Heat Transport During Drying of Iron Ore Pellets

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Preface

This thesis is the result of the final project of the Master of Science programme in Engineering Physics. The work was performed at the Division of Fluid Mechanics, Luleå University of Technology, as part of the Research Trainee programme 2005/2006. The project was done at the request of LKAB.

First, I would like to thank my examiner and supervisor Professor Staffan Lundström, Division of Fluid Mechanics, for help and support during the work. I would also like to thank PhD Kent Tano, Magnus Malm, Simon Töyrä and Mats Strömsten at LKAB and Ulf Sjöström at MEFOS for their valuable help in this project.

Finally, I would like to thank the Division of Fluid Mechanics for great support during the work, with special acknowledgement to Licentiate Daniel Marjavaara.

Luleå, May 2006
Anna-Lena Ljung
Abstract

Iron ore pellets are LKAB’s most refined product and the company is one of the leading suppliers in the world. There is for competitive reasons a great need for research in order to optimize the production and improve quality. The global goal with this project is to develop a tool with which the drying zone of the straight grate pelletizing plant in Malmberget, Sweden, can be optimized. The aim with this thesis is to make a model of temperature and velocity distribution in the up–draught drying zone, without any regard to moisture content in green balls.

The velocity distribution is described by laws of fluid dynamics in porous media. The dominating heat transfer mechanism is convection due to the hot air passing through the pellet charge. The air temperature is calculated from the energy equation and the average temperature of the pellet charge is calculated from a diffusive transport equation. Simulations of velocity and temperature distribution are made with aid of Computational Fluid Dynamics and the software CFX 10.0 is used. Result from simulations show a rapid cooling of air due to the high specific surface area in the porous material.

Experiments are performed at the Metallurgical Research Institute AB (MEFOS). The goal is to use experimental results to define unknown material parameters and to validate the simulation model. Two sets of experiments are carried out within the frames of this thesis. The first set has the aim to secure the equipment from possible measurement errors. In the second set of experiments, flow through pellets of different sizes and packing are investigated and compared with available equations.

Conclusions are that it is possible to make a heat transfer model in CFX 10.0 which calculates solid and fluid temperature. The experimental equipment at MEFOS is reliable for experiments made on small grains if results are to be implemented in the simulation model. Further investigations are required regarding on how to analyse measurements for particles in the size range of pellets and gas flows of higher magnitude when the Reynolds number becomes significant.
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1 Introduction

1.1 Background
LKAB is one of the leading producers of upgraded iron ore products for the steel industry. The company is divided into four divisions: Market, Mining, Minerals and Special Businesses. The Mining division mines magnetite ore of the Swedish Orefields and processes and transports iron ore products. There are iron ore mines, processing plants and ore harbours in northern Sweden and Norway. LKAB produces blast furnace pellets (BF pellets), direct reduction pellets (DR pellets) and two very similar magnetite fines products, both of which are used in sintering plants. Most of the iron ore products are sold to European steel mills.

Since iron ore pellets is LKAB’s most refined product, there is for competitive reasons a great need for research in order to optimize the production and improve quality.

1.2 Description of the Project
This project has its outline in modelling the drying zone of the straight grate pelletizing plant in Malmberget, Sweden, with aid of Computational Fluid Dynamics (CFD). After grained ore, binders and water have been formed to green balls, the pellets must be dried before they can be sintered. Transportation of moist should therefore be investigated both between pellets and through a single pellet. The process model must take into account both the interaction between these two types of transportation and the heat exchange from the process.

To reach the goal of optimized drying the following actions must be realised:
1. Model of temperature and velocity distribution
2. Model of moisture distribution
3. Boundary effects and geometrical variation on several scales

1.3 Aim with Thesis
The aim with this thesis is to investigate the first action stated in 1.2 and to examine if it is possible to develop a CFD model that takes temperature and velocity distributions in a bed of pellets into account. The proceeding steps 2 and 3 will be dealt with at a later stage.
2 Pelletization of Iron Ore

2.1 The Pelletizing Process

Before iron ores enter the blast furnace, it is necessary to remove a great portion of the mineral ballast components by graining. To remove these pollutions, concentrates are very fine grained and agglomeration is therefore necessary. Agglomeration can be achieved by sintering and pelletizing. Ores containing large quantities of pollution must be very fine-grained, and can therefore only be used for pellets. Due to advantages such as good transportability and mechanical strength, pellets are sometimes produced from good iron ore as well. Pellets are thus sintered spheres with high ore content. The average diameter for iron ore pellets is around 12 mm. 99 % of all pellets have a diameter in the size range 6.3 -16 mm and 70 % of these are within the interval 10-12,5 mm.

