ESTIMATION OF THE GAS EXHAUST RATE REQUIRED ON AN ALUMINIUM REDUCTION CELL DURING START-UP USING TASCflow3D

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ABSTRACT

During the start-up of an aluminium reduction cell of the VS Söderberg type, hydrocarbon and fluoride fumes are emitted into the cellroom building. Such fumes are undesirable because they contaminate the working atmosphere. This paper presents a study on the capture of these fumes by a gas collection system. The appropriate gas exhaust rate was determined by a study of the air flow near the cell.

This air flow is caused by turbulent natural convection due to the hot surfaces of some of the cell components and also due to partial combustion of the hydrocarbons. The air flow was calculated by CFD modelling using the TASCflow3D software of ASC. The gas exhaust rate required for the capture of the hydrocarbon and fluoride fumes was estimated at 21,000 SCFM.

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THE START-UP OPERATION OF A VS SÖDERBERG CELL

Aluminium is produced by a fused salt process called the Hall-Héroult process, which was invented in 1886 [1,2]. Industrially, the process has been implemented by three distinct cell technologies: cells with prebaked anodes, HS Söderberg cells with horizontal steel studs and VS Söderberg cells with vertical steel studs. The technology of the VS Söderberg cell is well documented [3].

The start-up of a VS Söderberg cell follows a number of well defined steps, which last several days. The space between the anode and the cathode is preheated by several burners using natural gas. When the target temperature is reached, the space between the electrodes is reduced from 10" to 1" and a number of crucibles of hot molten cryolite are added to the cell in order to achieve electrical contact. The current is then switched through the cell. After about 4 hours, more hot molten cryolite is added to the cell and the anode is raised by about 7-8". After about 16 hours molten aluminium is added to the cell. The cell voltage is kept higher than normal, in order to maintain the temperature of the molten cryolite at about 1050°C during the start-up.

During the preheating phase using the natural gas burners, the fume emission from the cell is small because the available quantity of fluoride is limited and the released volatile hydrocarbons are consumed in the burner flames. The large volume of monolithic mix at the sidewall of the cell is not heated during this phase because of a temporary insulating curtain around the edge of the anode.

After the removal of the burners and the curtains and shortly after the addition of the molten cryolite, the monolithic mix at the sidewall is baked thereby releasing the volatile hydrocarbons. Some of these hydrocarbons are ignited by the molten cryolite and burn partially in the air. The hot molten cryolite also creates the fluoride emissions.

After about 24 hours the monolithic mix at the sidewall is baked out and the emissions are limited to the fluorides. The fluoride emissions are significantly reduced after the temperature of the molten cryolite is reduced to the normal operating temperature and a stable crust has been formed over the entire surface of the molten cryolite. Most of the emissions from the cell are then captured by a gas skirt around the anode. The gas skirt is exhausted from both ends of the cell at about 500 SCFM per cell.

REDUCTION OF EMISSIONS DURING START-UP

Many emissions are being generated during the initial hours of the start-up of the cell. A number of options are available to reduce these emissions:

(1) bake the cathode using specialised equipment

(2) replace the monolithic mix by prebaked blocks

(3) install a hood with ducts and a scrubber system

The first two options would address the hydrocarbon emission problem, but not the fluoride emission problem during start-up. Hence the present study focussed on the third option. A completely closed hood around the cell was not chosen because the high temperatures under the hood could damage some structural parts of the cell and because the operators need to have frequent access to the cell during the start-up. An open hood around the cell was therefore chosen. The VS Söderberg cell with an experimental hood is shown in Figure 1.

The required gas exhaust rate at the hood was estimated by flow calculations using the finite volume CFD code TASCflow3D of Advanced Scientific Computing (ASC). Two cases were studied: the capture of the hydrocarbon and fluoride fumes and the capture of the fluoride fumes.

MODEL GEOMETRY AND MODEL ASSUMPTIONS

The VS Söderberg cell is about 30 feet long and 15 feet wide. In practice, the flow domain near the cell is open, but for the purpose of the simulation the domain was closed by an enclosure attached to the side of the Söderberg cell. The inlet opening to the enclosure was large in order to maintain a low flow velocity near the cell. The outlet opening was at the top of the small hood. Although there are some three dimensional flow effects, a two dimensional model was considered to be adequate for the present purpose. The model represented a vertical slice at full size near the side of the cell.

Following the recommendation of ASC, the depth of the model was represented by two layers and a symmetry boundary condition was applied to the two end planes of the two layers. The problem was thus defined as a pseudo-2D problem [4]. The 2D flow domain was divided using a structured mesh and the multi-block feature. The model geometry is shown in Figure 2. About 3800 elements were used for the model.

