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IN

PRODUCT AND PRODUCTION DEVELOPMENT

AIR CLASSIFICATION OF FINE AGGREGATES

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Air Classification of Fine Aggregates

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If knowledge can create problems, it is not through ignorance that we can solve them.
Isaac Asimov

ABSTRACT

Aggregates are defined as particles of rock which in combination are used as a civil engineering material. It is used in bounded form in asphalt and concrete. Historically natural sand has been used as fine aggregates for concrete production in Sweden. Due to environmental reasons the Swedish government is limiting the extraction of natural sand resources. Manufactured sand is therefore being investigated in Sweden as a replacement product.

Properties of the fine aggregates such as shape and particle size distribution are affecting the qualities of both the uncured and finished concrete. It is possible to produce manufactured sand with a good shape; however the crushing process results in a relatively large amount of fines (particles smaller than 63 µm). Research shows that the amount of fines in manufactured sand affects concrete properties such as, workability, water demand, drying shrinkage, compressive and flexural strength. To achieve a good concrete the manufactured sand should have somewhere between 5-10 mass percent of fines depending on rock type. It is common that manufactured sand has around 15-25 mass percent of fines after the crushing stage. In this thesis, dry air classification has been investigated to reduce the amount of fines in manufactured sand.

There exists a number of air classifiers produced for different industrial use. This work has investigated four different air classifiers using different design approaches. Two air classifiers using an internal aerodynamic cycle and two with an open aerodynamic cycle.

Both of the air classifiers with internal aerodynamic cycle investigated in the performed research are based around a centrifugal-crossflow separation zone. The classification process are for both of these air classifiers controlled by two fans, the circulating fan and the separator fan. The circulating fan creates the internal circulating air flow. The air flow created by the separator fan changes the cut size. Experiments performed on the air classifiers showed that it was possible to reduce the amount of fines from 15 mass percent to 5 mass percent.

The investigated air classifiers with an open aerodynamic cycle were a two-stage air classifier and a mobile air classifier. The first stage of the two-stage air classifier used the same design as the mobile air classifier and is designed around a gravitational-crossflow separation zone modified to allow for recirculation of particles towards the separation zone. The second stage is based around a vertical standing centrifugal-counterflow zone modified to allow for recirculation of material. Both air classifiers can produce a product with the desired amount of fines. The performed empirical measurements and CFD simulations showed that the recirculation is important for the classification process, reducing the influence of particle to particle interaction.

In conclusion, air classification has been technically proven to be able to reduce the amount of fines in the finished product. The classification result will depend on the chosen technology.

Key words: Air classification, Manufactured sand, Concrete, CFD, Fines, Aggregates

PUBLICATIONS

This thesis contains the following papers.

Paper A: Johansson, R. and Evertsson, M., *Circulating Air Classification of Manufactured Sand*, Presented at International Mineral Processing Congress XXV 2010, Published in conference proceedings 851-858. ISBN 978 1 921522 28 4

Paper B: Johansson, R. and Evertsson, M., *CFD Simulation of a Gravitational Air Classifier*, Published in Mineral Engineering (Journal), 2012

Paper C: Johansson, R. and Evertsson, M., *An Empirical Study of a Gravitational Air Classifier*, Published in Mineral Engineering (Journal), 2012

Paper D: Johansson, R. and Evertsson, M., *Modelling of a mobile Gravitational-Inertial Air Classifier*, Presented at European Symposium on Comminution & Classification 2013, Published in conference proceedings ISBN 978-3-86844-551-0

Paper E: Johansson, R. and Evertsson, M., *CFD simulations of a Centrifugal Air Classifier used in the aggregate industry*, Published in Mineral Engineering (Journal), 2014

Paper F: Johansson, R. and Evertsson, M., *Modelling of a Two-Stage Air Classifier*, Presented at MEI conference Physical Separation 2013

Paper G: Johansson, R. and Evertsson, M., *Simulation and Pilot Testing of a Circulating Air Classifier used in the Production of Manufactured Sand*, Submitted to Mineral Engineering (Journal), December 2014

CONTRIBUTIONS TO CO-AUTHORED PAPERS

In all the papers A-G, Johansson and Evertsson initiated the idea. The implementation was performed by Johansson. Johansson wrote the paper with Evertsson as a reviewer.

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APPENDIX

Paper A: Circulating Air Classification of Manufactured Sand

Paper B: CFD Simulation of a Gravitational Air Classifier

Paper C: Empirical Study of a Gravitational Air Classifier

Paper D: Modelling of a mobile Gravitational-Inertial Air Classifier

Paper E: CFD Simulation of a Centrifugal Air Classifier used in the Aggregate industry

Paper F: Modelling of a Two-Stage air Classifier

Paper G: Simulation and Pilot Testing of a Circulating Air Classifier Used in the Production of Manufactured Sand

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Robert Johansson

Göteborg, December 2014

1 INTRODUCTION

The aim of this chapter is to:

- *Introduce the aggregates industry and its relevance in today's society*
- *Describe the production of fine aggregates for concrete and asphalt*
- *Describe the influence of the sand used on the finished concrete*
- *Describe screening and cut-size in general*
- *Describe the principles and theory behind air classification*

1.1 AGGREGATE MATERIALS AND THEIR USE

Aggregates are defined as particles of rock which in combination are used as a civil engineering material [1]. The particles can either be used unbounded or bounded for example in concrete. The aggregates industry is an, by the public, often overlooked industry. It is an industry which is important to modern society and the existence and quality of roads, railroads, bridges and buildings all depend on the aggregates industry being able to deliver a product of sufficient quantity and quality. The demand for stone and crushed materials for construction has grown during the history of mankind. As an example; France during the early medieval Europe (eleventh to thirteenth century) quarried more stone than the history of ancient Egypt [2]. Today in Sweden a total of 79.7 million tonnes of aggregates were produced in 2011, of these was natural gravel 13.4 million tonnes [3]. For Europe the total production of aggregates was close to 3 billion tonnes [4].

Historical stone roads have been found in several parts of the world and early stone-paved streets date back to Ur in the Middle East (4000 BC). The credit as the first large scale road builder should however go to the Romans, who built a road network consisting of approximately 80000 km roads extending outward from Rome. As the Roman Empire collapsed so did also the maintenance of the roads and thus the only organized road system in Europe fell apart. The industrial revolution and the increased demand for transport in Great Britain during the onset of the 18th century meant that a new road system was needed. The demand for new roads created skilled road-makers such as Thomas Telford and John Loudon McAdam [5].

Thomas Telford worked on the influence of the size of stones on the robustness and the drainage of roads. John Loudon McAdam used crushed rocks as the base when designing roads; a design philosophy still in use today. Thus both the quality requirement and the demand for crushed material increased and the modern aggregate industry took form [5, 6].

Concrete and asphalt are aggregates in bounded form. Concrete is an ancient technology, historically known to have been used in the Roman Empire. It is often stated that the knowledge about concrete was lost during 13 centuries until 1756 when it was rediscovered by John Smeaton. However, Canal du Midi was built in southern France using concrete in 1670 [7], indicating that some tacit knowledge of the creation of concrete survived the fall of the Roman Empire. A modern concrete building under construction can be seen in Figure 1, the new bus terminal in the hometown of the author (Landvetter, Sweden).

Figure 1. Bus terminal under construction (2011).

Asphalt is created by combining aggregates and bitumen and has been in use since the middle of the 20th century. In order for the finished road to maintain its stability it is essential that the aggregates has good material strength and an appropriate particle shape [8].

1.2 PRODUCTION OF FINE AGGREGATES FOR CONCRETE

There are two principal methods to produce fine aggregates for concrete either from natural sand deposits or from a rock sources. In the natural sand case a sand pit is excavated by means of excavator and the sand is sieved into size fractions. If the aggregates come from a rock source a quarry is developed; in which the aggregate is produced through drilling, blasting, crushing and screening. A long term sustainable supply of fine aggregates is not believed to be possible from natural gravel and sand deposits; and in Sweden the supply of natural gravel has therefore been limited. Other countries that have either limited or introduced taxes on natural gravel and sand include the United Kingdom, the Czech Republic, Denmark and Italy [9, 10]. There is therefore an increased interest of fine aggregates from quarries for concrete production.

NATURAL SAND

In Sweden natural sand is produced, or more exactly extracted, from natural sand deposits. The extraction is done in a process similar to the one presented in Figure 2. The sand is extracted from the sand deposit using a front loader or excavator. Natural sand in the size fraction 0-8 mm is the most commonly used sand for concrete production in Sweden and thus the extracted sand need to be screened. Particles larger than 8 mm are fed into some kind of size reduction machine; in this case a cone crusher is used. The crushed material is then returned to the screens.

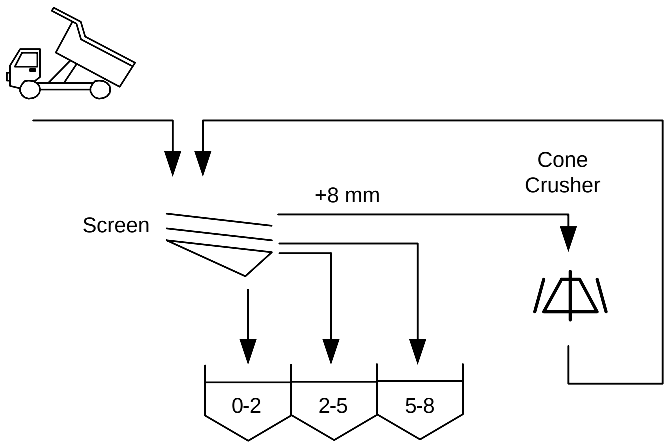

Figure 2. Layout for a possible processing plant at a natural sand deposit.

MANUFACTURED SAND

Production of manufactured sand from a quarry is a more complex process than extraction of natural sand from a deposit. The production process has several different size reduction steps, which consequently require various stages consisting of crushers, separation machines and transport equipment. The exact layout of a crushing plant may differ; Figure 3 shows a possible solution for a three stage crushing plant with a primary, secondary and tertiary crushing stages.

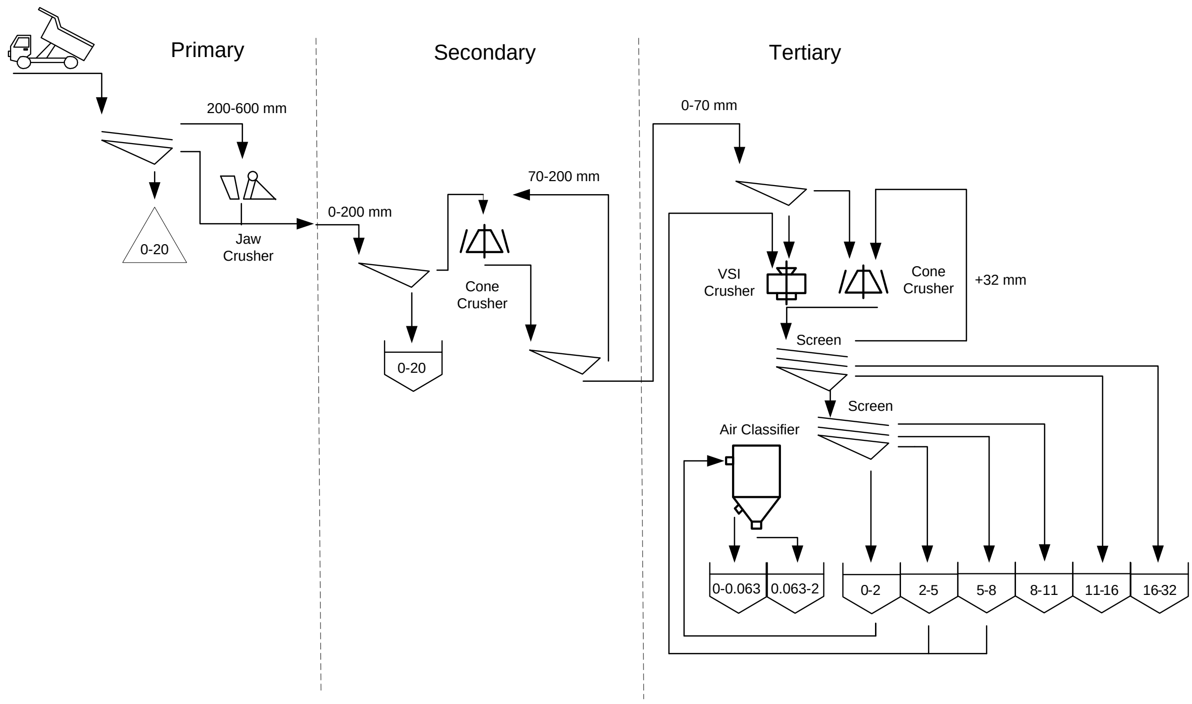

Figure 3. Layout for a possible three stage crushing plant used to produce manufactured sand from rock material.

The first step in the process is drilling and blasting of the rock material. Typically a 0-600 mm size fraction is produced. The blasted rock is loaded on trucks and hauled to the crushing plant. The distance between the rock pile and the crushing plant can vary.

Before the primary crusher, a jaw crusher, the product range 0-20 mm is extracted using scalping. This fraction may consists of soil etc. and is of poor quality. From the middle screen in the primary stage, 20-200 mm fraction can be bypassed to increase capacity. Larger rock particles (+200mm) will be crushed in the jaw crusher in the primary stage. In the secondary stage a gyratory or cone crusher is used to further reduce the size of the rock particles. The tertiary stage uses a cone crusher and a vertical shaft impact (VSI) to improve the shape quality of the final products. The final products are separated through a series of vibrating screens. Vibration screens normally are limited to screen particle sizes down to 2 mm. Therefore, to produce manufactured sand the 0-2 mm product is air classified, in this case into two products 0-0.063 mm and 0.063-2 mm.

1.3 AGGREGATES INFLUENCE ON THE CONCRETE

The properties of the aggregates influence both the fresh concrete and the cured concrete. This is due to the fact that aggregates differ in characteristics such as shape, surface texture, particle size distribution and properties of the used rock [11]. Historically, natural sand has been used in concrete, and therefore the concrete recipes have been developed with the properties of natural sand in mind. However, as mentioned in Chapter 1.2, due to supply and environmental issues, the concrete and aggregates industry is searching for a crushed replacement product; manufactured sand. The rock properties for the manufactured sand depend on the source material, whereas particle shape and particle size distribution are dependent on the crushing process itself.

The desired shape of the fine particles (0-2 mm) is cubical, defined as equal in width and length, to obtain a good rheology [12]. A good rheology is important because it reduces the amount of water needed which in turn means less cement to retain a good water to cement ratio. The particle shape is dependent on the choice of crushing method and how the chosen method is controlled [8]. The crushing methods available can be divided into two main principles, compressive crushing and impact crushing [13].

Compressive crushing is either form or force conditioned. Form conditioned means that the size reduction and applied force is a function of the displacement; hence the size reduction can be controlled by changing the compression. For force conditioned the displacement, and thus the size reduction, is controlled by the applied force. Cone and jaw crushers are examples of crushers using compressive crushing. Cone crushers, which have been investigated by Evertsson [13], Bengtsson [8] and Lee [14], have either single or inter-particle crushing, see Figure 4. The results indicate that inter-particle crushing creates a better shape than single particle crushing. This can be explained by the differences in the applied stress state [15].

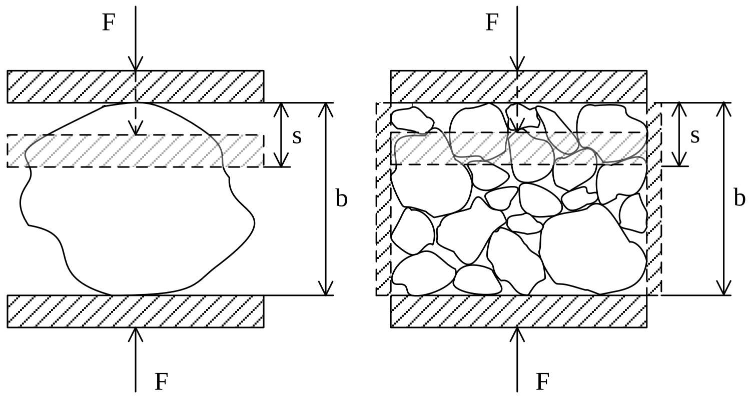

Figure 4. Crushing principles in compressive crushing, to the left single particle breakage and to the right interparticle breakage (cf. Lee [16]).

Impact crushing is an energy based crushing method. The size reduction is achieved by the rock particles being accelerated up to a given velocity and then released to hit a steel wall barrier or rock bed. Depending on the magnitude of the kinetic energy and the dynamic conditions of the movement of the particle, the breakage of the particle will either be due to impact or attrition [8], see Figure 5. Another energy based method is to hit rock particles with hammer type of tools (normally rotating). Examples of energy conditioned crushers are vertical shaft impact crushers (VSI), horizontal shaft impact crushers (HSI) and hammer mills. HSI crushers and hammer mills uses a hard metal hammers and plates as the impact media; which with high abrasive particles might lead to high wear. Due to the high wear, HSI crushers and hammer mills is mostly used with low abrasive rock sources such as limestone. VSI crusher often uses a rock bed as impact media and hence reduces the wear on the crusher. This has led the VSI crusher to be more common in the aggregate industry working with more abrasive materials such as granite. According to Bengtsson [8] the dominating breakage mechanism for fine particles is attrition and using a VSI will improve the shape of the rock particles.

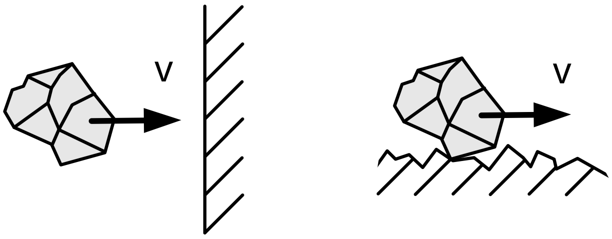

Figure 5. Crushing principles in impact crushing, to the left impact breakage and to the right attrition (cf. Bengtsson [8]).

Using the crushing methods available to produce good shaped manufactured sand will often lead to an increased amount of fines (particles smaller than 63 µm). Sometimes the amount of fines in manufactured sand will reach 15-25 mass percent. Several studies have been performed to investigate the influence of fines on concrete.

Bonavetti and Irassar [17] used natural sand mixed with different mass percent of crushed rock dust to find the influence of the amount of fines on several mortar properties. The water demand for mortars with 5 mass percent fines showed an insignificant increase; however as the fines amount increases above 10 mass percent the water demand started to increase rapidly. Drying shrinkage will also be affected; however the impact will depend on the rock type. For granite the drying shrinkage will increase with a large amount of fines (15-20%) meanwhile for limestone the drying shrinkage will be reduced. The amount of fines will also affect the compressive and flexural strength of the hardened mortar, the exact influence depends on the rock type used, and overall the compressive and flexural strength is reduced by increasing the amount of fines. Celik and Marar [18] compared different types of manufactured sand with natural sand. Their findings show that both compressive and flexural strength will first increase with an increase of fines; however after 10 mass percent both strengths will be reduced. Impact resistance peaks at 5 mass percent. The amount of fines in the manufactured sand clearly affects the properties of the finished concrete, and it should be possible to produce a good concrete with 5 to 10 mass percent of fines.

To produce adequate quality of manufactured sand it is important to address the issues about the shape of the particles and the amount of fines already in the crushing and classification process. Bengtsson [8] addressed the issues on how to achieve the right shape in the crushing stage. There is however not much research done in the aggregates industry about how to classify particles in the size range of 63-250 µm. It is therefore in the interest of the aggregates industry to investigate technologies that can classify the desired size range, one such technology is air classification.

1.4 Classification and screening

Classification is normally applied after the crushing stage of the aggregates to separate particles by size with to create different products. A schematic overview of a general classification process can be seen in Figure 6. A feed with given properties is fed into the classification stage and transported to a separation zone. At the separation zone a separation media is used to separate the feed into two separate flows; in this case a coarse and fines product. The separation media can be a fluid (air or water) or a solid object with a certain geometric shape (apertures).

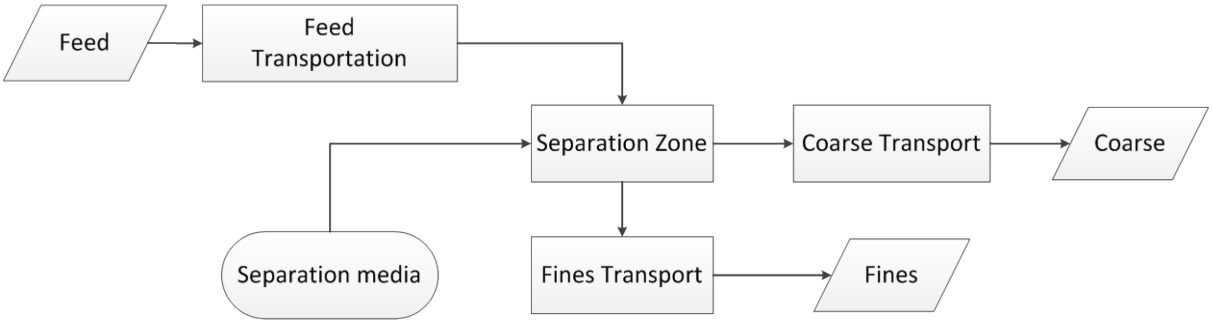

Figure 6. Schematic overview of a general classification process.

The most common classification technique implemented in crushing plants is screening, see Figure 7. The separation media in screens consist of steel wire or punched rubber cloths which oscillate. The oscillation transports the particles through the machine and allows for smaller particles to pass through the screen. The function of screens have been investigated and modelled in depth by Soldinger Staffhammar [19].

Figure 7. This screen is fed from the conveyor above coming in from the right. The products are then transported on different conveyor belts from the screen. NCC's Glimmingen operation, Uddevalla, Sweden (Photo E. Hulthén).

The basis of any analysis of any classification process is the mass balance of the particle flow, see Figure 8. The particle flow consists of three parts; the ingoing feed, the coarse product and the fine product. Each of the three parts is described by their individual particle size distribution (q_i in mass percentage where i is the particle size) and mass flow ($\dot{m}$). So the feed is represented by the mass flow $\dot{m}_0$ and particle size frequency q_{0i}; the coarse product is represented by the mass flow $\dot{m}_c$ and particle size frequency q_{ci} meanwhile the fine product is represented by the mass flow $\dot{m}_f$ and particle size frequency q_{fi}.

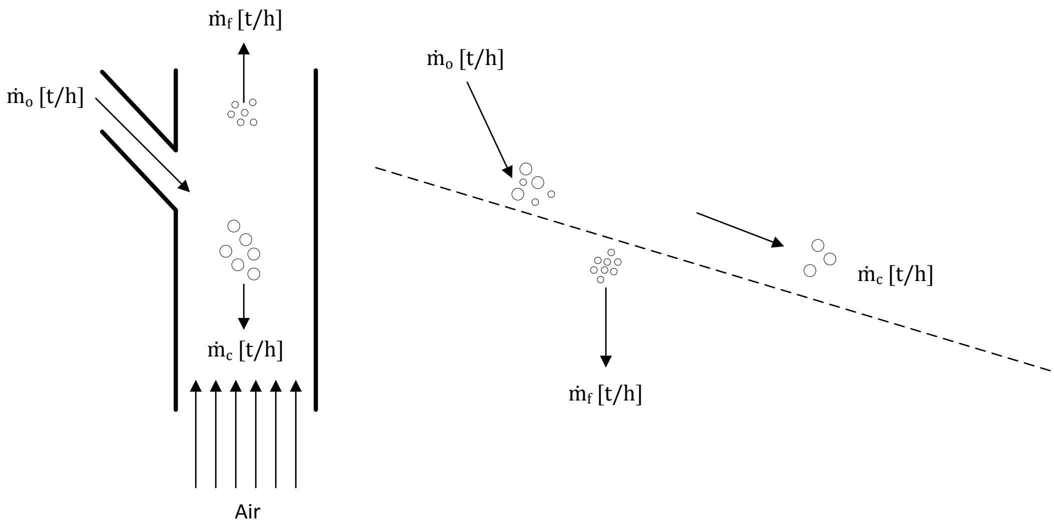

Figure 8. Mass balance in a simple air classifier (to the left) and on a screen (to the right).

The mass balance for the whole classification process is:

$$\dot{m}_0 = \dot{m}_c + \dot{m}_f \tag{1}$$

Meanwhile the mass balance for each particle size is:

$$\dot{m}_0 q_{0i} = \dot{m}_c q_{ci} + \dot{m}_f q_{fi} \tag{2}$$

Eq. (1) and Eq. (2) gives the mass flow split for the coarse material, Eq. (3), and the fines material, Eq. (4):

$$\frac{\dot{m}_c}{\dot{m}_0} = \frac{q_{0i} - q_{fi}}{q_{ci} - q_{fi}} \tag{3}$$

$$\frac{\dot{m}_f}{\dot{m}_0} = \frac{q_{ci} - q_{oi}}{q_{ci} - q_{fi}} \tag{4}$$

The efficiency of the recovery of the coarse material can then be expressed as Eq. (5) [20, 21]. King [22] presents Eq. (5) as the *classification function* and it is defined as the mass fraction of material in size interval *i* in the feed which leaves with the coarse fraction.

$$\eta_{ci} = \frac{\dot{m}_c q_{ci}}{\dot{m}_0 q_{0i}} = \frac{q_{ci}\left(q_{0i} - q_{fi}\right)}{q_{0i}\left(q_{ci} - q_{fi}\right)} \tag{5}$$

And the efficiency of the recovery of fines material can be expressed as:

$$\eta_{fi} = \frac{\dot{m}_f q_{fi}}{\dot{m}_0 q_{0i}} = \frac{q_{fi}\left(q_{ci} - q_{oi}\right)}{q_{0i}\left(q_{ci} - q_{fi}\right)} \tag{6}$$

Through multiplying Eq. (5) with Eq. (6) an overall efficiency, *E*, can be described:

$$E = \frac{q_{ci}\left(q_{0i} - q_{fi}\right) q_{fi}\left(q_{ci} - q_{0i}\right)}{q_{oi}^2\left(q_{ci} - q_{fi}\right)^2} \tag{7}$$

In this thesis Eq. (5) has been used to describe the efficiency of the classification process (also called Classification Efficiency in this thesis). This has been done as the efficiency of the recovery of the coarse material gives us the information needed to be able to predict the coarse product; which is the interesting product for the aggregate industry. This is a method commonly used when investigating and describing air classifiers and has successfully been applied by Eswaraiah et.al [23], Klumpar [24], Özer et.al [25] and Boulvin et. al [26].

To create an efficiency curve, the efficiency, Eq. (5), is plotted against the particle size on a logarithmic scale. The efficiency curve is sometimes also called a partition curve. Table 1 shows the particle size distribution for a feed, coarse and fines product. Combining these data the efficiency of the classification process can be calculated; see Figure 9.

For classification equipment such as screens, air classifiers and hydrocyclones the cut size, d_{50}, is defined as the particle size which has a 50% probability to either end up in the coarse product or fines product [21]. In this example the cut size is around 0.125 mm, where half of the feed ends up in the coarse product.

Table 1. Particle size distribution for the classification example used in Figure 9.

