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Recovery of base and precious metals from scrap TV boards using zig-zag air separator

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Abstract: Waste of Electrical and Electronic Equipments (WEEE) is one of the fastest growing waste streams in the world. The treatment of WEEE with high content of precious metals (Au in particular) has received the most attention due to their high economic potential. The development of simple, environmentally friendly and cost-effective methods for the recovery of metals from "low-value" WEEE (e.g., <100 g/t Au) is important from the circular economy perspective. In this study, the separation of base (Cu) and precious (Ag) metals from scrap TV boards (STVBs) by using a zig-zag air separator was investigated. Size-reduced scrap STVBs (-1 mm) were subjected to separation tests after the removal of the fine fraction (-0.1 mm). The sized scrap material (-1 +0.1 mm) was determined to have a metal content of 15.4% Cu, 47 g/t Ag and 0.05% Fe, with no gold. In the air separation tests, the effect of air flow rate (4-16 m/s) on the recovery of metals was studied. Increasing the air flow rate resulted in low metal recoveries with concurrent high metal grades in the concentrate. Separation efficiency (%) calculations showed that the most efficient separation is obtained at the highest air flow rate of 16 m/s. At this flow rate, 15.4% of the material was recovered in the concentrate which contains 62.3% Cu and 198 g/t Ag with recoveries of 63.3% Cu and 73.9% Ag. The findings indicated that zig-zag air separators can be used to obtain a metal-rich fraction under suitable conditions of the flow regime.

Keywords: WEEE, scrap TV boards, recycling, metals, copper, silver, air separation

1. Introduction

Waste of Electrical and Electronic Equipments (WEEE) or more commonly known as e-waste is one of the most rapidly growing waste streams in the world due to the advancement in technology and decreasing the life span of Electrical and Electronic Equipments (EEE) (Widmer et al., 2005; Ongondo et al., 2011; Sun et al., 2016; Shittu et al., 2021). Improper disposal/treatment of this waste stream may result in the contamination of water/soil/air by metallic and/or non-metallic hazardous pollutants (Pb, Cd, flame retardants etc.) (Jang and Townsend, 2003; Lincoln et al., 2007; Yazici et al., 2010; Yazici and Deveci, 2016). WEEE may well be regarded as an important secondary resource for many base, precious and critical metals owing to its high metals content (Hagelüken, 2006; Işıldar et al ., 2018). Therefore, the recovery of metals from WEEE is of economic and environmental interest. Various metal recovery options based on conventional physical and metallurgical (bio/hydro-, pyro- and electro-metallurgical) processes appear to be available (Cui and Zhang, 2008; Tuncuk et al., 2012; Kaya, 2016; Chauhan et al., 2018; Deveci et al., 2019, Işıldar et al., 2019; Sethurajan et al., 2019). WEEE that is rich in gold (i.e., >400 g/t Au) is considered as "high-value" WEEE with a high economic incentive for recycling (Hagelüken, 2006). Industrial metallurgical plants currently tend to treat "high-value" WEEE due to economic reasons (Hagelüken, 2006). There seems an increasing demand for some base/precious metals including copper and silver for the clean energy revolution (electric vehicles (EVs), renewable energy etc.) (IEA, 2021). The demand for copper is expected to increase by 28% by 2040. Higher quantities of copper (2.4 times) are required for electric vehicles (EVs) when compared with conventional ones. The silver demand is also increasing due to its key role in solar photovoltaic panels (PVs), in particular (IEA, 2021).

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Physical separation methods are commonly used as pretreatment for the recovery of metals into a concentrate (i.e., metal-rich fraction) due to their simplicity and low cost. Such a pretreatment improves the environmental and economic performance of subsequent metallurgical extraction processes. Separation methods exploit the differences in physical properties (i.e., specific gravity, conductivity, magnetic susceptibility, brittleness, etc.) of metals and nonmetals present in WEEE. The main shortcoming of physical separation methods is reported to be high metal losses (10-35%) (Goosey and Kellner, 2002; Yazici, 2012). Depending on the wide difference between the specific gravity of metals and nonmetals (e.g., 8.93 g/cm^3 (Cu) vs. ≤2 g/cm^3 (most of the plastics in WEEE)), many researchers investigated the use of different gravity separation methods for the recovery of metals from WEEE (Zhang and Forssberg, 1998; Peng et al., 2004; Zhao et al., 2004; Wen et al., 2005; Li et al., 2007; Das et al., 2009). Air separation/classification is a gravity separation method used in different industries including agriculture, mineral processing and waste treatment (Wills and Napier-Munn, 2006). Some researchers investigated the use of air separators for the recovery of metals from WEEE (Zhao et al., 2004; Eswaraiah et al., 2008; He et al., 2011; Ribeiro et al., 2019; Silva et al., 2019). Zig-zag air separator is a type of air separator in the form of a vertical air column (Fig. 1) in which the flow direction of the fluid (e.g., air) is upwards which allows the collection of light-fine particles into overflow stream while the heavy-coarse particles move downwards and collected in underflow (Fig. 1).

