Mumbai monorail - the first in India

Air Conditioning of Mumbai Monorail Rolling Stock

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Introduction

Last year, Mumbai welcomed one of the biggest technological innovations to happen in urban public transportation in India. Mumbai Monorail is India's first modern successful monorail system. The project was implemented by the Mumbai Metropolitan Region Development Authority (MMRDA) together with a consortium of Larsen & Toubro, based in Mumbai, and infrastructure firm Scomi Engineering Bhd. of Malaysia.

In the densely populated city of Mumbai, the monorail weaves its way through an 8.8 kilometre stretch, providing travellers between Wadala and Chembur a dedicated transport corridor. This first phase of Mumbai Monorail was opened to public on 2nd February 2014. The second phase, now in its final stages of completion, will extend the line from Wadala to Jacob Circle, to a total of 19.5 kilometres.

The monorail trains, designed and built in Malaysia, consist of four coaches each with a total length of 44.8 metres and a capacity of 568 passengers; each coach is equipped with on independent HVAC system.

HVAC System for Mumbai Monorail

The HVAC system for Mumbai Monorail is designed and supplied by Merak-Jinxin Air-Conditioning Systems (Wuxi) Co., Ltd., a joint venture company founded in June 2008 by Jinxin Group and Knorr-Bremse Group based in Wuxi, China. Merak specializes in design and production of railway Heating, Ventilation and Air Conditioning (HVAC) equipment for more than 45 years, with presence in Asia, Europe and America.

One modular roof-mounted HVAC unit is installed on each coach of Mumbai Monorail. This HVAC system is designed

About the Author

Peter Edwards is a Chartered Member of the Institution of Mechanical Engineers (UK) and has more than 23 years of urban transportation systems engineering and project management experience. He has performed in client, contractor and consultant roles working on urban rail projects in London, Singapore, Hong Kong, Manila, Mumbai, Kuala Lumpur, Sao Paulo, Manchester and San Francisco. He is currently the Head of Integrated Engineering Services for Scomi Rail Bhd, responsible for all engineering activities for Scomi's monorail projects in Malaysia, India and Brazil.

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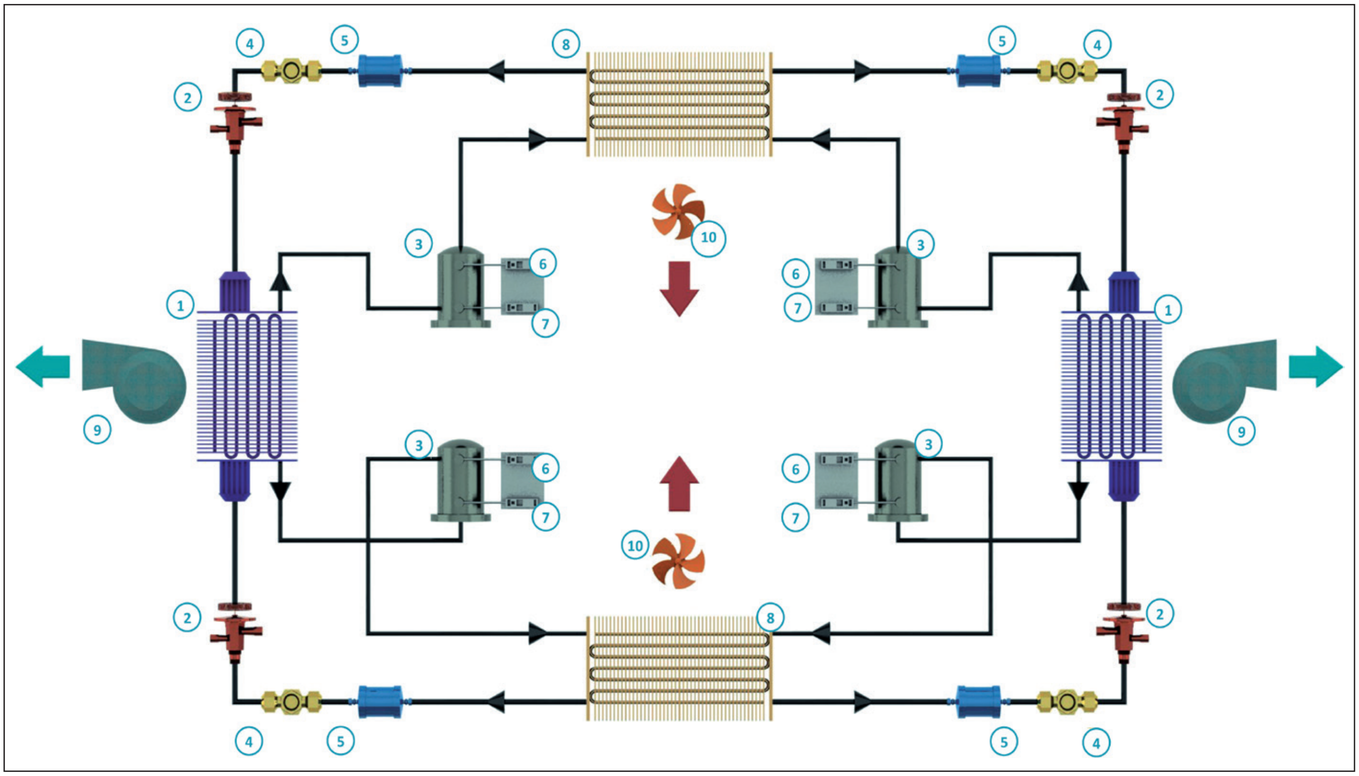

