Passive Design of an Indoor Railway Station

Matthew Payne and Matthew Jessup

Advanced Environmental, Sydney, Australia

ABSTRACT: This paper centres on the environmental design of a major piece of city infrastructure: an indoor railway station in Melbourne, Australia, that covers an entire city block.

A major design feature of the station is the successful incorporation of a natural ventilation strategy to ventilate the space of toxic diesel engine exhaust. The architectural form of the station facilitates the ventilation process through its unique 3-dimensional mogul-like formations. Together with a carefully designed double-skin, the station roof conceptually represents the lungs of the station, allowing the building to oxygenate and cleanse itself.

Thermal analysis of the station allowed careful consideration of occupant thermal comfort and ventilation airflow under varying weather conditions. Bulk air flow modelling confirmed the natural ventilation concept.

Flow modelling was used to prove and optimise the natural ventilation flow and informed the architectural design. Computational fluid dynamics presents the designer with a deeper understanding of the natural ventilation flow which in this case is primarily driven by buoyancy and assisted well by local breezes.

The indoor environment quality is complemented by the availability of natural light. Daylight levels within the space were optimised using computer based modelling.

Keywords: passive, ventilation, energy, daylight, comfort, natural ventilation

1. INTRODUCTION

Spencer Street Station has been a major transport hub for the city of Melbourne since 1859. Located at the west end of the central business district, Spencer Street Station provides interchange between local trains, interstate express passenger trains (XPT) as well as bus and airport shuttle services. The redevelopment of such an integral piece of city infrastructure is important for the progress of Melbourne as a city.

Spencer Street Station is located between the Melbourne central business district and the newly redeveloped Melbourne Docklands precinct which represents the “new” Melbourne. The Docklands is a precinct that will provide waterfront residential apartments, new quality office space and attract many visitors from Melbourne and abroad. The redevelopment of this entire precinct, as well as the promotion of Melbourne as an international city by government has raised the profile and image of this project.

The site covers an entire city block and caters for up to 30,000 people per hour during peak times.

This paper intends to demonstrate the benefits of considering opportunities for aligning the environmental and sustainable architectural practices of a project early in the conceptual design phase. Spencer Street Station is an excellent illustration of how “smart” architecture, can have a major impact on the sustainability of our cities and services.

This paper will guide the reader through the design process from design conception, through design analysis to design resolution. Important design considerations will be highlighted and the reader will be introduced to the modelling techniques used to test the design concepts and detail and will be shown the benefits that these techniques can bring to the design process.

2. DESIGN INTENT

Spencer Street Station has an important presence in the Melbourne urban landscape. The design of the station needed to be architecturally iconic as well as an efficient, functioning public transport interchange.

A major design consideration for the station was both the external and internal environmental impacts. The external environment is addressed through the lowering of greenhouse gas emissions and efficiency in materials utilisation and maintenance. The utilisation of a natural ventilation strategy was highlighted early in the design process as a design feature that would greatly reduce the impact of the station on the external environment.

The internal environmental impacts consider the quality of the indoor space. The design intent was to provide a quality internal environment that considered in particular;

- High indoor air quality
- Availability of natural light
- Suitable thermal comfort

Early in the design phase the architectural design was inspired by traditional architecture. The industrial revolution brought the advent of steam powered locomotives and hence the first railway stations. Protection from the elements was provided by high structures with large spans. Steam would rise from the train engines to the heights of the structure, away from the station occupants. High level windows provided large quantities of natural light to the platform spaces below. This design philosophy was transferred to the 21st century in the conceptual stages of the Spencer Street Station design. It provided a means of achieving the environmental agenda set for the project and delivering an iconic piece of sustainable architecture.

3. DESIGN ISSUES

The project posed a number of significant design issues. As the major rail hub in Australia's second largest city, and the end point for the majority of regional services, the station had a vision of airport like internal quality yet also sought to be able to handle both diesel and steam powered trains as part of its function.

