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NATURAL VENTILATION INSIDE TUNNEL TRAIN

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ABSTRACT

The need for rapid and comfortable urban mass transportation has been increasing parallel to the increasing duration of traffic in the last half of the twentieth century. Under ground transportation is one of the most effective and rapid means of urban mass transportation. Today more rapid transient systems involving subway facilities are so popular that every year transportation line been planned, design and built. In Egypt, the underground train (Tunnel Train) suffers from a lot of passenger which exceed one hundred passengers in each carriage at rush hours. The mechanical ventilation system of the carriages can't remove the excess heat and humidity especially in summer seasons, so the need of additional natural ventilation system is necessary to create comfortable environment inside the metro. This paper discuss the natural ventilation of the underground train experimentally and theoretically. In the experimental work, a train model was fabricated (using Plexiglas to scale 1 : 30) and an electric heating plate was fixed in the ground of the train. A different cases of window fines location were studied by measuring the temperature of the heated plated (33 points) and calculate the average temperature for each case, in which give a guide of good ventilation or less . In the theoretical work, the software ANSYS Flotran [1], is used to solve the problem using the finite element with 50,000 nodal points. The air flow distribution inside the train was presented in the form of contours and vectors. The results show the best fins location which give the best air movement inside the train results in a sensible temperature reduction of the heated plate inside the train model.

keywords: Wind tunnel; ANSYS computer package; Air flow and heat transfer inside train.

INTRODUCTION

The purposes of ventilation system are to provide acceptable microclimate in the space being ventilated; microclimate refers to thermal environment as well as air quality. There are two factors must be considered in the design of the ventilation system which are fundamental to the comfort and well-being of the human occupants of the performance.
Brown [2], carried out an analysis for the basic mechanism of rapid-transit tunnel ventilation due to train piston action and for the temperatures resulting in the system. Theory is in general agreement with experimental results, indicating air velocities in tunnels of the order of 1/5 of the train velocity even though trains occupy only 1/4 to 1/3 of the cross-sectional area of the tunnel. Little of the heat load owing to trains, brakes, passengers and machinery is conducted through the ground about the tunnel, but the ground serves as a heat reservoir, causing the amplitude of the

diurnal subway variation to be about half that of the ambient air temperature. With the help of a partly empirical theory combined with experiment, it was possible to indicate approximately the temperatures to be expected in a tunnel under differing climatic conditions. The effect of train scheduling on ventilation rate is discussed, as is the possibility of using models to obtain more precise design data. Gouse, et al [3], studied on the aerodynamic drag on vehicles moving in guide ways of varying degrees of enclosure. The reason for the study was that several potential high speed ground transport system concepts involve high speed motion of vehicles in enclosed guide ways for significant portions of their travel time. Analytical and experimental investigations have been carried out. The analytical studies developed the solution for the aerodynamic drag on a vehicle in an enclosed guide way in laminar flow. The analysis is based on an analogy between the governing equations for the unsteady flow resulting when an infinite body is started impulsively from rest and the steady flow that results from steady motion of a semi-infinite body. The results of this analysis for laminar flow provided a base from which to begin in turbulent flow and were used to justify the basing of a drag coefficient on the wetted surface area of a vehicle rather than the frontal area of a vehicle. Also, some experiments are conducted using spheres as vehicle models. Miklos and Sajben [4], studied the dynamic characteristics of bodies moving in long, finite channels using a one-dimensional, incompressible fluid description. It is shown that the motion of the body and the fluid contained in the channel are closely and nonlinearly coupled and therefore an understanding of the system dynamics requires consideration of both body and fluid. The character of the solution is investigated using phase plane methods. The findings are compared with numerically integrated solutions yielding body and fluid speeds, as well as drag coefficients. The effects of various body speeds are studied. Compressibility effects are estimated and found slight for present systems. Fox and Vardy [5] investigated the design of a rail tunnel with minimized air pressure transients generated during the entry of a high speed train, introducing the equations of motion for compressible flow in a one-dimensional duct. Henson and Fox (1974) [6], described a practical method of calculating the aerodynamic effects of trains passing through interconnected tunnel systems so that these can be designed for acceptable pressure pulse levels, air velocities and train drag. The equations of unsteady compressible flow were developed into a form suitable for solving by the method of characteristics on a computer. Results obtained were compared with measurements taken on models and real tunnels and some of the comparisons are shown and discussed. Woods and Pope [7] predicted a generalized one-dimensional flow method for calculating the flow generated by a train in a single-track tunnel. The method is capable of modeling the effects of friction, gradual area change, heat transfer, locomotive heat release, vehicle leakage and gravity body forces. The underlying theory is based on the method of characteristics and is built into a computer program which allows these effects to be modeled individually or simultaneously. An experiment was performed in full size rail tunnel, for providing validation data. The program provides the results for transient pressures, temperatures and velocities. They concluded that, when a railway train enters a tunnel, it displaces the air in front of it, forcing some along the tunnel and the rest out of the entrance portal. The pressure rises in front of the train and a pressure wave travels along the tunnel, compressing and accelerating the air. This wave subsequently reflects at the tunnel portals and at the front and rear of the train. It combines with the similar waves generated by the entry of the rear part of the train and causes complex wave motions. It is important to estimate the magnitude of these pressure waves so that, for instance the power to drive the train can be determined. Fuji and Ogawa [8] studied aerodynamics of high speed trains passing by each other.. A three dimensional flow field induced by two trains passing by each other inside a tunnel is studied based on the numerical simulation of the three dimensional compressible Euler/Navier-Stokes equations formulated in the finite difference approximation. The problem is treated as a moving boundary problem. The history of the pressure distributions and the aerodynamic forces acting on the trains are the main areas discussed. The results show that the phenomenon is complicated due to the interaction of the flow induced by two trains. Strong side forces occur between the two trains when the front portion of the opposite train passes by. The forces fluctuate rapidly and the maximum suction force occurs when the two trains are aligned side by side.

