THEORY AND APPLICATION OF COLUMN FLOTATION

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THEORY AND APPLICATION OF COLUMN FLOTATION

Kwang S. Moon* and Louis L. Sirois**

Abstract

The flotation mechanisms of various flotation machines are reviewed briefly. The inherently superior flotation mechanism of a countercurrent flotation column is described in more detail and is compared with that of conventional, mechanical flotation machines. The merits of countercurrent column flotation include: improved metallurgical performance in terms of grade and recovery; effective cleaning action in the long cleaning zone with a blanket of fresh water; smaller floor space required because of its vertical configuration; low capital, operational, and maintenance costs because of the absence of moving parts; and finally, easier flotation control as a result of the simplified circuit. Flotation studies on various minerals and coal at CANMET indicate that the Canadian countercurrent flotation column performs better than conventional, mechanical flotation cells in terms of concentrate grade and recovery. Some industrial experiences with the Canadian flotation column on various sulphides, oxides, and coal are also presented.

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THÉORIE SUR LA FLOTTATION PAR COLONNE ET APPLICATION DE LA MÉTHODE

Kwang S. Moon* et Louis L. Sirois**

Résumé

Le présent rapport comprend une brève description des mécanismes de flottation de diverses machines de flottation. Le mécanisme de flottation supérieur d'une colonne de flottation à contre-courant est décrit de façon détaillée et comparé à ceux des machines classiques de flottation mécanique. La flottation par colonne à contre-courant comporte plusieurs avantages, à savoir, l'amélioration du rendement sur le plan métallurgique en fonction de la qualité et du taux de récupération du produit et l'efficacité supérieure du long circuit de relavage, grâce à une couverture d'eau douce. De plus, la flottation à contre-courant n'occupe qu'un espace restreint en raison de la configuration verticale de la colonne. Par ailleurs, les coûts en capital, les charges d'exploitation et les coûts d'entretien sont peu élevés parce que le mécanisme ne comporte aucune pièce mobile. Enfin, comme le circuit de flottation est simplifié, on peut avoir un meilleur contrôle sur le procédé. D'après les études de CANMET sur la flottation du charbon et de divers minéraux, la colonne de flottation à contre-courant mise au point au Canada donne un meilleur rendement que les cellules de flottation mécanique classique en ce qui a trait à la qualité et au taux de récupération du concentré. L'industrie a mené des essais de flottation avec du charbon, divers minéraux sulfurés et oxydes, au moyen de la colonne de flottation canadienne. Les résultats de certains de ces essais sont également présentés.

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INTRODUCTION

The prolonged prosperity of modern technology in the past two decades has depended much on heavy consumption of non–renewable natural resources. As a result of exploitation of high–grade ores in the past, the mineral industry has had to process increasingly large quantities of raw materials that contain smaller amounts of economic minerals. At the same time, ores mined now are more complex, which makes the separation process more complicated and costly. The mineral processing industry has responded to this problem by adapting ever larger equipment.

Among many different techniques for mineral beneficiation, froth flotation has long been one of the most effective for selective separation of fine mineral particles. In many cases, froth flotation is the only separation process for efficient treatment of fine particles. Consequently, physical dimensions of the flotation cell have been increased. The largest conventional mechanical flotation cells now have a nominal capacity of 85 m^3 (3,000 ft^3). Scale–up of the conventional mechanical flotation mechanism, however, faces more and more constraints because of the hydrodynamic difficulties imposed by a large pulp body. The basic mechanism of a conventional, mechanical flotation machine has not been changed for more than half a century. Development of an efficient alternate flotation mechanism would much enhance the capability of the flotation industry. In his theoretical review, Moon (1) indicated that countercurrent column flotation has distinct advantages over conventional mechanical flotation.

In this paper the mechanisms of conventional mechanical flotation as well as countercurrent column flotation are reviewed briefly. Some results from column flotation studies on various ores at CANMET are given. Other industrial experience with the Canadian flotation column is also discussed.

FLOTATION MACHINES

As discussed by other investigators (2–7), the trend in development of modern flotation machines is their growth in size for economic treatment of large volumes of low–grade ores. Mechanical flotation cells with capacities of 14 m^3 (500 ft^3) are in wide use. More recently, some open–flow, mechanical flotation cells have been made available in sizes up to 85 m^3 (3,000 ft^3) by Wemco (8,9). Aside from these developments, the Maxwell flotation cell, with capacity of up to 57 m^3 (2,000 ft^3), has been in use in Canada, Australia, and South Africa for more than two decades. The machine is essentially a cylindrical conditioner with a mixing impeller and an air supply at the bottom.

The flotation of coal differs from sulphide flotation in many aspects. The bulk of the material has to be floated, leaving only small amounts of waste behind. Because the specific gravity of coal is much lower than that of ash minerals, modified mechanical flotation cells are being used for the flotation of coal. According to Young (5), better selectivity in coal flotation was obtained in a cell–to–cell flotation machine than in an open flotation machine. "Denver DR Coal" and "Denver Sub–A Coal," with capacities ranging from 2.8 m^3 to 14.2 m^3, are designed by Joy Industrial Equipment Co. to float coal at a low pulp density using a smaller impeller for low power consumption (10). These machines have restrictions in the cell to improve the recirculation of pulp and large–capacity froth paddles on both sides of the cell to remove voluminous froths. The Galigher Co. offers the "Agitair Coal Flotation Machine" with a capacity of up to 28.3 m^3. The "Wemco 1+1 Coal Flotation Machine," with a small hole disperser, has a capacity of 28.3 m^3. Both the "Humboldt Wedag Coal Flotation Machine" (capacity 12 m^3) and the "Minemet Industrie Coal Flotation Machine" have a shallow design for the handling of relatively coarse particles in coal flotation. Unifloc Ltd. is offering a Denver Sub-A cell-to-cell coal flotation machine with a capacity of 14.2 m^3. In the USSR several types of mechanical flotation machines are being used (11). One of them has separate zones for aeration and agitation to maintain a relatively quiescent pulp body in spite of the shallow cell.

Non-mechanical flotation machines have no mechanical mixing mechanisms and come in three types. In pneumatic flotation machines, compressed air is used for the simultaneous mixing and aeration of pulp. Some of these machines are still being used for the flotation of apatite-nephelin ores in the USSR (2,11). On the other hand, Heyl and Patterson Cyclo-cells are being used for fine coal cleaning in the USA (79). The second type of non-mechanical flotation machine is a froth separator developed in the USSR. As Malinovskii et al. (12) described it, the separation is achieved by percolating the conditioned pulp through a bed of froth. The third type of non-mechanical flotation machine is the countercurrent flotation column which is described here in more detail.

COUNTERCURRENT FLOTATION COLUMN

DESIGN AND DEVELOPMENT

The name "flotation column" implies that the vertical dimension is larger than the horizontal. "Countercurrent" means that the direction of flow for the pulp and for the air bubbles inside the column is opposite each other. Three types of flotation columns are available commercially at present: (a) the Canadian countercurrent flotation column (13, 14), (b) Deister Flotaire column (15, 16), and (c) Leeds flotation column (17, 18).

Among these, only the Canadian flotation and Deister Flotaire columns are true, non-mechanical, countercurrent flotation columns. Deister Flotaire column has the pulp inlet at the top but does not have the long cleaning zone that characterizes the Canadian flotation column.

Leeds flotation column is basically a modification of conventional mechanical flotation cells. It simply extends the vertical dimension to add a cleaning zone between the mechanically agitated pulp body and the froths. Inside the cleaning zone, mineralized air bubbles are cleaned by counter-flowing freshwater as they pass around the obstructions that are offered by horizontal rods placed inside it. Leeds flotation column has co-current flow of solid particles and air bubbles, although the cleaning water moves counter current to the air bubbles.