The station had to remain in operation throughout the construction process meaning the ventilation had to also be functional throughout the 2-3 year construction process as the roof was assembled above the platforms.

Major issues for the project included:

- How to handle Diesel trains and what is the appropriate air quality standard?
- How to provide appropriate comfort throughout the varied spaces, transient, waiting, retail etc, given the high volume open plan type space?
- How to design the ventilation such that the station could remain functional during construction?
- How to balance the free area of opposing facades, a key requirement of the ventilation design?
- How to achieve sufficient free area into the station whilst mitigating the impacts of wind and the external environment?
- How to mitigate the energy demands of the project and ensure the project does not become a financial burden on the public transport network as energy costs increase?

4. DESIGN RESPONSE

As discussed previously, the architectural design draws inspiration from traditional architectural practices. High spaces and long spans facilitate the natural lighting and natural ventilation characteristics featured in industrial revolution architecture.

Spencer St Station is designed to be an environmentally sustainable development that employs a number of best practice initiatives. The mogul form roof, visually a major design element, actively enhances the environmental performance of the station. The roof tempers the outdoor environment, protects from rain and wind, provides effective natural light and allows a high performance natural ventilation solution within the station, greatly reducing the station's dependence on carbon dioxide producing energy resources. The integrated nature of the design solution greatly reduces the overall environmental impact of the project and actively promotes its design objectives.

4.1 Thermal Design Response

The station has an effective and responsive envelope that optimises thermal comfort whilst maintaining the visual transparency of the facades and iconic architecture of the roof. The ETFE (ethyl-tetrafluoroethylene) roof lights have been selected to control radiant heat and the mogul ventilation system has been designed to passively draw fresh air past the occupants, even on days where there is little or no wind.

Three elements influence the thermal performance of the station. The high performance roof and facades protect the whole station from wind, rain and excessive direct sun. The design of the roof and façades minimise radiant temperatures within the space and drive the natural ventilation system across the station. The roof panels have been subjected to detailed thermal testing to ensure radiant heat is controlled throughout the whole station.

Further, within the station, the facilities have been located to maximise the benefits provided by the roof and façades thereby tempering further the outdoor environment. The waiting areas are located away from the entrances and in general, close to mechanically cooled spaces. This provides an additional tempering of space without dependence on energy intensive air-conditioning systems which are traditionally associated with good comfort performance. These spaces are all within the main station volume and are not enclosed. A traditional design response would be almost impossible to achieve without substantial enclosure being made.

Finally, where additional intervention is required to provide an acceptable indoor thermal environment supplementary heating and cooling is provided. As an example, the waiting area beneath the Collins St concourse has been provided with a dedicated air-conditioning system, a solution appropriate to a low volume space. Waiting areas that are within the main station area will be heated using slab heating systems. These systems effectively deliver radiant heat to the occupants in an energy efficient control of thermal comfort.

4.2 Ventilation Design Response

The ventilation solution for the station is a major design achievement. Typically the construction of a roof over a railway station where diesel trains operate would result in bulky and energy intensive mechanical services including fans, ductwork and acoustic treatment being installed to comply with the relevant air quality standards. These systems would demand not only ongoing maintenance and substantial running costs but would also require additional building structure to support the services. By integrating natural ventilation within the moguls, the ventilation solution will have a minimal impact on the built form whilst maintaining an indoor environment that meets the required performance levels. This design solution was achieved through best practice environmental design and simulation techniques that enabled an accurate prediction of the air quality within the station.

4.2 Daylighting Design Response

Spencer Street Station also incorporates an effective natural lighting solution. This solution provides natural light to the platforms whilst protecting the occupants from excessive radiant heat through the installation of a dual skin Teflon (ETFE) fabric directly above the platforms. A light diffusing frit has been applied to the roof light fabric to scatter sun light and protect against overly bright conditions. The daylight solution prevents the unnecessary operation of electric lights during the day that would otherwise be required given the introduction of the roof. The design reduces the need for lights to operate for 85% of daylight hours.

