PRINCIPLE OF EXTRACTIVE METALLURGY

JIGGING

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1. INTRODUCTION

Jigging is one of the oldest methods of ore treatment and remains one of the workhorses of the mining industry. Until recently, it was, together with dense medium separation (DMS), the main (when not the only) choice for pre-concentration and concentration of coarse-sized ores and coals. Jigging has also currently exceeded the limits of mineral processing, having found applications in different recycling industries, and growing concern related to water usage has led to a renewed interest in the use of dry jigging.

On the other hand, the current scenario of decreasing ore grades and the recent developments in sensor-based sorting (SBS) technologies have established increasingly challenging levels of operational efficiency. With compact installation units, dry operation, and the ability to deal with ores of complex mineralogy, like rare earth bearing minerals , SBS technology has the potential to replace jigs in many of its traditional applications, particularly those involving coarse particle treatment. The scenario is in some ways analogous to the beginning of the 20th century when the advent of magnetic separation and froth flotation partially replaced gravity concentration processes. Breakthroughs and innovations in the understanding, design, and optimization of jigs should be sought in order to keep the technique competitive.

The present paper provides an up to date review of the fundamentals of jigging operation and outlines some avenues for future research and developments. The configuration, operational principles, and main applications of different jig types have been comprehensively reviewed. A description of the main theoretical approaches used is presented, highlighting their strengths and weaknesses. Finally, suggestions for upgrading jigging technology through new conceptual approaches are made.

2. JIGGING: CONCEPTS AND DEVELOPMENT

Jigging is a method of gravitational preparation of natural resources, based on separation of mineral mixture on density in vertically oscillating water stream of variable direction. The end products of jigging are the following : concentrate with high content of useful component and wastes (sometimes there is separated intermediate product consisting of aggregation of useful component with dead rock or from their mechanical mixture, the so called intermediate product. Separation of material during jigging takes place as a result of periodical influence of the upward and downward of water (pulsations) on the layer of separating material (the so called jigging bed), located on the sieve. Under action of pulsations the bed is alternately loosened and compacted , and the particles of different density mutually move on its height : with small density – into upper layers, with big density - into bottom layers. The formed layers of different density are separately removed as a concentrate, wastes and, sometimes, intermediate product.

Gravity concentration methods aim to create conditions in which particles of different densities, sizes, and shapes may move relative to each other when under the action of gravity or centrifugal forces, originating multiple bands containing the light and dense materials . When the relative interparticle movement manifests itself in the form of vertical expansions and contractions of a particle bed caused by a pulsing fluid, the gravity concentration operation in question is known as jigging. Although its origin possibly dates back as far as Classical Antiquity , the first remarkable description of jigging appeared only in the 16th century in *De Re Metallica*, the well-known seminal work by Agricola . In this, the first jigs are depicted as perforated baskets (the "jigging sieve") containing the mixed ores that were manually and repeatedly dipped into a water tank, after which stratified layers of ore were removed by hand. Until the advent of the industrial revolution, modifications in jigging devices were limited to a little more than the inclusion of levers for using larger baskets The emergence of hydraulic systems like the piston pump and the plunger pump, with or without seals, are regarded as decisive for the introduction of mechanically pulsated jigs , giving rise to the basic configuration of modern jigs.

2.1. HYDRAULIC JIGS—CONFIGURATION AND TYPES

In modern water jigs, the original basket was replaced by a compartmentalized vessel equipped with a sieve (or screen) to support the particle bed, mechanical pulsation devices were introduced, and operation became continuous. The general scheme of most industrial jigs consists of a container divided into two compartments, one of them corresponding to the separation chamber where feed particles are located on a supporting sieve and through which the water performs its oscillatory motion. The other compartment contains the mechanism that drives fluid pulsation responsible for moving the bed during its passage by the jig (Figure 1). The pulse wave can be produced either mechanically through a plunger or by the pulsation of water or air that is intermittently fed into the jig vessel by using a special valve. In some types of jig, the relative motion between particles and water is obtained through the vertical displacement of the supporting sieve.