Gerhardt and Krüger [9] presents data of investigations into the wind and train driven air movements into three new stations in Germany. Means to control the air movement and in particular to prevent excessive air infiltration into the train stations are proposed and discussed in the paper. Howe [10]. Studied the validity of various approximations by comparison with the exact solution available for potential flow from a two-dimensional, flanged duct. Holmes et al [11], performed a solution to the problem of predicting the airflow over a train entering a tunnel is presented using parallel processing and moving boundary condition scheme. The method is demonstrated using both incompressible and compressible flow solvers based on finite element formulation. Tayfun [12], provided an overview of some of the CFD methods for three-dimensional computation of complex flow problems. The methods and tools include the formulations of flow with moving boundaries and interfaces. Flow around two high-speed trains in a tunnel is given as an example of flow simulation. Auvity et al [13] studied experimentally the unsteady aerodynamic field outside a tunnel during a train entry. The experimental work provides some insight to the resulting exit flow created at the tunnel portal and its main characteristics. The study focused on the influence of the train speed and the train nose geometry on the flow. Unsteady velocity measurements were taken to attempt to clarify the influence of the train speed on the jet induced at the tunnel portal when the train enters. A mass balance was undertaken to compare the quantity of air ejected from tunnel to compressed air inside. The jet momentum was also calculated and found to increase with train speed and is insensitive to the train nose geometry. Howe et al [14] studied theoretical and experimental investigation of the compression wave generated by a train entering a tunnel with a flared portal. Howe [15] made an analysis on the pressure transients generated when two high speed trains meet in a tunnel. Safe operation at speeds exceeding about 300 km/h usually demands that the hydraulic blockage produced by a train should be small. The problem can then be formulated in terms of the scattering of the potential flow near field of each train by the moving surface of the other train and this permits the derivation of closed form representations of the unsteady pressure in the special case of ‘snub nosed’ trains in a tunnel of semicircular cross-section. His solution is used to devise a general procedure for calculating pressure transients generated by trains of arbitrary

nose profiles in tunnels of arbitrary cross-sectional shape in terms of a knowledge of the local incompressible potential flow produced by each train travelling separately in the tunnel. Arturo et al [16] pointed out that the design of new high-speed railway lines requires longer and more numerous tunnel sections, where aerodynamic effects limit the maximum allowed train velocity for a given tunnel cross-section area. These effects influence the train power requirement, the traction energy costs and the pressure wave amplitude. The knowledge of the unsteady aerodynamic field around the train, is therefore essential to the optimum choice of the tunnel configuration and mainly of the diameter and of the existence and position of pressure relief ducts. The aerodynamic phenomena generated by a train travelling at high speed through a long tunnel of small cross-section is analyzed by means of quasi one-dimensional numerical simulations of the air flow induced by a train travelling at 120 m/s in a tunnel connecting two stations 60 km apart. Several tunnel configurations at high blockage ratio are discussed, together with the positive and negative effects of pressure relief ducts and of partial air vacuum. A numerical code named “Tunnel Nets and Trains (TNT)” has been developed based on the physical model and numerical method. The code reliability has been tested through comparison with analytical solutions for compressible flows, and with published experimental measurements in railway tunnels including section changes, ventilation shafts and train crossing in a wide range of thermodynamic and kinematic conditions. Aerodynamic phenomena are evaluated in terms of drag, pressure wave amplitude and shock wave onset on the train tail. Results suggest that configurations consisting of twin tunnels connected by pressure relief ducts near stations and operated under partial vacuum should be preferred. Mok and Yoo [17] showed a numerical study on high speed train and tunnel hood interaction. Numerical computations of the train-tunnel interaction at a tunnel entrance with real dimensions is discussed. Three-dimensional compressible Euler equations are simulated by finite element method. For a single-track tunnel, four kinds of tunnel entrance shapes were studied to investigate the formation of the compression wave front at the tunnel entrance. The results of the study can be used for countermeasures against the boom noise at the tunnel exit, for the air tightness design of the train body shell and the fatigue damage of the tunnel wall and structure.

This work divided into two parts, the first one is an experimental work in which a scale train model was tested in a wind tunnel for different window-fins location to obtain the best one which achieve maximum air flow inside the model (low average temperature). The Second one is a theoretical work using CFD program (ANSYS software) to investigate the air flow velocity inside the train in forms of velocity contours and vectors, The average air velocity inside the train was also calculated for comparison.

EXPERIMENTAL WORK

The first carriage of the train is taken as a model to simulate the air flow and thermal performance inside it. The model was fabricated with a scale 1:30 and tested experimentally in wind tunnel as shown in Figs. 1-a,b. Figure 2 shows a photo of the tunnel train. The model was made of plexiglass with three openings at left and right sides of the model, as shown in Fig. 3. This model was provided with an electric heating plate fixed at the floor of the metro and was isolated from the bottom. The heating plate was made of ceramic plate of dim 0.1 x 0.6 m and an electric hating wire (nickel –chrome, resistance 87 Ω) was wounded around the plate with increment 0.005 m to have a uniform heat flux along the plate. This heating source inside the metro simulate the heat generation from passengers due to metabolic processes. The heater was connected to a power supply 25 volt, 33 thermocouples were fixed along the heating plate and connected to a data logger to measure the surface temperature at different locations as shown in Fig. 4. Different experimental tests were conducted for different opening and fins arrangements to deduce the best one which attains a reduction in plate temperature which in accordance gives the best air movement inside the train.

