BBAA VI International Colloquium on:
Bluff Bodies Aerodynamics & Applications
Milano, Italy, July, 20-24 2008

EFFECTS OF TUNNEL VENTILATION MODES ON THE AERODYNAMIC DRAG OF A LOW SPEED TRAIN

HF Wang, Y Zhou, MM Alam and JF Huang

Department of Mechanical Engineering
The HongKong Polytechnic University, Hung Hom, Kowloon, Hong Kong
e-mail: mmyzhou@polyu.edu.hk, +00852-2766 6662

Keywords: Train aerodynamic, Tunnel effects, Friction drag, Form drag.

1 INTRODUCTION

Aerodynamic drag of a train is approximately proportional to the square of the train speed. For a strain at speeds of 250 ~ 300km/hr, around 75 ~ 80% of the total resistance is caused by aerodynamic drag [1]. Most of the previous studies are focused on the aerodynamic properties of a high speed train [2]. The aerodynamic drag of a train with relative low speed has not thoroughly understood, especially for the train runs through a tunnel with high blockage ratio. The aerodynamic drag of a train can be even higher when it runs through a tunnel relative to that in the open air. The accessional drag caused by the presence of tunnel is closely related to the blockage ratio (the ratio of the cross section of a train to that of the tunnel, *R*), length of the tunnel and train speed [2]. Consequently, a train running in a tunnel requires much higher power and incurs much more traction energy costs than in the open air. This problem is getting attention with recent rapid increase in fuel costs.

Like any other vehicles, the drag on a train consists of pressure drag (D_p) and surface friction drag (D_f). The former results from the pressure difference between the front and tail ends, while the latter is caused by the wall shear stress (τ_w). Vardy [3, 4] estimated that the ratio of D_f to D_p was around 5.5 for a typical case. Gaillard [5] suggested that D_f in a tunnel was increased compared to that in the open air by a factor of 1+2.21R. Sockel [6] found that this factor decreased with increasing train length and was nearly independent of the train speed when $R \approx 0.1$-0.2. However, Vardy [3, 4] pointed out that it was impossible to find a general applicable formula to determine the tunnel effects. In spite of previous investigations, the effects of a tunnel and the tunnel ventilation modes on the aerodynamic drag of a train, especially with high blockage ratio but low train speed, has yet to be better understood.

This paper reports an in-situ measurement of the aerodynamic drag on a full-scale train with 8 carriages during routine operation. The difference in D_f and D_p between the train running through the tunnel and that in the open air is estimated based on measurement results. The effects of two different tunnel ventilation modes, i.e. free-cooling mode and re-circulation mode, on D_f and D_p are also investigated. In the free-cooling mode, the tunnel ventilation is mainly provided by the piston effect induced by train movement with appropriate damper operations; in the re-circulation mode, cooled air is injected into the tunnel to provide extra cooling effects.

2 EXPERIMENTAL DETAILS

The wall shear stress τ_w can be determined by measuring the velocity gradient at the surface [7]. For a turbulent boundary layer, the velocity gradient is almost constant within the viscous sublayer [7, 8]. The most representative train speed is 11m/s (about 40km/h) and the boundary layer on the train surface may be assumed to be fully turbulent. The thickness of viscous sublayer is estimated to be about 0.54mm. Two hot-wire (55p71, Dantec Co.) were mounted on the roof of the first and last carriage to measure the corresponding velocity gradient. The separation Δy between the sensing element and the train roof surface was measured to be about 0.4mm, smaller than the thickness of the viscous sublayer. The air velocity relative to the train drops to zero at the train surface, τ_w can be determined from $\tau_w = \eta \cdot (u/\Delta y)$, where η is viscosity of air, u is the hot-wire-measured velocity.

Two pressure tabs, connected to pressure transducers (SMP 131 Leeg Co.) through rubber tubes with a diameter of 4mm, are mounted at the geometrical center of the front and tail surfaces of the train to measure the front and tail stagnation pressures, respectively. Since the present tested train is not streamlined, with its two end surfaces quite flat, the averaged pressures on front and tail end surface and hence D_p are linearly related to the stagnation pressures [9]. The schematic diagram of the equipped train is shown in Fig. 1.

