

CFD Simulation of Busbar Tunnels in EGA Jebel Ali Potlines

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Abstract

A recent project undertaken by EGA to investigate the busbar ventilation tunnel system for all Jebel Ali potlines is discussed. The purpose of the study was to perform Computational Fluid Dynamics (CFD) modelling to support findings from an ongoing site investigation of all busbar ventilation tunnels and optimize the ventilation configuration. Busbar temperature criteria were developed based on maximum continuous operating temperature of busbar insulation grouting materials and a volume-averaged temperature was used to reduce overall energy wastage. The modelling incorporated all heat transfer mechanisms – conduction, convection and radiation, fluid flow and turbulence within the ventilation tunnels, and Joule heating within the busbars. Ventilation fan performance curves, louvre openings, and gratings were incorporated to accurately predict the overall system behavior. A site measurement campaign was undertaken to validate and compare the CFD model results to temperature and flow rate measurements, with good agreement obtained. Various illustrative results are presented to demonstrate the use of CFD combined with site measurements as a useful tool to understand and optimize complex ventilation systems. Specific performance improvements to the ventilation systems as a result of the study included installation of additional fans, baffles to improve heat transfer, and walls to segregate ventilation zones.

Keywords: Computational Fluid Dynamics, Busbar ventilation in tunnels, Heat transfer from busbars, Industrial cooling fans, Fan curves.

1. Introduction

Emirates Global Aluminum (EGA) operates seven potlines at Jebel Ali. The smelter operations started in 1979 and went through various expansion and retrofit phases. The site now encompasses 1 577 cells using six different reduction technologies operating at currents ranging from 240 kA to 500 kA. A unique feature of the site is that the reduction cell groups are connected via underground busbars, to keep the smelter operating floor at the same elevation as the roads. The busbars are routed through concrete tunnels which include supports and electrical insulation positioned between the aluminium busbars and the supports. Fans connected to the tunnels provide forced ventilation cooling for the busbars while hot air is vented at specific louvred openings or allowed to exit at potline connections via installed gratings. Typical features of a busbar ventilation tunnel system for Potline 7 are highlighted in Figure 1. This tunnel system is quite complex because it interconnects three out of four potrooms of the potline. Potline 9 busbar tunnel system, shown in Section 5.3, is even more, exceptionally complex since it interconnects 10 short potrooms, built in this way because of limited space in the smelter.

EGA has recently experienced busbar overheating issues particularly within the Eagle section at Jebel Ali Potline 5 [1]. Excessive busbar temperatures can severely damage the electrical insulation between the busbar and the concrete support. The thermal expansion associated can cause unwanted displacement which can impact the busbar heat transfer and increase mechanical stresses in weak components such as welded joints. Damaged electrical insulation and excessive busbar displacement represent a risk for the potline stability.

A scope of work to examine the ventilation systems for all busbar tunnels on the plant was undertaken by Hatch. Computational Fluid Dynamics (CFD) modelling was used to assess the existing ventilation performance and recommend options for ventilation improvement if required based on busbar temperature limit criteria.

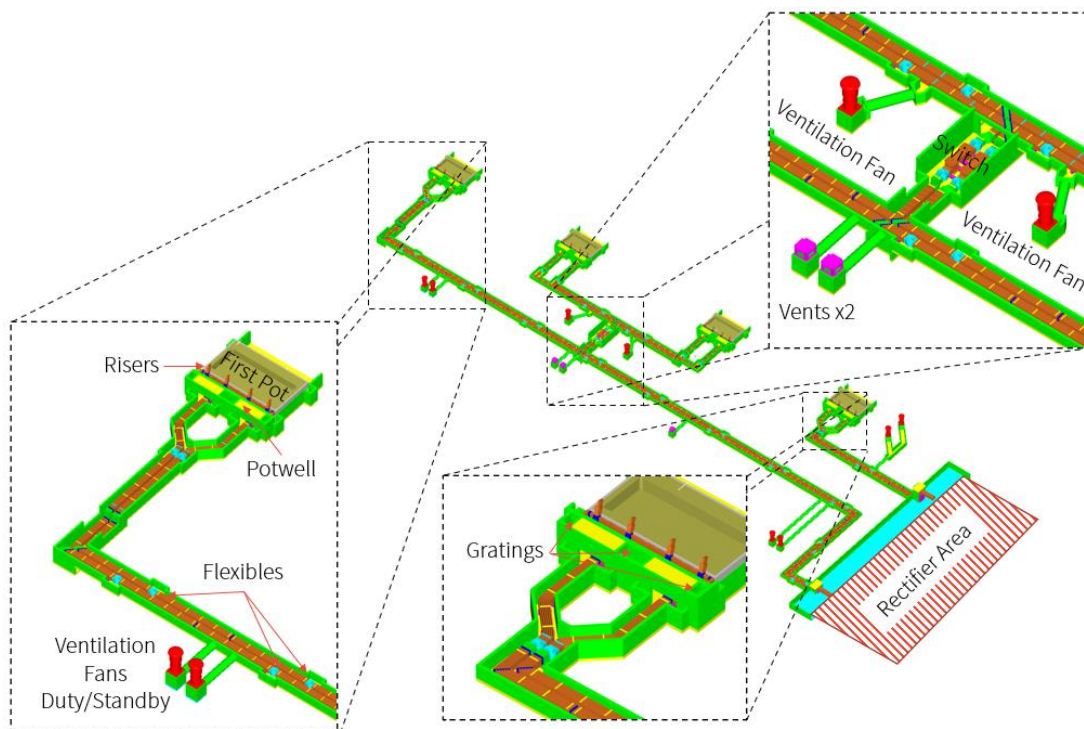


Figure 1. Potline 7 3D model highlighting typical busbar ventilation tunnel components (tunnel concrete covers not shown for clarity).

The objectives of the study were as follows:

1. Predict busbar temperature, air flow distribution, air temperature, and pressure drop in the tunnel networks.
2. Use the information gained from these initial models to optimize the air flow within the tunnel system in order to minimize busbar temperatures to acceptable limits considering future current creep. Measures available included: adding fans where required, additional outlets (including ventilation grills), baffles to improve heat transfer in local regions or practical tunnel modifications at suitable locations.

2. Evaluation Criteria

Following discussion with EGA personnel and EGA's consultant, Dr. Vinko Potocnik, the agreed upon criteria for busbar temperature were as follows:

- Volume averaged busbar temperature limit of 100 °C.
- Local maximum busbar temperature limit of 150 °C.

The purpose of the volume averaged busbar temperature limit is to minimize energy wastage (busbar electrical resistivity is linearly proportional to busbar temperature). The purpose of the local maximum busbar temperature limit is to maintain the integrity of the epoxy grout used below the busbars on concrete supports.

3. Methodology

3.1 CFD Modelling Approach

CFD is a numerical technique to simulate fluid flow, turbulence and heat transfer (amongst other phenomena). A commercial general purpose CFD code Siemens Star-CCM+ 2021.2 was used for this study. The physical domain representing the air space within each tunnel is sub-divided into a large number of cells in which conservation equations are discretised and solved. Volumetric heating in each busbar is modelled by accounting for Joule heating, as per Equation (1):

$$q_{vol} = \rho j^2 \quad (1)$$

where:

q_{vol}	Volumetric heat generation in a continuous busbar, W/m ³
ρ	Temperature dependent electrical resistivity, Ωm
j	Current density, A/m ²

In general, the following overall modelling approach was used:

- Air was modelled as an ideal gas with properties as a function of temperature.
- Radiation was modelled using the surface-to-surface approach with a suitable emissivity of aluminium (0.5-0.6) and concrete (0.85).
- All busbar ventilation tunnels were modelled as per the latest 3D drawings and/or site measurements. Thermal losses through the tunnel walls and cover were determined to be negligible, therefore these surfaces were treated as adiabatic.
- Outside of the ventilation tunnels/basement the busbars and supports were continued for a short distance to account for the blockage effect imposed on the system by these obstructions.
- Ventilation fans represented as a simple cylinder at the appropriate diameter which was measured on site. Intake fan characteristics were incorporated directly into the model with vendor provided fan curves. This allowed for the operating point on the fan curve to be determined as part of the model solution.
- Louvres were represented as porous media to account for pressure drop. A suitable discharge coefficient was determined from literature for similar louvre geometry, based on site measurements.
- Potwell gratings were represented as porous media to account for pressure drop. A suitable discharge coefficient was determined from literature for similar geometry, based on site measurements.
- Ambient temperatures evaluated ranged between 35 °C and 55 °C.
- Busbar currents were assigned based on present day operating and future amperage values.

3.2 CFD Model Validation

CFD model validation was undertaken to compare site measurements to model predictions. CFD model scenarios were built with conditions (ambient temperature, current, fan and louvre operations) matching on-site conditions when measurements were performed. Busbar temperature measurements were taken (either manually or with permanently installed thermocouples), and the data was provided for comparison to the model predictions. Figure 2 summarizes the comparison of CFD model predictions and on-site measurements for busbar temperature. Overall, there is reasonable agreement between CFD model predictions and on-site measurements of busbar

temperatures. The CFD model over-estimates busbar temperature by approximately 10 °C and is therefore deemed to be a conservative approach for the ventilation system evaluation from a design perspective. A similar conclusion was made in other potlines, where measured busbar temperatures were compared to the simulations.