Pellets can be indurate in shaft furnaces, in grate-kilns and on straight grates. The principle of sintering pellets is almost the same in grate-kilns and on straight grates. The process starts with up-draught drying (UDD), followed by down-draught drying (DDD), a preheating zone, a burn zone and a cooling zone. The zone for burning is called firing on straight grates and in great kiln for kiln. In the burning zone, magnetite is transformed to hematite through oxidation.

2.2 Drying

Before entering the drying zone, green balls are packed in a continuous bed on a conveyor belt. The height of the bed varies but is approximately 0.55 m for the plant in Malmberget. The top and bottom width of this bed is 3.654 m and 3.5 m, respectively. For protection of the bed surroundings, a layer of already fired pellets is used at the bottom and along the walls. The bed moves with a velocity of 3 m/min and remains in the zone for around 3 minutes.

There are, as already mentioned, two possible flow directions for the drying air. Often a combination of these two types of drying are used, in order to make the lower layers more resistant to pressure. In UDD, hot air will make the lower part of the bed dry quickly but the air will soon cool from its inlet temperature to its evaporation temperature, which may lead to condensation in the upper part of the bed. The green balls are weakened when water condensate in the bed and this is one of the reasons why there is a limitation in bed height. When the green balls reach DDD, their strength has improved enough to avoid problems due to condensation. The heat supplied has to be controlled so that the moisture existing in the pores can escape through the capillaries without any over-pressure which would weaken the pellet structure. This phenomenon when over-pressure occurs is called chock drying and is one of the greatest limitations in inlet air temperature [1]. Another reason to keep the temperature fairly low is the risk for early oxidation.

The inlet air temperature is approximately 300 C in UDD and the initial temperature of the pellet bed is about 35 C on straight grates.
On these grates the main heat supply is convection (> 90 %) when hot gases pass through the pellet charge.

Factors affecting heat transfer for straight grates are:

- **Pellet size:** Small grains will have a bigger specific area exposed to the air and the heat transfer will therefore be more effective.

- **Temperature:** A great temperature difference between pellets and air will give an effective heat transfer.

- **Height of bed:** A greater height of bed is more efficient.
3 Theory

3.1 Laws of Conservation

All fluid mechanics are based on the laws of conservation for mass, momentum and energy. These laws can be applicable to a point if stated in the differential form or applicable to an extended region if stated in the integral form [2].

The differential form of the principle of conservation of mass is called the continuity equation and has the form

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0. \tag{3.1}
\]

The conservation law of momentum can be expressed in differential form by applying Newton’s law of motion to an infinitesimal fluid element [2]. The equation with tensor notation has the form

\[
\frac{\rho Du_i}{Dt} = \rho F_i + \frac{\partial \sigma_{ij}}{\partial x_j}. \tag{3.2}
\]

Here \(\sigma_{ij}\) represents the stress tensor [3]. For a Newtonian fluid, \(\sigma_{ij}\) is expressed as

\[
\sigma_{ij} = -p \delta_{ij} + 2\mu \left( e_{ij} - \frac{1}{3} e_{kk} \right), \tag{3.3}
\]

where

\[
e_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). \tag{3.4}
\]

The equation of motion for a Newtonian fluid is obtained by substituting the constitutive Eq. 3.3 and Eq. 3.4 with Eq. 3.2 to obtain

\[
\frac{\rho Du_i}{Dt} = \rho F_i - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{1}{3} \frac{\partial e_{kk}}{\partial x_i} \right). \tag{3.5}
\]

This expression is usually called the Navier-Stokes equation of motion [3].
Conservation of energy is stated by the first law of thermodynamics. It asserts that total energy is a thermodynamic property. The law states that energy can neither be created nor destroyed; it can only change forms [4].

The first law of thermodynamics has both mechanical and thermal energy terms in it and has the differential form

\[
\rho \frac{D}{Dt} \left( e + \frac{1}{2} u_i^2 \right) = \rho g_i u_i + \frac{\partial (\tau_{ij} u_j)}{\partial x_i} - \frac{\partial q_i}{\partial x_i}.
\]

The heat flux tensor per unit area is denoted by \( q_i \) and \( e \) represents internal energy per unit mass. For a perfect gas \( e = C_v T \), where \( C_v \) is the specific heat at constant volume [2].

### 3.1.1 Fluid Flow in Porous Media

There are various forms of the momentum equation porous medium analogue to the Navier-Stokes equation [5].