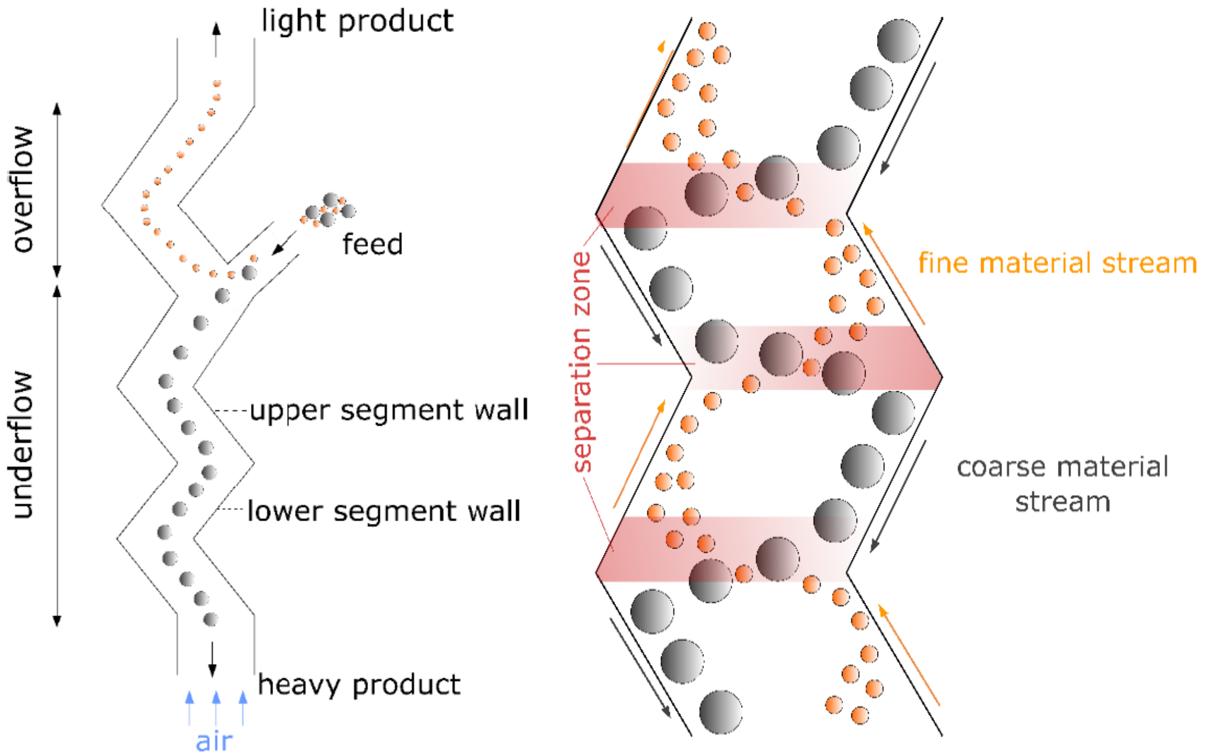

Fig. 1. General overview of a zig-zag air separator (left) and flow pattern of solid particles and separation zones of coarse-fine particles in the separator (right) (Kaas et al., 2022)

In the literature, there are many studies on the recovery of metals from e-waste. Most of these studies focused on the treatment of high-value e-waste. Considering the fact that a significant amount of "low-value" WEEE (<100 g/t Au) are generated worldwide, search for simple, environmentally sound and cost-effective routes for this type of WEEE is of economic and environmental importance. In addition, the increasing demand for copper for its use in electric vehicles (EVs) and renewable technologies re-addressed the importance of recycling copper from copper-rich waste streams such as e-waste. In this study, the separation of base and precious metals from a "low-value" WEEE (i.e., scrap TV boards) was investigated using a zig-zag air separator as a dry gravity separation equipment. The effect of air flow rate (4-16 m/s) on the separation of metals was investigated. Separation efficiency (%), enrichment ratio and ratio of concentration were also determined to assess the separation performance under the conditions tested.

