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Design Features and Quality Control Procedures for the Natural Ventilation of an Underground Space for the Safe Storage of Aircraft

Key Words
Natural ventilation calculation
Natural ventilation design
Natural ventilation intensification
Natural ventilation quality control
Air dehumidification

Abstract
The storage of aircraft in underground tunnels can only be achieved safely if there is adequate ventilation. The theoretical aspects of the design of such an underground space are considered from the point of view of providing natural ventilation. If the ventilation air is to be dried in an attempt to reduce corrosion of the stored aircraft, this should be achieved by placing a dehumidification plant near the air intake and ensuring that sufficient air flows through the tunnels in the same direction throughout the year. Cost-effective conditioning of the input air can be achieved with a salt solution liquid spray dehumidifier regenerated by solar power.

Introduction

Both military and civil aircraft can be stored safely in underground hangars, provided there is adequate ventilation to prevent the accumulation of water vapour and gases, such as methane, carbon dioxide and radon. Another problem that may arise with inadequate ventilation is the growth of mould and fungal colonies.

It is desirable to provide a stable level of natural ventilation, which means that allowances have to be made for local variations in temperature and wind flow throughout the year. Ideally, the system should be capable of quite wide variation in air exchange rates, which are mainly determined by the pressure heads generated by the external temperature and wind flow. Location of the air intake opening is also of obvious importance if the system is to avoid the importation of outdoor air pollutants. One of the best places to situate the opening is in a forest, where there is little air pollution.

The direction of surface air flow influences the air quality in the naturally ventilated underground space. With frequent changes in the direction of surface air flow, it is necessary to correct for this in the design of the system so that external supply of fresh air is maintained. Dampness should not be allowed to develop in the underground space. Although supply air may be dehumidified, such air-conditioning adds substantially to the servicing costs, so it is appropriate to attempt to achieve this by natural ventilation.

This paper addresses the design features that may enable the ventilation to be achieved by natural means [1–3], thus providing a safe shelter for the aircraft whilst avoiding the unnecessary consumption of energy.

Calculation of the Determinants of Natural Ventilation of an Underground Space [4]

Natural ventilation of an underground space depends upon the heat pressure head (Δp_t), which is a function of the difference in air temperature between the inside and outside of the space.

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The heat pressure head Δp_t is as shown in figure 1 as

$$\Delta p_t = H(t_s - t_o)\,\gamma_o/T_o \qquad (1)$$

where H is the height difference of the air outlet place and the air inlet place, t_s is the air temperature in underground space, t_o is the outdoor temperature, γ_o is the weight in unit volume, T_o is the thermodynamic temperature. It can be seen, the conditions causing the heat pressure head are the height difference H and the temperature difference $(t_s - t_o)$.

Although there is little difference in the height, temperature will vary during the day and throughout the year. In general, the air inlet gate should be set at its highest level in summer and at its lowest level in winter.

For a long tunnel, the temperature change caused by natural ventilation occurs mainly at the inlet section, whilst that in the deep section remains almost constant. If it is considered that the higher gate section can store heat and the lower gate section can store cooling energy, the upper section of the tunnel is appropriate for the storage of aircraft in cold weather and the lower section ideal in hot summers [3].

According to the Bernoulli equation [5, 6], the kinetic pressure of wind p_v is as

$$P_v = \gamma v^2/(2\,g) \qquad (2)$$

where v is the wind velocity (m/s), γ is the weight of air in unit volume (kg/m^3), g is the gravitational acceleration (m/s^2).

The residual pressure on windward side is p_1, i.e.

$$p_1 = n_1\, p_v, \qquad (3)$$

where n_1 is the kinetic pressure coefficient on the windward side, it is a positive value.

The residual pressure on the other sides is p_2, i.e.

$$p_2 = n_2\, p_v, \qquad (4)$$

where n_2 is the kinetic pressure coefficient on the sides with the wind and on the sides under the wind, it is some negative value [7–9].

The wind pressure head on a tunnel can be written as

$$\Delta p_v = p_1 - p_2 = (n_s - n_2)\, p_v. \qquad (5)$$

It can be seen, the full pressure head for the natural ventilation is as

$$\Delta p_o = \Delta p_t + \Delta p_v, \qquad (6)$$

which shows the full pressure head is the algebraic sum of the heat pressure head and the wind pressure head, which can either intensify or cancel out each other.

If the two gates of a tunnel are both placed on the leeward side or the windward side, then the wind pressure head becomes zero (i.e. $\Delta p_t = 0$).

Thus the pressure head necessary for adequate natural ventilation of an underground space can be controlled by appropriate use of landform, topography and natural climate.

