DETERMINING WATER LOSS IN MINERAL PROCESSING - A THERMODYNAMIC APPROACH

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ABSTRACT

With increasing competition for water resources and the potential impact on the environment, the mining industry's focus as expanded to include water in addition to energy consumption. Motivated by this changing competitive context, the aim of this work is to examine quantifying water loss in mineral processing operations by leveraging thermodynamics. Based on previous work this paper opens with the definition of a general thermodynamic model of a unit process which is then applied to describe energy and mass inputs and outputs of different mineral processing equipment (ie SAG and ball mills, screens, sumps, flotation, thickeners, reservoirs). The models are then used to estimate the evaporation losses of a generic 50000t/d mineral processing plant as well as explore different equipment design avenues to reduce water loss. A subsequent discussion explores the limitations of the models used, the potential benefit of reducing evaporation as well as a defining a possible metric that could be used to assess the water loss potential of different equipment and circuits.

INTRODUCTION

As highlighted by Boretti and Rosa (2019), the UN World Water Development Report (2018) claims that:

"Clean water scarcity is a major issue in today's' world of 7.7 billion people. The strain on the water system will grow by 2050 when the world population will reach between 9.4 and 10.2 billion, a 22 to 34% increase... …By 2050, more than half of the global population (57%) will live in areas that suffer water scarcity at least one month each year".

In their own analysis, Boretti and Rosa (2019) conclude that:

"Water is ultimately a finite resource and the marginal solutions for water scarcity currently being proposed in the United Nations (UN) World Water Development Report (WWDR) will prove hopelessly inadequate by 2050 in the absence of any serious effort to tackle these underlying truths".

In this context of increasing competition for water resources and the potential impact on the environment, the mining industry's focus has expanded to include water in addition to energy consumption. Motivated by this changing competitive context, the aim of this work is to examine quantifying water loss in mineral processing operations by leveraging thermodynamics.

This will be accomplished by first defining a general thermodynamic model of a unit process which is then adapted to different mineral processing equipment (ie SAG and ball mills, screens, sumps, flotation, thickeners, reservoirs). The water loss is estimated for a number of cases and as well as different design avenues to reduce water loss are explored. A subsequent discussion explores the limitations of the models used, the potential benefit of reducing evaporation as well as a defining a possible metric that could be used to assess the water loss potential of different equipment and circuits.

BACKGROUND

Estimating water loss in an open body of water scenario comes down to the use of Dalton relationship (ETB, 2023; Feistel & Hellmuth, 2023; Headrick, 1967; Jensen, 2010):

$$\dot{m}_{evap} = \Theta A_{sl}(x_s - x) \tag{1}$$

where:

$$\Theta = \left(25 + 19v\right) \tag{2}$$

and:

v - velocity of air over water surface [m/s],
A_{sl} - area of water surface [m^2],
x_s - humidity ratio in saturated air at the surface water temperature [kg/kg],
x - humidity ratio in the air [kg/kg].

The resulting energy lost by evaporation can now be determined as:

$$\dot{Q}_{evap} = \dot{m}_{evap} h_{evap} \tag{3}$$

where:

h_{evap} - heat of vaporization of water [kJ/kg]

ESTIMATING WATER LOSS

Before developing a model to estimate water loss through evaporation in mineral processing, it is important to underline that evaporation is a natural and ever-present phenomenon. At any given location, evaporation is a function of local water temperatures, humidity levels, water surface area, wind speeds and solar intensity.

Mining activities will bring increased water surface area through the use of holding tanks, flotation cells, thickeners, any equipment presenting a free surface which includes tailings facilities. Assuming that the temperatures of all of the bodies of water in a plant are the same and equal to that of the ambient outside temperature of the tailings pond or raw water tank, the Dalton relationship could be used to estimate water evaporation rates as illustrated in Gunson et.al. (2012).

However, water and ore (slurry) temperatures will increase in comminution circuits due to the heat generated in grinding. This added heat will increase water loss through evaporation beyond what the Dalton relationship estimates.