The Canadian countercurrent flotation column has many unique features, which are the main objectives of the present paper. In the original design (Fig. 1), the column is very long, usually 13 m (40 ft) and contains two zones for recovery and cleaning of valuable minerals. Conditioned mineral pulp is fed through a side inlet that is located about 2.4 m (8 ft) from the top. Mineral particles encounter rising air bubbles as they settle by gravity action down through the lower part of the column, i.e., the recovery zone, where the continuous phase is pulp. Fine air bubbles are generated using compressed air through a bubble generator located at the bottom of the column. The continuous head-on collision between the

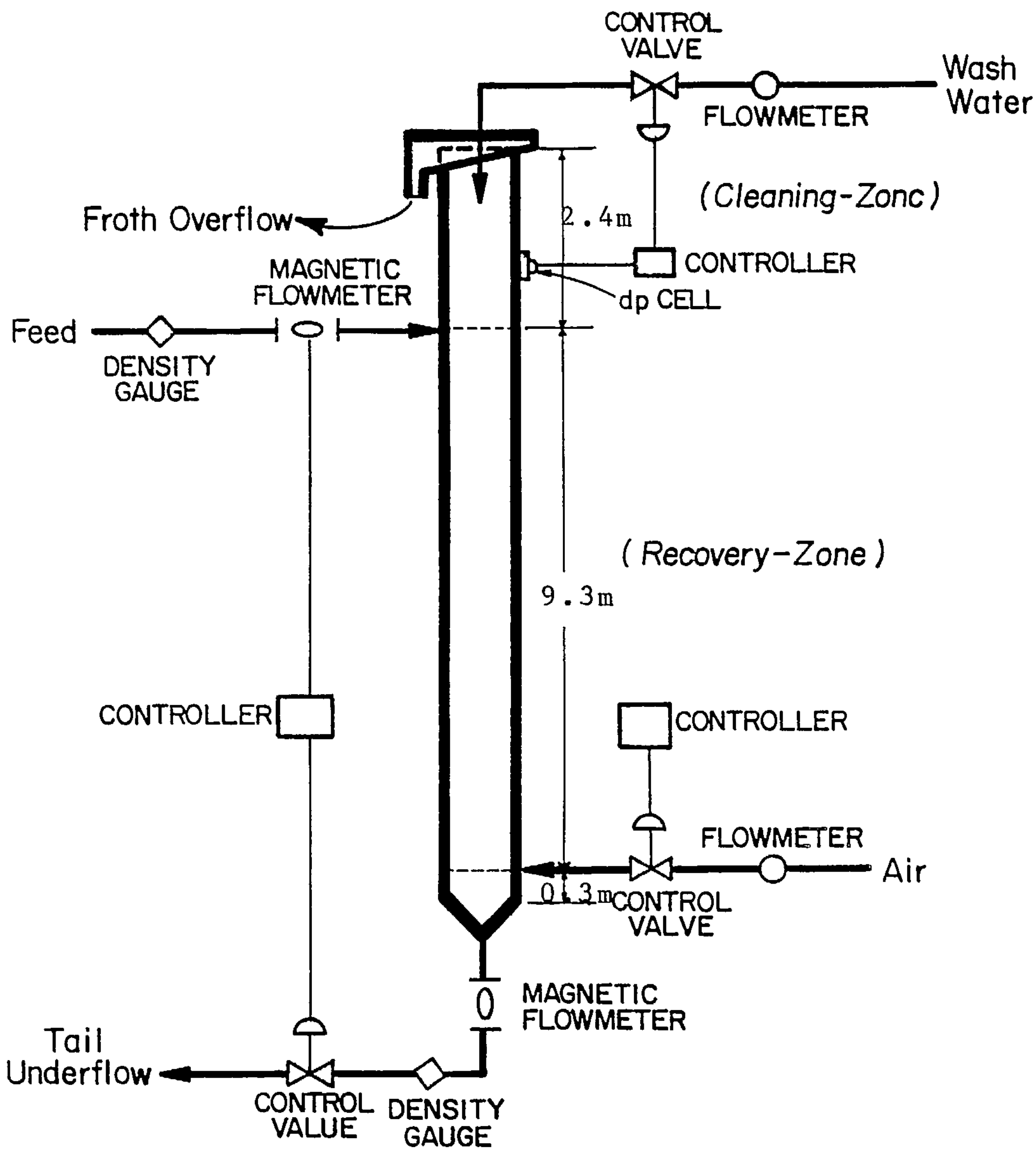


Fig. 1 – Schematic diagram of a countercurrent column flotation machine and its automatic control system

countercurrent air bubbles and mineral particles ensures the flotation of hydrophobic minerals. When the mineralized bubbles reach the upper portion of the flotation column, i.e., the cleaning zone, where the continuous phase is froth, they encounter a blanket of cleaning water so that no process water enters the stream of froth products. Cleaning water is distributed right beneath the surface of the froth. Cleaned froth product overflows and is discharged through a launder system. The cross-sectional area of the column mainly determines the throughput of the circuit, whereas the length of recovery and cleaning zones determines recovery and grade of the froth product, respectively.

Because there is no mechnical mixing mechanism, a quiescent condition always prevails inside the flotation column, which allows the flotation of even weakly hydrophobic minerals. The size of air bubbles in column flotation is much finer than in mechanical flotation, resulting in a higher interfacial area between air bubbles and pulp. The relative movement between mineral particles and air bubbles is co-current in mechanical flotation cells and countercurrent in flotation columns. Mineral particles and air bubbles move through the flotation column in a scheme of plug flow. Mechanical flotation, on the other hand, provides a condition closer to ideal mixing, which is inherently poorer than the plug-flow system.

In a sense, this simple countercurrent flotation column represents a long series of conventional, mechanical flotation cells. The major difference is in the spatial layout of the flotation system. A long, horizontal bank of mechanical flotation cells is replaced by a tall, vertical flotation column. In a series of mechanical flotation cells the froth product is removed from the system continuously at each stage of flotation. In a flotation column, however, all froth products must pass through only one froth surface at the top of the column. In some cases this bottleneck limits throughput for the flotation of bulky materials such as coal and potash ore.

Patents on the Canadian countercurrent flotation column were granted to Boutin and Tremblay (19, 20) some 20 years ago. Further development of the flotation column was described by Boutin and Wheeler (13, 14), by Wheeler (21), and anonymously (22). In Canada, almost all industrial flotation columns use this basic design (see Fig. 1). Various investigators are making great efforts to modify the flotation columns by borrowing the column distillation technology of the petroleum industry. It is hoped that an increase in effective residence time as well as an improvement in selectivity can be achieved by introducing various restrictions inside a flotation column (80). The column flotation machines of Deister Flotaire (16, 23) and Wemco–Leeds have a drastically low profile that differs vastly from the Canadian flotation column. The technology of column flotation has long been neglected by the Western world in favour of mechanical flotation, probably because of industrial momentum. Various forms of column flotation, however, have found many applications in the mineral industries of the USSR and Poland (11). Column flotation has also been used extensively for the beneficiation of various minerals in China (24), but its application has declined in more recent years.

ATTACHMENT OF MINERAL PARTICLES TO AIR BUBBLES

In mechanical flotation cells, air bubbles are formed by a rotating impeller, which generates negative pressure and draws in atmospheric or compressed air, depending on the design. The swirling action of the impeller breaks down the stream of incoming air into small, stable bubbles in the presence of frother in the pulp. The attachment of mineral particles to air bubbles occurs primarily in this so-called "active" zone behind the impeller blade, where cavity forms as a result of the negative pressure (25). The turbulent hydrodynamic conditions that enhance the attachment of mineral particles to air bubbles are negative factors, in that they also encourage the detachment of the particles from the bubbles. The relative collision velocity between the co-current air bubbles and mineral particles is negligible in an ideally mixed pulp in mechanical flotation cells, except in the active zone around the impeller. Thus, detached and first-encounter-missed particles must wait for the second round, which results in a much shorter effective residence time than the nominal one. Precipitation of air on the surface of mineral particles is insignificant, because the system is neither a vacuum nor a dissolved-air flotation.

On the other hand, inside the recovery zone of a flotation column, where the pulp moves downward quiescently, the mineral particles setting under gravity and rising air bubbles meet head-on continuously throughout two-thirds of the length of the column. All mineral particles must pass through the column of fine air bubbles rising from the bottom in the fashion of a plug-flow reactor. Therefore, because each mineral particle and air bubble spends all its residence time productively, effective residence time equals nominal residence time. This unique mode of attachment of mineral particles onto the surface of air bubbles in a plug-flow-type flotation column makes the system inherently more effective than mechanical flotation systems. Levenspiel (26) described a plug-flow reactor as an infinite series of ideal mixers.

MERITS OF COUNTERCURRENT COLUMN FLOTATION

Recovery

During conventional flotation, the major loss of economic minerals occurs in both coarse and fine size fractions. Because of the relatively fine size of air bubbles used in column flotation, their volume-specific surface area is much higher than in mechanical flotation. One reason for poor flotability of fine particles is the limitation of available interface between air bubbles and pulp. Each air bubble must journey up the long, vertical column from the bottom of the recovery zone to the top of the cleaning zone in plug-flow fashion, which results in a long, effective residence time (26). On the other hand, coarse mineral particles can be made to float by their attachment to several small air bubbles simultaneously. In the absence of external turbulence, this relationship is long-lasting. The total effect of these factors results in improved recovery of economic minerals. Improved recovery of both fine and coarse particles in column flotation was reported for chalcopyrite and molybdenite (23); for chalcopyrite, phosphate and coal (16); for sulphide minerals (5); and for coal (27, 28). One of the most important factors that controls recovery is the size and flow rate of air bubbles (29–31).

