The Physical Model Test’s Research of Ventilation in Super-long Highway Tunnels

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Abstract. Based on hydromechanics affinity theory and major control factor of highway tunnel ventilation, highway tunnel ventilation boundary condition was determined in this paper. Based on Navier-Stokes equation, tunnel ventilation model experiment affinity theory was deduced and Reynolds Number chosen as the affinity norm of the tunnel ventilation physical model. Based on Nikuradse Testing, the influence factor of Reynolds Number and the form reason of affinity self pattern area were analyzed. The experiment method of affinity self pattern area was discussed. Complete tunnel ventilation model-design method was given in this paper.

1. Introduction
Experimental study of a flow phenomenon involves many variables. In addition, due to limitations of experiment conditions it is mostly impossible to perform such study on real objects. Consequently, performing a test presents a host of challenges including how to more effectively design and organize the test, how to correctly process test data and how to extend the model test result to prototype.

Dimensional analysis and affinity theory offer theoretical basis for meeting these challenges. For example, based on dimensional analysis several variables in a flow phenomenon can be combined into dimensionless quantities and variables selected that are easy to handle and measure for the test. This can reduce test workload considerably and make it easier to organize and analyze test data.

The tunnel ventilation model test is based on affinity theory. Only if the affinity conditions prescribed by the affinity theory are satisfied, the model is affinitive to the prototype and data from the model test can be used to deduce data and conditions for the prototype.

2. Overview of Model Test
Scientific experiment is cognitive activities to explore natural law in which natural phenomena are simulated artificially using scientific instruments and equipment according to study purpose, with emphasis put on major factors and interferences excluded under conditions favorable to the study. Its most fundamental feature is purposiveness and intervention. Purposiveness means the experiment shall have a clear purpose. Intervention means the experimenter shall actively intervene in natural phenomena. Because numerous factors come into play in almost all natural phenomena, most natural phenomena are the result of many causes. In order to understand a natural process, it is desirable to separately study the effect caused by each cause. An experiment acts to isolate and control the cause to some degree. Observation and analysis of natural phenomena without active intervention cannot be called an experiment(1,2,3).
An experimental study shall follow the principles of conditionality, accuracy, reproducibility, etc. The principle of conditionality requires attention to all prerequisites of research basis wherever possible and requires the researcher to record external conditions at the time of study in an exhaustive and detailed manner as possible, such as atmospheric temperature, humidity and pressure. The principle of accuracy requires the pursuit of accuracy as far as practical and careful analysis of whether difference is reasonable when the same tests produce different results due to test errors even if improvement is tirelessly sought. The principle of reproducibility means making other people recognize your study result. In order to enable others to reproduce your result, attention is needed to the above mentioned conditionality principle and study conditions must be provided in a comprehensive, detailed and accurate manner. In addition, the principle of accuracy tells us reproducibility does not mean absolute repetition. As long as the difference is within a reasonable range, the test result can be deemed to have been reproduced. Consequently, the principles of conditionality and accuracy are the basis of reproducibility.

3. Basic Assumptions of Model Test

In the design of a model, its magnitude is determined based on physical quantity of the prototype, i.e. selection of model scale. The selection of model scale shall be based on the equal affinity number described in the previous section. From the theoretical point of view, flow affinity requires affinitive boundary conditions and all acting forces. Normally, a larger number of physical quantities of a phenomenon result in more deduced affinity criteria and more affinity conditions must be satisfied during model test.

For highway tunnel ventilation model tests, most affinity conditions can be regarded as minor factors. Therefore, assumptions are made as follows[4~7]:

1. Fluid incompressible

In a test with air as medium, the effect of air compressibility is negligible when wind speed is less than 0.3Ma. For highway tunnel ventilation current Chinese codes recommend a wind speed of 6m/s~8m/s for main tunnel and less than 30m/s for air intake. Therefore, the effect air compressibility can be ignored in a highway tunnel ventilation model test.