To estimate the water loss through evaporation related to the heat generated comminution, a control volume needs to be defined around a system such as a mineral processing plant along with all mass and energy inputs and outputs across the control volume boundary as illustrated in figure 1. In the following development, the plant control volume excludes the concentrate and the tailings.

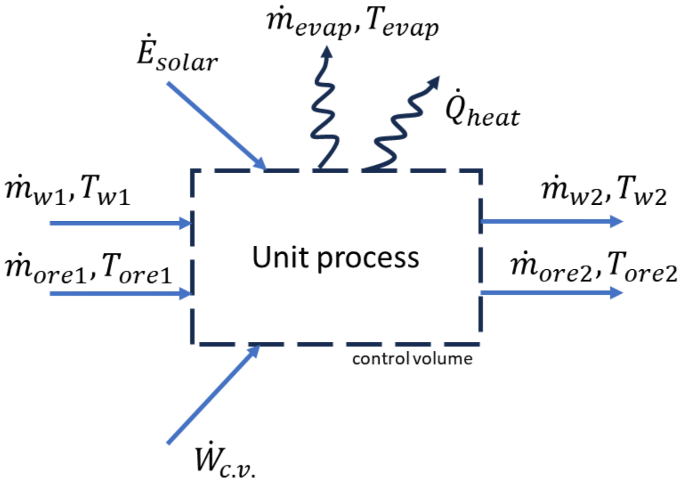


Figure 1 Generic control volume around a system

In the case of a mineral processing plant, mass and energy balances over the control volume are defined as follows:

$$\dot{W}_{c.v.} + \dot{E}_{solar} - \dot{Q}_{lost} = (\dot{m}_{ore2}h_{ore2} + \dot{m}_{w2}h_{w2}) - (\dot{m}_{ore1}h_{ore1} + \dot{m}_{w1}h_{w1}) \tag{4}$$

where:

$\dot{W}_{c.v.}$ - work input to the control volume [kJ/s or kW],
$\dot{E}_{solar}$ - solar energy input to the control volume [kJ/s or kW],
$\dot{Q}_{lost}$ - energy lost to the environment [kJ/s or kW],
$\dot{m}_{ore1}, \dot{m}_{ore2}$ - ore mass flow rate [kg/s],
h_{ore1}, h_{ore2} - ore feed and discharge enthalpy respectively [kJ/kg],
$\dot{m}_{w1}, \dot{m}_{w2}$ - water mass flow rate [kg/s],
h_{w1}, h_{w2} - water feed and discharge enthalpy respectively [kJ/kg].

and:

$$\dot{Q}_{lost} = \dot{Q}_{heat} + \dot{Q}_{evap} \tag{5}$$

The mass balance over the control volume is defined as:

$$\dot{m}_{ore} = \dot{m}_{ore1} = \dot{m}_{ore2} \tag{6}$$

$$\dot{m}_{w1} = \dot{m}_{w2} + \dot{m}_{evap} \tag{7}$$

Assuming (assumption #1) that the mass loss through evaporation ($\dot{m}_{evap}$) is small as compared to the total water used in mineral processing, it is possible to approximately equate the output water rate with the input water rate:

$$\dot{m}_{w} = \dot{m}_{w1} \cong \dot{m}_{w2} \tag{8}$$

Furthermore, it can be assumed (assumption #2) that the temperatures of the input ore and water as well as the temperatures of the output ore and water (slurry) are equal:

$$T_1 = T_{ore1} \cong T_{w1} \tag{9}$$

$$T_2 = T_{ore2} = T_{w2} \tag{10}$$

Assuming (assumption #3) constant pressure, an incompressible fluid and solid in the slurry, it is possible to reduce the energy balance to the following:

$$\dot{W}_{c.v.} + \dot{E}_{solar} - \dot{Q}_{lost} = (\dot{m}_{ore}c_{ore} + \dot{m}_{water}c_{water})(T_2 - T_1) \tag{11}$$

where:

c_{ore}, c_{water} - specific heats of the ore and water (Waples and Waples, 2004) [kJ/kg-K].

