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IMPACT OF SITE ELEVATION ON MG SMELTER DESIGN

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Abstract

Site elevation has many surprising and significant impacts on the engineering design of metallurgical plant of all types. Electrolytic magnesium smelters maybe built at high elevation for a variety of reasons including availability of raw material, energy or electric power. Because of the unit processes they typically involve, Mg smelters can be extensively impacted by site elevation. In this paper, generic examples of the design changes required to adapt a smelter originally designed for sea level to operate at 2700 m are presented. While the examples are drawn from a magnesium plant design case, these changes are generically applicable to all industrial plants utilizing similar unit processes irrespective of product.

Introduction

The earth's atmosphere is made up of a mixture of gases nominally 78% nitrogen, 21% oxygen, 0.9% Ar and 0.04% CO_2 with the remainder comprised of fractional percentages of some 12 gas species. The atmosphere of also contains a variable amount of water vapor ranging from 1-4 % depending on altitude, location and weather conditions.

Although there is no definite position that delineates the boundary of the earth's atmosphere it is commonly regarded as being 100 km above the sea level. However, the atmosphere is highly stratified with more than 80% its total mass within the lowest stratum called the Troposphere. The troposphere extends some 10 km above sea level and its properties and behavior are the only ones considered relevant to terrestrial engineering design procedures.

Within the troposphere the decrease in pressure with increasing elevation is approximately linear, a phenomenon that is emulated by temperature.

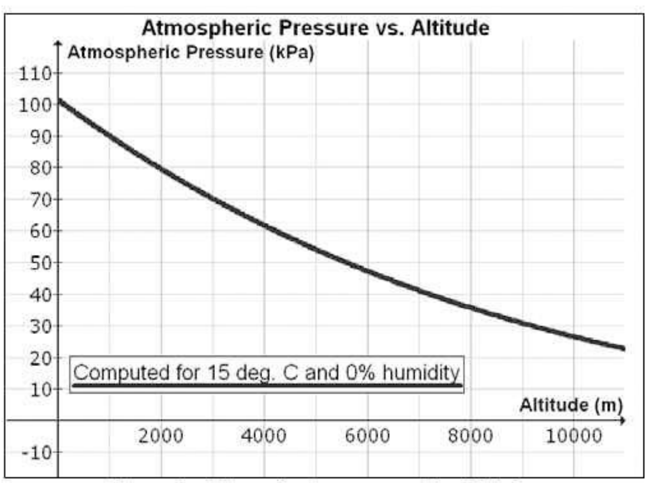

Figure 1. Atmospheric pressure Vs Altitude

So for conventional engineering design purposes the atmosphere may be considered as a column air 10 km high in which the pressure, temperature and density of the gas vary almost linearly with elevation.

Within the range of site elevation changes encountered in engineering projects, there can be significant impact on the design of engineering processes that involve any of the following;

- Phase changes
- Heat and/or mass transfer in gas phase
- System pressure drop
- System volumetric flows
- High voltage power

Magnesium Smelter Flowsheet

Unlike aluminum smelters the Flowsheet of a magnesium smelter is often unique to the feedstock and site conditions. Furthermore, magnesium smelter flowsheets are not all based on the same core technology and can represent unique technical solutions. Nevertheless the unit processes employed are often generic even though their configuration and detail design may be unique. We will consider the flowsheet shown below.