Figure 1: Refrigeration circuit and major components (refer legend in Table 2)

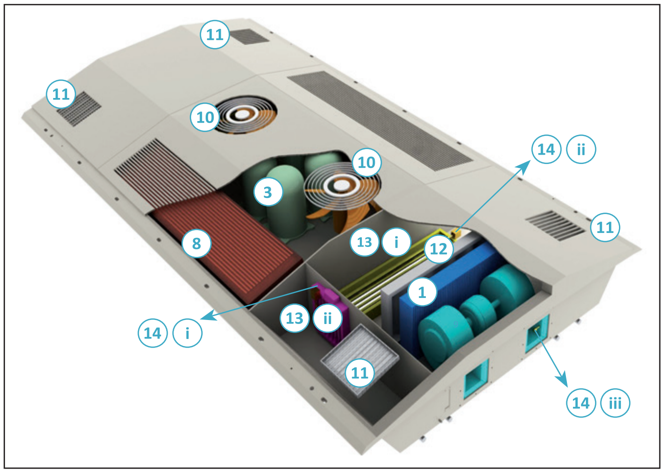

Figure 2: HVAC Unit (refer legend in Table 2)

for continuous climate conditioning of the passenger saloon area and drivers' compartment, taking into account passenger loading of 142 per coach, with environmental conditions of temperature and humidity experienced in Mumbai.

This system uses the alternative refrigerant R-407C, a Hydrofluorocarbon without Chlorine content; its properties and characteristics of performance are similar to refrigerants traditionally used for this type of applications (Chlorofluorocarbon refrigerants, or CFCs), but with reduced impact on the environment. R-407C has zero Ozone Depletion Potential (ODP) index rating, and fully complies with the Montreal Protocol requirements.

The conditioned air comprises a mixture of filtered fresh and re-circulated air, actuated by fresh air damper and return air damper. Air filters have been provided to eliminate dust and particles at the microscopic level, and are easily removable for cleaning or replacement. Safety and comfort of passengers and driver has been carefully considered with provision of emergency ventilation within the HVAC system in the event of mainline traction power failure.

Figure 1 shows the major components and the refrigeration cycle.