THEORITICAL WORK

The prediction of air flow patterns (velocity and pressure distribution) inside the train model in the wind tunnel requires the application of a computational fluid dynamics (CFD) program. ANSYS CFD FLOTRAN is a computer package used for predicting the air flow patterns, pressure and velocity contours. The program is a three dimensional one, that utilize the finite element approach which uses the k-ε turbulence model and solves the Reynolds equations, the energy equation and the equations for turbulence energy and its dissipation. In the present work, the boundary conditions stipulated that the flow velocity at all the solids surfaces is zero (satisfying the real viscous fluid configuration). As shown in Fig. 5. Also the approaching velocity profiles were prescribed by logarithmic law. Three general assumption are assumed , the first that the fluid is Newtonian, the flow is a single-phase one and the solution domain is of constant geometry, in addition, the flow is steady incompressible and the body forces are neglected. The continuity equation is the mathematical statement of the principle of conservation of mass, and can be expressed for steady incompressible-fluid flow as follow:

a) Continuity equation

$$\frac{\partial \mathrm{u}}{\partial \mathrm{x}} + \frac{\partial \mathrm{v}}{\partial \mathrm{y}} = 0 \qquad (1)$$

b) Momentum equation

The momentum equation of motion in tensor form for 2-D turbulent flow is given by:

$$\frac{\partial}{\partial x}(u_i\, u_j) = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{1}{\rho}\frac{\partial}{\partial x_i} \left\{ (\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij} K \right\} \qquad (2)$$

c) Energy equation

$$\rho\frac{\partial}{\partial x}(uC_pT) + \rho\frac{\partial}{\partial y}(vC_pT) = \frac{\partial}{\partial x}(K_x\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial T}{\partial y}) + Q_v \qquad (3)$$

To obtain a solution of the above governing equations, Boundary conditions related to the physical model under consideration must be specified as no slip condition is assumed at all solid boundaries (model surfaces & ground). Thus the velocity flow is set to zero at these boundaries and the velocity profile of the undisturbed flow (upstream of the model) is prescribed uniform.

Details of the solution of the above governing equations based on the k-ε turbulence modeling and the eddy viscosity approach are given in ANSYS [1]. Table (1) illustrates the different cases studies experimentally and theoretically for different windows and fines locations.

RESULTS

Experimental Result

This paper presents the analysis and discussion of the experimental data obtained for temperature measurements inside the train model for different window and fins geometry. The test models as described were constructed for wind tunnel tests in which the average temperature inside the metro was calculated,

Fig. (6) shows the normalized average temperature ($T_{norm} = T_{av}/ T_f$) inside the train for different window construction. It is noticed that the cases when window are closed and or no air flow (cases 2,3 &4) gives the higher average temperature than other cases (windows open) while the actual case gives the higher average temperature in comparison with the cases of different window locations (open cases) since a little of air flow inside the metro in actual case compared with the other cases. The figure shows also the best reduction in average temperature for the cases of all window were opened and with fines at the external sides of the windows. These results were agreed with the theoretical one as will discuss below. The figure shows also the effect of the distance between the side wall of the tunnel and the metro side case No. 9 , since as the distance (x) increase the average temperature increase this is due to the pressure difference between the front and rear opening decrease with increasing x (less of air flow).

Theoretical results

The prediction of air flow patterns (velocity distribution) inside the train model in the wind tunnel requires the application of a computational fluid dynamics (CFD) program. The results were obtained in the forms of velocity contours and vectors, the velocity contours and vectors give a good picture about the air flow inside the model (stagnation and wake flow zones), which help in developing of the opening-fins positions construction and layout which yields more air flow inside the train, the average velocity inside the train model was also predicted for different window-fins arrangements.

Figures from 7 to 11 give the velocity contours and vectors for different window-fins combination, case 1, Fig. (7) gives the less of air flow inside the train this represents the actual case in which the one third of the window was open to the inside with tilt angle 30o, the other cases with fines supported at the external sides of the window give a reasonable air flow inside the train. Generally due to the pressure difference between the front and rear openings the air flow passes from the first and second windows and exhausted from the rear windows.

Figure 12 shows a relation between experimental results (T_{norm}) and theoretical results (average velocity) of the tunnel train model for different cases of the window-fins combination the two trend show that as the average air velocity inside the carriage model increase the mean average temperature decreases i.e. the good ventilation can enhance the thermal and humidity stresses inside the train.

CONCLUSION

-The natural ventilation is important for removing the excess heat inside the train with the aide of mechanical one.

-The train model test inside the wind tunnel gives a reasonable investigation for the effect of window-fines combination on the air flow movement inside the train.

-The cases in which the fins supported at the outside window give good results of ventilation than the actual case.

-as the distance between the side wall and train side (case 9) decreases while the motion of the train the differences in pressure between train front and rear decreases, so the speed of the air flow rate inside the train increases and remove excess heat.

-The rear openings are important in removing the exec heat inside the train.

- The theoretical results give a good picture of the air flow distribution inside the train in which we can use it for whole train carriages simulation in which is difficult to study experimentally.

-The results can be applied for any ground transportation vehicles.