Due to the hot surfaces the flow near the cell is induced by turbulent natural convection. Cool air at low velocity is sucked towards the cell. The effect of turbulence was modelled by increasing the laminar viscosity and the thermal conductivity by a factor of 20. Although the k-ε model of turbulence was available in TASflow3D, previous work [5] has shown that the use of the k-ε model gives no better results than the enhanced viscosity model. The Reynolds Flux turbulence model is best suited to simulate such a mixed flow system, but it was not available in TASCflow3D.

The solution was obtained by solving the Navier-Stokes and the energy equation simultaneously and activating the buoyant flow feature in TASCflow3D.

The time-averaged Navier-Stokes equation is usually written:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g} \quad (1)$$

The time-averaged energy equation is:

$$\rho\, Cp \frac{\partial T}{\partial t} + \rho\, Cp (\vec{u} \cdot \nabla) T = k \nabla^2 T \quad (2)$$

For most of the surfaces of the flow domain, the velocities and heat fluxes were set to zero. A velocity and a temperature of 20°C were specified at the inlet opening. Zero pressure was specified at the outlet opening. The two flow cases were defined by particular boundary conditions on the hot surfaces of the flow domain.

The simulation runs were made by trial and error by specifying a velocity at the inlet opening. This velocity was decreased progressively until warm air started to spill from the hood and accumulated in the space at the top of the enclosure. This spill-over was unstable and varied with successive iterations. As the exhaust rate was decreased, the frequency of spill-overs from the hood was increased. The minimum required exhaust rate was thus the inlet flow which prevented any spill-over.

CAPTURE OF HYDROCARBON AND FLUORIDE FUMES

After molten cryolite at 1050°C has been added to the preheated Söderberg cell, the sidewalls of the cell are baked. The released volatile hydrocarbons ignite spontaneously and form plumes of hot combustion products, which still contain some hydrocarbon fumes. At the same time the molten cryolite emits fluoride fumes and together with other hot surfaces induce a natural convection flow adjacent to the cell.

The natural convection flow was modelled by specifying a heat flux of 10,800 W/m2 on a number of surfaces such as the molten cryolite, the part of the anode below the gas skirt, all the surfaces of the gas skirt and the sidewall lining including both the inclined and vertical parts.

The plume flow of the combustion products was modeled by a hot gas inlet at a velocity of 1.3 m/s and a temperature of 1944°C. The energy content of the hot gas inlet was the same as the energy released by the combustion products. This gas inlet was placed on the inclined part of the sidewall. The additional mass flow due to this inlet was about 5 %.

The trial and error procedure indicated that a minimum flow of 288 SCFM would capture all the hot gases in the model. The results of the velocity and temperature profiles are shown in Figure 3 for this condition. The velocity profile already shows a very small recirculating loop underneath the hood.

Applying these results to the cell would indicate that the gas exhaust rate should be at least 18,000 SCFM in order to capture all the hot air and hydrocarbon and fluoride fumes.

CAPTURE OF FLUORIDE FUMES

After the sidewall of a Söderberg cell is baked out and when molten cryolite is maintained at a temperature of 1050°C without forming a crust cover around the cell, a natural convection flow of hot air is set up around the sides of the anode. This flow carries a substantial amount of fluoride, which should be captured. The natural convection flow was modelled by specifying a heat flux of 10,800 W/m2 on a number of surfaces such as the molten cryolite, the lower part of the anode below the gas skirt, all the surfaces of the gas skirt and the sidewall lining including both the inclined and vertical parts.

The trial and error procedure indicated that a minimum flow of 108 SCFM would capture all the hot gases in the model. For this condition the results of the velocity and temperature profiles are shown in Figure 4. The velocity profile already shows a small recirculating loop underneath the hood.

Applying these results to the cell would indicate that the gas exhaust rate should be at least 7,100 SCFM in order to capture all the hot air and fluoride fumes .

CONCLUSION

The gas exhaust rate requirement changes during the start-up operation. During the first 24 hours, a minimum exhaust of about 18,000 SCFM per cell is required. A safety margin is usually applied in order to compensate for cross-drafts near open hoods. When allowance is made for a safety margin, then the actual exhaust rate should be about 21,000 SCFM for the capture of the hydrocarbon and fluoride fumes. After the bake-out period, the minimum gas exhaust rate is only 7,100 SCFM. The actual gas exhaust rate should be about 8,500 SCFM for the capture of the fluoride fumes.

