Stabilization of supersonic vent gas from autoclave pressure oxidation

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The ability to control the velocity distribution of a fluid flow is a fundamental problem in many industrial applications of fluid engineering. This problem is compounded in hydrometallurgy because the process fluid is typically two phase, as well as corrosive and abrasive in nature. This paper investigates the use of a perforated plate to achieve a stable and uniform flow field downstream of a shock wave in a blast shroud entering a quench vessel from pressure oxidation autoclave. Fluid mechanics analysis has been used to provide insight into the proper diffuser geometry in order to produce an adequate flow field both downstream and upstream of the plate. The addition of a perforated plate is found to reduce the maximum velocity entering the quench vessel to one-fifth of the original velocity, mitigating the risk of wear on the vessel bottom and excessive splashing of the water pool. The analysis also indicates that both the open area and the number of holes in the plate are important parameters in stabilizing upstream gas flow and minimizing flow separation downstream of the shock.

The mechanical design of the shroud and perforated plate addresses concerns around thermal expansion, natural vibration frequency, strength limitations of nitride-bonded silicon carbide, and the erosive environment created by supersonic flow with entrained particulate. Prudent mechanical design is required to ensure a durable long lasting perforated plate, which will reduce wear on pressure letdown equipment. Placing the perforated plate in a metal spacer ring allows it to float between top and bottom supporting flanges. Strict control of fabrication tolerance is required to maintain clearance between the plate, spacer ring, and other ceramic components, limiting stresses induced by thermal expansion to 0.5 MPa. Soft packing and gasket materials, which are susceptible to erosion, are isolated from the flow by a tongue-and-groove joint between the ceramic shroud liner and perforated plate.

Introduction

This paper presents the results of computational fluid dynamics (CFD) and finite element analyses (FEA) in the design of a novel blast shroud configuration using a perforated plate, as it applies to pressure letdown of vent gas from a pressure oxidation process. The blast shroud
is designed to let down the pressure of a vent gas discharging from an autoclave at 4100 kPa(g) into a quench vessel at 14.7 kPa(g). Figure 1 shows an example of a typical autoclave circuit, where slurry is processed in the autoclave at elevated temperature and pressure using steam and oxygen gas.

High-pressure vent gas composed mainly of steam and oxygen, but also containing slurry particles, is vented from the autoclave. The quench vessel condenses the steam and removes slurry carryover from the vent gas before final cleaning in a cyclonic separator, which then vents to the atmosphere.

A shock wave is expected within the blast shroud because of the large pressure drop. Therefore, the design must ensure that the shock wave is stable in order to prevent the risk of flow-induced vibrations on the blast shroud structure. Moreover, the design must also ensure that the velocities entering the quench vessel are minimized to prevent wear on the bottom of the vessel or excessive splashing of the water pool. The addition of the perforated plate is proposed to address both the shock stability and improve flow uniformity entering the quench vessel.

**CFD analysis result and discussion**

The geometry of the blast shroud is shown in Figure 2.

The gas, which is primarily composed of steam, passes through a conical upper section before reaching the perforated plate. The geometry of the conical section is defined based on an internal angle of $\alpha$ and a length of $L_1$. The second part of the blast shroud, downstream of the cone and perforated plate, is a cylinder with a diameter of $D$ and a length of $L_2$.

The boundary conditions used for the CFD model of the blast shroud are shown in Figure 2. The boundary conditions are set as the mass flow at the inlet and a specified gauge pressure at the outlet. The model inlet represents the throat of the diffuser and the flow at this location is

![Figure 1. Example of an autoclave circuit](image-url)
choked (i.e. $Ma = 1$). Due to model limitations phase change has been neglected. Phase change is an important phenomenon near the shock wave where the temperature decreases dramatically. Although the temperature is expected to drop below 0°C in a small region just prior to the shock wave, the impact of neglecting phase change is considered minimal because the flow has an extremely low residence time within the ‘cold zone’. The overall flow field and trends predicted by the CFD model are expected to be valid.

To understand the effect of adding a perforated plate to the blast shroud, the flow field is first modelled without a plate present. Figure 3 shows contours of gas velocity inside the blast shroud without a perforated plate.

