CFD MODELING OF THE FJARDAAL SMELTER POTROOM VENTILATION

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Abstract

The Fjarðaál Smelter Potline buildings are designed to achieve ventilation of heat and fugitive emissions using a system based on natural convection. The design of the Potline buildings is based on Alcoa's Aluminerie Deschambault, located in Deschambault, Québec, Canada. The Fjarðaál Smelter Potline buildings, located adjacent to a fjord in Eastern Iceland, are longer and are situated on a sloping site. The Fjarðaál Project is faced with additional unique factors – local terrain, high wind speed, and multiple approach wind directions – that interact in a complex manner, thus making the performance of the ventilation system difficult to predict.

To help guide the ventilation design, as in similar prior studies [1], [2] and [3], computational fluid dynamics (CFD) modeling was employed. The CFD analysis utilized state-of-the-art capabilities to capture in detail the velocities, temperatures, pressures, and emissions concentrations inside and outside the buildings. The model was validated against smoke tests conducted at the Deschambault smelter.

The model demonstrated that the ventilation system performance is relatively unaffected by the terrain and winds, implying that the claustra wall design is very effective. Pressure gradients can cause localized non-uniform flow patterns in the Potroom, however, these effects are manageable and within the system's performance design envelope.

Introduction

The Fjardaal Smelter Potline buildings (Potrooms) are designed to achieve ventilation of heat and fugitive emissions using a system based on natural convection. The design is generally robust, however its performance will change depending on local environmental conditions – particularly wind speed, wind direction and air temperature. A modeling study was conducted to determine whether or not the current design meets requirements for pot and busbar ventilation, ambient indoor emissions concentrations, air velocities and emissions monitoring equipment sensor locations.

The design of the Potline buildings is based on the existing design used at Alcoa's Aluminerie Deschambault smelter, located in Deschambault Québec, Canada. The Fjarðaál Smelter Potline buildings will be longer and are situated on a sloping site adjacent to a fjord in eastern Iceland. A rendering of the plant in its location is shown in Figure 1.

Beginning with the plot plan for the site layout and Potline buildings, drawings of nearby terrain, detailed drawings of the claustra wall and roof vent, and heat release design data for the pots, an analysis was performed using CFD modeling based on the commercial software program *Fluent 6.2* running on Bechtel computers in the San Francisco and Houston offices. The unstructured mesh was generated from CAD models using the *ICEM-CFD* meshing software program.

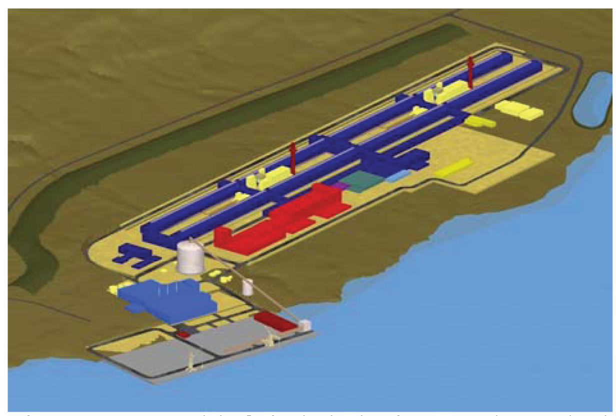

Figure 1. CAD Model of Fjardaal Aluminum Smelter, Iceland

The CFD analysis was conducted to generate sufficient data to address the following objectives:

1. Determine whether sufficient airflow for personnel cooling and ambient air quality is achieved
2. Determine if significant HF release gradients are to be anticipated along the length of the Potroom
3. Determine where emissions monitoring equipment must be located to ensure reliable readings
4. Confirm adequate performance of the roof ventilator
5. Determine if required cooling of the pot and busbar has been achieved
6. Determine whether the terrain is influencing the degree of re-entrainment and intake air velocity profiles
7. Confirm that Potroom ventilation achieves vertical evacuation of fumes with minimal "drifting" along the length of the Potroom
8. Evaluate impact of adding basement panels to restrict inlet airflow

9. Evaluate the Dispersion Modeling assumption that uniform release of HF along the length of the Potroom roof is not too unrealistic.

Validation of the CFD model was undertaken by comparing the computed air flow patterns and temperatures with those measured and observed during several smoke tests conducted at the Deschambault smelter. This validation does not apply to the wind conditions prevailing at Fjardaal; however it does confirm the accuracy of the CFD model to capture both the Potroom flow patterns around the roof and claustra wall and the effects of thermal buoyancy.