2. Materials and methods

2.1. Material

Scrap TV boards (STVBs) were kindly provided from a TV manufacturing plant (Türkiye) (Fig. 2). The obtained STVBs were reduced in size within a two-stage comminution operation. The first stage involved shredding the scrap initially to -8 mm and then to -3.35 mm, using a rotary cutting shredder (Fig. 2). The shredded material (-3.35 mm) was then fed to an ultra-centrifugal grinding mill (Retsch ZM 200) to grind the material down to -1 mm. Preliminary tests showed that the zig-zag air separator is ineffective in the separation of metals from fine fractions. Therefore, the fine fraction (-0.1 mm) was removed by sieving prior to separation tests. The sized material (-1 +0.1 mm) was determined to contain 15.4% Cu, 47 g/t Ag and 0.05% Fe. With no gold content, this material is classified as a "low-value" WEEE.

Fig. 2. Scrap TV boards (STVBs) (left) and size-reduced STVBs (-3.35 mm) (right)

2.2. Method

In the separation tests, a zig-zag air separator manufactured by DEMMAKSAN Machinery (Trabzon/Türkiye) was used (Fig. 3) to investigate the effect of air flowrate (4-16 m/s) on the separation performance of the metals (Cu, Ag, Fe) from STVBs in three levels as the most influential variable. Air suction was provided by a vacuum cleaner. The fine-light (rich in non-metallic materials) and coarse-heavy (metal-rich) fractions were collected from the overflow (tailings) and underflow streams, respectively.

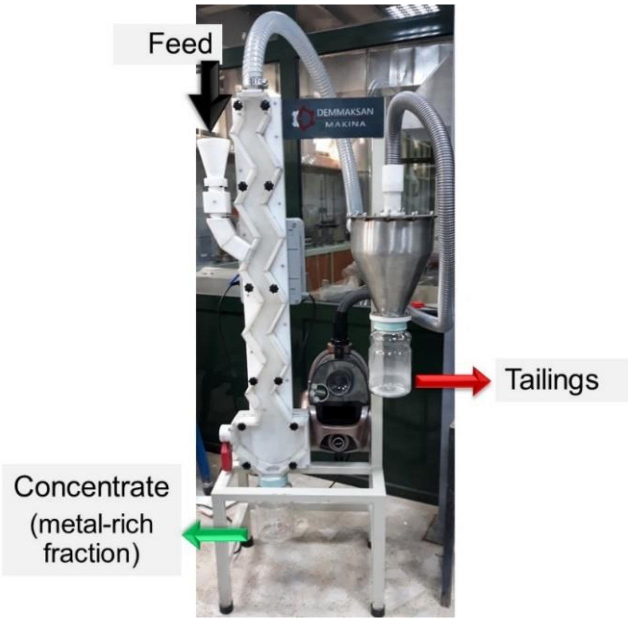

Fig. 3. Zig-zag air separator used in the tests

In the tests, a certain amount of sized (-1 +0.1 mm) STVBs (~35 g) was fed to the separator after adjusting the air flow rate to the required level using the digital flow meter. After the completion of feeding, the products (i.e., concentrate and tailing material) were collected and then weighed prior to the analysis for metals through wet chemical methods i.e., hot aqua regia ($HCl:HNO_3$=3:1 by volume) digestion followed by atomic absorption spectrometry using a Perkin Elmer AAnalyst 400 equipment. Analytical results were used to calculate the grade (%) and recovery (%) data for each metal (i.e., Cu, Ag, Fe).

3. Results and discussion

The separation of base (Cu) and precious (Ag) metals from STVBs was carried out at three different air flow rates (4, 10 and16 m/s). The products obtained are shown in Fig. 4. The results are presented in Tables 1-3 and Fig. 5.

