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Investigation of a Gas-Solid Separation Process for Cement Raw Meal

Claus Maarup^a, Klaus Hjuler^b, Karsten Clement^a, Kim Dam-Johansen^{a*}

^a Department of Chemical and Biochemical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

^a FLSmidth A/S, Valby, Denmark

Abstract

The gas/solid heat exchanger (2D-HX), developed to replace the cyclone preheaters in cement plants is presented. This design aims at reducing construction height and operation costs. The separation process in the 2D-HX is experimentally investigated, and the results show that separation efficiencies up to 90 % can be achieved in the gravitationally driven process. Based on the data, a model of the separation process is developed, utilizing relations from pneumatic transport and cyclone theory. The model fit is acceptable, especially in the area of interest. Based on experimental data, further development of the technology is encouraged.

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Keywords: Cement production; raw meal preheating; gas/solid heat exchanger; gas/solid separation; saltation; modeling

1. Introduction

1.1. Gas-solid separation process in cement production

In modern cement production, the utilization of the thermal energy in the flue gasses is essential for obtaining an overall acceptable fuel economy of the cement plant. The thermal energy is used to preheat the powderous raw

* Corresponding author. Tel.: +45 4525 2845; fax: +45 4588 2258.

E-mail address: KDJ@kt.dtu.dk

materials, called raw meal, prior to the calcination and clinker burning processes. Due to the cohesive nature of the raw meal, the preheating process is carried out in a series of mixing and separation processes, facilitated in a cyclone suspension preheater, containing three to five heat exchange stages. A schematic drawing of a single cyclone preheater stage including main gas and particle flows is provided in figure 1.

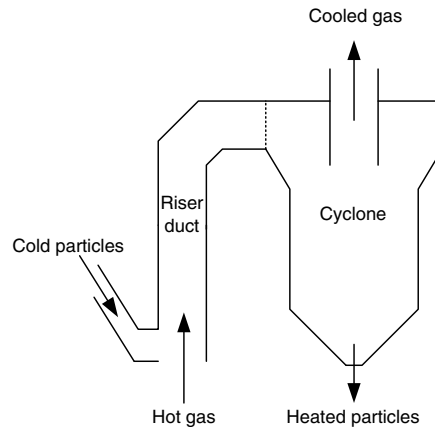


Fig 1. Schematic illustration of a cyclone preheater stage in a cement plant.

Each stage contains a riser duct for mixing of the gas and particles, thereby allowing the heat exchange to take place, and a cyclone for separation of the two phases. Combining the individual stages, a stepwise counter-current heat exchange pattern is achieved, enabling the particles to be heated to 700°C – 800°C using the exhaust gasses [1–3]. The efficiency of the separation process carried out in the cyclones influences the overall thermal efficiency of the cement production. Low separation efficiencies increases internal recycling of material and reduce the mass flow of heated solid material from each cyclone. In actual facilities, a compromise between pressure drop, cyclone cut size, and cyclone size is typically made, resulting in separation efficiencies as low as 70–80 % in the lower cyclone stages. In the top stage, collection efficiencies are optimally more than 95 % to reduce the amount of material leaving the preheater [1,3–6].

The separation efficiencies being significantly lower than 100 % is one of the major drawbacks of the cyclone-based technology. Another is total height of the preheating tower, the structure supporting the preheater cyclones, which typically ranges between 80 m and 120 m [7–9]. The height results from the cyclone dimensions, internal positioning requirements of the cyclones and risers, and their interfaces with the remaining equipment required in the cement production.

In order to reduce construction height and operation costs of the preheater facility, an alternative preheating concept has been developed, not utilizing cyclones, but a completely different design. This paper describes the investigation of the separation process in the developed gas/solid heat exchanger. The overall evaluation and functionality of the developed heat exchanger will not be considered here, but can be found elsewhere [10].

1.2. The two-dimensional Heat Exchanger (2D-HX)

The developed design is based on planar geometries, and is termed a two-dimensional heat exchanger (2D-HX). The heat exchange process takes place in a series of mixing and separation processes/stages similar to the cyclone-based process. The principle of operation is illustrated in figure 2, displaying a single stage. The term “two-dimensional design” is applied to this design as all essential design features can be contained in a single cross sectional illustration, which represents the entire geometry of the equipment, as given in figure 2.