Solving the energy balance (equ 4) for the energy lost term also defines energy lost:

$$\dot{Q}_{lost} = \dot{W}_{c.v.} + \dot{E}_{solar} - (\dot{m}_{ore}c_{ore} + \dot{m}_{water}c_{water})(T_2 - T_1) \tag{12}$$

For the control volume capturing the plant, it will be assumed (assumption #4) that the temperature of the concentrate and tailings that are being discharged from the plant are at the same temperature and that temperature equals the temperature of the input materials ($T_2 = T_1$). Consequently, the energy lost equation (12) can be equated with equation (5) and equation (3) can be substituted into the equation giving:

$$\dot{Q}_{lost} = \dot{W}_{c.v.} + \dot{E}_{solar} = \dot{Q}_{heat} + \dot{m}_{evap}h_{evap} \tag{13}$$

At this point, one can assume (assumption #5) that all energy lost ($\dot{Q}_{lost}$) is only through mass transfer due to evaporation (ie energy lost by heat transfer, $\dot{Q}_{heat}$, is equal to zero). Knowing that energy lost by evaporation is a function of evaporation enthalpy and mass loss rate, it is then possible to reformulate the following relationship for potential water loss of a given mineral processing plant as a function of the energy input into the plant control volume:

$$\dot{m}_{evap} = \frac{(\dot{W}_{c.v.}+\dot{E}_{solar})}{h_{evap}} \tag{14}$$

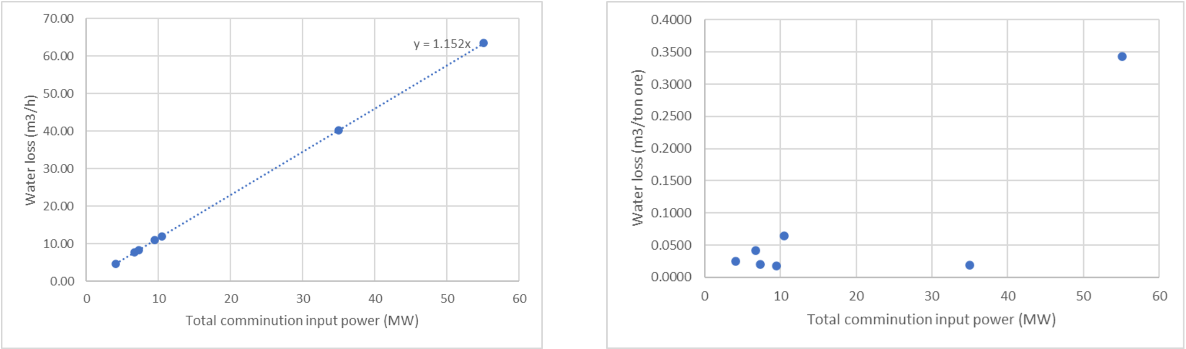
Evaporation enthalpy of water is a function of water temperature. However, between 0C and 100C, it only varies by about 10%. Consequently, the value used for evaporation enthalpy (at 0C) is 2500 kJ/kg.

With equation (14) and evaporation enthalpy, it is possible to revisit energy capture mill data illustrated in previous works (Radziszewski, 2013; Radziszewski and Hewitt, 2015; Bouchard et.al., 2019) and determine the potential water loss in these plants due to evaporation as illustrated in Table 1. Note that in these calculations solar energy input is considered negligible and input energy to heat the slurry in comminution is considered to be 80% (Bouchard et.al., 2019) of the input mill electrical energy.