5. DESIGN ANALYSIS

5.1 Thermal Comfort

Thermal Analysis Software (TAS) was utilised in the assessment of the thermal comfort within the station. The station includes a variety of spaces and purposes including waiting areas, ticket sales, concourses, platforms and the station entry.

Particular attention was paid to the unenclosed and non airconditioned areas. The following parameters were used in the assessment of thermal comfort; air temperature, radiant temperature, resultant temperature and PMV. Resultant temperature is an output parameter created by TAS that is an average between the air temperature and the radiant temperature. Whilst not exact, it is a good representation of what an occupant might feel. The graph below demonstrates the regulating effect on resultant temperature that the station environment provides for its occupants for conditions between the 5th and 95th percentiles

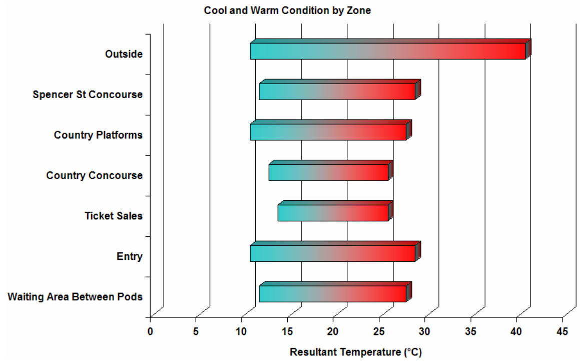

Figure 1 - Resultant Temperature Ranges

PMV is a statistical model that incorporates dry bulb temperature, radiant temperature, humidity, air movement, metabolic rate and clothing to provide an index of how comfortable a person is. The two graphs below demonstrate the improved PMV scores between the outdoor climate (Figure 2) and the station itself, in particular on the country concourse (Figure 3).

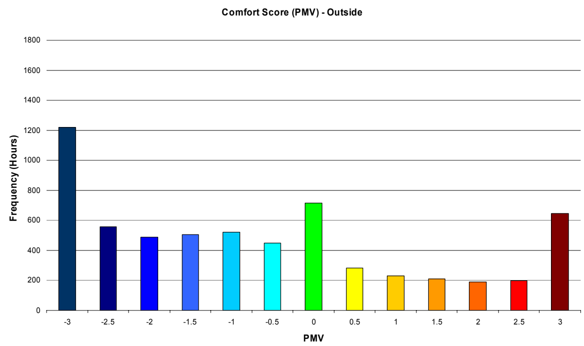

Figure 2 - External Conditions PMV

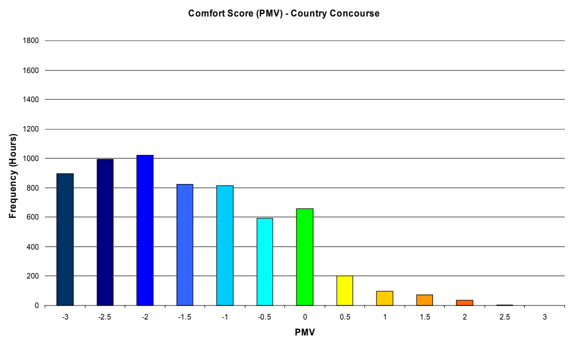

Figure 3 - Country Concourse PMV

5.2 Ventilation - Bulk Airflow Modelling

Thermal Analysis Software (TAS) was again used as the software modelling tool, but this time to explicitly ascertain the potential for buoyancy ventilation. The TAS modelling incorporates test reference year weather data in the analysis and accounts for the solar gain diversity and people and equipment loads to accepted profiles.

The TAS model also accounted for free areas necessary for the ventilation flow. These include;

- Free area through the moguls (8m² each)
- Free areas through the four primary facades

Tested over every day in the Test Reference Year, a distinct number of days with varying temperature, wind and solar radiation characteristics were chosen as test days. These air flow rates demonstrated to the design team that each mogul has the potential for between 16,000L/s and 43,500L/s. Compared with the planned mechanical ventilation scheme, which was designed to achieve 15,000L/s, the natural ventilation strategy offers increased air flow quantities. The TAS modelling therefore confirmed that the buoyancy ventilation scheme offered the logical environmental ventilation strategy.