Figure 2. Geometry of the blast shroud and boundary conditions for the CFD model

Figure 3. Velocity distribution inside the blast shroud without perforated plate
The supersonic flow accelerates with increasing cross-sectional area. As the gas velocity increases, the pressure decreases until a shock wave occurs. As expected, the flow separates immediately downstream of the shock wave and a central jet of high speed flow persists. The result is a complex pattern of shocks within a jet of mixed supersonic and subsonic flow. Furthermore, the position of this jet was found to be unstable. The flow separation downstream of the initial shock causes the jet to move toward the wall of the shroud. This behaviour sets up an unstable separation bubble, causing the jet to oscillate with time. The instability in the flow field is a concern because it may pose a risk of flow-induced vibrations in the structure of the shroud. This would occur if the frequency of the oscillations were to coincide with any of the natural frequencies of the structure.

Figure 4 shows the initial perforated plate geometry that was investigated. The use of a perforated plate for this application is novel, so no standard practices are available for selection of hole size or open area.

A 50% open area and 1" holes were selected as a starting point based on Hatch experience in other fields.

Figure 5 shows pressure contours and a plot of the pressure and velocity along the centerline of the shroud both with and without the perforated plate.

The presence of the plate dramatically affects the upstream and downstream flow fields. A pressure drop of approximately 13.5 in-H₂O (3360 Pa) across the plate, which is very low relative to the total pressure let down, effectively creates a higher and more uniform pressure field upstream. The shock wave is stabilized and the flow separation and secondary shocks are prevented.

The velocity distribution and flow field inside the shroud are shown in Figure 6.

Comparing this result to that of Figure 5, a significant improvement in the uniformity of the velocity field across the shroud is seen. The two key improvements observed are: (1) the elimination of the unstable, high speed jet observed in the previous case, and (2) a uniform or plug flow profile exiting the shroud. Based on these improvements, the risk of flow induced vibrations and of wear and pool disturbance in the quench vessel are mitigated.

Figure 7 shows the effect of the perforated plate on the exit velocity distribution from the blast shroud and entering the quench vessel.
Figure 5. Pressure and velocity variation through the blast shroud (a) without the perforated plate, and (b) with the perforated plate.

Figure 6. Velocity distribution and flow field inside the blast shroud with a perforated plate.
Without a perforated plate, the separated flow upstream affects the exit velocity profile, which is non-uniform and unstable. The maximum velocity entering the quench vessel is in the range of 110 m/s to 285 m/s. By contrast, with the perforated plate in use, the velocity profile is uniform and the maximum velocity entering the quench vessel is reduced to 62 m/s. This velocity is considered acceptable for the current application.

**Effect of perforated plate geometry**

The geometry of the perforated plate has a significant effect on the flow stabilization inside the shroud. CFD modelling was used to test another design for the perforated plate to determine the effect of the opening density (as defined by Equation [1]).

$$opening\ density = \frac{N_{open}}{A_{plate}} \quad \text{where} \quad N_{open} = \text{percent open area} \times \frac{D_{H}^2}{d_H^2}$$  \[1\]

$$D_H = \text{hydraulic diameter of plate}$$

$$d_H = \text{hydraulic diameter of opening}$$

With the open area maintained at 50%, the hole diameter was increased from 1” to 2”, i.e. the hole density was decreased from 987 m$^{-2}$ to 247 m$^{-2}$. Figure 8 compares the velocity distribution inside the blast shroud with this new perforated plate geometry to the previous two cases.

With the reduced hole density the pressure drop across the plate is reduced from 13.5 in-H$_2$O (3360 Pa) to 11.5 in-H$_2$O (2870 Pa) and a mix of sub and supersonic flow exists upstream of the perforated plate. Comparing this result to the velocity distributions without any plate, the downstream flow has been somewhat stabilized; however, the upstream jet still exists. This penetrating jet creates normal shocks upstream of the plate. Further work is underway to determine the critical pressure drop at which the upstream flow field is fully stabilized and the best combination of percent open area and hole density to achieve this pressure drop.
FEA analysis result and discussion

Geometry

The perforated plate geometry is driven by the process opening of the blast shroud and the requirement for 50% open area, as defined by the CFD analysis. For practical reasons the geometry is modified slightly from that shown in Figure 4; however, the hole diameter and open area are maintained. The outside diameter of the perforated plate is oversized to allow for a clamping annulus, as depicted in Figure 9.

