Energy recovery potential in comminution processes

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Abstract
Comminution processes are cited as having an efficiency of less than 1%. Even if the efficiency of these processes could be increased to 5% as is suggested to be possible, the conclusion would remain that comminution processes are very inefficient with some 95% of the input energy lost to the environment as heat. This is an interesting observation as one could suggest that, although comminution systems are very inefficient in producing new surface energy, they should be very efficient in producing heat. On the other hand, high efficiency in generating heat might be offset by a limit on the energy that can be recovered.

In this paper, four issues will be addressed: heat generated in comminution, potential energy recovery, different means to increase energy recovery in comminution processes and avenues to possible implementation. It will close with a discussion of a number of issues surrounding energy recovery in comminution processes.

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1. Introduction

One of the most eloquent descriptions of energy consumption in comminution was provided by LaNause in his 1998 paper (LaNauze and Temos, 2002) where he laid out the energy consumed per operation and expressed in CO2 equivalent tonnes at the Lienster nickel mine and plant. In that presentation comminution stood out as the operation that consumed the most amount of energy of any of the mining operations. Subsequent investigations by Norr and Haque (2010) confirm this trend in copper concentrate production (see Fig. 1) where again crushing and grinding is illustrated as the process that contributes the most to CO2 emissions.

This is indeed understandable as the new surface energy produced in comminution, as described by Lowrinson (1974), is less than 1% of the energy consumed by a given mill. Even if this ratio which is a definition of efficiency could be increased to 5% as is suggested by Tromans (2008), the conclusion would remain that comminution processes are very inefficient.

This is an interesting observation as one could suggest that, although comminution systems are very inefficient in producing new surface energy, they should be very efficient in producing heat. On the other hand, high efficiency in generating heat might be offset by a limit on the energy that can be recovered.

In this paper, four issues will be addressed: heat generated in comminution, potential energy recovery, different means of increasing energy recovery in comminution processes and avenues of possible implementation. It will close with a discussion of a number of issues surrounding energy recovery in comminution processes.

2. Heat generation in comminution processes

Using thermodynamics, it is possible to define an energy balance around the grinding circuit for the heat entering and leaving the grinding circuit (see Fig. 2) as follows:

\[ \dot{W}_{c} - \dot{Q}_{out} = \dot{m}_{sl}(h_{2} - h_{1}) \]  

(1)

Knowing the work input into the circuit as well as the circuit feed rate, there remain four unknowns in this equation.

Two of these unknowns define the enthalpy difference between the circuit discharge and feed. At constant pressure, this difference can be determined using a relationship that is valid for an incompressible fluid or a solid and is a function of the temperature difference and the heat capacity of the slurry (Sonntag et al., 2002). It is defined as follows:

\[ (h_{2} - h_{1}) = c(T_{2} - T_{1}) \]  

(2)

However, slurry is a mix of ore and water. The heat capacity of water at 1 atm is 4.18 [kJ/kg K]. Not knowing the exact composition of the ore, the ore heat capacity will be assumed to be 1.0 [kJ/kg K]. This is a conservative estimate based on the work of Waples and Waples (2004). A sampling of the heat capacities found in this reference is presented in Table 1.

Therefore assuming that the temperature difference and heat capacity for all components of the slurry is known, it would be possible to calculate the heat lost to the environment as follows:


\( Q_{\text{lost}} = W_{C.V.} - \sum_{i=0}^{n} \left( m_{\text{ore Core}}(T_2 - T_1) \right) \) \hspace{2cm} (3)

Limiting the components to water and an average ore and assuming both the feed and discharge temperatures are the same for both components, it is possible to reduce Eq. (3) to the following:

\[ Q_{\text{lost}} = W_{C.V.} - \left( m_{\text{ore Core}} + m_{\text{water Core}} \right)(T_2 - T_1) \] \hspace{2cm} (4)

Assuming the temperature difference between the circuit feed and discharge is 10 K (10 °C) and knowing power (7300 kW), feed rate (10,000 t/day) and slurry density of 70% solids for a given mill (Brunswick SAG mill, Orford et al., 2005), it is possible to determine the energy lost rate as 4069 kW which represents 56% of the power input into the mill control volume. That leaves 43% of the energy input into control volume captured in the slurry and the remain 1% is found in the new surface energy produced in comminution.