2. Fluid continuum assumption

Fluid is composed of large amounts of molecules. Normal fluids are gas and liquid. Two basic methods are available to study macro movement of fluid. One is statistical physical method where the statistical average method is used to establish an equation satisfied by macro physical quantities based on molecule and atom movements and then to determine the pattern in fluid movement. Despite its many advantages this method cannot provide adequate theoretical basis for fluid mechanics. The other one is a method based on continuous medium assumption that the space occupied by real fluid can be approximated as a space filled continuously without gap by fluid particles. Macro physical quantities of fluid particles satisfy all physical laws that should be observed. Experiments show theoretical values obtained from continuous medium assumption are well fit to experiment results.

3. Steady flow of fluid

Steady flow is defined as a situation in which the pressure and flow velocity at any point during fluid flow do not change with time, i.e. the pressure and velocity are only a function of point coordinate. In a model test it can be assumed that the air flow in a model tunnel is steady flow.

4. Fluid flow conforming to energy conservation law

When it gradually flows in a pipe, the incompressible steady fluid moves at a pressure and velocity that change (including frictional loss) along the flow path in compliance with the energy conservation law. This is called Bernoulli's theorem and can be expressed as Bernoulli equation.

4. Affinity Criteria for Model Test

An accurate investigation of prototype characteristics and the process of movement through a model test requires understanding of movement affinity conditions.

Under normal conditions, ventilation air flow in a tunnel can be deemed as equal-temperature
movement of incompressible viscous fluid. Its affinity conditions may be based on differential equation Navier—Stokes for actual fluid movement. For incompressible viscous fluid, the most common movement equation is the continuity equations of Navier—Stokes equation:

$$\begin{align*}
\frac{\partial \nu_x}{\partial t} + \nu_x \frac{\partial \nu_x}{\partial x} + \nu_y \frac{\partial \nu_x}{\partial y} + \nu_z \frac{\partial \nu_x}{\partial z} &= X - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nabla^2 \nu_x \\
\frac{\partial \nu_y}{\partial t} + \nu_x \frac{\partial \nu_y}{\partial x} + \nu_y \frac{\partial \nu_y}{\partial y} + \nu_z \frac{\partial \nu_y}{\partial z} &= Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nabla^2 \nu_y \\
\frac{\partial \nu_z}{\partial t} + \nu_x \frac{\partial \nu_z}{\partial x} + \nu_y \frac{\partial \nu_z}{\partial y} + \nu_z \frac{\partial \nu_z}{\partial z} &= Z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \nabla^2 \nu_z
\end{align*}$$

(1)

where \( \nu_x, \nu_y \) and \( \nu_z \) - velocity component;

\( P \) - pressure;

X, Y and Z - component of external forces per unit of mass, usually X=0, Y=0, Z=g.

All fluid movement systems obey this common differential equation. If two systems are affinitive, then physical quantities are surely proportional, \( \nu_x'/\nu_x = \alpha_x, \nu_y'/\nu_y = \alpha_y, \nu_z'/\nu_z = \alpha_z \). After putting these ratios (affinity constants) into the equation, it still holds:

$$\begin{align*}
\frac{\alpha_x \frac{\partial \nu_x}{\partial t} + \alpha_x^2 \nu_x \frac{\partial \nu_x}{\partial x} + \nu_y \frac{\partial \nu_x}{\partial y} + \nu_z \frac{\partial \nu_x}{\partial z}}{\alpha_i} &= X - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nabla^2 \nu_x \\
\frac{\alpha_y \frac{\partial \nu_y}{\partial t} + \nu_x \frac{\partial \nu_y}{\partial x} + \alpha_y \frac{\partial \nu_y}{\partial y} + \nu_z \frac{\partial \nu_y}{\partial z}}{\alpha_i} &= Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nabla^2 \nu_y \\
\frac{\alpha_z \frac{\partial \nu_z}{\partial t} + \nu_x \frac{\partial \nu_z}{\partial x} + \nu_y \frac{\partial \nu_z}{\partial y} + \alpha_z \frac{\partial \nu_z}{\partial z}}{\alpha_i} &= Z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \nabla^2 \nu_z
\end{align*}$$

(2)

