城市轨道交通车辆智慧空调技术

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摘　要　智慧空调技术作为城市轨道交通车辆智能化运营的重要技术手段，主要根据车辆运行环境数据来调整空调运行模式，进而改善车内舒适度，对空调机组运行状态进行实时监测及关键零部件故障预警，实现空调机组的智能化健康管理，提升空调运营维护效率。智慧空调系统由车辆空调、车载网络及PHM(故障预测与健康管理)地面支持系统结合搭建而成，通过传感器来监控车辆空调使用环境数据，并自适应性调节空调运行状态以改善车内空气质量。在故障预测及健康管理方面，智慧空调技术通过搭建诊断模型，采集并传输空调机组运行状态数据，实现对空调机组多发性故障的及时预警，对关键零部件使用寿命进行老化预测并采取相应的健康管理措施，进而保障空调机组的安全运行。在车辆的维修维护中，智慧空调技术结合不同的诊断及预警模型数据，合理制定空调机组修程，将空调机组故障修与定时修为主的传统维修模式发展为基于安全监控和健康管理的智能化"状态修"模式。

关键词　城市轨道交通车辆；空调；故障预测；健康管理；智能运维

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Urban Rail Transit Vehicle Smart HVAC Technology

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Abstract　As an important technical means of urban rail transit vehicle intelligent operation, smart HVAC (heating, ventilation and air-conditioning) technology mainly adjusts the AC (air-conditioner) operation mode according to the vehicle operating environment data to improve ride comfort, conducts real-time monitoring of AC units operation status and fault prediction and early-warning of key components, so as to realize intelligent health management and improve the operation-maintenance efficiency of AC units is improved. Smart HVAC system is established by combining vehicle AC, vehicle on-board network and PHM (prognostics health management) ground support system, setting sensors to monitor the environment data and adaptively adjust the AC operation status to improve the interior air quality. In terms of PHM (prognostics and health management), the safe operation of AC units is guaranteed by building a diagnostic model, collecting and transmitting AC unit operation data, timely warning frequent faults of AC units in time, predicting the service life of the aging key components and taking corresponding health management measures. For vehicle maintenance, with different diagnostic and prediction model data, the smart HVAC technology formulates reasonable maintenance process for AC units and develops the conventional maintenance mode, turning fault repair and timing repair into an intelligent 'state repair' mode based on safety monitoring and health management.

Key words　urban rail transit vehicle; air-conditioner; fault prediction; health management; intelligent operation and maintenance

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城市轨道交通作为绿色、节能型交通工具，已在全球范围内得到广泛应用，国内外大多数国际性大都市，轨道交通已作为市民出行的主要交通工具。随着我国城市轨道交通技术的不断发展，以大数据、云计算和移动互联为战略，数据导向为发展，实现决策的智慧化，打造"智慧地铁"、实现车辆运行及维护的智能化已成为城市轨道交通车辆新的发展趋势及车辆各系统新的研究方向。城市轨道交通车辆的空调系统直接关系到乘客舒适性。受其运行环境及长时间运行状态的影响，如何提升维修维护及故障处理的效率受到越来越多用户的关注。采用智慧空调技术，可实现城市轨道交通车辆空调系统智能化运营管理，具有非常显著的理论意义及实际应用前景[1]。

1　智慧空调系统功能

智慧空调系统即采用智慧空调技术的城市轨

道交通车辆空调系统。智慧空调技术主要用于改善车内环境及空气质量,提高乘客舒适性;对空调系统进行 PHM(故障预测与健康管理)[2];实现空调系统 MRO(运营维护及操作)的智能化[3]。

智慧空调技术利用空调系统本身构造特性、部件性能参数,以及运行环境、线路条件和负载状况等相关信息,实现精准的车内温度控制,提高车内舒适度的同时降低空调运行能耗;通过搭建预诊断系统,以实现对空调设备健康状态进行模型建立和诊断评估,预测设备可能发生的故障及潜在影响,对车辆运营方给出及时的报警与处置;根据健康状况诊断由定时修改变成状态修,节省不必要的维护维修,减少运营维护时间,降低运营维护成本[4];根据设备性能变化趋势曲线,可以推断设备剩余的有效使用寿命[5],指导架修和大修的成本分析和降低维修成本;建立全生命周期的数据库和实时诊断,制定空调系统部件的维护维修章程和部件标准,降低全生命周期成本。