The full pressure head can overcome the friction as the air flow passing through the runway. The friction can be represented as the pressure head loss, which includes the local pressure head loss and the pressure head loss along the air flow path.

The local pressure head loss occurs when the air flows through the inlet, the outlet, the corner, and the contraction, as well as expansion. The pressure head loss along the path corresponds to the air flow passing through the straight part of a tunnel.

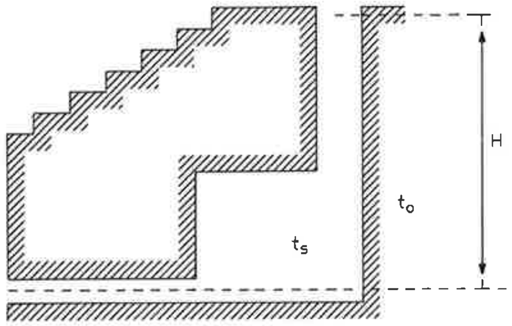


Fig. 1. The heat pressure head for an underground space.

The expressions are written as follows:
The pressure head loss at air inlet is as

$$\Delta p_1 = \zeta_1\gamma_1 v_1^2/(2\,g) \qquad (7)$$

The pressure head loss at air outlet is as

$$\Delta p_2 = \zeta_2\gamma_2 v_2^2/2\,g) \qquad (8)$$

The pressure head loss at corner is as

$$\Delta p_{ri} = \zeta_{ri}\gamma_i v_i^2/(2\,g) \qquad (9)$$

The pressure head loss at contraction is as

$$\Delta p_{cj} = \zeta_{cj}\gamma_j v_j^2/(2\,g) \qquad (10)$$

The pressure head loss at expansion is as

$$\Delta p_{ek} = \zeta_{ek}\gamma_k v_k^2/(2\,g) \qquad (11)$$

The pressure head loss along the path is as

$$\Delta p_{al} = \zeta_{al}\gamma_l v_l^2/(2\,g) \qquad (12)$$

where ζ_1, ζ_2, ζ_{ri}, ζ_{cj}, ζ_{ek}, ζ_{al} are respectively called the inlet friction factor, the outlet friction factor, the corner friction factor, the contraction friction factor, the expansion friction factor, and the straight path friction factor.

The straight path friction factor is as

$$\zeta_{al} = \lambda_l l_l/\delta_l \qquad (13)$$

where λ_l is the surrounding surface friction for unit length, l_l is the length of a straight part section of the tunnel, δ_l is the characteristic diameter. We have [8]

$$\delta_l = 4F/U \qquad (14)$$

$$\lambda_l = 1/[1.74 - 2\log_{10}(2\varepsilon_l/\delta_l)]^2 \qquad (15)$$

where ε_l is the roughness of the tunnel surface, $\varepsilon = 2$ mm for concrete surface, F is the area of the tunnel cross-section; U is the periphery of the area F.

The balanced equation is

$$\Delta p_o = \Delta p_1 + \Delta p_2 + \Sigma_i\Delta p_{ri} + \Sigma_j\Delta p_{cj} + \Sigma_k\Delta p_{ek} + \Sigma_l\Delta p_{al} \qquad (16)$$

where i, j, k and l is respectively the order number of the corners, the contractions, the expansions and the straight tunnel sections.

By the theorem of continuity for flux, we have

$$F_l v_l = F_2 v_2 = F_{ri} v_i = F_{cj} v_j = F_{ek} v_k = F_{al} v_l = F_c v_c \quad (17)$$

where Fs are, respectively, the area of the corresponding cross-section, that is, the products of the velocity v and the cross-section area F equals a constant, or

$$Fv = \text{constant}. \quad (18)$$

By the above-mentioned relation, let us take a cross-section area F_c as controlled area, passing through which the air velocity is v_c, so the air velocity v_χ passing through the area F_χ then we have

$$v_\chi = (F_c/F_\chi)\, v_c \quad (19)$$

Substituting expressions 8 to 12 into expression 16 and considering expression 19, we have

$$p_o = [\zeta_l \gamma_l (F_c/F_l)^2 + \zeta_2 \gamma_2 (F_c/F_2)^2 + \Sigma_i \zeta_{ri} \gamma_i (F_c/F_{ri})^2 + \Sigma_j \zeta_{cj} \gamma_j (F_c/F_{cj})^2 + \Sigma_k \zeta_{ek} \gamma_k (F_c/F_{ek})^2 + \Sigma_l \zeta_{al} \gamma_l (F_c/F_{al})^2] v_c^2/(2\,g) \quad (20)$$

if the air temperature in underground space is approximately equal to a constant, γ, we have