ASC has implemented a combustion model into TASCflow3D, but enough computer memory was not available when this study was made. Hence the plumes of the combustion products were modelled by a flow of hot gas from a boundary. It might be more accurate to use the combustion model instead of the hot gas boundary condition.

The present two-dimensional study could lead to a possible under-estimation of the required gas exhaust rate, because the horizontal cold flow interfered with the vertical hot flow as noted by the oscillatory nature of the flow near the minimum exhaust rate. Further testing using a fully 3D model would avoid this interference problem. However, such testing could not be done due to limited computer resources.

ACKNOWLEDGEMENT

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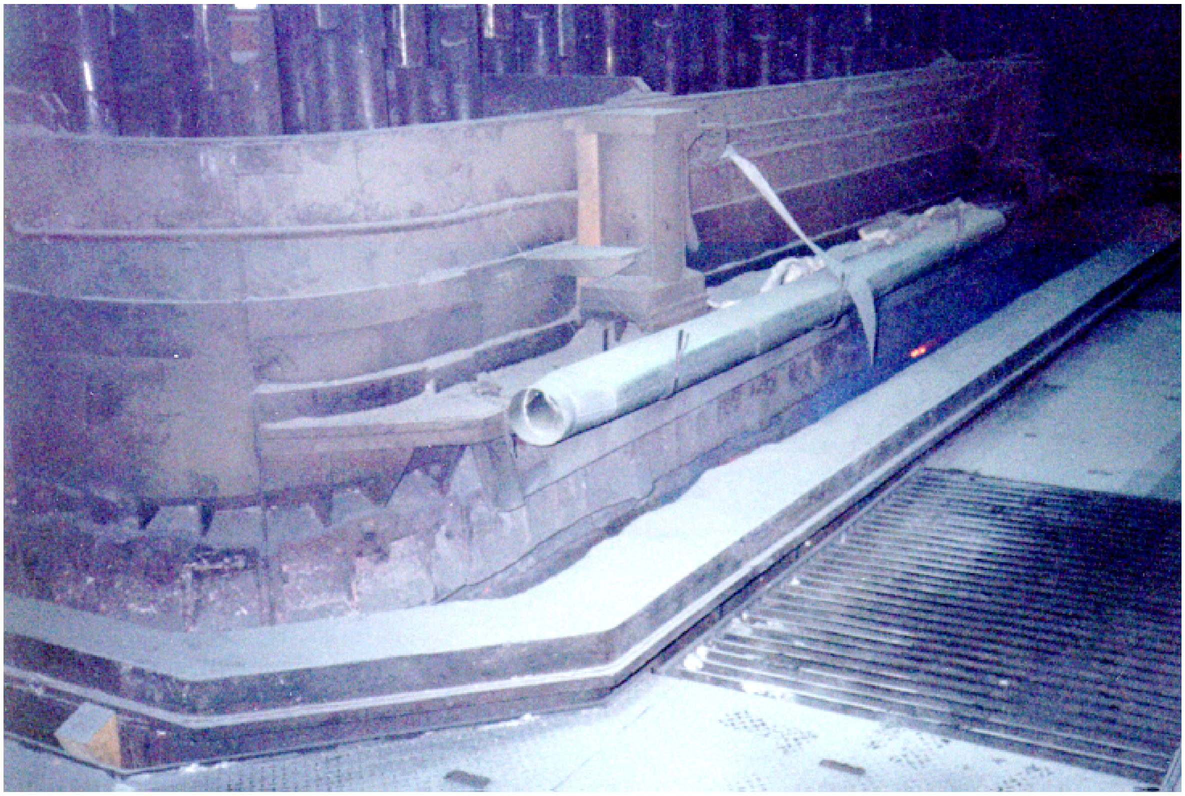