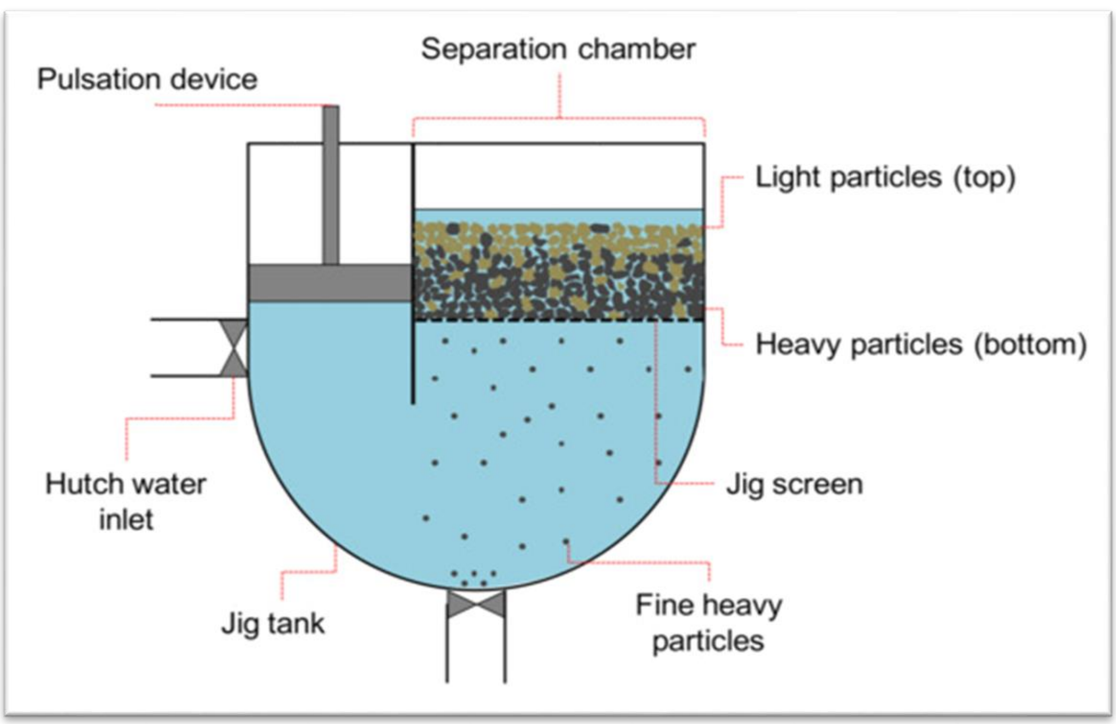

Figure 1. General scheme of a jig (front view).

In the case of continuous operation, particles of varied composition (like non-beneficiated ores) are fed at one end of the jig tank and distributed over the screen, which is slightly inclined towards the outlet end (see **Figure 2**). As particles pass through the equipment, they are subject to successive cycles of expansion and compaction that promote the stratification action. When reaching the discharge end, the particle bed must be separated into two distinct zones: a layer of light material, located in the upper portion of the bed; and a layer of dense particles concentrated in the lower fraction. The target content and yield of the desired product will define the height ("*cut point*" or "*cut height*") in which the stratified bed should be split at the discharge end. In hydraulic jigs, most of the water is withdrawn from the jig with the products, so that replacement water ("*hutch water*") is regularly pumped into the jig vessel.