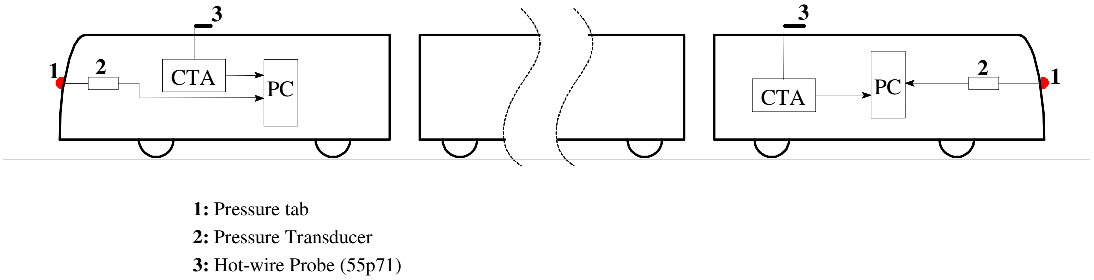

Figure 1: Schematic diagram of the equipped train.

The measurements were conducted when the instrumented train ran in the open air and in tunnels. Two tests were performed, with the tunnels under the two ventilation modes, respectively. In each test, the signals from hot wire anemometers and pressure transducers were offset, low-pass filtered at a cut-off frequency of 1kHz, ant then sampled at a frequency of 2kHz. The signal of the train speed was also recorded for validation. The sampling duration for each record is 30min.

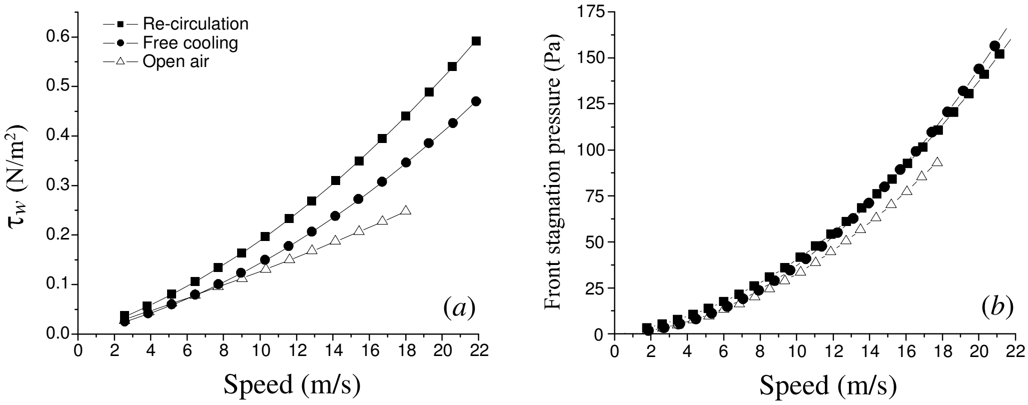

Figure 2: Wall shear stress and front stagnation pressure in different ventilation modes and in open air. (*a*) Wall shear stress, τ_w; (*b*) Front stagnation pressure.

3 RESULTS AND DISCUSSIONS

Fig. 1 shows the averaged τ_w for the two ventilation modes and that in the open air. The averaged τ_w is the mean value of those measured at the first and last carriages. The presence of the tunnel significantly increases τ_w, especially at higher speed. For example, at the speed of 18m/s (65km/h), τ_w in the free cooling mode is about 40% higher than that in the open air. It should be noted that the tunnel ventilation modes have a profound effect on τ_w. The application of re-circulation mode results an increase in averaged τ_w, compared with that in the free-cooling mode, which is more remarkable as the train speed increases. This is because the injected of cool air in the re-circulation mode raises the turbulence level in the tunnel and leads to an increase in surface friction [10, 11].