Physical Description

The Fjardaal Smelter Potline buildings are designed to achieve ventilation of heat and emissions, such as Hydrogen Fluoride (HF), using a system based on natural convection. The turbulent natural convection present in the Potrooms may be described as: the heat dissipated from the pots generates a buoyancy-driven "chimney", which draws outside air into and through the building side openings, and exhausts the air through a "tulip" type roof ventilator. This design is one of a number of standard designs for Potline buildings.

Thermal buoyancy is virtually impossible to replicate accurately in a scale model due to: the nature of the convection scaling laws, the convection current and thermal differentials in the building, and the high Raleigh number. Since buoyancy is the driver for flow through the building, the heat flux from the pots and the building dimensions must be prescribed as near to full scale as possible. Otherwise it is likely that the flow patterns and flow rates determined by the model would be incorrect.

Annual wind roses were obtained at four meteorological stations from both observations and predictions from CALMET, a diagnostic meteorological model. These wind roses were plotted from a study of the wind directions and speeds over a period of 5 years, from 1998 to 2002. A detailed study of the wind rose data revealed that a few of the wind directions and speeds were predominant. These predominant wind directions are representative in the sense that the plant is subject to these conditions during most of the year. Consequently, these wind directions were chosen for the present CFD analysis, and, as the CFD analysis is a steady state analysis, one wind direction at a particular wind speed was studied as one case.

Based on the above study, and noting the Potrooms longitudinal West-to-East axis, the following wind speeds and directions were chosen as boundary conditions for the CFD analysis of the full model study:

1. East wind at 10.8 m/s and 3 m/s,
2. West wind at 10.8 m/s,
3. West-South-West to East-North-East wind at 8.5 m/s,
4. East-North-East to West-South-West wind at 10.8 m/s,
5. Northwest wind direction at 8.5 m/s, and representative of wind blowing down from the high ground,
6. Calm condition with an East wind of 0.3 m/s.

Analysis Methodology

The CFD model was fully three-dimensional and incorporated several key factors likely to affect the performance of the ventilation system, e.g., wind speed, wind direction, thermal buoyancy, local terrain and all the Potline design features – side-by-side pot arrangement, a tulip-shaped roof ventilator, floor grills between the pots, and claustra wall details.

The local terrain surrounding the plant was modeled, as well as nearby structures of significant size. The model was configured to allow for closing a portion of the basement panels – to study the effect of closing a number of basement panels during the winter months.

The following assumptions were made when using the CFD model as a ventilation analysis tool for the study of air movement both within and external to the Fjarðaál Potline Buildings:

- The model assumed steady state wind direction and velocity for each case. The ambient temperature was assumed to be 2 °C and the temperature rise was calculated as a delta rise from ambient.
- No other sources of heat other than heat dissipated from the pots and busbar were taken into account for the calculation of roof vent temperature rise and the overall quantity of heat in the pot room building.
- The floor grills were taken into account; however gaps in the floor between concrete slabs were not modeled.
- Based on the information provided, a certain amount of heat (100 kW) was assumed to re-enter the pots (sucked into the pot gas exhaust system through small gaps between the pot hoods).
- For turbulent natural convection, gravity was taken into account through buoyancy, while the density of the air was computed based on the physical properties of air as an incompressible Ideal Gas, i.e., the Boussinesq approximation was used.
- Turbulence models were selected with care. A turbulence model that gave the most accurate results was taken as the norm for all calculations. This model was the k-w model with *Fluent 6.2* default parameters.
- A fully unstructured hexahedral grid was taken as the best approach to model complicated structures such as the roof vent and terrain.
- Considering the complex geometries of the roof vents, floor grills and claustra walls, each of these was modeled as a sub-model. For each of these items, the individual pressure drop values were compared against available test data. Subsequently, a flow *versus* pressure drop curve based on the actual design was generated. Then, a lumped parameter "porous media" input that describes the permeability of the model was used in the CFD calculation. Finally, in the case of the claustra wall, a directional coefficient was used. .
- Concentration profiles of pot emissions such as Hydrogen Fluoride (HF) were modeled either as line sources or inlets emanating from the sides, ends or the top of the pots.