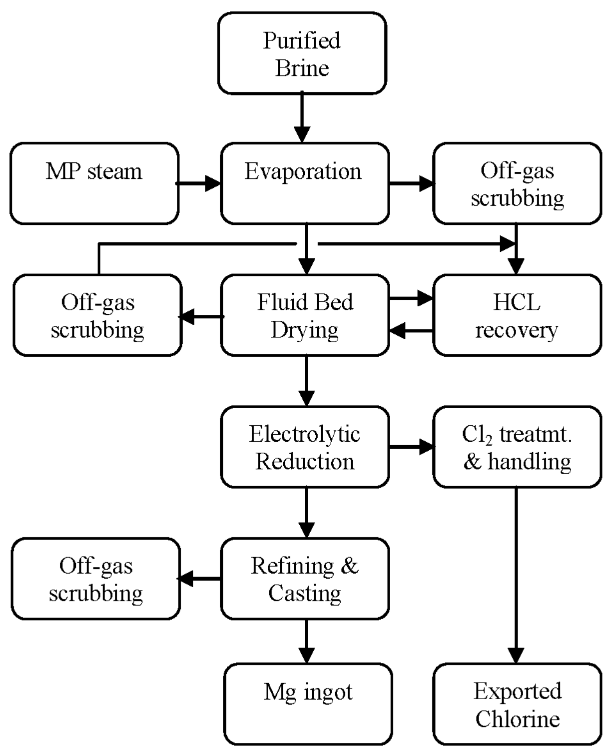

Figure 2. Process Block Diagram

The flowsheet described by the block flow diagram above involves the continuous evaporation and concentration of $MgCl_2$ brine followed by cooling and transformation into a solid hydrate intermediate. This intermediate product is then dehydrated in two stages of fluidized beds with the final stage being performed in an environment of HCL gas. The HCL lost to scrubbers and bled from the system must be recovered purified and returned to the process. All off-gases must be cleaned of contaminants before release to the environment.

The anhydrous magnesium chloride solid is used as feedstock for the electrolytic reduction process which produces liquid magnesium and chlorine gas. Melt refining and casting processes also require off-gas handling and treatment for environmental reasons.

The integrated chemical process includes a wide range of smaller chemical process equipment including;

- Pumps
- Fans, blowers and compressors
- Heat exchangers

Brine Evaporation Process

Industrial Evaporators are designed in a variety of forms and configurations but all depend on the boiling behavior of the process media.

The objective of evaporation unit process in this flowsheet is to a produce hot liquid at a critical concentration (refer to Cc in Figure 3**)** which when cooled will transform into the desired hydrate phase. It is essential for plant operation that after the required concentration has been reached no premature precipitation of solid will occur in the pipe work leading to the cooling process. This requires an acceptable range of temperature between boiling and solid transformation in which the concentrate can be maintained as a stable liquid.

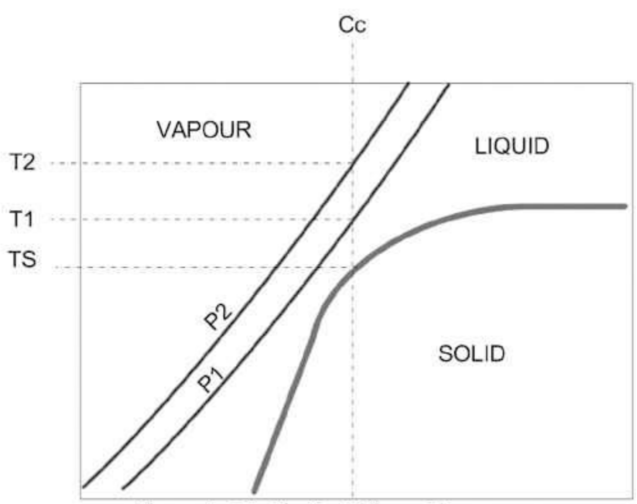

Figure 3. $MgCl_2$-H_2O Phase Diagram

P2 and P1 shown in Figure 3 above represent the Liq-Vap transition line at sea level and site elevations respectively. At sea level this range is wider, T2-TS Vs T1-TS, because the liq-sol transition temperature is unaffected by pressure but the boiling temperature is reduced at the increased elevation.

The question for the process engineer is can the temperature be reliably controlled in the narrower temperature range or should the process be operated at elevated gauge pressure simulating sea level conditions. Lower temperature operation offers additional energy savings but risks operational robustness unless reliable control is possible.

Fluidized Bed Drying Process

The objective of the fluidized bed drying stages is to remove the water of hydration to produce solid anhydrous MgCl2 free of oxide and hydroxychloride. To accomplish this, a substantial quantity of water must be transferred to the fluidizing gas and substantial energy must be transferred in order to raise the temperature of the feedstock to the reaction temperature. Both heat and mass transfer operations are dependent on the density of the fluidizing gases, air and HCL, and are therefore directly impacted by the site elevation.

