effect. From the findings following consequences can be extracted:

a. In the first stage, forced ventilation with axial fans set at the access entrance is the best choice with only access connected to the ground, fan arrangement is shown in Table 2. With temperature difference between inside and outside storage caverns increases, peak value of CO concentration and required time to meet the CO concentration qualification decrease and exhausting time of dirty air shortens, but the influence degree in this stage is quite limited.

b. It has only limited effect of ventilation performance with different locations, diameters and lengths of shafts. In other word, there is no need to build middle ventilation shafts and construct shafts as large and long as possible. Shafts with diameters 3 m for inlet and 6 m for outlet and 80m in height are finally adopted in Jinzhou project.

c. GNVT, taking advantages of shafts and tunnels as air ducts, takes in fresh air from one outcrop and exhausts dirty wind from the other outcrop, which allows air to circulate effectively. Moreover, it not only saves costs of middle construction ventilation shafts and traditional air ducts, but also offers convenience to construction. In the second stage of construction ventilation, Axial-GNVT with shafts taking in fresh air and access tunnel ejecting dirty air, whose performance turns out to be much better than traditional forced ventilation from access tunnel. Air flow has the same direction as slag tapping, which guarantees working face always full of fresh air and develops one clear, ordered and scientific ventilation network.

d. Calculated required airflow and wind speed should be revised by reduction coefficient $\xi_{bs} = 0.69$, obtained from tested wind speed and anti-calculated required airflow in consideration of super-large section. Also, there is no difference if the axial fan is at the shaft mouth or in the bottom; hence, in view of installation convenience of fans optimum fan assignment, 1 axial fan is installed at the mouth of shaft of each storage cavern to supply fresh air to every storage cavern. Furthermore, energy saving scheme is developed to save construction costs by the use of temperature difference between outside and inside.

New ventilation technique - GNVT is proposed to conduct construction ventilation for underground tunnels. And reasonable scheme obtained from numerical simulation results has been adopted in practical construction ventilation system as a reference. This study may benefit the construction of underground crude petroleum storage caverns, and provide a case study for construction ventilation technique in similar underground energy storage or tunnels project with shafts or other outcrops on surface.

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