2 智慧空调系统构架

智慧空调系统整体架构由车辆空调系统、车载网络系统及 PHM 地面支持系统等组成。

2.1 车辆空调系统

车辆空调系统主要包括空调机组、车控器及 PDS(预诊断)装置。车辆空调系统控制框图如图 1 所示。每个车厢装有 1 台车控器,其通过列车通信总线和 TCMS(列车控制及管理系统)通信。车控器将 TCMS 下达的命令传达给 2 台空调机组。通过车控器,TCMS 也可对本节车厢的 2 台空调机组进行单独控制。其中车辆控制柜配备了 PDS 装置。车控器与 PDS 装置同时连入车辆以太网中。PDS 装置实时收集车控器送来的数据,并通过列车通信网络将空调数据发送至数据中心,由数据中心对数据进行分析,做出故障预诊断[6]。

2.2 车载网络系统

车载网络系统拓扑图如图 2 所示。车载网络系统主要进行车辆空调智能监测与诊断分析,依托列车智能以太网或 MVB(多功能车辆总线)高速通信网络架构,自主实时远程采集列车空调机组各部件的运行状态信息,包括空调运行状态数据、温度、压力等传感器数据,并以特定的位置区识别码形式通过特定网络的车地传输通道端口传输各空调机组特定的数据信息,完成与 PDS 装置的信息交互,在车辆智能运营应用平台发布列车空调系统健康实时诊断结果及运维管理建议。

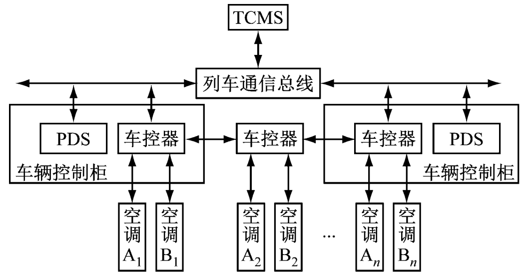
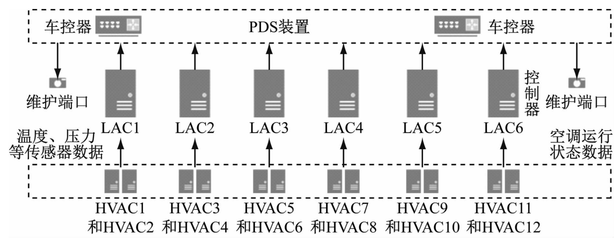


图 1 车辆空调系统控制框图

Fig. 1 Block diagram of vehicle air-conditioning system control



注:LAC 为位置区码;HVAC 为空调机组。

图 2 车载网络系统拓扑图

Fig. 2 Topology diagram of on-board network system

2.3 PHM 地面支持系统

如图 3 所示,PHM 地面支持系统包括数据收集层、数据传输层、数据处理层、数据存储层及数据展示层。

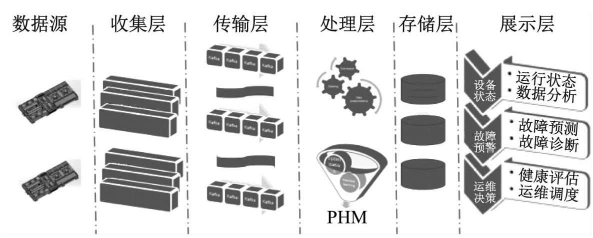


图 3 PHM 地面支持系统构成示意图

Fig. 3 Composition diagram of PHM ground support system

2.3.1 数据收集层

数据收集层示意图如图 4 所示。数据处理过程主要为输入、过滤及输出,能实现特定的数据采集、数据处理及数据输出等功能。

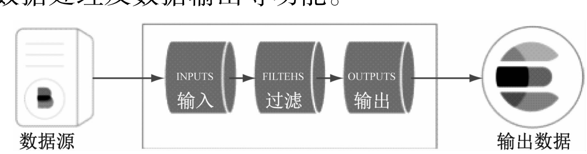


图 4 数据收集层示意图

Fig. 4 Diagram of data collection layer

2.3.2 数据传输层

数据传输层采用高吞吐的分布式消息系统处理所有数据收集层的输出数据，保证汇聚的日志及消息的可靠传输。

2.3.3 数据处理层

数据处理层通过预诊断算法对数据传输层汇聚的输出数据与 PHM 地面支持系统中设定的性能特征数据进行对比分析，找出空调机组运行过程中存在的隐患。

2.3.4 数据存储层

数据存储层将不同用途处理后的数据基于数据性能特征分层存储，简化初始存储放置数据，基于 I/O(输入/输出)负载平衡数据，提高了数据检索速度，缩短数据存储规划及配置时间，减小了数据存储的占用空间，通过优化放置提高了数据利用率。