Table 1 Potential Water Loss estimates

Parameter	Units	Brunswick	Cadia	MIDUK	Raglan	Agnico Eagle Goldex	Canadian Malartic	New Afton
SAG mill*	MW	7.3	19	3.5	2.258	3.357	19.4	5.22
Ball mill*	MW		16	6	1.853	3.357	35.7	5.22
Total input power	MW	7.3	35	9.5	4.111	6.714	55.1	10.44
Heating efficiency	%				80			
Heat lost	kW	5840	28000	7600	3288.8	5371.2	44080	8352
Evaporation enthalpy @ 0C	kJ/kg				2500			
Evaporation enthalpy @ 0C	kWh/kg				0.69			
Potential water loss	m^3/hr	8.41	40.32	10.94	4.74	7.73	63.48	12.03
Plant ore feed rate*	t/day	10000	49560	15000	4440	5200	55000	15000
Specific water loss	m^3/t	0.0202	0.0195	0.0175	0.0256	0.0418	0.3431	0.0650
**source*			*Radziszewski, 2013*		*Radziszewski, Hewit, 2015*		*Bouchard et.al., 2019*	

Graphing some of the results found in Table 1, it is possible to illustrate the impact of comminution on water loss potential in two different ways. The first way is obvious from the application of equation (14). Potential water loss is proportional to comminution energy input (see figure 2a). Consequently, improving comminution grinding efficiency affects directly the water loss potential of a given plant. The second way is to examine potential water loss on a per ton ore processed (see figure 2b). In this case, the results indicate that on a per ton processed basis, comminution energy input is not necessarily the only indicator of water loss potential. The difference between the two might point to new opportunities to reduce water use.



a) hourly potential water loss *b) potential water loss per ton of ore processed*

Figure 2 Potential water loss results

AVENUES TO MITIGATE POTENTIAL WATER LOSS

Having established that total water loss potential through evaporation for the plant captured by a control volume is a function of comminution energy input, the control volume approach illustrated in figure 1 can guide the investigation of different avenues to reduce water loss of the 9 equipment types found within a plant as illustrated in figure 3.