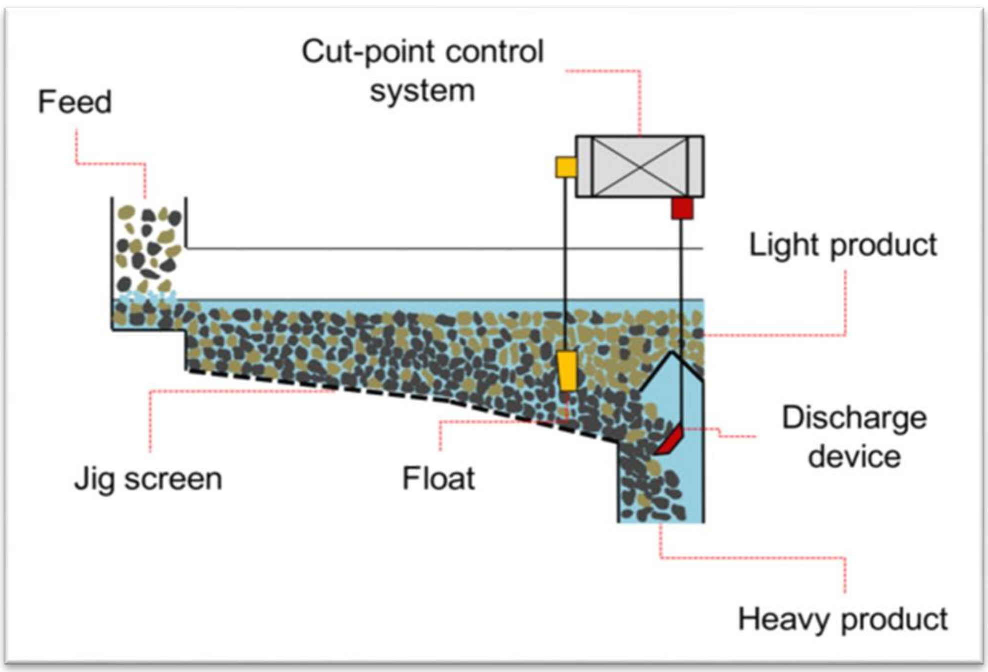

Figure 2. General scheme of a jig (side view).

The differences among the various types of industrial jig are associated with a plethora of factors, including vessel geometry, pulsation mechanism, bed transport, discharge system, and separation control scheme. In this sense, Sampaio and Tavares have proposed a broad classification of jigging devices based on three main aspects: (a) condition of the jig sieve (fixed or mobile), (b) method of extraction of the heavy product, and (c) bed pulsation mechanism.

In the most common fixed-sieve jigs, the water moves through a sieve that remains immobile inside the separation chamber, as previously mentioned. In some jigs, however, the bed motion is produced through the mechanical displacement of the jig sieve within a stationary fluid. Versions of this type of jig were developed in the 19th century, as exemplified by the already obsolete Hancock and James jigs . Current jig models in this category include the ROMJIG and the In Line Pressure Jig . In both, the jig screen is cyclically moved up and down by a hydraulic servo system connected to the screen.

While the light product is invariably removed by overflowing, the dense product leaves the jig in two distinct manners: "through the screen" and "over the screen". In the first case, used for finer-sized feeds, heavier particles pass through the screen to be drawn off as the dense product, collected into the bottom of the jig compartment and removed through a spigot. In these jigs, a layer of heavy, coarse material (called "ragging") is placed on the screen onto which the feed is introduced. Thus only particles of high density can penetrate through the ragging and then reach the jig screen.

When jigging "over the screen" is used, a discharge device equipped with sensor systems controls the withdrawal of the heavy product. The most utilized methods of discharge include the regulation of opening of a mobile gate or the adjustment of the rotation speed of a rotary discharge valve. In order to maintain an accurate cut-point, the thickness of the heavy material layer is continuously measured by sensors, and the immersed float method is still used. In this, a float calibrated with weights to exhibit an apparent density equal to the separation density is used to adjust the height in which the bed will be split . Electromagnetic or ultrasonic displacement sensors measure the position of the float, which is the input of proportional–integral–derivative PID controllers that drive the discharge device. Floats are eventually subject to inaccuracies due to their invasive nature and the harsh environment inside a jig bed. Radiometric density sensors have been pointed out as a more accurate option by allowing tracking changes in density over the bed pulsation cycle and have been recently used to validate a dynamic model of discharge in a coal jig .

Jigs can also be divided concerning the pulse generation mechanism into piston-type jigs, diaphragm-type jigs, air-pulsated jigs, and mobile-sieve jigs (described above). One of the first mechanical jigs is the Harz jig . This consists of a two-chamber tank, as illustrated in **Figure 1**, equipped with a piston linked to a connecting rod and crank system, thus resulting in a harmonic movement. Although it has simple mechanical design and operation, water leakage is a recurring concern when operating this jig due to the difficulty of maintaining the seal between the piston and the housing walls.