2.3.5 数据展示层

PHM 地面支持系统可实现状态监控、故障诊断、故障预测、故障分析、健康评估、运维决策及信息推送等 7 个功能。处理后的数据结果可以在 PHM 地面支持系统大屏及便携式移动终端进行展示与应用推送。

3 智慧空调系统的实现方案

3.1 车内舒适度调节方案

采用智慧空调技术的车内舒适度调节方案为：设置各种传感器，实时监测车内空气质量与各项指标，并根据监测数据实时调整空调运行模式。该方案可有效改善车内空气质量，提高乘客舒适性，减少空调机组能耗。主要功能有：

1）自动调节湿度，即根据湿度传感器的数据进行调节。湿度过高时，空调可开启电加热功能进行除湿；没有电加热功能的空调系统还可采用降低目标温度的除湿方式。

2）自动调节温度。首先，参照国际标准 EN 14750-1：2006《铁路车辆-城市轨道车辆空调-舒适参数》中的车内目标温度设定调整曲线，按温度曲线公式计算车内目标温度，具体为：

$$T_d = 22\ ℃ + 0.25 \times (T_f - 19\ ℃) \qquad (1)$$

式中：

T_d——车内目标温度，℃；

T_f——环境温度，℃。

然后，根据乘客数量的变化，自动升高或降低车厢目标温度设定值。

3）自动调整运行参数。空调机组根据不同工况下的实测制冷量及车辆载荷等数据，自动调整压缩机运行频率、风机转速及冷凝风机工作状态等，以适应车厢制冷需求的变化，减少制冷量的超额投入，实现节能目标。

4）自动新风。根据 CO_2 传感器监测的空气中 CO_2 的质量浓度数据，空调机组能够调整新风阀开度、增加新风量，以降低 CO_2 质量浓度。但是，在环境温度较高时，新风量的增加将导致车厢内温度过高，故需在保证车厢内温度适宜的基础上适当增加新风量。

3.2 PHM 方案

3.2.1 故障预测模块

故障预测模块是结合多年的列车空调运行数据，利用空调本身构造特性、部件性能参数，以及运行环境、线路条件和负载状况等相关信息，搭建而成。

故障预测模块整体构架如图 5 所示。其中：客室控制层负责单个车厢空调历史数据的纵向对比及标准模型数据的参考，列车运行中心控制层(列车中控层)负责整列车空调数据的横向对比及数据对比分析，数据中心层负责分析整个项目内的所有空调数据。

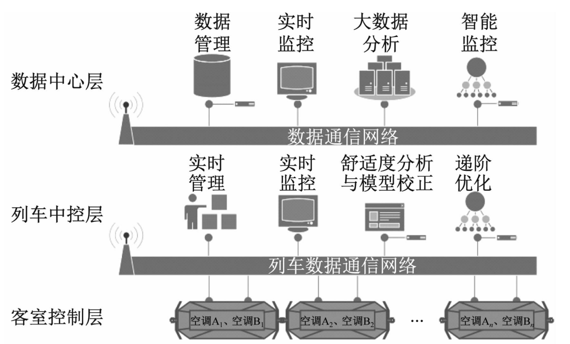


图 5 故障预测模块整体构架

Fig. 5 Overall structure of fault prediction module

故障预测模块运行时，先通过列车通信网络，将空调设备运行状态数据上传给数据处理中心；数据处理中心对数据进行实时的专业分析处理，并将预诊断结果传送给客户端的预诊断系统软件；客户可以通过预诊断系统软件所发布的状态或建议信息，对设备采取对应的维护或保养措施，以保证该设备的运行状态始终保持良好。

3.2.2 诊断数据

车控器收集的数据类型包括指令、空调运行模

式和数据、部件状态及部件故障。指令是指通过列车通信网络发送给控制器的指令;空调运行模式和数据是指空调实际运行的模式及内部温度等信息数据;空调的部件状态是指部件实际是否处于运行;部件故障数据通过 MVB 等方式上传,并同时向 PDS 发送。

3.2.3 数据采集及传输

数据主要来源于空调各传感器数据以及各部件状态监控信号;车控器数据采集仪负责提取电流、温度、压力及状态特征等关键数据,并通过通信接口实时传输给车控器;车控器将上述关键参数同内置的标准健康模型数据进行比对,从而实现对压缩机、风机及制冷系统等重要空调部件的故障预测及诊断等。

3.2.4 空调健康管理

通过大数据技术,对空调关键部件进行研究,加深对产品结构和性能的认知深度;应用大数据技术对海量运用检修数据进行分析,结合检修运用的实际需求,判断空调系统健康状态并采取相应的健康管理措施,以保证空调系统正常运营。