3. Potential energy recovery

Heat engines convert heat to a mechanical form of energy that can be used directly or converted into electricity where the maximum theoretical efficiency is defined by Carnot’s efficiency relationship. The Carnot efficiency is a ratio of the temperature difference present in the thermal system over the maximum or high temperature found in the system:

\[ n_c = \frac{T_H - T_C}{T_H} \] \hspace{2cm} (5)

where \( T_H \) (K) is the high temperature, \( T_C \) (K) is the low temperature where temperature is expressed in Kelvin (K).

It is interesting to note how the Carnot efficiency increases with increasing temperature difference as illustrated in Fig. 3. It should be underlined that the cold temperature is taken as 10 °C for all cases.

With respect to the previous case, it was suggested that a typical difference between the discharge and feed slurry temperature can be 10 °C. If the slurry feed temperature is about 20 °C (293 K) that would put the discharge temperature at 30 °C (303 K). If one could find a ground source for water cooling at 10 °C (283 K), one could then propose that the Carnot efficiency is determined between 283 K and 303 K. For this case, Eq. (5) gives the Carnot efficiency as 6.6%. Applied to the energy captured in the slurry in the previous case, one can propose that a maximum 6.6% of it can be recovered and converted to electricity. That represents 213 kW of power which over a year at 97% availability is 1.8 GW h of energy. At 20 cents/kW h, that represents some $360,000 of potential annual energy savings if the Carnot efficiency can be met.

4. Means to increasing energy recovery potential

Energy recovery efficiency as defined by Carnot is a function of the temperature difference between the hot source and a cold source. Essentially, increasing this temperature difference will increase the energy recovery potential.

In the comminution circuit case, the cold source is assumed to be water at the lower temperature (10 °C; 283 K) than the feed slurry temperature while the hot source is the discharge slurry temperature. The discharge slurry temperature can be estimated using a rearranged form of Eq. (4) giving:

\[ T_2 = T_1 + \frac{W_{C.V.} - Q_{\text{lost}}}{(m_{\text{ore Core}} + m_{\text{water Core}})} \] \hspace{2cm} (6)

Based on this equation, it is clear that the means to increasing the slurry discharge temperature is through (i) reducing the heat loss, (ii) increasing the energy input into the comminution circuit as defined by the control volume or (iii) both reducing heat loss and energy input into the comminution circuit.

4.1. Heat loss reduction

Heat loss reduction and possible elimination (\( \dot{Q} = 0 \)) can be potentially achieved through the insulation and sealing on the
equipment and associated piping, pumps and sumps reducing all heat losses as well as mass losses through evaporation. In the case of the Brunswick mill presented previously, heat loss elimination would increase the energy captured in the slurry to 99% of the input energy. This would drive the discharge slurry to a temperature of 42°C using Eq. (6) and a Carnot efficiency of 7.1% using Eq. (5). This represents an annual energy recovery potential of 4.3 GW h which at 20 cents/kW h is an energy saving of $870,000 annually.

4.2. Increasing the energy input

Increasing the energy input into the comminution circuit can be interpreted by increasing the control volume over which the temperature difference is determined.

Referring to the Cadia SAG mill (19 MW, 2065 tph) (Hart et al., 2001) and assuming slurry feed temperature of 20°C and 44.3% slurry heat capture rate, it is possible to calculate the slurry discharge temperature as 29.7°C using Eq. (6) and a Carnot efficiency for a 10°C cold source of 5.1% using Eq. (5). Expanding the Cadia control volume to include, not only the SAG mill, but also the two ball mills (8 MW/mill) (Fig. 4) leads to a slurry circuit discharge temperature of 29.7°C and a Carnot efficiency of 6.5% using Eqs. (6) and (5) respectively. The resulting effect of expanding the control volume to include the two ball mill circuits on the annual energy recovery potential is a recovery of 6.7 GW h for the SAG mill circuit and 8.6 GW h for the SAG/ball mill set or a potential annual energy saving at 20 cents/kW h of 1.7 million dollars.

4.3. Reduced heat loss and increased energy input

Reduced heat loss and increased energy input combined is expected to yet further increase the energy recovery potential. Table 2 presents the previous results along with the results combining both reduced heat loss means and increasing the control volume to include more comminution equipment.

![Fig. 4. Simplified Cadia grinding circuit.](image)

![Fig. 5. eTEG HV56 power output as a function of temperature difference (reproduced from Nextreme, (2012b)).](image)

One observation can be made from this table is that the maximum energy recovery potential can be obtained through insulation and sealing plus a control volume that includes all comminution systems present in a given grinding circuit.