As shown in Eq. (2), as long as its continuity is maintained, the continuity equations do not present restrictions in ratios on the affinity of two flow systems. Each term in the Navier—Stokes equation is multiplied by a coefficient. To make the equation hold these coefficients shall be equal:

$$\frac{\alpha_x}{\alpha_i} = \frac{\alpha^2_x}{\alpha_i^2} = \frac{\alpha_y}{\alpha_i} = \frac{\alpha^2_y}{\alpha_i^2} = \frac{\alpha_z}{\alpha_i} = \frac{\alpha^2_z}{\alpha_i^2}$$

(3)

Each term in Eq. (3) is divided by \( \alpha^2_x/\alpha_i \):

$$\begin{align*}
\frac{\alpha_x}{\alpha_i} &= \frac{\alpha_y}{\alpha_i} = \frac{\alpha_z}{\alpha_i} = \frac{\alpha^2_x}{\alpha_i^2} = \frac{\alpha^2_y}{\alpha_i^2} = \frac{\alpha^2_z}{\alpha_i^2} = 1
\end{align*}$$

(4)

Thus 4 relationships (1)–(4) are derived. The proportional constants of 7 main variables, L, t, v, g, p, \( \rho \) and V in fluid movement cannot be designated at will but must observe the above relationships to maintain affinity. At this point there are 7 variables and 4 relationships. Therefore 3 proportional constants can be determined or assumed while the rest must be derived from these relationships.
All relationships in Eq. (4) are affinity indicators. They can be rewritten as affinity criteria as follows:

\[
\frac{V \cdot t}{l} = \text{idem}, \quad \frac{V^2}{gL} = \text{idem}, \quad \frac{V \cdot L}{\nu} = \text{idem}, \quad \frac{P}{\rho V^2} = \text{idem}
\]

Not considering tension and elasticity on fluid surface, from Newton’s law of universal affinity and dimensional analysis method the following can be derived:

\[
\frac{V \cdot t}{l} = St \quad \text{(harmonic criterion (Strouhal Number))}
\]

\[
\frac{V^2}{gL} = Fr \quad \text{(gravity affinity criterion (Freud Number))}
\]

\[
\frac{V \cdot L}{\nu} = Re \quad \text{(internal friction force affinity criterion (Reynolds Number))}
\]

\[
\frac{P}{\rho V^2} = Eu \quad \text{(pressure affinity criterion (Euler Number))}
\]

To maintain the affinity of two systems, one or several affinity criteria must be equal (or affinity indicator equals 1).

Under normal conditions, ventilation in a highway tunnel can be deemed as normal flow, then Strouhal criterion which reflects time affinity does not work. For longitudinal air movement along the tunnel, the effect of gravity is far less than internal friction. The Freud criterion reflecting gravity affinity can be ignored while the Euler criterion reflecting pressure affinity is an inexorable outcome of affinity movement and only a atypical criterion. Therefore, the Reynolds criterion reflecting internal friction force affinity is the only defining criterion for air flow affinity.

Therefore, to maintain the affinity between the model and prototype, two flow systems must satisfy the following relation:

\[
f(Re, Eu) = 0 \quad (5)
\]

Additionally, from flow mechanics it is known that velocity of laminar flow in a pipe is in parabolic distribution, i.e.

\[
\frac{V}{V_{\text{max}}} = \frac{r_o^2 - y^2}{r_o^2} \quad (6)
\]

where \(V\) —— velocity at \(y\) from the center, \(r_o\) —— tube radius, \(V_{\text{max}}\) —— maximum velocity at tube center.

If geometric affinity is satisfied i.e. \((r_o/y)_{p} = (r_o/y)_{m}\), then velocity distribution is affinitive.

The distribution of turbulent velocity in the tube can be expressed using (T·E· Stanton) equation:

\[
\frac{V_{\text{max}} - V}{V^*} = f(y/r_o) \quad (7)
\]

where \(V^*\) ——shear velocity, \(V^* = \sqrt{\tau \rho / \nu}\); \(V_{\text{max}} - V\) ——velocity deficit.

The above equation suggests for turbulent flow, if geometric affinity is satisfied i.e. \((r_o/y)_{p} = (r_o/y)_{m}\), then velocity distribution is affinitive.