High Grade of Concentrate

One unique feature of the Canadian countercurrent flotation column is a long cleaning zone (see Fig. 1). Mineralized froths leaving the recovery zone, in which the continuous phase is pulp, carry not only the desired hydrophobic particles but also some unwanted hydrophilic particles along with process water. The absence of turbulence at the interface between recovery and cleaning zones minimizes the chance of the physical entrapment of unwanted particles. As the mineralized froths enter the cleaning zone, where the continuous phase is froth, they immediately encounter a blanket of cleaning water distributed beneath the surface of the froth. The cleaning water washes down entrapped, unwanted particles, and prevents process water that contains waste materials from entering the cleaning zone. Finch and Dobby (32) reported that less than 1% of the process water reached the concentrate product stream during a trace study of the column flotation circuit at Gaspé Copper Mines. The net effect is improved selectivity, which results in a high grade of concentrate product. This inherent cleaning action is the main reason that the flotation column finds its application mostly in cleaning of various sulphide concentrates including copper, nickel, zinc, and molybdenum in Canada. Halvorsen (27, 33) reported that column flotation of coal produced a cleaner product containing 3.0% ash, whereas conventional mechanical flotation yielded a product containing 6.6% ash.

Differential Specific Gravity Effect

The difference in specific gravity of minerals can also affect the selectivity of flotation. The turbulent hydrodynamic condition in mechanical flotation cells, however, destroys the differential specific gravity effect. The quiescent condition in a flotation column can take full advantage of this effect, especially when light minerals are floated from heavy gangue minerals. Thus, a flotation column is ideal for the flotation of fine coal (specific gravity 1.2) from silicate ash minerals (S.G. 2.1–2.3) and pyrite (S.G. 5.0). In general, this method also works in the flotation of heavy sulphides from light silicate or carbonate gangue minerals. What matters is that the effective density of a mineralized air bubble is lower than gangue minerals in the pulp.

The sphalerite cleaning circuit at Brunswick Mining and Smelting uses several stages of conventional cleaning flotation. The desired concentrate grade of 50 to 52% zinc was not being obtained, because of the co–flotation of the pyritic gangue mineral with sphalerite, until a reverse flotation of pyrite was carried out. In one plant trial (21), the metallurgy of zinc cleaning was improved after replacing the entire conventional and reverse cleaning circuit with a flotation column. This improvement can be explained in part by the differential specific gravity effect of sphalerite (S.G. 4.0) and pyrite (S.G. 5.0). Pyrite grains are not only heavier but also larger than sphalerite grains as a result of the difference in their hardness. The hardness in Moh's scale is 6 to 6.5 for pyrite and 3.5 to 4.1 for sphalerite (34). Similar findings were reported by Petruk and Schnarr (35) in their detailed mineralogical studies on various flotation products from the plant. Thus, rejection of relatively heavy and large pyrite particles to the tailing can be enhanced under the quiescent condition in a flotation column.

Large–capacity Unit Operation

In mechanical flotation cells, the ideal mixing of the pulp body inherently results in short–circuiting of pulp, which dilutes the concentrate with gangue minerals and the tailings with economic minerals. No short–circuiting is inherent, however, in a countercurrent column flotation cell because of the special plug–flow mechanism of the counter–flowing pulp and air bubbles in the recovery zone. Because of the improved metallurgical performance in column flotation, a whole bank of mechanical cells can be replaced by a single column (5), which simplifies complicated, conventional circuits, as has been demonstrated industrially at Gaspé Copper Mines Ltd. (36, 37). In general, a mechanical flotation cell cannot be used alone to produce final concentrates, even though it has a large enough capacity, because of the inherent short–circuiting of both desired and undesired minerals reporting to the wrong products. To achieve a reasonable grade and recovery, a minimum number of cells is required for mechanical flotation machines whereas comparable results may be achieved using only one flotation column.

Unlimited Scale-up Capacity

Most of the largest mechanical flotation cells that are now offered by various manufacturers have capacities of about 40 m^3, comparable to those of Canadian countercurrent flotation columns. Exceptions are the latest flotation cells, namely Wemco 225 at 85 m^3 (3,000 ft^3) (8, 9) and Dorr–Oliver DO–2,500 at 70.8 m^3 (2,500 ft^3) (6). Regarding scale–up, the mechanical flotation machine has a limit beyond which the simple scale–up of each component can no longer work properly, as a result of the complex hydrodynamics of pulp inside the cells. On the other hand, the scale–up of a column flotation machine entails only a simple multiplication of the cross–sectional area. Scale–up from 45 cm (18") to 90 cm (36") and 180 cm (72") has been shown to produce no change in the basic flotation mechanism in the column (7). Therefore, there is reason to believe that there is no limit to the scale–up of countercurrent flotation machines. This finding is significant for modern ore–processing plants that must treat larger tonnages of lower–grade ores. Conventional mechanical flotation machines have some limitations in further scale–ups. The scale-up factor will be discussed later in the section on specific surface area and specific lip length.

Low Cost Per Unit

Today's trend towards larger and larger machines has led to reduced costs of flotation machines, which is an added advantage for the flotation column. The 180–cm Canadian countercurrent flotation column (40.8 m^3) is one of the largest flotation machines now available. The column itself has no mechanical mixing mechanisms, which eliminates the necessity for such costly items as electric motors and special, wear–resistant agitators. Where corrosion is a problem (e.g., in potash flotation), a flotation machine without any moving parts is the ideal choice. Furthermore, the quiescent condition inside a column eliminates the need for abrasive–resistant inner walls. These factors contribute to making the column a low–cost machine. Costs can be further reduced by the use of a cylindrical shape as opposed to a rectangular one (27).

Small Floor Space

Because the countercurrent flotation column is a vertical unit, its use in a new mineral processing plant reduces initial capital investment by limiting the required floor space. The flotation column is an ideal choice when a dense–packed design and economical use of plant space are required by circumstances, such as a prefabricated plant for barge transportation (72). When a bank of conventional mechanical flotation machines is replaced by a new column unit, the floor space saved can be used, as an added bonus, to increase circuit capacity.

Low Installation Costs

A large–capacity countercurrent flotation column means fewer control points, thus reducing installation costs of both instrumentation and auxiliary units.

Low Operating Costs

Because there is no mechanical mixing in the system, the cost of electricity is significantly reduced. The quiet flotation conditions prolong the life of the machine and reduce the cost of maintenance. Few control points and instrumentation as well as supporting units reduces the need for staff and maintenance costs. Improvement in metallurgical performance results in an overall reduction in operating cost per unit of production.

Process Optimization

With relatively few control points and the special flotation mechanism, the countercurrent flotation system is highly amenable to modern instrumentation and automatic control techniques, which thus allows easy optimization of the process. Many investigators have studied the mathematical model of column flotation for optimization of the process. Computer control of a laboratory flotation column was reported by McDonough et al. (38). Clingan and McGregor (39) reported that column flotation at Magma Copper Company resulted in more or less constant–grade recovery over a wide range of such operating variables as air rate, froth depth, bias rate, and feed density. This tolerance of varied conditions makes a flotation column easy to control.

Simple Flotation Mechanism for R&D

For turbulent mechanical flotation machines, the flotation mechanism itself (including the generation of air bubbles, contact between air bubbles and mineral particles, the transfer of mineralized froth to the surface, and so on) has yet to be understood properly and is difficult to study and simulate mathematically. In the Canadian countercurrent flotation column, the simple mechanism of contact between rising air bubbles and settling mineral particles and pulp flow in a quiescent column, makes R&D on the subject much easier. Thus the system continues to be improved. An early mathematical model of a countercurrent flotation column was conceived by Sastry and Fuerstenau (40, 41). The dispersion effect during column flotation was studied using a tracer technique by Flint (42) and Rice et al. (43) in the absence and presence of baffles, respectively. Numerous authors (44–52) have also studied the problem of bubble dispersion. More recently, several others (53–57) have investigated residence time distribution for the scale–up of a flotation column. Mathematical modelling for column flotation of fluorite ore was researched by Peterson et al. (58) and Mankosa et al. (59).

DISADVANTAGES AND DESIGN MODIFICATIONS

In a countercurrent flotation column, the gravity–induced velocity of rising air bubbles has to compete against the downward movement of pulp. If throughput of pulp is at more than a certain maximum level, the fine air bubbles are unable to rise through the column and are drained with the tailings. Besides, the plug–flow mechanism of a flotation column might cause a potential problem in dealing with a large throughput for the flotation of bulky materials such as coal, as discussed later. Some specific design modifications are also reviewed for the increase of its throughput.

