Fundamental Experiments for the Development of an Aero-suspension Dense Media Separator for Aluminium-Copper Scrap Recycling

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ABSTRACT

The EU's circular economy concept necessitates the recycling of one or more times used material streams into the production – consumption cycle again and again. The commonly known problem of limited numbers of recycling cycles of plastics drives economy into metals usage again, because for these materials the number of recycling cycles is not limited. Therefore, the efficient and economic separation of mixed aluminium and copper scraps is an important issue for our society. There are existing wet (dense media separation, etc.) and dry (eddy current separator, but its applicability is limited for this task, air separator, etc.) technologies for the upgrading of the 30-100 mm particle size range scraps. Wet separation has to be faced to the handling of contaminated water, therefore authors has started the development work of a dry aero-suspension dense media separator. Fundamental research has been done. Laboratory scale test equipment had been made by with a given powder could be fluidised, the necessary air pressure could be set and the air flow rate could be measured. Systematic test series had been made with the lab-scale test equipment to find suitable particulate materials, to figure out their optimal particle size range, to find suitable technical parameters to establish stable fluidised bed and to find a suitable construction to distribute air below the powder charged bed. Design and construction of continuous operation pilot-scale and industrial size machines had also been done.

Keywords: *Fluidised bed, aero-suspension, dense media separator, aluminium and copper scrap, Bingham-plastics rheology.*

1. INTRODUCTION AND LITERATURE SURVEY

The fluidised bed aero-suspension dense media separator is well-known equipment (Anjaneyulu and Khakbar 1995, Basu 2006, Beeckmans and Minh 1977, Gibilaro 2001, Sahu et al. 2009). According to its operating principle there is a solid-gas fluidised bed made by blown in air from the bottom into the bulk granular working media. The mixture density of the fluidised solid-liquid dense media can be controlled by the quantity of the blown in air and then the heavier particles of the raw material will settle and lighter particles will float. Comparing to the wet dense media separation, there is no need for any liquid for the dry process, therefore no need for the clarification for the separated products and no need for a water handling system. Therefore dry dense media separators are widely applied in the industry. The first application of fluidisation was invented by Brötz in 1900. Brötz applied a counter-current water flow to loosen a sand water filtration bed. First patent of fluidisation was applied for a catalyst by Phillips and Bulteel in 1910. The catalyst was transported into a fluidised gas chamber where the reaction was more efficient in the diluted solid – gas system. The first industrial application was the Winkler gas generator developed by BASF in Germany in 1921. Brown coal was gassed in the cylindrical shape fluidised bed reactor (Leva, 1967). This process was first applied in the pharmaceutical industry by Wurster for the coating of tablets in 1960. Afterward, it had been applied widely in pharmaceutics (Dévay, 2013). Aero-suspension dense media separation is also widely used in waste management. A gas-solid fluidized bed separator was applied in laboratory scale for shredded municipal bulky solid waste separation (Sekito et al. 2006). Separation of harmful impurities from refuse derived fuels (RDF) was carried out in a solid-gas fluidized bed (Krüger et al. 2014).

There are several scientific and practical challenges to be solved for the development of a separation machine. The most important might be the one of how to establish homogeneous solid-gas distribution in the fluidised bed. There are several unwanted phenomena that might occurs at insufficient bed operation such as, bubbling, slugging, channelling and agitation and turbulent fluidisation (Ghosh 2013). Fig. 1 shows the typical pressure loss of fluidised solid-gas beds as function of the air velocity (Dévay 2013).

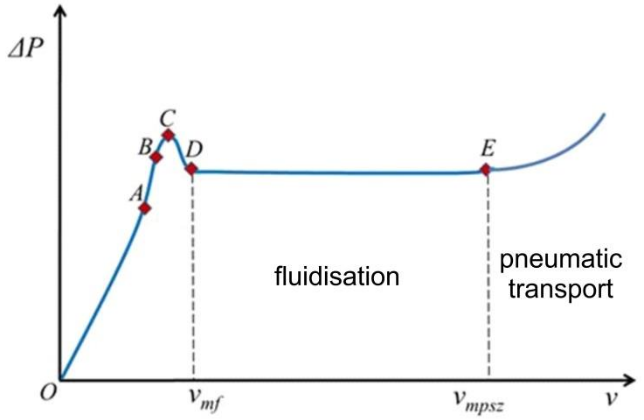


Figure 1. The pressure loss of fluidised solid-gas beds as function of the air velocity (Dévay 2013)