Figure 1: VS Söderberg Cell with Experimental Hood

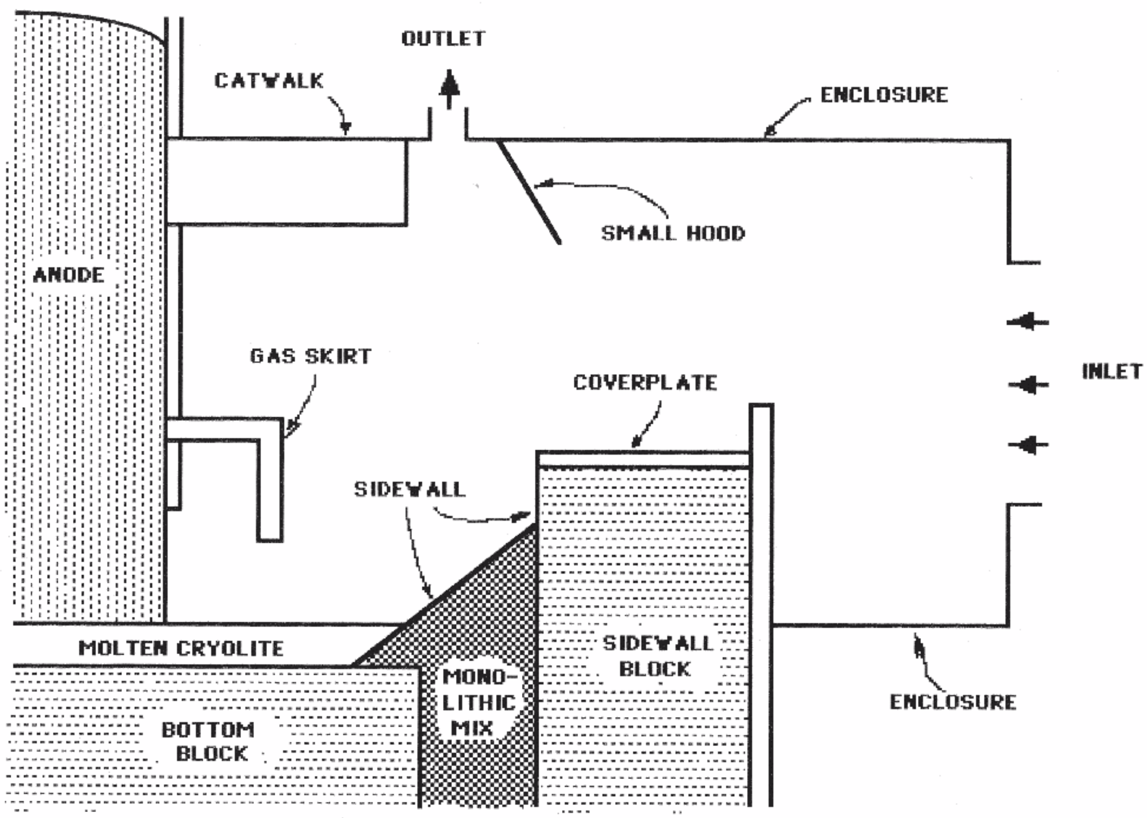

Figure 2: Model Geometry

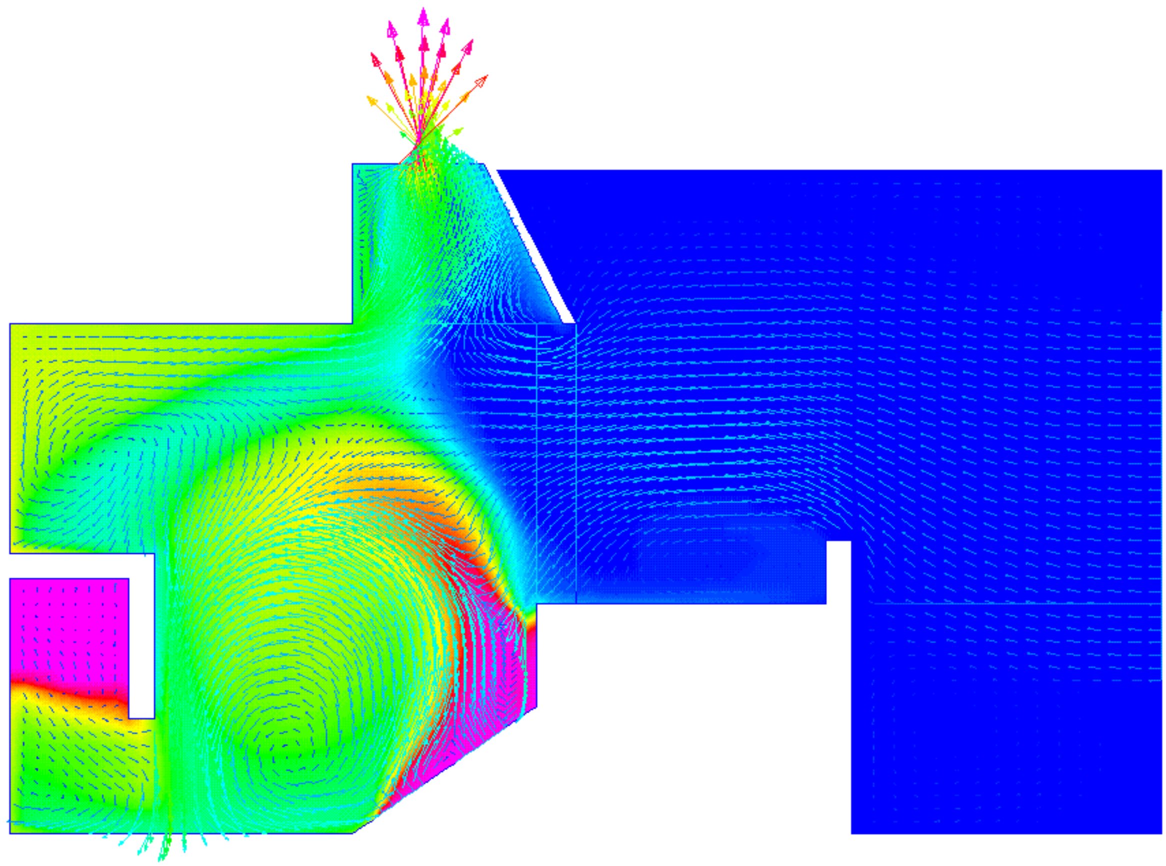