Specific Surface Area and Specific Lip Length

The dimensional characteristics of seven large, mechanical flotation cells offered by different manufacturers are compared with the Canadian countercurrent flotation column in Table 1. These eight machines represent the largest flotation devices being offered at present by the manufacturers.

Table 1 – Dimensional characteristics of some large flotation cells

Flotation machine	Volume (m^3)	Open surface area (m^2)	Specific surface area (m^2/m^3)	Specific lip length (m/m^3)
Denver D–R No. 1275 (USA)	36.1	14.7	0.41	0.12
Aker FM–40 (Norway)	40.0	14.1	0.35	0.09
Agitair 165 AX 1500 (USA)	42.5	15.4	0.36	0.10
Sala AS4–44 (Sweden)	44.0	24.2	0.55	0.11
Outokumpu OK–50 (Finland)	50.0	19.4	0.38	0.09
Dorr–Oliver DO–2500 (USA)	70.8	20.9	0.30	0.13
Wemco 225 (USA)	85.0	32.5	0.38	0.13
Column 180 cm (72") (Canada)	40.8	3.3	0.08	0.18

Specific surface area and specific lip length of a flotation cell are defined as surface area and lip length per unit volume, respectively. The seven mechanical flotation cells have specific surface areas from 0.30 to 0.55 m^2/m^3 and specific lip lengths from 0.09 to 0.13 m/m^3. For the flotation column, the specific surface area (0.082 m^2/m^3) is much smaller than those of mechanical flotation machines, because of its height. However, the specific lip length (0.18 m/m^3) is larger for the column than the others, because of the four-sided overflow arrangement.

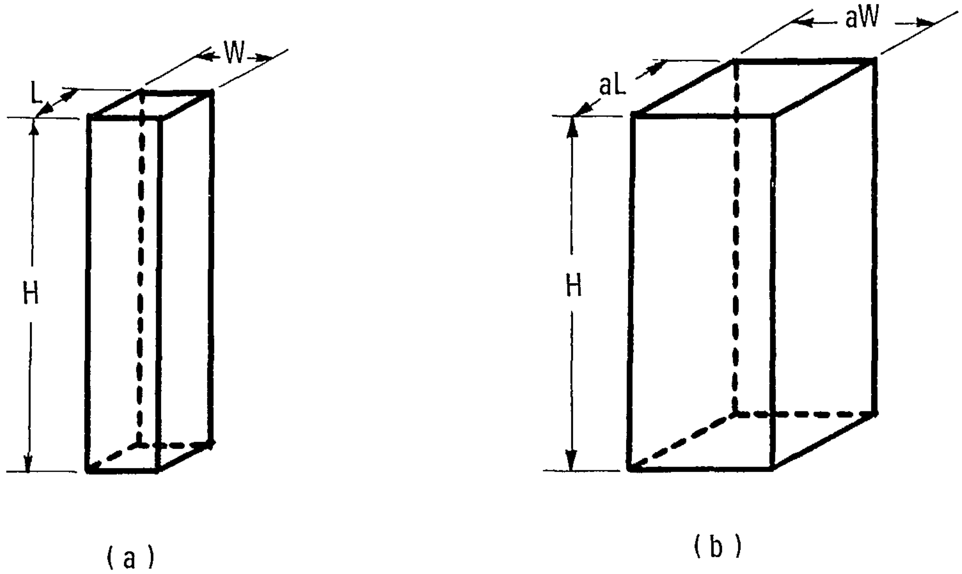
Specific surface area of a flotation cell relates to the formation and drainage of froth. Specific lip length, on the other hand, is related to the removal rate of froth. Thus, specific surface area and lip length may play an important role when the formation and/or removal of froth controls flotation throughput.

In the Canadian flotation column, the scale-up is done by multiplying the horizontal dimensions only, keeping the vertical column length constant. This two-dimensional scale-up strategy results in a constant specific area whereas the specific lip length decreases by a factor of "1/a," as the two horizontal dimensions are increased by a factor of "a" (Fig. 2).

However, simple geometric study indicates that if a larger mechanical flotation cell is built by increasing all three dimensions with a scale-up factor of "a," specific surface area and specific lip length of the flotation cells will decrease by a factor of "1/a" and "$1/a^2$," respectively (Fig. 3). Therefore, these two criteria are affected "a-times" more during the scale-up of mechanical flotation cells than for the scale-up of countercurrent flotation columns. This is indeed the case as shown in Figures 4 and 5, which were constructed using data from various manufacturers.

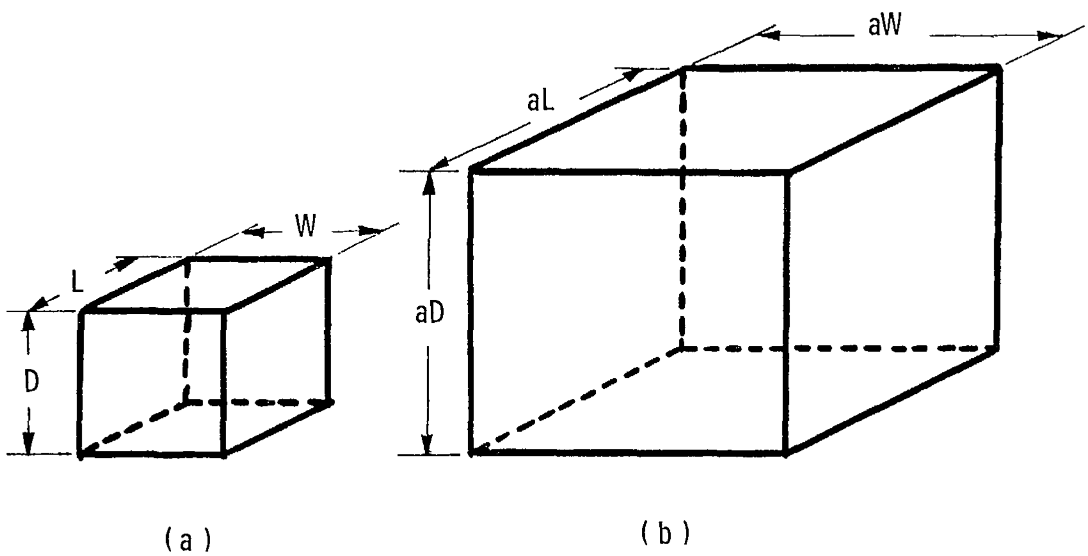
In Figure 4, specific surface area of all the mechanical flotation cells decreases following the theoretical cubic system, whereas that of the flotation column remains constant as cell volume increases. The Humboldt Wedag coal flotation machine provides the largest specific surface area to process the voluminous froth produced by coal. However, these machines have a maximum capacity of only 12 m^3. The designs of other manufacturers use the same dimensions for both coal and metallic mineral flotation. All mechanical flotation cells have similar specific surface areas with one exception: the Sala shallow cell design allows a relatively high specific surface area at the capacity of 36 m^3. However, when mechanical flotation machines reach capacities of 40 m^3, such exceptions no longer exist. As a result of various constants in scale-up, all large mechanical cells have specific surface areas that average about 0.4 m^2/m^3. On the other hand, the Canadian flotation column maintains a constant specific surface area of 0.082 m^2/m^3 regardless of its capacity.