Maintaining equivalent gas mass flow rates at an elevation of 2700 m means volumetric flow rates are increased by a factor of 1.40. Without increasing vessel diameter the increased gas velocities will change the fluidizing behavior of the bed and unacceptably increase elutriation losses which then increase the contamination of the scrubber liquor.

In this case the design engineer must choose between increasing bed diameter and adding additional units to meet the throughput and capacity requirements. In either option, sensitive process parameters inside the beds such as temperature profile, residence time and fluidization mode must be adhered to or problems such as feedstock accretion, melting and oxidation can occur.

Compressors, Blowers and Fans

The process flowsheet under discussion is supported by many machines that provide the motive force to move gases at the correct flow rates and pressures. High elevation projects require a reevaluation of all of these machines.

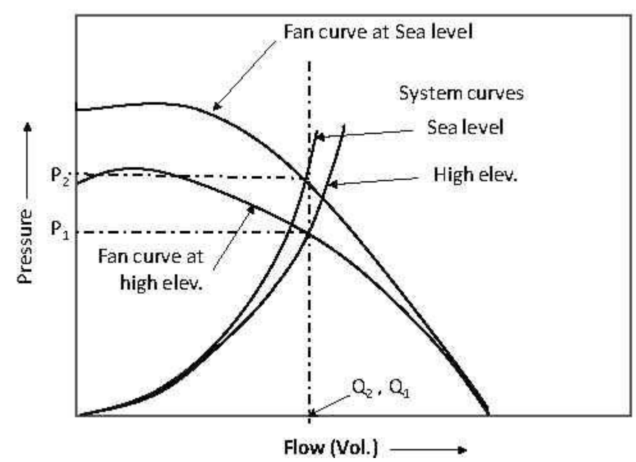

Figure 4. Change of Gas Density

Figure 4 shows that if only the gas density is changed then a fan operating at sea level will deliver the same volumetric flow rate in the same system as at high elevation but at lower pressure. That the flow rate is unchanged is to be expected as fans/blowers are volumetric machines but less intuitive is that head generated is proportional to fluid density.

Consider the case of the fluid bed dryer: the pressure drop across a fluidized bed at minimum fluidization velocity is equal to the weight of the bed and is therefore independent of air density. Therefore to fluidize the same bed at high elevation requires the same pressure drop but from Figure 4 we can see that $P_1 < P_2$. However, if we must also maintain the velocity as constant then the fan cannot simply operate at higher speed but instead should use a larger diameter impeller to produce more pressure at the same speed but with narrower vanes displacing the same volume of gas with each rotation as the originally specified fan. Other solutions can be formulated using dampers but none are energy efficient.

An additional concern is moving the operating point of the fan towards its region of instability where the flow rate is sensitive to small head change can lead to "hunting" (varying flow rate).

In situations where mass flow of gas must be maintained such as in heat transfer applications, higher volumetric flows must be produced. This cannot always be accomplished by increasing the number of fans. Consider the case of heat extraction from the process buildings where a higher volumetric flow will require a higher pressure drop through the building because pressure drop varies linearly with gas density but according to the square of the velocity as follows;

$$\Delta p = k.\rho.v^2$$

For constant mass flow at different gas densities:

$$\rho_1.v_1 = \rho_2.v_2$$

$$v_1 = \left(\frac{\rho_2.v_2}{\rho_1}\right)$$

$$\frac{\Delta p_1}{\Delta p_2} = \left(\frac{k.\rho_1.(v_1)^2}{k.\rho_2.(v_2)^2}\right)$$

Substituting for v_1 ;

$$\frac{\Delta p_1}{\Delta p_2} = \left(\frac{\rho_2}{\rho_1}\right) = \left(\frac{v_1}{v_2}\right)$$

The pressure drop required to maintain the same mass flow through the same building is increased in proportion to the increase in volumetric flow rate. Hence cooling fans must support both a higher flow rate and pressure to maintain cooling effectiveness at higher elevations. In the case of sea level versus 2700 m, a 40% increase in both volumetric flow rate and pressure drop can be expected where no changes are made to the flow path.