The affinity of the tunnel ventilation model test is ensured through affinity in the following 3 aspects\(^4\)[5].

(1) Geometric affinity

The affinity of flow boundary is ensured by geometric affinity.

(2) Flow affinity

Generally, flow affinity includes geometric affinity, movement affinity and dynamics affinity while
dynamics affinity includes the former two affinities. As a result, dynamics affinity is the basis for the affinity between the model and real flow.

For flow under pressure, the pressure difference is caused by viscous resistance, gravity or inertia force. When viscous resistance, gravity or inertia force meets affinity conditions, the pressure difference will also meet affinity conditions, so the Euler criterion is automatically satisfied. Meanwhile, for one-dimensional flow under pressure, gravity affinity criterion can be ignored.

Meanwhile, since frictional resistance along the length of the tunnel has a big impact on the distribution of air flow velocity, affinity in frictional resistance along the tunnel must be ensured in flow affinity analysis.

Flow affinity must satisfy the most basic affinity condition - Newton’s affinity law, \((Ne)_p=(Ne)_m\), then

\[
\frac{\lambda_p}{\lambda_F} = \frac{\lambda_p \cdot \lambda_T^2 \cdot \lambda_i^2}{\lambda_F \cdot \lambda_T^2 \cdot \lambda_i^2} = \lambda \cdot \lambda_T^2 = 1
\]

This is resistance affinity condition for tunnel air flow. It requires the friction resistance coefficients of the model and prototype be equal. From the above equation it is known that \(\lambda = 1\), i.e. to maintain flow affinity between the model and real flow, friction resistance coefficients of the model and prototype must be equal. However, from \(\lambda\) change patterns it is known that after flow enters full turbulence, \(\lambda\) is just a function of roughness and unrelated to Reynolds Number and the friction resistance coefficient \(\lambda\) is a function of relative roughness \(\frac{\Delta}{D}\) of wall surface and Reynolds Number, i.e. \(\lambda = f\left(\frac{\Delta}{D}, Re\right)\). However, for fluid entering resistance square zone, the friction resistance coefficient \(\lambda\) is related only to connected roughness \(\frac{\Delta}{D}\), i.e. \(\lambda = f\left(\frac{\Delta}{D}\right)\). Therefore, For the affinity of tunnel air flow entering the resistance square zone, Reynolds affinity criterion may be ignored and ensuring equal relative roughness alone can satisfy the requirement of resistance affinity. Equal relative roughness means affinitive surface roughness, which still falls into the scope of geometric affinity.

Equal relative roughness means affinitive surface roughness. Roughness of tunnel surface only has marked influence on flow state and velocity distribution near the wall and no effect on the flow state and velocity distribution some distance away from the wall surface. Therefore, when the model space is relatively large, it is unnecessary to ensure relative roughness of wall surface is equal. At this point, it suffices to make model flow enter fully developed turbulence while ensuring geometric affinity.

(3) Pressure field affinity

By affinity transformation of one-dimensional unsteady differential equation of air flow and introducing affinity scale of each physical quantity, it can be derived that:

\[
\alpha_p \alpha_T = 1
\]

In conjunction with gas state equation \(P=\rho gRT\) the following is derived:

\[
\alpha_p = \alpha_p \alpha_T = 1
\]

Thus the model and prototype fluids are equal in pressure when no consideration is given to one-dimensional unsteady flow affinity for temperature field changes.

5. Determination of Affinity Self Pattern Area

For incompressible fluids in geometrically affinitive closed systems, equal Reynolds Numbers of the two systems alone can ensure all affinity conditions are met. For the highway tunnel ventilation model test, fluid media of the two systems are both air and their temperature difference is small, having little impact on test results. Therefore, the temperature difference between the two systems is ignored.
assuming temperatures in the two systems are equal. Thus:

$$\rho_p = \rho_m = \rho$$  \hspace{1cm} (8a)

$$\mu_p = \mu_m = \mu$$  \hspace{1cm} (8b)

Let Reynolds Numbers of the model and prototype systems be equal:

$$R_{ep} = \frac{\rho_p V_{op} L_p}{\mu_p} = R_{em} = \frac{\rho_m V_{om} L_m}{\mu_m}$$  \hspace{1cm} (9)

Put Eq. (8) into (9) deriving:

$$V_{op} L_p = V_{om} L_m$$  \hspace{1cm} (10)

$$C_L = \frac{L_p}{L_m} = \frac{V_{om}}{V_{op}} = \frac{1}{C_v}$$  \hspace{1cm} (11)

where p and m denotes prototype and model respectively.