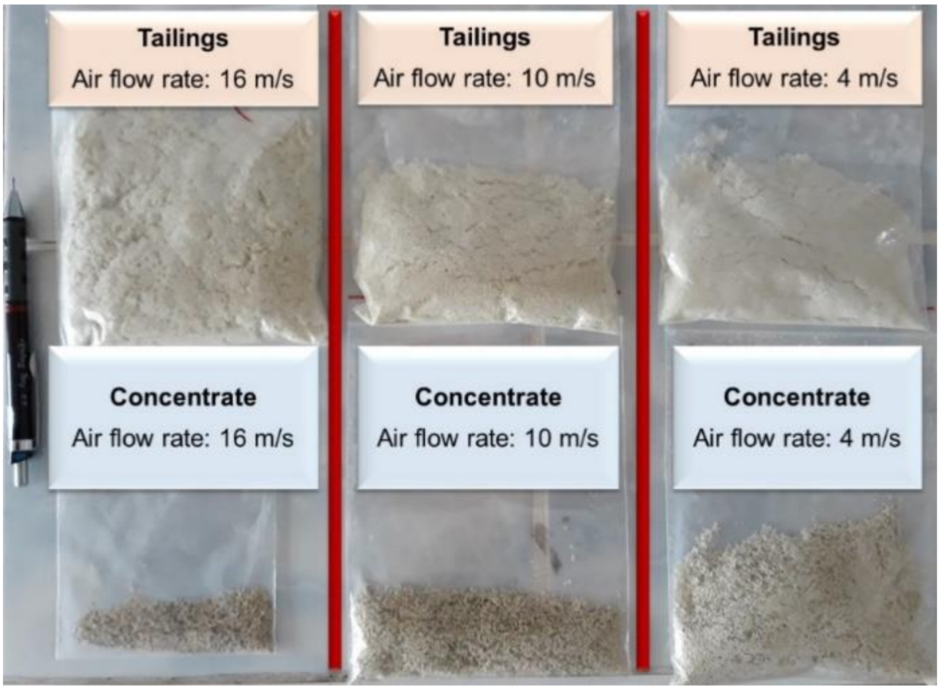

Fig. 4. Photos of the products (concentrate and tailings) obtained from zig-zag air separation tests of STVBs under different flow rates of air (4-16 m/s)

At the highest flow rate tested (i.e., 16 m/s) 15.4% of the material was collected into the metal-rich fraction that contained 62.3% Cu and 198 g/t Ag at recoveries of 63.3% Cu and 73.9% Ag (Table 1, Fig. 5). Decreasing the flow rate from 16 to 10 m/s produced a metal-rich fraction (46.2% of the feed) with copper and silver grades of 29.8% and 61.1 g/t, respectively. At this flow rate (10 m/s) 94.2% and 81.7% of Cu and Ag, respectively, were recovered (Table 2, Fig. 5). At the lowest flow rate tested (4 m/s), most of the material (i.e., 75.6%) was reported to the metal-rich fraction with increased recovery of both metals (≥99.7%) at the expense of low grade of copper in the concentrate (i.e., 21.6%) (Table 3, Fig. 5). Consistent with the current findings, researchers (Zhao et al., 2004; Eswaraiah and Soni, 2015) who used different kinds of air separators, found that high air flow rates led to an increase in metal grades with a concurrent decrease in recoveries.

Table 1. Results of the separation test carried out at an air flow rate of 16 m/s

Product	Mass (%)	Copper (Cu)		Silver (Ag)		Iron (Fe)	
		Grade (%)	Recovery (%)	Grade (g/t)	Recovery (%)	Grade (%)	Recovery (%)
Concentrate	15.4	62.3	63.3	198	73.9	0.33	71.7
Tailings	84.6	6.58	36.7	12.8	26.1	0.02	28.3

Table 2. Results of the separation test carried out at an air flow rate of 10 m/s

Product	Mass (%)	Copper (Cu)		Silver (Ag)		Iron (Fe)	
		Grade (%)	Recovery (%)	Grade (g/t)	Recovery (%)	Grade (%)	Recovery (%)
Concentrate	46.2	29.8	94.2	61.1	81.7	0.07	63.8
Tailings	53.8	1.59	5.8	11.8	18.3	0.03	36.2

Table 3. Results of the separation test carried out at an air flow rate of 4 m/s

Product	Mass (%)	Copper (Cu)		Silver (Ag)		Iron (Fe)	
		Grade (%)	Recovery (%)	Grade (g/t)	Recovery (%)	Grade (%)	Recovery (%)
Concentrate	75.6	21.6	99.7	86.2	99.9	0.03	86.8
Tailings	24.4	0.22	0.3	0.4	0.14	0.02	13.2