$$\gamma_l \sim \gamma_2 \sim \gamma_i \sim \gamma_j \sim \gamma_k \sim \gamma_l \sim \gamma \quad (21)$$

then we can solve the air velocity passing through the controlled area as

$$v_c = [2g\Delta p_o/(\gamma \zeta_\Sigma)]^{1/2} \quad (22)$$

where ζ_Σ is the total friction factor as

$$\zeta_\Sigma = \zeta_l (F_c/F_l)^2 + \zeta_2 (F_c/F_2)^2\, \Sigma_i \zeta_{ri} (F_c/F_{ri})^2 + \Sigma_j \zeta_{cj} (F_c/F_{cj})^2 + \Sigma_k \zeta_{ek} (F_c/F_{ek})^2 + \Sigma_l \zeta_{al} (F_c/F_{al})^2 \quad (23)$$

The friction factors in the last expression can be assigned some approximate value as

$$\left.\begin{array}{l} \zeta_l = 1.5;\ \zeta_2 = 1.0;\ \zeta_{cj} = 1.5;\ \zeta_{ek} = 1.0; \\ \zeta_{al} = \lambda_l l_l \delta_l \text{ (by expression 6)} \\ \zeta_{ri} = 0 \text{ (for streamline curve surface)} \end{array}\right\} \quad (24)$$

Substituting expressions 1 and 5 into 6, we have

$$\Delta p_o = H\gamma_o(t_s - t_o)/T + (n_l - n_2)\gamma\, v_o^2/(2g) = [2gH(t_s - t_o)/(v_o^2 T) + (n_l - n_2)]\, \gamma\, v_o^2/(2g) \quad (25)$$

where v_o is the outdoor wind velocity.

Put

$$n_T = 2gH(t_s - t_o)/(v_o^2 T) \quad (26)$$

which is called the equivalent wind pressure factor for heat pressure head, then we have

$$\Delta p_o = [n_T + n_l - n_2]\, \gamma\, v_o^2/(2\,g) \quad (27)$$

Substituting the expression 27 into 22, we have

$$v_c = [(n_T + n_l - n_2)/\zeta_\Sigma]^{1/2} v_o \quad (28)$$

or

$$v_c = k_c v_o \quad (29)$$

$$k_c = [(n_T + n_l - n_2)/\zeta_\Sigma]^{1/2} \quad (30)$$

where k_c is called the natural ventilation factor for a controlled cross-section of the tunnel. It is shown that the air velocity at the controlled cross-section is in proportion to the wind velocity on the ground.

Substituting expression 29 into expression 19, we have

$$v_\chi = (F_c/F_\chi) k_c v_o \quad (31)$$

which shows that the air velocity v_χ at any cross-section is in proportion to the wind velocity on the ground.

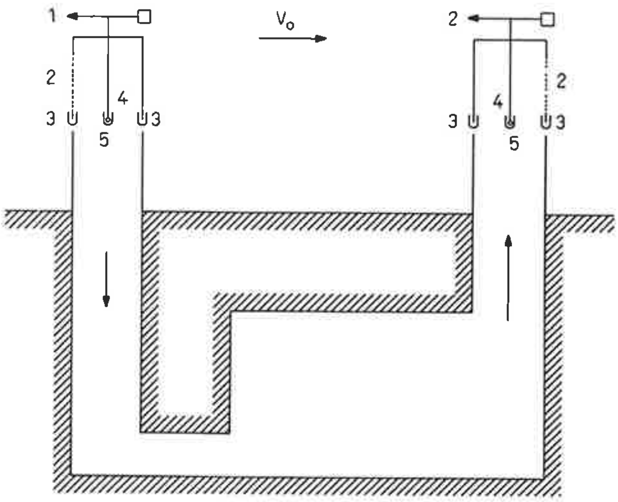
Quality Control of the Natural Ventilation of an Underground Space

The natural ventilation factor (k_c) is crucial in the optimization of the design: the kinetic characteristics that contribute to the numerator should be maximized, whereas the frictional characteristic that influence the denominator should be minimized. In this way, improving the kinetic characteristics of the underground wind path will increase natural ventilation: this can be achieved by increasing the height difference between the air inlet and outlet, and by taking air from the windward direction and venting it on the leeward side. Friction factors can be reduced by providing a smooth inner surface, and by streamlining the tunnel by avoiding any abrupt changes in its direction.

In a hilly area, the heat pressure head can be utilized to raise the value of n, but this is not possible when the underground space is situated on a plane. In this latter location, the wind pressure head has to be used, and the design objective is to maximise n_l and n_2. It is possible to design an air inlet to catch the wind, no matter what its direction. This can be achieved with rotatory air inlet and outlet devices fitted with hoods and orientated by a wind vane (fig. 2). A trumpet-mouth design can be used to collect wind in a hilly location.