NOMENCLATURE:

A: Projected area of the model normal to the air flow, m^2.
K : Kinetic Energy, joule.
k_x , k_y , k_z : Thermal conductivity in both x , y and z directions, w m^{-1} k°
Q_v : Volumetric heat source, joule.
T_i : Inlet temperature, C°.
U_{ref} : Free stream velocity, m/s.
u, v, w : Velocity-components in x, y and z directions, m/s.
ρ : Density of fluid, kg/m^3.
μ : Dynamic viscosity, Pa.sec.
μ_i : Turbulent or Eddy viscosity, Pa.sec.
δ_{ij} : Constant equal to 1 when i = j and equal to zero when $i \neq j$.
T_{norm} : normalized temperature, ^oC.
T_{sav} : average surface temperature, ^oC.
T_f : air flow temperature, ^oC.

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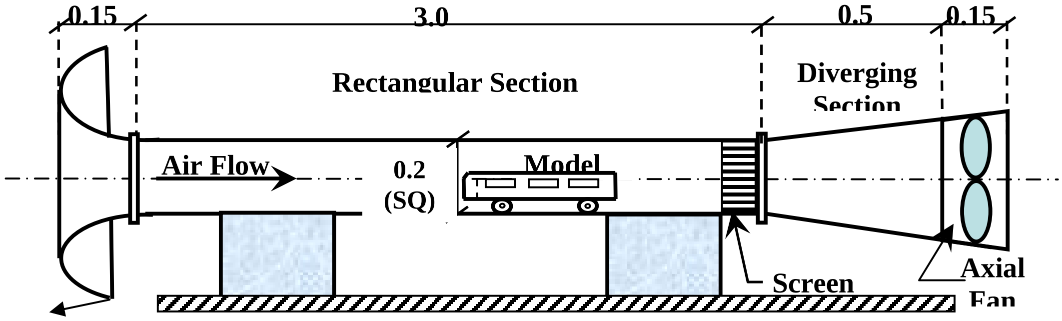


Figure 1-a: Schematic diagram of wind tunnel, (Dim. in m).

Fig. 1-b: A Photo of wind tunnel

Fig. 2 : A photo of the metro   Fig. 3 : A photo of the metro model.

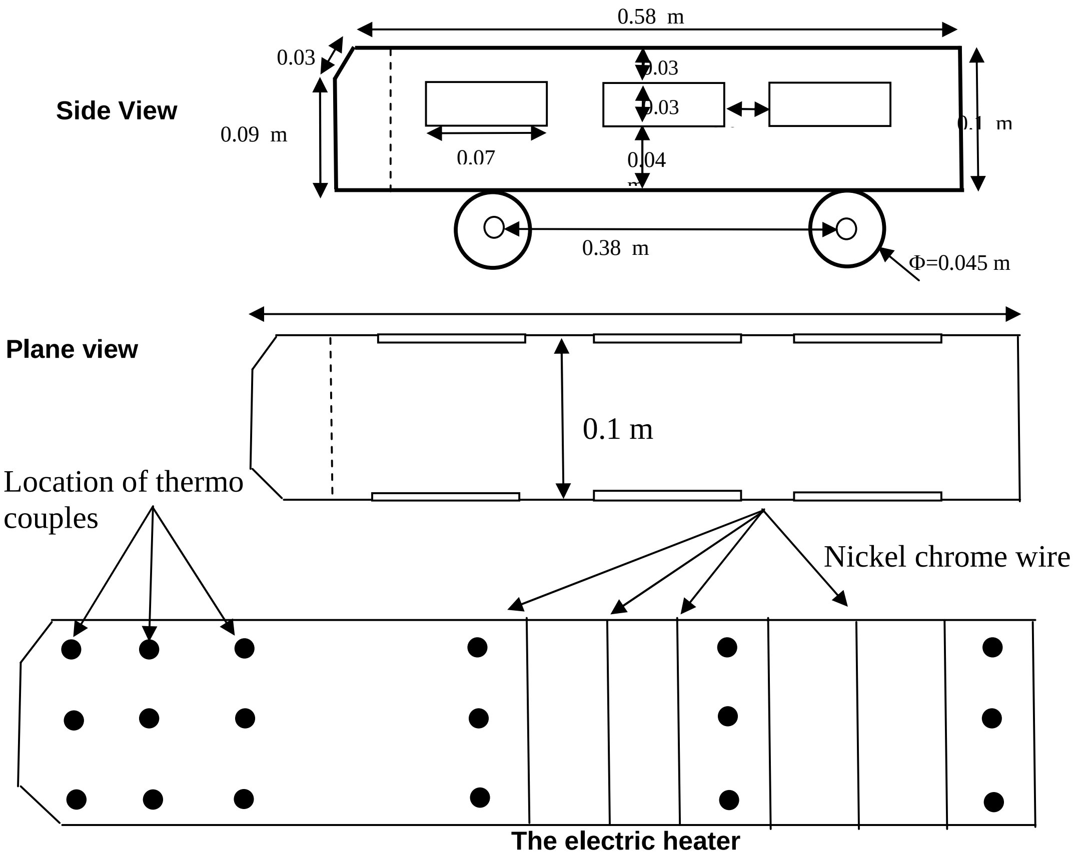


Fig. 4 : Schematic diagram of the metro model (side view & plane view) and the layout of thermocouples