When the flow rate of the blown-in air is increasing from 0, up the point A the solids are still packed in the bed and the pressure loss is increasing linearly with air velocity because of the laminar flow between the particles (Dévay 2013). In between points A-B, the velocity is increasing exponentially and from point B the solid particles start to levitate and in between points B-C they can have a better orientation and that decreases the resistance, therefore the pressure loss is also decreasing a little. From point B to E good fluidisation can be established. In this desirable zone the particles typically do not contact, they are levitating in the air stream, the pressure loss does not depend on the fluid velocity and it does not depend much on the solids concentration either in this zone. From point E, the transport of the particles starts and that is another process, namely the pneumatic transport. That is clearly avoidable in fluidised bed technologies. Fig.1 is extremely important for process engineering point of view! The air flow rate range in between points D-E is small; it is a practical challenge to establish stable condition here. The density of the fluidised solid-gas bed depends on the air flow rate in zone D-E and this range is limited. The density of the fluidised solid-gas bed is crucial for the separation, because this is the cut density. The density of the applied solids as working media basically determines this mixture density. However, theoretically it is possible to set different fluidised solid-gas bed density and therefore different cut density by changing the air flow rate.

To address the above mentioned challenge laboratory scale test equipment was developed. Fundamental examination of different air inlet systems had been carried out to figure how to avoid the mentioned stable fluidisation flow disturbing phenomena. The specific air flow rate and pressure need for a given height and material solid-gas fluidised bed was measured. The air flow rate versus bed resultant density functions and the settling velocity of given scrap particles in given density solid-gas fluidised beds had been also measured. On the basis of the lab-scale examination a pilot-scale separator was designed and made. Fundamental research with the pilot scale machine had been carried out and after the industrial size separator was designed and made. Fundamental applied research with the industrial machine had been carried out with aluminium – copper scraps.

3. MATERIALS AND METHODS

3.1. Laboratory scale test equipment

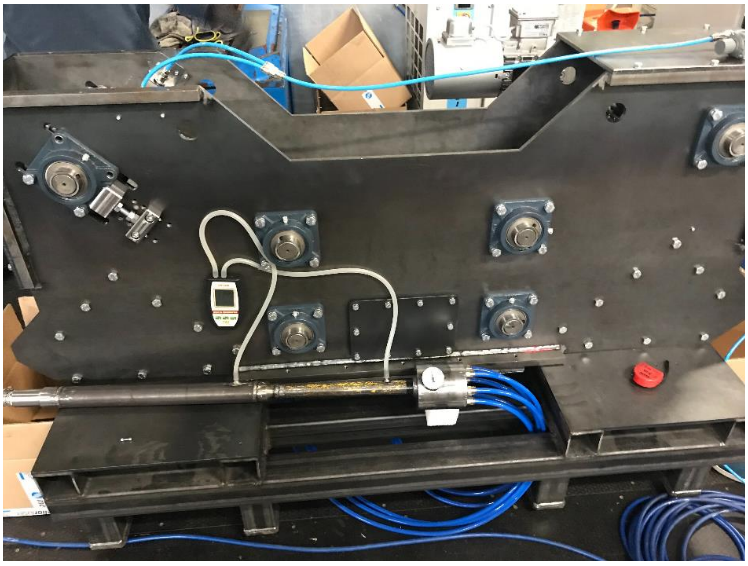
Fig. 2 shows a photo and schematic drawing of the built laboratory scale test equipment. The air was supplied by a compressor in our laboratory. The pressure was first regulated by a dedicated pressure regulator valve (1). This static pressure plays a key role, because the downstream fluidised bed represents a given flow resistance and that determines how much energy is consumed, namely what air flow rate will be developed in the common operating point.

Figure 2. Laboratory scale test equipment
(1. Pressure regulator, 2. Venturi tube, 3. Differential pressure meter, 4. Laboratory model fluidised bed reactor)

The air flow rate was measured indirectly by a built Venturi tube (2) and a differential pressure meter (3). The lab-scale fluidised bed reactor (4) had two parts, the bottom and the top. The air distribution system was built into the bottom part. Many different systems had been tested to reach stable fluidising conditions. The top part was made by transparent walls to observe flow disturbances.

3.2. Pilot scale separator

Fig. 2 shows two photos about the pilot-scale aero-suspension dense media separator. Left photo shows the side view and the right one shows the top view of the machine.