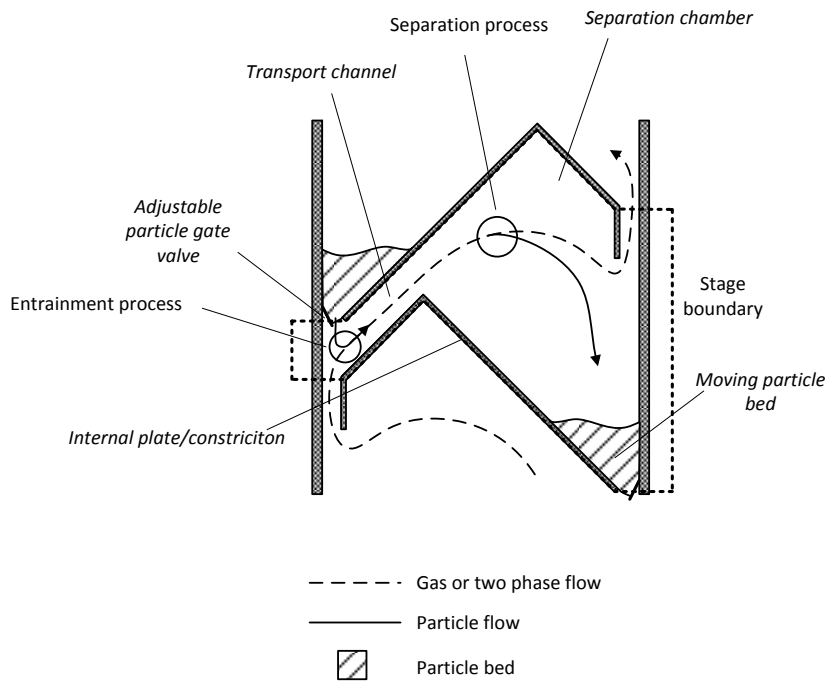


Fig 2. Schematic drawing displaying nomenclature of a single stage and operation principles of the two-dimensional heat exchanger (2D-HX). Nomenclature is given in italic. The outline of a single stage is outlined in red.

In each stage, particles are continuously fed from a moving particle bed into a flow of fast moving gas, where gas and particles are mixed and exchange heat. The suspension is transferred via the transport channel into the separation chamber, where the separation of the two phases is facilitated. The separated particles form the particle bed of the subsequent stage, where the process is repeated. The particle beds are an essential feature, preventing gas from shortcutting. The particle free gas moves upwards to the above stage. The overall heat exchange pattern is thereby a stepwise countercurrent heating of the particles and cooling the gasses, principally similar to the cyclone suspension preheater.

The advantages of the 2D-HX design include: Modular construction, reduced construction height compared to the cyclone preheater process, and easy-to-manufacture geometries. The former point, the modular construction, is a property not typically included in chemical engineering design procedures, however, it greatly simplifies the design and reduces construction costs. An illustration of the design principle of the 2D-HX is provided in figure 3.

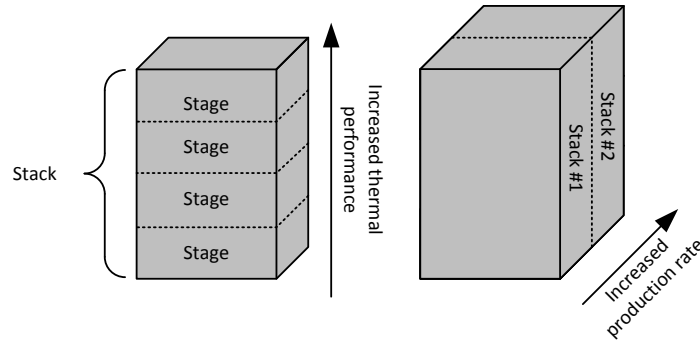


Fig3. Illustration of the modular properties of the 2D-HX. Number of stages and production rate can be increased by the addition of identical modules.

Each module contains of a stage, principally as shown in fig. 2, of a certain depth. These modules can then be placed on top of each other with every second stage rotated 180° around a vertical axis, resulting in a stack of identical modules. To increase the production rate, stacks can due to the two-dimensionality be placed next to each other, as indicated in fig. 3. This allows the 2D-HX to be designed for a wide range of process requirements (thermal efficiency and production rate) from a single stage.