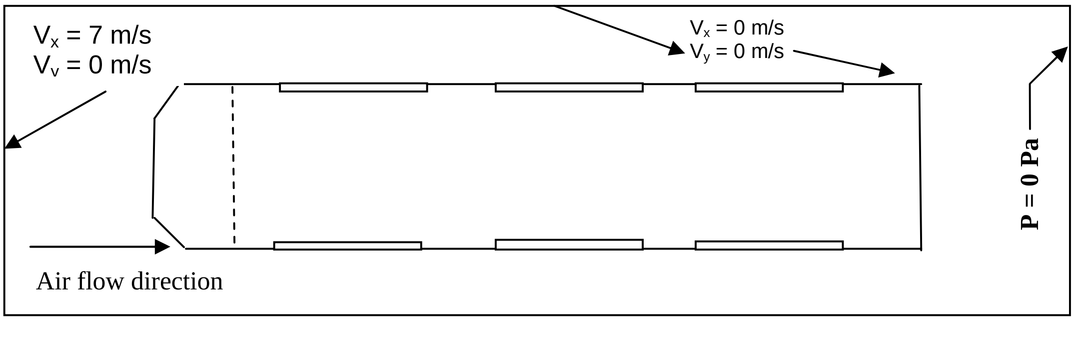
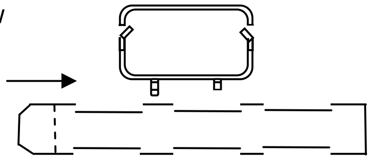
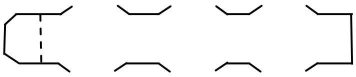
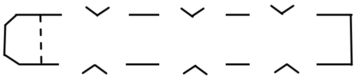
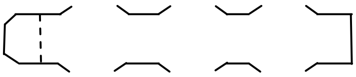
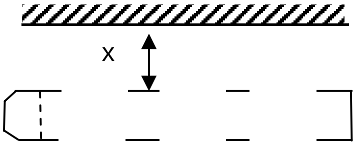


Fig. 5 : The boundary condition at the wind tunnel and model surfaces (Plane view).

Table 1 : Experimental (wind tunnel) and Theoretical (ANSYS) Program for Metro Model with Different Window Locations and Construction.

Tests \ Cases	Wind tunnel	ANSYS	Description	Model sketch
Case 1	√	√	Actual case One third of windows are open to the inside with tilt angle 30^o , air flow=7 m/s	Front view air flow Top view 
Case 2	√	X	All window are closed and no air flow	Top view 
Case 3	√	X	All window are closed (air flow = 7m/s	Top view 
Case 4	√	√	Window open – no air	Top view 
Case 5	√	√	Window open with air flow	Top view 
Case 6	√	√	Fins are end to end of the window	Top view 
Case 7	√	√	Fins are at the centre of the window	Top view 
Case 8	√	√	Fins at 1 cm from the end of the window	Top view 
Case 9	√	X	Window open & the distance between the side of the metro and the tunnel (x) was varied (1,2,3,4,5 cm)	Top view 

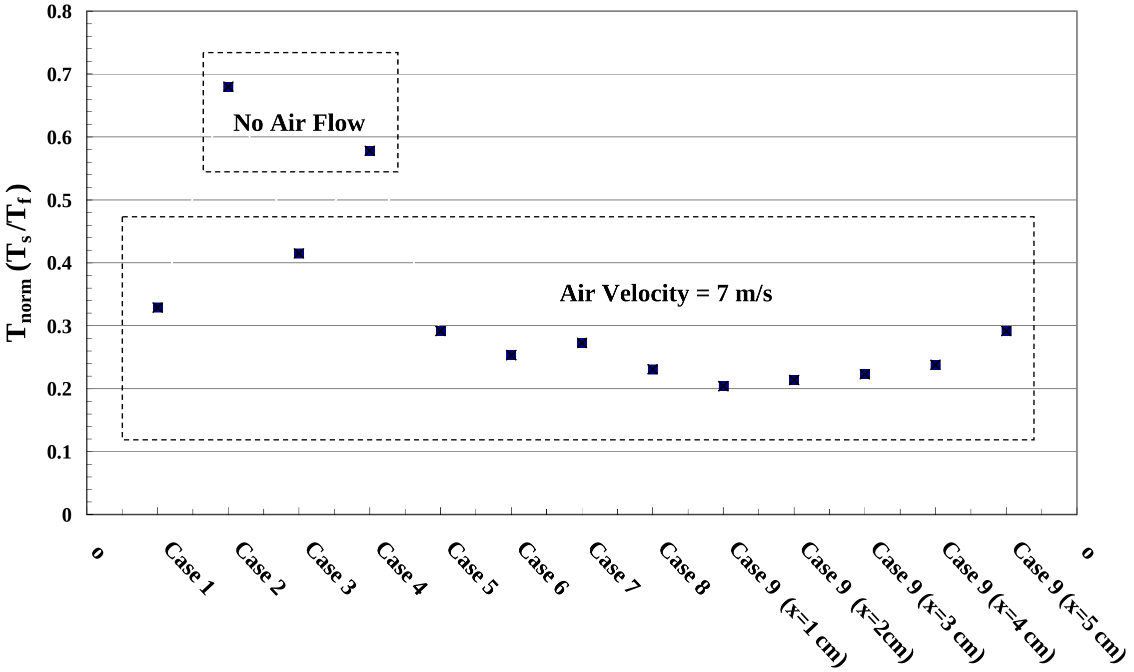
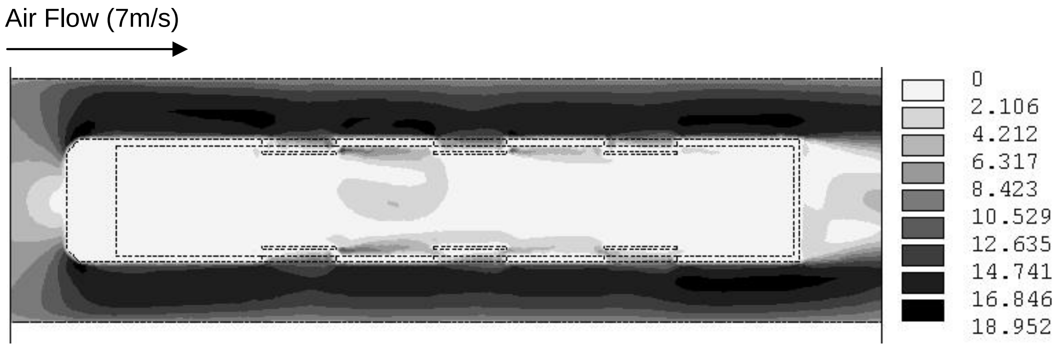


Fig. 6 :Normalized average temperature. for different windows shapes with and without fines.