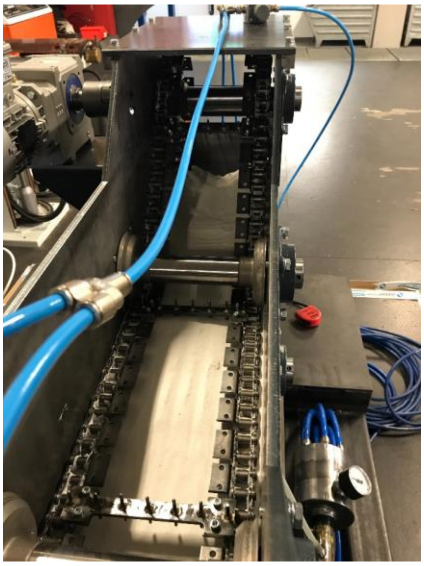


Figure 2. The pilot-scale aero-suspension dense media separator
Figure 2 left. Side view, Figure 2 right. Top view

The built machine is an aero-suspension dense media separator with an endless chain to discharge the separated products. A similar design was made by the China University of Mining and Technology in 1994 (Sahu 2009). The so called CMUT separator was installed and operated in the coal mine of Qitaihe Coal Co. for dry coal upgrading. Fig. 3 shows the schematic drawing of the built chain system with 6 rollers. The 6 bearings of the chain routing rollers can be well seen on Fig. 2 left. The built Venturi tube with a differential pressure meter and the air distribution head are also shown. The pilot-scale device was loaded with zirconium-oxide media as it is shown on Fig. 2 right.

3.3. Industrial size machine

Fig. 3 shows the schematic drawing of the industrial scale aero-suspension dense media separator. The mechanical engineering design of this machine was made by the Institute of Machine Production of the University of Miskolc. The machine has a massive steel frame. The frame is necessary to withstand the load because of the moving chain and comb elements of the discharge system in the fluidised bed. The discharge chain should be working in non-fluidised working media too. There are two endless chains at the front and the back sides of the machine and there cross sectional combs to discharge products. There are two toothed wheels and four non-toothed rollers. One toothed wheel is driven.

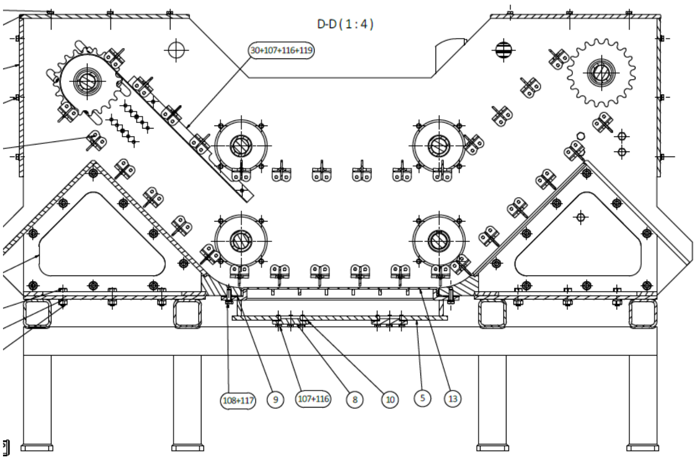


Figure 3. Schematic drawing of the industrial scale aero-suspension dense media separator

The centre part of the machine is charged with the working bulk media. The level of media charge is higher than the level of the upper horizontal chain section, but it is lower than the products discharge points. The air is supplied by a compressor, the pressure should be higher than 2 bar. There are built in mechanical and air nozzle cleaning parts to clean the chains from the particles of the charged media. The machine is modular, the width can be modified by changing the in depth parts of it. Fig. 6 left shows a photo about the industrial scale machine.

3.4. Materials

As the working media iron- and zirconium-oxide powders were used presented in this study. Different particle size fractions were made by manual laboratory sieving with a standard 200 mm laboratory sieve series. The size fractions were as follows in the case of iron powder: 0-100, 100-160, 160-200, 200-250, 250-315, 315-400 μm. These size fractions are shown in Fig. 5.