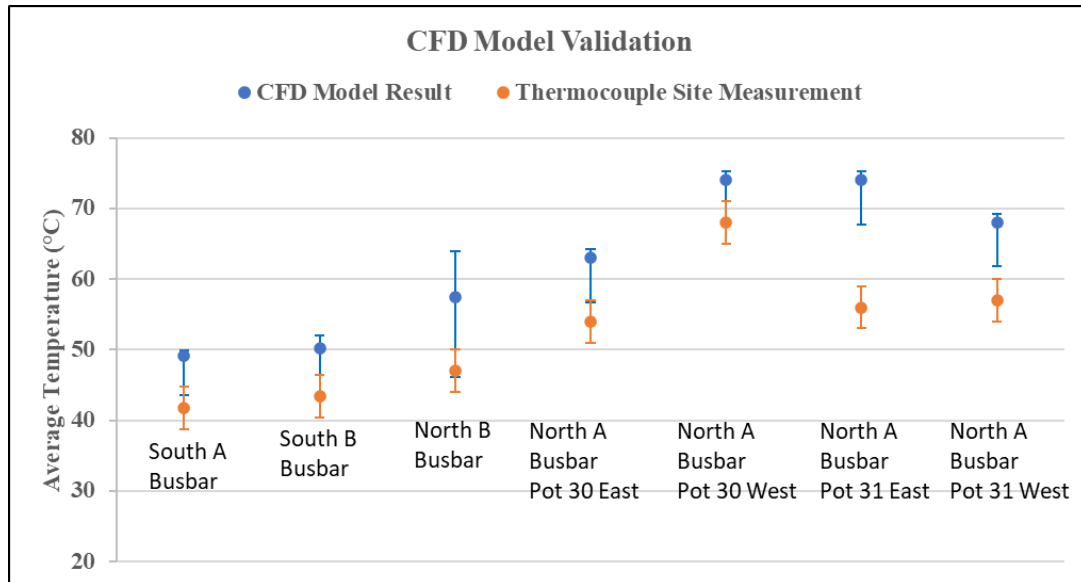


Figure 2. CFD model comparison to site measurements taken on Potline 7.

4. Eagle Section CFD Model

4.1 Thermal Damage Observed at Eagle Section

The existing Eagle Section operates at the highest current density in the plant [1], therefore adequate ventilation is critical to maintain busbar temperatures below acceptable limits. Recent overheating damage was observed on busbar electrical insulation epoxy grout and tunnels in the higher current carrying tunnels, shown in Figure 3.

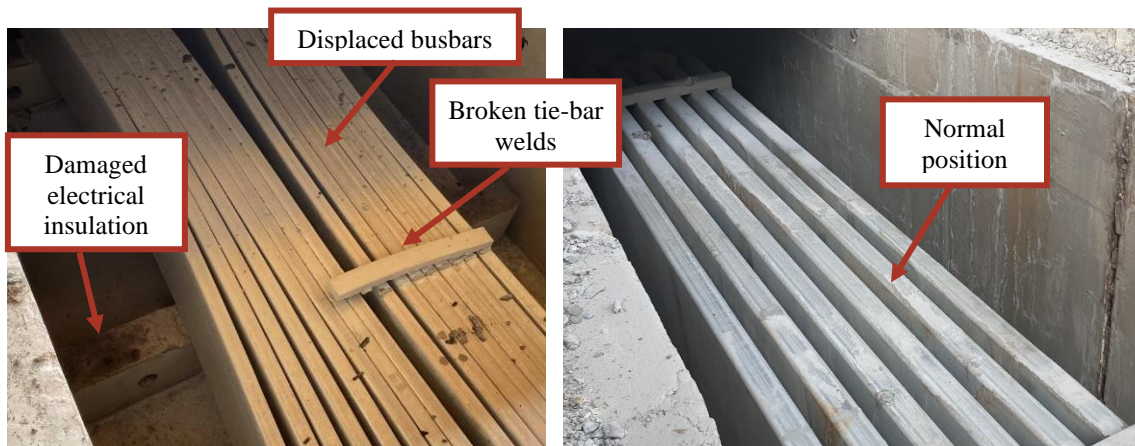


Figure 3. Photos illustrating thermal and electromagnetic damage observed on Eagle section busbars (left) compared to normal conditions (right).

4.2 Eagle CFD Model Investigation

The overall CFD model for the Eagle Section consisted of two sub-models, namely the input circuit and output circuit, shown in Figure 3 overall.

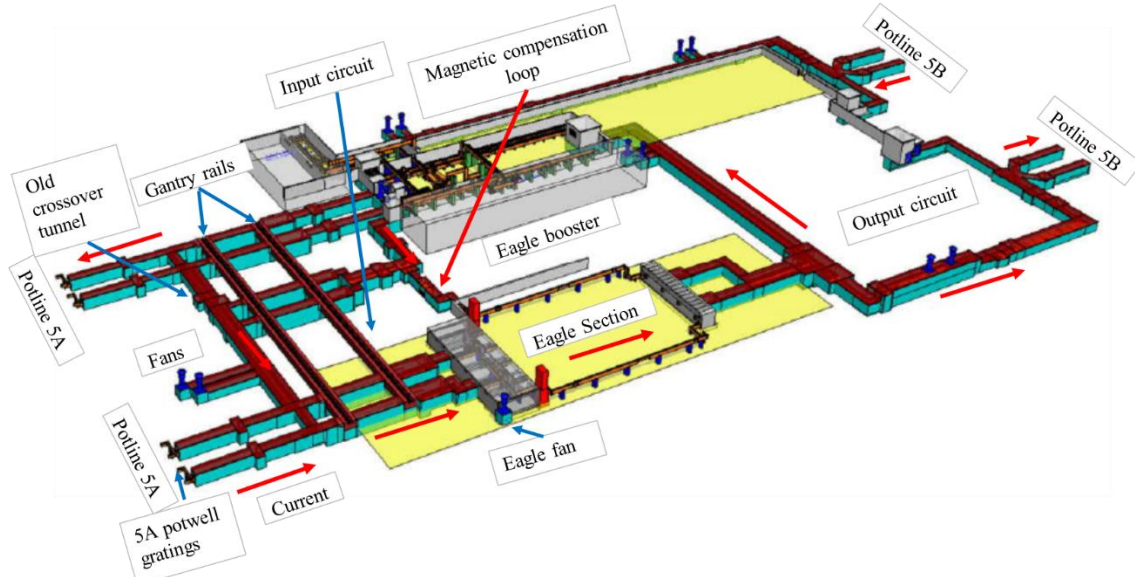


Figure 3. The system of busbar tunnels in Eagle section of Potline 5. Blue columns are fans [1].

Figures 4 and 5 show the input and output circuit separately with corresponding results for the operating case a) Eagle input circuit before Eagle incident at 480 kA and 30 °C ambient temperature, duty/standby fans, and b) Eagle output circuit at 500 kA and 50 °C ambient temperature, duty/standby fans.

Key takeaways from the results are summarised as follows:

- For the Eagle input circuit:
 - The flow in the high current carrying tunnels beneath the road going towards the basement is restricted by the discharge openings within the basement as well as back pressure created by the Eagle fan discharging in this area. This results in high busbar temperatures (>200 °C) beneath the road leading into the basement which is well above the temperature criteria. This corresponds well to high temperature damage of concrete observed on-site during demolition of these tunnels and failure of the busbars in the input tunnels [1].
 - A lot of flow escapes through the old crossover tunnel, where no current flows now as well as through the very large-area Potline 5A potwell gratings.
 - The existing duty 5A fan services the entire busbar network. This is problematic as different tunnels require more/less flow depending on the current density.
- For the Eagle output circuit:
 - The highest current carrying tunnels in the Eagle output section do not comply with the temperature limit due to the reduced air flow entering this area. The relatively larger cross-sectional area of the output tunnels results in lower velocities which reduces heat transfer compared to other locations in the system.
 - Busbar temperatures within the main section of the eastern and western tunnel conform to the temperature limits.

