THE CONCEPT OF THE AIR INTERCHANGE STATIONS APPLIED IN THE HSUEHSHAN TUNNEL

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ABSTRACT

The Hsuehshan Tunnel, with a length of nearly thirteen kilometers, is a twin-tube tunnel composed of two unidirectional traffic road tunnels. Besides system reliability, the construction costs, the fan installation costs and the operating costs, the main issue during the design stage was the long tunnel ventilation system.

The ventilation system of the Hsuehshan Tunnel is a longitudinal ventilation system. When the two tubes are ventilated separately as in a conventional design, the ventilation equipment is usually sized for the maximum traffic flow in each tube. For most cases, the maximum traffic flow in each tube would not happen simultaneously. Also, the maximum fan capacity required for each tube would not be the same due to the tunnel gradient. If the twin tube tunnel could be considered as one unit, then the required maximum fan capacity would be smaller than the sum of the fan capacities required by each of the two tubes when they are ventilated separately. As a result, the fan installation costs, the operating costs and even the number of ventilation shafts can be reduced. The concept of an air interchange station is just to combine the two separate tubes into one unit.

Keywords: longitudinal ventilation, interchange.

INTRODUCTION

The ventilation system of the Hsuehshan Tunnel contains three air exchange stations and three air interchange stations. At each of the three air exchange stations the polluted air in each tube is exchanged for fresh air using separate fresh and exhaust air shafts. At each air interchange station the air in one tube is diverted into the other tube. This interchange of air between the two tubes permits one tube to be used as an auxiliary air duct for the other tube to help maintain satisfactory air quality. The heavily polluted air in one tube is replaced with lightly polluted air from the other tube while the lightly polluted air in one tube is replaced with heavily polluted air from the other tube (Figure 1.).

One of the main features of this system is the momentum supplied by the flows from the air exchange stations and air interchange stations into the tubes which generate a longitudinal air flow in a similar way to the jet fans. The air is blown into the tunnel at the ceiling level with a speed of about 30 m/s. In this way the air exchange stations and air interchange stations acts as very powerful booster jets.

Air interchange stations are located between the two tubes. Each air interchange station is comprised of four sets of air interchange fans. Two sets (in parallel) are used for diverting air from the Westbound tube into the Eastbound tube and the other two sets are used for diverting air from the Eastbound tube into the Westbound tube. (Figure 2.)

If the traffic volume in both tubes were the same during peak times and the tunnel were constructed with a slight gradient, that would mean the required maximum ventilation flow of the two tubes during peak traffic times would be the same. For this case it wouldn't make sense to use the air interchange station approach in this tunnel ventilation system. But the Hsuehshan Tunnel is an inter-urban tunnel between Taipei City and Ilan City with a gradient of 1.25% from the East to the West. The designed peak traffic volume in the westbound tube (uphill) is 3700 pcu/hr. At the same time the designed

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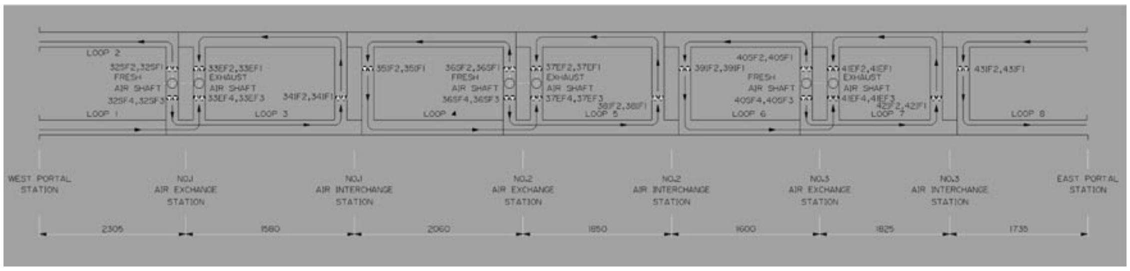

Figure 1. The Flow Diagram of the Hsuehshan Tunnel Ventilation System

traffic volume in the eastbound tube (downhill) is 2467 pcu/hr. As a result, the required ventilation flow of the westbound tube is about 4 times that of the eastbound tube during the westbound peak traffic time (refer to Table 1). This is the main reason why the air interchange station approach was adopted for use in the ventilation system of the Hsuehshan Tunnel. The benefits of using an air interchange station system are described as follows:

Reduced Construction Costs

If a conventional longitudinal ventilation system were to be used in the Hsuehshan Tunnel, it would have resulted in a shaft every 2.5km or 5 ventilation shafts for the westbound tube (Figure 3.) and just 2 ventilation shafts being required for the eastbound tube. It would involve constructing 3 fresh air/exhaust air ventilation shafts up to 300m in depth for the westbound tube and 2 fresh air/exhaust air ventilation shafts up to 560m in depth for both the westbound and eastbound tubes.