The 2D-HX is in this context being used for raw meal preheating, yet it is suitable for a wide range of particle types and operation conditions.

2. Experimental Approach

The actual performance of the 2D-HX design has been experimentally investigated, with focus on the mechanism and performance of the separation process. The separation process is evaluated in a continuously operating single stage set-up, as shown in figure 4. Gas flow can be varied, while particle flow is set to be around 80 kg/h. The set-up was equipped with weights monitoring the mass of the produced particles, the total mass of the heat exchanger.

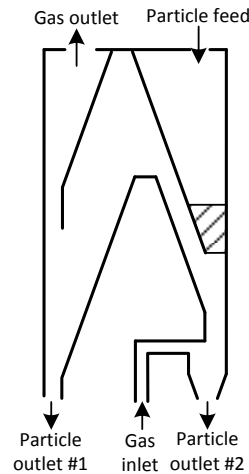


Fig 4. Process diagram for the single stage set-up used for investigation of the separation process.

Particles were introduced into the top stage by a weight controlled particle feeder, designed for handling cohesive powders. At a sufficient level of particles in the particle bed, the gate valve below the particle bed is

opened and stable operation can be achieved. The system is operated for at least 10 minutes, measuring continuously the mass of the collected particles. From feed rates and mass of collected particles at the particle outlets, the separation efficiency has been evaluated. Gas flow was generated by a frequency controlled fan, located downstream of a bag filter. The powder used was an industrial raw meal, classified as very cohesive with a flowability factor of 2.8, measured on a Schulze ring shear tester at 6 kPa [11]. The average particle diameter was measured to 12 μm .

The set-up was constructed with transparent side panels, allowing visual access to the interior of the setup. In order to obtain information on the particle flow pattern in the separation chamber, high speed video recordings were made during operation.

3. Results

The experimental investigation focused on identifying the effect of the gas velocity and the underlying mechanism, governing the separation process.

Visual observations revealed a very turbulent gas/particle behavior in the separation chamber where the main flow of particles was observed to move downward in a particle strand or rope. The position of this particle rope was mostly in the center of the separation chamber. Furthermore it was observed, that the particle flow was pulsating. This pulsation is generated by the entrainment process, which is not covered here.

In order to evaluate the performance of the separation process, a total of 14 experiments will be reported here, of which seven have been used to determine experimental uncertainty and reproducibility. Gas velocities in the transport channel were between 0.7 and 7.6 m/s. The gas velocity in the separation chamber is between half and a third of that, depending on the actual position. Therefore the gas velocity in the transport channel will be used to depict data, which is easier to define, and directly proportional to velocity in the separation chamber.

A plot of the measured separation efficiencies as a function of the transport channel gas velocity is provided in figure 5.

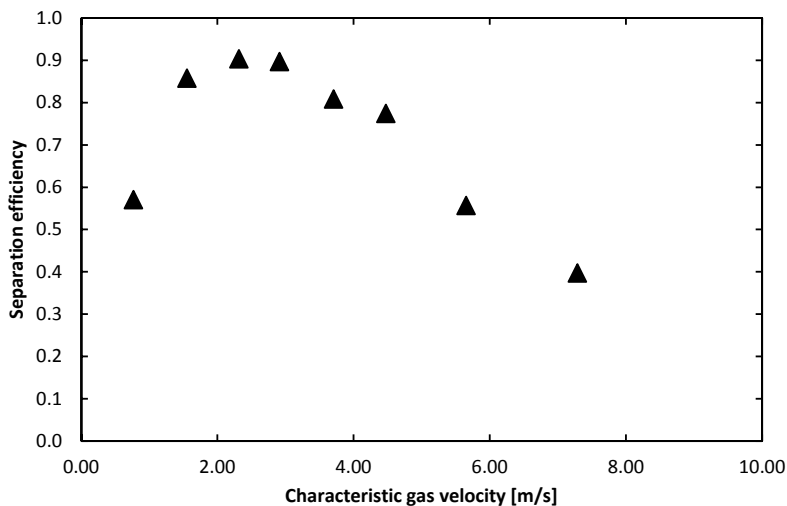


Fig. 5. Measured separation efficiencies obtained in a single stage. Measured over at least 10 minutes of stable operation.