5.2 Ventilation - Conceptual CFD Modelling

Computational fluid dynamics (CFD) is a powerful computer modelling technique that predicts the flow patterns of fluids. CFD software calculates behavioural properties of the fluid at discrete locations to present the designer with a reasonably accurate impression of the expected flow in actuality.

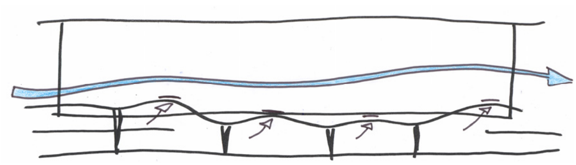

Figure 4 - Wind assisted ventilation flow (concept sketch)

Like all modelling techniques, CFD often requires that a number of simplifications on reality be implemented to enable the designer to utilise the tool in a time effective and cost effective manner. Generally speaking, the following simplifications or approximations are inherent in the CFD models presented;

- adiabatic solids and surfaces
- air behaves as an ideal gas
- flow model using K-ε parameters to approximate turbulent flow
- flow areas modelled as 100% open space

These simplifications are considered reasonable for testing the concepts and design of the station. Results from the CFD modelling were verified against the bulk air flow modelling as well as independent wind tunnel testing of a scaled model of the station and city to assist in the confirmation of these modelling results.

CFD was used extensively to inform the design at all stages. Initially, CFD was utilised to demonstrate the merit and the thinking behind the mogul-like roof design. A simple 2-D model can show that the wave shapes create areas of negative pressure at the top of the mogul, or crest of the wave.

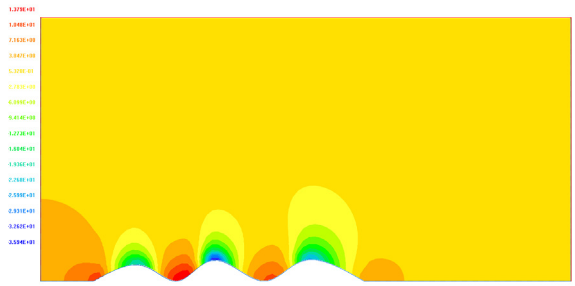

Figure 5 - 2D CFD Image showing negative pressure at mogul tips

This model illustrates well the fact that external wind conditions will favourably influence the capacity of natural ventilation exhaust volumes through the moguls.

The design was then tested further, in 3 dimensions, to test the indoor air quality of the station whilst diesel locomotives are running. These simulations test the ventilation principles based on the buoyancy provided by the exhaust alone. Where the bulk flow analysis shows that the space can relieve heat build up in the space, the CFD model shows that the heat properties of the exhaust alone is enough to drive the ventilation. The CFD model does not simulate internal heat loads or solar heat loads that would assist the ventilation flow rate.

The “worst-case” scenario is difficult to know intuitively. On the one hand the worst case can be considered the scenario where trains are running at full throttle. In this case exhaust contaminants are more plentiful. On the other hand however, it could be argued that the full throttle scenario also creates extra heat and exhaust flow, thereby artificially enhancing ventilation quantities. Thus an idling train scenario was also tested.

Two adjacent trains were tested under the full throttle and idling conditions. Figure 6 and Figure 7 below show the graphical representation of the results.