Henry Darcy’s experiments in 1856 led to the conclusions that the rate of flow through a porous media is proportional to its cross-sectional area, the pressure difference over it and are inversely proportional to its length \( L \) [6].

A generalised form of Darcy's one dimensional law is in refined form expressed as [5]

\[
\frac{dp}{dx} = \mu \frac{Q}{K A}.
\]

Here \( \frac{dp}{dx} \) is the pressure gradient in the flow direction and \( \mu \) is the dynamic viscosity of the fluid. The coefficient \( K \), called permeability in single phase flow, is independent of the nature of the fluid and is exclusively given by the geometry of the medium. One of the most widely accepted derivations of permeability and its relationship to porous media that was proposed by Kozeny and later modified by Carman. The Kozeny-Carman equation has the form

\[
K = \frac{n^3}{(1-n)^2 5M_s^2}.
\]

In this equation, \( M_s \) represent specific surface and \( n \) the volume porosity. The specific surface for a sphere of uniform radius is [6]

\[
M_s = \frac{3}{r}.
\]

Porosity is a macroscopic porous medium property. It is defined as the ratio of volume of the void space to the bulk volume. Porosity can be calculated from the following equation when values of solid density and bulk density are known.
$$n = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{solid}}}.$$  \hfill (3.10)

Darcy’s law is valid as long as the Reynolds number based on average grain diameter does not exceed some value, often between 1 and 10 [6]. As the velocity $v = \frac{Q}{A}$ increases, the transition to nonlinear drag is quite smooth. This transition is not from laminar to turbulent flow since at such comparatively small Reynolds number the flow in the pores is still laminar. The breakdown in linearity is rather due to increased inertia and is therefore a consequence of the tenuity of the porespace.

An equation that quite often fits data well over the entire range of Reynolds number is the Ergun equation which has the form [7]

$$\frac{\Delta P}{z} g = 150 \frac{(1 - n)^2}{n^3} \frac{\mu v}{D_p^2} + 1.75 \frac{(1 - n) \rho v^2}{D_p}.$$ \hfill (3.11)

Viscous losses per unit length are expressed in the first term and kinetic losses by the second term of Eq. 3.11.

Regarding turbulence, it is proposed that the flow becomes turbulent in the domain $\text{Re}_p > 300$ where the pore Reynolds number, $\text{Re}_p$, can be stated as

$$\text{Re}_p = \frac{v_p d_p}{v},$$ \hfill (3.12)

in which $d_p$ is the pore size and [5]

$$v_p = \frac{v}{n}.$$ \hfill (3.13)

Although $d_p$ should be a length dimension representing the elementary channels of the porous medium, it is customary to employ some representative dimension of the grains for $d_p$. Often the mean grain diameter is taken as the length dimension [6].

### 3.2 Heat Transfer

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas in motion and it involves the combined effects of conduction and fluid motion. Since motion of fluid is involved, heat transfer by convection is partially governed by the laws of fluid mechanics [4]. To investigate convection in a porous media, the first law of thermodynamics must be considered. Since the region with the porous media contains both fluid and solid, two energy equations are required. The energy equations can be presented in following form by taking averages over an elemental volume of the medium [5].
Fluid phase energy equation:

\[
n(\rho C_p)_f \frac{\partial T_f}{\partial t} + (\rho C_p)_f \nabla T_f = n \nabla \cdot \left( k_f \nabla T_f \right) + n q^\prime_f + a_s h_{sf} (T_s - T_f)
\]  \hspace{1cm} (3.14)

Solid phase energy equation:

\[
(1 - n)(\rho C_p)_s \frac{\partial T_s}{\partial t} = (1 - n) \nabla \cdot \left( k_s \nabla T_s \right) + (1 - n) q^\prime_s + a_{sf} h_{sf} (T_f - T_s).
\]  \hspace{1cm} (3.15)

Specific heat, \( C_p \), is a measure of the ability of a material to store heat. Thermal conductivity, \( k \), is in its turn, a measure of a materials ability to conduct heat and the ratio of thermal conductivity to volumetric heat capacity is called thermal diffusivity. In addition, \( q^\prime \) is the heat production per unit volume [5]. The last terms in Eq. 3.14 and 3.15 have their origin in Newton’s law of cooling. The convective heat transfer coefficient, \( h_{sf} \), is an experimentally determined parameter whose value depends on all variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid and the bulk fluid velocities [4]. Specific Surface area, \( a_{sf} \), is finally stated by the following expression which can be developed from geometrical considerations [8]

\[
a_{sf} = \frac{6(1 - n)}{d}. \hspace{1cm} (3.16)
\]

Indications are that turbulence drag coefficients are different laminar ones but that turbulence will not qualitatively change convective flow in porous media except when the porosity is high [5].