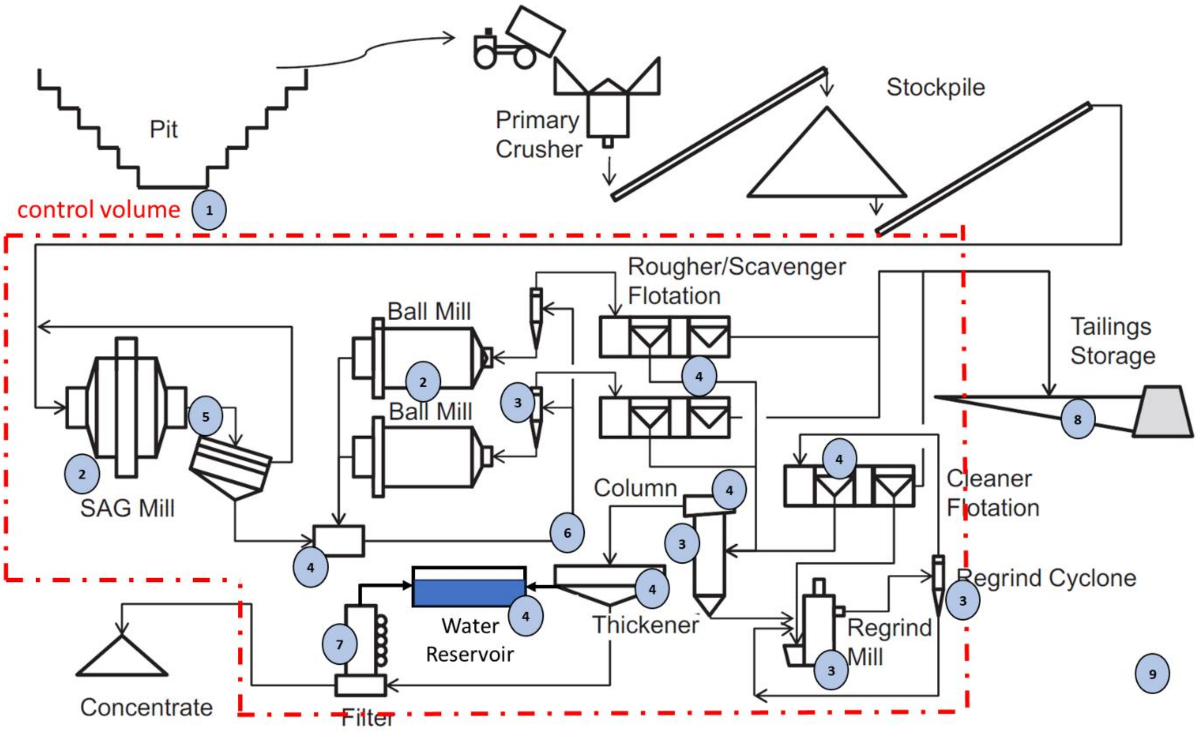


Figure 3 A generic 50000 t/day mineral processing plant (Gunson et.al., 2012)

1. The Plant - On a clear day at the equator, the solar energy ($\dot{E}_{solar}$) input averaged over 365 24 hour days is about 320 W/m^2. Assuming that most slurry carrying equipment in a plant are exposed to the sun, the input energy is not negligible. By adding an insulated roof, this input energy can be eliminated from the plant. Furthermore, depending on how the roof is designed and oriented, it can also serve as a means to generate convection currents through the plant as well as provide a platform for solar panels and electrical generation.

2. Tumbling mills - All wet tumbling mills present two avenues for energy loss: mass transfer due to evaporation and heat loss. In terms of mass transfer ($\dot{m}_{evap}$), it is expected that this will be a function of the wetted surface inside the mill and the velocity of air over that surface. The potential impact of this source of water loss can be reduced by adding a shroud at the discharge of the mill restricting and slowing air flow through the mill. In terms of heat loss ($\dot{Q}_{heat}$) through the cylindrical wall, it is proportional to the thermal conductivity of the liner and shell material used. Noting the difference in thermal conductivities of steel and rubber (steel: 30 to 60 W/m-K; rubber: about 0.1 W/m-K), it is expected that the heat loss through the mill shell lined with steel liners will be significantly greater than that with rubber liners.

3. Tall stationary equipment - This refers to equipment such as stirred mills, column cells, and hydro-cyclones which have large non-moving shells. Contrary to rotating equipment such as tumbling mills where a convection current over the shell is inherent to its operation, in stationary equipment this is not the case. Consequently, potentially creating convection currents over stationary equipment by an appropriately designed roof could increase heat loss ($\dot{Q}_{heat}$). Heat loss over such equipment can be increased further by adding fins to the equipment. In this case, the choice of fin material such as aluminium (Al thermal conductivity is about 100 W/m-K) can enhance heat transfer through the shell.

4. Open bodies of water - This includes water reservoirs, thickeners, flotation cells, column cells and sumps. However, before addressing mitigating measures for this type of equipment, it is important to address the rate of evaporation from open body surfaces of mineral processing equipment.

The Dalton equation (1) is typically used to estimate water loss ($\dot{m}_{evap}$) from open bodies of water. However, some of these equipment slurry surface conditions deviate from that of a pond or a lake on which the Dalton equation was developed. In the case of flotation cells and column cells, the evaporation surface is not only defined by the open area of the cell, but also by the size and number of air bubbles being pushed through the cell. Consequently, potential water loss from flotation cells would be greater than what the Dalton equation would predict.

It was suggested that covering water reservoirs would reduce the evaporation of recycled plant water, reducing the need for the use mineralised ground make-up water. This could in turn reduce corrosive wear of grinding media significantly (Radziszewski, 2004). Today, covering water reservoirs, flotation cells, thickeners, and any open body of plant water is seen as a viable avenue to reduce water lost through evaporation in mineral processing (Gunson et.al., 2012).