The selection of ventilation exhaust shaft locations for road tunnels is always a thorny matter. No one likes to have a shaft close to their house or land. The location of exhaust shafts is usually determined by local acceptance rather than by engineering considerations. Hence, minimizing the number of shafts becomes a critical issue in road tunnel projects.

Between two shafts or between a portal and a shaft, 3 air interchange stations are located between the westbound and eastbound tubes of the Hsuehshan Tunnel where the air in the two tubes can be exchanged. The heavily polluted air from the uphill tube is replaced with the lightly polluted air from the downhill tube and vice versa. The result is that it is possible to minimize the number of shafts to 3 fresh air/exhaust air ventilation shafts for both tubes (Figure 4.) and to locate them at environmentally less sensitive areas and suit the local topography to give moderate shaft depth with easy access. Hence the construction cost (excavation cost) can be reduced by a large extent.

Reduced Fan Installation Costs

If, as described above, a conventional longitudinal ventilation system were to be used in the Hsuehshan Tunnel, the capacity of the main ventilation fans (installed in the air exchange stations) of the westbound and eastbound tubes must be sized for the maximum flow required by each of the two tubes (i.e. 100% and 47% , refer to Table.1). Since the maximum flow requirement will not happen at the same time in the two tubes, using an air interchange station system the main ventilation fan capacity could be sized to (100% + 24%) /2 = 62% for the westbound and eastbound tubes.

During maintenance work in one tube its traffic would be diverted into the other tube which would then have bidirectional traffic flow. With bidirectional traffic, the piston effect of the vehicles would become a disturbance factor rather than being one of the main forces providing the longitudinal ventilation flow. The worst condition would arise with the highest traffic in the opposite direction to the normal traffic direction (also the ventilation flow direction). Hence, a sufficient number of jet fans must be installed to provide the necessary longitudinal ventilation flow. For conventional longitudinal ventilation, the required number of jet fans for the two tubes is based on the worst traffic conditions of each tube. Using an air interchange station system can reduce the number of jet fans to be installed in the tunnel.

As a result, using an air interchange station system can reduce the fan installation costs including the power supply systems.

Reduced Operating Costs

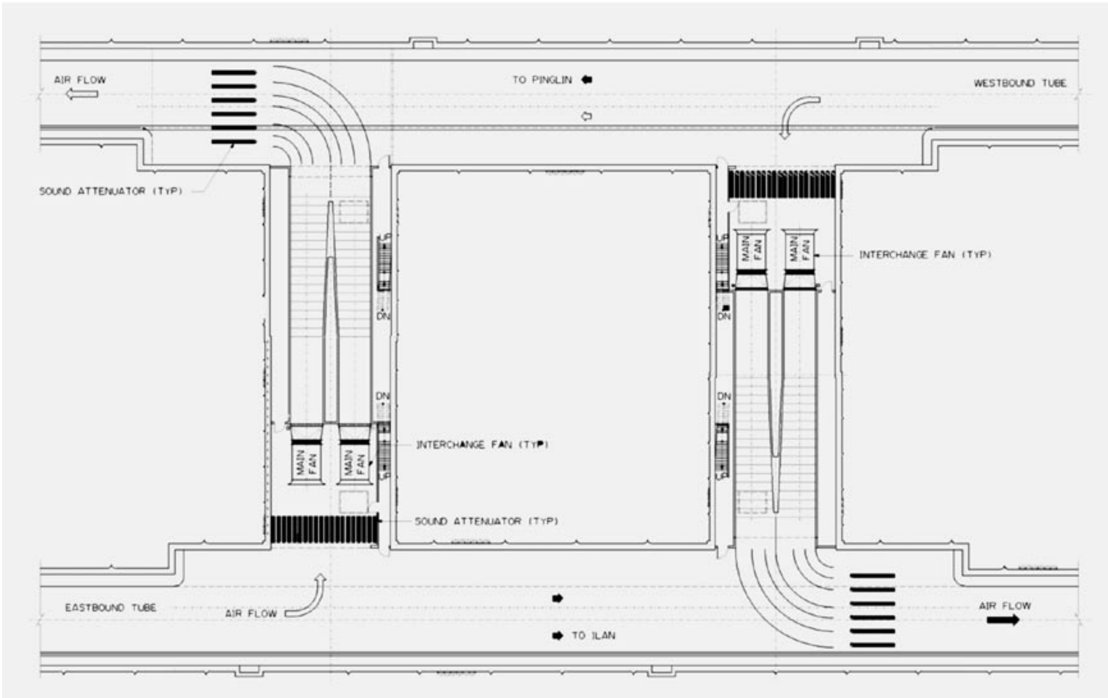

Figure 2. Typical Air Interchange Station Plan

Table 1. Ventilation Flow Requirements

	Ventilation Flow	
	Peak Traffic in Westbound	Peak Traffic in Eastbound
Westbound Tube	100%	62%
Eastbound Tube	24%	47%