The averaged front stagnation pressures (P_f) at the two ventilation modes and in the open air are shown in Fig. 2. Magnitude of the stagnation pressure on the tail end surface is only about 1/10 of that on the front, thus not presented here. P_f increases quickly with the train speed. The tunnel effect on P_f is more appreciable at a higher speed; for example, in the free cooling mode the P_f is 24% higher than that in the open air at the speed of 18m/s (65km/h). The effect of ventilation modes on P_f is almost negligible compare to its effect on the shear stress (Fig. 1). Since D_p is about 10% of total aerodynamic drag [2], the effects of tunnel ventilation modes on the total aerodynamic drag of a train is largely attributed to the surface shear stress.

4 CONCLUSIONS

The effects of tunnel ventilation modes on the aerodynamic drag of a train are investigated In-situ measurements were conducted to investigate how the tunnel and different tunnel ventilation modes affect aerodynamic drag of a train. Following conclusion may be drawn from the investigation:

1) It has been found that the presence of the tunnel increases both friction and form dragson the train even at the present relatively low train speed. The tunnel effects on the friction drag is more remarkable than that on the form drag; the increase in the friction drag due to the presence of the tunnel is almost twice that in the form drag at 18m/s,.

2) The tunnel ventilation mode has a profound effect on the friction drag. In the re-circulation modes, pumping in the cool air raises the turbulence level inside the tunnel and results in a significant increase in the shear stress on the train, compared to that in the free-cooling mode.

3) The effect of the ventilation mode on the friction drag increases with the train speed. The increase in the friction drag for the re-circulation mode, compared to that in the free-cooling mode, is negligibly small at 3m/s but reaches 26% at 18m/s.

ACKNOWLEDGEMENTS

The support of Hong Kong MTRC to this work is gratefully acknowledged.

REFERENCES

[1] R. G. Gawthorpe. Aerodynamics in railway engineering: aerodynamics of trains in the open air. Proc. World Congr. Inst. Mech. Eng. Railway Eng. Int. 7-12. 1978

[2] J.A. Schetz. Aerodynamics of high-speed trains. *Anun. Rev. Fluid Mech.* **33**, 371-414, 2001

[3] A.E. Vardy. Aerodynamic drag on trains in tunnels: Synthesis and definitions. Proc. World Congr Inst. Mech. Eng. 210: 29-38. 1996.

[4] A.E. Vardy Aerodynamic drag on trains in tunnels: Prediction and validation. Proc. World Congr Inst. Mech. Eng. 210: 39-49. 1996.

[5] M.A. Gaillard. Aerodynamic measurements with high-speed trains (250km/hr) in the Heitersburg tunnel. Proc. Int. Symp. Aerodyn. Vent. Vent. Tunn., 3rd, Sheffield, UK, 343-62. 1979.

[6] H. Sockel. The aerodynamics of trains. Handbook of Fluid Dynamics and Fluid Machinery. J.A. Schetz & A.E. Fuhs, New York: Wiley & Sons. 1721-41. 1996

[7] M.K. Mazumder, S. Wanchoo, P.C. Mcleod, G.S. Ballard, S. Mozumdar & N. Caraballo. Skin friction drag measurements by LDV. *Applied Optics*, **20**, 2832-2837, 1981.

[8] J.F. Douglas, J.M. Gasiorek & J.A. Swaffield. *Fluid Mechanics*, Pearson Education, England, 2001.

[9] B. Zhang & X.F. Liang. Measurement of pressure distribution on a real high-speed train. *Railway & Vehicles*, **38**:14-16. 2000.

[10] P.E. Hancock & P. Bradshaw. The effect of free-stream turbulence on turbulent boundary layers. *ASME J. Fluid Eng*. **105**: 284-289, 1983.

[11] V.K. Kuzenkov, V.N. Levitskii, E.U. Repik & Y.P. Sosedko. Effect of free-stream turbulence on surface friction in a turbulent boundary layer. *Fluid Dynamics*. **20**, 210-218, 1995.