From Eq. (11) it is derived that if the model and prototype have equal Reynolds Numbers then their velocity scale is reciprocal of their length scale. If the model is n times smaller than prototype then air velocity in the model is n times that in the prototype. If the prototype has a large Reynolds Number, then it is difficult to maintain the same Reynolds Number in the model. Under a high Reynolds Number, velocity in the model reaches a considerable value which is hard to achieve using lab fans. Even if velocity requirement is met by increasing fan power, the fluid compressibility may have reached a level that is not negligible. To enable simulation of the affinity between prototype and the model to continue, approximate modeling approach is often taken.

As demonstrated by Nikuratse test results, viscous fluid has self affinity. When the Reynolds Number Re is large enough, prototype Reynolds Number Re is in the affinity self pattern area and resistance affinity does not require equal Re. In this case the model Re does not need to be equal to prototype Re, i.e. not related to Re. This flow characteristics is called "self affinity state". In this area because resistance coefficient is not influenced by Re, the model Re does not need to be equal to prototype Re and flow affinity is automatically ensured as long as it is in the same affinity self pattern area as the prototype.

During testing, when the prototype Re is in the affinity self pattern area in which the model Re is located, it is not necessary to require model Re equal prototype Re. This can facilitate model study by reducing fan power considerably and cutting model cost while meeting affinity requirements.

Self affinity - when viscous fluid is in driven motion and the Reynolds Number Re is less than the first critical value, i.e. Re<2320 the flow is laminar flow. In this case the flow state of fluid is unrelated to Re and mutually affinitive. Velocity along the pipe interface is in parabolic distribution. Such automatic affinity under certain conditions is called self affinity.

Affinity self pattern area - for viscous fluid flow, the affinity self pattern area is divided into first and second affinity self pattern areas by Re values. When viscous fluid flows, the scope where Re is greater than the first critical value is called the first affinity self pattern area. When viscous fluid flows and Re is greater than the second critical value, fluid velocity distribution and flow state no longer change and are mutually affinitive and unrelated to Re. This is called the second affinity self pattern area.
For the first affinity self pattern area, entry of fluid into the first affinity self pattern area is marked by the point when Lagrange criterion $La$ is unrelated to $Re$, as shown in Fig. 1. Entry of fluid into the second affinity self pattern area is marked by the point when the Euler Number $Eu$ of the flowing fluid in the area under study is unrelated to $Re$, as shown in Fig. 2.

For an object of study, what value of $Re$ enables it to enter the second affinity self pattern area can be known through test only after building a model. This makes model design difficult. When designing a model, the second critical value of $Re$ and fan capacity are required to determine its size. In general, the value of $Re$ for the test model under study can be approximated by reference to the second critical value of $Re$ for similar test models. Alternatively, a small model can be built to derive the second critical value of $Re$ before designing a formal model.

The second affinity self pattern area, $Re_{critical 2}$, is determined as follows:

1. Select and determine the area under study.
2. Measure physical parameters in this area including fluid velocity $v$, pressure drop $\Delta \bar{p}$ in the area under study, equivalent diameter of the selected area, fluid $\rho$ and $\mu$.
3. Calculate a set of $Re$ and $Eu$ and plot them into curves in rectangular coordinates, as shown in Fig. 1.
4. When $Re$ is unrelated to $Eu$, the value of $Re$ is the second critical value of $Re$, as shown in Fig. 2.

For complex flow, entry of a certain zone into the affinity self pattern area does not mean the whole system has entered the affinity self pattern area. In this case, the correctness of the study can be ensured only if the area under study enters the affinity self pattern area.