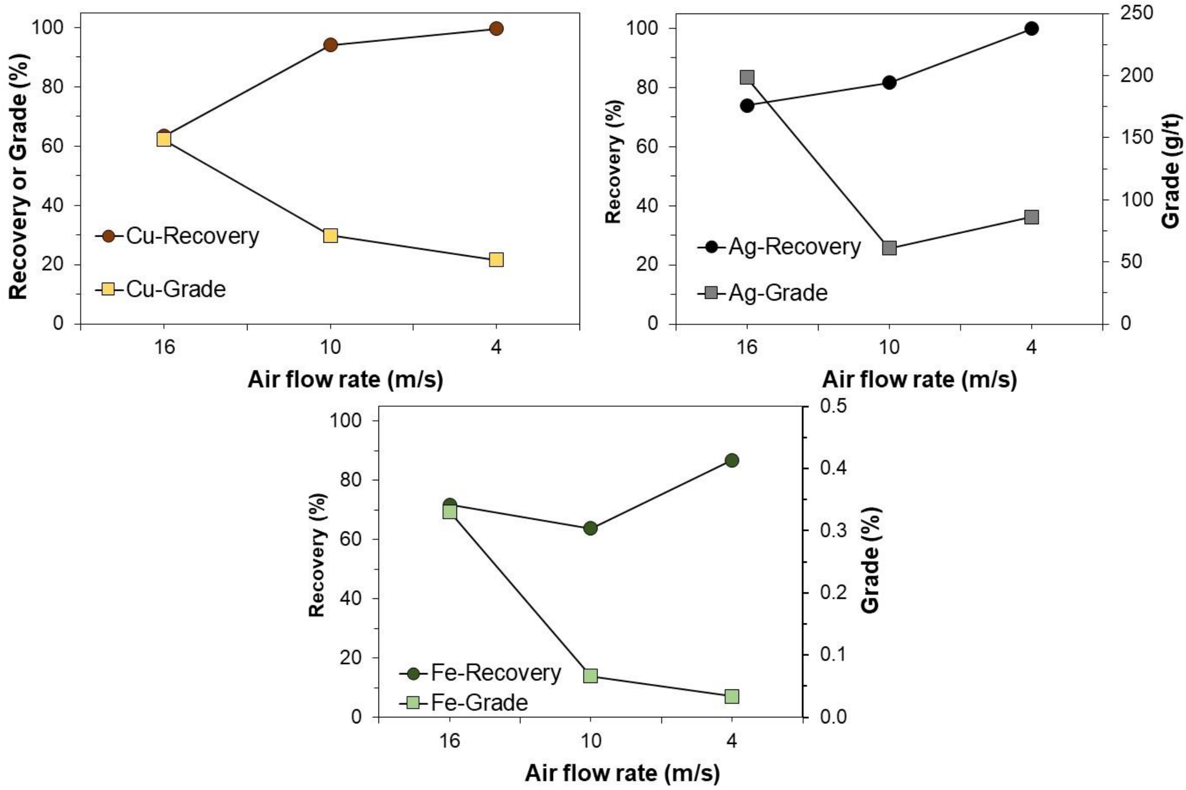

Fig. 5. Recovery (%) and grade (% or g/t) plots for metals

Various indexes are proposed to evaluate the separation performance in mineral processing operations (Drzymala, 2007). Separation efficiency is commonly used to evaluate the separation performance of metals/minerals to reflect the concentrate recovery and grade of the metals/minerals in mineral processing operations (Eqs. 1-3) (Schulz, 1969).

$$\text{Separation efficiency (\%)} = R_m - R_g \quad (1)$$

$$R_m = \frac{C\ x\ c_m}{F\ x\ f_m}\ x\ 100 \quad (2)$$

$$R_g = \frac{C\ x\ (1-c_m)}{F\ x\ (1-f_m)}\ x\ 100 \quad (3)$$

where R_m and R_g are the recoveries of the metal (such as Cu, Ag or Fe) in question, and other metals and materials (i.e., other metals and non-metal fractions) into the concentrate, respectively. C and F are the weight of the concentrate and feed, respectively. c_m and f_m are the grades (% or g/t) of the metal (Cu, Ag or Fe) in the concentrate and feed, respectively.