Figure 3: Velocity and Temperature Profiles at 288 SCFM

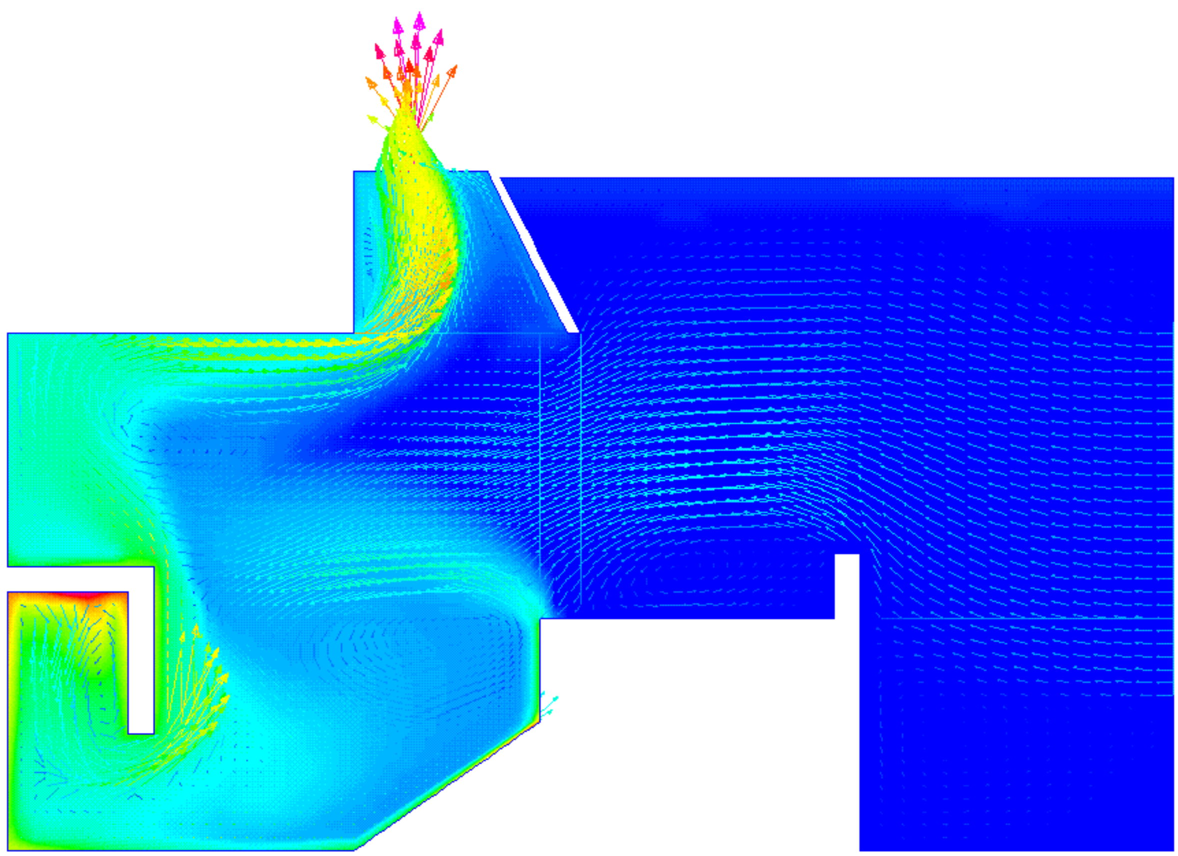

Figure 4: Velocity and Temperature Profiles at 108 SCFM