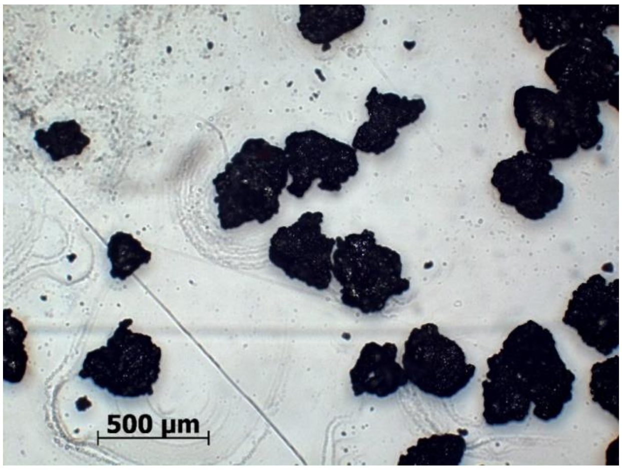


Figure 4. Particle shape of iron powder taken by an optical microscope

Figure 5. Different particle size fractions of iron powder

The 160 – 400 μm iron powder size fraction was used for the laboratory scale fluidisation experiments. The particle density of this fraction was measured many times in laboratory pycnometers; the average particle density was 6820 kg/m^3. The bulk density was measured by a volume calibrated glass cylinder, the average bulk density was 3085 kg/m^3. The porosity of the loosen bulk state iron powder fraction was 0.548 (volume of air/volume of bulk).

Another material, namely zirconium-oxide were also used for the laboratory-, pilot- and industrial scale tests. The particle density of the 200-300 μm size fraction was 6060 kg/m^3 and the loosen bulk density was 3600 kg/m^3.

For the upgrading experiment aluminium and copper scraps were used, a sample is shown on Fig. 6 right.

4. Results and discussion

Preliminary experimental series had been carried out with the lab scale test rig shown in Fig. 2. Different quantity (m) of 160 – 400 μm iron powder was filled into the reactor and the non-fluidised height (H_{nf}) of the charge was measured first. Then in a case the spring valve of the pressure regulator was gradually opened up to a given point and by this way the regulated pressure after the regulator was set. Fluidisation conditions of the charge in the reactor were observed. If the regulated pressure was too low, therefore the air flow was too low and then insufficient fluidisation (not working) happened. Increasing the pressure resulted good fluidisation conditions and then further increasing the pressure resulted higher and higher dust formation above the charged bed. The condition of the fluidised bed was manually checked by some aluminium and copper scrap particles hanged on wires. The surface of the fluidised bed looked like boiling water; many times bubbles were randomly released. Fig. 6 left shows the industrial machine filled with zirconium-oxide charge and a bubble is clearly visible. Despite the fact that on the surface this bubbling and dusting phenomenon was not constant the average height of this “bubbling zone” was also measured. The level increase of the charge in the reactor was not observable, only the bubbling zone was developed above the material bed. Table 1 shows the measured results.

Table 1. Results of preliminary experiments carried out with the lab-scale test rig

No. 1.	**mass of charge, m = 8 kg; non-fluidised height, H_{nf} = 11 cm;**				
Regulated pressure after the regulator [bar]	1	1.5	2	2.5	3
Height of bubbling zone [cm]	2	3	4	5	6
Air velocity in the supply tube [m/s]	87.6	101.6	110.2	119.7	127.5
Condition	Not working	Not working	Not working	Not working	Not working
No. 2.	**mass of charge, m = 12 kg; non-fluidised height, H_{nf} = 15 cm;**				
Regulated pressure after the regulator [bar]	1	**1.5**	2	2.5	3
Height of bubbling zone [cm]	0	**3**	4	6.5	8.5
Air velocity in the supply tube [m/s]	92.4	**105.4**	114.9	123.9	129.5
Condition	Not working	**Good**	High dust	High dust	High dust
No. 3.	**mass of charge, m = 16 kg; non-fluidised height, H_{nf} = 16.5 cm;**				
Regulated pressure after the regulator [bar]	1	**1.5**	2	2.5	3
Height of bubbling zone [cm]	0	**2**	4	6	8
Air velocity in the supply tube [m/s]	87.6	**101.4**	111.3	120.5	134.7
Condition	Not working	**Good**	High dust	High dust	High dust

Results shown in Table 1 had highlighted a design problem with the lab-scale test device, namely that the air velocity was too high in the air supply tubing, and therefore this pipe system was modified afterward. Pressure loss of the small tubing air supply was significant compared to the one of the fluidised bed. On the basis of the results of the lab-scale tests the pilot-scale machine (Fig. 2) was designed and built. Systematic fluidised bed fundamental and separation experiments had been carried out. One of the aims of these tests was to determine the air supply requirements for the industrial size machine. Results of a pilot-scale test are shown in Table 2. The charge was filled into the 0.146 m^2 effective surface area pilot-scale machine at a non-fluidised height of 30 cm.