Cooling by Natural Convection

Natural convection is important in heat loss even where forced convection is superimposed the local impact of buoyancy is substantial. In smelters heat loss to the air by natural convection is important to much of the process equipment including fluidized bed, reduction cells, high amperage bus bar and refining furnaces.

The impact on the bus bar has been studied in more detail using CFD modeling under these conditions and is presented in another Hatch authored paper at TMS 2013.

Air behaves as an ideal gas; its density varies linearly with absolute pressure and inversely with absolute temperature. Thermal buoyancy forces drive velocities and are a consequence of the different masses of unit volumes of gas. Lower density air at high elevations means reduced driving force, less velocity and so reducing heat transfer. Furthermore the mass flow rate of cooling air past the hot surface which is already decreased due to lower velocity is further reduced by its lower density resulting higher film temperatures as the air rises past the hot surface.

More precisely, the Prandtl number (Pr) is relatively unaffected by the change in barometric pressure, since specific heat, dynamic viscosity and thermal conductivity are nearly independent from pressure. Air density, however, is not, and the drop in barometric pressure translates into a considerable impact on buoyancy. Since natural convection depends on Grashof number (Gr), the impact of density on heat transfer coefficients is significant. Refer to the calculated heat transfer coefficients in the table below for sea level and smelter site elevation.

		72.4 kPa	101.3 kPa
Prandtl, *Pr*, [-]		0.7160	0.7162
Grashof, *Gr*, [-]		1.239E+10	2.424E+10
Raleigh, *Ra*, [-]		8.871E+09	1.736E+10
Nusselt *f* [-]	Single vertical surface	207.0	258.9
	Horizontal, facing down	82.86	98.01
	Horizontal, facing up	217.4	271.9
h_c [W/m^2.K]	Single vertical surface	4.516	5.649
	Horizontal, facing down	1.808	2.138
	Horizontal, facing up	4.741	5.932

Depending on surface orientation, h_c is calculated to be 15% to 20% lower at the proposed smelter site altitude than at sea level. This conclusion is supported by other work in Avionics design. [1]

For critical facilities within the smelter Hatch has carried out CFD modeling of ventilation designs where forced convection design supports natural convection to ensure adequate cooling performance will be achieved.

Pumps

Pumps in process plants are designed to move a wide range of liquids across a range of temperatures. They must be specified and installed in such a way that Cavitation is avoided. Cavitation is the result of the fluid being exposed to pressures lower than its vaporization pressure and if prevalent can rapidly damage pump impellers and housings and other system components.

High site elevation reduces ambient pressure moves all fluids closer to their vaporization point for given process temperatures. The design engineer must consider the location of the pump and its design to avoid

In this application many circumstances existed where hot and often corrosive liquids must be pumped. In all such cases proper determination of net positive suction head (NPSH) was required to ensure that Cavitation corrosion does not occur and allow the leakage of hazardous and corrosive fluids.

Vacuum Transfer

To extract the liquid metal from the electrolytic cells a vacuum line is connected to a mobile ladle equipped with a siphon tube. The tube is lowered into the cell and the vacuum applied to lift the metal and electrolyte into the ladle. The difference in pressure between the ladle under vacuum and the ambient pressure provides the required driving force to accomplish this transfer.