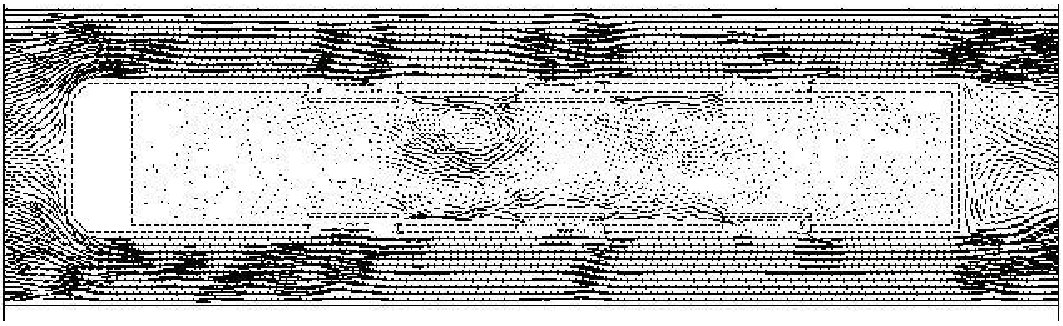


Fig. (7) : Velocity contours and vectors for case 1 (Actual case, one third of windows are open to the inside with tilt angle 30^o , air flow=7 m/s (Plane view, Top view)

Air Flow (7m/s)

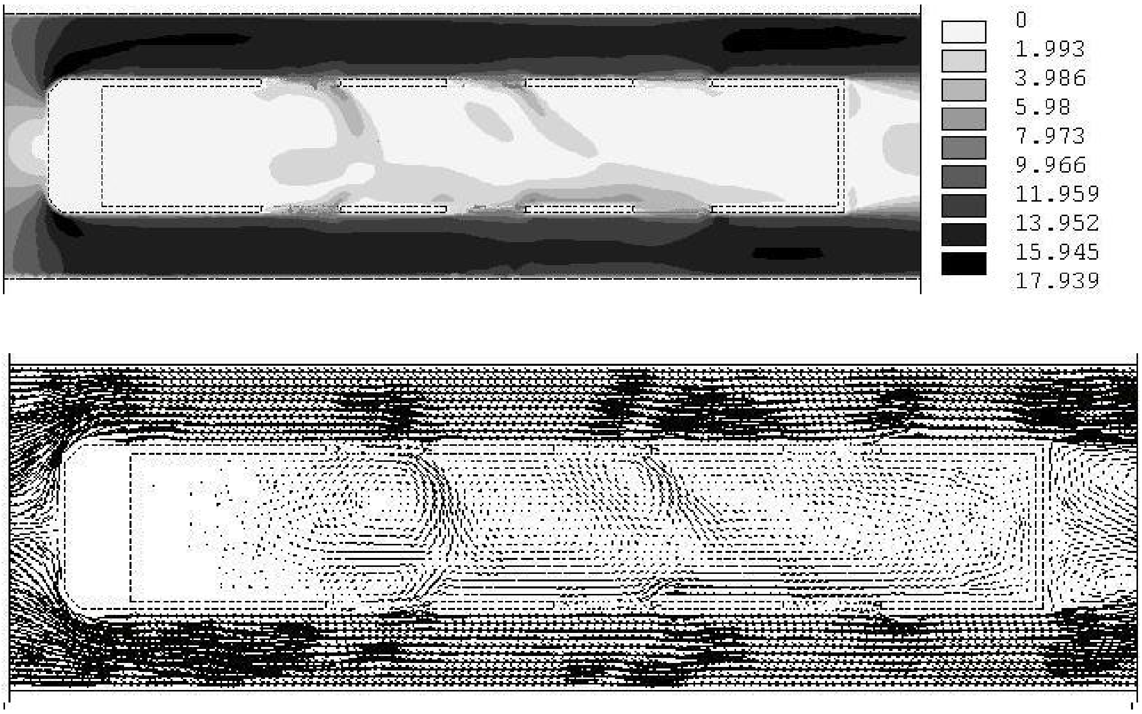


Fig. (8) : Velocity contours and vectors for case 5 (all windows are closed) (Plane view)

Air Flow (7m/s)