Table 2. Fluidisation conditions in the pilot-scale machine

No.	Regulated pressure after the regulator [bar]	Air flow rate [m^3/h]	Condition
1.	0.26	121	Non-sufficient fluidisation
2.	0.38	150	Good fluidisation with slight air breakthrough
3.	0.4	159	Unacceptable air breakthrough

Data of test No. 2 in Table 2 were used for the calculation of the specific air need of the given charge material and height aero-suspension dense media separator, because during that test good fluidisation condition was experienced. Table 3 shows the results of specific air need calculations.

Table 3. Specific air need of the 0.146 m^2 effective surface, 30 cm charge height pilot-scale machine

Regulated pressure after the regulator	0.38 bar
Diameter of Venturi tube no. 1	0.04 m
Cross section of Venturi tube no. 1	0,001256 m^2
Diameter of Venturi tube no. 2	0.027 m
Cross section of Venturi tube no. 2	0.000572265 m^2
Density of air (assumed to be incompressible)	1.2 kg/m^3
Measured pressure loss on the Venturi tube	1700 Pa
Air velocity in Venturi tube no. 2	72.1 m/s
Air flow rate	148.7 m^3/h
The measured specific air need of the pilot-scale separator	**1021 $m^{3/}h\cdot m^2$**

On the basis of the results of the pilot-scale tests the industrial machine (Fig. 6) was designed and built. Systematic fluidised bed separation experiments had been carried out.

Figure 6. The industrial size aero-suspension separator
Figure 6 left. Top view of the machine with charge
Figure 6 right. Copper-aluminium scrap for a separation test

Results of one test is shown here just as an example. 5 kg material was evenly fed to the equipment by a vibrated feeder during 60 seconds. Mass flow rate of feed was 300 kg/h. The copper-aluminium scrap sample is shown in Fig. 6 right. Table 4 shows mass yield and component yield data of the test.

Table 4. Mass yield and component yield data of the test

	Al [g]	Cu [g]	Mass yield of product[%]	Al yield [%]	Cu yield[%]
Al product	3900	0	81.25	84.23	0.00
Cu product	730	170	18.75	15.77	100.00

270 g of aluminium remained in the equipment (not marked in the table). However, if the machine will operate continuously, probably this remaining material will also come out from the equipment. The Al product was pure 100% aluminium, but the Cu product was not clean, it contained some aluminium too. These badly separated Al particles came to the Cu product probably by two different ways: (1) an Al particle was stick to the combs and then

travelled through the fluidized bed by the chain and then fell out on the Cu side. (2) On the Cu side a dead space (non-fluidised separation medium) was formed and the Al particle which was trapped in this volume was discharged on the Cu side. Flat aluminium particles are difficult to handle by the combs. At discharge, they may slip back into the separation space under the teeth of the combs (this was the reason of 270 g of residual aluminium). Certain crumpled aluminium particles could stick to the teeth of the combs, even very tightly, and the combs make several turns with them. By installing more than one comb, the combs would be subjected to a lower load, so the capacity would be increased.

5. Conclusion

After a comprehensive literature survey a laboratory scale fluidised bed reactor was built. It was charged with different granular materials and fluidisation was studied. A pressure regulator could be applied and by opening its spring valve up to a given point, steady-state air flow rate could be set. If the air supply was low the charged bed was not fluidised. There was only a very narrow air flow rate range, when good fluidised bed was formed. In this range too, the surface of the charged bed started to "boil", bubbles were formed. However Al particles floated and Cu particles settled in this good fluidised bed. If the air flow rate was further increased, bubbling increased and dust was released, the operational condition was no longer appropriate.

On the basis of the results of the lab-scale tests the pilot-scale machine (Fig. 2) was designed and built. One of the most important engineering features, namely the specific air supply need of a given charge and charging height separator was measured. The measured specific air need of the 200-300 μm size zirconium-oxide charged, 30 cm charge height pilot-scale machine was 1021 $m^{3}/h \cdot m^{2}$.

The industrial size aero-suspension dense media separator (400 kg/h) had been designed and built. One separation example is shown here, where the Al product was pure 100 % aluminium; the Cu product contained some aluminium and some aluminium rested in the machine. Further examination and industrial tests are planned.

6. Literature

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