Chimneys may be employed to adjust the position of the air inlet and outlet openings, because these permit a vertical movement of air, which will be intensified by solar heating of the air outlet [10, 11], and may reduce any effect on wind velocity from the terrain. Air flow can also be controlled from the heat pressure head by employing twin air inlets, so that there are two main tunnels connected to two branch tunnels. In winter the upper tunnel can act as the air outlet for the main tunnel, whereas in summer the lower tunnel serves this purpose.

Dehumidification of the air cannot be achieved easily, unless the wind direction along the tunnel can be controlled. If the air providing natural ventilation always proceeds in one direction down the tunnel, it is possible to dehumidify it before it enters the main tunnel. Refrigeration dehumidification is not possible from cost consider-



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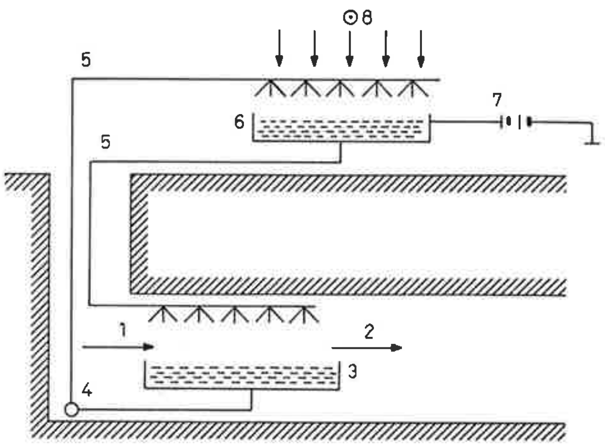

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ations. However, both solid and liquid adsorbents can be used, because these can be regenerated by solar energy, thus permitting a cost-effective dehumidification of the ventilation air.

The combination of a spray dehumidifier and adequate air flow permits good surface contact and little reduction in the ventilation rate. The system can be automated (fig. 3) by connecting the dehumidifier to a salt tank on the ground with a salt pump. This pump provides the potential energy to operate the dehumidifier, and the concentration phase is effected by evaporation, driven by solar energy. The rate of evaporation can be accelerated by charging the salt liquid in the tank, thus causing a higher vapour pressure on the charged liquid surface (fig. 3).

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Fig. 2. The air inlet and air outlet for an oriented natural ventilation in underground space.

Fig. 3. The dehumidified section at the air inlet of natural ventilation. 1 = Wetted air flow; 2 = dried air flow; 3 = salt tank in air inlet section; 4 = salt pump; 5 = plastic tubes; 6 = salt tank at higher potential; 7 = charged the tank to increase the evaporation; 8 = the solar ray.

References

1 Chen Q: Thermal observation and analysis for a tunnel in hilly region. A Booklet. Chongqing, CIAE Press, 1965.
2 Chen Q: Decreased temperature and dehumidified moisture in subsurface space by ventilation. A Booklet, Chongqing, CIAE Press, 1965.
3 Chen Q: The theory of heat transfer in a tunnel with natural ventilation. Design in Geotecture, Proc 2nd Int Conf on Earth-Sheltered Buildings, Minneapolis, 1986.
4 Chen Q: Natural ventilation design and its quality control in an underground space for aircraft defence. Underground Space (Chinese) 1983; 9/2.
5 Whelan PM, Hodgson MJ: Essential principles of physics. London, Murry, 1978, pp 70–75.
6 Milne-Thomon LM: Theoretical hydrodynamics. London, Macmillan, 1960, pp 6–12.
7 Givoni B: Man, climate and architecture. London, Applied Science Publishers, 1976, chap 14.
8 Kimura K: Fundamental theories of building services. Tokyo, Japan Literature Press, 1975, pp 59–71.
9 Kamenev PN: Heating and ventilation. II. Ventilation. Moscow, Construction Literature Press, 1964, chap 10.
10 Snahab S: Ventilating animal shelters with solar heat. St Paul, University of Minnesota, 1979.
11 Guo C: The organization of oriented natural ventilation in underground project by utilization of solar energy; in Hou X (ed): New Development of Underground Space Use. Proceedings of the International Conference on Underground Space and Earth-Sheltered Buildings. Shanghai, Tongji University Press, 1988, pp 625–628.
12 Guo C: The oriented natural ventilation and control of air quality in underground projects; in Hou X (ed): New Development of Underground Space Use. Proceedings of the International Conference on Underground Space and Earth Sheltered Buildings. Shanghai, Tongji University Press, 1988, pp 621–624.