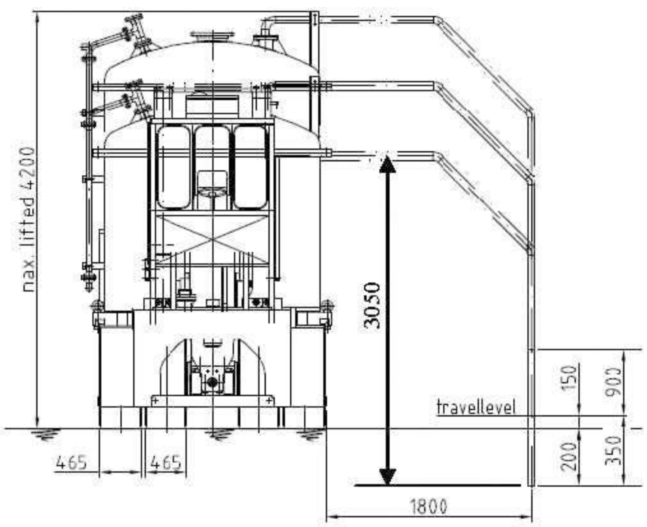

Figure 5. Tapping Geometry

Commercially available tapping trucks have a maximum static head height of more than 3 m requiring a pressure differential of;

- 46.0 kPa for liquid Mg (ϱ_{Mg} = 1.60 g/m^3)
- 53.5 kPa for electrolyte ($\varrho_{elec.}$ = 1.82 g/m^3)

Because salt is always drawn through the siphon tube first, the higher value must be used for design. Dynamic head loss required to cause flow is not included in the above and adds a further Δp to provide for rapid lifting of the salt/metal to prevent freezing within the siphon pipe.

Simple vacuum systems based on single stage air ejectors that are commonly used to generate vacuum for cell tapping cannot reliably produce absolute pressures lower than 20 kPa. The available differential pressure at a site elevation of 2700 m with a single stage ejector will be 52.4 kPa (72.4 – 20), insufficient overcome the static head required to lift salt from the cell into the vacuum ladle and borderline for liquid magnesium even without accounting for dynamic head loss requirements. Consequently design engineers must select higher performance vacuum systems able to generate higher vacuums unless radical changes are made to the design of the tapping trucks.

HCL Recovery

As shown on Figure 2, the HCL returned from the drying and scrubbing processes is recovered and regenerated as dry HCl gas before being returned to the process. The recovery of HCl from aqueous solution involves distillation and breaking of the azeotrope to recover HCl from solutions less than 20% HCl. Technologies available to do this include vacuum and pressure swing technology as well as extractive rectification by the addition of a reboiler circuit of a strongly hydrophilic salt such as $CaCl_2$.

The fundamental processes of HCl recovery include distillation and reboiling are both impacted by the change in elevation from sea level to 2700 m. Additionally, the change to the volumetric flows of gaseous and vapor phases must be accounted for in the design and specification of the process equipment.

Scrubbing and Off-Gas Systems

The process flow sheet includes single and multi-stage scrubber systems designed to handle the off-gas products emanating for the various process areas. The off-gas ductwork systems, fans/blowers, baghouses and the scrubber units themselves are impacted in similar ways to other process facilities that involve significant gas flows and must be designed specially to suit the lower atmospheric pressure at the high site elevation.

High Voltage Facilities

High voltage power is delivered to the Air Insulated Switchgear (AIS) at 330 kV. The dielectric rating of air varies with the density of the air such that lower air density means a reduced electrical insulation effect as follows;

$$BIL_{site} = BIL_{sea\ level} / f$$

Where:

BIL standard lightning impulse withstand voltage
f altitude correction factor

At 2700 m elevation *f* = 0.8 so that;

$$BIL_{site} = \frac{1175}{0.8} = 1468\ kV$$

This increased design potential impacts the spacing of the HV equipment such as the transformer rectifiers must be more widely spaced at high elevations that at sea level. This increase the footprint of the switchgear facilities overall and impacts the layout and design of DC bus bar from the rectifiers to the potroom.

Conclusion

The location of smelters and indeed industrial facilities in general, at high elevations has far reaching consequences for the design of those facilities. These different atmospheric conditions impact all processes involving gas flows used in mass and heat transfer, phase changes, liquid pumping, off gas handling, vacuum transfer and high voltage facilities design. These effects require detailed consideration by the design engineers and the suppliers of equipment destined for high elevation process plants.

Reference

1. Doron Bar-Shalom, *Altitude Effects on Heat Transfer Processes in Aircraft Electronic Equipment Cooling,* (M.Sc. thesis, MIT, Dept of Aeronautics, Feb. 1989)