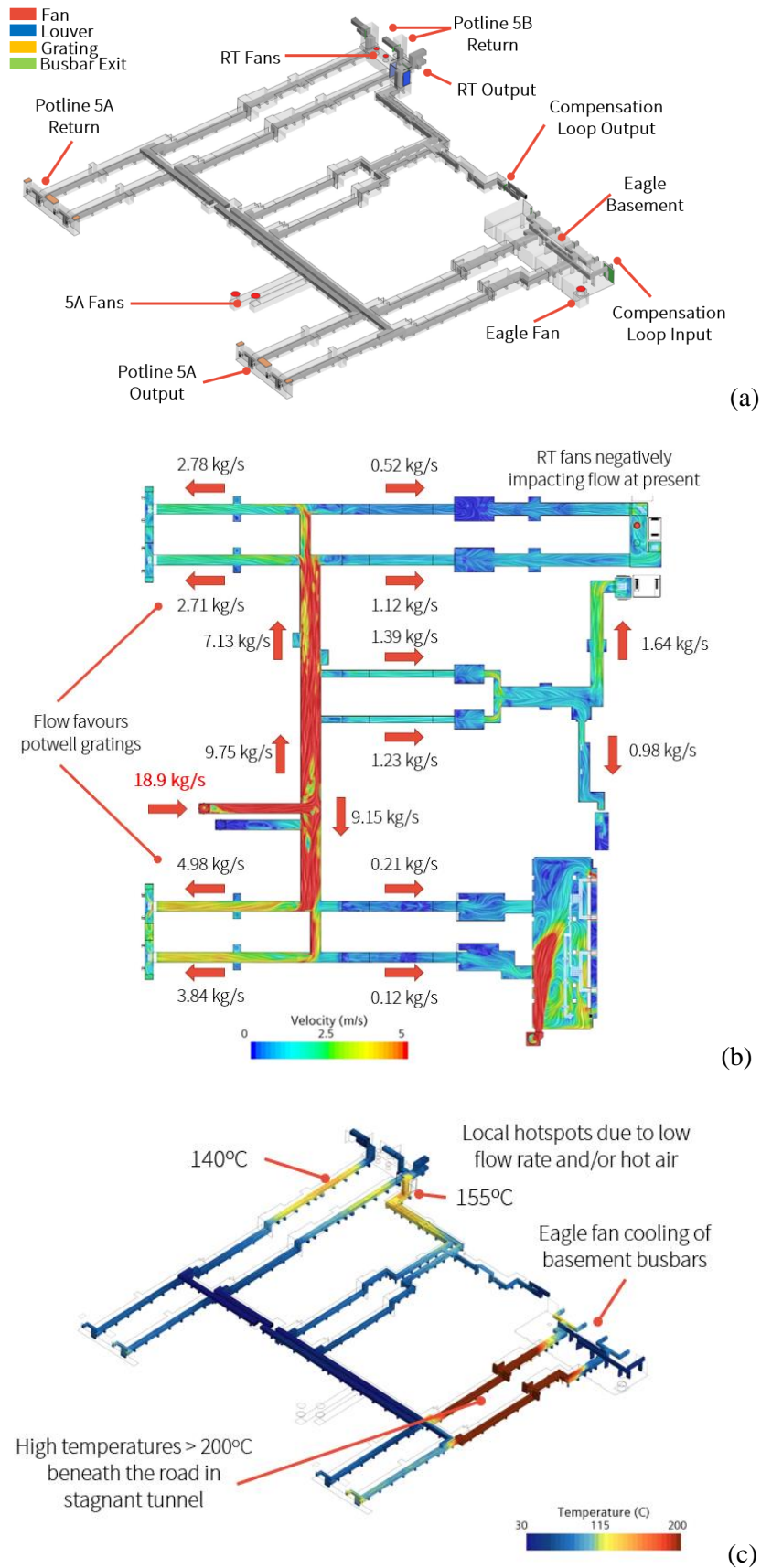


Figure 4. Eagle input circuit before Eagle incident: (a) overall arrangement (b) air flow velocity and mass flow rate and (c) predicted busbar temperatures.

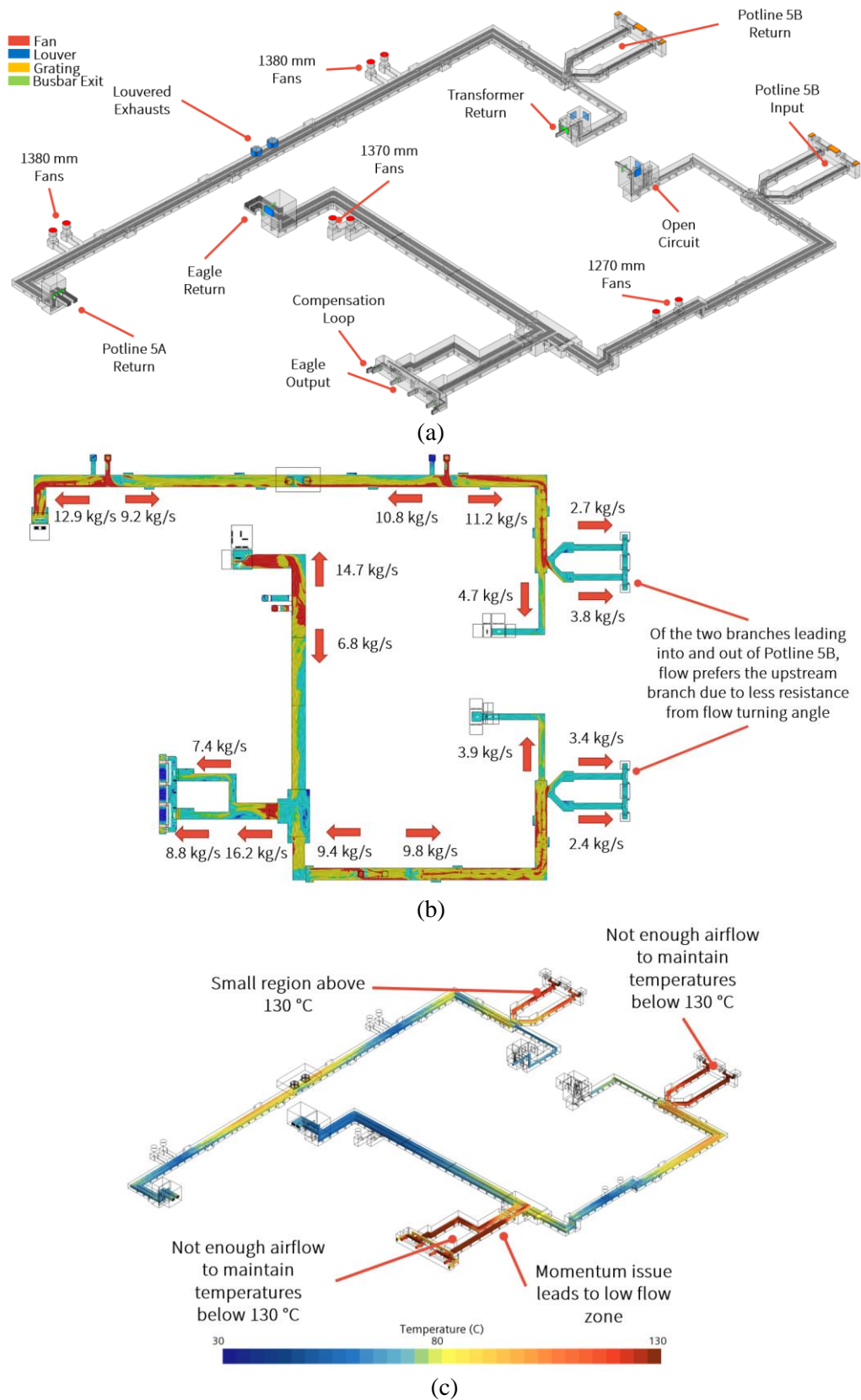
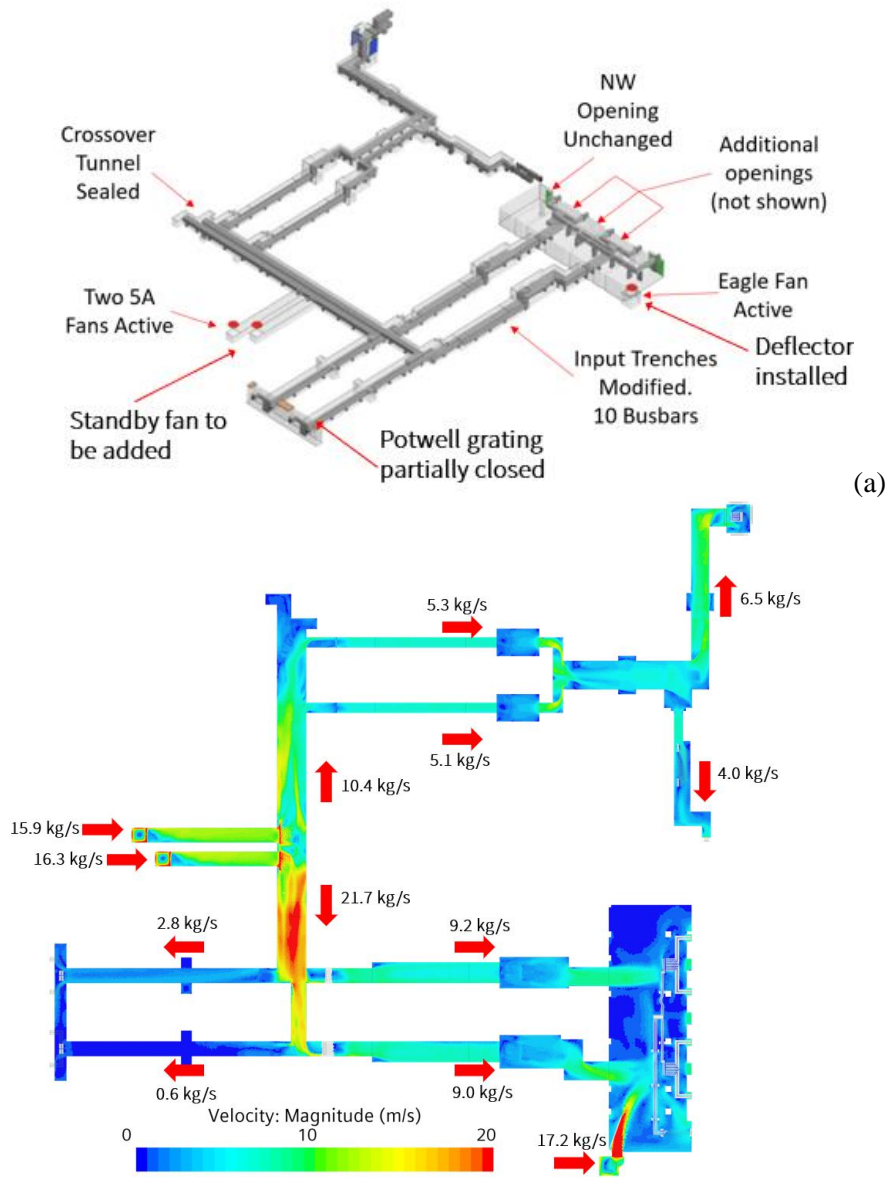


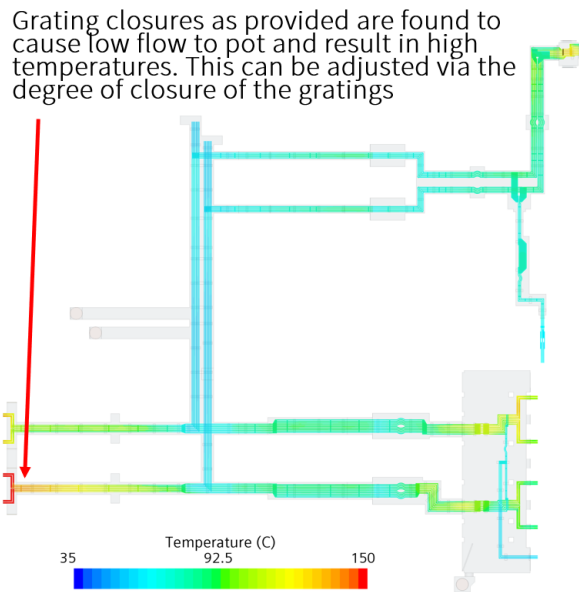
Figure 5. Eagle output circuit (a) overall arrangement (b) Air flow velocity and mass flow rate and (c) predicted busbar temperatures.