The heat dissipated from the pots was based on a prescribed heat flux condition. Based on measurements and heat balance calculations, as shown in Figure 2, the heat flux values were prescribed to various surfaces on the pot.

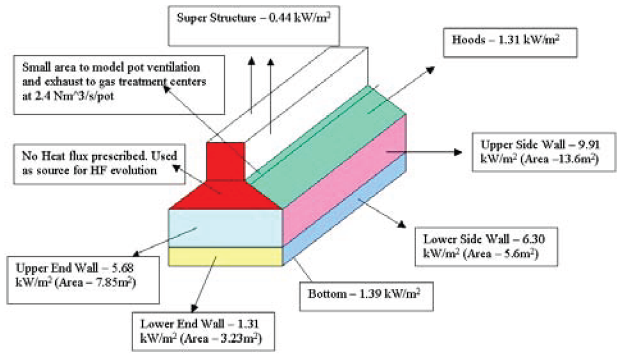

Figure 2. Prescribed pot surface heat flux used in CFD model

Simulation of the different Potroom physical phenomena requires varying length scales. Near the pot, to effectively capture heat dissipation effects, the grid needed to be of the order of a millimeter. A coarser grid was used to accommodate convection in the pot room. The terrain included in the model domain extends at least two kilometers in all directions. To conserve the total mesh size within manageable limits, grids with large control volumes, of the order of 1 m^3, were required. With such variation in length scales it was not always easy to maintain an adequate grid with grid element aspect ratios within acceptable limits.

The final model included the two Potroom buildings with 336 pots and all the surrounding terrain, buildings and silos. Several models were considered and were subsequently used as validation models. The full model mesh was fully hexahedral and unstructured. This allowed for the dense grid needed to accurately capture the heat transfer from the pots. The approach was equally effective with the use of prismatic elements in a tetrahedral far field – even though the number of finite volumes was likely to be much larger in number. The most effective use of the computer resources was obtained by limiting the total mesh size, using hexahedral elements with increasing geometric expansion further away from the wall. Figure 3 shows a model of a single 42-Potoom segment with surrounding terrain.

The full model – 336 pots in two buildings, terrain, roof vents, silos and surrounding buildings – consisted of 2.8-million hexahedral control volumes.

The basement panels were modeled as thin walls such that portions could be changed into walls, thus simulating open, closed and partially open basement panels. Opening and closing basement panels effectively regulates the air entering the building and was used to study the effects of emissions spread at worker level under conditions of reduced airflow entry into the building, i.e., when basement panels are closed. Figure 4 shows a section of the model configured with the basement panels 40% open.

Model Validation

The detail design for the new Icelandic smelter is not completely finalized. However it is expected that the Potroom design will be similar to the Potroom buildings at the Alcoa plant at Deschambault, Québec. Hence, the main focus of the validation was to study the thermal buoyancy model employed by the CFD analysis and to compare the flow patterns and vectors with those observed and photographed during the smoke test at Deschambault.

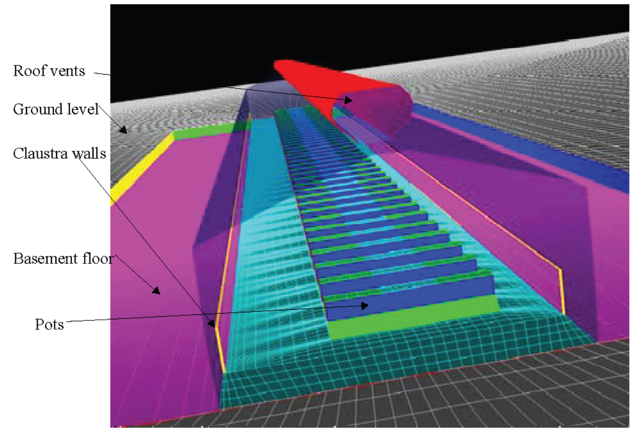

Figure 3. Surface grid for section of Potline building CFD model

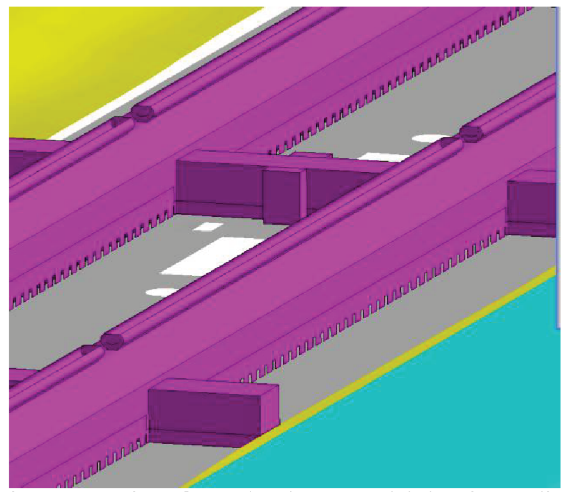

Figure 4. Section of completed CFD model showing Potline building sections with partially closed basement panels.