In Figure 5, specific lip length is shown to decrease with an increase in flotation cell size. Both the Sala and the Canadian column flotation cells have relatively higher values of specific lip length, whereas the rest of the mechanical flotation cells have specific lip lengths remarkably similar to the theoretical cubic system. At flotation cell capacity of about 40 m^3, the Canadian flotation column has a higher specific lip length of 0.18 m/m^3, because its design permits froth overflow on all four sides. Specific lip length for the mechanical flotation cells ranged from 0.09 to 0.13 m/m^3 (see Table 1). Some manufacturers of flotation machines maintain that relatively higher values for specific surface area and/or specific lip length will result in improved metallurgy. However, they also claim that large flotation cells with relatively small surface areas and lip lengths perform at least as well as small ones. Therefore, the specific surface area and the specific lip length of a mechanical or column flotation machine may not play a significant role in



	(a) Original	(b) Scale-up	Scale Factor
Volume :	LWH	a^2 LWH	a^2
Open Surface Area :	LW	a^2 LW	a^2
Specific Surface Area :	1 / H	1 / H	1
Lip Length :	2(L+W)	2a(L+W)	a
Specific Lip Length :	2(L+W)/LWH	2(L+W)/aLWH	1 / a

Fig. 2 – Two-dimensional scale-up of a flotation colum



	(a) Original	(b) Scale-up	Scale Factor
Volume :	LWD	a^3 LWD	a^3
Open Surface Area :	LW	a^2 LW	a^2
Specific Surface Area :	1 / D	(1 / a)(1 / D)	1 / a
Lip Length :	W	aW	a
Specific Lip Length :	1 / LD	(1 / a^2)(1 / LD)	1 / a^2

Fig. 3 – Three-dimensional scale-up of a conventional mechanical flotation cell

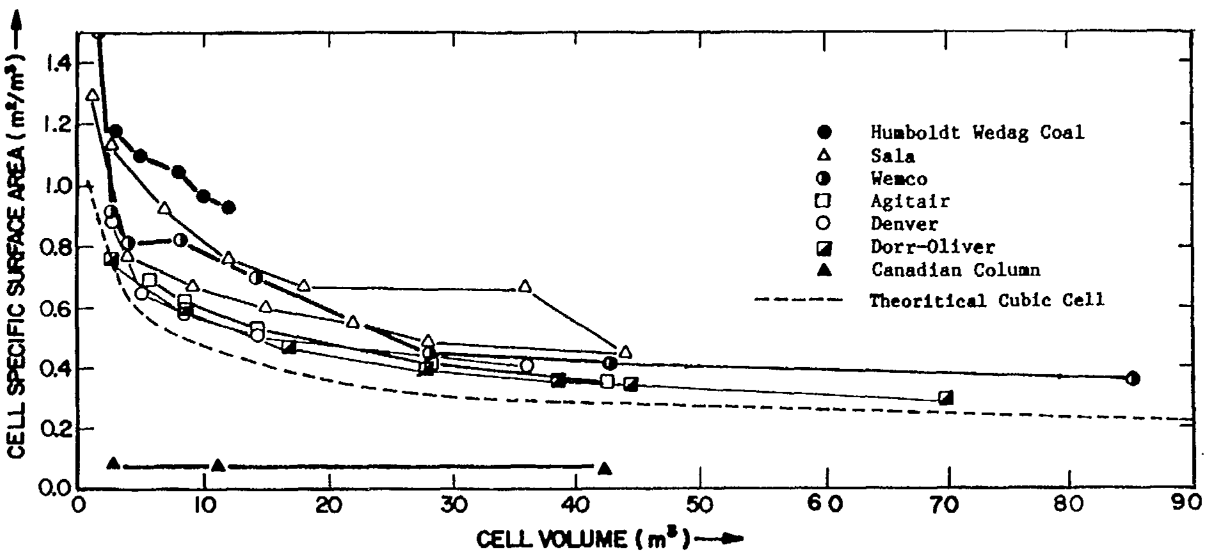


Fig. 4 – Specific surface area vs volume of flotation cells

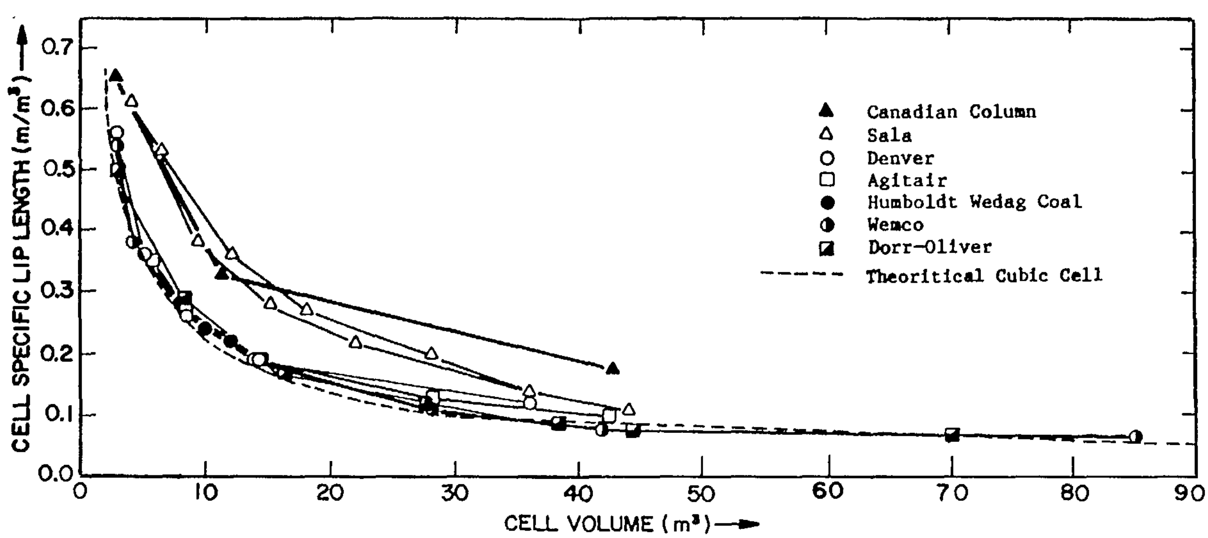


Fig. 5 – Specific lip length vs volume of flotation cells

throughput as long as the flotation rate is not limited by the formation and/or removal rate of froth. This situation holds for the flotation of metallic minerals that are minor constituents of the feed. Conditions may not be the same, however, for coal flotation in a column that has a small specific surface area. The Canadian flotation column has a relatively long lip length for fast removal of froth, but throughput may be limited by its small surface area. The severity of this problem in capacity is unknown at present, but Halvorsen (27, 33) has provided reason to be concerned.

Flotation Column for Coal

Some modifications in the design of a flotation column may resolve the problem of a throughput limited by its small specific surface area. The removal rate of froth could also be increased further by installation of paddles, as in some mechanical cells. The technology of vacuum flotation could be hybridized with that of column flotation to produce a vacuum flotation column, to allow faster removal of voluminous coal froths.

Because naturally buoyant materials such as coal float rapidly, only the top portion of the 10–m long recovery zone may be useful for interaction between air bubbles and coal particles. If the length of the column were divided into two half–sized columns, the effective throughput would be doubled. Another possibility in design modification would be to enlarge the surface area of the cleaning zone by fashioning the column after an inverted cone or pyramid, which would allow effective use of the upper part of the column.

APPLICATIONS

The application in the USSR of various modified countercurrent column flotation machines for the flotation of various sulphides, oxides, coal, and other industrial minerals was discussed extensively by Tyurnikova and Naumov (11). At the 14th International Mineral Processing Congress (Toronto, October 1983), various industrial applications were discussed of countercurrent column flotation machines in China, Poland, and Yugoslavia for the beneficiation of various ores.

As mentioned previously, the adaptation of countercurrent column flotation technology by the mineral processing industries in the Western world has been minimal. Early air–bubbler systems which provided only poor bubbling performance did little to promote this technology. The momentum gained by the mechanical flotation machine industry drove the mineral processing industry in that direction. Furthermore, the cold war between East and West during the development of flotation machines discouraged the Western world from adopting the countercurrent flotation system. However, the special advantages of the countercurrent column flotation system have recently been realized after a long period of laboratory and pilot–plant investigation, which has led to a number of applications in the West.

LABORATORY STUDIES

Countercurrent column flotation has been studied for many different ores by various investigators. Hollingsworth (60) analyzed the beneficiation of phosphate ore and Narashimhan et al. (61) researched the beneficiation of graphite. Foot et al. (62) and McKay et al. (63, 78), in conjunction with the U.S.

Bureau of Mines, Salt Lake City Research Center, reported a superior result in the column flotation of chromite and fluorite ore, in comparison with conventional mechanical flotation.

At the Canada Centre for Mineral and Energy Technology (CANMET), Mathieu (64) studied the cleaning of molybdenite and Honeywell (65) investigated uranium ore, both using a 5–cm pilot–plant flotation column. This facility was used recently for the beneficiation of chalcopyrite, galena, sphalerite, molybdenite, and coal, as discussed later in more detail.

During comparative tests (Table 2) using a conventional mechanical flotation and a countercurrent flotation column for both the rougher and the cleaning flotation of molybdenite, the column flotation method resulted in much cleaner products than conventional flotation, at the same level of recovery.

A pilot column flotation study on lead–zinc ore from the Kidd Creek Mine produced 54% zinc concentrate, whereas the mill produced only 50% zinc concentrate. The cleaner zinc concentrate from the column operation was much finer than that produced by the mill (Fig. 6).

A pilot column flotation of complex lead–zinc–copper ore from the Brunswick Mining and Smelting Corporation Limited achieved the concentrate grade of 52% zinc at 85% recovery, a result that conventional flotation machines were unable to match. Figure 7 demonstrates the superiority of column flotation as opposed to mechanical flotation.