4.3 Optimized Eagle Ventilation Configuration

Following the detailed CFD model investigation which resulted in busbar temperatures within acceptable limits, a number of modifications were implemented on site, shown in Figures 6 and 7. The final optimized ventilation configuration of Eagle input circuit relative to the existing configuration resulted in the following modifications:

- Sealing of the old crossover tunnel to reduce the ventilation system demand.
- Running two installed 5A fans to provide sufficient air flow. A third fan will be installed as a standby.
- Redesign of the busbar tunnels beneath the road to accommodate additional busbars (increased from 6 to 10 per pack) to reduce the current density and therefore heat generation.
- Modifications to the basement discharge upstream of Eagle cells to reduce the blockage effect and promote more flow towards this area.
- Partial closure of potwell gratings near Potline 5A.
- Installation of a deflector plate at Eagle fan outlet to increase cooling on busbars within the basement and reduce the imposed back pressure at the basement entrance.



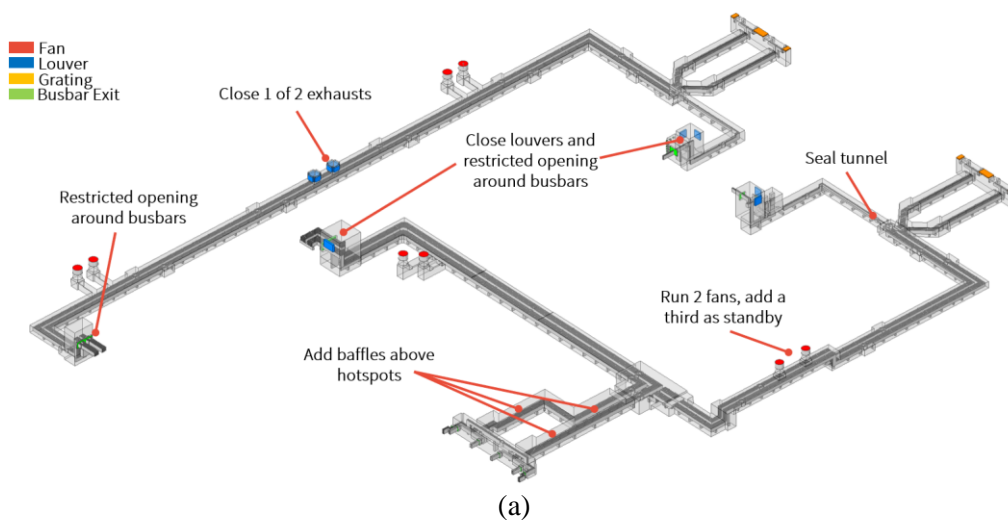


(c)

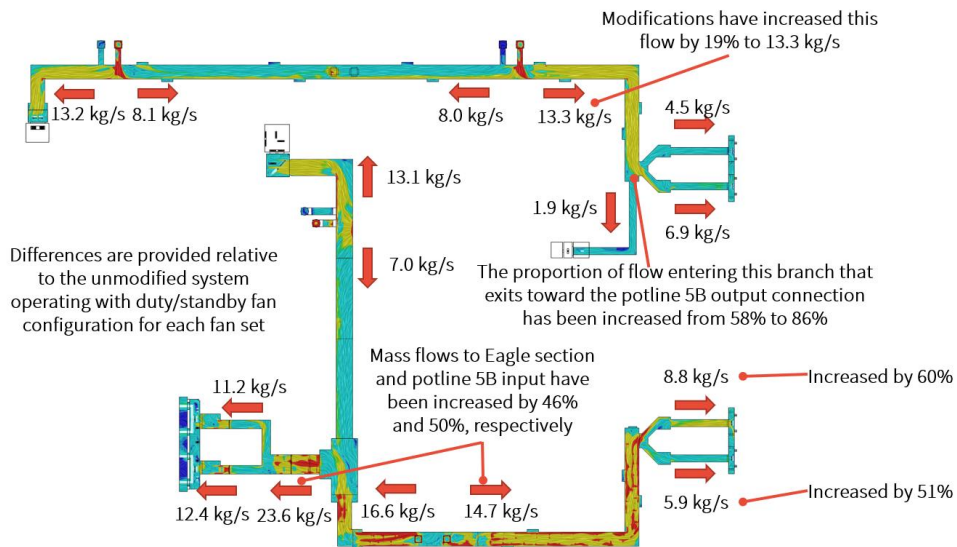
Figure 6. Optimized Eagle input circuit (a) overall arrangement (b) air flow velocity and mass flow rate and (c) predicted busbar temperatures. For ambient temperature of 50 °C.

The final optimized ventilation configuration of Eagle output circuit relative to the existing configuration resulted in the following modifications:

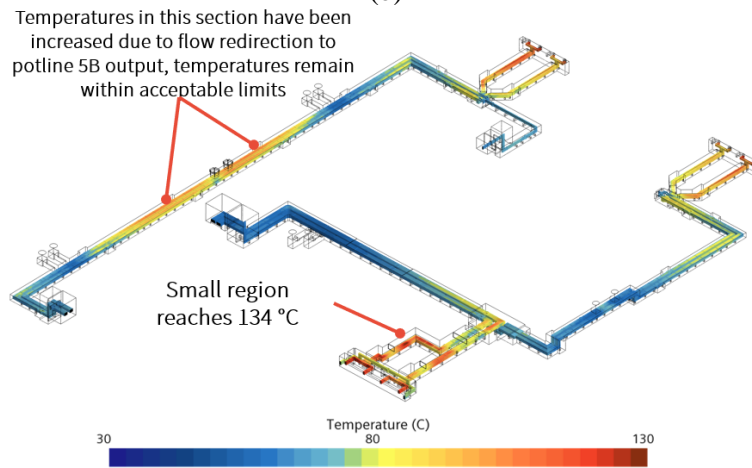
- Closing 1 of 2 exhausts on the western tunnel.
- Closing louvers and restricting openings on the headhouses above grade at the ends of the tunnels.
- Sealing a tunnel that does not require active cooling.
- Installing a third fan on the eastern-most set of fans.
- Installing baffles above hotspots in the Eagle output location. Baffles are installed near the Eagle circuit output above the predicted hotspots where the tunnel cross-section has considerable headspace above the busbars. Baffles greatly increase heat transfer without reducing overall flow due to pressure drop.
- Openings and louvers are closed or restricted to redirect air from over-ventilated areas to under-ventilated areas.
- An additional fan is installed at the eastern side of the busbar tunnels, where the fans have the largest heat load to address.



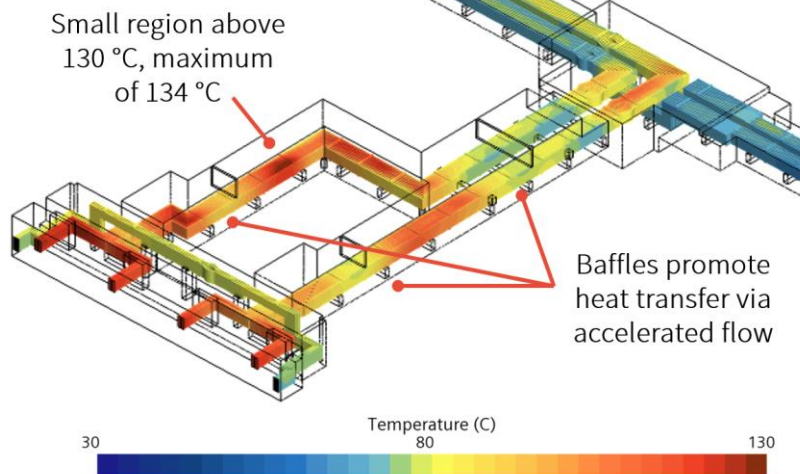
(a)



(b)



(c)



(d)

Figure 7. Optimized Eagle output circuit (a) overall arrangement (b) Air flow velocity and mass flow rate (c) predicted busbar temperatures and (d) predicted busbar temperature in the high current carrying tunnels.

4.4 Site Validation of Recommended Ventilation Configuration

Following rebuild of the input tunnels and implementation of other recommended modifications, a site measurement campaign was undertaken to confirm satisfactory operation of the Eagle input tunnels. Site measurements were compared to the CFD model predictions which showed good agreement, shown in Table 1. Note the CFD model prediction is reported as a range to account for local gradients and averaging that occurs in turbulence modelling.

Table 1. Comparison of CFD model predictions to site measurements in in Eagle input circuit tunnels at exit into the basement upstream of Eagle cells.