Particle size	**Feed**	**Coarse**	**Fines**
mm	$\dot{m}_0$ = 40 ton/h	$\dot{m}_c$ = 35.4 ton/h	$\dot{m}_f$ = 4.6 ton/h
5.6	8%	9%	0%
4	22%	25%	0%
2	15%	17%	0%
1	14%	15%	0%
0.5	13%	15%	0%
0.25	10%	9%	12%
0.125	9%	5%	37%
0.063	9%	4%	50%

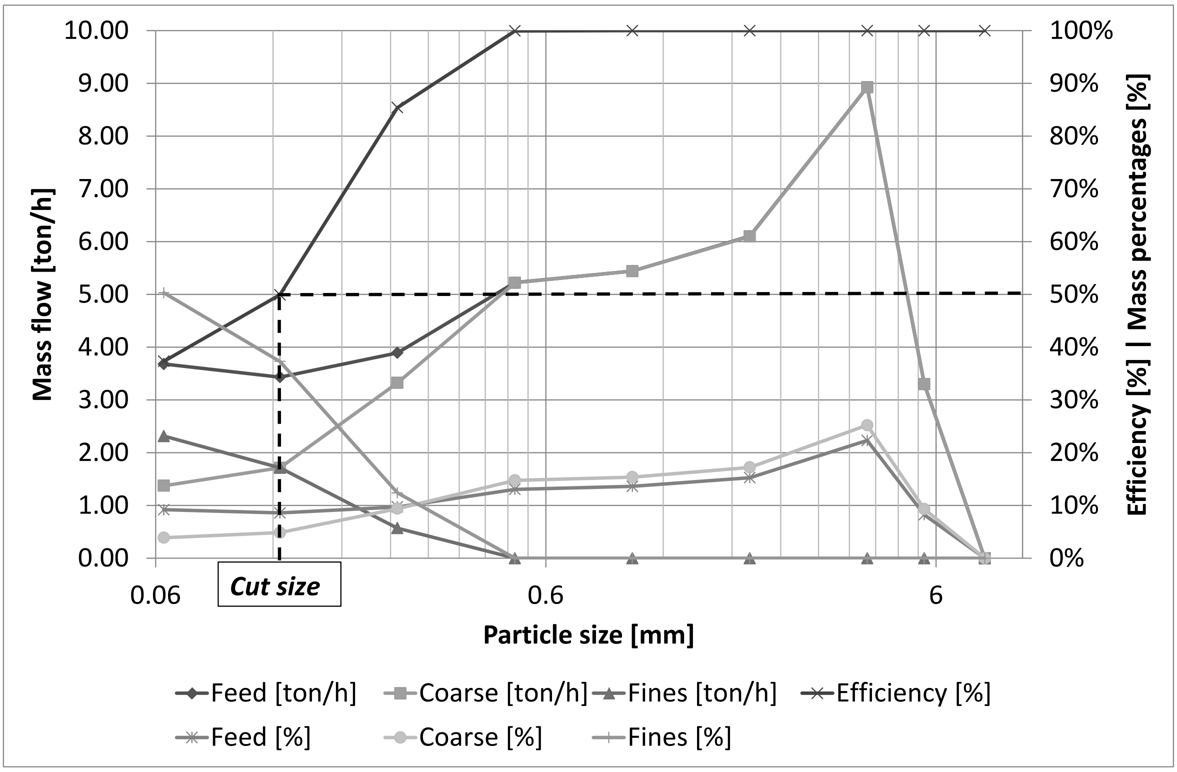

Figure 9. Efficiency curve with mass flow and particles size distribution.

1.5 AIR CLASSIFICATION

Air classification is a technology that uses air as a separation media to classify a product by size and form. It is a technology that is commonly in use in several industries, for example; the coal industry uses it before the furnace, the mineral industry uses it to separate minerals from the parent rock and the medicine industry uses it in both the industrial process and in inhalators. As air classification is used in a large variety of industries, several different methods of implementation are available.

A number of air classifiers have been developed to meet the needs of a variety of industries. Shapiro and Galperin [20] have presented a number of modern design ideas, including gravitational, cascade, fluidized bed, inertial, rotor and circulating air classifiers.

The classification of the particles occurs in the separation zone which is where the particles interact with the air flow [20]. According to Shapiro and Galperin [20] four basic separation zones exist, gravitational-counterflow, gravitational-crossflow, centrifugal-counterflow and centrifugal-crossflow zone, see Figure 10.

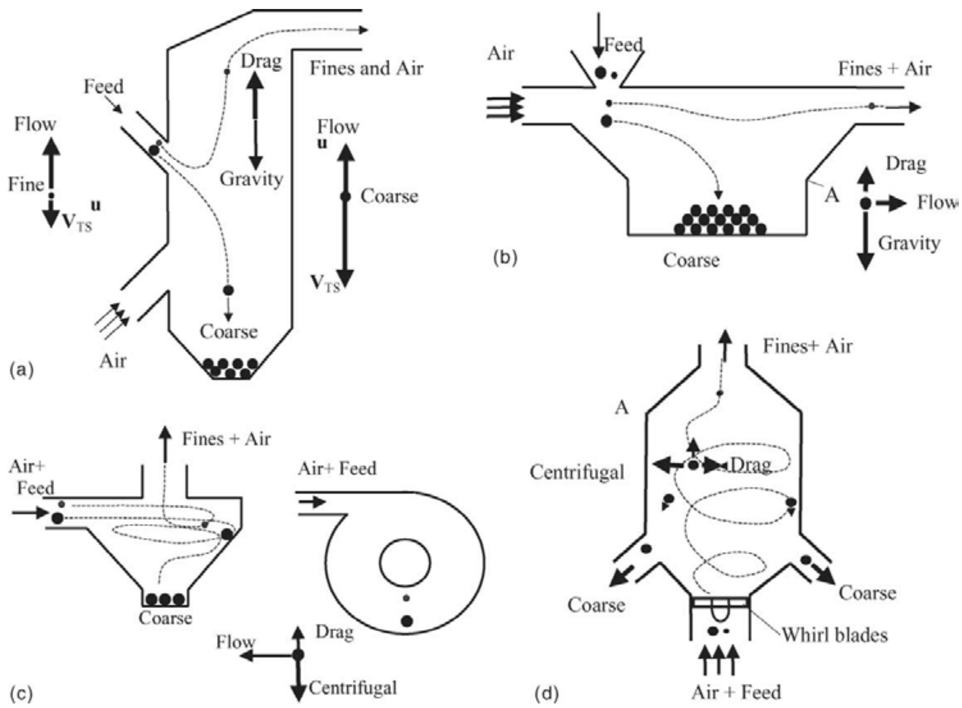

Figure 10. The different separation zones available: (a) gravitational-counterflow zone, (b) gravitational-crossflow zone, (c) centrifugal-counterflow zone, (d) centrifugal-crossflow zone. Figure reproduced with permission from M. Shapiro [20].

If an air classifier uses a gravitational-counterflow zone, see Figure 10(a), it means that the classifier is designed around a rising air flow inside a vertical chamber with parallel walls. The particles fall from the top of the air classifier and the drag force acts in the opposite direction to gravity. Thus the classification occurs where the drag force is larger than gravity. Coarse particles will continue downwards while fines will follow with the air flow. In theory the cut size particles will experience that the drag force and gravity cancel each other out. This means that the cut size particles will hover indefinitely in the separation zone. However, due to stochastic effects all particles will be separated [20].

For the gravitational-crossflow zone, see Figure 10(b), the air flow enters the machine horizontally while the particles enter vertically from the top. This means that the drag force acts perpendicular to gravity, meaning that particles will fall with a ballistic trajectory. Coarse particles will land closer to the particle entrance than fines which will end up further away. The cut size is thus dependent both on the drag force and the length of the air classifier chamber. Some cascade classifiers use this separation zone.

The base of a gravitational separation zone is balancing the drag force and the gravitational force. Eq. (8) describes the drag force and Eq. (9) describes the gravitational force [27].

$$F_D = \frac{1}{2} A C_D \rho_a \left(v_a - v_p\right)^2 \tag{8}$$

$$F_g = mg \tag{9}$$

The drag force is dependent on the area of the particle in the air surface direction, A, the drag coefficient, C_D, the density of the carrying media ρ_a, the velocity difference of the carrying media v_a and the particle velocity v_p. If the drag force, F_D, on the particle becomes larger than the gravitational force the particle will follow the air flow. Combing Eq. (8) and (9) for a spherical particle gives the cut size d_{50}, see Eq. (10).

$$\frac{\pi d^3 \rho_p g}{6} = \frac{1}{2}\frac{\pi d^2}{4} C_D \rho_a \left(v_p - v_a\right)^2 \rightarrow d_{50} = \frac{3C_D \rho_a \left(v_a - v_p\right)^2}{4\rho_p g} \qquad (10)$$

Where d is the diameter of the particle and ρ_p is the density of the particle. Thus the theory of gravitational air classification is that the separation size can be controlled by changing the velocity of the air flow.

The centrifugal-counterflow zone, see Figure 10(c), uses a flat air vortex inside a cylindrical chamber. The air flow is fed into the chamber by a tangential inlet and exit in the centre. This means that the air flow in the vortex rotates and flows radially towards the central exit. The radial flow is what controls the separation. The particles which are fed into the machine will rotate with the radial flow and this rotation means that the particle will experience centrifugal (inertial) force. Separation is controlled by balancing the centrifugal force and the drag force. Coarse particles will, due to the centrifugal force, drift outwards from the exit and downwards due to the gravity. The fines will follow the air flow towards the centrally placed exit. The centrifugal force will be dependent on the radial position of the particle if the classification chamber is not designed to create constant tangential velocity. This means that the cut size may vary due to the radial position, which is the difference between separation process of the centrifugal-counterflow zone and the gravitational-counterflow zone. A modified version of the centrifugal-counterflow is also used in impeller wheel classifiers at different types of mills [28].

A centrifugal-crossflow zone, see Figure 10(d), is created by feeding air and particle mixture through whirl blades into a classification chamber which has an exit in the opposite direction to the inlet. The whirl blades are designed to create a screw-type flow without any radial component. As the particles travel through the chamber towards the exit they will drift, with velocity depending on the particle size, towards the chamber walls. The cut size will depend on the chamber design. The size of the particles that reach the chamber walls precisely before the exit should be the same as the cut size.

For a centrifugal separation zone is based on balancing the drag force for particle (Eq. (11)) and the centrifugal force that the particle experience in the air flow (Eq. (12)) [29].

$$F_D = \frac{1}{2} A C_D \rho_a \left(v_r - v_{pr}\right)^2 \qquad (11)$$

$$F_C = m\frac{V_\theta^2}{r} \qquad (12)$$

Where, as in Eq. (8), A is the area in the surface direction, C_D is the drag coefficient and ρ_a is the density of the carrying media. Meanwhile v_r is the radial velocity of the air outward from the centre of the air classifier and v_{pr} is the radial particle velocity. The centrifugal force is based around the particle mass m, the angular velocity v_θ and the radial distance of the particle from the centre of the air classifier r. The cut size of a centrifugal air classifier is where the drag force and centrifugal force is balanced and the radial velocity for the particle is zero, see Eq. (13) [29].

$$d_{50} = \frac{3\rho_a r C_D v_r^2}{4\rho_p v_\theta^2} \qquad (13)$$

Both methods described above are valid for a single particle in an perfect undisturbed flow. An industrial air classification system will however process a large amount of particles in different sizes and the air flow will be turbulent. The turbulence and particle to particle interaction will affect how individual particles will follow the air flow and thus the cut size will depend on more factors than just the velocity of the air flow.

Independent of which separation zone is used in an air classifier, a reliable air flow is necessary. The air flow can either be created by using an external or an internal aerodynamic system. Using an external system means that the fans and dust collectors will be installed in a separate unit which is connected to the air classifier through pipes. An internal system places the fan inside the system and it therefore uses a smaller production footprint than an air classifier with an external system. An air classifier with internal aerodynamic cycle encloses the air flow reducing the chance of dust problems in the quarry.

1.6 PROBLEMS WITH AIR CLASSIFICATION OF MANUFACTURED SAND

As described in Chapter 1.5, air classification is used in a large number of industries and there exist several types of design solutions. Adopting air classification to the requirements of the aggregates industry is however not without problems. Although air classification is an old technology, which has slowly evolved, few theoretical and modelling studies have been performed. Thus, models that have been created are of recent origin [23]. This means that the evolution that has occurred in the field of air classification originates from the need to solve specific industrial problems.

Commercially available air classifiers might therefore not be perfectly adaptable for the industrial needs of the aggregates industry. Requirements like cut size, classification efficiency and production volume might differ between the industries. Depending on the industry requirement the goal of the classification process may differ between industries. For example the coal industry uses air classifiers to separate fines to be fed into pulverized coal boilers; thus the product is the fines and coarser products are fed back into the mill. For the aggregates industry the main product is the coarse sized particles with the fines as a secondary product.

For a successful air classification of manufactured sand it is therefore important to create a fundamental understanding of how air classifiers work. Which alternative air classifier designs can be used for the aggregates industry? How those machines work and how can they be adapted to the requirements of the aggregates industry and the demand from the concrete industry, described in Chapter 1.3, needs to be clarified.

2 OBJECTIVES

The aim of this chapter is to:

- *Describe the aim and objective of the research project*
- *Formulate the research questions*
- *Clarify the delimitations of the research undertaken*

2.1 RESEARCH OUTLINE

The hypothesis in this research states that it is possible to manufacture high quality sand, fine aggregates, for the concrete and asphalt industries if the correct industrial process is used. This means producing sand with the correct particle shape and the correct particle size distribution. The correct particle shape is achieved by controlling the crushing process [8], while classification processes are used to achieve the correct particle size distribution.

When producing aggregates with desired particle shape crushers tend to generate large amounts of unwanted fines (particles below 63 µm). Controlling the particle size distribution is thus dependent on classification of very small particles. Air classifiers might be used for this purpose; however air classifiers are not common in the Swedish aggregates industry. The objective of this research is therefore to:

- Increase the knowledge about air classification of manufactured sand
- Present design advice for future air classifiers for use in the aggregates industry
- Present advice on how to operate the investigated types of air classifiers
- Present empirical models of existing air classifiers

2.2 RESEARCH QUESTIONS

The following research questions have been stated:

RQ1. Which air classification techniques are suitable for use in the aggregates industry?

RQ2. Can air classification be used to satisfactorily change the particle size distribution curve of manufactured sand according to the demands of the concrete industry?

RQ3. Which properties of manufactured sand will influence the air classification result?

RQ4. How should air classifiers be operated to achieve a desired product?

RQ5. What design considerations are important for an air classifier used in the aggregates industry?

RQ6. Is air classification a feasible method for industrial production of fine aggregates for concrete and asphalt?

2.3 DELIMITATIONS

The research has a holistic approach to air classifiers and their impact on particle size distribution. No studies have been performed on mineralogy or petrology. The full-scale test performed in this report is therefore analysed and evaluated by the particle size distribution in combination with machine parameters. As the research work activities have been focused on air classification methods no other form of classification is included such as hydrocyclones, water settling tanks or dense media separation. The size reduction process is beyond the scope of the work performed in this thesis.

3 RESEARCH APPROACH

The aim of this chapter is to:

- *Introduce the research methodology used.*
- *Explain the relevance of the applied research method with respect to the project and the research questions.*

This project was carried out at Chalmers Rock Processing Systems (CRPS), which is a part of the Machine Elements group at the Department of Product and Production Development at Chalmers University of Technology. The group has been active in research within the field of equipment and process control for the aggregates production and the mining industry since 1993 [8, 13, 14, 19, 30-33].

3.1 RESEARCH METHODOLOGY

The research foundation for the Machine Elements group is problem oriented and the methodology been used for several research projects. The method is described in detail by Evertsson [13], Soldinger Stafhammar [19] and Lee [14], an overview of the research flow can be seen in Figure 11. Problem oriented means that the problem is the focus of the research. The methods and tools to solve the problem are chosen in order to find an adequate solution process to the original problem. The advantage of problem oriented research is it can handle complex problems and that the result often is directly implementable in the industry.

Research is defined as the process which creates an increase in knowledge which can be used to solve the specific problem [34]. Knowledge is often defined as *true justified belief*, this means that the belief can be supported with rational argument [35]. The nature of how the research is performed can differ. According to Svensson et al. [36] it is possible to divide a research process into a discipline oriented research or a multidisciplinary research. The problem oriented research methodology applied is multidisciplinary research with its focus on development and usage instead of theory, specific knowledge instead of general and short time perspective.

The problem itself can be of different nature, malfunctions on machines or working principle of individual components, a process, performance demands or the actual knowledge about a the internal machine. It can be noted that the focus of the research, performed within the Machine Element group, is to create knowledge or improve technology. Thus the focus is technology research/applied science [34, 37].

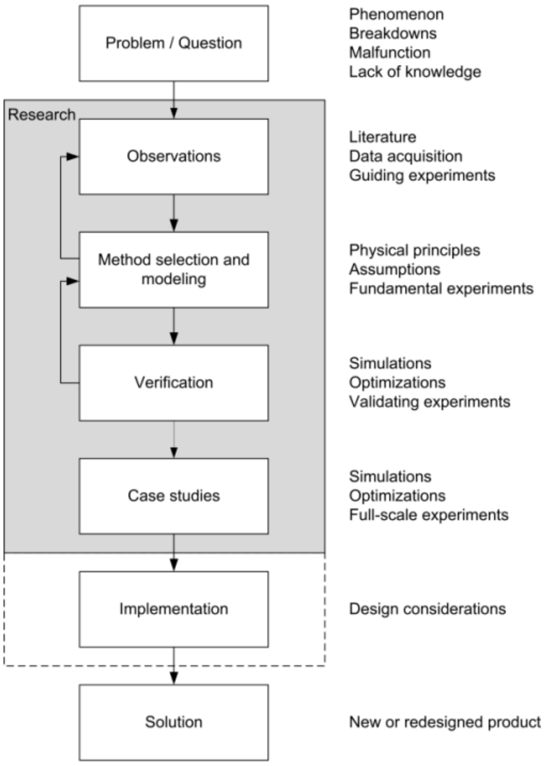

Figure 11. The applied research model (cf. Evertsson [13] and Lee [14]).

The research process starts with identifying the knowledge gap which is the essence of the problem. Observations are the key component of finding the knowledge gap. These can be made through literature studies, acquiring data or by using guiding experiments. As the knowledge gap is more understood in detail the objectives of the research can be formulated [38].

From the formulated research objectives it is possible to build models and chose methods to solve the questions raised in the objectives. The chosen models and methods can be physical simulations, fundamental experiments and assumptions based on previously obtained knowledge. The physical simulations should be based upon sound physical principles such as the Navier-Stoke equations or the laws of Newton. Complex problems might need simplifications to the physical simulations, in such a case it is important to understand how the simplifications will affect the solutions.

The knowledge obtained during the modelling and method selection part of the research process might change the understanding of the problem. The gained knowledge will create an iterative process where observations and models will be remodelled to better answer new or old questions.

A hypothesis or a simulation is formulated to explain or solve the identified problem. Verification of the hypothesis is done by performing experiments, and the level of agreement needed will depend on the information that the hypothesis or model is supposed to answer. For technology oriented research is it important to create usable results that increase the value for the end user, this is of course subjective of the user of the technology [37]. As technology does not exist in a vacuum it will experience competition from other forms of technology to solve the problem and thus the market of ideas will test the technology. Increasing the complexity of the model might yield more accurate results but will be more time consuming; meanwhile reducing the complexity might show trends and be strong enough to create basic understandings. A hypothesis or a model that fails the verification must be evaluated again with new methods and possibly even be replaced by a better hypothesis or model.

Hypotheses that pass the verification should be implemented in case studies. These studies should be used to build experience, gained through simulations or full-scale experiments. The experience gained from the case studies can then be used for implementing design considerations for solving the investigated problem.

3.2 The research methodology applied on the performed research

The problem oriented research approach has been applied to the work performed to solve the stipulated research questions in Chapter 2. The basis of the performed research is an empirical view; knowledge comes from observation and experience, as opposed to rationalism where the theory which the observer stands on is seen as more important [39]. The observation part was focused on literature studies, where the goal was to create a knowledge base to stand on.

As the problem was of the nature to investigate a possible introduction of an existing technology into a new industry; guiding and fundamental experiments were performed in full scale using existing air classifiers. Using industrial scale air classifiers in experimental research has pros and cons. Any experimental study that is performed has to deal with questions about reliability and validity [40]. The nature of the industrial environment means that it is hard to isolate the variables that are chosen to investigate in the experiment; this means the internal validity of the experiments is harder to measure. However, from the standpoint of the external validity of the results an industrial scale means that it is somewhat easier to gain a higher degree of generalizability. The external validity is highly dependent on the sampling process so it is important to ensure that sampling is performed correctly.

Virtual experiments were performed in the form of computational fluid dynamics models in order to complement the industrial scale experiments. The modelling performed during the work was conducted parallel to the performed experiments. The reason for the parallel work was that the models were used to create an understanding of how the air and particles flow through the air classifier. The internal validity of any model, especially one dealing with the Navier-Stoke equations, will be dependent on how the model is setup. For computational fluid dynamics this means that the suitable turbulence model has to be used.

Verification of air flow simulations is difficult because of several reasons. As an example measuring probes themselves tends to influence the air flow. In road vehicle aerodynamic research this tends to be solved by measuring the influence indirectly; the drag coefficient is calculated from the measured drag force. Even if the measuring probes are not disturbing the air flow; the air flow itself might behaving in such a way that the errors in the measuring methods is large or that it is unclear what actually has been measured [41].

For simulation of the air flow inside industrial scale air classifiers verification comes with specific measuring problems. The air-particle flow is a problem for measuring probes as the abrasive influence of the particles might damage the equipment. Only measuring the air flow is hard as the dusty environment these machines are standing in means that particle dust will always be present. This leaves the possibility of indirect verification methods.

Indirect verification of simulations of the air flow in air classifiers with open aerodynamic cycles can be measuring of the air flow into the air classifier or sampling the resulting products; both of these methods have been applied for the simulations that have been performed on the open aerodynamic cycle air classifiers.

For the investigated air classifiers with internal aerodynamic cycle, see Chapter 5, indirect verification of the air flow field is harder. It is possible to measure products produced by the air classifier. However as pointed out the air flow is created internally which means no air flow is going into the air classifier; hence it is not possible to measure the air flow into the air classifier. Measuring or visualization the inside air flow of the investigated air classifiers has a number of difficulties. The difficulty comes from the design of the air classifier design; with rotating parts and several layers of steal to get through.

As the measuring of the air flow for verification of simulations is difficult the verification of the air flow simulations has to come from the source math itself. The methods for the simulations have to be chosen by care and be based on previous knowledge in the field. This means that the external validity of the simulations is somewhat reduced.

Results from the experiments could then be compared to the air flow and a hypothesis could be formed to answer the research questions. The models also meant that it was possible to remove unwanted external parameters that could influence results. The internal validity of the simulations will depend on the settings of the individual case. The external validity for the simulations is lower than the full scale experiments and should therefore be used only to explain phenomena that cannot be investigated in full scale.

3.3 METHODS APPLIED IN THE PERFORMED RESEARCH

The performed research has combined two main methods; simulations and empirical measurements. Simulations have been performed using *Computational Fluid Dynamics* (CFD) and have been focused on the air flow inside air classifiers and its influence on the particles. The empirical measurements have been performed on existing air classifier to evaluate how they can be applied in the aggregates industry.

SIMULATIONS

The reason behind the performed simulations has been to explain those aspects that cannot be described or observed in the experimental setup, mainly the air flow inside the air classifiers. Direct measurement of the air and particle flow inside a full scale air classifier is difficult; the measurement instruments will affect the air flow, particles might destroy instruments and local measurements might not describe the flow field correctly. Thus, to understand the internal process of an air classifier, models and simulations that can describe the interaction inside an air classifier are necessary.

The geometry of the investigated air classifiers was created by using the commercial *Computer Aided Design* (CAD) software CATIA V5. To create the mesh volume the geometries were exported into the mesh software ANSA in which the surface mesh was created. For Paper A the volume mesh was created in the mesh software Harpoon. In the rest of the cases the volume mesh was done in the mesh software Tgrid. In all papers a mesh study was performed to guarantee mesh independent solutions. Independently of the mesh procedure used, the volume mesh was then used to set up the problem in the commercial CFD software Fluent. All models were done in three dimensions (3D).

The simulations performed in Paper A, Paper E and Paper G was performed on a eight core Linux machine. In Paper B the one-phase simulations were performed on the same machine as Paper A, Paper E and Paper G meanwhile the multiphase simulations were performed using a cluster with 32 cores.

Computational fluid dynamics

The modelling has been performed using CFD. CFD is a method for numerically solving the governing equations of the flow in a fluid or gas. The governing equations are the continuity, Eq (14), the momentum, Eq (15), and the energy equation, Eq (14) and are often referred to as the Navier-Stoke equations [42].

$$\partial_o \rho + \partial_o u_i = 0 \tag{14}$$

$$\partial_o \left(\rho u_i \right) + \partial_j \left(\rho u_j u_i \right) = \rho F_i - \partial_i p + \partial_j \tau_{ji} \tag{15}$$

$$\partial_o \left[\rho \left(e + \frac{1}{2} u^2 \right) \right] + \partial_i \left[\rho u_i \left(e + \frac{1}{2} u^2 \right) \right] = -\partial_i q_i + \partial_i \left(T_{ij} v_j \right) + \rho v_i F_i \tag{16}$$

As mentioned earlier the validity of the simulations performed is dependent on the solution strategy for the Navier-Stokes equations. The Navier-Stokes equations are nonlinear partial different equations and as such cannot be solved analytically. To solve this, the turbulence has to be modelled. There exist a number of methods to model the Reynold stresses [43]. In this study two models have been employed, the k-ε model and the *Reynold Stress Model* (RSM). The construction of the models differs and each has its advantages and disadvantages.

The k-ε model is an eddy viscosity model which means that it is based on the Boussinesq assumption. The Boussinesq assumption states that the Reynold stresses are linked to the velocity gradients via the turbulent viscosity [44]. This statement has the underlying assumption that the air flow is isotropic; the ratio between the Reynold stresses and the turbulent viscosity is the same in all directions [43]. Thus care has to be taken to the nature of the simulated air flow when applying the k-ε model. The advantages of the model are its simplicity which in turn leads to low calculation load, commonly used in the industry and with documented good performance. The disadvantage is that it has poor performance in rotating flows.

RSM improves on the k-ε model as it is not based on the Boussinesq assumption, this allows for a model that can deal with anisotropic flows. Instead RSM uses partial differential equations for the Reynold stresses [44]. Aside from the partial differential equations the derivation is similar to the k-ε model [44]. The advantage of this is a general and very accurate model of the flow and the Reynold stresses. The disadvantage is a very large computing cost as it uses seven partial differential equations. It should be noted that in some cases RSM can perform as poorly as the k-ε model, e.g. unconfined recirculating flows [43]. Paper B used the k-ε model due to limitations of available computational power. For Paper A, E and G the full RSM was used.

Multiphase flows

Modelling flows with more than one media, e.g. air and particles, by using computational fluid dynamics can be performed using two different approaches to discretize the fluid problem: Euler-Lagrange or Euler-Euler. The main difference between the two approaches is how the particle phase is modelled. Euler-Lagrange solves the particle phase by tracking a large number of particles through the flow field meanwhile the Euler-Euler approach treats the phases as interpenetrating continua [45]. Both approaches have been used in the performed research; Paper B used Euler-Euler and Paper E used Euler-Lagrange.

Solving a multiphase flow with an Euler-Euler approach means the introduction of a volume fraction for each modeled phase. The assumption is that these volume fractions are continuous functions in space and time. Each phase has its own set of conservation equations which are closed constitutive relations; for granular flows, e.g. particle flows, kinetic theory is used.