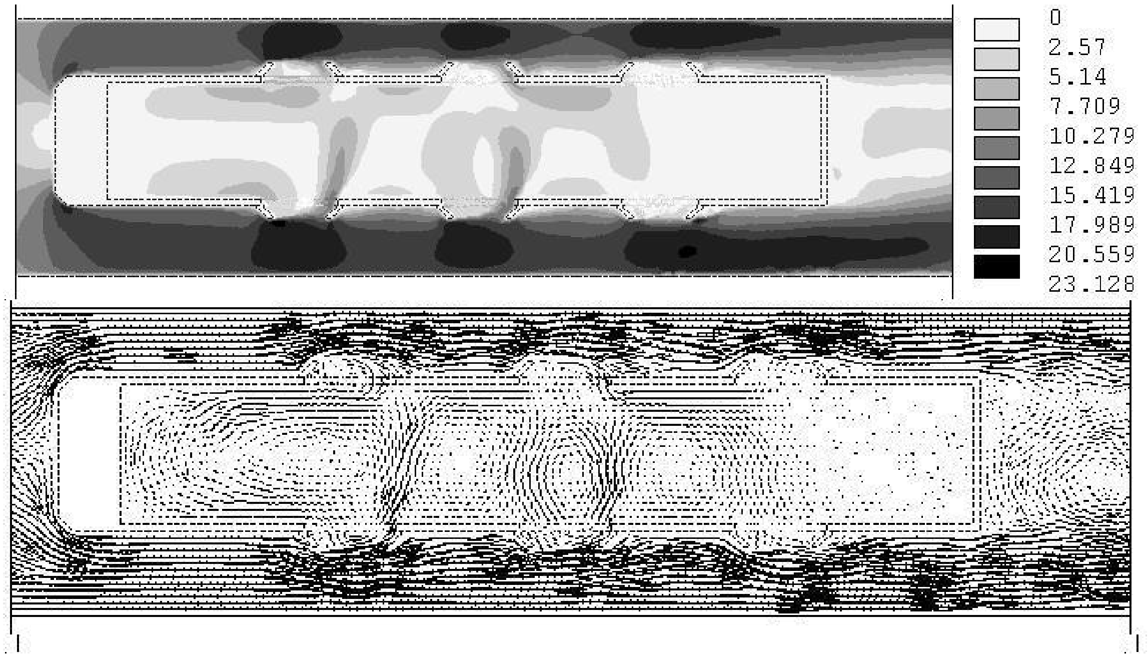


Fig. (9) : Velocity contours and vectors for case 6 (Fins at the end to end of the window)

Air Flow (7m/s)

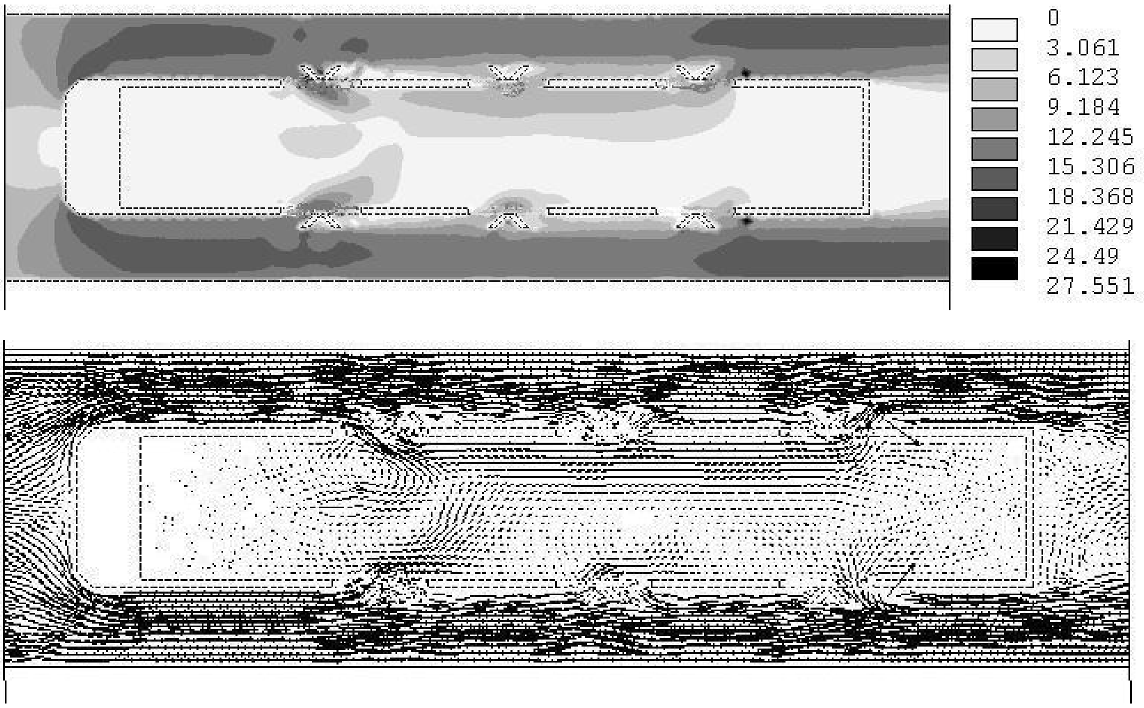


Fig. (10) : Velocity contours and vectors for case 7 (Fins at the center of the window)

Air Flow (7m/s)