The smoke test was carried out on the 27th of April 2004 at 4 A.M. Simultaneously, several velocity and temperature measurements, obtained using hand-held thermal anemometers, rotating vane anemometers and thermocouples were obtained. The test locations were chosen such that the influence of localized changes in the flow direction and magnitude could be qualified. Velocity and temperature measurements were made from the walkway near the roof vent, and at the floor grill, basement inlets and claustra wall. Additionally, data from the meteorological station local to the plant was obtained.

The following benchmark comparisons were chosen for the validation of both the CFD software set-up and chosen method of utilization, and the Potroom model results:

- Pictures and videos of the smoke test against velocity vectors at corresponding sections in the CFD model;
- Velocities obtained using both rotating vane and thermal anemometers;
- Temperatures obtained using hand-held thermocouples;
- Temperatures and velocities measured at the roof monitor;
- Heat and mass balances inside the Potroom building, the heat balance being obtained from pot external surfaces measured heat flux.

The specific models that were chosen for validation studies included: three dimensional models of two pots with periodic boundary conditions, a ten pot model, and a 42-pot single building model. All the models included: claustra wall and floor grills, both with porous media inputs from the corresponding sub-models; pot ventilation and exhaust at a nominal flow rate of 2.4 Nm^3/s per pot; and the exact geometry of the roof vent with dampers in the open position.

The Potroom ventilation pattern is driven by mixed convection effects, and, with a mean pot shell temperature of ~200 °C, strong buoyancy driven currents dominate the airflow. The Grashof number evaluated as approximately 1.0E+10, consequently, the flow is either inherently unstable or transient in nature. Thus, under assumed steady state conditions, a robust turbulence model is required for reasonable solution convergence. Several turbulence models were studied during the validation phase. Of significance were the k-ε turbulence model, the Reynolds Stress Model (RSM) and the k-ω model with the Shear Stress Transport (SST) enhanced option. By noting the convergence trends, it was observed that the k-w model performed very robustly and produced the best solution in the shortest time.

The first part of the validation study was to compare the flow field obtained from the analysis with the smoke test conducted at Deschambault. The smoke test flow patterns observed were videotaped. On the wide aisle side, it was observed that the smoke entering the claustra wall travels at least two thirds of the pot length, parallel to the ground and the pot, before buoyancy effects from the hot pots and the flow from the narrow aisle force the flow to move upwards. However, the flow entering the claustra wall on the narrow aisle side travels only a small distance along the pots before being driven upwards. Subsequently, the upward moving hot air crosses the roof vent, hence taking a curved path before encountering the roof vent. An example of this can be observed from the photograph shown in Figure 5.

The CFD analysis produced the flow patterns shown in Figure 6 – where it may be noted that the flow patterns are very similar to the observations from the smoke test. Fresh air from outside is pulled into the Potroom building by the hot pots and enters the Potroom through the floor grills and the claustra wall on both sides of the building. The main "flow through" air follows an arc, and then exits through the roof monitors. A secondary flow, driven by the natural convection, forms a recirculating flow which drops back down to the top of the claustra wall. The fresh incoming air flow has more energy than the recirculating flow and does not allow the recirculating flow to reach floor level. Hence, qualitatively we were able to demonstrate that the flow patterns obtained from the smoke test are reproduced quite accurately by the CFD analysis. As shown in Figure 7, temperatures in the Potroom calculated by the CFD model also showed good agreement with the measured values, particularly at the roof vent intake; where the air was observed to have increased in temperature by ~20 °C.

An additional example of temperatures in the Potroom calculated by the full-scale CFD model is shown in Figure 8, which shows temperature cross-sections for a 10 m/s East wind for the basement 100% open (summer) case.