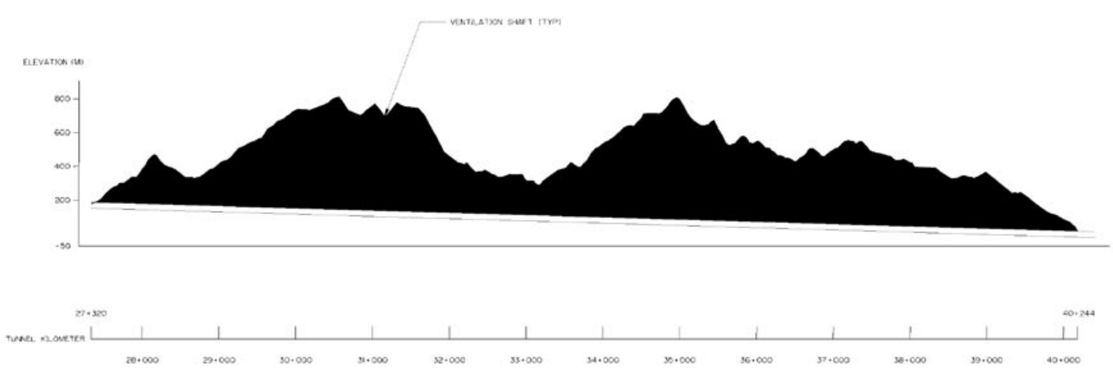

Figure 3. Hsuehshan Tunnel Longitudinal Profile
(Conventional Longitudinal Ventilation System)

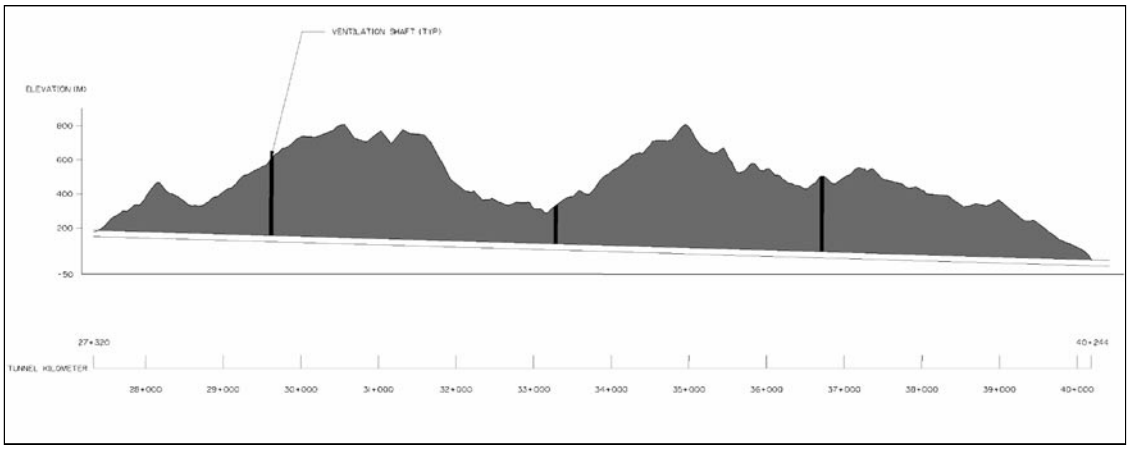

Figure 4. Hsuehshan Tunnel Longitudinal Profile
(Air Interchange Station System)

The fan's power consumption is proportional to the cube of it's flow. If conventional longitudinal ventilation were to be used in the Hsuehshan Tunnel, the maximum ventilation flow of the westbound and eastbound tubes during peak traffic in westbound tubes would be 100% and 24% respectively (refer to Table 1). When using air interchange stations the maximum ventilation flow of the westbound and eastbound tubes during peak traffic in westbound tube would be the average of 100% and 24%, which is 62%. Then the power consumption of the fans during the westbound peak traffic time would be:

- Conventional longitudinal ventilation: $100^3 + 24^3 =$ 1,013,824
- Air interchange station system : 3 62^3 = 714,984

Although the air interchange fans would add some additional power consumption, the overall power consumption using the air interchange station system is still lower than that of the conventional longitudinal ventilation system.

The main ventilation fans of the Hsuehshan Tunnel are equipped with Variable Frequency Drivers (VFD) to modulate the fan capacity to get the desired air quality. Table 2 shows the combined efficiency of the main ventilation fans (w/VFD). It is obvious that the fan's combined efficiency gets lower as the air flow rate goes down.