Fluent, the commercial CFD software used in this work, has a number of Euler-Euler models. The Eulerian model has been used which is the most complex model. The model solves the momentum and continuity equation for each phase and couples the phases through pressure and interphase exchange coefficients.

An Euler-Lagrangian approach in CFD simulations requires that the dispersed second phase occupies low volume fractions (less than 10%). With an Euler-Euler approach the local concentration of the dispersed phase can exceed 10%.

As CFD can cause a very high computational load the modelling approach was dependent on the size of the case and the available computer resources. Limitations were required on the choice of turbulence model, number of phases and time-dependence.

Paper B used an Euler-Euler approach to model the multiphase system. A single size spherical particle with the diameter of 125 µm and a density of 2780 kg/m^3 was used. The reason for the choice of a single particle size was the computational load that was needed to add more phases. The choice of the particle size was the empirical research indicated that it was close to the cut size of the air classifier investigated. All simulations in Paper B were run with no slip wall boundary conditions and the simulation was solved with a transient time of 1 µs. The phases was fully coupled using the Eulerian model [45]. The interaction between the phases were simulated by model the momentum exchange coefficient using the Syamlal-O'Brien model.

Paper E used the Euler-Lagrange approach. This approach meant that a lower amount of particles than for an Euler-Euler. The air flow was solved in steady-state which allowed for more particle sizes to be included in the simulations. Four different particle sizes were simulated: 30 µm, 63 µm, 125 µm and 250 µm, with a density of 2780 kg/m^3. To simulate different particle shapes, two types of drag models were used, one for spherical particles [46] and one for non-spherical particles [47]. The base of the drag force for both cases can be seen in Eq. (17):

$$F_D = \frac{18\mu C_D R_e}{24\rho_p d_p^2} \tag{17}$$

The difference between the two models is how the drag force is calculated or more exactly how the drag coefficient C_D is calculated. For the spherical model (Eq. (18)):

$$C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re} \tag{18}$$

For the non-spherical model (Eq. (19)):

$$C_D = \frac{24}{Re_{sph}}\left(1 + b_1 Re_{sph}^{b_2}\right) + \frac{b_3 Re_{sph}}{b_4 + Re_{sph}} \tag{19}$$

Where (Eq. (20)):

$$b_1 = exp\left(2.3288 - 6.4581\phi + 2.4486\phi^2\right)$$

$$b_2 = 0.0964 + 0.5565\phi$$

$$b_3 = exp\left(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3\right)$$

$$b_4 = exp\left(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3\right) \quad (20)$$

Where φ is the shape factor, Eq. (21), defined as the surface area of a sphere with the same volume as the simulated particle, s, divided by the particles actual surface area, S. Three non-spherical particles were investigated with a shape factor of 0.3, 0.5 and 0.7.

$$\phi = \frac{s}{S} \quad (21)$$

The air velocity where solved using a mixture of a semi-implicit trapezoidal integration and an implicit Euler integration. If the trapezoidal equation is unstable the implicit equations is solved instead. The particle position where solved using a strict implicit approach. The wall boundary conditions for the wall were no slip for the air flow and reflect for the particles.

EMPIRICAL MEASUREMENTS

The empirical measurements performed have been focused on the measurements of the particle size distribution and the correlating classification efficiency. If possible the air flow into investigated air classifier using an open aerodynamic cycle has been measured. It was not possible to measure the air flow in air classifiers using an internal aerodynamic cycle due to that the particle flow would damage the measuring equipment.

Samples have been taken from the material feed into the air classifier and the different products that the air classifier produces. The samples have been handled according to the Swedish standard SS-EN 933-1.

The design of the experiments has differed between the different papers; however the base has been the same. Either a full factorial design has been performed over the parameters that are of interest or a scan of a single parameter setting has been made [48]. The different parameters and settings in the performed experiments will be presented with the results from these experiments.

4 LITERATURE REVIEW

The aim of this chapter is to:

- *Provide an overview and introduction to research performed related to air classification.*

The research performed on air classification for the aggregates industry is limited; the number of references directly related to the aggregate industry is therefore limited. However air classification is either in use or investigated for a number of other industries. Air classification is common in the waste industry in everything from sorting municipal waste [49, 50] to handling electronic waste [51, 52]. In the food industry air classification is for instance used to enrich barley [53, 54] and to sort peas after protein fraction [55-57]. Cement manufacturing are using air classifiers in grinding circuits [58, 59]. The design criteria and demand on the classification process may differ between industries; however the technology behind the air classifier is based on the same principles.

AERODYNAMIC CYCLE

There are two different approaches to create the aerodynamic cycle needed for the classification process, either by external or internal air supply [20]. Using an internal air supply comes with the advantage of not needing an external fan system with filters, thus reducing the overall industrial footprint. Eswaraiah et.al [23] and Shapiro and Galperin [20] point out that an internal air supply will have lower operational efficiency than an external air supply, thus indicating that the choice of aerodynamic cycle will be between complexity and efficiency.

CLASSIFICATION CRITERIA INFLUENCE ON AIR FLOW DESIGN

In an air classification process the particle properties, such as size, shape, drag coefficiency and density, will decide in which product the particle will end up. Crow and Peirce [60] point out that as a particle reaches its maximum velocity or the terminal velocity the influence of particle density will be reduced, and the classification process will depend on the particle drag force. Thus particles reaching terminal velocity will be classified after size and form. Everett and Peirce [61] show that it is possible to classify after density by using a pulsing air flow in the classifier and this is used widely in the waste industry. The pulsing air flow can be created either by active or passive means. A pulsing air flow is active if the pulse is created by varying the fan speed. For a passive pulsing air flow the fan speed is constant, and the pulse is created by the geometry of the air classifier. The geometry creates the pulse by forcing the air flow to decelerates and accelerate depending on position in the air classifier. The particle thus accelerates and decelerates depending on its position in the air classifier. Research has shown that active pulsing air classifiers are more efficient than passive air classifiers [62].

Classification after particle size depends on controlling the air flow in such a way that the terminal velocity of the particles reflects the desired cut size. This means that an air classifier for a given industry might not be suitable for another industry. In the food industry classification of pea protein is done with a cut size between 3-20 µm [57]. Meanwhile in grinding circuits for the cement industry the first stage air classifier has a cut size around 0.2 mm and the second stage as low as 30 µm [58, 63].

Gravitational classifier

Wang et al. [64] used a gravitational cross-flow air classifier to investigate the influence of turbulence and particle load (particles per volume air) on the sharpness of the cut size. The cut size is influenced by several parameters such as feed rate, classification air speed, turbulence and particle to particle interaction. The performed study included both experiments and numerical simulations performed by *Computational Fluid Dynamics* (CFD). The CFD simulations showed that vortices will develop close to the air inlet and that those vortices could alter the desired route of the fine material and end up with the coarse material. The simulation also showed that the turbulence affected the fine particles more than the coarse particle, by changing the design Wang et al. [64] was able to reduce the vortices and improve the sharpness of the cut. The experiments showed that the particle load clearly affect the sharpness of the cut, by increasing the particle load the amount of fines increased in the coarse product.

Lai et al. [65] performed experiments on a gravitational air classifier to increase the knowledge of the impact from feed rate and air velocity on the efficiency of sorting of fine particles. The experiments were carried out by changing the feed rate and the air velocity independently. An increased feed rate was shown to increase the amount of fines in the coarse product, confirming the findings of Wang et al. [64] that particle to particle interaction will affect the sharpness of the cut. Increasing the air inlet velocity will reduce the amount of fines in the coarse product and increase the amount of coarse particles in the fines. The experiments showed that in order to reduce the particles below 10 µm from 7.61 mass percent to 0.61 mass percent it was necessary to recirculate the material.

Centrifugal classifier

Johansen and Silva [66] studied centrifugal air classification and came to similar conclusions as Wang et al. [64] and Lai et al. [65] did with gravitational classifiers. The real air flow in the centrifugal air classifier investigated was turbulent and not uniform. The turbulence meant that the centrifugal air classifier cannot produce as good product as predicted by theory. According to Johansen and Silvia [66] a centrifugal air classifier is sensitive to particle load, air velocity and rotor speed. Another problem noted is that for some centrifugal air classifiers it is possible that not all material will pass the separation zone.

In a perfect classification the feed material will be divided into a coarse and a fine product at a given particle size. Due to the previously mentioned sensitivity to particle load, air velocity and rotor speed, a perfect classification is not possible and the classification efficiency will vary with particle size. The coarse fraction will thus include fines to some degree. According to Johansen and Silvia [66] it is common for centrifugal classifiers to have a classification efficiency which minimum is not at the smallest particles. The efficiency for a centrifugal classifier first falls after passing the cut size and then rises for the smallest particles. This is called the fish hook phenomena and examples of this can be seen in the finer part of air classifier in the cement industry shown by Benzer [59] and Aydogan et al [67].

Majumder et al. [68] has investigated this phenomena closer and states that the reason for this is the influence of the particle size and density on the settling velocity, which controls the classification. The dependency arises from that individually sized particles will experience different Reynolds numbers and thus experience different drag coefficients. For very low Reynolds number, as experienced by the smallest particles, the drag coefficient is larger than for higher Reynolds number, see Figure 12. A higher drag coefficient on the smallest particles will increase the experienced drag force which will affect the efficiency in the way described by Johansen and Silvia [66].

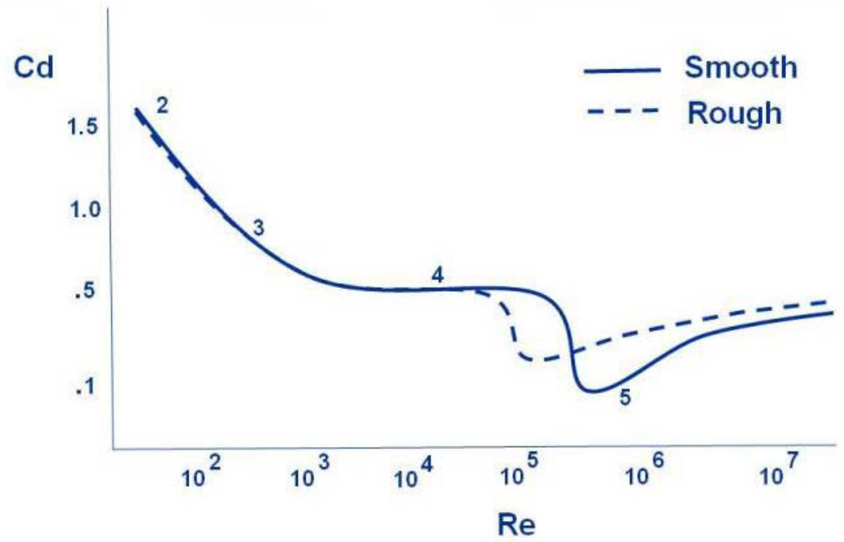

Figure 12. Drag coefficient for a sphere as function of the Reynold number (source NASA).

COMPUTATIONAL FLUID DYNAMICS

CFD has been applied to investigate several types of fluid based classifiers (such as air classifiers and hydrocyclones). As described in Chapter 3.3 there is a need to model the turbulence in the fluid flow. Most of the commercial CFD software available has several turbulence models to choice between. It is therefore important to understand which results can be expected from the different turbulence models.

Narasimha [69] investigated the cut size in hydrocyclones using the k-ε model. The result from the performed simulations was compared to empirical measurements. The comparison showed that the CFD simulations were promising however the simulated cut size was somewhat larger than the experimental cut size. Similar investigations on the cut size of hydrocyclones has been performed by Brennan [70]; however using the full Reynold Stress Model (RSM). The empirical result from two plants and the CFD results were very close for all particle sizes except for particles around 30 µm.

The results from Narasimha [69] and Brennan [70] are consistent with the results from Bhaskar [71] which compared the RSM model and the k-ε model to empirical data. The RSM model was closer to the empirical data than the k-ε model.

5 AIR CLASSIFIER WITH INTERNAL AERODYNAMIC CYCLE

The aim of this chapter is to:

- *Introduce the air classifiers with internal aerodynamic cycles investigated*
- *Present the results from the empirical experiments performed*
- *Present the results from the performed simulations*

5.1 INTRODUCTION OF AIR CLASSIFIERS WITH INTERNAL AERODYNAMIC CYCLE

Figure 13 shows a functional flow sheet of the internal process for the air classification process in an air classifier with an internal aerodynamic cycle. As the feed enters the air classifier it is transported into a mixing zone where the feed meets the air flow; which is created internally in the air classifier. In the separation zone the air flow separated the coarse particles from the fines. Two transport flows then moves the coarse particles and the fines to their separate exit areas where the particles is separated from the air flow. The air is then circulated and reused in the separation process.

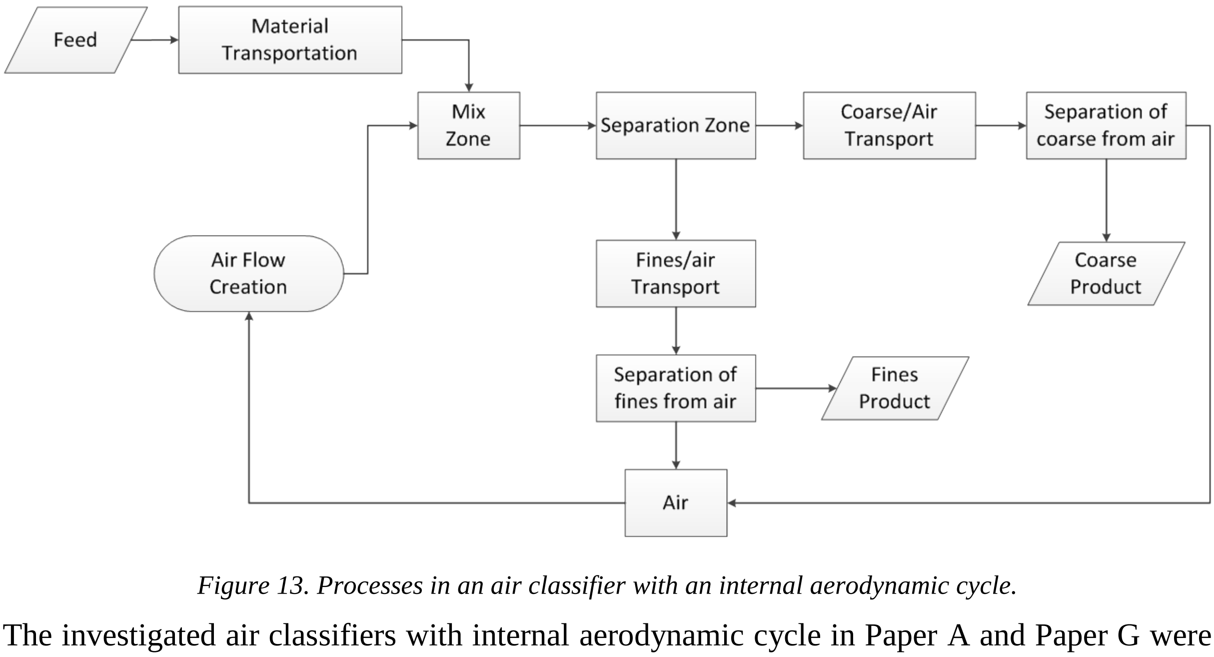

Figure 13. Processes in an air classifier with an internal aerodynamic cycle.

The investigated air classifiers with internal aerodynamic cycle in Paper A and Paper G were similar in design. Both air classifiers used a centrifugal-crossflow separation zone; an overview of the investigated air classifiers can be seen in Figure 14. The CAD-model to the left represents the air classifier investigated in Paper A meanwhile to the right the air classifier investigated in Paper G is shown. Two things differed between the investigated air classifiers, the overall size and the method of transporting the feed into the air classifier. The size of the air classifier in Paper A are roughly 5 meter in height and an outside diameter of 3 meter meanwhile the air classifier in Paper G is 2.2 meter in height and has an outside diameter of 1 meter. In the air classifier in Paper A the inlet pipe is a separate screw feeder which enters the air classifier from the side. For the air classifier in Paper G the feed enters from the top of the air classifier through the hollow axel which drives the separator fan.

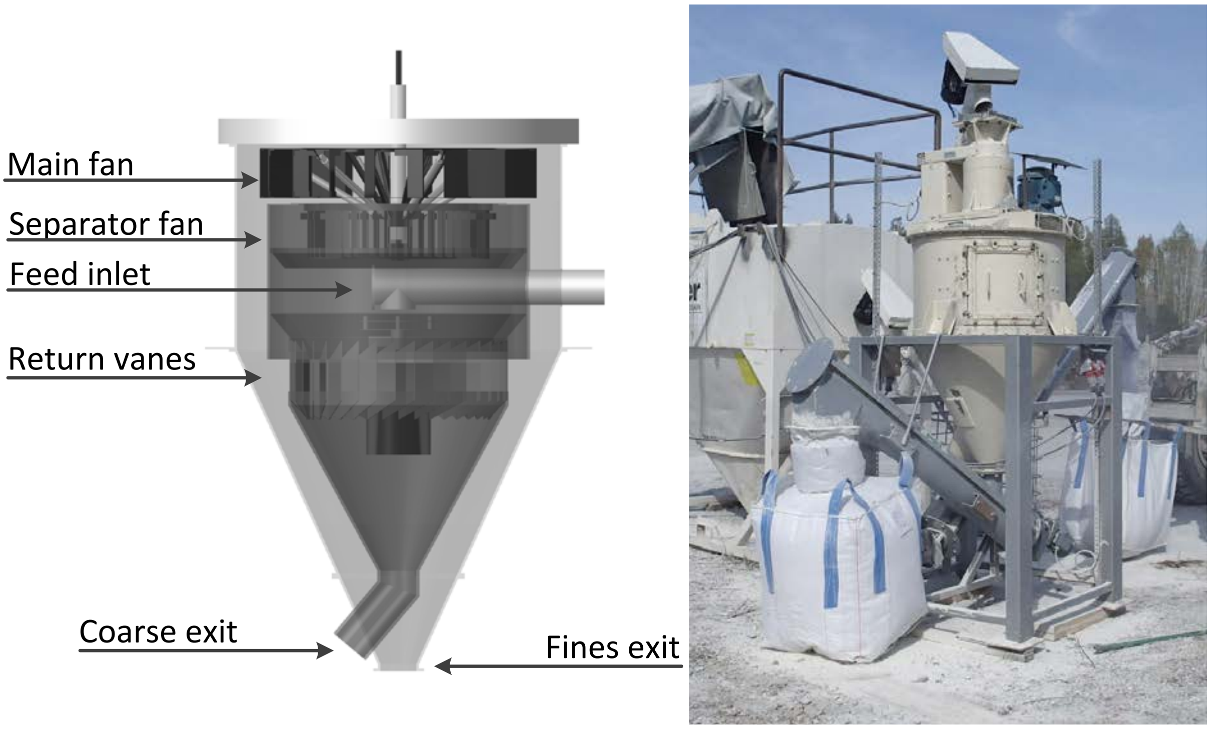

Figure 14. Investigated air classifiers overview, Paper A (to the left) and Paper G (to the right).

The classifier consists of two coaxial cylinders which work like an external cone and an inner cone. The circulating fan creates a centrifugal air flow that rises within the inner cylinder and then descends in the intermediate zone between the two cylinders. At the return vanes the air flow returns to the central cylinder.

The particles are fed by a screw feeder into the centre of the classifier where they are dispersed by a rotating plate and then meet the rising centrifugal air flow. The fine particles will rise with the air flow and pass through the circulating fan while the coarse particles will be pushed outwards, due to greater centrifugal force, against the surrounding wall and fall downwards. As the fines descend with the air flow to the return vanes the particles lose momentum and continue downwards when the air flow turns into the centre of the classifier.

5.2 Empirical measurements on air classifiers with internal aerodynamic cycle

Both air classifiers with internal aerodynamic cycle have been investigated by empirical measurements. The results from these measurements will be presented separately for each air classifier. A combined overview of the scientific findings of all air classifiers will be presented in Chapter 7.

Empirical measurment Paper A

In Paper A, an experimental study on the circulating air classifier was performed at the crushing plant Vikan in Gothenburg, Sweden, which is owned by Skanska. Conveyor belts fed the air classifier with a 0-2 mm crushed fraction. The crushed fraction was produced in a VSI crusher. The goal of the experiment was to investigate the influence of the circulating fan and the separator fan on the cut size.

The effects of the circulating fan and the separator fan were tested separately. For the circulating fan three different fan speeds were tested by varying the frequency of the electrical motor driving the fan rotor. The tested circulating fan speeds were 30, 40 and 50 Hz (where 50 Hz corresponds to 340 rpm due to gearing). During the three tested speeds the separator fan was held at a constant speed of 20 Hz (140 rpm).

The separator fan was tested in 5 Hz intervals from 20 to 40 Hz (where 40 Hz is equal to 270 rpm); meanwhile the circulating fan was held at a constant speed of 50 Hz (340 rpm). Samples were taken from these five different setups.

Figure 15 shows the particles size distribution for the feed and the coarse product for the three tested circulating fan speeds. It can be seen that the particle size distribution is altered by the classification process compared to the feed. As expected the separation of material into the fine product is increased as the speed of the circulating fan is increased. At no circulating fan speed is a single particle size completely removed; the smallest particles, below 63 µm, are reduced at most from 15 to 4 mass percentage.

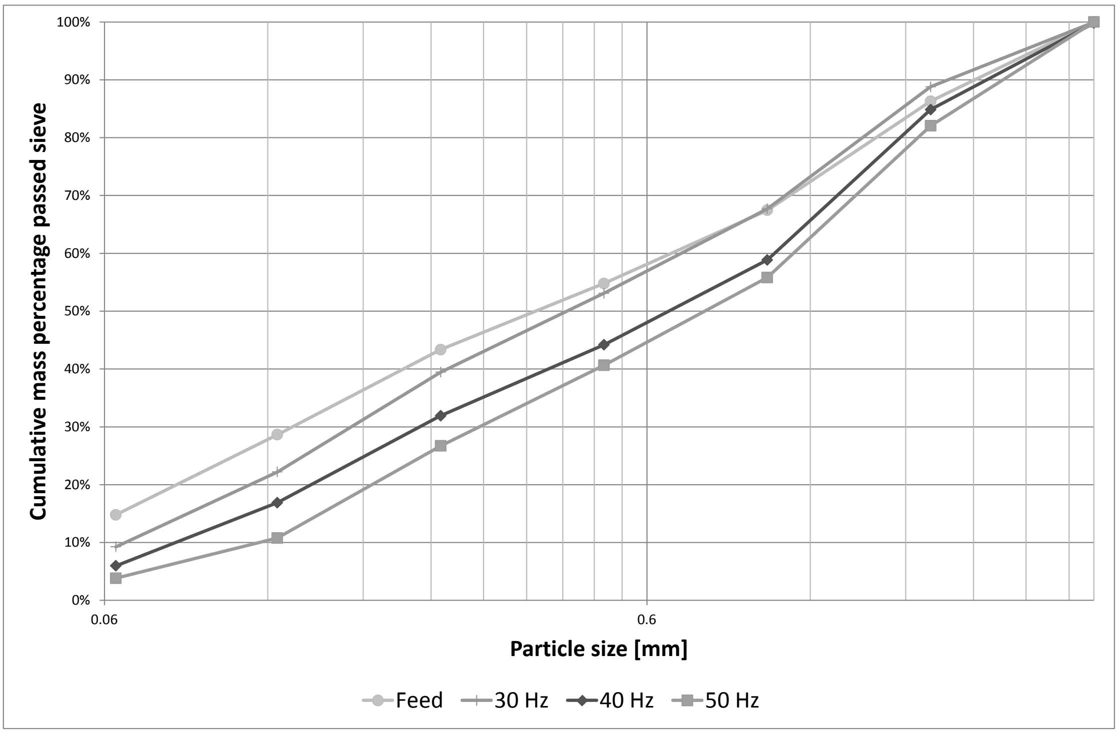

Figure 15. Particle size distribution of the coarse product depending on the circulating fan speed [Hz].

Figure 16 shows the particles size distribution dependency on the separator fan speed, the particle size distribution for all of the samples has been reduced compared to the feed. In the case of the separator fan, an increased speed will mean that fewer particles are separated away from the feed.

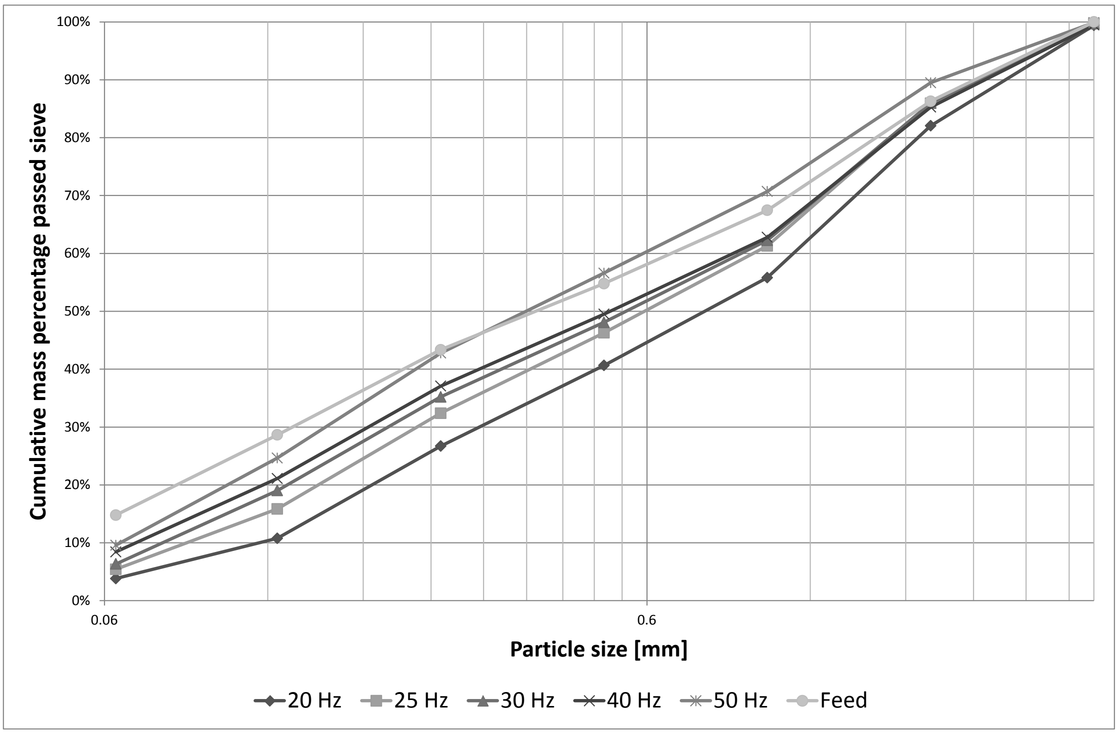

Figure 16. Particle size distribution for the coarse product depending on the separator fan speed [Hz].

EMPIRICAL MEASURMENTS PAPER G

The air classifier investigated in Paper G was a part of a pilot plant, see Figure 17, owned, operated and designed by Chalmers University of Technology to evaluate the production of manufactured sand for different industrial uses. It consists of a VSI crusher, a vibration screen and the investigated air classifier.

Figure 17. Pilot plant used in Paper G (photo A. Hjalmarsson 2014).

The pilot plant toured Sweden during 2013 to 2014 and Paper G includes data from three of the quarries visited. For two of the quarries a full factorial design was used, see Table 2. The factor design was employed to investigate the influence from the main fan and the separator fan. The base of the two-level factorial design is repeated twice as the top speed of the VSI crusher is changed, 58 m/s respective 79 m/s. The reason for this was to investigate if the classification efficiency changed with the amount of fines produced.