5. Implementation

Depending on the grinding circuit, the energy recovery potential as defined by the Carnot efficiency can be quite significant. However, this will remain a “potential” until a viable recovery system can be implemented.

Consider that at the discharge of the comminution circuit, the working fluid mineral slurry has captured a certain amount of energy that can be defined by its heat capacity and temperature. Therefore, the greatest potential for energy recovery is found at the discharge of the grinding circuit which of course coincides with the input to the flotation circuit. It is at this location that one would find the highest slurry temperature. Also, at this location one could either deviate the energy carrying slurry into a separate heat conversion system or find a heat conversion system that has the potential to be integrated or retrofitted directly with the flotation circuit.

As the temperature difference is rather small, the number of possible means to recovering energy is limited. Two possible mechanical means to convert low temperature heat into electrical energy are the use of Sterling engines or organic Rankine cycles. The Sterling engine holds the promise of meeting the theoretical efficiency of Carnot while the organic Rankine cycle provides potentially an efficiency approaching that of Carnot. However, these would require separate infrastructure and space to allow their use. On the other hand, devices such as thermoelectric systems (TEG Power, 2012; Custom Electric, 2012; Termo-Gen AB, ...) would be limited by their high cost and the need for a large area to cover the necessary temperature range.
2012; Nextreme, 2012a) show the potential of being integrated and potentially retrofitted to existing mineral processing equipment. The trade-off for the use of thermoelectric systems is much lower efficiency requiring larger surface area for heat transfer. Essentially, the external surface area of flotation cells could provide an adequately large thermal interface for the installation of thermoelectric systems for heat conversion.

As an example, one can take the MIDUK circuit (MIDUK, 2004) which is composed of a SAG mill (3.5 MW) feeding two ball mills (2 x 3 MW) with 625 tph feed. Assuming this circuit is insulated and sealed, the discharge slurry circuit temperature would be 29.4°C. Using a 10°C cold source, the resulting Carnot efficiency would be 9.4% which represents an energy recovery potential of 7.5 GW h.

Using the data from one of these thermoelectric device manufacturers (Nextreme, 2012b) (see Fig. 5), the energy capture performance for a temperature difference of 30°C is about 1.27 kW/m². With an energy capture performance of 1.27 kW/m², it would require a rather large heat transfer area of some 680 m² of surface area to capture the 7.5 GW h of energy. In this particular plant, the grinding circuit discharge splits to feed five rougher column flotation cells which are 4 m in diameter and 12 m high. If 90% of the column surfaces can be used, it is possible to capture 7.3 GW h and convert it directly into electricity on an annual basis. The energy savings at 20 cents/kWh would be in the order of 1.4 million dollars for this plant.

6. Discussion

The preceding development illustrates that there is potentially a lot of heat generated in comminution and captured in the mineral slurry and that potentially a significant portion of this heat can be captured and converted back to electricity. However, this development also raises a number of issues which include the validity of the thermodynamic model of comminution, the assumptions used in the application of the model, the challenge of insulating and sealing a comminution circuit, the implementation of a capture and energy conversion system and comminution efficiency. Further, the application of an energy recovery system might have an impact on other dimensions to mineral processing such as flotation, wear and water recovery this possibly impact of which is also briefly discussed.

6.1. Validity of the thermodynamic model

Defining the control volume around a comminution circuit or circuits requires that all of the mass and energy flows entering or exiting this control volume be accounted for and included in the thermodynamic model. Similar to what would be done for say an oil-fired boiler circuit (Tarasiewicz and Radziszewski, 1990), one could, and in the future will, decompose any given comminution circuit into its main components and separate control volumes over which separate component thermodynamic models can be defined. However, this added level of detail would not negate the observation made using a thermodynamic model defined for a control volume around a complete comminution circuit or circuits which is “there is potentially a lot of heat generated in comminution and captured in the mineral slurry and that potentially a significant portion of this heat can be captured and converted back to electricity”.

6.2. Assumptions used

On the other hand, five of the assumptions used in the application of the model can be called into question with the first being the heat capacity of the ore and the use of Eq. (2). A conservative estimate of 1 kJ/kg K was used. However, it would be better to determine the composition of the ore and use it to calculate the actual heat capacity of the slurry. It should be noted that Eq. (2) especially with respect to water is valid at constant pressure which is assumed to be at atmospheric pressure. In a completely sealed system, the pressure would undoubtedly increase which would require including the difference in pressure along with the different in temperature to determine the change in slurry enthalpy. The subsequent analysis would need to be modified. However, this modification would not negate the observation underlined previously.