	East tunnel (tap end)	West tunnel (duct end)	CFD model prediction
Busbar temperature (centre busbar) (°C)	76	86	70-90
Air temperature (°C)	56	55	45-55

5. Potline 7 and Potline 9 CFD Model

Two sets of illustrative results are presented for potlines which required ventilation configuration modifications. These two potlines represented the most complex arrangements on the plant. The majority of the ventilation tunnel configurations were found to perform adequately for the most onerous evaluation case (future current creep and highest ambient temperature of 50°C).

5.1 Existing Ventilation of Potline 7

The CFD model for Potline 7 South is shown in Figure 8. Potline 7 was evaluated as a high priority since overheating of busbars in some section of the long tunnel had been observed in the summer of 2021.

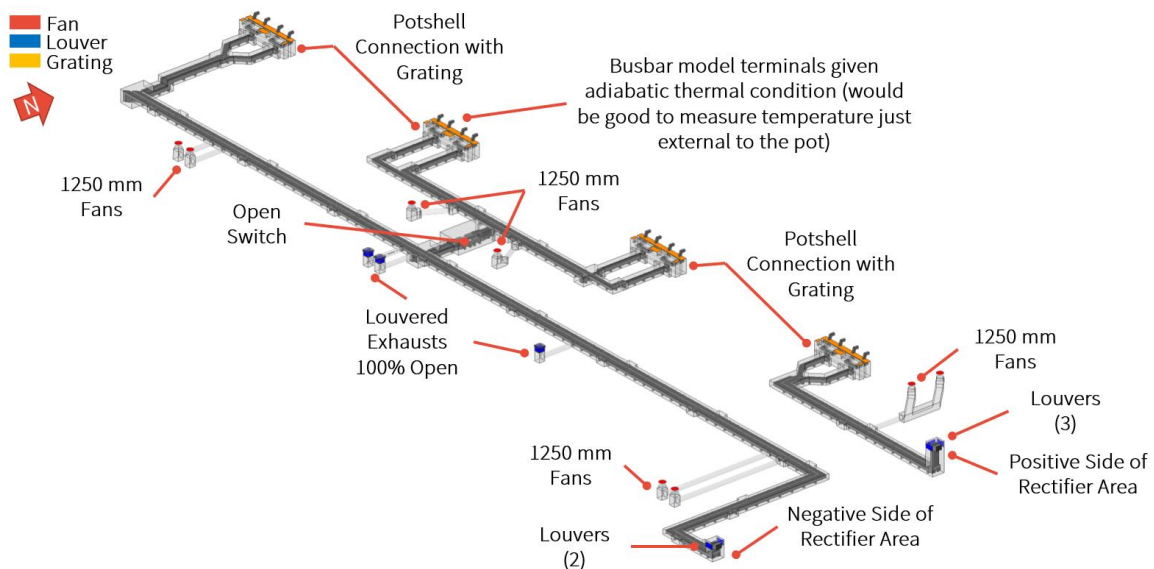


Figure 8. Overall Potline 7 South CFD model.

The results for the conservative operating case (50 °C ambient temperature, duty/standby fans, with operating current of 265 kA) are shown in Figure 9 (a) and (b). Key takeaways from the results are summarised as follows:

- The tunnel between the vents 1-2 and 3 in the south section receives little air flow when these vents are all open.
- A consequence of low air flow between vents 1-2 and 3 is high busbar temperatures in that region that are well above the acceptable limits.
- The air flow from the two sets of fans in the southern section predominately flows toward the nearby exits (rectifier area and Potroom A) rather than toward the centrally located vents.
- The fans from the north section and the fans from the south section do not balance which results in net air flow through the interconnecting switch tunnel toward the south.
- Majority of the air flow from the north section fans exits from the potroom connections in the north section.

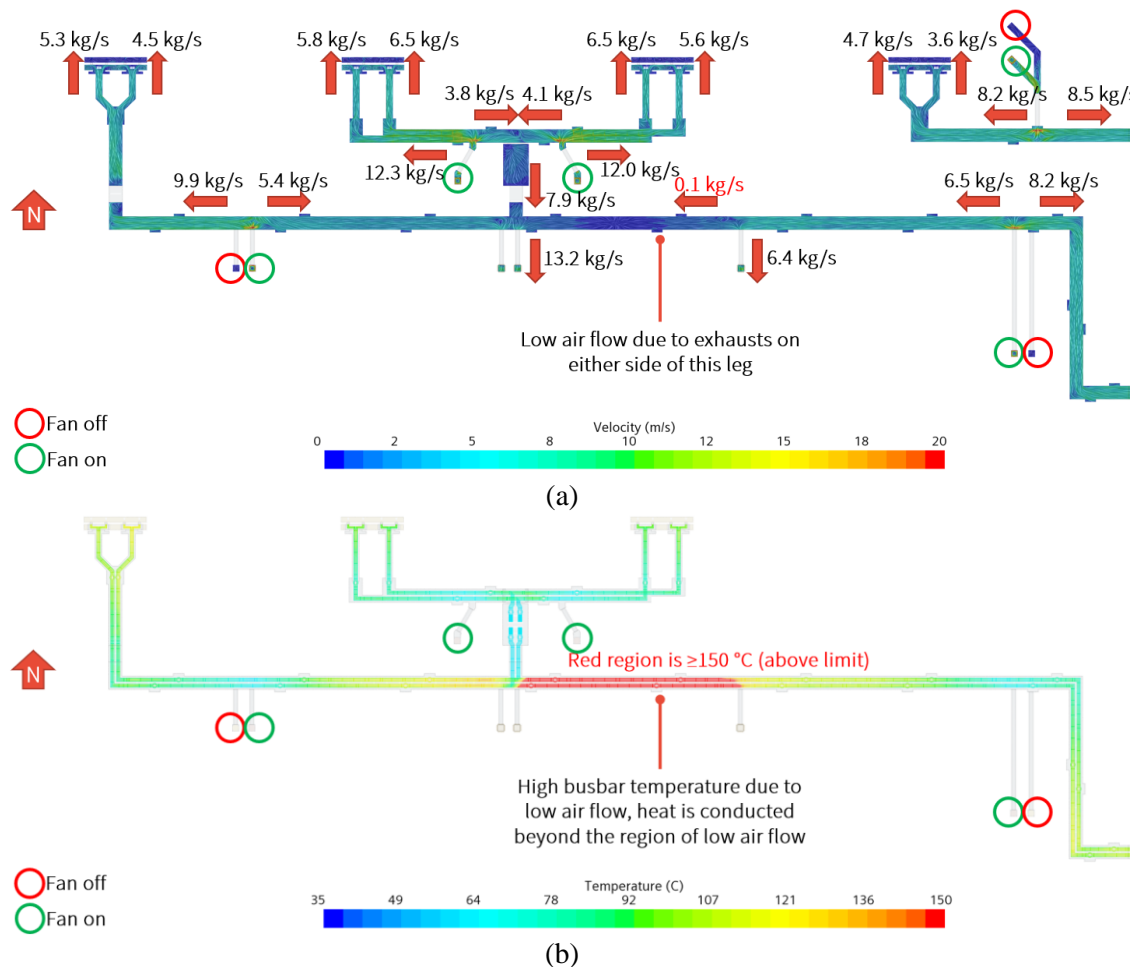


Figure 9. Existing Potline 7 South operation (a) air flow velocity and mass flow rate and (b) predicted busbar temperatures.

5.2 Optimized Potline 7 Ventilation Configuration

Following the initial CFD results, various ventilation configurations were evaluated. The final optimized ventilation configuration relative to the existing configuration resulted in the following modifications:

- Sealing to air flow the switch room between the short north crossover and the long tunnel.
- Permanently closing and sealing louvers on vent 3.
- Closing 1 of 2 louvers on south section near the rectifier area.
- The two fans servicing the northern section run as duty/standby.

- Installing two additional standby fans in the southern section (each fan set has 2 duty and 1 standby).

Air flow patterns and busbar temperatures for the optimized configuration are shown below in Figure 10 (a) and (b) which resulted in acceptable busbar temperatures.