Figure 5. Still from videotape of smoke test conducted at Deschambault

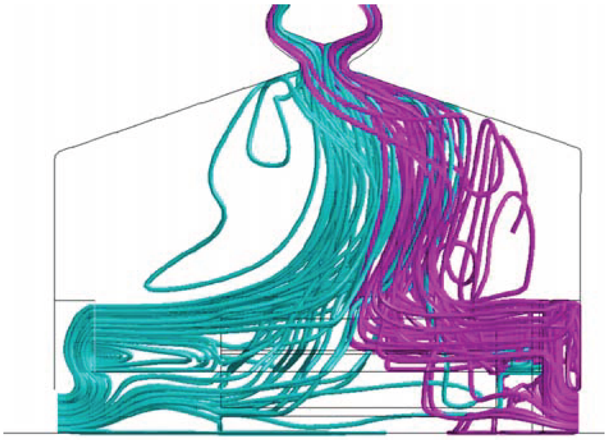
Figure 6. Flow streaklines through a cross-section of the Potroom generated from the CFD analysis

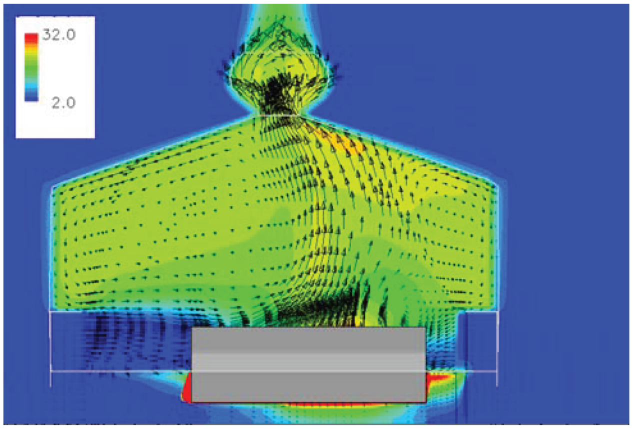

Figure 7. Ambient temperature (°C) through a cross-section of the Potroom generated from the CFD analysis

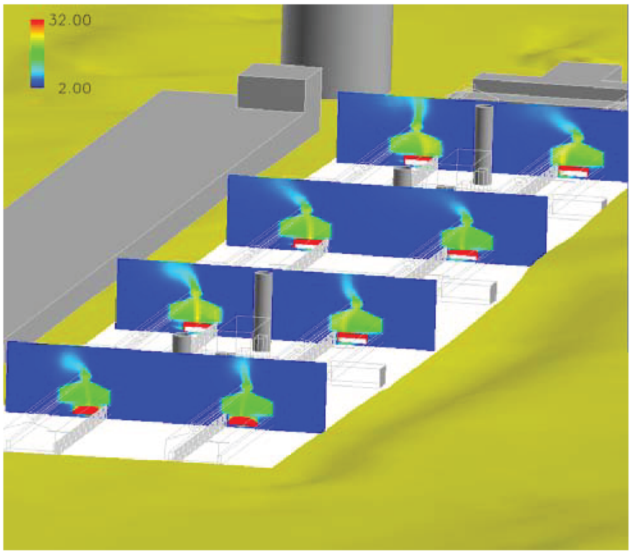

Figure 8. Ambient temperature (°C) through several cross-section of the Potroom generated from full-scale CFD analysis.

Key Findings

The CFD analysis showed that flow patterns around the Potline buildings are affected by the local terrain, wind direction, and nearby buildings. Lower wind speeds (i.e., calm conditions) show results typical for Potline buildings sited at low-wind locations. In Figure 9, an example of the velocity patterns around the buildings is shown for the Northwest (NW) wind. Several areas of low velocity – referred to as "dead zones" – are noted, both between the Potrooms and in the wake of the buildings. In particular there are pronounced dead zones downwind of the passageways that extend sideways from the Potrooms. As shown in Figure 10, these areas tend to produce a slight pressure buildup on the windward side and a negative pressure on the leeward side, thus creating local regions of pressure gradient that can cause the internal ambient flow to be either pushed away from or pulled toward those areas. Such effects increase with increasing wind speed, however were not found to be significant in the final performance analysis.