A solution to prevent water leakage through the flanks of the plunger is to replace the piston with a rubber diaphragm connected to an eccentric vertical shaft, such as in the Denver jig . With a layout nearly similar to the Harz jig, the Denver jig has a rotary valve operating in synchrony with the plunger, which avoids the input of hutch water during the suction stroke and allows more precise control of the jigging cycle. Variations in tank design and the position of the plunger in the chamber have originated many other models of diaphragm-pulsated jigs, such as the Bendelari jig, the Pan-American jig, and the Yuba jig . **Figure 3** depicts a basic scheme of these types of equipment.

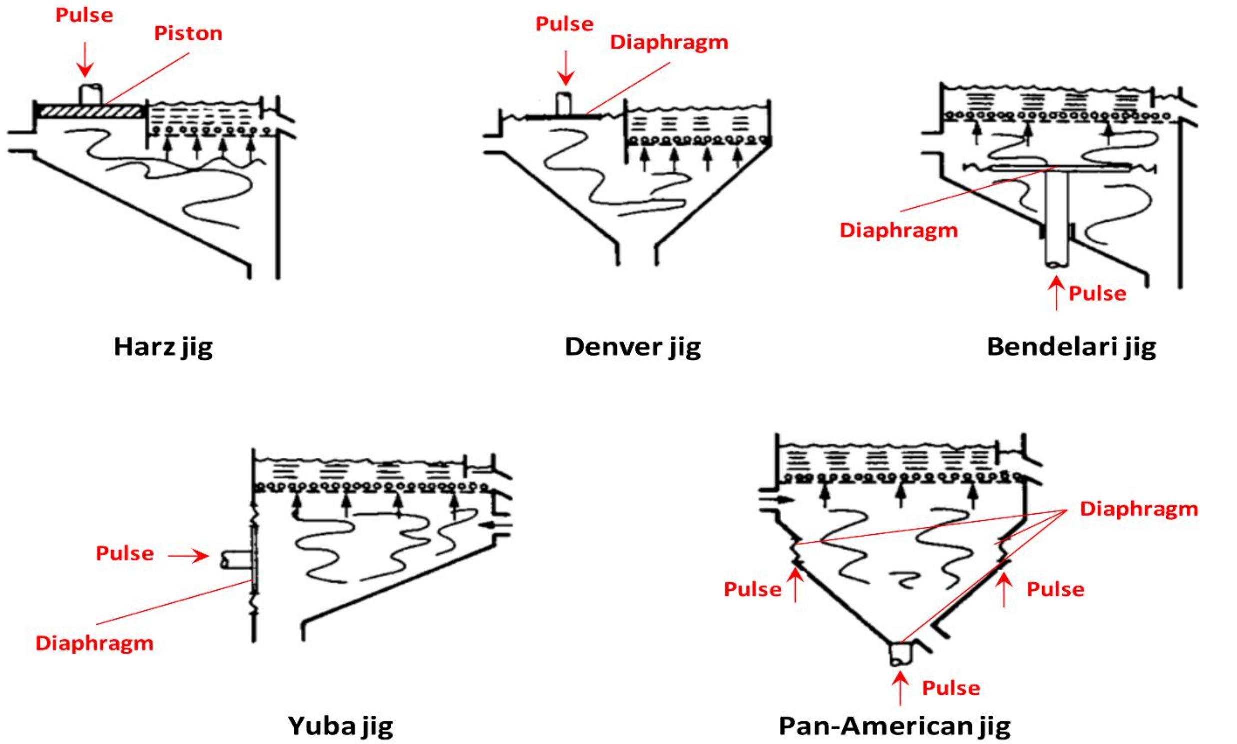

Figure 3. Scheme of some piston and diaphragm-type jigs (adapted from Sampaio and Tavares

2.2. Alternative Jigs

A few separators have been developed or adapted using the basic principle of jigging, i.e., bed stratification induced by fluid pulses, although one or more design and operating features may significantly differ from those of conventional hydraulic jigs. The most distinguishing equipment in this class includes dry jigs, centrifugal jigs, and a range of jigging machines exclusively developed for plastics recycling.

2.2.1. Dry Jigs

Dry jigging (also called "pneumatic" or "air jigging", though these designations may be mistaken as air-pulsated water jigs) is becoming more and more relevant as the concern with slurry waste disposal and water handling costs intensifies. Dry jigging was introduced in the coal industry during the 1920s by applying the concepts involved in wet jigging technology to the design of pneumatic cleaning machines . Since then, significant improvements have been implemented in its conception and operation.