The second of these assumptions is the portion of energy being lost as heat. Other forms of energy loss are due to abrasive wear of steel media and liners as well as acoustics and vibration energy losses. In the case of abrasive wear of steel media and liners, one can make the case that abrasive wear is a different form of comminution. As such, the production of wear particles would result in an increase in new surface energy. It is reasonable to expect that the new surface energy produced in wear would also be less than 1% of the total energy dissipated in the wear process and the remaining would be lost as heat. On the other hand vibration energy would be dissipated through dampening of the mill structure which would generate heat in the mill structure. Vibrations in the audible frequency range would produce noise which should represent a fraction of the energy dissipated in vibration. As such, it is reasonable to assume that close to 99% of the net energy input into comminution would eventually find itself converted into heat.

The third of these assumptions is the portion of energy captured in the slurry in current operations. The number of 54.7% was arrived at through the use of anecdotal information on the temperature difference between the slurry at the mill feed and at the mill discharge. This is an important assumption as it can be used to justify the effort and cost of insulating and sealing the grinding circuit. The actual energy lost to the environment for any mill can be estimated by first measuring the temperatures of the feed and discharge slurries, determining the heat capacity of the different components of the slurry and then using Eq. (4) to obtain the energy loss.

The fourth of these assumptions is related to the adiabatic and sealed conditions used to determine the maximum amount of heat captured in the slurry. Although it is possible to envision the development of a completely sealed grinding circuit, it is somewhat difficult to ensure truly adiabatic conditions at reasonable cost. The result will be a somewhat insulated and sealed circuit that falls short of the adiabatic target and therefore short on the amount of energy that can be captured in a slurry.

And fifth of these assumptions is related to water being added only to the circuit with the mill feed to ensure a 70% solids slurry mix. This of course is not the case as water is typically also added at the cyclones in order to obtain the desired separation (cut) size distribution. In this particular case, it was assumed that the water added to the circuit also included the water added at the cyclones. It is expected that an increase in the water to the circuit would reduce the slurry density to 60% solids resulting in a reduction of the circuit discharge temperature and consequently the recoverable energy. As an example, for the Cadia sealed and insulated SAG/Ball mill circuit, the recoverable energy would drop by some 6% from 29.6 GW h to 27.8 GW h. As a result, it would be important to ensure that all water input into a given circuit control volume would be accounted for and included in the calculation.

With respect to water addition to the circuit, it should be noted that reduced water usage and therefore increased percent solid slurries would have the contrary effect on circuit discharge temperature and consequently the associated recoverable energy. Using again the Cadia sealed and insulated SAG/Ball mill circuit
example, increasing the slurry density to 75% solids would increase the recoverable energy by some 2.7% from 29.6 GW h to 30.4 GW h.

6.3. Insulation and sealing

The insulating and sealing an existing comminution circuit is in itself a non-trivial challenge. The minimal requirement of an insulating system a rotating mill such as SAG or ball mill would be that it does not increase the downtime for liner change-outs. Further, it would be unrealistic to completely seal an existing comminution circuit. However, measures can be made to reduce such loss by covering mill trunnions and sumps.

6.4. Implementation

The development of energy harvesting systems, such as the thermoelectric system used in this paper, is in its infancy and it is evolving with improving power generation performance (Huesgen et al., 2008; Hsu et al., 2011; Karabetoglu et al., 2012). One of the motivations for improving performance is that fact that currently these systems have relatively low efficiency as compared with other heat engine technologies which in turn are lower than the Carnot efficiency. Typically, thermoelectric generator systems are used to power small instrument packages mounted to equipment that provide a high temperature difference in order to overcome the low efficiency. Another possible means to increasing performance is through the use of larger surface areas for energy harvesting such as the use of floatation columns in the case of the MIDUK circuit. In this particular case and due to the small size of the individual thermoelectric units (HV56 footprint is 3.1 mm × 3.3 mm, MIDUK, 2004), the energy recovery application would require stringing a number of such devices in series to generate a larger voltage and then tying these strings in parallel in order to obtain a higher current. The system would undoubtedly require a transformer to step the voltage up to that required for it to be recycled into the plant electrical grid. All of this will affect the stated performance and will required further and focused development of such energy harvesting systems tailored to the conditions in the mining industry.