To obtain the required flow characteristics, the disk has 187 holes arranged in triangular pitch pattern, as depicted in Figure 10.

Figure 8. The velocity distribution inside the blast shroud with (a) no perforated plate, (b) a perforated plate with a hole density of 987 m\(^{-2}\), (c) a perforated plate with a hole density of 247 m\(^{-2}\)

Figure 9. Mechanical assembly of ceramic blast shroud and perforated plate. Gaskets and PTFE are shown in their hot, compressed form
Figure 10. Plan view of perforated plate showing hole pattern and pitch details. A total of 187 holes combine to create 91,793 mm$^2$ of open area. Radii on the circumferential slot and leading/trailing edges of holes are visible.

Table I

<table>
<thead>
<tr>
<th>Physical properties of nitride bonded silicon carbide (NBSC) provided by Blasch Precision Ceramics, Albany, NY, USA</th>
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<tbody>
<tr>
<td>Young’s modulus</td>
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<td>Poisson’s ration</td>
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<td>Density</td>
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<td>Thermal expansion</td>
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<td>Thermal conductivity</td>
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<td>Specific heat</td>
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<td>Tensile strength</td>
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The layout is critical to provide sufficient webbing between holes to ensure structural integrity. Stress concentrations are minimized by smoothing sharp junctions with 6 mm radii on concave corners and 1 mm on convex edges, specifically at the leading and trailing edges of holes. The outer annulus has been slotted circumferentially to accommodate overlapping of the ceramic blast shroud and perforated plate to protect the PTFE packing and gasket. This is required to prevent the abrasive process fluid from eroding the soft packing and gasket material, thus compromising the pressure barrier. The diverging ceramic shroud and perforated plate are constructed from nitride bonded silicon carbide (NBSC). This material was chosen for its hardness and resistance to erosion. Physical properties of NBSC required for FEA analysis are listed in Table I.
Mechanical design

It is critical that thermal expansion of the blast shroud and perforated plate be managed to mitigate the risk of overstressing the NBSC resulting in cracking, and ultimately failure. To simulate operating conditions the temperature profile in Figure 11 is generated by applying temperature and convection coefficients to the top, bottom and outer plate surfaces.

Temperatures for the top and bottom faces are from the CFD analysis. The temperature and convection coefficient applied to the outer edge of the plate is approximated from past FEA experience.

Thermal growth in the axial and radial directions is reported in Table II, along with maximum stresses due to the temperature gradient through the perforated plate. As expected, the stresses in the unconstrained case are orders of magnitude lower. Generally, stresses are...
developed in the plate when the hot centre portion expands and is constrained by the cooler outer clamping annulus. As shown in Figures 12 through 14, this generates compressive stresses in the centre portion and tensile stresses in the outer portion of the plate.

These stresses are intensified in the thin wall sections between holes and the slotted circumferential groove. There is also a variation in stress between the hot and cold faces due to the 2°C temperature difference between them. Ceramic materials tend to fail in a brittle manner, which occurs abruptly with no yielding as the rupture strength is exceeded. The tensile strength of NBSC is given by the manufacturer as 30–33 MPa. In the unconstrained state (case 1), peak stress levels in the plate are 0.36 MPa in tension and -0.52 MPa in compression. These values are less than 2% of the rupture strength. However, if growth of the perforated plate is restrained as seen in cases 2 and 3, stress levels rise dramatically and will certainly exceed the tensile limit causing failure.

It is of absolute importance that the perforated plate be allowed unrestrained thermal growth, while being held in place to minimize vibration. Radial expansion is permitted by centring the ceramic perforated plate within the metal spacer ring. All mechanical loads from piping, bolting and pressure will be transferred through the spacer ring instead of the fragile ceramic plate. The spacer ring inside diameter is slightly larger than the perforated plate.
outside diameter, thus allowing ample space for radial thermal expansion. Axial thermal growth is taken up by compressing the PTFE packing on the top and bottom surfaces of the clamping annulus. In the cold state, the PTFE will be uncompressed, but not loose. As the assembly is heated, the metal and ceramic components will expand compressing the PTFE up to 20%, while holding the perforated plate in position. Also, the PTFE will cushion the perforated plate from impacting other metal or ceramic components.