Modern dry jigs consist of an inclined vibrating deck in which the feed distributed at one end is subjected to the action of two distinct upward air streams (see **Figure 4**). One of them is continuous, having the function to loosen the bed and so allow a uniform air distribution. A second superimposed pulsed airflow promotes density stratification of the bed during its passage on the jig deck. The combined effect of the two independent air streams allows precise control of stroke frequency and amplitude . Nuclear density sensors are installed near the discharge end of the deck to control the bed level and the cut-height . Stargate discharge valves are normally used for the withdrawal of the products. The equipment is enclosed and a dust collector system handles the generated dust.

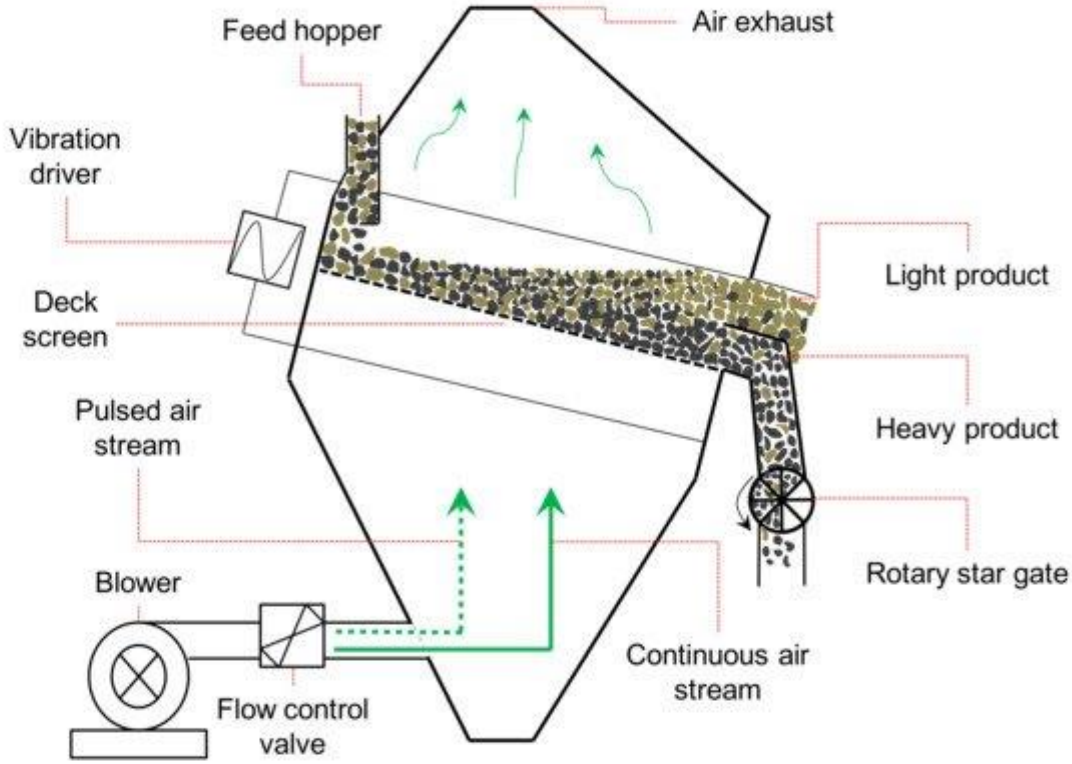

Figure 4. Basic scheme of a dry jig.

The evident advantage of dry jigging is its complete elimination of process water, which is particularly desirable in places with limited or difficult access to water or if the jig feed is affected by moisture. However, its separation efficiency is recognizably lower than that of hydraulic jigs since the density of air is negligible compared to the density of water. Such low density is compensated for by using high air stream velocities, thus increasing turbulence and remixing effects. Consequently, dry jigs are applied to separate only close-sized material, normally larger than 2 mm , containing relatively low content of near-gravity material (NGM).