Table 2. Factorial design used at quarry 1 and 2 in Paper G.

Test nr	Main fan	Separator fan	Tip Speed VSI
T1	55 Hz	30 Hz	58 m/s
T2	40 Hz	30 Hz	58 m/s
T3	55 Hz	50 Hz	58 m/s
T4	40 Hz	50 Hz	58 m/s
T5	55 Hz	30 Hz	79 m/s
T6	40 Hz	30 Hz	79 m/s
T7	55 Hz	50 Hz	79 m/s
T8	40 Hz	50 Hz	79 m/s

At quarry 3 a frequency scan was performed see Table 3. In this case the VSI tip speed was held at 79 m/s to produce as much fines as possible. The results from the empirical study in Paper G were focused on how the classification efficiency for particles at 63 µm was affected by the main fan and the separator fan.

Table 3. Frequency scan at quarry 3 performed in Paper G.

Test nr	Main fan	Separator fan	Tip Speed VSI
s1	55 Hz	30 Hz	79 m/s
s2	48 Hz	30 Hz	79 m/s
s3	40 Hz	30 Hz	79 m/s
s4	55 Hz	50 Hz	79 m/s
s5	55 Hz	40 Hz	79 m/s

Empirical results Paper G

Figure 18 and Figure 19 shows the classification efficiency for Test 1-4, with the VSI at 58 m/s, for quarry 1 and 2. It can be seen that both quarries show similar trends in the split of the feed into a coarse product and a fines product. With T1 showing the largest removal of fines, particles below 63 µm, from the coarse fraction. T4 removed the least fines from the coarse product; meanwhile the classification results for T2 and T3 is between T1 and T4. The statistically analysis of test setting T1 to T4 shows that it is statistical significant that the main fan increases the removal of fines whereas the separator fan lowers the removal of fines.

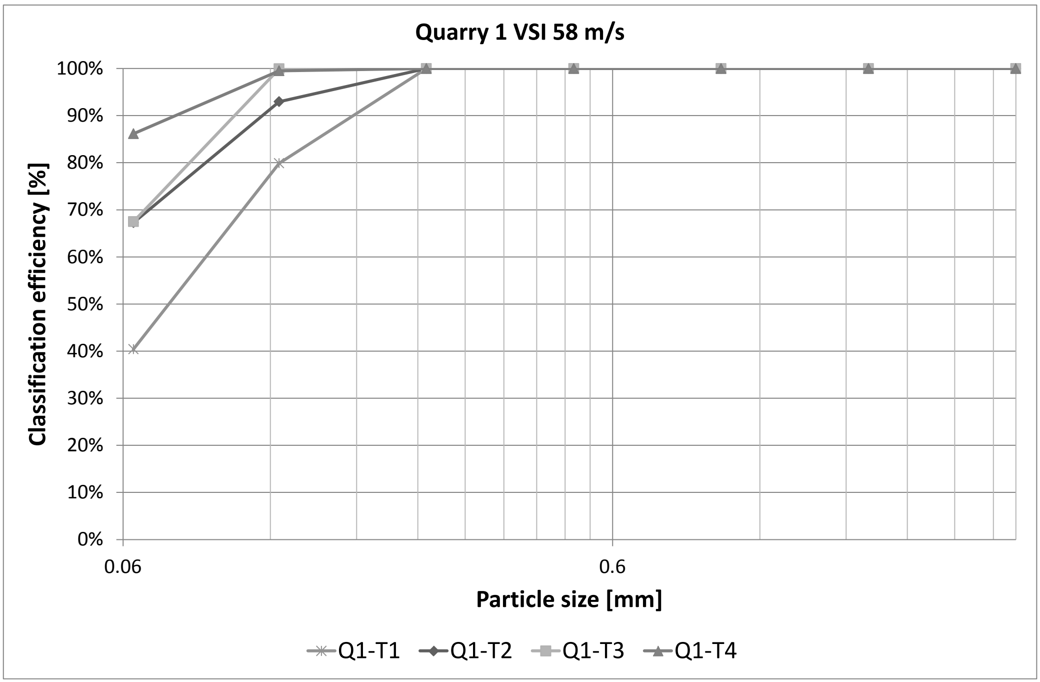

Figure 18. Efficiency for the classification process for quarry 1 with VSI tip speed of 58 m/s.

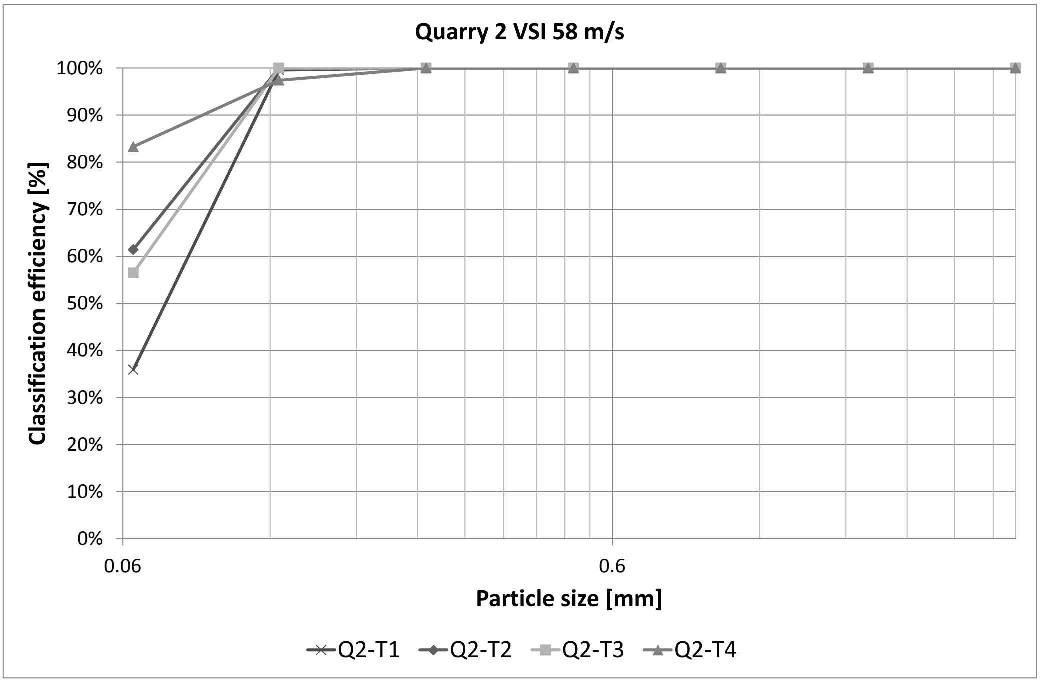

Figure 19. Efficiency for the classification process for quarry 2 with VSI tip speed of 58 m/s.

The resulting classification efficiency for test setting T5-T8 for quarry 1 and 2 can be seen in Figure 20 and Figure 21. A similar trend can be seen for T5-T8 as for T1-T4, with T5 having the lowest amount of fines (same fan settings as T1). The difference between the remaining test settings is not as clear. The statistical analysis shows as T1-T4, that it is statistically significant that the main fan will lower the level of fines in the coarse product; however it is not statistically significant that the separator fan will reduce the removal of fines.

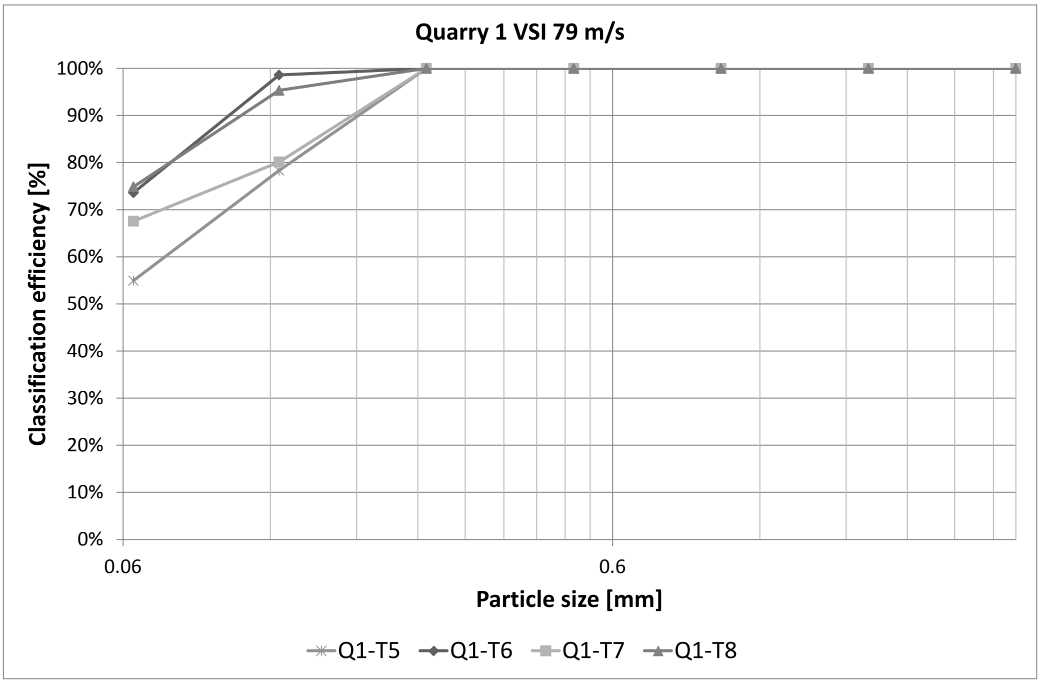

Figure 20. Efficiency for the classification process for quarry 1 with VSI tip speed of 79 m/s.

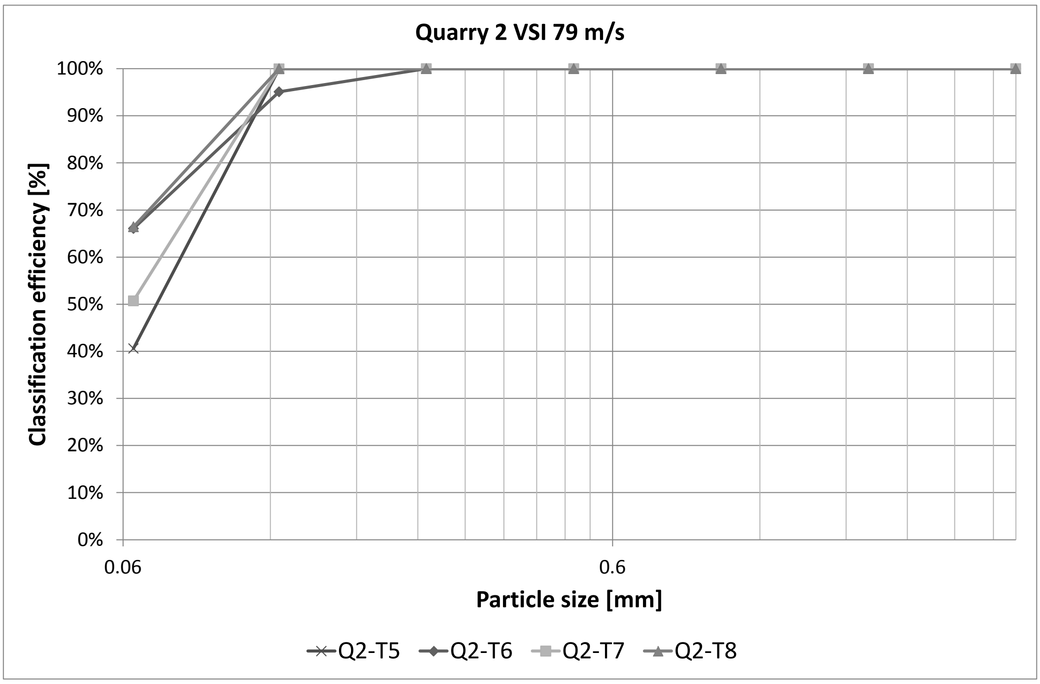

Figure 21. Efficiency for the classification process for quarry 1 with VSI tip speed of 79 m/s.

Figure 22 and Figure 23 shows the classification efficiency dependent on the main fan speed respectively the separator fan speed at quarry 3. It can be seen that a higher main fan speed increases the removal of fines from the coarse product with the separator fan speed held constant at 30 Hz. An increase in the separator fan speed reduces the removal of fines with the main fan speed held constant at 55 Hz. Quarry 3 showed an increased removal of particles in the size range of 125 µm than quarry 1 and 2. The reason for this is probably that rock source for quarry 3 includes a larger amount of mica compared to quarry 1 and 2. This gives more flaky particles which are shown in Chapter 6.3 to increase the chance of following the air flow with the fines.

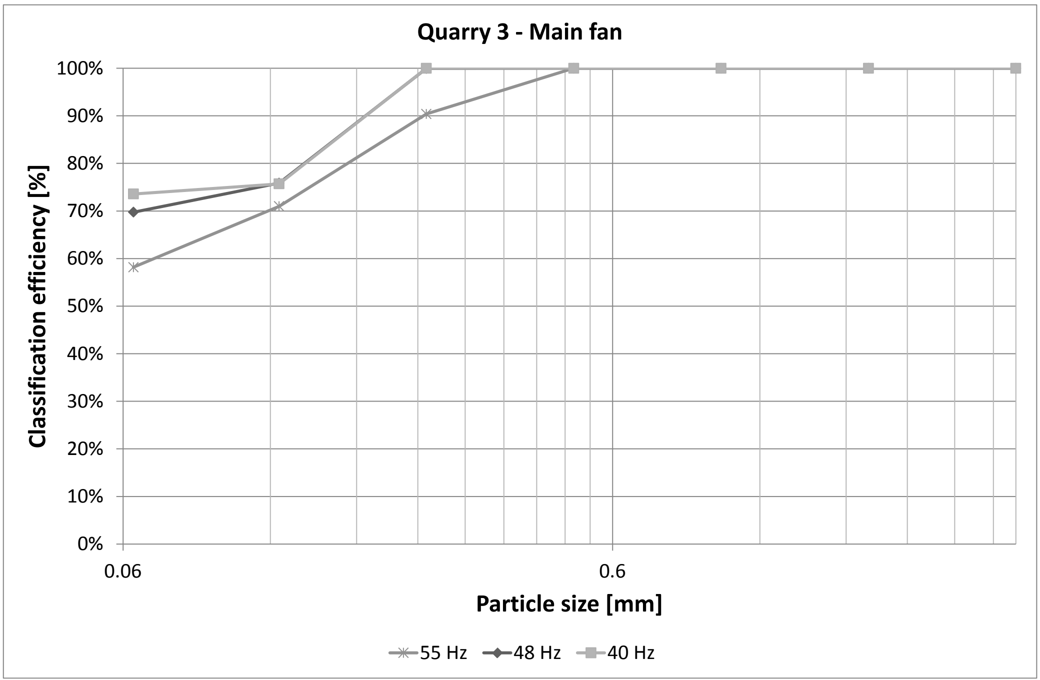

Figure 22. Influence from main fan (separator fan at 30 Hz) on the efficiency for the classification process.

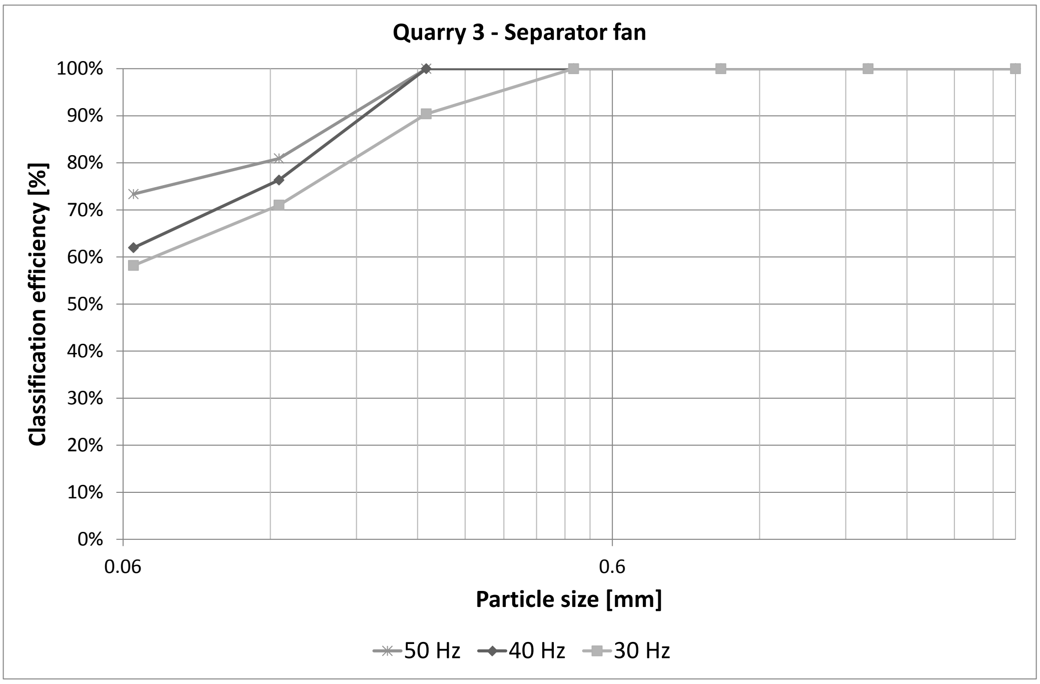

Figure 23. Influence from separator fan speed (main fan at 55 Hz) on the efficiency for the classification process.

5.3 SIMULATION RESULTS ON AIR CLASSIFIERS WITH INTERNAL AERODYNAMIC CYCLE

In Paper G simulations using computational fluid dynamics were performed for the investigated air classifier. The CFD simulations were performed using the commercial software Fluent 12.1.4 with a volume mesh of 1 million cells, see Figure 24; with the boundary mesh consists of triangular elements and the volume mesh consists of pyramids. To simulate the rotation of the main fan and the separator fan, the mesh was split into three regions; two regions of moving mesh for the fans and one stationary mesh for the remaining region.

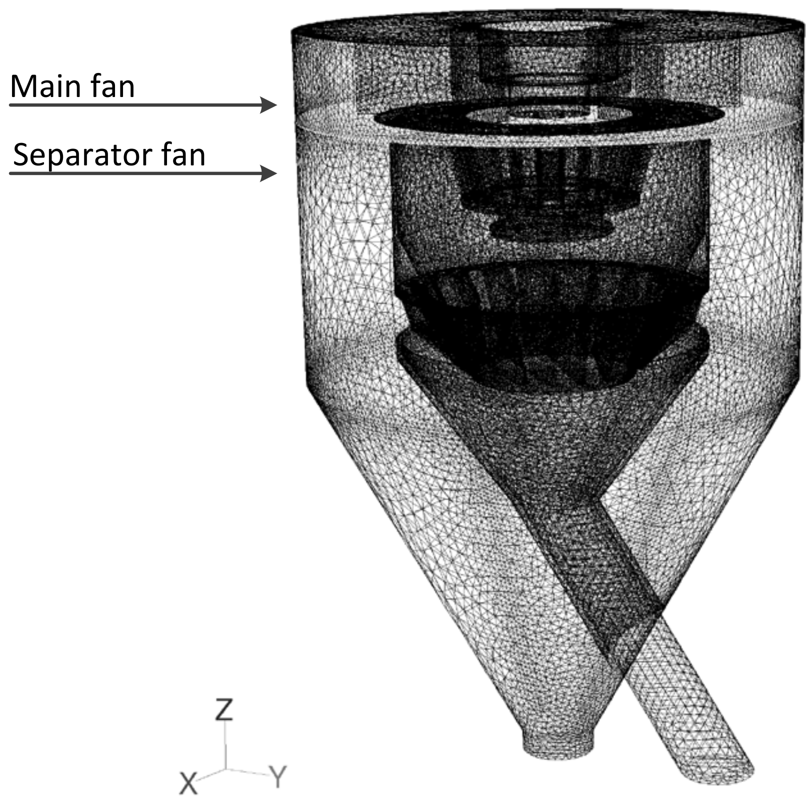

Figure 24. The mesh used in the simulation.

A transient time dependent was employed in the solver to properly simulate the moving fans. Three cases were simulated for the original air classifier, see Table 4. For Case A and Case B the main fan was set at 55 Hz meanwhile the speed of the separator fan was set at 30 Hz for Case A and 50 Hz for Case B. This represents the empirical test case of T1 and T3. For Case C the main fan was set to 40 Hz and the separator fan to 30 Hz, which is the setting for the empirical test T2. The speeds were chosen to study how the fan speed changes used in empirical tests affected the air flow.

Table 4 Overview of the investigated cases.

Case	Main fan [Hz]	Separator fan [Hz]
A	55	30
B	55	50
C	40	30

Learning from the three cases above Case D was introduced with a small change in central cylinder was introduced to improve the air flow inside the air classifier. The length of the inner cone at the return vanes was shortened by 8 cm; thus leading to the lowest point of the cone being above the lowest point of the return vanes. The mesh was created in similar fashion as those for the original cases. Case D was tested with the same fan settings as Case A.

Results from the performed simulations in Paper G

Figure 25 shows an overview of the air flow for Case A and Figure 26 shows the same for Case B. The overall shape of the air flow is similar for both cases however the velocity magnitude is somewhat different between the cases. This difference must be connected to the change in rotation velocity of the separator fan, as the speed of the main fan remains constant. The change is mostly in the central area were the air flow entering from the external cone is somewhat lower for Case B than Case A. Not surprisingly the air flow around the separator fan is increased; this increase seems also to affect the air flow in the upper part of the external cone around the main fan.

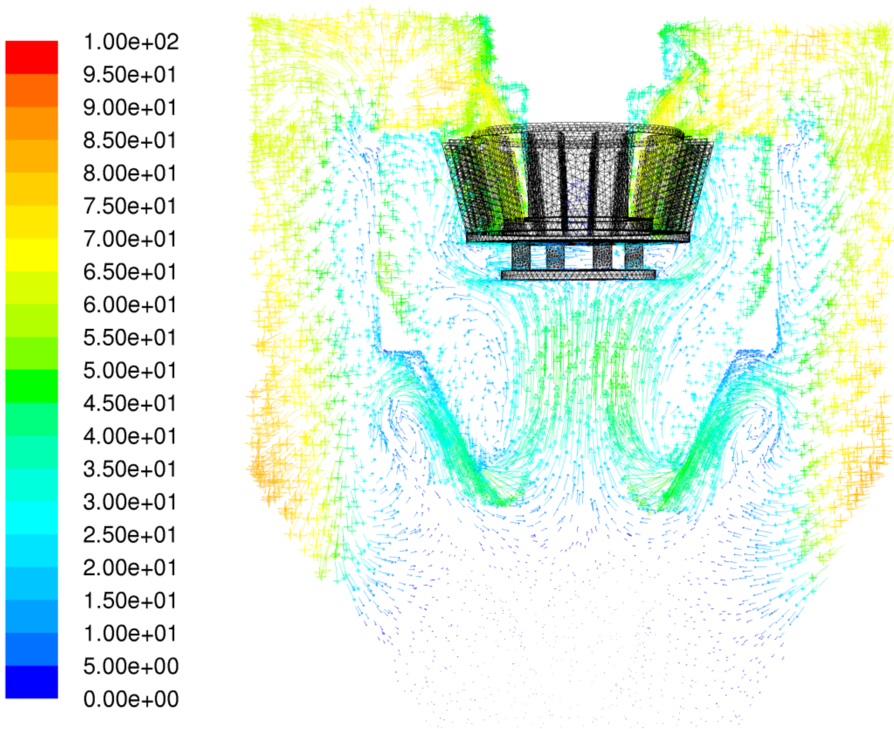

Figure 25. Velocity magnitude (m/s) in the x-z plan for Case A (main fan 55 Hz, separator fan 30 Hz).

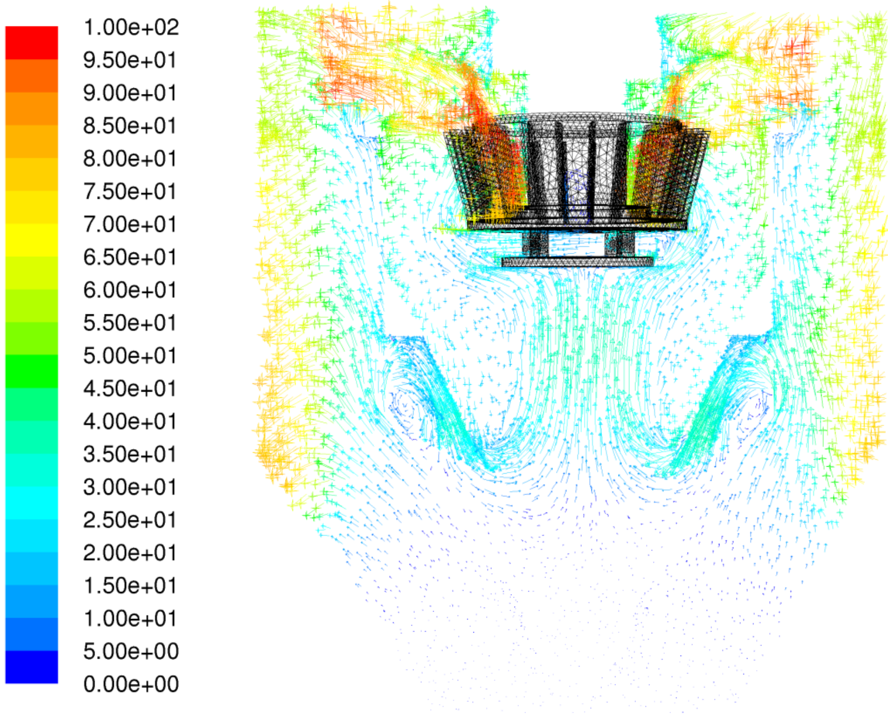

Figure 26. Velocity magnitude (m/s) in the x-z plan for Case B (main fan 55 Hz, separator fan 50 Hz).

The air flow below and to the sides of the separator fan shows a recirculation area, see Figure 27 and Figure 28. The area is similar in both cases. This area might be negative for the classification efficiency as the air flow is not homogenous in the separation zone. Earlier research has shown that especially small particles will be affected by turbulence [64].

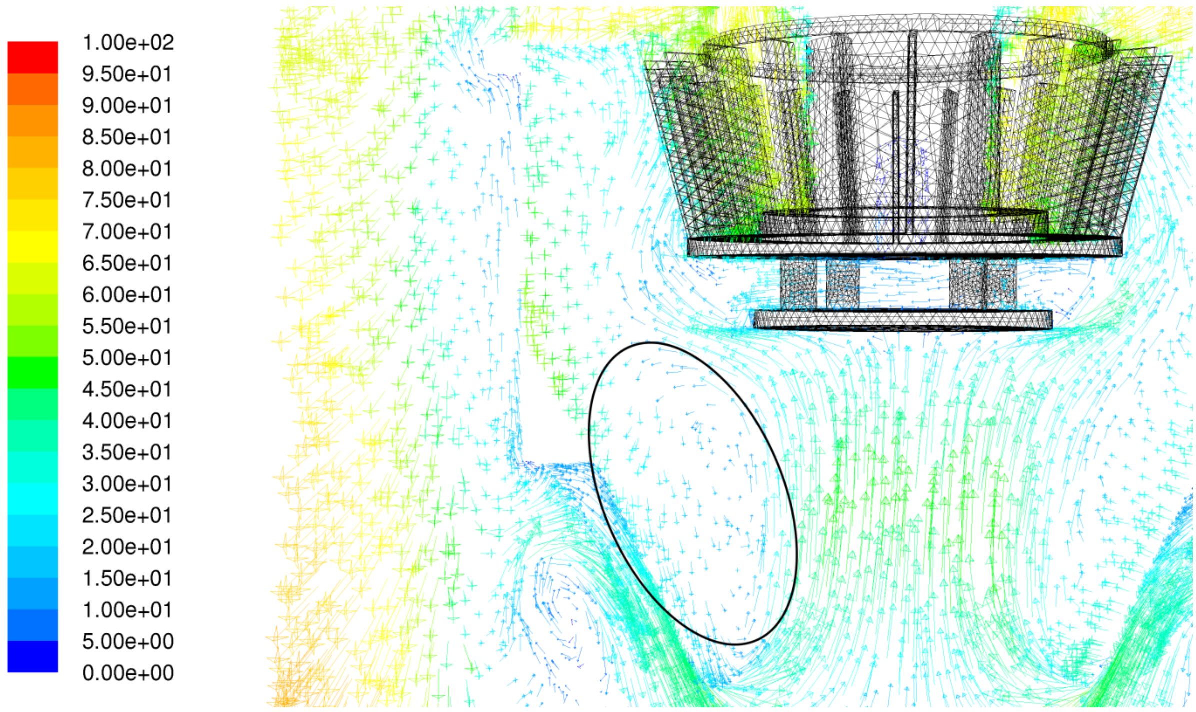

Figure 27. Velocity magnitude (m/s), recirculation area for Case A (main fan 55 Hz, separator fan 30 Hz).