**Natural Frequency**

There is potential for vibration to cause cracking and failure of the ceramic plate. The first and second natural frequencies are calculated by axially restraining the plate around the outside top edge. The first and second natural frequencies occur at 442 and 1129 Hz respectively. The undamped deformation pattern is shown in Figure 13. The first natural frequency is quite high (442 Hz or 26520 RPM) making it unlikely for process equipment such as pumps to vibrate at this frequency. However, it is difficult to predict all sources of vibration and it is possible for process valves to create excitation frequencies at this level. If vibration causes the failure of the perforated plate it is possible to increase or decrease the natural frequency by reducing or increasing the thickness of the perforated plate.

![Figure 13. Maximum principal stress plots in true scale from Ansys Workbench](image)
Design benefits and conclusions

The CFD analysis has shown that the use of a perforated plate in the blast shroud improves the flow field by eliminating the unstable, high-speed jet downstream of the shockwave and by creating a uniform flow profile exiting the shroud into the quench vessel. The reduced entry velocity eliminates the need for replaceable wear components such as impingement blocks and ceramic tiles. The absence of a high-speed jet eliminates the need for a large liquid pool for energy dissipation, while protecting the vessel lining and shell from erosion. As a result, pressure let down vessels can be made more compact and cost-effective without sacrificing availability or performance. The stability of the shockwave will mitigate the risk of flow-induced vibration and fatigue in metallic the blast shroud, nozzle and vessels components. The ability to control large pressure drops has further economic potential in that multistage letdown might be achieved in fewer stages, reducing the required number of vessels and capital cost.

The analysis shows that the performance of the perforated plate is related to the pressure drop across it. The hole density and percent open area are two key design parameters that can influence the pressure drop. Two bounding cases were studied, but further investigation is required to determine the optimal design case.
Thermal stresses can be minimized through generous filleting and contouring of corners, and most importantly, by allowing unrestricted thermal growth in both radial and axial directions. The spacer ring is designed to carry all mechanical loads and provide enough support to prevent chatter, thus ensuring the longevity of the ceramic perforated plate.

Acknowledgements
The authors would like to acknowledge Dave Warnica, Hatch Ltd., for suggesting the use of a perforated plate flow diffuser for this application.

References
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Michael is experienced in mechanical engineering in the development of high pressure acid/oxygen leach process plants and in pressure vessel design and knowledge of the ASME Boiler and Pressure Vessel Code Section VIII Division I & II and the associated ASME/ANSI/ASTM Standards. He is proficient in the use of calculation spreadsheets to perform detailed mechanical equipment design. He has worked with exotic metals such as titanium, duplex and super duplex stainless steels, tantalum, and nickel alloys. His expertise in various other computer programs including Codeware Compress, AFT Arrow and Fathom.

Michael has the ability to conduct finite element analysis (FEA) using Ansys Workbench, Design Modeller and ICEM. He has completed Div II thermal, structural, modal and buckling analysis of refractory lined pressure vessels, large bore ducting and various vessel internals.

- Barrick Gold Corporation, Pueblo Viejo, Dominican Republic – Detailed Engineering—responsibilities to date include pump sizing and the preparation of a pump specification for budget quotation, as well as finite element analysis of pressure equipment, ducting and vessel internals.
- Barrick Gold U.S. INC., Donlin Creek, Alaska, USA, Bankable Feasibility Study—responsibilities included sizing of mechanical equipment for pressure oxidation circuit using Codeware Compress. He assembled specifications and drawing for tender packages, and completed vendor bid evaluations. He completed bankable capital cost estimate for autoclave area.
- Metals Enterprise, Moa Bay, Cuba, 16K Expansions—modelled mechanical equipment using Codeware Compress and checked vendor calculation to ensure code compliance.
- Sargold Resource Corporation, Sardinia, Italy, Class Four Estimate—carried out equipment sizing for a pressure oxidation autoclave circuit and generated factored capital cost and operating cost estimates

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Jennifer received her MA Sc in the area of fluid in 2004 from the University of Waterloo in Canada. She has been working at Hatch since 2004, specializing in the application of computational/fluid dynamics (CFD) modelling techniques to solve problems for which traditional analysis trials are not sufficient.

Jennifer contributed to the design of a variety of purposes vessels as well as capture hoods and ventilation systems.