Table 1: HVAC Unit Specifications

Type	Compact roof-mounted
Dimension	4000x2131x428mm (LxWxH)
Weight	575 kg
Cooling capacity	36 kW
Temperature set point	20°C – 25°C
Refrigerant	R407C
Total air flow	5200 m^3/h
Fresh air flow	850 m^3/h
Return air flow	4350 m^3/h
Emergency ventilation air flow	1700 m^3/h
Internal control	Siemens PLC
External control	Train-borne Vehicle Management System (VMS) via RS485
AC Power supply	415V, 50 Hz, 3 phase
DC Power supply	24 V

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Table 2: Major components and specifications (legend for Figure 1 and 2)

S. No.	Component	Quantity
1	**Evaporator Coil** • Copper tubes, 1/2" diameter • Aluminium fins, 0.15mm thickness, 3.0 mm pitch	**2**
2	**Thermostatic Expansion Valve** • Welded connection with external equalizer	**4**
3	**Compressor** • Vertical scroll type • Supply: 415V AC-3P-50Hz • Max current: 9 A	**4**
4	**Sight Glass**	**4**
5	**Dehydrator Filter** • Desiccant: Silica gel activated Aluminium oxide • Absorption: 660 drops at 25°C approximately • Working pressure: < 42 kg/cm^2	**4**
6	**High Pressure Switch/Service Valve** • Open: 31±1 bar, Close: 25±1 bar • Proof pressure: 41 bar	**4**
7	**Low Pressure Switch/Service Valve** • Open: 0.5±0.4 bar • Close: 1.5±0.4 bar • Proof pressure: 27.6 bar	**4**
8	**Condenser Coil** • Copper tubes, 3/8" diameter • Aluminium fins, 0.15 mm thickness, 2.4 mm pitch	**2**
9	**Evaporator Fan** • Centrifugal, forward curve • 2,600 m^3/h airflow • Static pressure: 380 Pa • IP55, Class F insulation	**2**
10	**Condenser Fan** • Axial multi-blade • 8,000 m^3/h airflow • IP56, Class F insulation • Power: 0.75 kW	**2**
11	**Fresh Air Filter** • Type: Metallic mesh • Class: 30-mesh	**4**
12	**Mixed Air Filter** • Type: Woven, washable/disposable • Average Arrestance (EN 779) : <85% • Initial Dust Spot Efficiency: <20% • Class (EN 779): G3	**2**
13	**Air Dampers** **(i) Fresh air (ii) Return air** • Supply: 24 VDC • Power: 2 W • Torque: min. 5 Nm • Angle of rotation: max. 90°	**(i) 4** **(ii) 2**
14	**Temperature sensors** **(i) Fresh air (ii) Return air (iii) Supply air** • Type: PTC thermistor • Tolerance from 0°C to +70°C: ± 0.2°C • Alpha at +25°C: 109.73 Ω • Beta Value 25/85: 23.07 K • Tolerance on Beta Value: 0.5% • Operating Temperature: -40°C to +125°C	**(i) 1** **(ii) 1** **(iii) 1**
15	**Control Panel** *(not shown—mounted inside saloon cabinet)*	1

System Description

Each HVAC unit has two groups of cooling circuits, controlled by one PLC Control Module located inside the saloon cabinet; one pair of the four compressors work in each circuit, and all other major components are also duplicated and perform the same cycle, alternating based on running time of 8 hours total.

The refrigeration cycle functions as follows: liquid refrigerant flows from the condenser coil, through the dehydrator filter and the sight glass/moisture indicator. The dehydrator filter is a cylindrical receiver, mounted on the liquid line, composed of a dehydrator cartridge and a metal filter; this device sieves out any solid particle that may be in the piping of the system, as well as retains the humidity existing in the refrigerant circuit. A safety valve is provided to avoid any overpressure in the circuit. The sight glass/moisture indicator allows the verification of moisture content in the refrigerant circulating in the system, inferred from the presence of bubbles in the refrigerant which can be observed behind the sight glass.