However, the covers for equipment with open bodies of water should be designed as heat exchange surfaces where water vapor condenses and falls back into the slurry or is collected and pumped elsewhere in the process. In order to increase the rate of condensation and the associate heat transfer ($\dot{Q}_{heat}$), the outside of the cover would need to be finned in a similar fashion as stationary equipment.

5. Trommels and screens - This type of equipment has the potential to have high evaporation rates ($\dot{m}_{evap}$) as they are found at the discharge of SAG mills where the slurry temperature is potentially high. Assuming that the whole ore size distribution is now "wetted", the potential evaporation surface is undoubtedly quite high. Consequently, trommels and screens need covers similar to those used for open body of water equipment to reduce evaporation and increase heat loss ($\dot{Q}_{heat}$).

6. Pipes - Pipes do not present any risk of water loss through evaporation. However, similar to tall stationary equipment, pipes provide a lot of heat transfer area. Consequently, adding fins to these surfaces can increase heat transfer rates ($\dot{Q}_{heat}$) by 30% to 50% (Abbas & Wang, 2020; Frederick & Samper, 2010; Mokhtari et.al., 2017; R et.al., 2021; Saqr & Musa, 2009).

7. Filters - It is known that the amount of water removed by filtering increases with a coarser grind. In addition, a coarser grind reduces the amount energy consumed in grinding. However, a coarser grind will undoubtedly increase the amount of valued mineral being lost to the tailings. As a result, it is doubtful that coarser grinds will be adopted in the near future as a means to reduce water loss.

On the other hand, there are tailings treatment process technologies that are being explored that may alleviate the hesitancy to grind courser. One such process technology (Radziszewski and Blum, 2023, 2024; Radziszewski, 2023a, 2023b) is electrochemical in nature and aims to remove all sulphide minerals from a massive sulphide ore, capture that value along with hydrogen and electricity by-products. If successful, the use of such tailings treatment process technologies could motivate a faster transition to not only coarser grinds, but potentially dry processing.

8. Tailings - Although outside of the initial plant control volume description, traditional tailings ponds are a source of both recycled water for the plant as well as water loss due to evaporation. If all the energy captured in the slurry has been dissipated by the time tailings discharge is reached, then the only source of heat to a tailings pond will be the sun. As a result, the Dalton equation (equation 1), which is a function of interdependent variable of humidity, surface area and wind speed over that surface, can be used to estimate the water loss by evaporation. This suggests that covering the water surface area of a tailings facility would reduce if not eliminate the pond's surface area. Such a cover would also eliminate the impact of wind speed which in turn would greatly reduce water loss by evaporation.

9. Dry processing - Substituting a dry grinding process for the wet grinding process found in figure 2 would also require a wet conditioning process preceding flotation. The resulting potential water loss for a control volume defined around the dry circuit would be, by equation (14), equal to zero. A dry HPGR is 25% to 30% more energy efficient than a wet SAG mill (Rosario & Hall, 2010). A dry VRM is documented as being almost 50% more energy efficiency than a wet ball mill (Swart, 2020; Swart et.al., 2022). Furthermore, if development efforts succeed for comminution technologies such as the conjugate anvil hammer mill (Li et.al., 2019; Wilson et.al., 2023) or the ARBS mill (ARBS, 2024), it is possible to suggest up to 80% reductions in energy use for the same grind duty increasing grinding efficiency yet again. Consequently, the potential water loss for a plant having a more efficient dry grinding circuit will be significantly less than a wet processing plant.

In addition, pneumatic fines transport will increase heat loss from the ore while adding fins to any large surface will further increase heat loss ($\dot{Q}_{heat}$).

Subsequent mixing of the dry warm ore with cooler plant water will diffuse the remaining heat in the slurry and bring the energy content to that of the baseline environment. As most if not all of the energy input into the ore through comminution has been lost or dissipated, the main driver of evaporation will be water surface area through any free surface present in the process such as that found in flotation, thickening, and the like. As a result, the wet conditioning process along with subsequent processes having free surfaces will need heat exchanger covers to reduce further potential water loss.