3.3 智能运维方案

对空调内零部件建立不同的故障诊断模型及预警模型,进而对空调检修规程进行分析。空调所有的检修项目都可根据空调健康管理诊断的预警结果,动态制定维修计划,进行提示性维修。故障诊断预警模型的预警判定值及相关技术参数可根据实际需求调整。主要故障诊断模型及预警模型的诊断过程如下:

1)空气温度诊断模型。空调运转模式处于制冷状态,若新风温度高于 19 ℃,则制冷开始计时。开始制冷 30 min 内,车辆空调压缩机电流应不等于 0 A,而且若目标温度保持不变,则应有|回风温度-目标温度|≥5 ℃。当不满足上述条件时,触发 PHM"某车空调机组 X 制冷系统温度异常预警"。

2)制冷系统压力诊断模型。空调运转模式处于制冷状态,压缩机启动超过 2 min 时:低压压力监测范围为 0.15~0.70 MPa,下限值触发动作;高压压力监测范围为 1.10~2.90 MPa,上限值触发动作。当 PHM 低压值低于 0.15 MPa,且持续时间>5 s 时,触发"某车空调机组 X 制冷低压异常预警";当高压值高于 2.90 MPa,且持续时间>5 s 时,触发"某车空调机组 X 制冷高压异常预警"。

3)制冷系统泄露诊断模型。①某车制冷系统的高压压力及低压压力持续明显低于设定参照车系统压力值,例如高压压力差值≥0.30 MPa 且低压压力差值≥0.20 MPa;②车内/回风温度与参照车有较大差异(例如温差≥5 ℃);③空调机组停机静置≥1 h,系统平衡的高低压力值明显低于参照车制冷系统 0.20 MPa 以上。若满足上述条件之一,则触发 PHM"某车空调机组某制冷系统制冷剂泄露预警"。

4)滤网压差诊断模型。根据监测压差开关反馈量,当滤网前后端压差超过 120 Pa 时,记录 1 次,且每天最多记录 1 次(120 Pa 后续参考实际数据进行修正)。当连续 3 天内记录 3 次时,触发 PHM"某车空调机组某空调过滤网清洗更换预警",且每天最多报警 1 次。

5)冷凝进出风短路预警模型。空调运转模式处于制冷状态:①某车压缩机电流>0 A;②运行 30 min 后开始计时,连续 1 min 内高压压力值上升速率>0.20 MPa/min;③某车空调机组某冷凝温度持续>70 ℃。当满足上述条件之一时触发 PHM"某车空调机组 X 冷凝进出风短路预警"。

6)蒸发/冷凝风机寿命预警模型。当单台风机累计运行时间≥33 250 h 时,触发 PHM"某车空调机组 X 蒸发/冷凝风机 X 轴承寿命预警"。

7)压缩机寿命预警模型。当单台压缩机累计运行时间≥47 500 h 时,触发 PHM"某车空调机组 X 压缩机 Y 寿命预警"。

4 结语

综上所述,智慧空调技术在营造舒适的乘车环境、精确的故障预测及高效的维修维护等方面均起到了重要作用和积极影响[7]。目前,应用于城市轨道交通空调系统的智慧空调技术刚刚起步,还有很大的发展空间。许多技术的应用还在研发阶段,不仅需要更多的理论支持、数据分析及试验验证,还需要不断进行设计的优化和改进。相信随着更多智能技术的研发与应用,城市轨道交通车辆的空调系统也将发展成为更安全、更可靠、更智能的高品质、高科技产品,为广大乘客及用户提供更舒适的体验与更便捷的服务。

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(上接第 130 页)

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Commentary

Hydrogen-energy Urban Train

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As a response to the increasingly severe global climate change problem, Paris Agreement was adopted at the 21st Session of United Nations Climate Change Conference held in 2015, formulating action guidelines against global warming. To further implement the commitment made at the Climate Change Conference, Government of China has introduced a series of policies and has incorporated the 'carbon peaking and carbon neutrality' strategy into the Report on the Work of the Government 2021, to which point, 'carbon peaking and carbon neutrality' is launched as a national campaign. The energy industry is currently undergoing the third revolution aiming at low-carbon and carbon-free, and hydrogen is receiving widespread attention as an important green carbon-free energy. In the 14th Five-Year Plan by the State Council and the relevant plannings by the Energy Bureau of National Development and Reform Commission, it is clearly stated that hydrogen is an important constituent of the future national energy system, and the clean and carbon-free characteristics of it should be fully exploited to promote the green and low-carbon transformation of high energy-consumption and high emission industries, including transportation and heavy industry. For rail transit industry, countries have carried out a lot of research and practice in the field of hydrogen-energy trains. Since China has laid a solid foundation of hydrogen energy and rail transit industry and possesses the broad market of rail transit, there is a significantly dominant position in developing hydrogen-energy rail transit. The integrated development of hydrogen energy industry and rail transit is one of the important measures to boost the achievement of 'carbon peaking and carbon neutrality' goal in China.