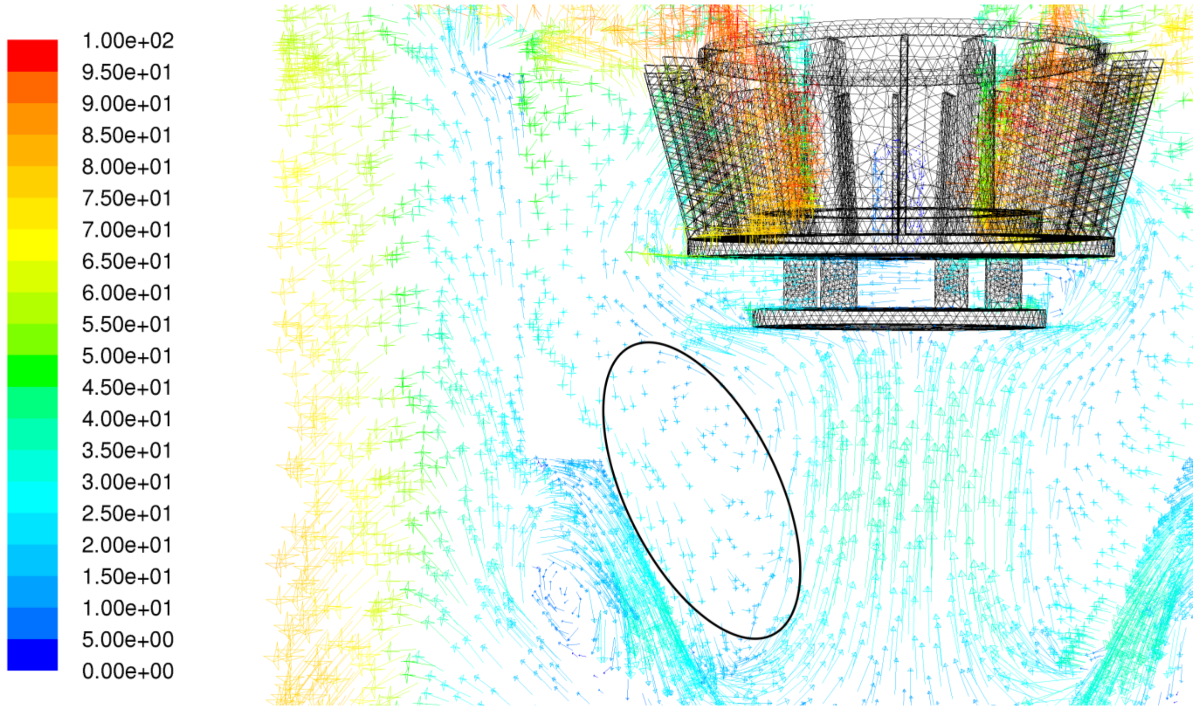

Figure 28. Velocity magnitude (m/s), recirculation area for Case B (main fan 55 Hz, separator fan 50 Hz).

Figure 29 shows the velocity magnitude for Case C. Case C differs from Case A (see Figure 25) with reduced main fan speed. It can be seen that Case C shows the same tendency as Case A and Case B in the internal cone; with the difference that the overall air velocity is reduced. The same recirculation area is present. It can however be seen that the air flow in the outside cone does not have the same split with a higher air flow velocity closer to the external cone wall.

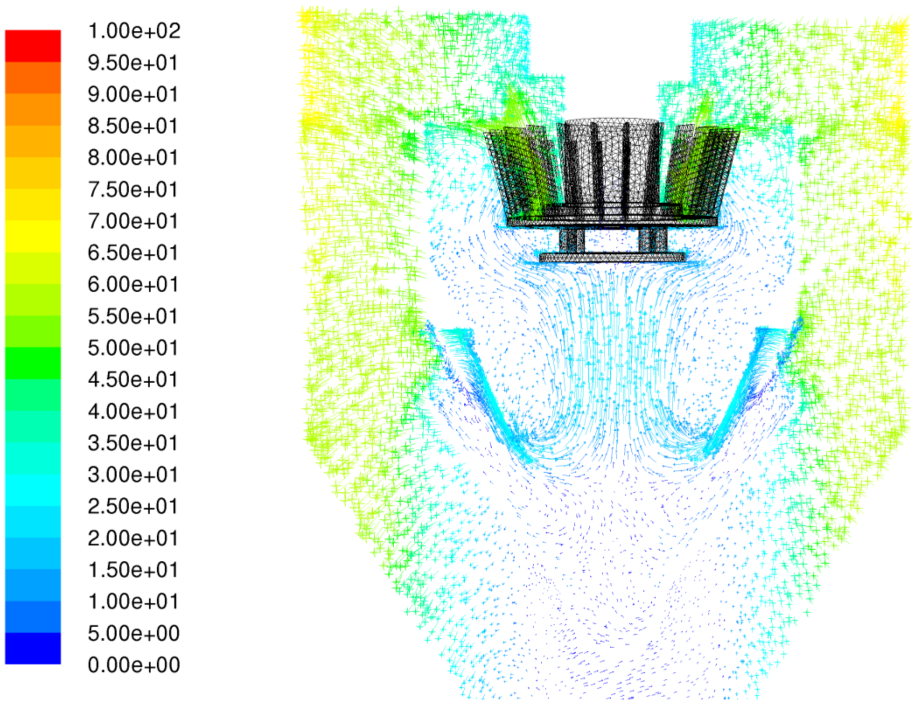

Figure 29. Velocity magnitude (m/s) in the x-z plan for Case C (main fan 40 Hz, separator fan 30 Hz).

In order to reduce the recirculation area present in all the investigated cases, the geometry around the return vanes was changed, see Case D. Figure 30 shows the result from this change, it can be seen that the recirculation area is still present, but it has been reduced in size compared to Case A in Figure 27. It is better with a reduced recirculation zone as the smaller particles will follow with the air flow upwards and later to the outer chamber to be released and fall down to the fines outlet.

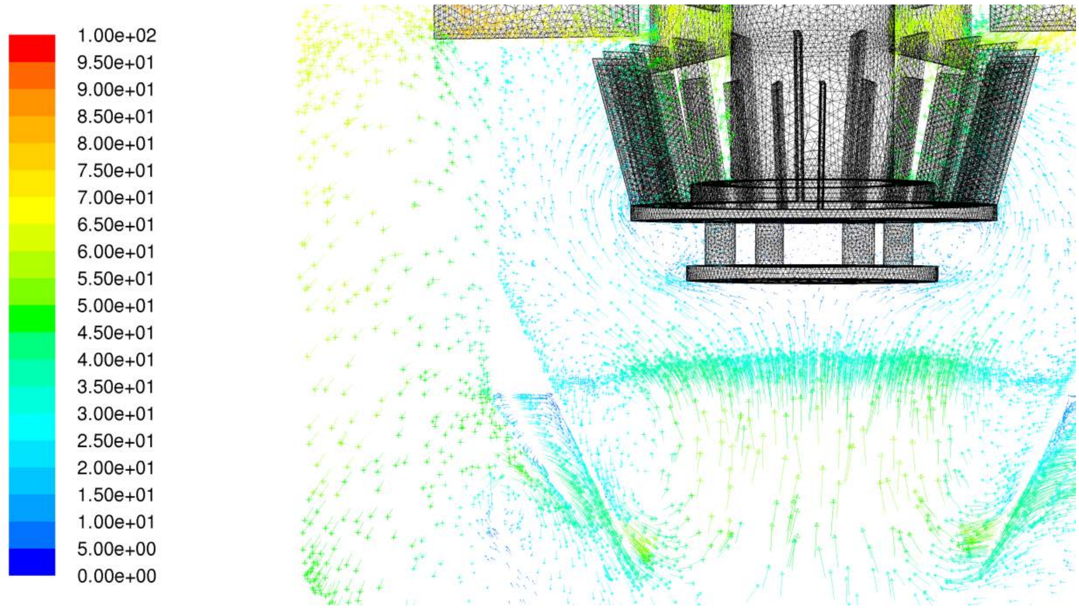

Figure 30. Velocity magnitude (m/s), recirculation area for Case D (main fan 55 Hz, separator fan 30 Hz).

It seems that a small change of the internal design, might affect the air flow in positive manners. It might be so that small changes, hard to discover through empirical means, can improve the air flow and thus the classification efficiency.

6 AIR CLASSIFIER WITH OPEN AERODYNAMIC CYCLE

The aim of this chapter is to:

- *Introduce the air classifiers with open aerodynamic cycles investigated*
- *Present the results from the empirical experiments performed*
- *Present the results from the performed simulations*

6.1 INTRODUCTION OF AIR CLASSIFIERS WITH OPEN AERODYNAMIC CYCLE

The functional model with the different process steps in an air classifier with an open aerodynamic cycle can be seen in Figure 31. The Feed enters the air classifier and is by some means transported into a mix zone where the feed meets the air flow. The air flow is created separately by either drawing or pushing air through the air classifier. In the separation zone the air flow separated the coarse particles from the fines. Two different transport flows then moves the coarse particles and the fines to their separate exit areas where the particles is separated from the air flow. The air then leaves the air classifier.

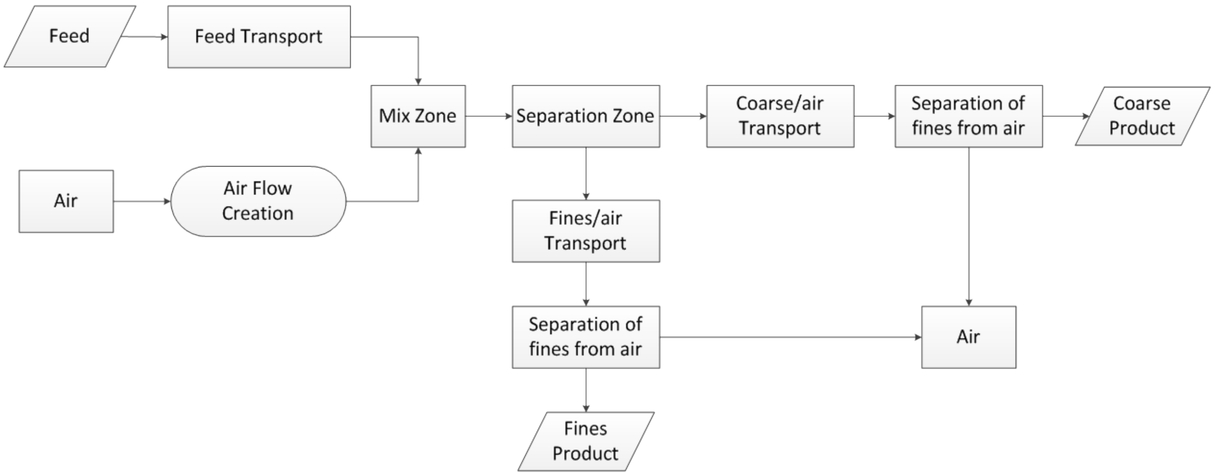

Figure 31. Processes in an air classifier with an open aerodynamic cycle.

Two air classifiers with open aerodynamic cycles were investigated in the performed research; a commercial two-stage air classifier mounted above three product silos and a mobile air classifier (see Figure 32). The air classifiers are similar as the mobile air classifier has a similar design as the first stage in the stationary two-stage air classifier. As the air classifiers use an open aerodynamic cycle a filter system has to be applied to remove fines from the air leaving the air classifiers before the air is let out to the surroundings.

Figure 32. Investigated air classifiers, to the left two-stage air classifier and to the right mobile air classifier.

The two-stage air classifier investigated uses two different separation zones in series, where the first stage is the same as the mobile air classifier. A schematic layout can be seen in Figure 33. The first stage uses a modified version of the gravitational-crossflow zone and the second stage uses a vertical standing centrifugal-counterflow zone. The air classifier uses one single external fan to create the airflow through both stages. The two stage setup means that three products will be created; coarse, intermediate and fines.

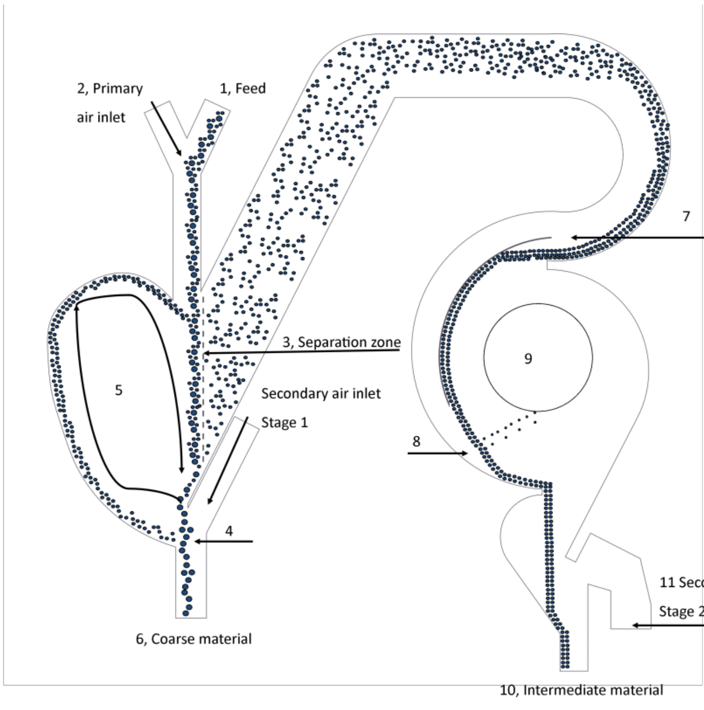

Figure 33. Two-stage air classifier schematic layout, first stage to the left and second stage to the right.

The feed enters the air classifier into stage 1 from the top, see Figure 33 point 1. The primary air inlet is located next to the entrance for the feed and can be controlled by a valve. The feed and the air from the primary air inlet are subsequently mixed throughout their progress through the machine. When the air-particle flow reaches the separation zone (see point 3 in Figure 11), the air turns and passes through the separation vanes with the fines. Coarse particles will continue downwards and leave the stage at point 6. Point 4 shows the modification on the classic gravitational-crossflow zone where a second air flow crosses the coarse particle flow a second time. This air flow comes from the secondary air inlet.

The air and particle mixture which leaves stage 1 continues into stage 2. Using the geometry of stage 2 the air and particles are separated into two flows at point 7. The particles will pass on the central side of a guiding plate meanwhile the main part of the air flow will pass on the outside. This allows for a separation cut at point 8 where the main air flow crosses the path of the particle flow; fines will then follow the air flow in a circulating motion and leave the stage at point 9. Intermediate particles will pass out from the machine at point 10. Stage 2 also has secondary air inlet at point 11, allowing for recirculation of particles and thus increasing the possibility of a good classification.

Instead of the second stage the mobile air classifier has a cyclone that separates the fines from the outlet air. The cyclone is followed by a filter system that removes any existing fines from the air.

6.2 EMPIRICAL MEASUREMENTS ON AIR CLASSIFIERS WITH OPEN AERODYNAMIC CYCLE

Both air classifiers with open aerodynamic cycle have been investigated by empirical measurements. The results from these measurements will be presented separately for each air classifier. A combined overview of the scientific findings of all air classifiers will be presented in Chapter 7.

TWO-STAGE AIR CLASSIFIER

The two-stage air classifier was investigated empirically in Paper C and Paper F. Where Paper C laid the foundation for the empirical understanding of the two-stage air classifier; meanwhile Paper F builds on Paper C to create an empirical model of the two-stage air classifier. The test plan used in Paper C and Paper F can be seen in Table 5. The test factors are the air inlets into the air classifier presented in Figure 33; in PA1 the primary air inlet is in stage 1, SA1 is the secondary air inlet in stage 1 and SA2 is the secondary air inlet in stage 2. The percentages indicate how much the air inlet is opened.

Table 5. Empirical measurements performed in Paper C and Paper F, percentage open.

Factor Paper C			
Test	**PA1**	**SA1**	**SA2**
1	0%	0%	0%
2	100%	0%	0%
3	0%	100%	0%
4	0%	0%	100%
5	100%	100%	0%
6	100%	0%	100%
7	0%	100%	100%
8	100%	100%	100%

Factor Paper F			
Test	**PA1**	**SA1**	**SA2**
1	100%	100%	100%
2	50%	100%	100%
3	100%	50%	100%
4	100%	100%	50%
5	100%	75%	100%
6	100%	25%	100%
7	0%	100%	100%
8	100%	100%	0%
9	50%	50%	100%

The resulting particle size distribution for the coarse product for the test performed in Paper C can be seen in Figure 34. It was noted in Paper C that the particles size distribution for the different tests could be divided into two groups; one group clearly separated more material to stage 2 than the other group. The group with higher separation grade showed up in tests 3, 5, 7 and 8. The other tests resulted in a group with lower separation grade.

To explain which valve affects the particle size distribution curve a statistical analysis was performed using the experimental setup shown in Table 5. The responses investigated were the mass percent at 0.125 mm, 0.25 mm, 0.5 mm and 1 mm. It was found that the secondary air inlet for stage 1 (SA1) was the dominating factor for controlling the classification efficiency for all the investigated responses.

It also showed for the largest particle size, 1 mm, that the primary air inlet for stage 1 (PA1) influenced the response. So also did the interaction between PA1 and SA1, however this interaction is just inside the standard deviation and is therefore not statistically assured. The author argues however in Paper C that this interaction could be of importance for larger particles due to that PA1 changes the classification efficiency in the same direction as SA1, thus a small amplification effect could exist between PA1 and SA1

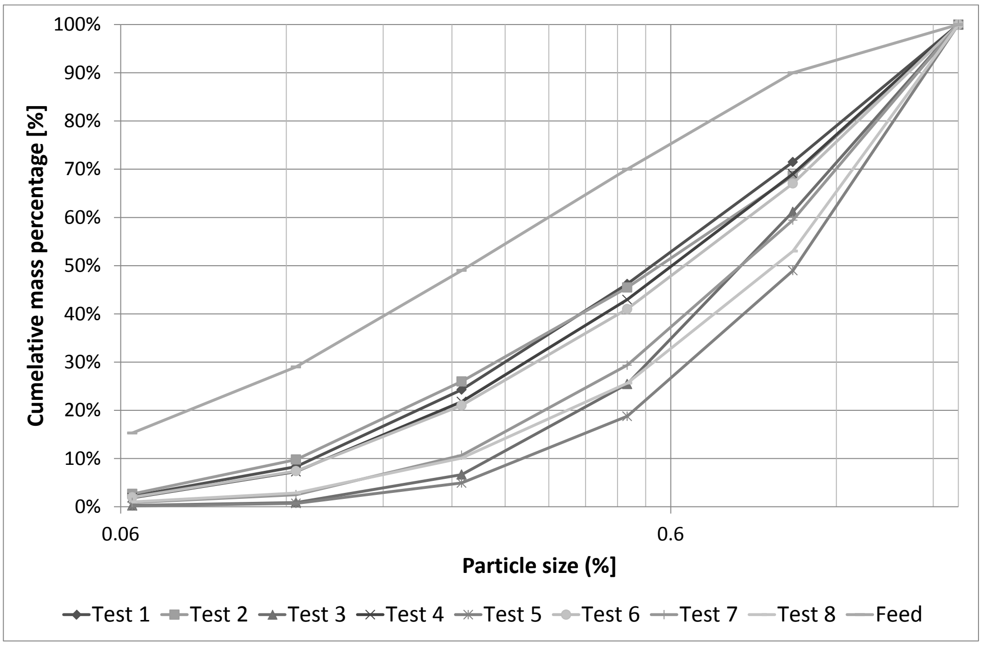

Figure 34. Particle size distributions for the coarse product for the different test setups.

The particle size distribution for the intermediate product for the different test setups is shown in Figure 35. No feed is plotted in Figure 35 due to that the feed into stage 2 is dependent on the classification efficiency of stage 1. The particle size distribution curve can clearly be varied by using different settings on the valves. To connect the classification results with the actual settings of the valves, the results were analysed using Table 5. The responses chosen for this analysis were mass percent of particles below 63 and 125 µm. The first response, 63 µm, was chosen due to the fact that all the test setups in stage 1 had removed almost all of the particles in that size. The second response was chosen to see if stage 1 or stage 2 were the dominating factor of what is produced in stage 2.

The results from the analysis show that for the first response the classification efficiency was only dependent on the secondary air inlet for stage 2 (SA2). The other valves did not influence in any way; however for the second response, 125 µm, SA2 did affect the classification efficiency but less so than the secondary air inlet for stage 1 (SA1).

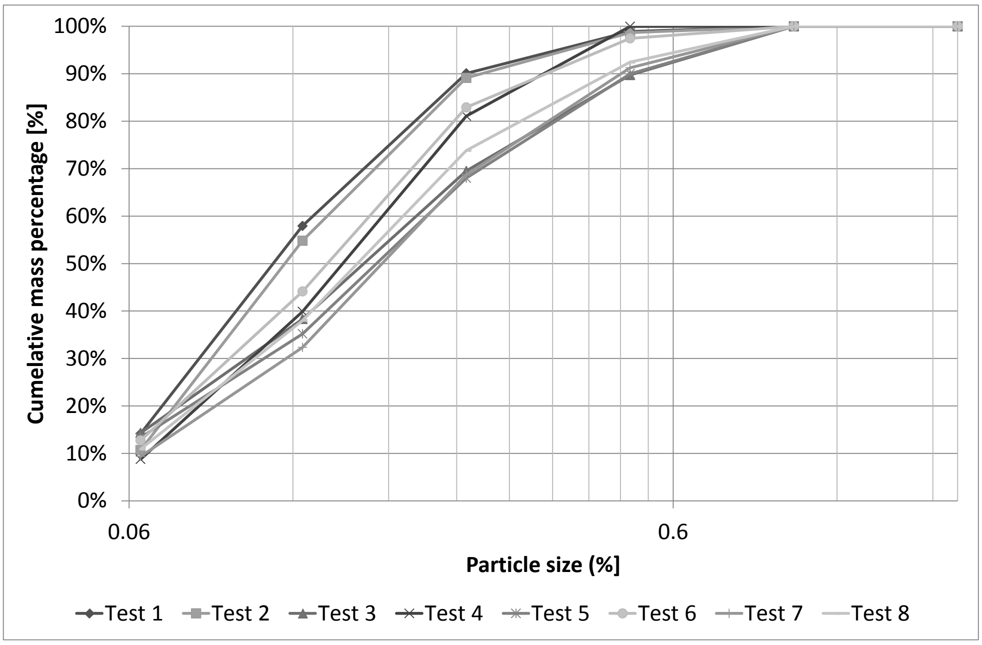

Figure 35. Particle size distributions for the intermediate product for the different test setups.

Paper F focused on the classification efficiency of the two-stage air classifier. The classification efficiency curves for stage 1 are shown in Figure 36. No fish-hook phenomena can be seen in stage 1.

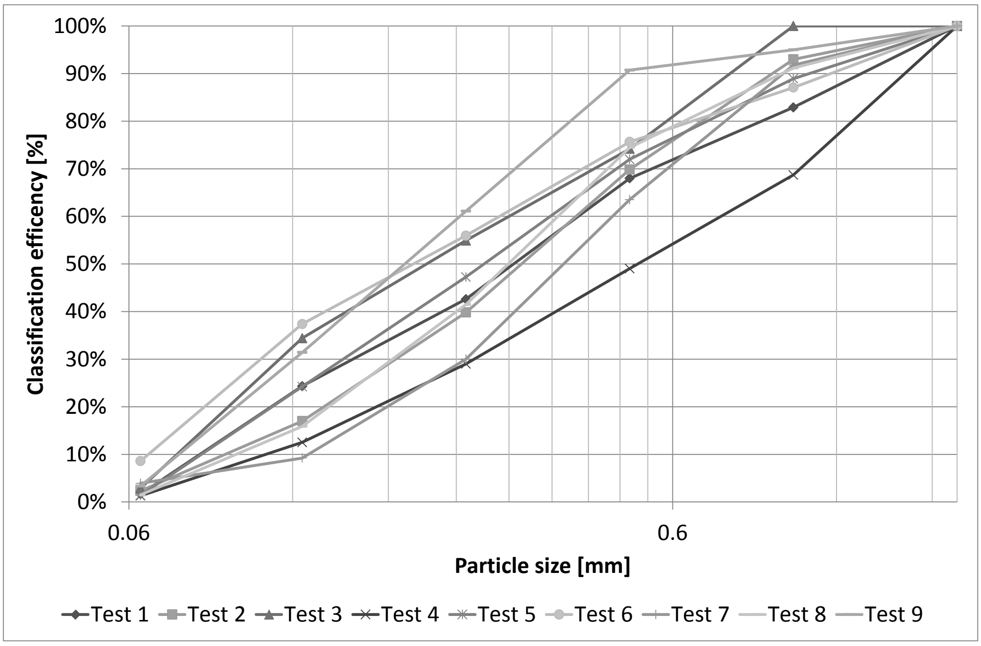

Figure 36. Classification efficiency for stage 1, percentages of feed ending up in the coarse product.

Figure 37 shows the classification efficiency for stage 2 for different test settings. As in stage 1, there is no visible fish hook. This result is expected because fish-hook behaviour is dependent on the air flow speed and particle size [68]. Fish-hook behaviour is often seen below 63 µm, which is the resolution measured in these experiments. The cut size is somewhat similar for all tests, except Test 9. The reason for this might be that the reduced air speed into the first stage slows the circulating air flow in stage 2, which, in combination with the air flow through the secondary air inlet 2, might increase the cut size.