One result of the pilot column flotation of copper–molybdenum ore from British Columbia is shown in Figure 8. In comparison with a conventional mechanical flotation cell, the flotation column produced a better–grade recovery for copper but a worse one for molybdenum. The poor results for the latter were probably caused by close mineralogical association between molybdenum and gangue minerals rejected efficiently during column flotation.

The selective flotation of molybdenite from the copper–molybdenum bulk concentrate from Whitehorse (Table 3) showed that column flotation produced not only a higher grade of molybdenum concentrate than conventional flotation, but also less copper contamination.

Another comparative study for the cleaning of rougher copper concentrate from Flin Flon, Manitoba, indicated that the concentrate was up–graded from 4.5% to 10.5% copper. At the same time, the flotation column recovered 80% copper whereas a conventional flotation machine recovered only 70%, under identical reagent conditions.

Because of the effect of different specific gravities, as discussed previously, column flotation is particularly attractive for the flotation of light coal from heavier shale and pyrite. Some results at CANMET of column flotation on high–sulphur coal were reported earlier by the authors (66). That study indicated that the ratio of enrichment for total sulphur in coal product was less than unity for various coals containing different amounts of sulphur. This result shows clearly that pyrite reports to the tailing product during column flotation. However, when fuel oil was used as collector for coal, most pyrite reported in concentrate along with coal. The laboratory (5–cm) Canadian flotation column performed excellently up to pulp density of 32.5% solids. At the same time, pyritic sulphur content was reduced to 0.9% from 3.4% after a reverse flotation of coal (–300 μm) using the same flotation column. Encouraged by these results, CANMET installed a pilot flotation column at the Victoria Junction Coal Preparation Plant, Sydney, N.S., in co–operation with DEVCO, for flotation studies of fine high–sulphur coal.

Table 2 – Results of mechanical and column flotation on molybdenite from Newfoundland

Flotation machines	Concentrate products	% Weight	% Assay Mo	Fe	Pb	Zn	Insol.	% Rec. of Mo
Mechanical flotation	Rougher conct.	3.5	5.1	7.7	1.4	2.7	71.5	86.6
	Final conct.	0.36	42.3	7.0	7.8	9.9	14.9	74.1
Column flotation	Rougher conct.	1.1	17.1	16.6	3.4	4.8	28.1	86.4
	Final conct.	0.25	63.1	6.5	7.4	5.4	4.1	72.7

Source: Mathieu (64).

Table 3 – Column vs mechanical flotation for selective flotation of Mo from Cu–Mo bulk concentrate

Products by flotation mechanisms		% Assay Mo	% Assay Cu	% Distribution Mo	% Distribution Cu
Column flotation	Mo Ro. conc.	13.00	19.5	87.2	9.3
	Cu tail.	0.45	49.3	12.8	90.7
	Calc. head	2.84	43.2	100.0	100.0
Mechanic. flotation	Mo Ro. conc.	11.20	22.3	86.7	12.6
	Cu Tail.	0.45	49.6	13.3	87.4
	Calc. head	2.68	43.0	100.0	100.0

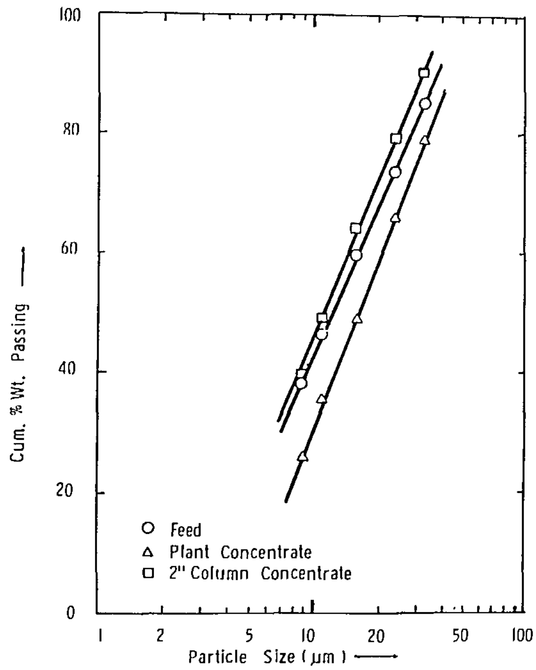


Fig. 6 – Particle size of zinc concentrates from plant operation and flotation column pilot operation

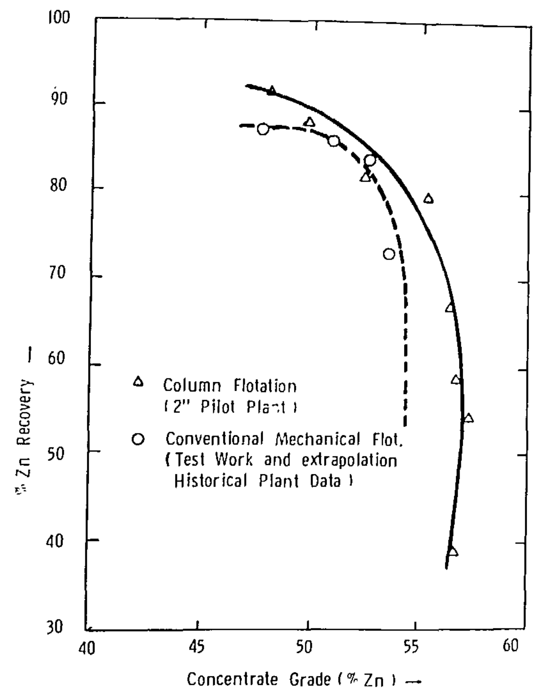


Fig. 7 – Comparison of column flotation vs conventional mechanical flotation for zinc cleaning

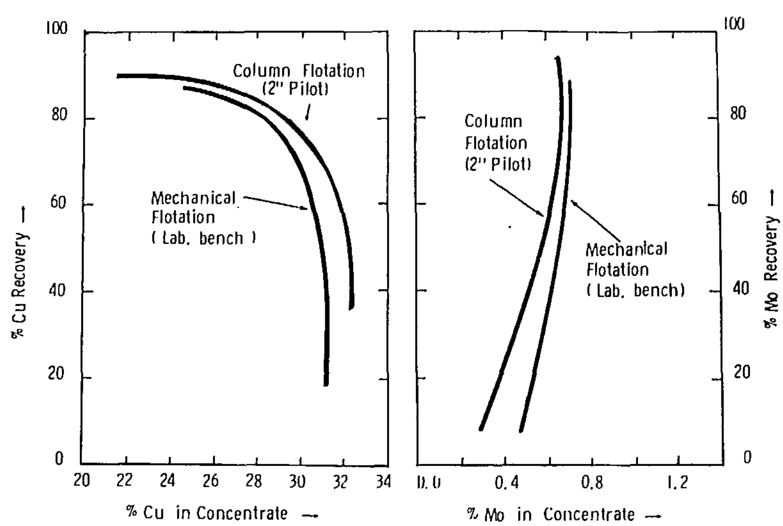


Fig. 8 – Comparison of column flotation vs conventional mechanical flotation for Cu–Mo bulk flotation

Dell (18) reported earlier that the laboratory Leeds flotation column (14–cm dia.) produced a cleaner coal product than a Denver laboratory flotation machine at the same yield. More recently, according to Parekh et al. (31), column flotation produced cleaner coal product containing 3.0% ash, whereas that from conventional mechanical flotation was 7.5% ash at the same yield of 95%. Groppo (67) reprocessed the tailing (50% ash, 60% −25 μm) from a coal processing plant and found that the Canadian flotation column produced cleaner products than a mechanical flotation machine. Parekh et al. (31) and Groppo (67) emphasized that the optimum results with the Canadian flotation column were obtained at 10 to 17% solids, whereas the pulp density for a mechanical flotation was limited to 5% solids only.

Besides CANMET, many other research organizations in North America are engaged in research and development programs on column flotation, as indicated in Table 4.

INDUSTRIAL R&D AND APPLICATIONS

The nominal cross–sectional sizes of Canadian industrial flotation columns vary from 45 cm x 45 cm (18" x 18") to 90 cm x 90 cm (36" x 36") and 180 cm x 180 cm (72" x 72") (Figs. 9a and b). The height of Canadian flotation columns is about 13 m (44 ft). The manufacturer of these flotation columns in Canada used some of them for on–site pilot–plant investigations of various ores and coals. These studies included copper flotation at the Opemiska Copper Mines, Chapais, Québec, at the Cobriza Mine of Cerro Corp. in Peru, and at the Gaspé Copper Mines in Murdochville, Québec; hematite flotation and reverse flotation of silica from hematite, respectively, at Iron Ore Co. of Canada facilities in Labrador City, Newfoundland and Sept–Iles, Québec; separation of molybdenite from chalcopyrite in Chile and in Zambia; graphite flotation at Portland Graphite, Ontario; and finally, fluorospar flotation at ALCAN, in Arvida, Québec. Besides the mineral industry, some oil refineries are looking into the possibility of recovering elemental sulphur from the slurry of the flue gas scrubber, using the column flotation method. According to claims of the manufacturer of the Canadian flotation column (21), various on–site pilot–plant investigations have indicated that metallurgical performance is improved in using it.