6. Study on Model Test Scale
The scale of a ventilation model test relates to the velocity state under study in addition to economy and
operability. As noted in the previous section, on the premise of geometric affinity the only condition of maintaining affinity to prototype is to make model fluid enter rough area (also called resistance square area). From Moody diagram it is known that in the case of wall surface friction loss coefficient \( \lambda = 0.025 \), to make fluid enter the rough area the \( R_e \) must satisfy \( R_e > 8 \times 10^5 \), i.e.

\[
R_e = \frac{v \cdot D}{\nu} > 8 \times 10^5
\]

Take \( v = 2 \text{m/s} \) and movement viscosity coefficient \( \nu = 1.66 \times 10^{-5} \text{m}^2/\text{s} \), then model equivalent diameter \( D > 6.62 \text{m} \). Obviously, it is economically unviable for a model test.

On the other hand, from Moody diagram it is known that there are two means of making fluid enter the resistance square area: (1) increase \( R_e \); (2) increase relative roughness \( e/D \) of the model. Increasing \( R_e \) means increasing velocity \( v \) or model equivalent diameter \( D \). To achieve dynamics affinity through movement affinity, velocity scale \( \lambda_v \) must be 1:1. Therefore it is impossible to increase fluid velocity. Similarly, endless increase of equivalent diameter is unrealistic and unviable for a model test. Consequently, in order to ensure model fluid enters the resistance square area, the only way is to increase the model surface relative roughness \( e/D \) by roughening wall surfaces under the condition of a reasonable equivalent diameter.

However, roughening wall surfaces will result in disaffinity between prototype and model in relative roughness, i.e. \( \left( \frac{e}{D} \right)_p \neq \left( \frac{e}{D} \right)_m \) thus damaging the prerequisite of geometric affinity. Due to rough state of tunnel surfaces, under turbulence condition (\( R_e > 2300 \)), it has noticeable effects only on flow state and velocity distribution near wall surface while has no effect on the flow state and velocity distribution outside the viscous bottom layer (viscous bottom layer thickness \( \delta \approx 0.02D \)). Meanwhile, for flow in a large space like the tunnel, wall surface friction resistance is not an object of test and study, so affinitive flow does not require affinity in wall surface roughness or equal relative roughness. From Moody diagram it is known that the condition for fluid in an industrial pipe with a relative roughness of \( e/D = 0.015 \) to enter the resistance square area (in which case friction resistance coefficient along the length of the pipe \( \lambda = 0.025 \)) is \( R_e > 6 \times 10^2 \).

Take air movement viscosity coefficient \( \nu = 1.66 \times 10^{-5} \text{m}^2/\text{s} \) and consider the air velocity to be studied is above 1.5m/s. To make model fluid enter resistance square area, the following relationship exists:

\[
R_e = \frac{v \cdot D_m}{\nu} = \frac{1.5 \times D_m}{1.66 \times 10^{-5}} > 6 \times 10^4
\]

Thus model equivalent diameter \( D_m > 0.662 \text{m} \); based on tunnel equivalent diameter of 10.0m, the geometric proportion of the model shall be greater than 1:12.

7. Conclusions
Based on hydromechanics affinity theory and major control factor of highway tunnel ventilation, the paper had made certain highway tunnel ventilation boundary condition. Based on Navier-Stokes equation, the paper had deduced tunnel ventilation model experiment affinity theory and chosen Reynolds Number as the affinity norm of the tunnel ventilation physical model. Based on Nikuratse Testing, the paper had analyzed the influence factor of Reynolds Number and the form reason of affinity self pattern area. The paper had discussed the experiment method of affinity self pattern area.

To sum up, from the study of model test affinity theory it can be seen that: on the premise of geometric affinity, movement affinity is embodiment of dynamics affinity; the most straightforward method to achieve affinity of tunnel air flow is making it become fully developed turbulence, i.e. the fluid enters the resistance square area. Therefore, for tunnel ventilation air flow, the only condition to
maintain affinity to prototype flow is making the model flow become fully developed turbulence on the premise of geometric affinity. Taking into account model material, the relative roughness e/D of model surfaces can be increased by roughening wall surfaces so as to make model fluid enter the resistance square area. It is deduced that the geometric proportion of the model shall be greater than 1:12.

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