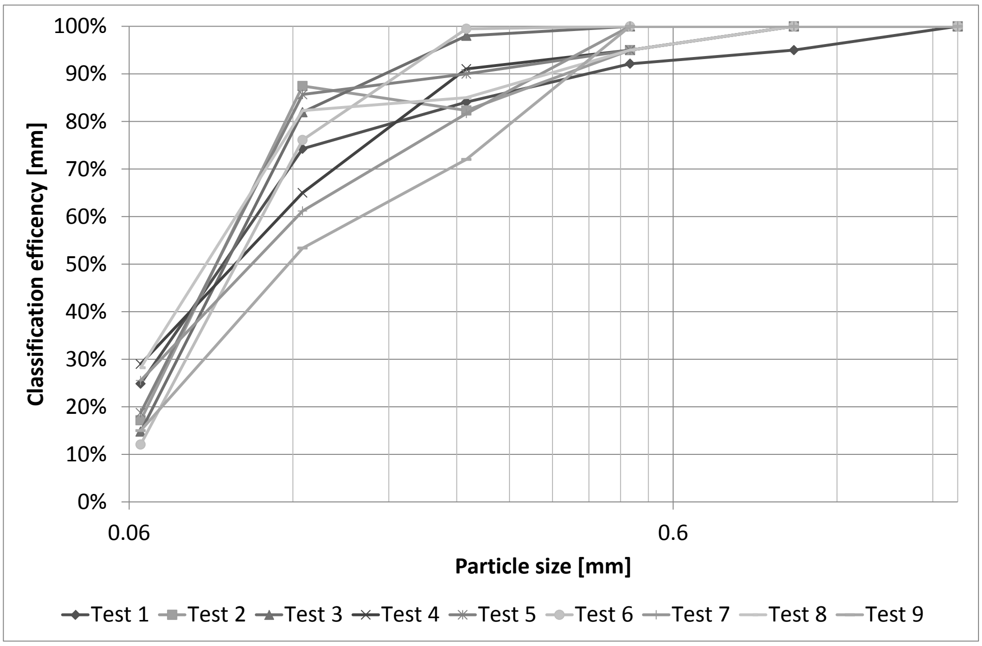

Figure 37. Classification efficiency for stage 2, percentages of feed up in the intermediate product.

In Paper F the classification efficiency was statistically analysed. It was shown that the cut size for stage 1 was dependent on SA1 and PA1. SA1 was the air inlet that most influenced the cut size; more air through SA1 increased the cut size. Thus the findings in Paper F verified the findings in Paper C. Paper F also showed the sharpness of the cut in stage 1 was mostly influenced by PA1. The experiment showed no influence on the cut size on stage 2 from PA1, SA1 or SA2. The sharpness was influenced from SA2; thus showing an improved separation of fine particles from larger particles when SA2 is open.

MOBILE AIR CLASSIFIER

Paper D investigated the mobile air classifier; which has the same air inlets as stage 1 for the two-stage air classifier. This means that the air classifier has two air inlets, a primary air inlet (PA) and a secondary air inlet (SA), positioned as shown for stage 1 in Figure 33. The mobile air classifier was investigated using a full factorial design, see Table 6.

Table 6. Factorial design used in Paper D, percentage open.

Factor Paper D		
Test	**PA**	**SA**
1	50%	50%
2	100%	50%
3	50%	100%
4	100%	100%

The resulting classification efficiency for the tests performed in Paper D can be seen in Figure 38. As can be seen the results differ somewhat between the tested settings. It can however be noted that the difference is small between the settings used in Test 2 and Test 3. Test 4 and Test 1 differ from Test 2 and Test 3 for the classification efficiency for small particles. The sharpness of the cut is also similar for all test settings. The difference that does exist is not statistically significant.

The similarity between the different test settings when it comes to cut size and sharpness is surprising. Only Test 1, where both the air flow through PA and SA is reduced, showed a lower cut size. The results presented for the two-stage air classifier in Paper C and Paper F showed a clear influence from the secondary air inlet. The reason for this might be a lower feed rate for the mobile air classifier than for the investigated stationary air classifier thus reducing the influence of particle to particle interaction. When trying to increase the feed rate into the mobile air classifier the belt with the coarse product was overloaded and stopped.

If true this would mean that the total mass flow of air is more important than the recirculation of material, an idea that is strengthened by the somewhat smaller cut size of Test 1 (0.12 mm instead of 0.15 mm).

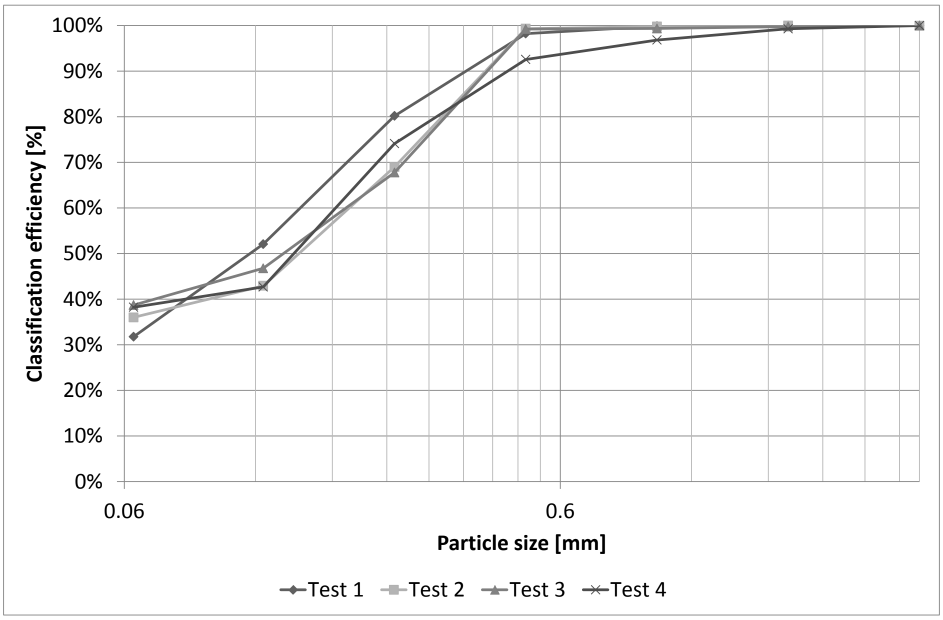

Figure 38. Classification efficiency for the mobile air classifier, percentages of feed ending up in the coarse product.

6.3 SIMULATION RESULTS ON AIR CLASSIFIERS WITH OPEN AERODYNAMIC CYCLE

The air flow inside the air classifiers was investigated using computational fluid dynamics (CFD). Paper B investigated stage 1 and Paper E investigated stage 2. The goal of Paper B was to investigate how the secondary air inlet for stage 2 aided in classification process as noted in the empirical work performed in Paper C. This was done through multiphase simulations. Paper E dealt with the focus on parameters that could affect the classification efficiency of stage 2, including particle shape, particle size, air velocity and geometry.

GRAVITATIONAL AIR CLASSIFIER – STAGE 1

Two cases were used in the multiphase study of the gravitational air classifier. The difference between the cases was the recirculation, for the first case recirculation was enabled whereas for the second case recirculation was disabled. The cases were set up using the same mesh, see Figure 39, with around 1.1 million cells. To enable recirculation the boundary condition for the secondary air inlet was set to pressure inlet. A pressure inlet is used when velocity or flow rate is unknown and the pressure is known. In this case the pressure was set to atmospheric pressure. Closing the secondary air inlet by changing the boundary condition, from pressure inlet to wall disabled recirculation. Changing the secondary air inlet to a wall means that no air can pass into the air classifier from the inlet. The boundary condition for the primary air inlet was set to pressure inlet. For both cases a particle and air mixture entered the air classifier from the primary air inlet, with the particle volume fraction mixture set to 0.3. To reduce the computational load a single particle phase with 125 µm particles was used. Using only one particle size comes with some disadvantages. The results cannot show how different particle sizes interact, nor can it show if a given particle size act different than others. It can however give an insight in how particles behave in the air flow.

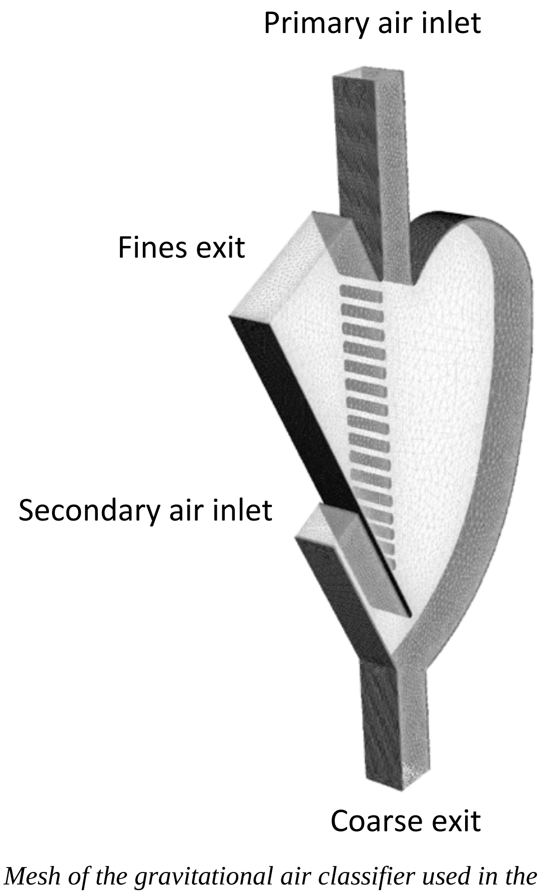

Figure 39. Mesh of the gravitational air classifier used in the multiphase studies.

Figure 40 shows the particle volume fraction for Case 1 which has the secondary air inlet open and thus enables recirculation. Particles enter from the top of the stage through the primary air inlet. The classification of the particles occurs when the particles fall in front of the separation vanes. This is the separation zone where the air turns and flows out from Stage 1 and continues to Stage 2. Fine particles, such as the particle size investigated, will follow the air through the separation vanes to stage 2. It can however be seen that there is a build up of particles in front of the separation vanes. This build up represents particle to particle interaction which means that some particles that should pass through the separation vanes instead will continue downwards. Those particles that have not passed the separation vanes will, by the air flow from the secondary air inlet, be recirculated towards the separation zone.

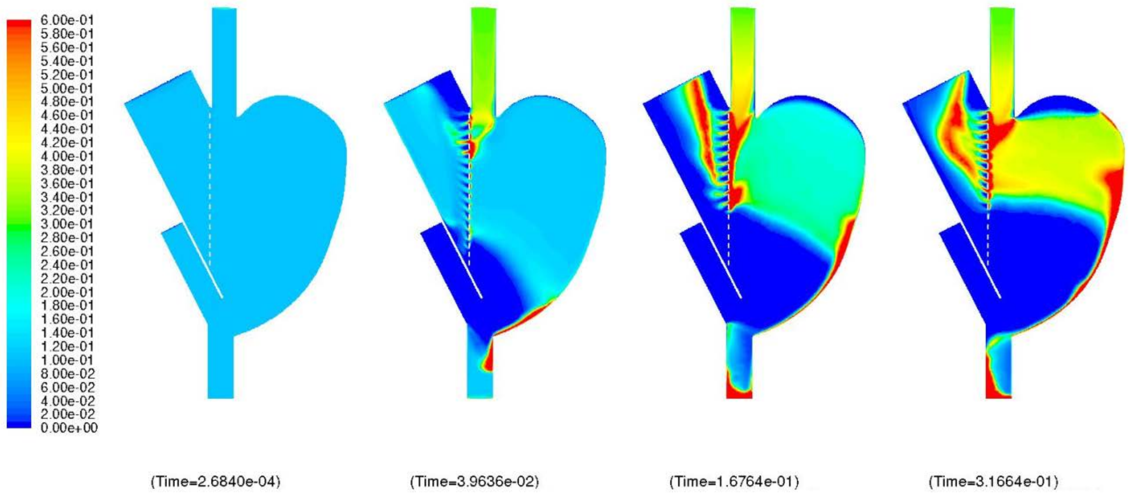

Figure 40. Volume fraction of the particle phase depending on time with secondary air inlet open.

For the case with the secondary air inlet closed, the particle motion path will change. In Figure 41 the particle volume fraction is shown dependent on time. As the particles pass the separation zone some particles will not pass through the separation vanes and thus not follow the air flow to the second stage. The same happens in the first case; however the difference between the cases is the recirculation. For the second stage no recirculation occurs, and thus the particles that are not classified at the first passing through the separation zone end up at the coarse particle exit. The difference in classification efficiency can thus be coupled to the recirculation of particles towards the separation zone.

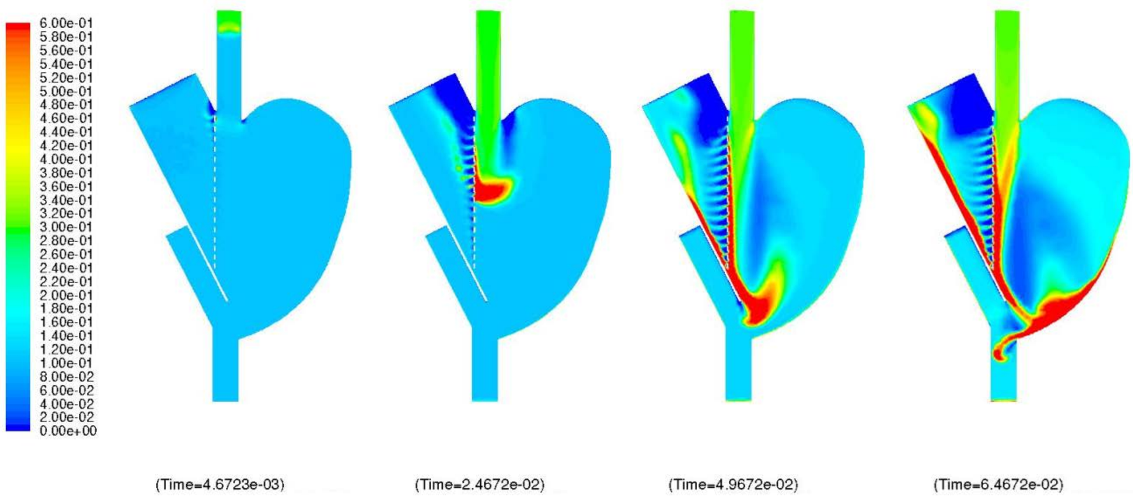

Figure 41. Volume fraction of the particle phase depending on time with secondary air inlet closed.

Centrifugal air classifier – Stage 2

Stage 2 of the two-stage air classifier was investigated in Paper E. The mesh and an outline of second stage, which is a vertically mounted centrifugal air classifier with a secondary air inlet, can be seen in Figure 42.

Three different particle inlet velocities were used: 50 m/s, 70 m/s and 80 m/s. The secondary air inlet velocity was set to 3 m/s. Four different particle sizes were simulated: 30 µm, 63 µm, 125 µm and 250 µm. The particles were modelled as being injected at the particle inlet, as shown in Figure 42. Outline of the mesh used for the centrifugal air classifier investigated in Paper E. The particle material simulated was granite, with a density of 2,780 kg/m^3, which is the material used in the chosen aggregates plant. To simulate different particle shapes, two types of drag models were used, one for spherical particles [46] and one for non-spherical particles [47]. The shape factor was set to 0.7 for the non-spherical particles. For the inlet velocity of 70 m/s, another two non-spherical shapes were simulated, with shape factors of 0.5 and 0.3. The fines exit hole has a standard diameter of 1,200 mm. The study also investigated a smaller exit hole 1,000 mm in diameter.

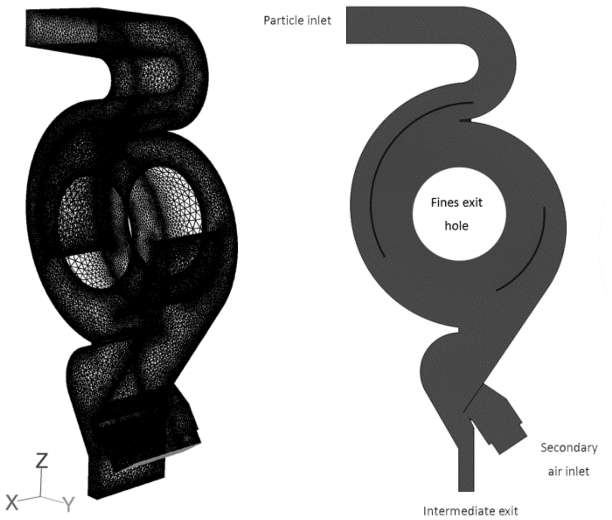

Figure 42. Outline of the mesh used for the centrifugal air classifier investigated in Paper E.

The influence of the air inlet velocity on the centrifugal air flow can be seen in Figure 43. The air flow patterns themselves are not very different. The velocity magnitudes differ to the same degree as the inlet velocities; indicating that it is possible to predict changes in the air flow from changes in the inlet velocity.

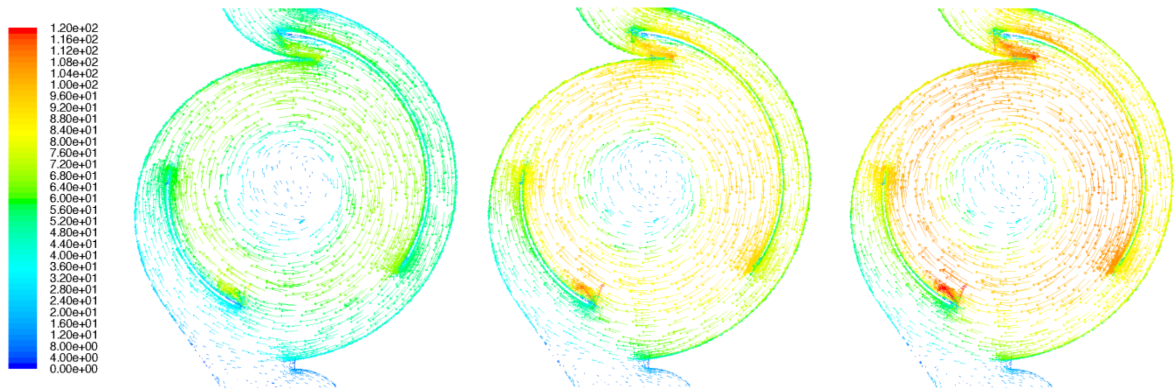

Figure 43. Velocity Magnitude [m/s] for particle inlet velocities of 50 m/s, 70 m/s and 80 m/s, from left to right, in the centre plane.

Figure 44 shows the velocity vectors in the x-z plane in the centre of the separation zone. For each particle inlet air velocity, some areas with circulating air are noticeable. This air flow goes from the centre of the separation zone to the exit and then returns to the centre (see black circle). The velocity magnitude of the circulating air is not very large compared to the main air flow. However, Wang et al. [64] noted that fine particles are more affected by turbulence than large particles.

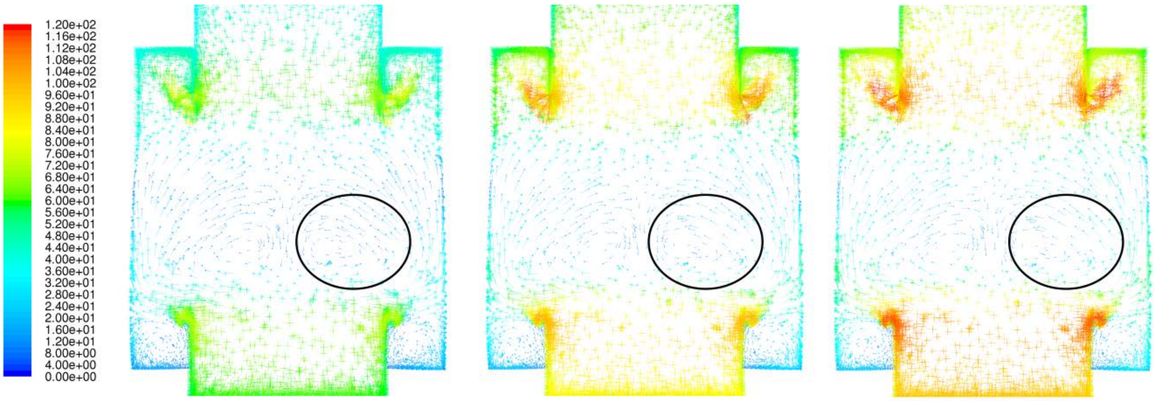

Figure 44. Velocity magnitudes [m/s] for particle inlet velocities of 50 m/s, 70 m/s and 80 m/s, from left to right, in the x-z plane.

Similar zones of circulating air flows can be observed in the x-y plane, as shown in Figure 45. However, in the x-y plane, the centre of the circulating zone is closer to the sides (black circle). The circulating zones are smaller than those in the x-z plane, and the position of the zone indicates that it might not be as negative as those in the x-z plane. This is because the zones are closer to the exit, and particles caught up in the flow should not be able to move far from the exit without being moved back to the exit.

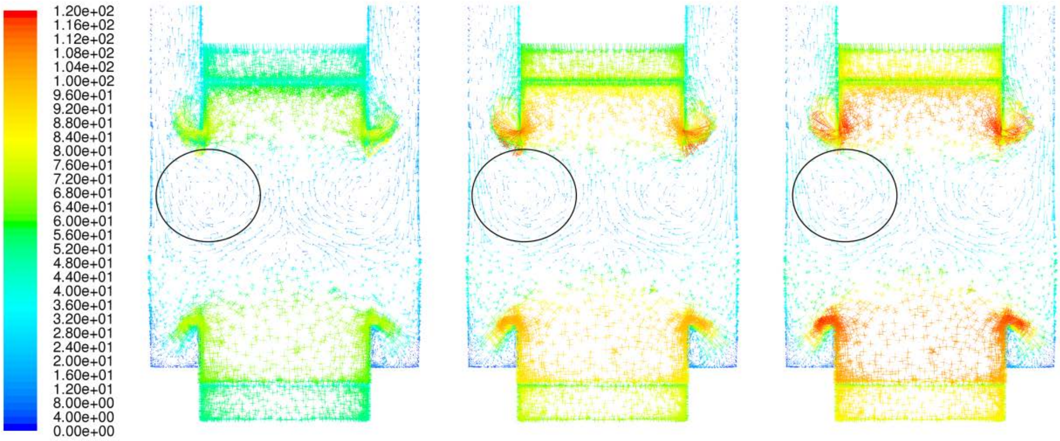

Figure 45. Velocity magnitudes [m/s] for particle inlet velocities of 50 m/s, 70 m/s and 80 m/s, from left to right, in the x-y plane.

The influence of the inlet velocity on the simulated classification results can be observed in Figure 46. No 30-µm particles were found in the intermediate product for any of the inlet velocities used. This was true independent of the particle shape. The proportion of fine particles in the intermediate product increased as the particle inlet velocity increased.

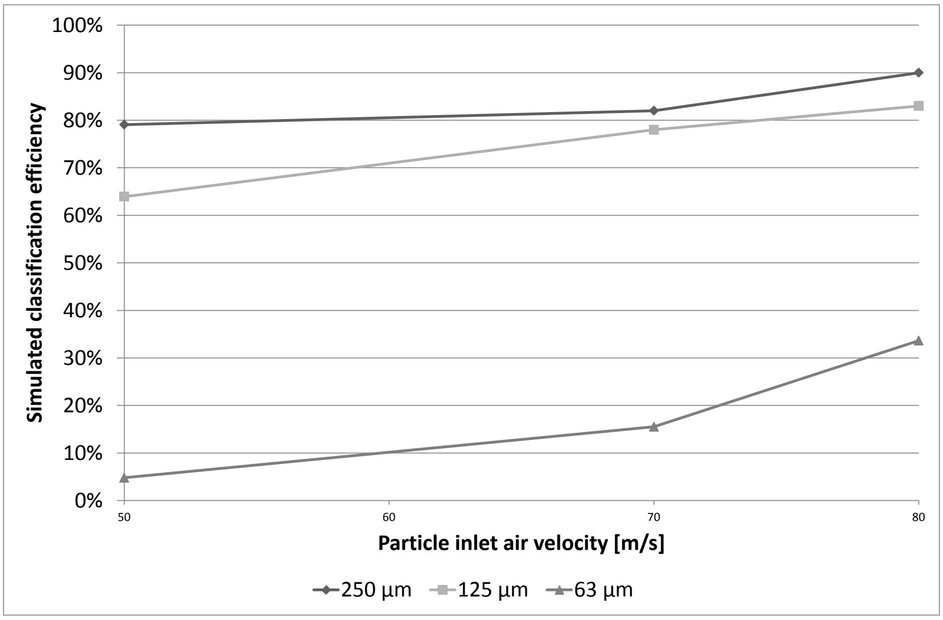

Figure 46. Classification efficiency for spherical particles of different sizes depending on the particle inlet air velocity.

Similar trends were observed for the non-spherical particles, as shown in Figure 47. Higher inlet air velocities result in greater proportions of fine particles in the intermediate product. Non-spherical particles tended to be less likely to end up in the intermediate product. The probable explanation for this is that the drag on the particle is dependent on the shape.

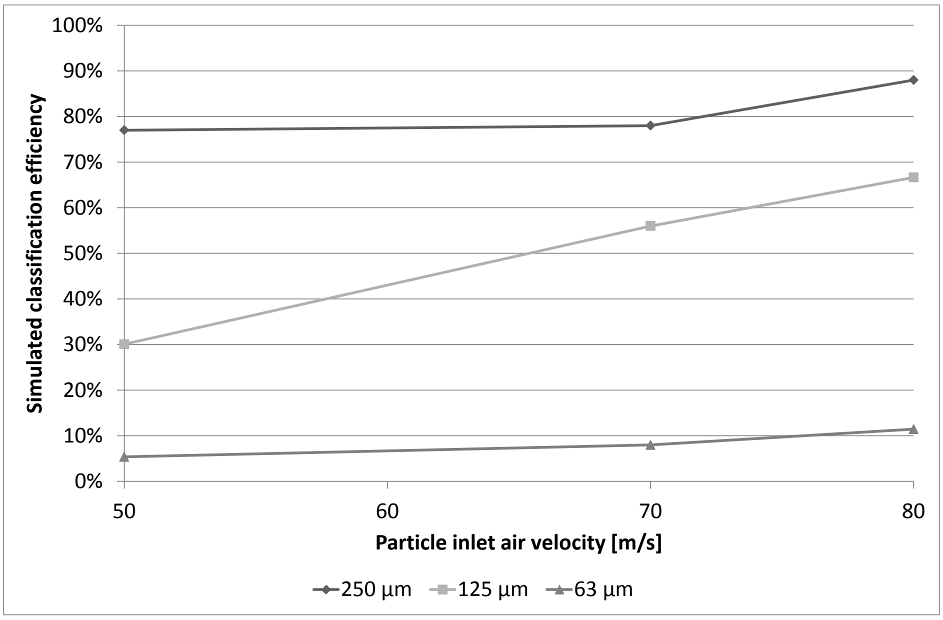

Figure 47. Classification efficiency for non-spherical particles of different sizes depending on the particle inlet air velocity.

To further investigate how the particle shape influences the classification, simulations were performed with four different particle shapes (non-spherical particles with shape factors of 0.3, 0.5 and 0.7 and spherical particles) and an air inlet velocity of 70 m/s. Again, the less spherical particles were more likely to end up with the fine product, see Figure 48. This finding suggests that air classification may be used by the concrete industry to remove mica and other unwanted flaky particles from the desired product.