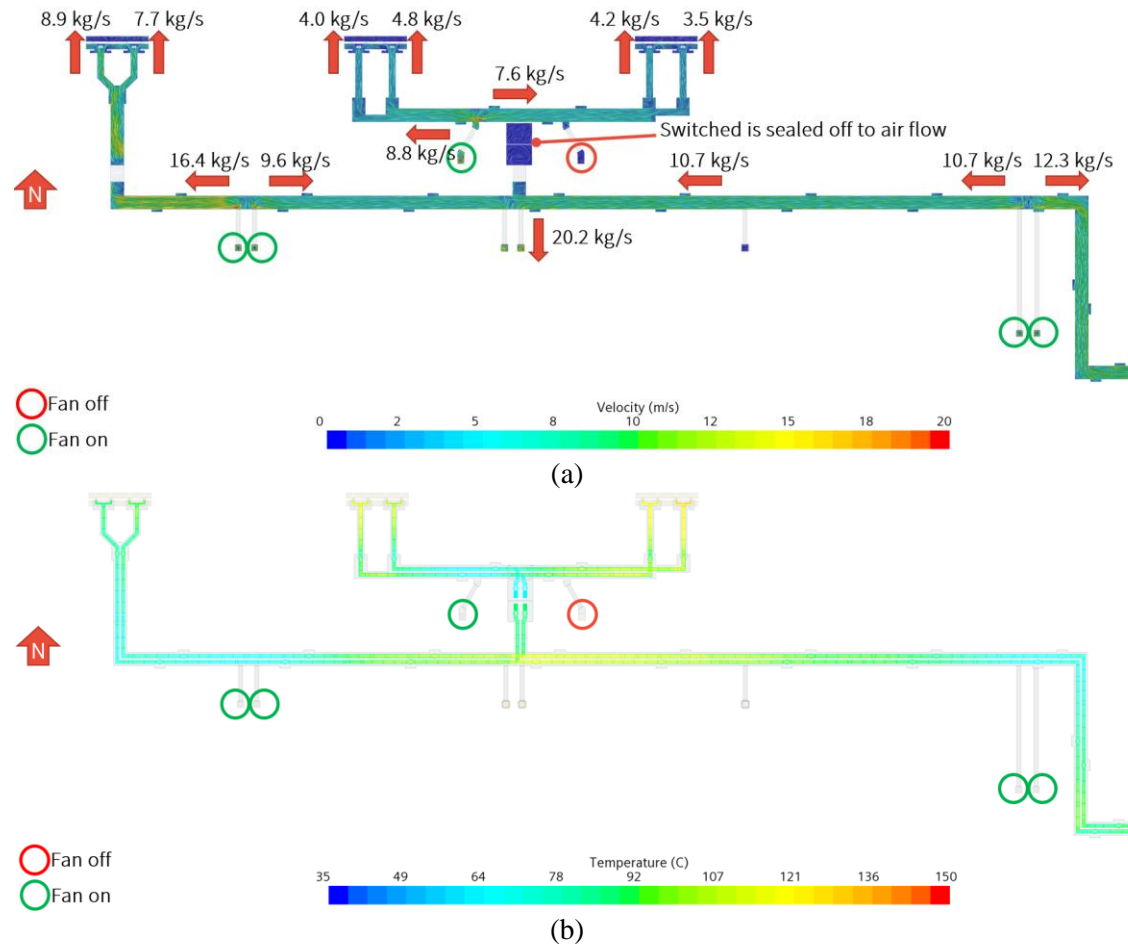


Figure 10. Potline 7 recommended ventilation configuration (a) Air flow velocity and mass flow rate (b) Predicted busbar temperatures.

5.3 Existing Ventilation Configuration of Potline 9

The CFD model for Potline 9 is shown in Figure 11. Potline 9 is the most complex and interconnected ventilation tunnel system in the plant due to a number of additional potlines being constructed over the years and subsequent modifications made to existing potlines. Due to this fact, the ventilation system is influenced by changes made anywhere in the network which would be almost impossible to diagnose on site.

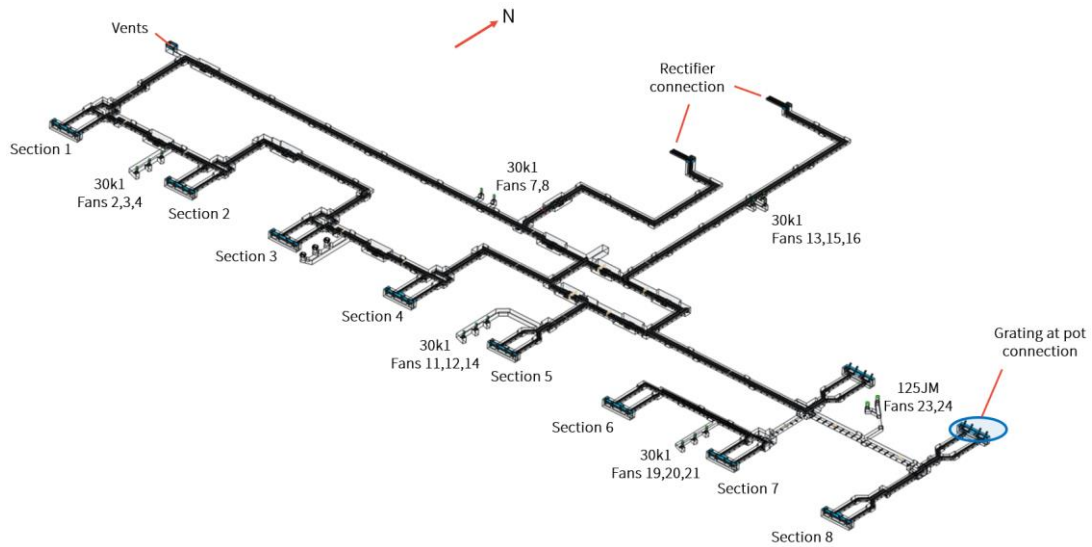
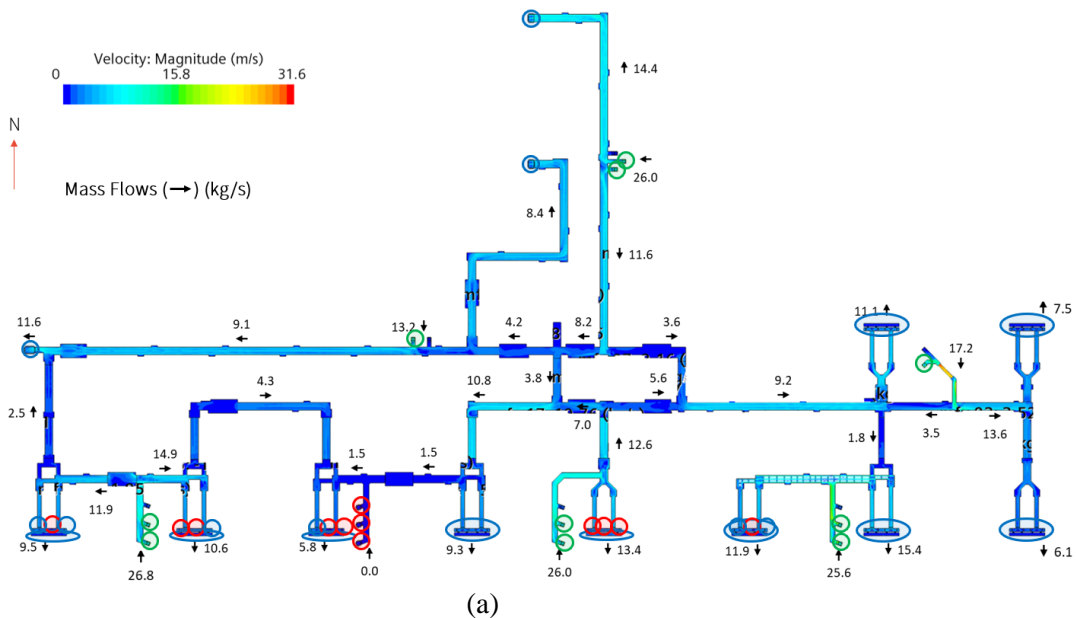


Figure 11. Overall Potline 9 CFD model.

The results for the conservative operating case (50 °C ambient temperature, duty/standby fans, with operating current of 256 kA) are shown in Figure 12 (a) and (b). Key takeaways from the results are summarised as follows:

- The volume average and maximum busbar temperatures are predicted to reach 120 °C and 200 °C respectively near sections 2 to 3, significantly exceeding the busbar temperature criteria.
- Busbar temperatures also exceed criteria between section 1 and the rectifier, and between section 7 and the rectifier.
- Due to the layout of the flow network, the fans are significantly influenced by each other.



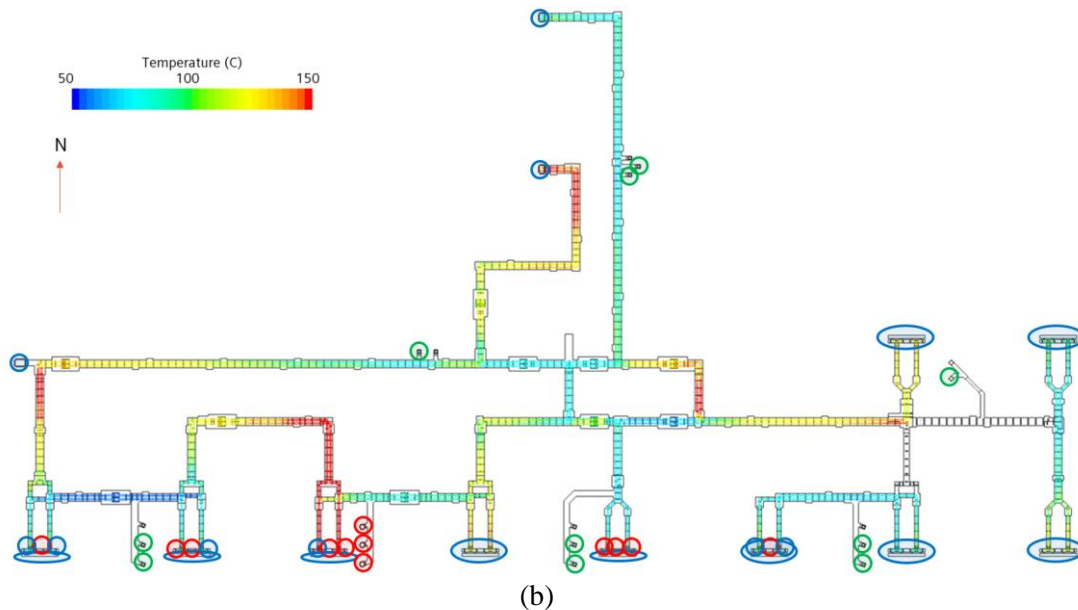


Figure 12. Existing Potline 9 operation (a) air flow velocity and mass flow rate and (b) predicted busbar temperatures. Active fans are indicated in green, open gratings are indicated in blue, and closed gratings are indicated in red.

5.4 Optimized Potline 9 Ventilation Configuration

Following the initial CFD results, various ventilation configurations were evaluated. The final optimized ventilation configuration relative to the existing configuration resulted in the following modifications:

- The addition of blockages at the open switch locations (7 total) to segregate the flow network. This prevents parallel ventilation sections between fans/vents from influencing one another directly.
- Requires one fan to be moved (fan #21 to become an additional standby fan at #7/8 location).
- Restricting flow at the rectifier openings and losing the outlet vents in the section 1 / rectifier tunnel (in the north-west)
 - Having closed / open grating sections as depicted in Figure 13 (b), pink lines.