DISCUSSION

Limitations - The limitations to the development and eventual use of equations (4) to (14) resides in the validity of the assumptions used.

Assumption 1: Using Gunson's (Gunson et.al., 2012) results for the 50000 t/day, it is expected that some 116667 m^3/day of water is required. From Table 1, the daily tonnage for Cadia is 49560 t/day and for Canadian Malartic is 55000 t/day which is somewhat similar to that of the Gunson plant. Assuming the water requirements in processing are also similar, then the potential water loss through evaporation would be 0.8% and 1.3% respectively. Assumption 1 is considered valid.

This approximate 1% defines the upper limit of potential daily water loss. Assuming that 1% of the plant's 116 667 m^3/day (1166.7 m^3/day) water requirement is lost every day, over a year, the loss would be about 425 800 m^3/yr (365 x 1166.7 m^3/day) which is 3.65 times the daily water requirement of the plant.

Assumption 2: This is appropriate in order to simplify the relationship. However, measuring input and output temperatures would more precisely determine the energy captured or retained in the slurry, the concentrate or the tailings.

Assumption 3: This is appropriate as most if not all typical equipment found in mineral processing plants are not pressurized and all fluids are incompressible.

Assumption 4: As with assumption 2, this is an appropriate assumption in order to simplify the relationship. However, measuring input and output temperatures would more precisely determine the energy captured or retained in slurry, concentration or tailings.

Assumption 5: This assumption is appropriate in the context of estimating an upper limit to water loss through evaporation. However, as noted previously, there is some energy lost by heat transfer which would require a more in depth analysis of the materials used, equipment dimensions as well as the heat transfer properties of conduction, convection and radiation. On the other hand, the general guidelines presented here for increasing energy loss through heat transfer are valid.

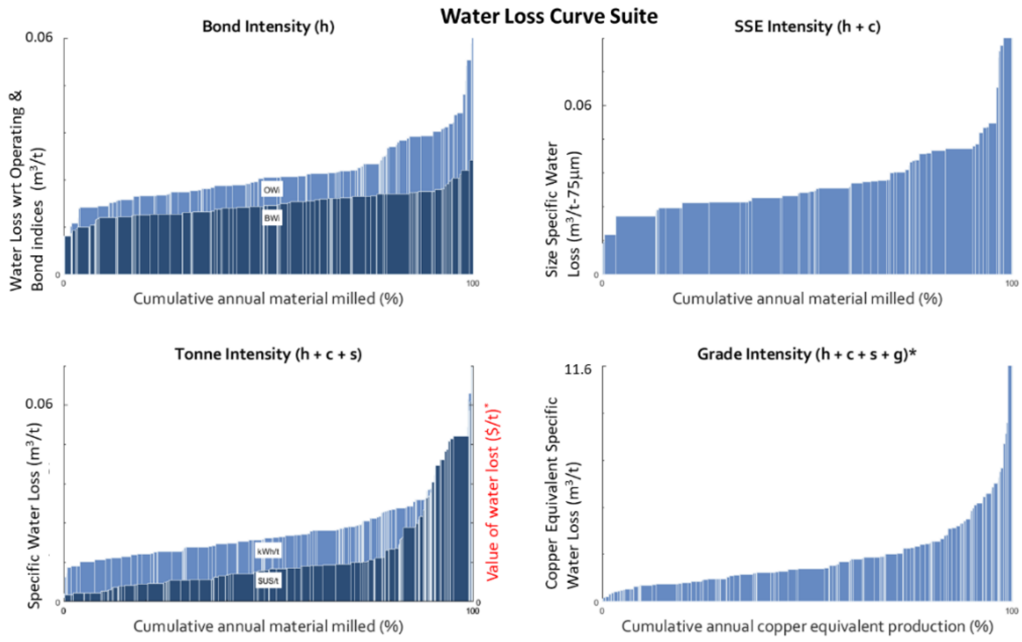
In summary, the definition of potential water loss as a function of comminution energy input (see equation 14) is valid. This defines an upper limit where all energy loss by heat transfer has been eliminated (ie the whole process is insulated). With respect to the use of the Dalton equation (1), it would then define the lower limit for water loss by evaporation. The actual water loss by evaporation for a given plant would be somewhere between these two limits. Determining more precisely where would require further investigation to determine the magnitude of varying degrees of heat loss and more precisely determine site specific water loss characteristics per equipment type.