During initial stages of development, however, the flotation column experienced a problem with its air–bubbler system. The early mechanical problems of the bubbler were caused by the deterioration of its material and the deposition of scale on the bubbler, which blocked the tiny holes. Both problems were resolved, and the air–bubbler system at Gaspé Copper Mines, Québec, had been in service for more than eight months without any significant sign of deterioration in its performance when the circuit was closed down for economic reasons (21).

In recent years, most major mining companies in Canada have become involved in column flotation (Table 5). The most important industrial application of column flotation is found in cleaning circuits. Most companies use home–designed flotation columns similar to the long Canadian flotation column. The Column Flotation Co. of Canada Ltd., however, is still the only commercial manufacturer of column flotation machines with a capacity of about 40 m^3. Recently, Wemco–Leeds and Deister Flotaire have been developing somewhat smaller flotation columns of their own design with low profile.

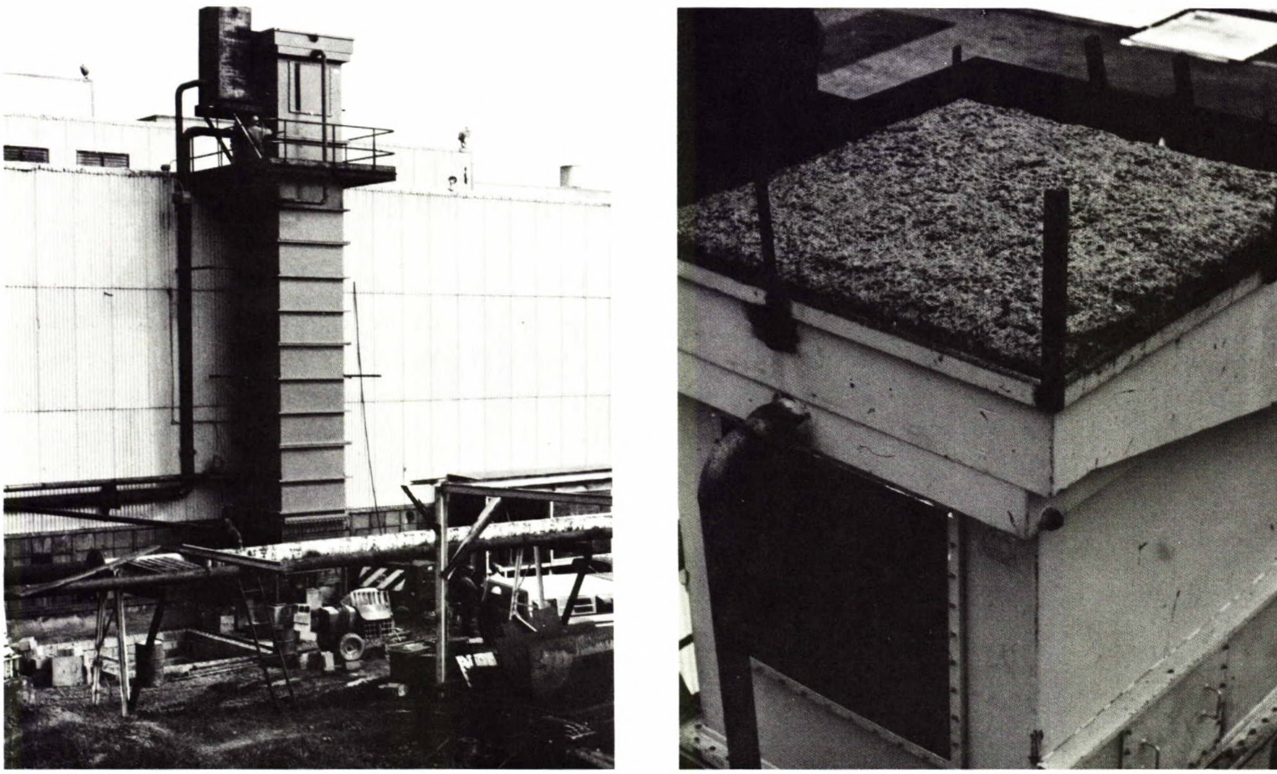
Encouraged by the improved metallurgical performance of flotation columns, CANMET has been supporting many plant–scale R&D projects on column flotation, such as the up–grading of zinc concentrate at Ruttan Mine of Hudson's Bay Mining and Smelting Co., Manitoba, and at Cominco Ltd. in Kimberly,

Table 4 – Laboratory R&D on Column Flotation in North America

1.	Mineral Processing Laboratory, CANMET, Ottawa, Ontario
2.	U.S. Bureau of Mines, Salt Lake City Research Center, Salt Lake City, Utah
3.	Kentucky Center for Energy Research Laboratory, Lexington, Kentucky
4.	Ohio Coal Development Office, Columbus, Ohio
5.	Centre de Recherches Minérales, Sainte–Foy, Québec
6.	EXXON, Florham Park, New Jersey
7.	Iron Ore Co. of Canada, Sept–Iles, Québec
8.	Victoria Junction Coal Preparation Plant of DEVCO, Sydney, Nova Scotia
9.	Lakefield Research of Canada Limited, Lakefield, Ontario
10.	Norton Hambleton Inc., Ann Arbor, Michigan
11.	Kerly Industries Inc., Sahuarita, Arizona
12.	University of British Columbia, Vancouver, British Columbia
13.	University of Toronto, Toronto, Ontario
14.	McGill University, Montreal, Québec
15.	Technical University of Nova Scotia, Halifax, Nova Scotia
16.	Michigan Technological University, Houghton, Michigan
17.	Virginia Polytechnic Institute and State University, Blacksburg, Virginia
18.	University of California at Berkeley, California

Table 5 – Industrial R&D and Applications of Column Flotation in North America

1.	Inco, Thompson, Manitoba
2.	Inco, Copper Cliff, Ontario
3.	Falconbridge Nickel Mines Ltd., Falconbridge, Ontario
4.	Hudson's Bay Mining and Smelting Co., Ruttan Mine, Manitoba
5.	Gibraltar Mines Ltd., Mcleese Lake, British Columbia (68, 7)
6.	Lornex Mining Corp. Ltd., Highland Valley, British Columbia (69, 70)
7.	Brenda Mines Ltd., Peachland, British Columbia (71)
8.	Utah Mines Ltd., Island Copper Mine, Port Hardy, British Columbia
9.	Cominco Ltd., Kimberly, British Columbia
10.	Cominco Ltd., Polaris Project, Little Cornwallis, Northwest Territories (72)
11.	Cominco Ltd., Red Dog Project, Alaska (72, 77)
12.	Noranda Mines Ltd., Gaspé Copper Mine, Murdochville, Québec (36, 37)
13.	Noranda Mines Ltd., GECO, Manitouwadge, Ontario (21)
14.	Noranda Mines Ltd., Brunswick Mining and Smelting Corp. Ltd., Bathurst, New Brunswick (21)
15.	J.R. Simplot Company, Pocatello, Idaho (73)
16.	Magma Copper Company, Superior, Arizona (39)
17.	Wemco, Sacramento, California
18.	Deister Concentrator Co. Inc., Fort Wayne, Indiana (15, 16)
19.	Column Flotation Co. of Canada Ltd., Dorval, Québec (13, 14)



(a) (b)

Fig. 9 – Industrial Canadian flotation column (1.8m x 1.8m x 13m): (a) general view; and (b) froth surface in coal flotation

B.C., and the rejection of pyrrhotite from copper–nickel concentrates at Inco, in Thompson, Manitoba. Falconbridge Nickel Mines Ltd., at Falconbridge, Ontario, is also studying the possibility of increased pyrrhotite rejection from the copper–nickel concentrates in an attempt to reduce sulphur dioxide emission in its smelting operation. Feeley et al. (74) studied column flotation at Inco's matte separation plant.