As mentioned above, if conventional longitudinal ventilation were to be used in the Hsuehshan Tunnel, the main ventilation fan capacity of the westbound and eastbound tubes must be sized for the maximum flow required by each of the two tubes. That is 100% for the westbound and 47% for the eastbound (Table 1).

During peak traffic time in the westbound tube, the main ventilation fans of westbound tube will operate in full load and their combined efficiency is 0.77, but the main ventilation fans of eastbound tube will operate in partial load of 24 / 47 = 51% and their combined efficiency is 0.69. During peak traffic time in the eastbound tube, the main ventilation fans of westbound tube will operate in partial load of 62% and their combined efficiency is 0.73 and the main ventilation fans of eastbound tube will operate in full load and their combined efficiency is 0.77.

When using an air interchange station system, the main ventilation fan capacity will be the average of 100% and 24%, which is 62%. During peak traffic time in the westbound tube, all the main ventilation fans will operate in full load and their combined efficiency will be 0.77. During peak traffic time in the eastbound tube, all the main ventilation fans will operate in partial load (62+47) / (100+24) = 88% and their combined efficiency will be 0.77.

During the off peak traffic times, the operating efficiency of using an air interchange station system is still better than that of using a conventional longitudinal ventilation system.

Hence, the overall operating efficiency of using an air interchange station system is better than that of the conventional longitudinal ventilation system no matter what the traffic conditions or volume in the two tubes is. As a result, using an air interchange station system can

Table 2. Combined Fan Efficiency in Partial Load Conditions

Air Flow Rate	Fan Efficiency	Motor Efficiency	VFD Efficiency	Combined Efficiency
100%	0.84	0.94	0.97	0.77
90%	0.84	0.94	0.97	0.77
80%	0.84	0.94	0.97	0.77
70%	0.84	0.93	0.95	0.74
60%	0.84	0.93	0.93	0.73
50%	0.84	0.92	0.89	0.69
40%	0.84	0.89	0.84	0.63
30%	0.84	0.86	0.70	0.51

reduce the operating costs of the fans.

OPERATION

Unidirectional Operation

In longitudinal ventilation, the air velocity in the tunnel must be controlled under 10m/s. If the air velocity exceeds 10m/s, it becomes difficult to open the doors of vehicles and dust is blown about. In low traffic flow conditions, when the fresh air flow induced by the vehicles from the portals or supplied by the air exchange stations is sufficient to satisfactorily ventilate the tunnel from portal to shaft, shaft to shaft or shaft to portal and the air velocity in the tunnel is under 10m/s, then it may be more energy efficient to operate the tunnel ventilation system with the air interchange fans being stopped and the air interchange dampers closed. The air flow rate and the concentrations of the pollutants can be monitored in each ventilation loop and fan speed can be modulated to maintain the desired air quality.

In high traffic flow conditions, interchange fans shall be started to maintain the desired air quality. The three sets of fans (fresh air fans, interchange air fans and exhaust air fans) in each ventilation loop are operated and controlled together as a group to allow effective overall control of the tunnel ventilation system.

Bidirectional Operation

When one tube is closed due to maintenance or for other reasons, it will be necessary to operate the ventilation system with bidirectional traffic in the other tube. Whether the air interchange station can be used or not during the bidirectional operation depends on the condition of the closed tube. If air interchange station cannot be used for some reasons (for example, the closed tube is being painted), the jet fans need to be started to provide sufficient thrust. If an air interchange

Table 3 Combined Fan Efficiency of Conventional Longitudinal Ventilation System & Air Interchange Station System

	Combined Fan Efficiency			
	Conventional Longitudinal Ventilation System		Air Interchange Station System	
	Westbound Tube	Eastbound Tube	Westbound Tube	Eastbound Tube
Peak Traffic in Westbound Tube	0.77	0.69	0.77	0.77
Peak Traffic in Eastbound Tube	0.73	0.77	0.77	0.77

station can be used, it will take first priority over using jet fans for energy efficiency.

Emergency Operation

In a fire emergency condition, the interchange fans must be stopped and the relevant dampers must be closed automatically in order to prevent the spread of smoke from one tube into the other tube. All other procedures would be the same as using a conventional longitudinal ventilation system.

CONCLUSION

The maximum capacity of the installed ventilation fans is only used for a small percentage of the total operating time. Especially in the years immediately following the opening of the tunnel, the traffic volume will be much lower than the designed peak traffic volume. The ventilation fans are operating in partial load for most of the operating time. This new concept of using an air interchange station system has the potential to minimize the number of shafts and fan capacity used, thus reducing both capital costs and operating costs by a large extent without any adverse effects on the reliability of the ventilation system.

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