Fig. 7 shows the plots for the separation efficiency of copper, silver and iron in the zig-zag air separation. The separation efficiency for copper was determined to be 56.2% and 56.4% at air flow rates of 10 m/s and 16 m/s, respectively. This indicates that an air flow rate of 10 m/s is sufficient for effective separation of copper (Fig. 7). However, in the case of silver and iron, there appeared a trend of decrease in the separation efficiency with decreasing the air flow rate. The highest efficiency was achieved for these metals at 16 m/s (Fig. 7).

"Enrichment ratio" and "ratio of concentration" were also calculated as presented in Fig. 6. Enrichment ratio is the ratio of the metal grade of concentrate to that of feed (i.e., grade of Cu, Ag or Fe. Ratio of concentration represents the ratio of the amount of feed to that of the concentrate (Drzymala, 2007). The enrichment ratio tended to increase with elevating the air flow rate with the highest ratio having been obtained at the highest air flow rate tested i.e., 16 m/s. In other words, at high air flow rates, a cleaner concentrate with a high metal content can be produced (Fig. 6). For the ratio of concentration, rising the air flow rate led to increasingly higher ratios (Fig. 6). This suggests that the amount of material reported to the overflow (i.e., tailings) increases with the air flow rate as expected.

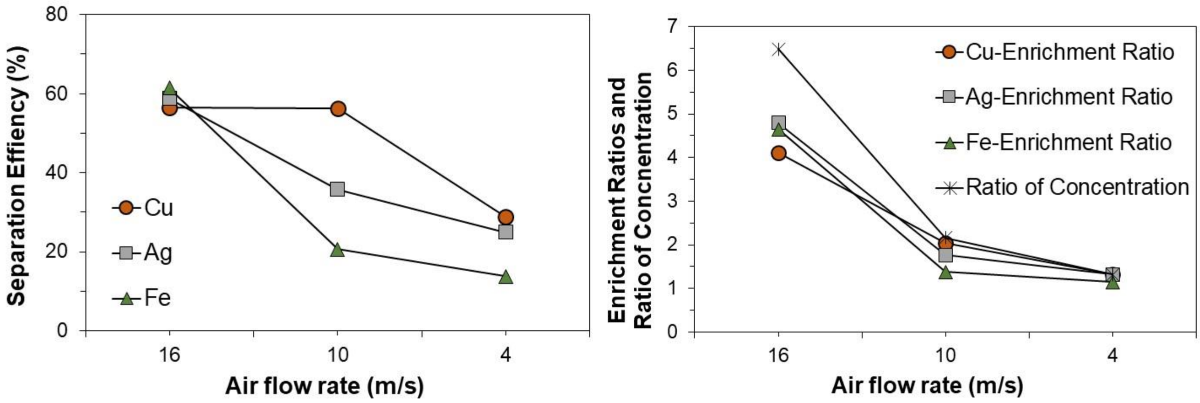

Fig. 6. Separation efficiency (left), enrichment ratio and ratio of concentration (right) plots

4. Conclusions

This study reports the effect of air flow rate on the separation of metals from scrap TV circuit boards (STVBs) in a zig-zag air separator. The sized scrap material (-1+0.1 mm) was used in the tests after the removal of the fine fraction (-0.1 mm) from the ground material. The feed material was determined to contain 15.4% Cu, 47 g/t Ag and 0.05% Fe. Increasing the air flow rate was found to result in a decrease in metal recoveries despite the improved metal grades. Separation efficiency (%) was used to evaluate the separation performance under the test conditions. A similar separation efficiency was obtained for copper at 10 m/s and 16 m/s air flow rates. On the other hand, the separation efficiency for silver was found to decrease with decreasing the air flow rate in the range tested. Based on the separation efficiency, the highest air flow rate (i.e., 16 m/s) can be selected as the optimum condition for the separation of copper and silver from STVBs. At this air flow rate, a metal-rich concentrate containing 62.3% Cu and 198 g/t Ag was produced at recoveries of 63.3% Cu and 73.9% Ag. Also, the highest enrichment ratio and ratio of concentration were also obtained at 16 m/s. The findings demonstrated that zig-zag air separation can be used as a pretreatment step to obtain a metal-rich fraction from low-value WEEE (e.g., STVBs) prior to metallurgical extraction processes.

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