From the obtained data trend, it is obvious that gas velocity influences the separation performance. Generally, the data indicates that the higher the gas velocity, the lower the separation. A maximum separation efficiency of around 0.9 is observed at gas velocities around 2 – 4 m/s. Average experimental error have been estimated to 3 – 5 %, indicating excellent reproducibility

Another parameter of possible relevance for the separation efficiency is the mass-based ratio of the feed rates of gas and particles, called solid load. However, solid load in the separation chamber could not be controlled directly, as it depends on both feed conditions and the amount of particles entrained and carried into the separation chamber. At low gas velocities, the entrainment is low, resulting in low solid loads in the separation chamber.

Assuming that the solid load influences the separation process in such a way that the higher the solid load the better the performance can explain the optimum behavior seen in figure 5. This is in line with observations reported on related processes in literature [12].

The data trend observed suggests that the process is driven by gravity, as any inertia driven process would increase in efficiency at increasing gas velocities.

4. Modeling

In order to enable modeling of the entire heat exchanger, a separation process model has been attempted constructed. As no useable generic model has been found in the available literature and due to the pulsating, turbulent behavior in the separation chamber, an overall model depending on geometry and process conditions were desired. Initially, a screening of several possible separation models was carried out, including considering:

- The separation chamber as settling tank.
- The separation a function of the Froude number.
- The separation process to be driven by a mass loading effect as seen in cyclones, described by Trefz and Muschelkautz [13].
- The separation process to be governed by agglomeration of particles.
- The separation chamber an analogue to pneumatic transport pipes.

More details on the screening procedure can be found elsewhere [10]. In terms of fit and parameter dependencies, the latter of the above screened models performed the best.

Considering the separation chamber an analogue to a pneumatic transport pipe involves saltation of particles, which is a phenomenon, where a stable particle layer is formed on the floor of the pipe. Saltation occurs when the solid load surpasses a certain value at a given gas velocity. The higher the solid load and the lower gas velocity, the higher the likeliness of saltation in a pipe. The saltation limit is described by Rhodes [12], using semi-empirical expressions:

$$c_{0,sal} = \frac{Fr^{1100 \cdot d_p + 2.5}}{10^{1440 \cdot d_p + 1.96}} \Rightarrow \quad (1)$$

Where $c_{0,sal}$ is the solid load at saltation, Fr is the Froude number, and d_p is the particle diameter. Expanding equation (1):

$$\frac{m_{p,sal}}{\rho_G \cdot v_{G,sal} \cdot A} = \left(\frac{1}{10^{1440 \cdot d_p + 1.96}} \right) \cdot \left(\frac{v_{G,sal}}{\sqrt{g \cdot L_{system}}} \right)^{1100 \cdot d_p + 2.5} \quad (2)$$

$m_{p,sal}$ is the mass flow of particles at saltation conditions, $v_{G,sal}$ is gas velocity at saltation, A is cross sectional area, ρ_G is gas density, g is gravitational acceleration, and L_{system} is the characteristic length of the considered pipe. However, computing a saltation velocity is not sufficient for evaluating the separation performance. In order to compute the separation efficiency, η_{Sep} , a well-known expression from cyclone efficiencies can be applied [14]:

$$\eta_{Sep} = \frac{\left(k \cdot \frac{v_{G,sal}}{v_G} \right)^m}{1 + \left(k \cdot \frac{v_{G,sal}}{v_G} \right)^m} \tag{3}$$

In the above equation, two fitting parameters are included: m is an efficiency parameter, also known from cyclone theory, and k is a geometric parameter compensating for the separation chamber being different from a pipe. A schematic drawing of the saltation phenomenon in a pipe and the approximated 2D-HX is depicted in figure 6.

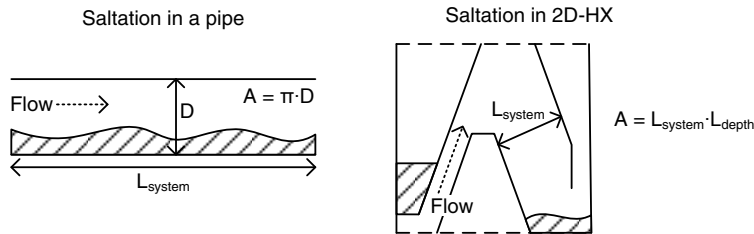


Fig. 6. Illustration of saltation in a pipe and in the 2D-HX.