6.5. Comminution efficiency

Having applied established thermodynamic principles to a control volume defined around a comminution circuit and demonstrate that energy harvesting systems hold the potential of recovering a portion of the energy captured in a slurry, one can now revisit the definition of the efficiency of comminution processes. The goal of comminution is to grind a given ore from one granulometry to another smaller granulometry. In the accomplishment of this goal, heat is generated and in current operations, it is simply lost to the environment. However, it has been demonstrated that it is possible to capture this energy in the slurry and then recover a portion of it. Therefore, it might be time to propose that the desired goal of comminution processes is not only to grind a given ore to a target granulometry, but also to capture and recover the heat generated in comminution. If one accepts that there are two desired goals to be accomplished in comminution, then one can propose that the efficiency of comminution processes should be a sum of the efficiency of grinding and energy recovery possibly illustrated as follows:

\[
n = n_b + n_c n_s.
\]

Table 3 presented the resulting comminution circuit efficiency assuming that the new surface energy or simply breakage efficiency is equal 1%.

The use of a modified measure of comminution efficiency may lead to exploring other measures to increase the efficiency of comminution through thermal means. The main motivation could be the observation that energy recovery is a function of the temperature difference. Increasing the temperature of the slurry will lead to a higher Carnot efficiency which in turn leads to a higher potential for energy recovery.

However, independent of the comminution technology used, it should be underlined that the Carnot efficiency outlines the upper limit or maximum potential of the slurry energy that can be converted back to electricity. The actual efficiency will depend on the technologies used to convert the energy captured in the slurry such as thermoelectric generators.

In addition to the issues above, there are a number of other implications related to capturing all comminution energy in the slurry. These are:

6.5.1. Flotation performance

In the literature a number of sources (Lazarov et al., 1994; Engel, 1996; Mukai and Nakahiro, 1970) indicate that there might be an advantage to flotation in increased temperature situation. More focused research should be initiated to explore in more detail the effect of increased slurry temperatures on flotation performance.

6.5.2. Corrosive wear

It is uncertain that an increased slurry temperature will always increase the rate of corrosive wear in a mill. One study on the wear of steel media (Radziszewski, 2002) indicates that depending on the composition of the ore and the water, the resulting combination might result in a temperature independent corrosive wear environment or potentially even reduce corrosive wear. As with flotation performance, more research should be initiated to better understand the temperature effect on corrosive wear in a grinding environment.
6.5.3. Water recovery

Assuming that the grinding circuit is insulated and sealed, all water losses in the grinding circuit would be eliminated. However, as the slurry temperatures increase, the water lost due to evaporation at the flotation circuit would increase. With the increase of water loss due to evaporation, the case might be made that the equipment in the grinding circuit should also be sealed up until a point in the circuit where the remaining energy in the slurry can be drawn off through evaporation and the water vapor condensed and recycled.

It is interesting to note that if water usage was reduced to nothing such that the comminution circuit was converted to dry grinding there would be an important effect on the energy recovery potential. To illustrate this point, one can take the Cadia SAG/Ball mill circuit case and remove water from the calculation while assuming the same mill power draw and mill tonnage. The resulting mill circuit discharge temperature of the ore would be 80 °C. Using 10 °C cold source, one could obtain a Carnot efficiency of 19.9%. The resulting energy recovery could then potentially become 58.7 GW h as compared to the previous 29.6 GW h with 70% solids slurry.

7. Conclusion

There is room to propose that the goal of a comminution system is not only the size reduction of a given ore to some target granularity, but it is also the capture and recovery of the heat generated in comminution. With this dual task, the notion of comminution efficiency changes to include Carnot efficiency along with the efficiency to produce new surface energy in the ore. With this inclusion, efforts can now be justified to increase the efficiency of the comminution process through thermal means the impact of which can be estimated through the use of a thermodynamic model of comminution. One such effort would lead to the insulation and sealing of the grinding circuit to eliminate all heat losses to the environment with the resulting comminution circuit efficiency becoming 10%. In the Cadia SAG/Ball mill grinding case, the use of energy harvesting technologies such as a thermoelectric generation system could possibly recycle annually up to 7.3 GW h of energy which a 0.2 $/kW h potentially represents over 5 million dollars in energy savings.

In this analysis, only SAG and ball mills were considered. However, higher intensity stirred mills and in general higher intensity grinding may provide higher slurry discharge temperatures and therefore higher energy recovery potentials. This observation may justify the development of new yet higher intensity grinding systems that may provide both increased throughput and higher energy recovery potentials resulting in higher overall comminution efficiencies. Despite the promise of increased comminution circuit efficiency and potentially substantial annual energy savings, there remain a number of challenges before such energy harvesting technologies can be brought successfully to the mining industry.

References