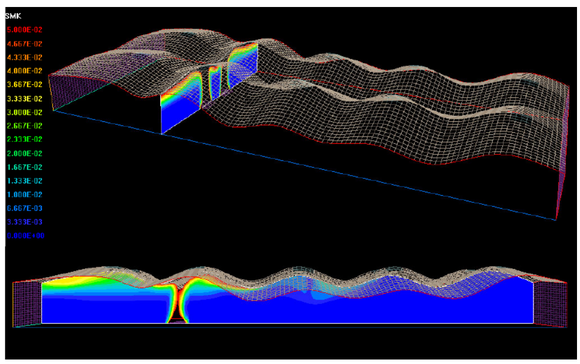

Figure 6 - Full throttle train scenario, passive solution

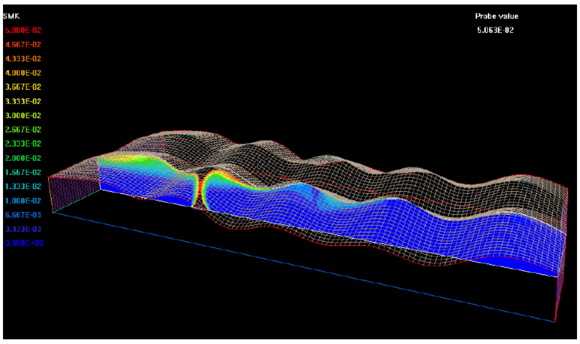

Figure 7 - Idling train scenario, passive solution

Both produced acceptable air quality results. The CFD analysis showed that;

- The roof geometry is an ideal opportunity to enhance the ventilation efficiency of the station through careful design
- The passive design enables the exhaust quantities to be achieved by virtue of the hot exhaust gases and is not reliant on solar gain or internal heat loads

5.3 Ventilation - Detailed CFD Modelling

The bulk air flow analysis and conceptual CFD modelling demonstrated that the buoyancy ventilation concept would provide the space with sufficient ventilation flows.

However, a deeper level of analysis was required to assess;

- the entire station geometry concurrently
- wind effects on actual ventilation flows
- specific removal of train exhaust gases and particulates
- necessary façade free areas and façade balancing design

The model geometry shown below in Figure 8 was the basic geometry used for a series of detailed design investigations aimed at satisfying the design requirements outlined above.

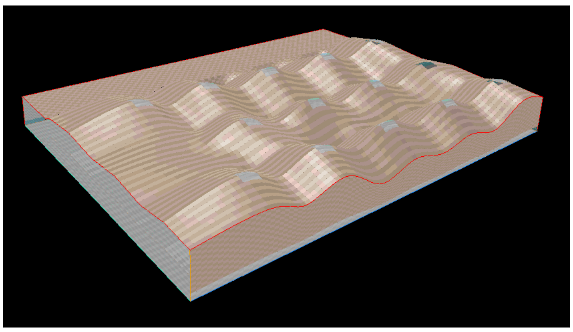

Figure 8 - CFD model geometric representation

Evaluation of the station ventilation performance was assessed using different visualisation techniques available to the designer. These techniques include:

- contour plots – colour gradients used to show varying levels of a particular variable, e.g. carbon monoxide concentration
- surface contours – shows the extent of a variable at a particular level, e.g. carbon monoxide at 30ppm
- streamlines – traces the ventilation path
- point-velocity arrows – shows the direction of movement at every simulated calculation point

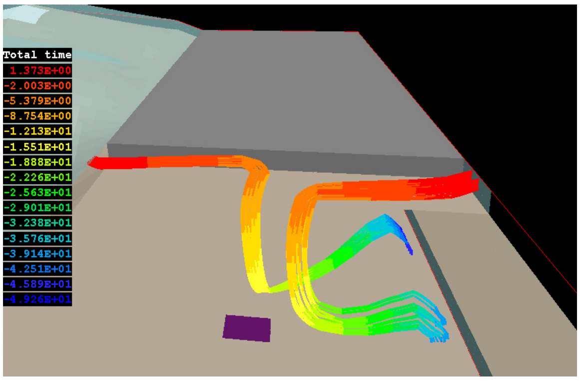

Figure 9 - Flow visualisation using streamlines

The CFD modelling process enabled the design team to confirm with confidence that air quality standards were met, despite the presence of diesel trains in a covered area. In particular the model predicted that:

- CO levels complied with standards and health and safety requirements
- NO_2 levels complied with standards and health and safety requirements

5.4 Ventilation - Fire CFD Modelling

The design needed also to consider the performance of the station in a fire scenario. CFD was again utilised to assess the design in a fire simulation.