Due to the origin in pneumatic transport, the model contains parameters that would not have been possible to include if the model would have been developed solely for the separation chamber, such as gas density. Additionally the model has the correct limiting behavior in terms of the effect of gas velocity.

Fitting the model predictions to the measured data, the parameters have been found to $m = 4$ and $k = 0.5$. The model fit has been illustrated in figure 7.

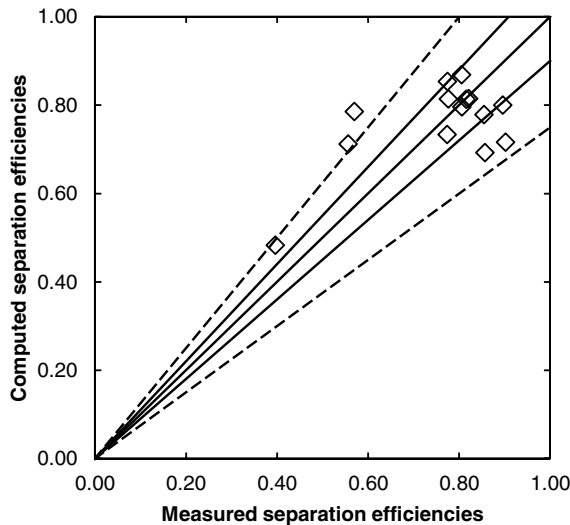


Fig. 7. Illustration of model fit. Dashed lines indicate 10 and 25 % deviation.

Overall model fit is acceptable, however, the data point at $v_G = 0.7$ m/s is represented with more than 25 % deviation, as the model predicts a separation efficiency close to close to 0.80, while the measured data is 0.57.

5. Discussion

The modeling of the process is required in order to construct a mathematical model describing the entire heat exchanger, thereby enabling the evaluation of the concept at other conditions than the tested. However, the developed separation model shows some deviations in terms of predicting the measured behavior, especially evident at low gas velocities. The reason for this deviation is either a shortcoming of the model or an error in the measured data.

A source of uncertainty in the application of the model is the influence of neighboring stages. The data gathered here is from a single stage set-up. In an actual application, several stages would be applied, possibly interacting with each other. This interacting is not represented in the model.

Mechanistically, the separation process in the industrial cyclones and the 2D-HX are different: The industrial cyclones utilize an inertia driven process, while the 2D-HX is gravity driven. The separation efficiencies of the industrial cyclones are between 70 % and 95 %, depending on operation conditions and design of the cyclones, while the achieved separation efficiency in the 2D-HX is up to 90 % at optimal conditions. This indicates that acceptable separation efficiencies can be achieved in the 2D-HX, but also that the window of acceptable performance is rather narrow, at gas velocities of 2 – 4 m/s. When directly comparing the two types of equipment it should be noticed that the 2D-HX is a bench-scale set-up, operating at cold conditions, which alone influences the performance. However, the achieved data indicate that the separation efficiency in the 2D-HX concept can be made high enough, encouraging the further development of the technology.

Additional experiments could be relevant in order to clarify the exact influence of solid load, however, the overall scope of the experimental and modeling work on the 2D-HX is first and foremost to achieve a proof of concept of the design operating with raw meal, secondly to provide data for an optimized, larger test facility, enabling more industrial-like test conditions. For this purpose, the provided experimental data and the developed model seem adequate.

6. Conclusion

The separation of gas and particles in an alternative gas/solid heat exchanger, termed the two-dimensional heat exchanger (2D-HX), developed and tested for cement raw meal preheating, has been experimentally investigated through a series of experiments. It has been found that the separation process is driven by gravity, and that separation efficiencies up to 90 % can be achieved at the optimal operation conditions. Gas velocities in the transport channel between 0.7 and 8 m/s have been investigated, revealing an overall trend: The higher the velocity, the lower the separation. The effect of the solid load (mass of particles/mass of gasses) in the separation chamber on the separation efficiency has not been identified.

A model of the separation process based on saltation, incorporating pneumatic transport and cyclone efficiency relations, has been developed. The majority of the data is represented with less than 10 % inaccuracy, however, deviations of up to 30 % between the model and the measured data has been found. The separation process model is a vital part for predicting the overall performance of the heat exchanger.

The investigation of the separation process proves that acceptable separation of gasses and cement raw meal can be achieved, further indicating that the technology appears promising.

7. Acknowledgement

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