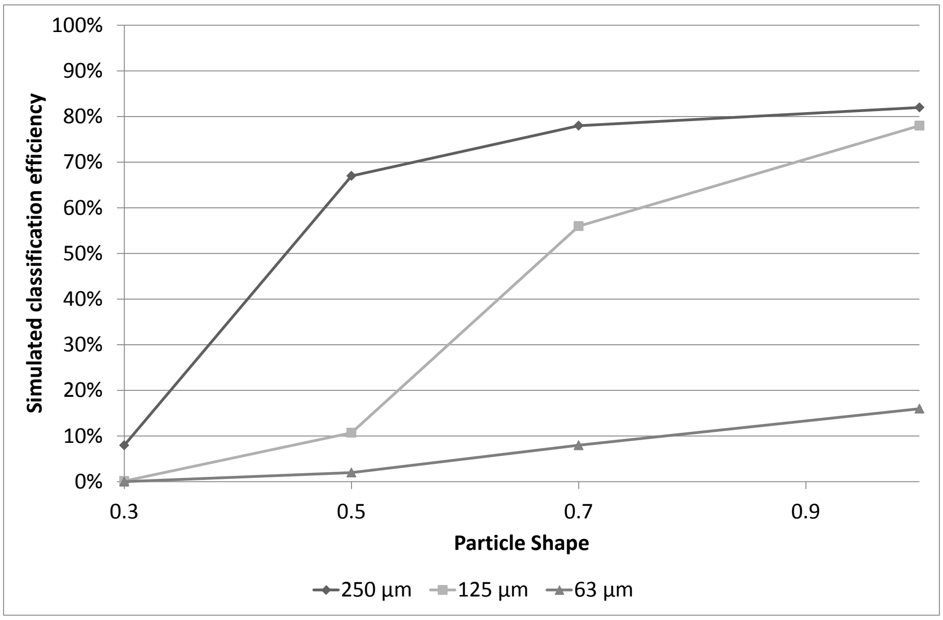

Figure 48. The influence of particle shape on the classification efficiency.

Figure 49 shows the particle tracks for the simulated particles at the start of the simulation. It is noticeable that the feed particles at the top of the air classifier are mixed with the particles present in the separation zone. In a continuously operating air classifier, this mixing would lead to a large amount of particle to particle interaction. This interaction adversely affects the classification efficiency, as small particles might be affected by coarser particles, and also disturbs the flow field.

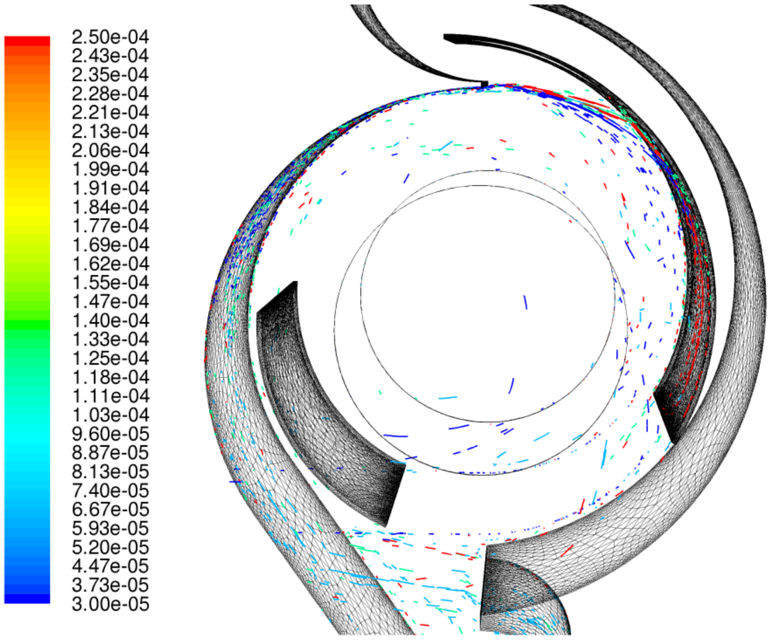

Figure 49. Particle tracks for the simulated particles (particles colored by size).

The influence of the size of the fines exit hole was investigated by comparing the standard opening (with a diameter of 1,200 mm) with a smaller opening with a diameter of 1,000 mm. The smaller hole seemed to result in fewer fine particles (smaller than 125 µm) in the intermediate product, while 250-µm particles seemed not to be influenced (Figure 50). Reducing the opening size could therefore be a possible solution to improve the classification of particles smaller than 63 µm.

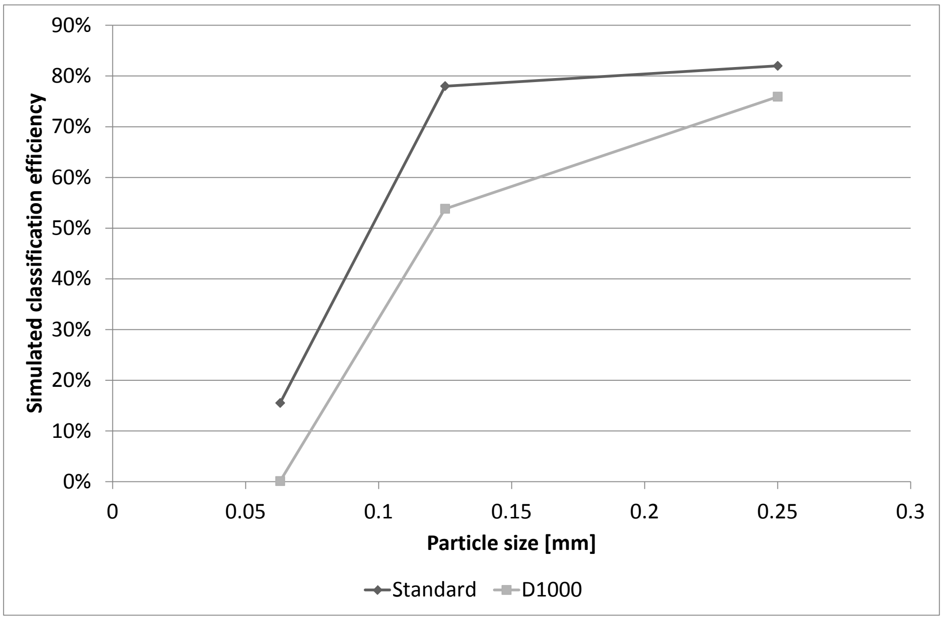

Figure 50. Classification efficiency versus particle size for different sizes of the fines exit opening.

6.4 EMPIRICAL MODEL OF THE INVESTIGATED AIR CLASSIFIERS

Two empirical models have been presented in the performed research. Paper F presents a model for the two-stage air classifier and Paper D presents a model for the mobile air classifier. Both models presented are modelled according to the efficiency curve approach. The efficiency curve approach has been successfully applied by the cement industry [59] and the recycling industry [52].

EMPIRICAL MODEL FOR THE TWO-STAGE AIR CLASSIFIER

The goal of the model presented in Paper F was to be able to predict the particle size distribution for the three products (coarse, intermediate and fines) from the input data. An overview of the model can be seen in Figure 51. The input parameters of the model are the feed rate in ton/h, *F*; the particle size distribution, *f*; the sharpness for stages 1 and 2, α_1 and α_2, respectively; and the relation between the cut size and particle x_i for stages 1 and 2, X_1 and X_2, respectively. The outputs from the model are the particle size distribution and the production rates for the three products, coarse (C, c_i), intermediate (B, b_i) and fines (A, a_i).

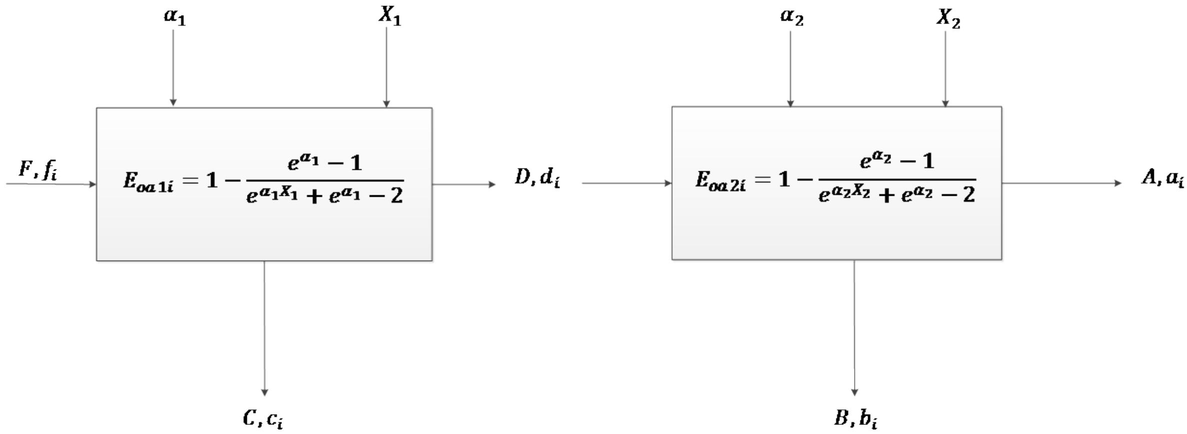

Figure 51. Overview of the empirical model of the two-stage air classifier.

Using the experimental results in Paper F, it is possible to connect the efficiency curve parameters, α_1, α_2, X_1 and X_2 with the air classifier air inlets. As shown in Chapter 6.2, the cut size of stage 1 was dependent on SA1 and the sharpness of PA1. For stage 2, the resulting cut size was more stable, and the sharpness was controlled by SA2. The resulting parameters can be seen in Table 7.

Table 7. Model parameters for the two-stage air classifier.

Parameter	Value
α_1	0.26xPA1 + 0.65
X_1	0.16xSA1 + 0.26
α_2	0.09
X_2	4-SA2

The model was validated by comparing the model results with the experimental results taken from the crushing plant. The validation shown in this part is a comparison between the particle size distribution from the model results and the experimental results.

Figure 52 and Figure 53 shows how PA1 changes the particle size frequency for the measurements and model. Shown is the coarse and intermediate fraction. The settings of the air classifier were such that SA1 and SA2 were completely opened, while PA1 was closed or half-open. For the coarse data, the model shows similar results as the measurements. The model underestimates the amount of approximately 2 mm particles and thus somewhat overestimates the level of fines. The results for the model of the intermediate product are close to those of the measurements when PA1 is closed. When PA1 is half-open, the amount of 125 µm particles in the intermediate product is overestimated. The reason for this overestimation is unclear.

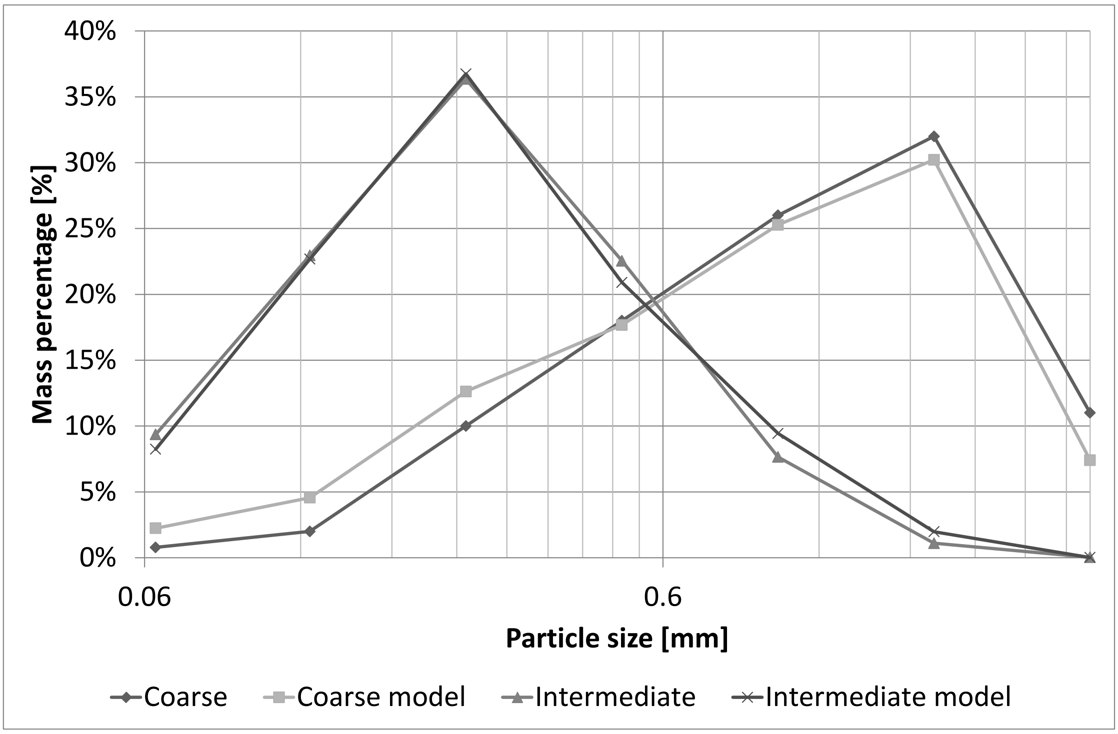

Figure 52. Comparison between the measurement and model for settings SA1 100%, SA2 100% and PA1 0%.

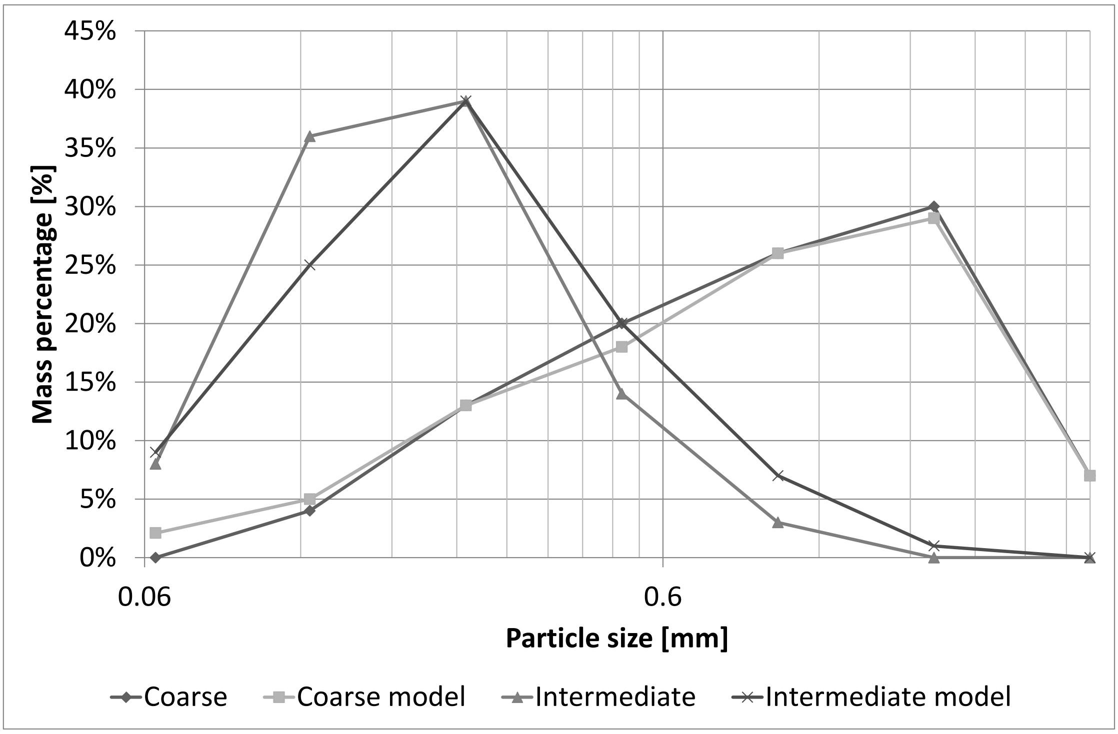

Figure 53. Comparison between the measurement and model for settings SA1 100%, SA2 100% and PA1 50%.

Figure 54 and Figure 55 shows the changes in the particle size frequency for the model and measurements from changes in the air flow through SA1. The model shows good results for both the intermediate and coarse products. However, the model underestimates the amount of 2 mm particles and overestimates the fines, similar to the air flow through PA1.

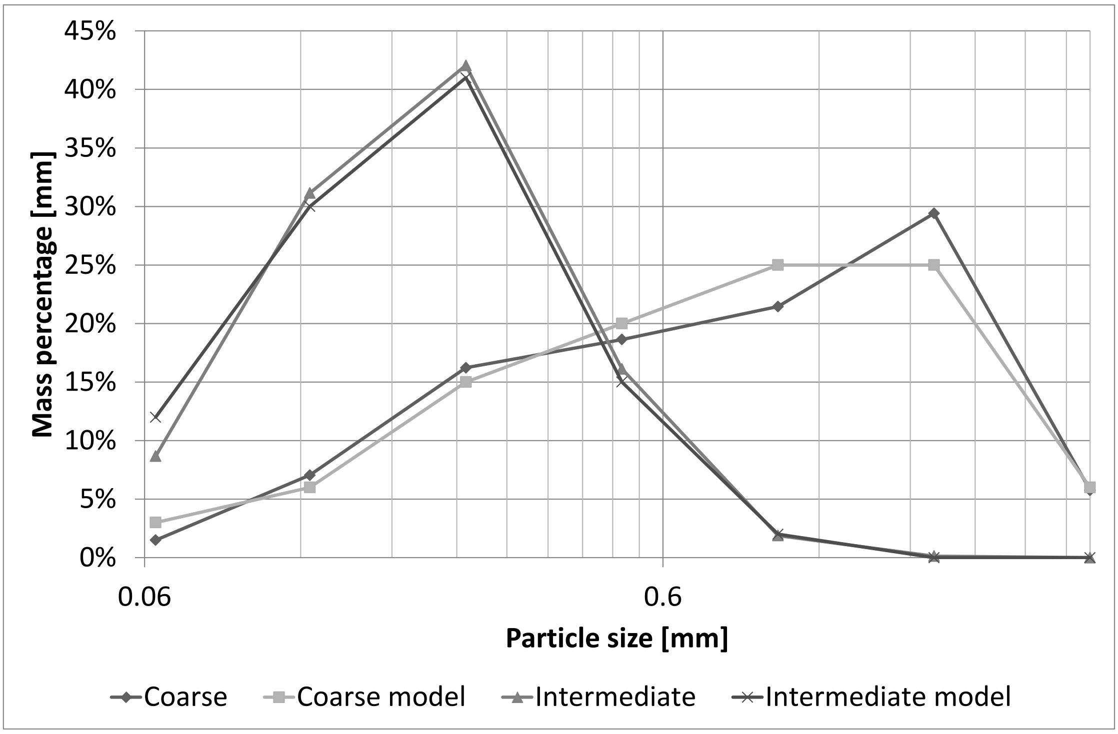

Figure 54. Comparison between the measurement and model for settings PA1 100%, SA2 100% and SA1 25%.

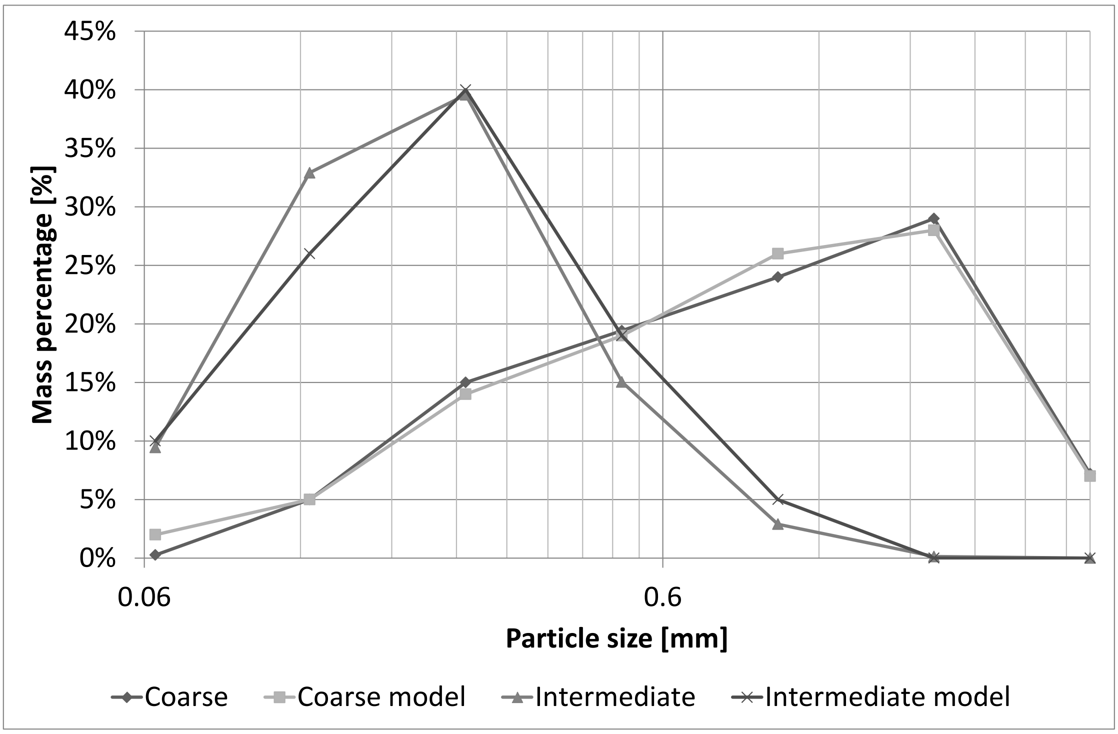

Figure 55. Comparison between the measurement and model for settings PA1 100%, SA2 100% and SA1 75%.

Figure 56 and Figure 57 shows the influence of SA2 on the measurements and model. The result is good when SA2 is open. However, the model underestimates the amount of 2 mm particles and overestimates the level of fines. The results are good overall, except for the intermediate product for a low air flow through SA2.

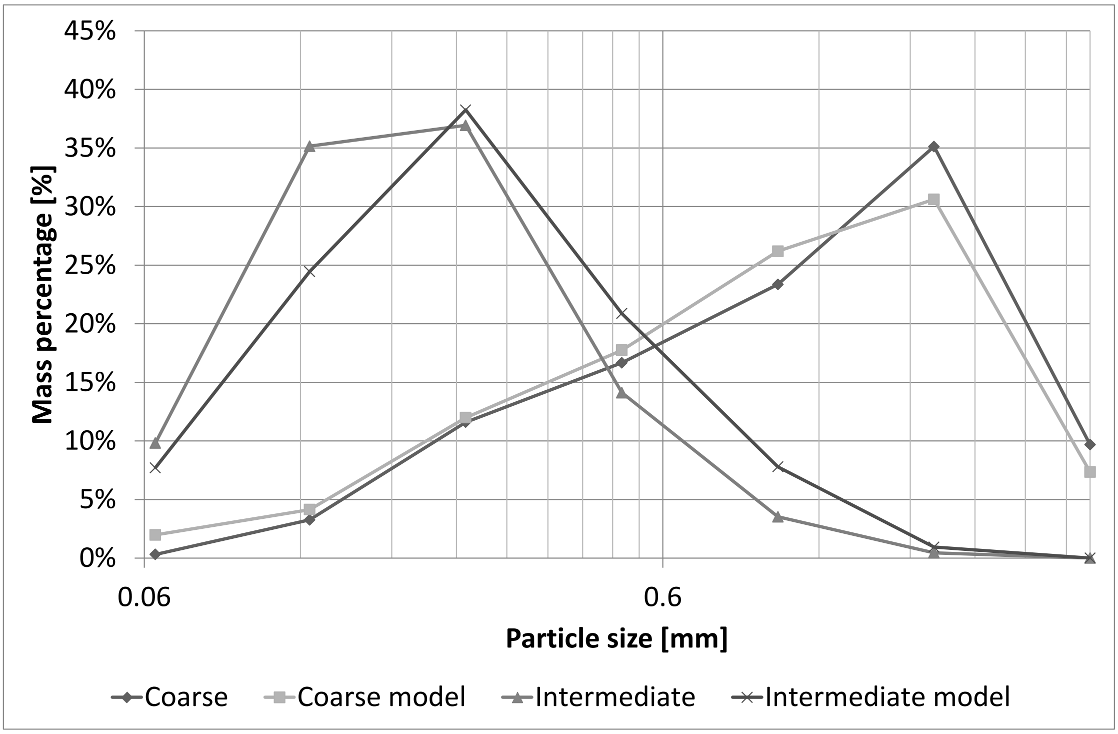

Figure 56. Comparison between the measurement and model for settings PA1 100%, SA2 100% and SA2 50%

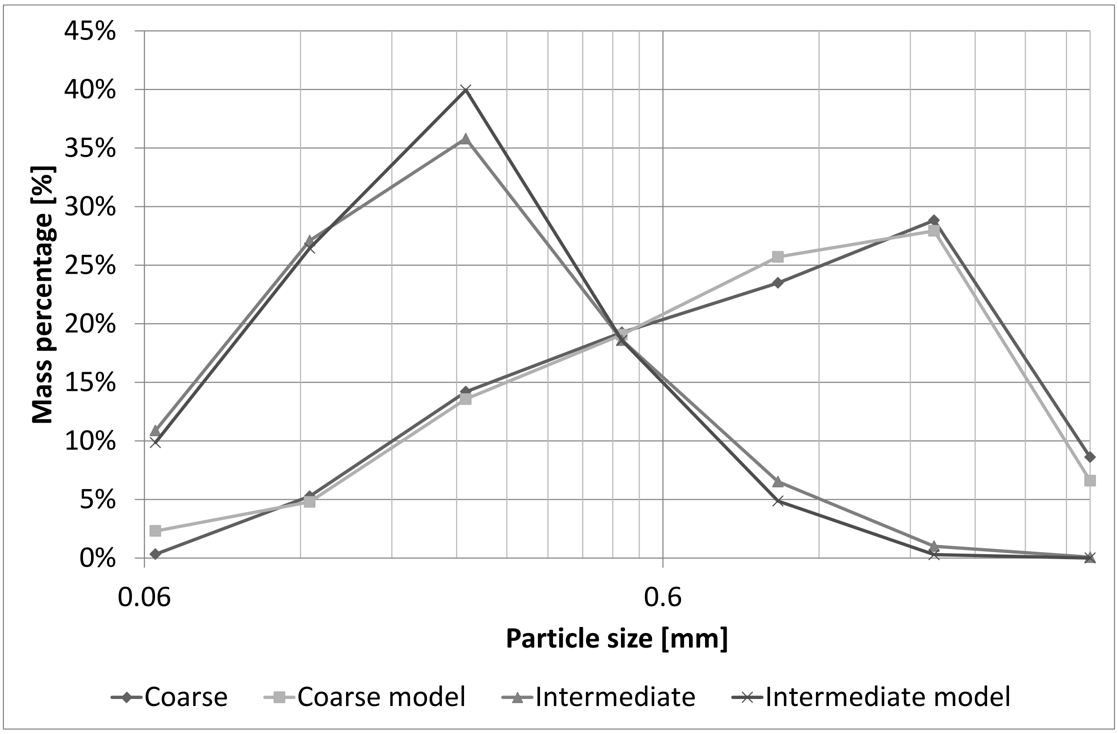

Figure 57. Comparison between the measurement and model for settings PA1 100%, SA2 100% and SA2 100%.

EMPIRICAL MODEL FOR THE MOBILE AIR CLASSIFIER

The experimental results indicate that the classification efficiency of the air classifier is independent of the air inlet valves. This means that the efficiency curve can be modeled as a static formula, see Figure 58. The input parameters to Equation 1 were calculated from the average of the four test data. The sharpness, α, was set to 1.1 and the cut size, d_{50}, was set to 0.14. This gives X equal to x_i/d_{50} where x_i is the particle size i where the classification efficiency is modeled. This gives a model as seen in Figure 3, where a feed, represented by particle size distribution and feed rate, is divided into two products by a formula for the classification efficiency.

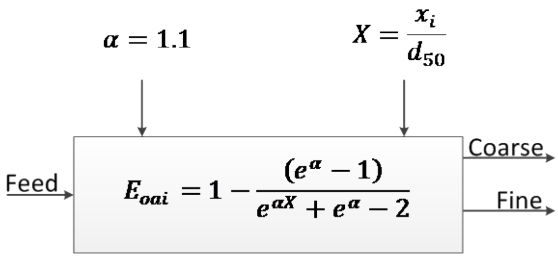

Figure 58. Model overview for the mobile air classifier.