The same basic principles apply to the fire scenario as apply to the ventilation of diesel exhaust fumes. The heat from the fire will drive the fire smoke toward the station roof cavity using buoyancy.

The beauty of the natural ventilation scheme is revealed here as we witness the natural responsiveness of the system. That is, as the fire gets hotter and hotter the system responds by providing more and more ventilation.

A 20 Mega-Watt "ultra-fast" train fire was tested over a time period of 8 minutes using the detailed CFD model. The test location was a section of the station that is underneath a building, rather than the mogul shape roof of the rest of the station.

The CFD model enabled the visualisation of temperature and smoke variable distribution.

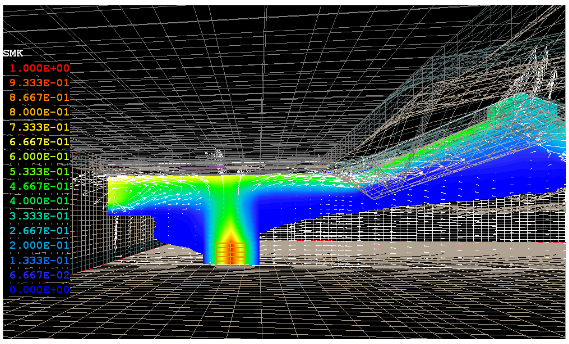

Figure 10 - Fire in early stages of development

5.5 Daylight Modelling

The performance of the daylighting has been assessed using photometrically accurate, radiosity based, computer rendering software. The geometry of the model was supplied by the architect.

The daylighting performance of the model was assessed using an overcast sky that is exceeded by Melbourne conditions for 85% of daylight hours. The model was assessed against a minimum illuminance level of 250 Lux.

The modelling process allowed the environmental engineering team to resolve the light transmission properties of the ETFE (ethyl-tetrafluoroethylene) double layer cushion that has been employed. The ETFE cushion provides a scattering effect to the natural light to reduce direct light transmission to the space, reduce radiant heat and to reduce the potential for the daylight to act as a glare source.

The resolved model demonstrated that 250 Lux on the platform areas is exceeded for at least 85% of daylight hours. This is realised as an environmental benefit by:

- reducing station running costs by allowing station lights to be switched off for 85% of the year
- providing a quality internal environment, complimenting the natural ventilation and thermal comfort of the space

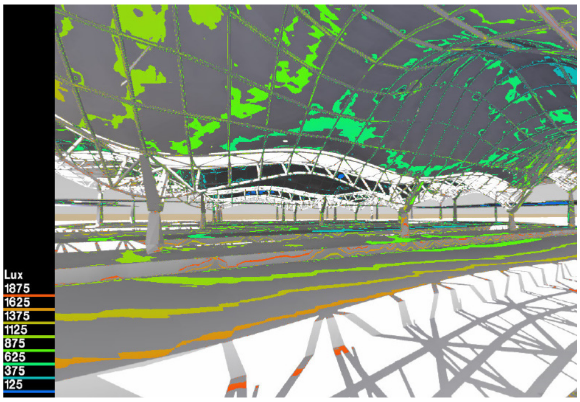

Figure 11 - Daylight iso-lux analysis, December 3pm sunny sky

7. CONCLUSION

This paper has demonstrated a few important points for the environmental engineer and sustainability-minded architect. In particular we have shown;

- Important lessons in sustainable architecture can be learnt from traditional architectural practices
- the alignment of environmental and architectural design goals early in the design phase is pivotal in creating quality sustainable architecture
- advanced environmental design and modelling techniques are valuable for informing the design process and optimising environment quality indicators such as natural light, air quality, natural ventilation and thermal comfort.

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