The CFD analysis confirmed that the Fjardaal Potroom ventilation performance is adequate for all expected wind conditions. The claustra wall design does an excellent job both of dampening the effects of outside winds on the internal Potroom environment, and of drawing in sufficient amounts of fresh air to prevent HF and heat build-up in the main worker areas. The Potroom design generally accommodates the secondary flows while preventing such recirculating air from penetrating the worker level in the wide aisles. Additionally, vertical thrust of the plume over the pots is facilitated by sufficient Potroom height, roof pitch, and roof vent dimensions. The primary findings from the analysis are summarized below:

- As shown in Figure 11, the standard deviation of the roof vent exhaust HF concentration is fairly low for all wind conditions without basement panels and moderate for East and West wind conditions with basement panels. This result indicates that the variation in exhaust concentration is reasonably stable along the Potroom length.
- As shown in Figure 12, temperature levels in the Potroom at medium and high elevations are as expected (consistent with measured data from Deschambault) and reasonably uniform over the range of wind conditions evaluated. This implies that heat removal from the pots is effectively accomplished under all wind conditions.
- Velocity magnitudes in the Potroom are as expected with stronger inflow on wider aisle, demonstrate some cross-flow recirculation, and are dominated by the central vertical plume. This is consistent with observations from the Deschambault smoke tests.
- HF concentrations are acceptable in the Potroom worker aisles and outside the Potroom buildings. For all high wind speeds without basement panels, the accumulated HF in the aisles is not significantly higher than the low wind speed case. It was found that the accumulated HF in the worker aisles can increase by 50% to 100% when the basement panels are closed.
- As described above, the flow patterns in the Potroom can be affected by local external pressure gradients. Specifically , as shown in Figure 13, it was found that for prevailing winds parallel to the buildings some "drift" may occur in some areas, e.g., near the roof.
- Higher wind speeds do not appear to increase the velocity of the "cross-flow" patterns near the roof; i.e., patterns that are induced by the asymmetric air flow in the Potroom. The cross-flow velocities are similar for low and high wind speeds, both with or without basement panels. Consequently, the procedure for installing emissions monitoring equipment should not be affected.
- Re-entrainment of roof vent exhaust is not a concern. Some minor "dead zones" exist between the buildings; however HF buildup in these areas is negligible.

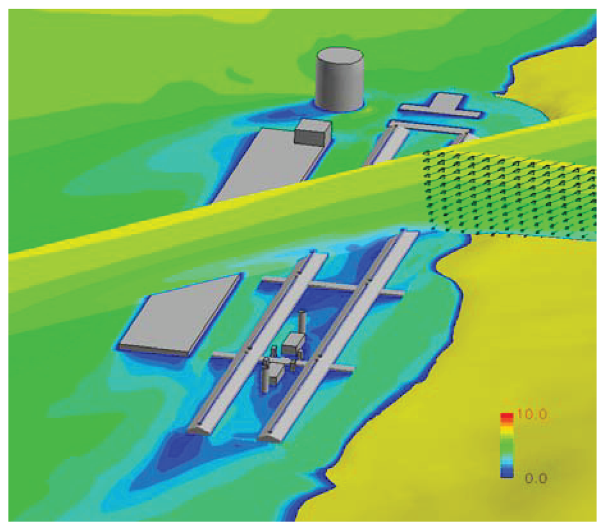

Figure 9. Velocity contours (m/s) around Potline buildings at an elevation 12 meters above grade and cross-section through terrain for Northwest wind case.

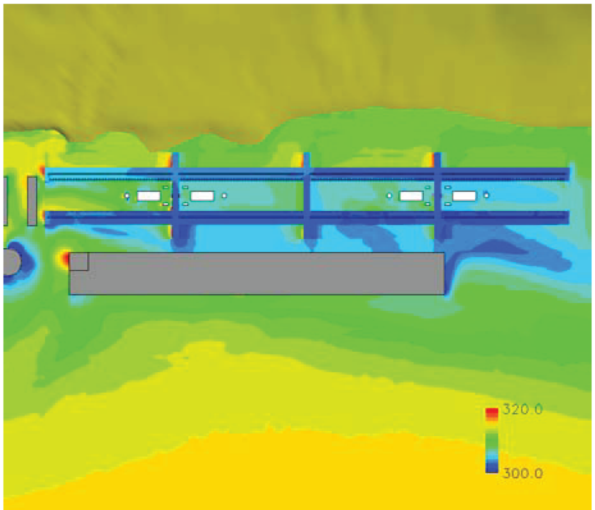

Figure 10. Pressure contours (Pa) around Potline buildings at elevation 12 meters above grade for Northwest wind case.