Benefits - There are obvious social, cultural and environmental benefits to reducing water loss in mineral processing. However, the business benefit comes down to the net value that an operation can generate by reducing the amount of water lost through evaporation. The net value for mining operations in polar or near polar regions will be different from those at or near the equator.

In polar or near polar regions, mineral processing plants are packed into large, insulated buildings. The cost of water is essentially zero as there is potentially plenty in proximity to any mine. However, water loss by evaporation, if not evacuated from these buildings, tends to condense, and potential freeze on plant walls and roof especially during winter months. To mitigate this, greater heating as well as building ventilation is required. In addition, the presence of condensed water on inside building walls and structures contributes to infrastructure corrosion and associated maintenance costs. As a result, the value of reduced water loss through the measures described in this paper is measured by a reduction in energy use for building heating and ventilation as well as reduced building maintenance costs associated with corrosion.

In equatorial or near equatorial regions especially those that are water stressed, access to water may require a coastal desalination plant and pumping the desalinated water a few hundred kilometers. In such cases, the cost of water is related to desalination and pumping along with the associated operating costs. As a result, the value of reduced water loss through the measures described in this paper is measured by a reduction in desalination, pumping and operating costs.

Potential water loss metric - Knowing that potential water loss is a function of comminution energy, it becomes possible to revisit CEEC's energy curves (CEEC, 2023) and integrate a water loss metric. Every comminution kWh in the CEEC energy curve data can be first multiplied by 0.8 to determine the heat energy captured by a given slurry followed by dividing the enthalpy of evaporation and then multiplying the result with water density. The resulting potential water loss curves can be found in figure 4.



** The value of water lost is sight specific and needs to be determined*

Figure 4 The water loss curves

(modified from CEEC Energy Curves, (Ballantyne et.al., 2016; CEEC, 2023))

It is important to note that contrary to the energy curves, the cost or rather the value of water loss is not proportional to specific water loss. The value of water loss is a site-specific parameter and needs to be determined for each site. As a result, it will have to be plotted independently of the specific water loss data.

As mentioned, there are two limits to potential water loss: the upper and the lower limit. The upper limit is plotted in figure 4. However, by gathering surface area data on any open surface equipment and associated data in any given process, it would be possible to add to these water loss curves a lower limit value for potential water loss.

Conclusion

This work examined quantifying water loss in mineral processing operations by leveraging thermodynamics. Based on this analysis, which was limited to the processing plant, the following observations have been made:

- Comminution is the main driver for process water loss through evaporation. Consequently, choosing the most efficient grinding equipment has the potential for reducing water loss through evaporation.
- The upper limit for potential water loss through evaporation in a hypothetical 50000 t/day plant, can be as much as 1% daily which on an annual basis would equate to 3.65 times the daily plant water requirement. The lower limit for potential water loss through evaporation would be defined by the Dalton equation.
- Solar energy input can be reduced or eliminate from the plant with the installation of a roof. Depending on the design of the roof, it can also promote increased air flow through the plant.
- Water loss through evaporation can be reduced by increasing heat transfer through material selection, convection fin design and installation, and heat transfer covers for equipment such as trommels, screens, flotation cells, thickeners, and reservoirs.
- Dry grinding holds the potential to reduce significantly potential water loss through the use of more efficient grinding and classification technologies.

More research is required to determine, with greater precision, heat transfer rates of different mineral processing equipment and its impact on evaporation.

Acknowledgements

To Rampart Detection Systems for supporting the preparation of this paper and the associated presentation.

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