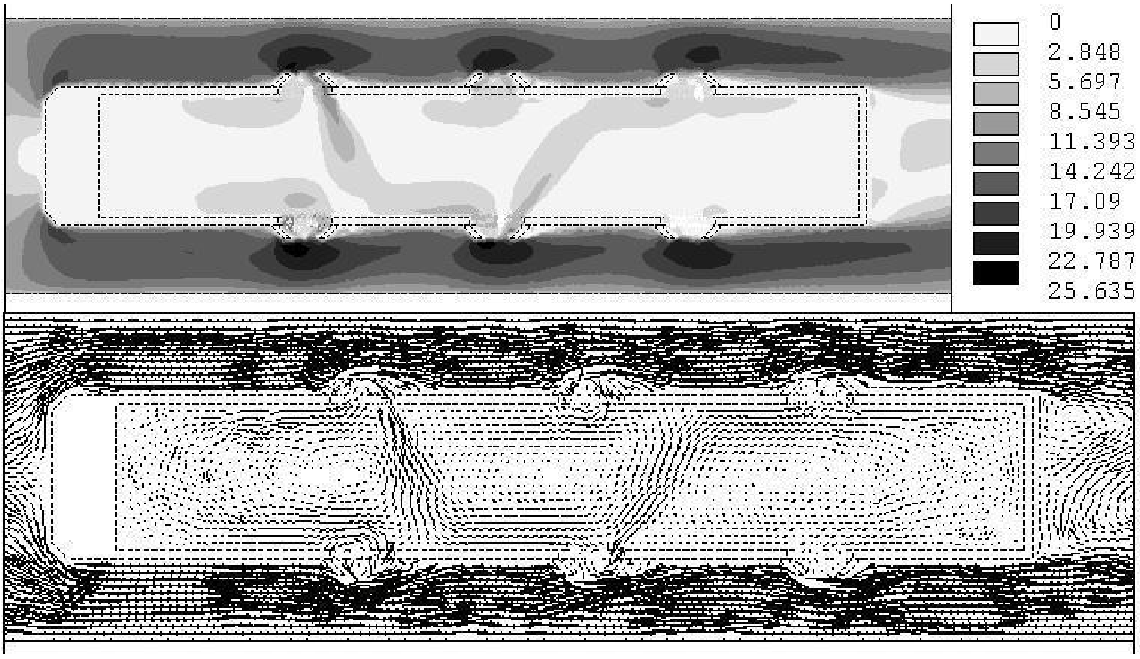


Fig. (11) : Velocity contours and vectors for case 8 (Fins at 1 cm from the window edges)

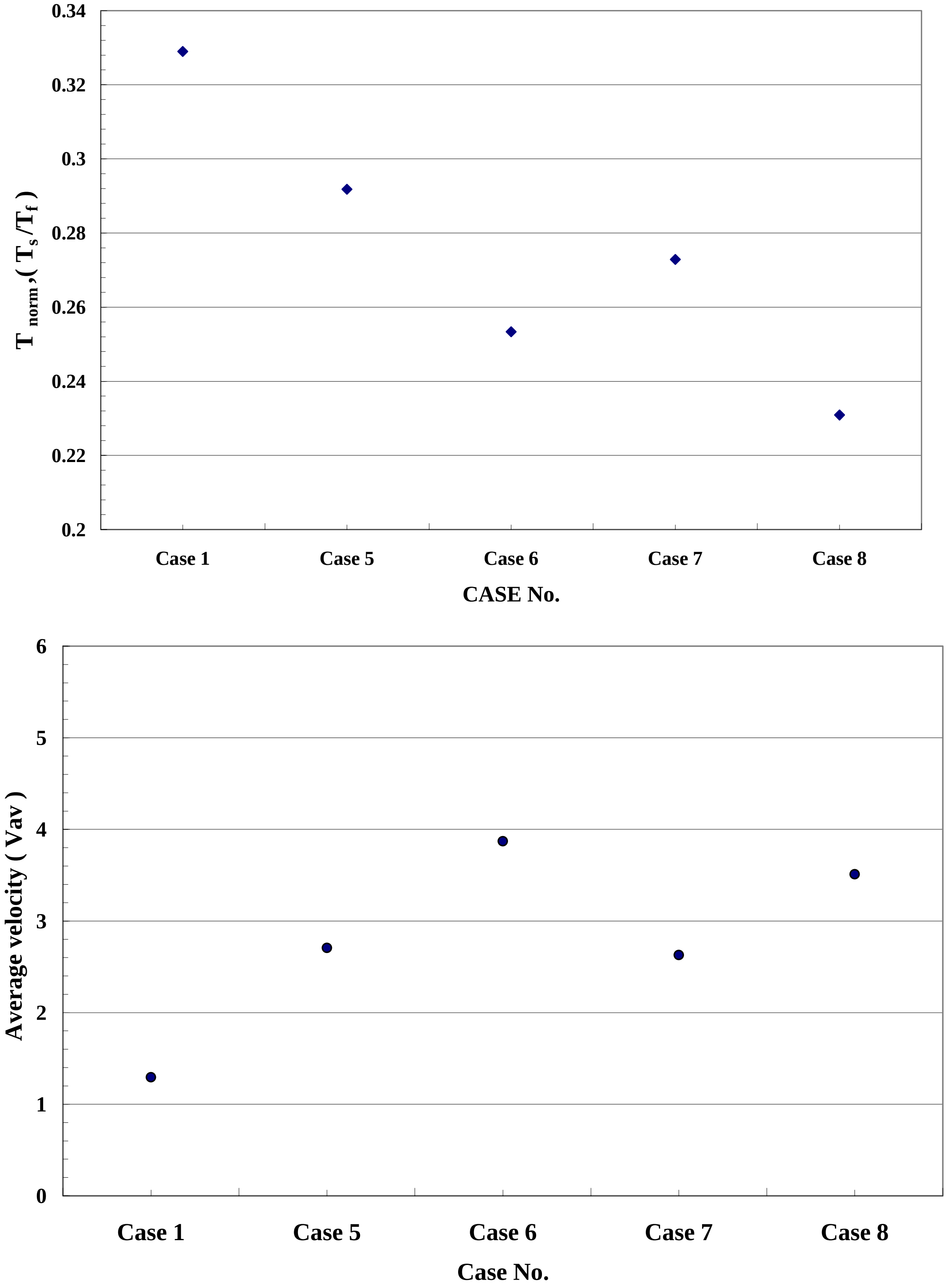


Fig. (12): Relation between experimental results (T norm) and theoretical results (average velocity) of the tunnel train model.