To evaluate the model the results were compared to experimental data. The particle size distribution of the feed was used as input data into the model. Figure 59 and Figure 60 shows the calculated particle size distribution and the measured particle size distribution. The results from the model are promisingly close to the experimental results. However the modelling of Test 4 differs somewhat from the experimental data at the coarse end of the particle range [1-4 mm] where the model underestimates the amount of particles. The reason for this is unclear but the difference is at most 3 mass percent.

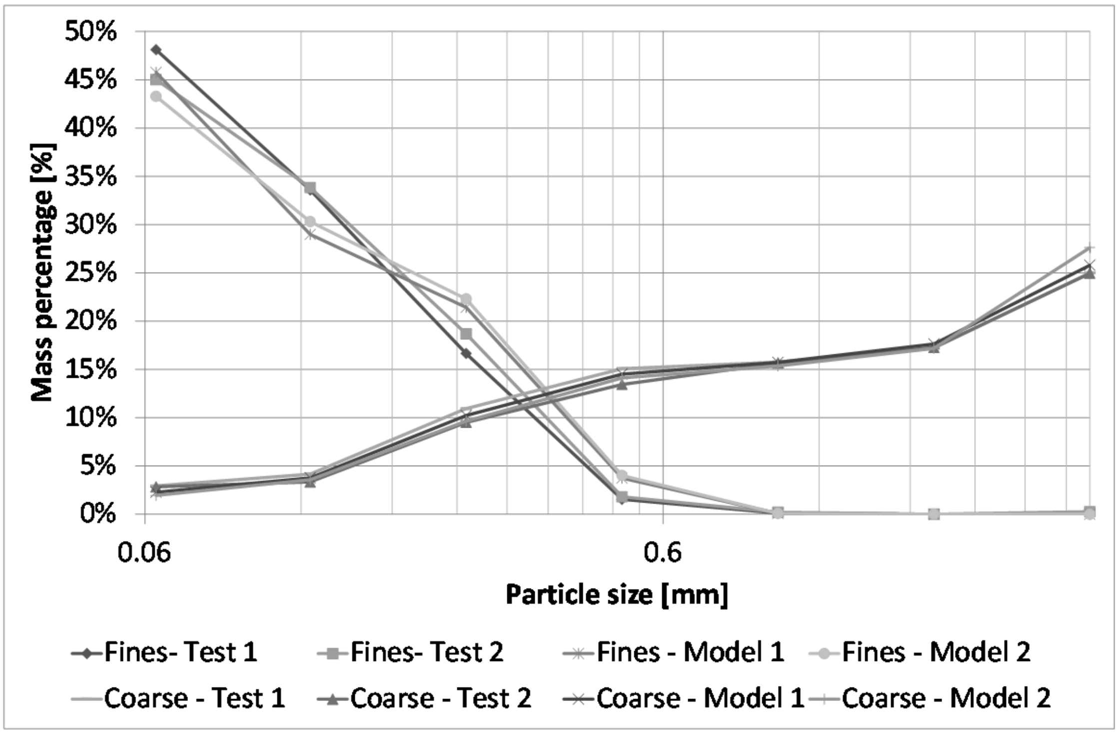

Figure 59. Comparison between model and measurements for Test settings of 1 and 2.

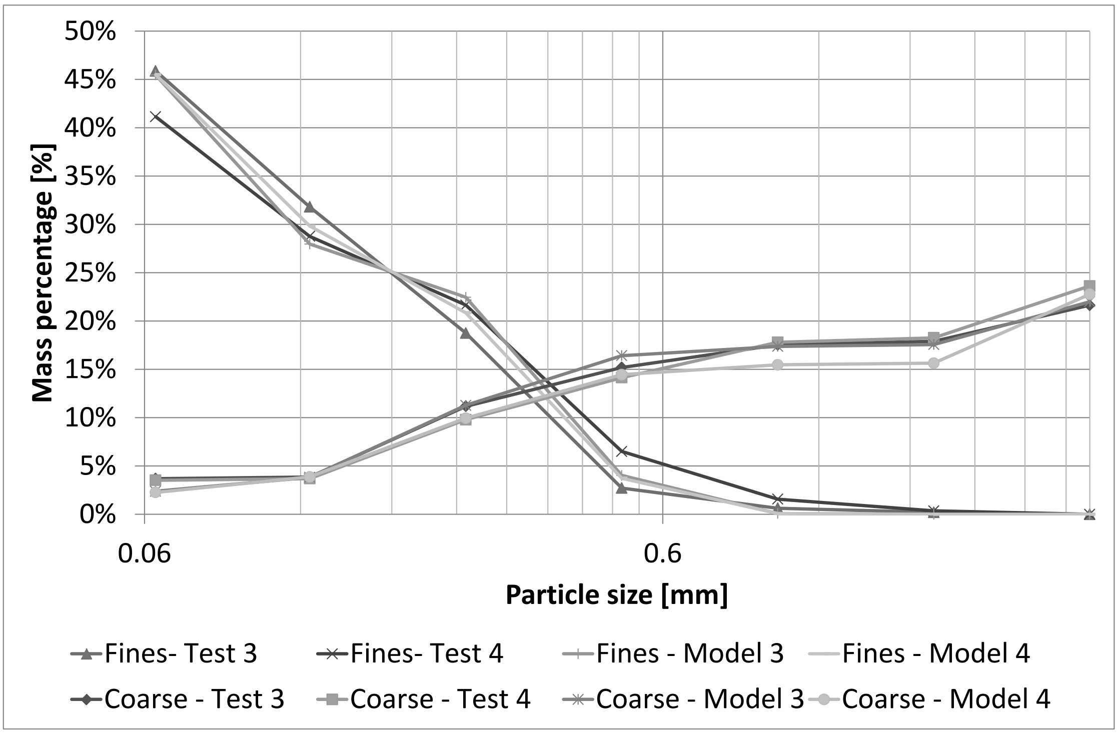

Figure 60. Comparison between model and measurements for Test settings 1 and 2.

7 RESULTS AND DISCUSSION

The aim of this chapter is to:

- *Present and discuss the results from previous chapters.*
- *Discuss the work in more general terms.*

The research performed has included four different commercial air classifiers. Empirical experiments and simulations have been performed and these should be evaluated together to be able to present a broad knowledge base. As different types of air classifiers have been investigated the results will be presented individually for each classifier and then combined. Discussing the classifiers individually will create understanding of what is possible to achieve for each classifier, meanwhile a discussion around the all investigated classifier types will create a broader understanding around design choices. The results and discussion will combine the findings from both the performed experiments and the computational fluid dynamics (CFD) simulations.

7.1 INTERNAL AERODYNAMIC CYCLE

In Chapter 5 the results are presented from the air classifiers investigated in Papers A and G. These air classifiers employed an internal aerodynamic cycle with a centrifugal separation zone. In both of these cases the empirical results indicated that it was possible to reduce the amount of fines (particles below 63 µm) to an amount close to what is desirable for the concrete industry. No experiment was performed that completely removed the amount of fines.

The empirical measurements showed for both air classifiers investigated in Papers A and G that the main fan increased the cut size meanwhile the separator fan lowered the cut size; however it was noted that it was hard to raise the cut size well above 63 µm. It could possibly be that a further increase of the main fan speed than what was technically possible for the investigated air classifiers could increase the cut size. The simulations performed in Paper G on how the main fan speed affected the air flow speed showed an overall increase in air velocity with the increased main fan speed, without changing the overall structure of the air flow. If this will result in a higher cut size is however not certain as the investigated air classifier uses a centrifugal separation zone. Thus if an increase in main speed should increase the cut size the centrifugal force must not increase further than the drag force.

The CFD simulations performed in Paper G also showed that the air flow in the investigated air classifier was not uniform. Small changes could be applied to improve the air flow; in this case a shorter inner cone. This indicates that even existing technology might have areas where it could be improved. However it can be noted that these changes will depend on the design of the air classifier.

From the view of the aggregates industry it can be stated that the investigated air classifier with an internal air classifier is quite robust and should be easy to maintain. The fan blade geometry, see Figure 61, is not optimal from an air flow point of view; however it is a very simple design that can be easily replaced on site without advanced tools. An internal aerodynamic cycle means that there are no external filters; which in turn leads to fewer parts that need to be maintained.

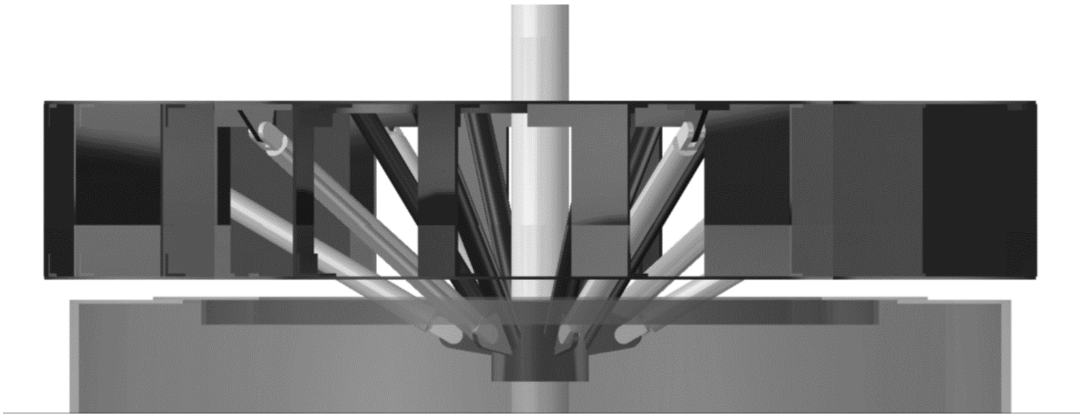

Figure 61. CAD of main fan for the air classifier in Paper A.

7.2 EXTERNAL AERODYNAMIC CYCLE

In Papers B to F two air classifiers using an external air cycle were investigated; one two-stage air classifier and a mobile air classifier. The two-stage air classifier consists of two air classifiers in series, a gravitational air classifier and a centrifugal air classifier, and the mobile air classifier consisting of the first stage of the two-stage air classifier.

For the gravitational air classifier both the empirical measurement and the performed CFD simulations showed the importance of a secondary air inlet; an inlet that creates a recirculating airflow back towards the separation zone. This recirculating air flow reduced the influence of particle to particle interaction. It can be speculated that the reduced influence of particle to particle interaction could come from other factors; for example lower feed rate of material per volume air or more separation stages.

The mobile air classifier had a cut size of 125 µm meanwhile the cut size for the two-stage air classifier was 250 µm. The difference in cut size is dependent on the overall setup of the air classifiers. For the mobile air classifier three products are produced, meanwhile for the mobile air classifier two products are produced, thus a higher cut size can be allowed in the first stage. From a production view three products gives more freedom in achieving a desired particle size distribution through mixing of the three products.

The centrifugal air classifier used in the second stage of the two-stage air classifier differs from centrifugal air classifiers investigated with an external air classifier as its separation zone is placed vertically instead of horizontally, see Figure 62.

Figure 62. Second stage for the two-stage air classifer.

It had a cut size around 63 µm and produced an intermediate product with a top size of 0.5 mm, and around 10 mass percentage of fines. CFD simulations showed that it was possible to reduce the amount of fines by reducing the air flow velocity through the centrifugal air classifier. This will however affect the cut size of the first stage and be less than optimal for the overall production results.

CFD simulations of the centrifugal air classifier shows that the air flow is overall uniformed; however some areas have an air flow that returns inwards from the fines exit into the centre classification zone. As fines are more likely to be affected by turbulence, the inward turning air flow might reduce the classification efficiency somewhat.

The CFD simulations also showed that the particle shape would affect the classification efficiency. A flaky particle will have a larger chance to end up with the fines than a more cubical particle. This indicates that the classification process can be used to remove unwanted particles from the finished product.

An external aerodynamic cycle means that an external filter system is necessary. This will increase the amount of parts need to be maintained.

7.3 LESSONS LEARNED FROM THE DIFFERENT AIR CLASSIFIERS

The investigated air classifiers differ in many ways and a comparison between them has to be based on technical strength and the application the air classifier should fulfil. It can however be noted that all the four air classifiers can produce manufactured sand with a reduced amount of fines. The difference lies in the cut size, so the choice of air classifier might simply depend on the cut size required.

The different design approaches for the classifiers mean that the resulting products are hard to compare directly. Three of the air classifiers produce two products, coarse and fines; meanwhile the two-stage air classifier produces three products, coarse, intermediate and fines. It is however possible to draw some general conclusions.

The cut size differed between the different air classifiers, see Figure 63, which one is optimal depends on the industrial need. A low cut point can be optimal if it can create a good sand product for the concrete industry as it creates less waste. It can however be noted that it is possible to reduce the cut size of the first stage in the two-stage air classifier. An increased cut size was hard to achieve in the air classifiers investigated with internal aerodynamic cycles. A high cut might also open up the possibility to later mix in more fines if desired if the infrastructure is present.

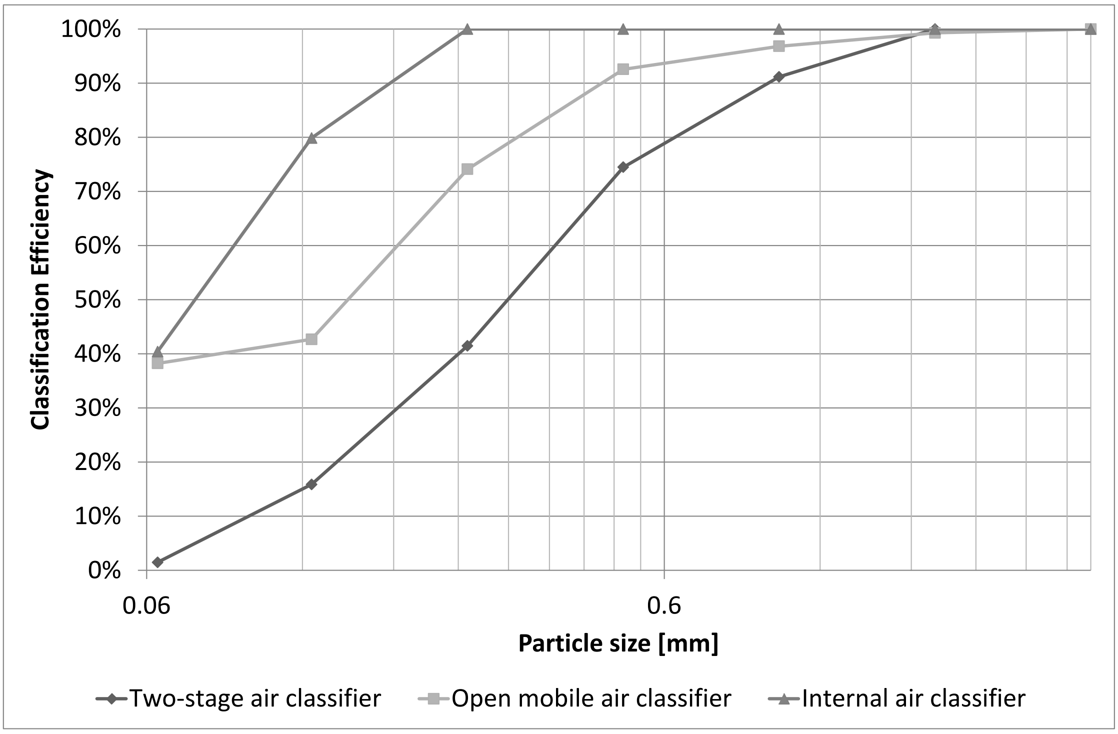

Figure 63 The Efficiency for the air classifiers investigated in Paper B to G.

Comparing the single stage air classifier with internal aerodynamic cycle investigated in Paper G with the mobile air classifier with open aerodynamic cycle investigated in Paper D, it can be seen that the amount of particles below 63 µm is similar for a given feed. It can however be noted that the mobile air classifier removes more particles around 125 µm; which indicates a larger cut size. Thus the choice between these air classifiers can be based around the desired cut size. If the rock source has a large amount of mica in the size range 125-250 µm, an air classifier with a larger cut size can aid in the removal of badly shaped particles.

The studies on the second stage of the two-stage air classifier clearly showed that particle shape will affect the classification result. This could be advantageous for removing unwanted particles from the finished product. It can however diminish the possibility to later feed the fines back into coarse product to create a desired particle size distribution as the fines will be of low quality.

The investigated air classifier using an open aerodynamic cycle tends to have a larger industrial footprint than air classifiers using an internal aerodynamic cycle. This is due to the external filter system necessary to prevent fines entering the fan system or creating large amounts of dust in the quarry, see Figure 64. The extra industrial footprint should not pose any larger problem for a stationary crushing plant, but it might mean that the air classifier is harder to move.

Figure 64. Mobile air classifier with air filter.

Regardless of which aerodynamic cycle that is used experience from field trials indicates that dust might be a problem. However this is not due to the air classification process itself but the material handling around the air classifier.

The CFD simulations on the two-stage air classifier (Paper B and E) and the empirical measurements showed that particle to particle interaction will reduce the classification efficiency. These lessons should be possible to introduce in any further air classification technology.

The production experience from the Vinnova project ‘Sustainable Production of Fine Grained Products from Rock Materials’ is that weather complicates the use of air classifiers. Thus any installation of air classifiers should be planned in such a way to that exposure of the material to be classified to adverse weather conditions is minimized.

8 CONCLUSIONS

The aim of this chapter is to:

- *Present the most important conclusions drawn in this thesis.*
- *Answer the research questions stated in Chapter 2.*

The goal of this work was to investigate how air classification works and which alternatives exist for production of manufactured sand suitable for concrete and asphalt. During the performed work four different air classifiers have been investigated. These classifiers represent different design approaches; the designs differ in the number of classification stages, the type of separation zone and the type of aerodynamic system used.

8.1 GENERAL

The intention of air classification in this work was to use the technology to refine manufactured sand for use in concrete and asphalt. Air classification can be used in the aggregates industry to classify the rock particles by form and size. To be successful in delivering a product that fulfils the requirement of the concrete industry it is important to understand what the air classification process should do, which is linked to the following:

1. The properties of the parent rock which is processed in the quarry
2. The crushing method used in the quarry
3. The requirements on the material from the concrete and asphalt industry

Point 1 and 2 will provide the quarry owner the starting point for any classification process designed to refine the finished product. The third point describes the goal of the refining process. All three points will decide which air classification process should be used.

The author wants to recommend the quarry owner to work closely together with the requirement owner to learn which changes are necessary to produce high quality manufactured sand. If the requirement demands a sharp cut size, an air classifier which allows for recirculation of the manufactured sand towards the separation zone should be chosen. As a sharp cut size often demands a more advanced air classifier, the complexity and costs will rise. The author therefore wants to point out that a perfect separation might not be optimal due to the cost involved.

8.2 ANSWERS TO THE RESEARCH QUESTIONS

The answers to the research questions stipulated in Chapter 2.3 are presented below.

RQ1. WHICH AIR CLASSIFICATION TECHNIQUES ARE SUITABLE FOR USE IN THE AGGREGATES INDUSTRY?

There exist a number of air classification techniques, both commercial and theoretical; these can be categorized after separation zone and aerodynamic cycle. Throughout this work several commercial air classifiers have been investigated. These air classifiers use either open or closed aerodynamic cycles. The air classifier investigated in Paper A and Paper G used a closed aerodynamic cycle with a centrifugal separation zone. Whereas Paper B to Paper F investigate air classifiers with an open aerodynamic cycle with both gravitational and centrifugal separation zones.

The results show that all the investigated techniques are suitable to the aggregates industry. It can be noted that no air classifier with a closed aerodynamic cycle with a gravitational aerodynamic cycle has been investigated and thus the author cannot say anything about these.

Examples of manufacturers of air classifiers with a closed aerodynamic cycle are Sturtevant, Schmidt, BritishRema, Hosokawa, Micron and Fischer. The design differs somewhat however the basic design is the same. The investigated air classifiers with an open aerodynamic cycle are all from Buell/Metso.

RQ2. CAN AIR CLASSIFICATION BE USED TO SATISFACTORILY CHANGE THE PARTICLE SIZE DISTRIBUTION CURVE OF MANUFACTURED SAND ACCORDING TO THE DEMANDS OF THE CONCRETE INDUSTRY?

The demand on manufactured sand for concrete depends on the recipe used by the concrete manufacturer. It is therefore hard to answer this question as the demands might vary dependent on the concrete manufacturer. However performed concrete research indicates that an amount of fines (particles below 63 µm) of 5-10 mass percentage dependent on rock source, is acceptable. All the investigated air classifiers did succeed in producing manufactured sand with less than 10 mass percentage. It can be noted that the two-stage air classifier investigated in Papers B, C, E and F produces a coarse product with much less fines than 5 mass percentage. The two-stage air classifier however produces three products which makes it possible to mix in fines in a later stage if necessary. Thus it can be concluded that it is likely that air classification can be used to alter the particle size distribution of manufactured sand according to the demands of the concrete industry.

RQ3. Which properties of manufactured sand will influence the air classification result?

The main physical properties that describe a sand particle are density, size and shape. For manufactured sand the density of the individual sand particles is very similar, thus the density will have a limited influence on the classification results. It should also be noted that research on air classification of particles of different density in the recycling industry has shown that the airflow must fluctuate between acceleration and deceleration if density shall dominate the classification process [60].

Particle size and shape will be the main factors that influence the classification results. Papers A, B, C and D focused on the influence of size while Paper E showed that the classification results will also be dependent on shape. A large flaky particle has a higher possibility to end up in the fine product than a large spherical particle because of the difference in C_D.

Experience from the field has clearly shown an impact on the air classifier performance from moisture and bad weather. The air classifier investigated in Paper B, C, E and F is operated with online moisture sensors and the production is stopped at moisture levels above 2 percentages. Similar results were found when investigating the air classifier in Paper G. The air classifier in Paper G was part of a pilot plant which was used from the north to the south of Sweden. During the production it was quickly noted that it was not worth to run the plant if the feed was not dry or the weather was unfavourable (rain or snow). From field experience it can therefore be noted that the feed should be kept as dry as possible.

RQ4. How should air classifiers be operated to achieve a desired product?

To answer this question it is fundamental to define which qualities the desired product should have, a definition that can only be answered by the customer of the aggregates industry. This means that the aggregates industry must have an understanding of the difference when choosing an air classifier. The cut size and classification will depend on the air classification technique employed and thus correct choice of air classifier will improve the possibilities to achieve the desired result.

Comparing the two air classifiers with closed aerodynamic cycle in Paper A and Paper G with the open aerodynamic cycle used in the air classifiers investigated in Papers C to F it can be seen that the cut size is smaller in the closed aerodynamic cycle. The method of controlling the cut size does also differ between the different types of air classifiers.

The investigated air classifiers with closed aerodynamic cycle are very similar the only difference is the size; both have a main fan and a separator fan. The empirical results shown in Paper A and Paper G shows that the cut size is increased with an increased speed of the main fan. An increase in the speed of the separator fan decreased the cut size. The CFD simulations in Paper G showed that this is due to that the main fan increases the air flow speed throughout the whole air classifier; meanwhile the separator fan increases the air flow only around the separation fan. Increased air flow around the separation fan increases the centrifugal air flow and thus the centrifugal force.

The open aerodynamic air classifiers investigated differs in such a way that the air classifier investigated in Paper B, C, E, and F is a two-stage air classifier installed in a stationary crushing plant; whereas the air classifier investigated in Paper D is a one stage mobile air classifier. The similarities are that the studied mobile air classifier is very similar to the first stage in the studied two-stage air classifier in design. Both empirical investigations and simulations show that the important factor in controlling the amount of fines is to control the recirculation of material back towards the separation zone. This is done for the investigated air classifiers through a secondary air inlet.

Paper D and F introduced empirical models of the two open aerodynamic cycles based on the efficiency curve approach. These models are of such a nature that they can easily be used in the aggregates industry to investigate if these air classifiers can provide what the concrete industry asks for.

RQ5. What design considerations are important for an air classifier used in the aggregates industry?

The performed empirical studies on the investigated air classifiers (Papers A to G) show that a wide selection of separation zones and aerodynamic cycles can be used in the aggregates industry. The technical implementation of these techniques will be discussed below.

Any classification process with a fluid as classification medium like air or water is based around the idea that the fluid-particle interaction is predictable. Thus the fluid flow throughout the separation zone needs to be homogenous as a particle in the separation zone should be affected in the same way throughout the system. In Paper E the centrifugal air classifier of the second stage of the two-stage air classifier was simulated. It was shown that there existed areas where the airflow turned backwards from the exit into the separation zone. The air classifier investigated in Paper G with a closed aerodynamic cycle with a centrifugal separation zone showed areas in the separation zone that were far from ideal. These areas risked both a build up of material in the separation zone and transportation of fines away from the exit point. Such areas, should as much as possible, be limited by proper design to reduce the risk of particles ending up in the wrong area.

Aside from interaction with air a single particle in an air classifier also interacts with other particles in the air classifier. In Paper B it was shown that particle to particle interaction will reduce the classification efficiency. Reducing the influence of particle interaction can be done in several ways, either reducing the amount of particles in a given air volume or making it possible to pass the separation zone several times. The influence of the latter was shown in Paper B and E.

RQ6. Is air classification a feasible method for industrial production of fine aggregates for concrete and asphalt?

Whether or not a technique is feasible for industrial purposes is based on if the technique can deliver the desired product at a competitive cost for the required volume. Air classification has been shown to be able to deliver a product within the limits presented in the scientific literature. Thus the question is if the product can be produced with air classification at an acceptable cost.

Economical calculation of the production cost is based on investment cost, cost of capital and cost of operation, as such the cost is divided into fixed and variable cost. A circulating air classifier in the size range of 50 ton/h costs around 2 million SEK. The two-stage air classifier cost around 8 million SEK and has a capacity of around 50 ton/h. From experience the two-stage air classifier has a maintenance cost of around 2 SEK/ton and energy cost of 2 SEK/ton. The energy consumption for the circulating air classifier used in Paper F is around 8 kW when producing roughly 3 ton/h; with an electrical cost of around 1 SEK/kWh means an electrical cost of 2.3 SEK/ton.

As the variable cost in total is around 4 SEK/ton and the investment cost is somewhere between 2 to 8 million SEK, the investment cost will be the most significant cost to the finished product price. What the investment cost per ton will be depends on how the quarry decides to calculate the cost distribution. As an example a 2 million investment of an air classifier producing 50 tons/h with depreciation of 10 years with an internal rate of return of 10% with an availability of 50% will cost around 7.4 SEK/ton.

8.3 Future work

For further industrial use it might be of interest to evaluate if there is any difference in maintenance need between air classifiers with open and closed aerodynamic cycles. How does the wear on the fan blades compare to the need to maintain the air filters used in the open aerodynamic cycle?

For the internal air classifiers investigated with centrifugal separation zone it would be interesting to investigate if it is possible to increase the cut size if desired by the aggregates industry. This could allow for more freedom in producing manufactured sand for different purposes.

This study has mainly worked with existing air classification technologies, machines that might not have been developed having the specific needs of the aggregates industry in mind. Further research should maybe be focused on how to integrate air classification into the process. Should the air classifier really be a separate part from the crusher?

Aside from research of the actual air classifiers, it could also be interesting for the aggregates industry to investigate how the dust should be handled when a dry product is desired. This means that using water to bind the dust is undesirable.

This research has focused on creating an understanding of the different air classifiers. Further studies on the robustness of the classification process can be desirable. For this more long term studies need to be performed.

It might be of interest to investigate other methods of classification in the size range required; a possible solution might be electrical heater if the technology can be scaled up for large enough volumes.

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