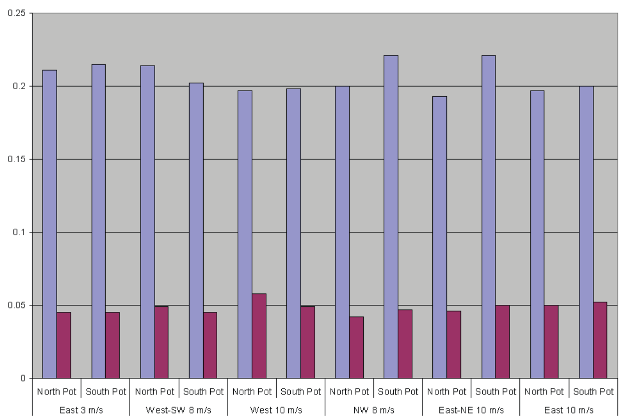

Figure 11. HF Concentration (average (blue) and standard deviation (red)) through roof vent (mg/m^3) calculated from CFD analysis for all cases without basement panels

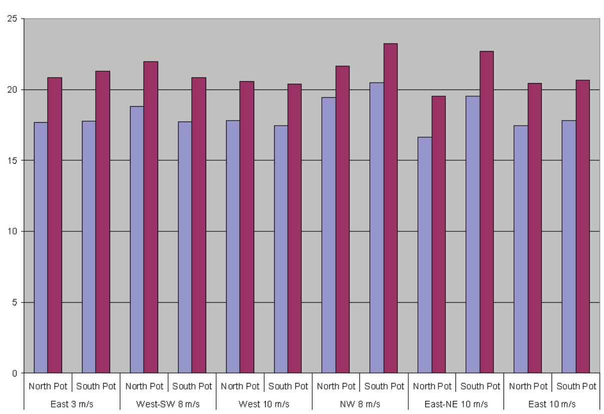

Figure 12. Potroom temperature just above hoods (blue) and at roof vent intake (red) calculated from CFD analysis for all cases without basement panels

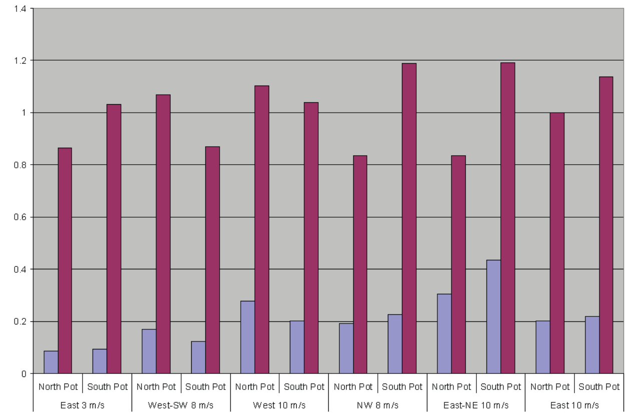

Figure 13. Potroom air velocity in axial (drift) direction (blue) and vertical (thrust) direction (red) below roof vent intake calculated from CFD analysis for all cases without basement panels

Conclusions

The CFD analysis confirmed that the performance of the Fjardaal Potroom ventilation is adequate for all expected wind conditions. Most importantly, under normal operating conditions, it was shown that workers both inside and outside the Potroom buildings will not be exposed to unacceptable HF concentrations. Equally important, it was shown that the low level HF release through the roof vent does not vary greatly along the length of the Potroom, thus an assumed uniform release of HF along the Potroom roof is not too unrealistic an assumption for Dispersion Modeling.

The CFD modeling techniques employed state-of-the-art software programs to account for detailed features of the Potrooms, pots, and outside terrain. For Potroom internal flow conditions, the model was successfully validated against measurements taken from smoke tests at Deschambault. The impact of outside conditions such as wind and terrain could not be explicitly validated since the Fjardaal plant is not yet built. However, the impact of these outside conditions is judged to have been reproduced reasonably well to provide sufficient capability for an evaluation of the Fjardaal Potroom ventilation performance and a verification of the ventilation design.

Acknowledgements

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We would like to recognize Aluminium Pechiney, the original Technology Supplier of the Ventilation system at Deschambault Smelter, for their permission to publish this paper.

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