Halvorsen (27, 33) investigated coal flotation using the 180–cm (72") Canadian flotation column at the Champion Coal Preparation Plant of the Consolidation Coal Company Inc., Bethel Park, Pennsylvania. The column flotation produced very clean coal with 5% ash coal product from feed that contained 30% ash, with a yield of about 80%. One concern was, however, that the throughput might be limited by the fast–floating bulky coal as discussed earlier. According to Sorokin et al. (75), a column (2m x 2m x 4m) flotation followed by mechanical scavenger flotation improved the yield by 0.7% at Magnitogorsk Coal Cleaning Plant. At the same time, ash content in the clean coal product was reduced from 9.5% to 7.8%.

Numerous industrial installations of countercurrent Canadian flotation columns now process sulphide ores. For instance, three flotation columns (45 cm x 45 cm, 90 cm x 90 cm, and 180 cm x 180 cm) are used as molybdenum–cleaners at Gaspé Copper Mines in Murdochville, Québec; one (180 cm x 180 cm) is used as a zinc–cleaner by the Brunswick Mining and Smelting Corp. Ltd. (BMS) in Bathurst, New Brunswick; and finally, one (90 cm x 90 cm) is employed as a copper scavenger at GECO in Manitouwadge, Ontario. All three mills are located in eastern Canada, and all belong to the Noranda Group. For economic reasons at the time of the plant tests, however, the two mills at BMS and GECO were closed down before their flotation columns were fully operational. However, initial operations indicated that the conditions of flotation at GECO might cause problems by plugging the holes of the air–bubbler. On the other hand, in one trial at BMS, after the conventional multistage cleaning circuit, including a reverse flotation of pyrite, was replaced by a two–stage column flotation, an exceptionally high–grade zinc concentrate was produced. The differential specific gravity effect, as discussed previously, may favour the depression of the relatively heavy and coarse pyrite particles.

In British Columbia, home–made flotation columns have also been used as molybdenum–cleaners at Island Copper Mines of Utah Mines Ltd. in Port Hardy; and for copper–molybdenum flotation at Gibraltar Mines Ltd., Mcleese Lake (68, 7), at Lornex Mining Corp. Ltd., Highland Valley (69, 70), and at Brenda Mines Ltd., Peachland (71). They reported that column flotation reduced the circulating load in the cleaning circuit and increased the grade of molybdenum concentrate at reduced power consumption.

The most successful application of flotation columns as molybdenum–cleaners was the conventional molybdenum–cleaning circuit at Gaspé Copper Mines described as very complex (36, 37). It included 6 flotation banks, consisting of 14 stages, with long retention periods and large circulating loads (Fig. 10a). These were replaced by a much simpler circuit of four flotation banks and two flotation columns, with a total of eight stages (Fig. 10b). The flotation columns have retention times of 15 to 20 minutes and use about 2000 standard cubic feet of air and 3000 U.S. gallons of cleaning water per metric ton of ore.

The simple circuit using the two flotation columns (see Fig. 10b) was not only easy to operate, but also improved the metallurgical performance (Table 6).

The flotation column increased recovery of molybdenum mainly in the fine (–38 μm) size fraction (36). Flotation columns performed better at high pulp density than did conventional flotation machines. They

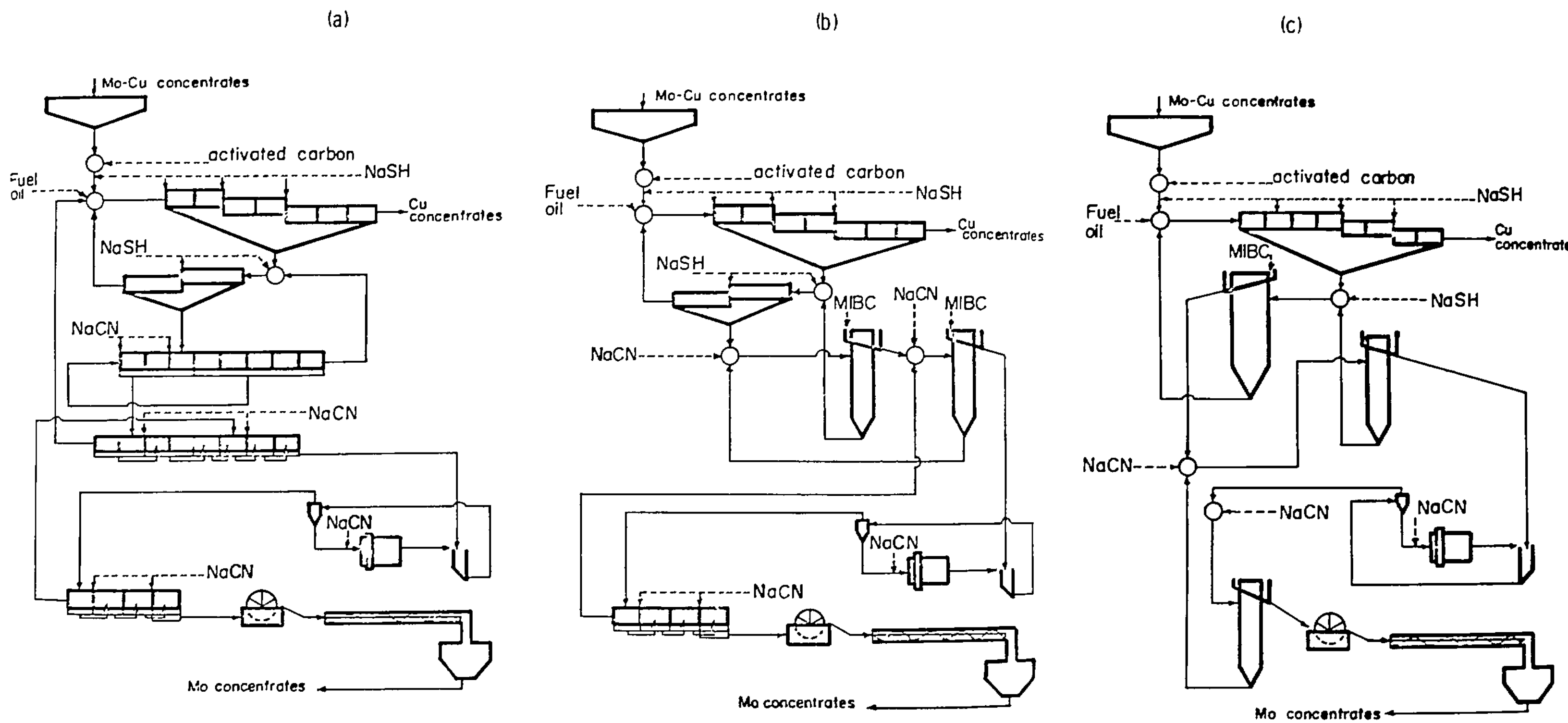


Fig. 10 – Molybdenum–cleaning circuits at Mines Gaspé: (a) all conventional flotation cells; (b) with two flotation columns; and (c) with three flotation columns

Table 6 – Improved mill performance at Gaspé Copper Mines Ltd. after the installation of flotation columns

Plant operation	Date	Feed % Mo	% Rec. Mo circuit
Conventional flotation only	Sept 1977	0.88	66.5
	Oct. 1977	1.21	69.6
	Nov. 1977	1.18	61.2
With column flotation	Oct. 1980	0.91	73.5

Source: Coffin (36).

performed so well that a third one was introduced in February 1982, to replace the conventional first cleaner (Fig. 10c). Unfortunately, for economic reasons, the mill was closed before the effect of the new circuit could be fully appreciated.

At present, new column flotation plants are being built for lead–zinc cleaning at Red Dog of Cominco in Alaska (72) and for reverse flotation of siliceous gangue minerals from fluoroapatite at the Simplot Company in Pocatello, Idaho (73).

CONCLUSIONS

Until recently, despite their merits, non–mechanical flotation machines, specifically countercurrent column flotation machines, have not been much used in the Western world. Although many different methods of froth separation, pneumatic flotation, and column flotation are widely accepted in the East today, mechanical flotation machines remain the dominant workhorse in the West.

Laboratory and industrial experience with the Canadian countercurrent flotation column indicates that it can outperform conventional mechanical flotation machines in beneficiation of various metallic ores and coals. In the Canadian countercurrent flotation column, the plug–flow mechanism of counter–flowing air bubbles and mineral particles in the quiescent recovery zone has been found to be responsible for improved metallurgical performance. The cleaning action of a blanket of wash water in the cleaning zone improves the selectivity to produce a cleaner concentrate. Scale–up can be achieved easily by increasing the cross–sectional area of the flotation column. The absence of any moving parts reduces capital, operational, and maintenance costs. The simplified column flotation circuit is easy to control.

Considering these potential benefits, countercurrent flotation machines well deserve greater consideration for service in the mineral processing industry.

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