After passing the sight glass/moisture indicator, the liquid goes through the thermostatic expansion valve. The regulation of the amount of refrigerant coming into the evaporator coil via the expansion valve results in a quick reduction in the pressure of the refrigerant, which, by evaporating, cools the tubes and fins and the air around them. Evaporator fans blow this air into the saloon through the ducting set. Cold gases go out of the evaporator at low pressure through the suction line to the compressors. The high and low pressure service valves allow connecting the gauges to verify the working pressures of the HVAC system, and are used to carry out maintenance operations such as purging, vacuuming and charging the refrigerant in the circuit.

The air flow impelled through the evaporator coil is produced by a mixture of exterior air and air re-circulated from inside the saloon. This ratio of fresh air to re-circulated air is dependent on variables such as the evaporator capacity and its dewpoint (coil ideal average temperature), and is regulated by fresh air damper and return air damper respectively.

External fresh air is first filtered by a metal mesh type filter, to remove larger foreign particles such as insects, leaves and twigs. A PTC temperature probe at the fresh air opening detects the temperature of this fresh air and reports it to the PLC. Once mixed with re-circulated air inside the air handling chamber of HVAC unit, the mixed air passes through a G3-class air filter, washable and reusable. This filter is made of woven material and folded in a convoluted pattern to maximize surface area and filter life by reducing the face velocity. This filtering is absolutely necessary as the air contains dust, pollen, and harmful particles in suspension; the air conditioning quality largely depends on the filter's cleanliness. Lastly, the filtered mixed air passes through the evaporator coil where it is cooled down and impelled by two centrifugal impellers actuated by AC motors. A PTC temperature probe at the supply air opening detects the temperature of this supply air and reports it to the PLC.

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The air, once conditioned, is impelled to the coach through one air supply duct network situated above the coachceiling. The duct is made of WARO® foam, an extremely lightweight composite sheet, consisting of a base of glass fibre reinforced melamine or phenol resin, and is designed to uniformly distribute conditioned air throughout the length of the coach via diffusers at ceiling level. The material itself is lightweight and is resistant to seawater, detergents and light acids. The material is odourless and tasteless and therefore suited for this application as a thermal insulator.

Operating Modes

The HVAC system operates in multiple modes; its on-board controller calculates the functional cooling need based on several factors including interior temperature (T_{ia}), outside air temperature (T_{oa}), relative humidity conditions, set point temperature (T_s) and external command by the driver via VMS's RS485 network, auxiliary power status, and health of its components. In each mode, feedback signals are reported from the HVAC controller to VMS. The different modes are as follows:

Pre-Cooling

When the HVAC is switched on for the first time in the day, the HVAC controller calibrates determining if it can run in 'cooling' mode; once the unit gets the command of 'cooling' from VMS, the HVAC system will run in 'pre-cooling' mode until $T_{ia} \leq T_s+1$ is reached, or for up to 20 minutes. Both refrigeration circuits are operational, with the fresh air damper closed to block external air and accelerate cooling down of the saloon for revenue service.

Cooling

Comparing T_s and T_{ia}, when $T_s+1<T_{ia}$, and the control panel receives 'cooling' command from VMS, the unit will run in 'cooling' mode. In this mode, both refrigeration circuits are operational and the evaporator fans supply maximum filtered and conditioned mixed air into the passenger cabin.

Half-Cooling

The HVAC switches from full cooling mode to half-cooling when the saloon temperature has stabilized to $T_s-1<T_{ia}\leq T_s+1$, i.e. there is less cooling need and the HVAC goes into a more energy-saving and reduced noise operation. The VMS can also send a 'half-cooling' command to HVAC controller, and the controller makes a judgement if the right operating conditions are met. In 'half-cooling' mode, only one pair of compressors runs, and evaporator fans run in low speed. In order to keep running time equilibrium, each group works cumulative 8 hours, and then the system changes to another group.