Air flow patterns and busbar temperatures for the optimized configuration are shown below in Figure 13 (a) and (b) which resulted in acceptable busbar temperatures. Key takeaways are highlighted as follows:

- With future operating currents (275 kA) the volume average and maximum busbar temperatures reach 108 °C and 156 °C respectively. The project determined the temperatures are acceptable relative to the busbar temperature criteria due to the conservative CFD model assumptions.
- With the recommended ventilation system design, the existing number of operating / standby fans can be maintained. One of the existing fans (fan #21) is moved to the fan #7-8 location. A new fan tunnel is required, recommended to be located adjacent (on the west side) to the existing fan 7 location.
- The addition of walls as indicated in Figure 6 (b) effectively segregates the flow network and prevents sets of fans from interacting with one-another. Any future ventilation system adjustments will become more direct and the risk of adversely influencing ventilation flows elsewhere in the system will be avoided.
- These recommendations apply to the existing busbar electrical current distribution and switch configuration, and EGA has communicated that this busbar switch configuration is intended

to be used for the foreseeable future. In the scenario that the busbar switch configuration is changed in the future, Hatch recommends re-examining the ventilation system of Potline 9.

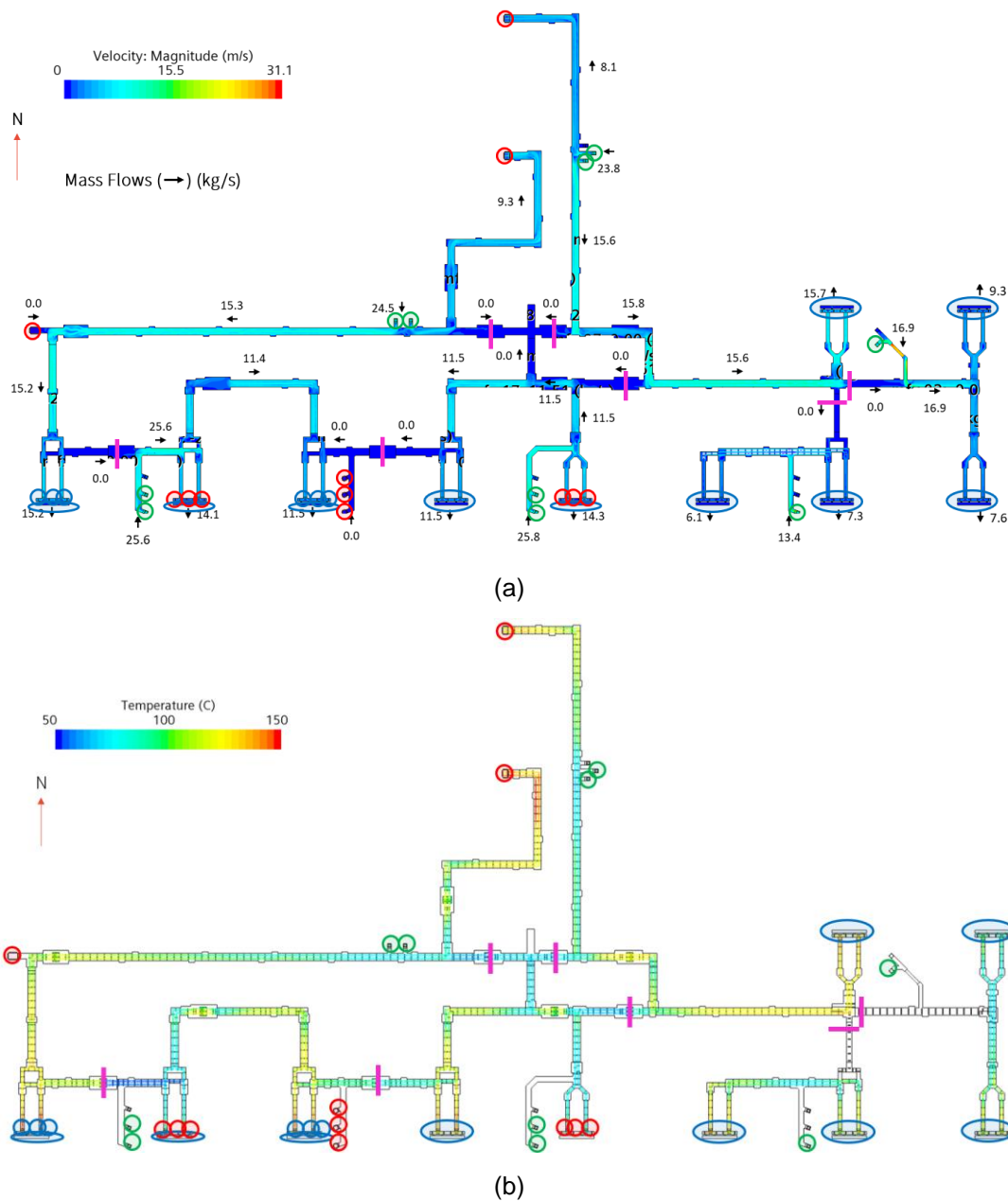


Figure 13. Potline 9 recommended ventilation configuration (a) Air flow velocity and mass flow rate (b) Predicted busbar temperatures. The airflow blockages in open-switch tunnels are indicated with the pink line. Active fans are indicated in green, open gratings are indicated in blue, and closed gratings are indicated in red.

6. Other Crossovers and Tunnels

Many other models of simpler tunnels were simulated, so that all geometrically different tunnels for the whole Jebel Ali plant were represented by these simulations.

6.1 Simple Configurations that Need no Modification

As an example, Figure 14 shows the predicted air flow patterns and busbar temperatures for the Potline 7 North busbar sections.

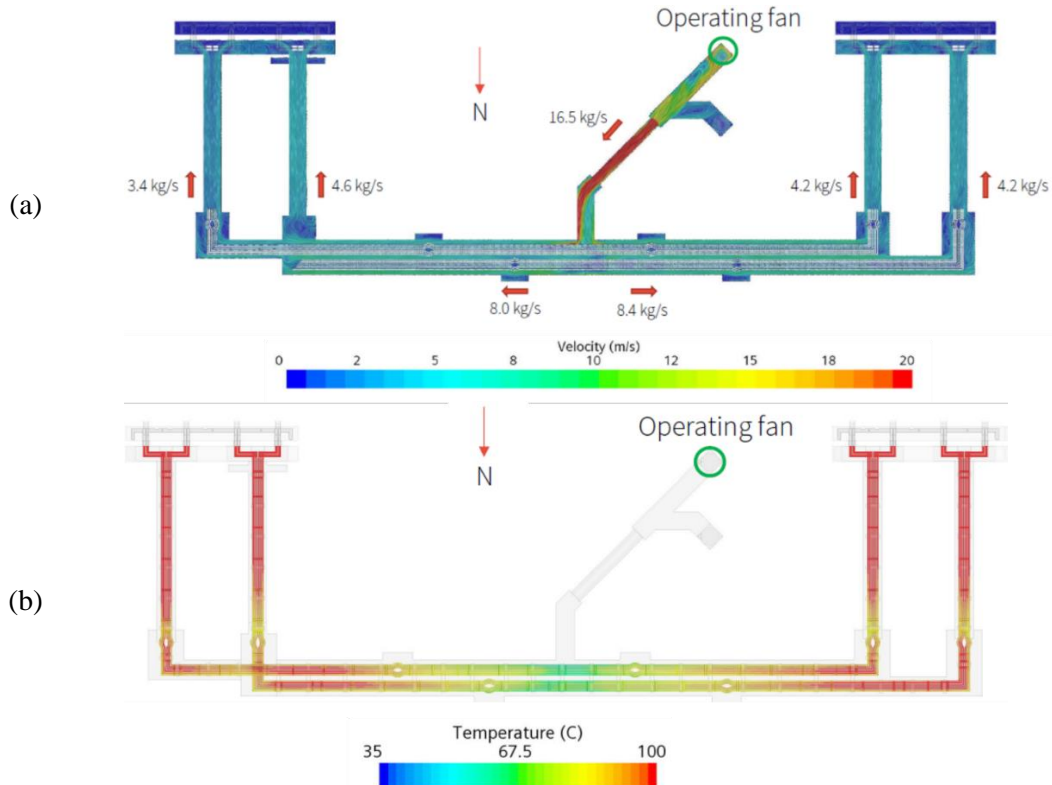


Figure 14. (a) Air flow in the tunnel of Potline 7 North (b) Busbar temperatures in the tunnel of Potline 7B North for ambient temperature of 55 °C. Maximum predicted busbar temperature of 129 °C. All areas shown in red have temperature > 100 °C. Predicted average busbar temperature (hottest bar) 94 °C.

Key takeaways are highlighted as follows:

- There is an approximately uniform flow distribution among busbar sections.
- Volume averaged busbar temperatures are predicted to be 89 °C while operating at an ambient temperature of 50 °C and current of 275 kA.
- Local maximum busbar temperatures are predicted to be 124 °C while operating at an ambient temperature of 50 °C and current of 275 kA.
- Based on the CFD model predictions and key observations, Potline 7 North can operate with acceptable busbar temperatures using the as-designed, single fan (duty/standby) ventilation configuration.