In the tide of the times guided by policies and powered by industries, CRRC Changchun, that is joined by the participation of research institutes at home and abroad, hydrogen, energy storage and other technology partners along the industry chain, successfully developed the world′s first hydrogen-energy city rail transit train with independent intellectual property rights, by following the design philosophies of more low-carbon and environmental-friendliness, advanced intelligence, more safety and comfort, and more distinctive characteristics, and working closely with the practical demands in green and intelligent operation-maintenance. The train is 4-formation with 2 motor cars and 2 trailer cars, allowing the maximum speed of 160 km and the maximum operation mileage of 600 km. The successful development of such train marks a further breakthrough in the application of hydrogen energy in rail transit for China, making the development of hydrogen-energy city rail transit train to lead on a global scale.

More low-carbon and environmental-friendliness. Being green and environmental-friendly is one of the most competitive advantages of hydrogen-energy city rail transit train. As a kind of clean energy, hydrogen has abundant and diversified sources. With its higher calorific value and pollution-free reaction, hydrogen is one of the few new energy sources that simultaneously satisfy the comprehensive requirements of resources, environment and sustainable development. As the energy source of hydrogen-energy city rail transit train, a hydrogen-electricity hybrid power system supplies the energy with no other by-products but water and adopts the independently developed hydrogen-electricity hybrid energy management strategy to realize the coordinated control of hydrogen fuel cell and energy storage system, meeting the requirements of whole vehicle dynamic response and affording the function of energy recovery from braking process. The hydrogen fuel consumption rate during the operation is reduced, and the train operation mileage is increased. In addition, the train is provided with more efficient and energy-saving traction auxiliary equipment, realizing operation of higher efficiency through energy-saving control technology.

Advanced intelligence. Intelligentized technological means are comprehensively applied to the hydrogen-energy city rail transit train in aspects such as control, communications, and monitoring. In terms of operation control, a highly automated train control system realizes intelligent train operation and dispatching for the whole network. In terms of train communications, the vehicle-vehicle communication technology is applied to provide better traction and braking control strategies for trains, which effectively improve the train operation efficiency and save the dispatched resources. In terms of train monitoring, multiple intelligent monitoring systems are coupled to effectively carry out rapid early warning, positioning and diagnosis of train faults during operation. Meanwhile, the railway vehicle monitoring technology based on big data analysis realizes the multi-system coupling network for vehicle-wayside bidirectional information transmission, guarding vehicle safe operation by real-time monitoring and analysis of train operation status parameters in driving.

More safety and comfort. Safety is the primary premise for hydrogen-energy city rail transit train operation. Multi-dimensional and multi-level design of safety protection guarantees the driving safety through equipment installation protection, system real-time state monitoring and fault alarm, as well as linkage of multi-system active and passive fault prevention. To improve passenger travel experienc, intelligentized passenger information display technology is applied to satisfy the passenger demands of diversified information. Intelligent lighting system also grants passengers more ease. Panoramic windows installed in the head and rear cars improve passengers′ visual experience of the journey.

More distinctive characteristics. The train is artfully designed to contain the prospect and hope for the future hydrogen-energy trains. In an all-inclusive style of design, the streamlined head and the smoothly designed body at train front highlight the elegance and beauty. In combination of dark blue and light blue, the carbody′s appearance of hydrogen symbol ′H2′ indicates the technical feature of the train. The light blue lines spreading all over the carbody look like winding and flowing sea waves, interspersed with blue dot arrays sparkling in the sunlight, embodying the majestic power and environmental-friendly property of hydrogen-energy trains. The interior ornamented by light blue elements shows a quiet and elegant atmosphere, which coincides with its green and low-carbon characteristics.

In conclusion, the hydrogen-energy city rail transit train conforms to the application requirements of green and intelligentized operation-maintenance, with the features of low-carbon and environmental-friendliness, advanced intelligence, safety and comfort, and distinctive characteristics. It provides valuable technical reserves and practical experience for the research and application of hydrogen-energy trains in China, creates a precedent of applying hydrogen energy to city rail transit trains and provides powerful support for the achievement of ′carbon peaking and carbon neutrality′ goal and the construction of low-carbon transportation.