Ventilation Mode

When the coach does not require any cooling, evaporator fans continue to supply air but the refrigeration system does not operate. The PLC will automatically select this mode if the measured return air temperature indicates $T_{ia}\leq T_s-1$, and the control logic determines no cooling required; this mode allows air to be circulated throughout the vehicle and the fresh air continually induced into the vehicle. If internal temperature starts to increase past the dead band and PLC determines cooling is required, the HVAC system automatically restarts the refrigeration system and switches to 'Cooling'/'Half-Cooling' mode, depending on the calculated need. If the control panel does not receive the set temperature from VMS, the unit will determine the cooling need based on comfort parameters, including temperature, humidity and fresh air rate, as prescribed in UIC 553, an International Railway standard for rail passenger vehicle's air conditioning systems. VMS can also send a 'ventilation' command to HVAC via RS485, causing the HVAC to run in 'Ventilation' mode.

Emergency Ventilation Mode

This mode will operate under loss of traction supply (750V DC). The evaporator fans, supplied by the emergency inverter, will provide the saloon interior with airflow rate of 1700m^3/h of fresh air per monorail vehicle. When the HVAC control panel receives a counter-command of 'emergency ventilation' signal or detects the power supply has recovered, the system will exit 'emergency ventilation' mode and revert to its previous commanded mode.

Degraded Mode

In the event of auxiliary inverter failure and loss of 415V AC supply at one particular coach, the VMS provides a digital input to the HVAC unit to prevent full power demand by the HVAC system on its adjacent coach. This allows continued operation of two separate HVAC units for the two adjacent vehicles by drawing their power supply from one functioning HVAC inverter. Based on the rake's power demands, VMS will determine and command the two HVAC systems to operate in either 'half-cooling' mode or 'ventilation' mode.

Off

This mode is manually connected by train staff and sent to the HVAC control panel via a hard cable, disconnecting the signal of 'HVAC On'. The HVAC confirms this state by sending feedback data bit 'HVAC On/Off Disconnected' to the train VMS. In 'off' mode, all HVAC elements are off, but the controller continuously monitors exterior and interior temperatures.

The standard protection provided for the system includes high and low pressure, high voltage (AC supply), frost protection, extreme temperature, phase loss detection and over-current. Status feedback and fault reporting are communicated between the HVAC control module and VMS

Table 3: Component states in different operating modes

Components	Component states in different operating modes				
	Pre-cooling	Cooling	Half-cooling	Ventilation	Emergency ventilation
Compressor	✓✓✓✓	✓✓✓✓	✓✓××	××××	××××
Condenser fan	✓✓	✓	✓✓	××××	××××
Evaporator fan	✓✓	✓✓	✓×	✓✓	✓✓
Fresh air damper	●	○	○	○	○
Return air damper	●	○	○	○	●
✓= ON	×=OFF		○=OPENED		●=CLOSED

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via RS485. This communication medium allows the driver to monitor operational parameters of each HVAC unit throughout the monorail. The same parameters can be viewed using a service laptop connected to a maintenance terminal on the HVAC controller module; this allows for precise troubleshooting and quick maintenance.

Conclusion

Regional urbanization calls for a modern, efficient public transportation system. The mobility of Mumbai's dense population and highly congested roads is being transformed by the introduction of the monorail, with its state-of-the-art compact HVAC system ensuring passenger comfort. Environment friendliness, optimum performance and safety in operation are among the top-priority design criteria. Weaving through the city at 6.5-metre height through shifting landscape and weather conditions, the HVAC system is equipped to operate in various modes to suit the ambient environment and passenger loading, while ensuring energy efficiency and compliance to International Rail standard. Analysis of operating conditions, failure modes and maintainability parameters leads to the fruition of the HVAC system that guarantees both operational and passenger safety. Not surprisingly, the Mumbai Monorail first phase achieved the milestone of ferrying over 5 million passengers in its first year of operation, presenting a pleasant alternative for the harassed Mumbaikar's commute.