6.2 Simple Configurations that Require Modifications

As an example, Figure 15 shows the existing configuration for Potline 6 between columns 103 and 106. This section has a unique ventilation supply arrangement due to the spatial constraints created by other equipment and civil works in the vicinity. Figure 15 shows the predicted air flow patterns and busbar temperatures for the existing Potline 6 between columns 103 and 106.

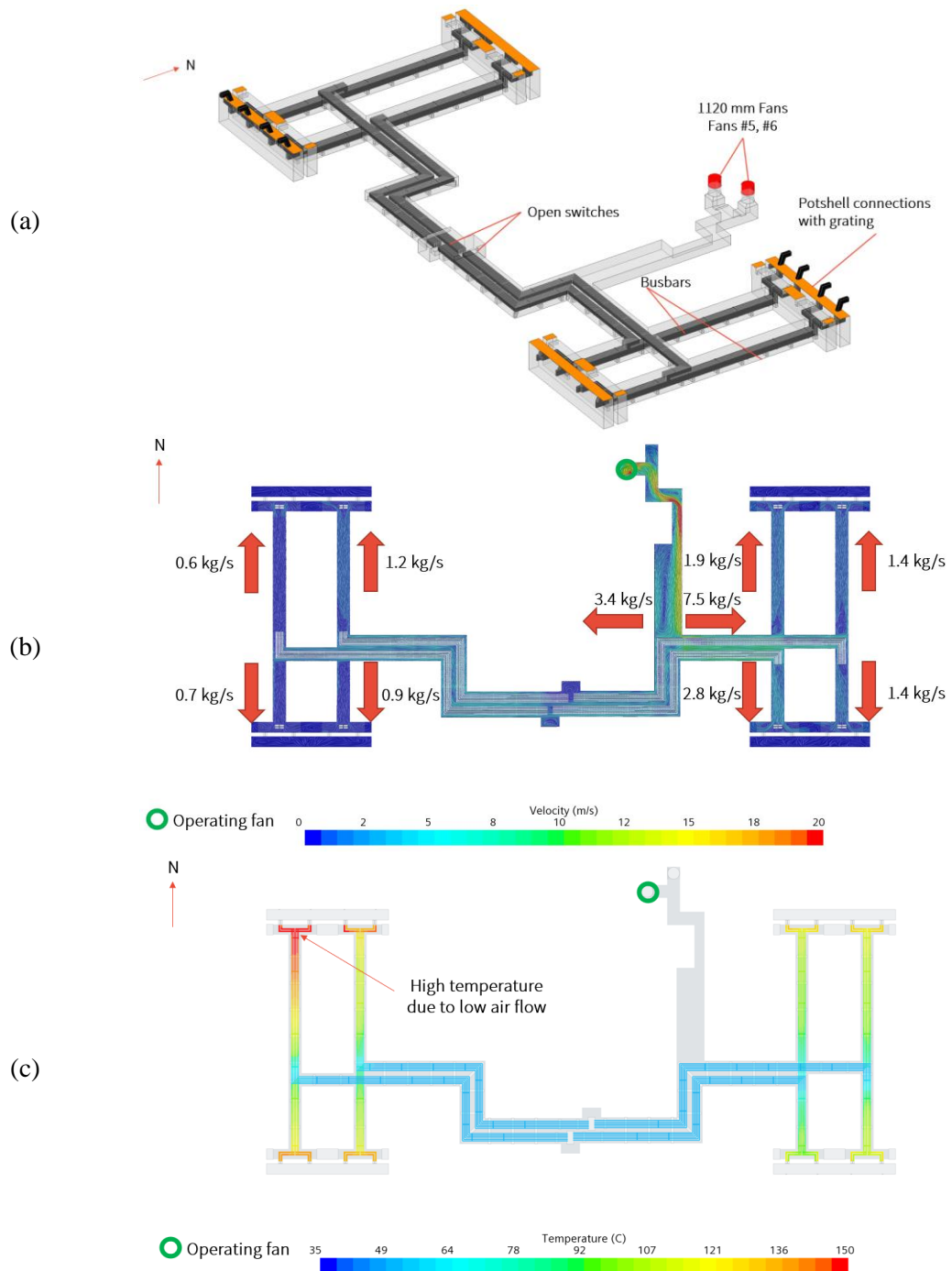


Figure 15. (a) Tunnels in Potline 6 at columns 103-106 (b) air flow velocity and mass flow rate and (c) predicted busbar temperatures.

Key takeaways are highlighted as follows:

- Approximately 70% of the ventilation air moves toward to the eastern pots due to the proximity of the fans to the eastern tunnels.
- The busbar tunnel furthest from the fans receives the least amount of air, and as a result the temperature reaches 161 °C near the pot.

The performance of the recommended ventilation configuration can be seen in Figure 16. The recommended system configuration includes:

- The addition of a pipe that redirects the ventilation supply air to discharge centrally to the switch location.
- Sealing the previous inlet connection to the busbar tunnel.

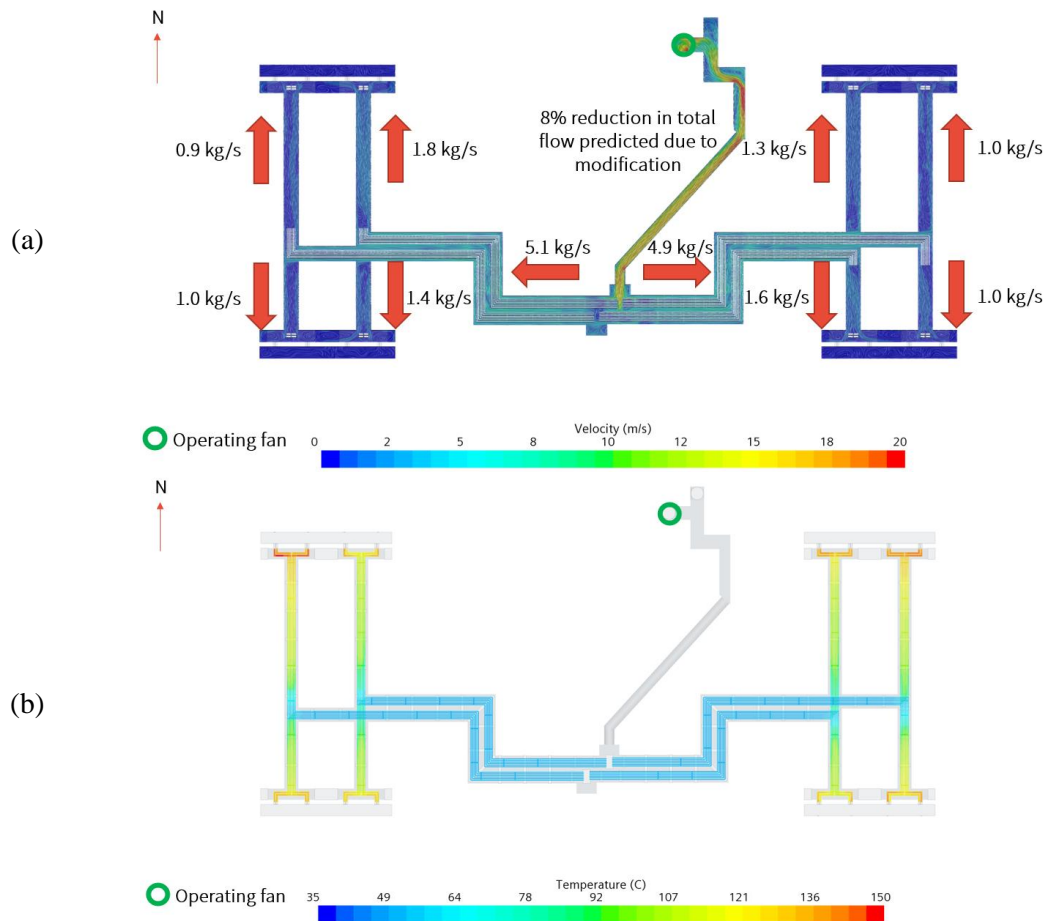


Figure 16. Air flow in tunnels of the optimized Potline 6 at columns 103-106.

Key takeaways are highlighted as follows:

- Flow rates are more evenly distributed between all tunnels.
- Busbar temperatures near the northwestern pot are reduced to acceptable values.
- Busbar temperatures are slightly increased in the eastern tunnels due to a portion of the total flow being redirected toward the western tunnels. All busbar temperatures meet the temperature criteria.

7. Conclusions

CFD was demonstrated as a useful tool in solving large, complex ventilation problems to ensure future current creep results in acceptable busbar and electrical insulation temperatures that are within agreed upon limits.

- Existing ventilation configurations for all potlines were evaluated based on sensibly selected temperature limit criteria. Regions where ventilation is problematic were identified using the CFD model.
- Proposed ventilation configurations to rectify problematic areas were evaluated and the most suitable solution was identified based on ease of implementation and capital cost. Further site measurements were performed on an ongoing basis following implementation of modifications and showed good agreement to CFD predictions.

- Following the CFD modelling outcomes on the project, further engineering scope to implement ventilation configuration changes is ongoing on other potlines.
- Implementation of CFD modelling recommendations will assure adequate busbar cooling in all tunnels and safe operation of the potlines at planned future amperages.

Acknowledgements

The authors wish to acknowledge the support from EGA personnel and Dr Vinko Potocnik who consulted throughout the duration of the project and performed site measurements for model validation. The authors would also like to thank all the colleagues at Hatch who have assisted in this work.

8. References

1. Ghalib Alfalasi, Ahmad Aljawhari and Sudip Ghosh, Busbar integrity in potline tunnels in EGA Jebel Ali smelter, *Proceedings of 40th International Conference of ICSOBA*, Athens, Greece, 10-14 October 2022, Paper AL15, TRAVAUX 51, 1163-1178.