2.2.2. Centrifugal Jigs

In centrifugal jigs, the jig screen consists of a rotating cylinder in which centrifugal forces dozens of times higher than gravity are produced. Therefore, it is classified as one of the so-called "enhanced gravity concentrators" or simply centrifugal concentrators, which also include the Knelson, the Falcon, and the multi-gravity concentrators . Currently, there exist two commercial models of centrifugal jigs: the Kelsey jig and the Altair jig . In both versions, the rotating bowl is placed vertically inside a casing having launders to collect the concentrate and tailings. The jig hutch is enclosed and equipped with a side-pulsed mechanism consisting of rubber diaphragms linked to pulse arms. During operation, feed slurry enters the jig through a pipe near the middle of the bowl and is distributed onto the jig screen by the action of centrifugal forces. The screen is covered with a layer of coarse heavy material (ragging) so that the discharge of the heavy product is of "through the screen" type. Pressurized water is periodically injected to keep the bed dilated as well as to ensure that only fine, dense particles can pass through the ragging. Low-density particles move upwardly onto the screen and are withdrawal over the bowl top.

The ability to greatly increase the apparent gravitational field allows centrifugal jigs to separate ultrafine particles (<40 μm), far below the minimum size limit of any other jig . However, special attention must be paid to feed classification to avoid blockage of the jig screen by excessively coarse particles. Centrifugal jigs also figure among the gravity concentrators having the largest specific water consumption (up to 15 m^3/ton of ore) .

2.2.3. JIGS FOR PLASTIC–PLASTIC SEPARATION

In recent years, the growth in the application of jigging for solid wastes recycling has driven the conception of some unique jig separators. One such case is the set of jig prototypes developed exclusively for separating plastics. The first of these prototypes was the RETAC jig, a modified TACUB jig in which water pulsation and jigging cycle were optimized to address the difficulties related to the separation of materials with densities close to that of water, like plastics. A further development consisted of installing an aeration diffusion tube (air bubbler) under the jig screen of a RETAC jig, giving rise to the so-called hybrid jig. This equipment allowed the separation of plastics having similar densities but different surface wettability after a pretreatment step. The issue of separating plastics lighter than water was settled by conceiving of the Reverse jig prototype . In this, a second screen installed at the top of the RETAC jig container allows separating plastics based on differences in levitation velocity. Improvements in the scheme of product extraction were subsequently made for the RETAC and hybrid jigs. Recently, the separation of metal wires and plastics was tested with relative success in the RETAC jig . Although tailored to the recycling context, undiscovered benefits could result from the adaptation of some concepts involved in the design and operation of such jigs to the framework of mineral processing (e.g., the use of under-screen aeration to change the apparent density of particles, as in the hybrid jig).

2.3. Applications

The various types of hydraulic jig find vast application in mineral processing, ranging from minerals as dense as native gold (19 g/cm^3) to vitrinite (up to 1.3 g/cm^3) . It is par excellence a traditional item in coal processing plants while typical examples of using jigging for ore processing include beneficiation of iron ore, alluvial gold concentration, beneficiation of chalcedonite, pre-concentration of tungsten ores , cleaning of phosphate ores, as well as the concentration of tin and copper ores . Dry jigs, otherwise, are mostly used in coal processing.

In recent decades, jigging has surpassed the limits of mineral processing, being currently utilized in a variety of sectors. As noticed by Turner, jigs have found applications as peculiar as in the separation of bones and cartilages for chewing gum production. Most notably, jigging has found particularly fertile ground in recycling and waste processing. As mentioned earlier, recycling of plastics like polyethylene, polycarbonate, and polyvinyl chloride PVC has even been boosting the development of new jigging devices, particularly in Japan. In the case of metals recycling, jigging has been used to recover ferrous and non-ferrous metals from different sources, such as automobile scrap, steelmaking slag, and electric cable wastes.

Dry jigs, in particular, have been described as a promising method for recycling and upgrading the quality of coarse aggregates from construction and demolition wastes (CDW). The results obtained by Sampaio et al. showed it to be possible to obtain recycled aggregates of composition that meet the minimum standards of quality of many countries. On the other hand, dry jigs showed a relatively high unit energy consumption (of the same order of crushers) in the economic analysis of a CDW plant performed by Coelho and Brito.