### 3.3 Computational Fluid Mechanics

Flows and related phenomena described by partial differential equations can only be solved analytically for special cases. To obtain solutions numerically, a discretization method which approximates the differential equations by a system of algebraic equations can be used. Iterative methods are used out of necessity for non-linear problem but they are also valuable for sparse linear systems, since the discretization error usually is much larger than the accuracy of the computer arithmetic. An iterative method uses a guess of the solution to start with, and then uses the equations to systematically improve it [9]. The CFD software applied in this thesis uses the Finite Volume (FV) method as discretization approach.

In the FV method the integral form of the conservation equations is employed as starting point. The solution domain is subdivided into a finite number of contiguous control volumes (CV), and the conservation equations are applied to each CV. At the centroid of each CV lies a computational node at which the variable values are to be calculated. Interpolation is used to express these values at the CV surface in terms of the nodal values [9].
3.3.1 Errors and Accuracy

Numerical solutions for fluid flow problems have various types of unavoidable errors, mainly Modelling Errors, Discretization Errors and Iteration Errors.

Modelling Errors

Fluid flow is usually described by integral or differential equations. Together, these equations form a mathematical model of the problem.

Modelling errors can be defined as the difference between the real flow and the exact solution of the mathematical model. Modelling errors occurs in the case of:

- Turbulence and other phenomena that are difficult to describe exactly and requires modelling approximations.
- Initial and boundary conditions.
- Exact representation of the geometry.

Modelling errors might be the most difficult errors to estimate, since data of the real flow is needed. Modelling errors are therefore often only estimated for some test cases, for which experimental data are available. Comparison between numerical solution and experimental data should only be carried out when the results converge toward a grid-independent solution and the discretization errors are small enough.

Discretization Errors

Discretization error can be defined as the difference between the exact solution of the governing equations and the exact solution of the discrete approximation.

Since the computational effort is proportional to the number of discrete elements, proper distribution and size is essential for computer efficiency.

Discretization errors can only be estimated if solutions on systematically refined grids are compared. As the spacing becomes smaller, the higher order accuracy will become more accurate. A good grid should be as nearly orthogonal as possible and it should be dense where large truncation errors are expected [9].

Discretization error can be estimated by retrieval of an extrapolated value when measurements from different grids are available. The method is known as Richardson’s extrapolation and requires monotone convergence. GCI (Grid- Convergence Index) represents a simple method for grid convergence studies and is based on Richardson’s extrapolation. With this method an extrapolated value can be found by comparison of the discrete solutions [10]. The extrapolated value can be calculated as

\[
f_{\text{exact}} \approx f_i + \frac{f_1 - f_2}{r^p - 1}
\]

where

\[
r_p = \left( \frac{N_j}{N_i} \right)^{1/5}.
\]
In Eq. 3.16 \( f_i \) represents the discrete solution and \( N_i \) the number of nodes. The order of the convergence rate, \( p \), may be calculated from results on three consecutive grids.

\[
\frac{f_3 - f_2}{r_{23}^p - 1} = \frac{f_2 - f_1}{r_{12}^p - 1}
\] (3.19)

The discretization error is then estimated as [10]

\[
e = \frac{f[\text{exact}] - f_i}{f[\text{exact}]}.\] (3.20)

**Iteration Errors**

The iteration error can be defined as the difference between the exact and the iterative solution of the discretized equations. The discretization process normally produces a coupled set of non-linear algebraic equations. These are usually linearized and solved by an iterative method since direct solution is usually too expensive. A convergence criterion must be defined in order to stop the process when the level of residual has been reduced by a particular amount. The iteration errors should be of an order of magnitude lower than discretization errors. The rate of reduction of error is the same rate at which the residual and the difference between successive iterations are reduced, except in the initial stage of iteration. If the error level at the start of computation is known, the error will fall 2-3 orders of magnitude if the norm of residuals has fallen 3-4 orders of magnitude. This would mean that the first two or three most significant digits will not change in further iterations, and that the solution is accurate within 0.01-0.1 %.

**3.3.2 Transient Simulation**

The dimensionless parameter Courant number is one of the key parameters in CFD. It is defined as

\[
c = \frac{u\Delta t}{\Delta x}
\] (3.21)

which is the ratio of time step \( \Delta t \) to the characteristic convection time \( u/\Delta x \), the time required for a disturbance to be convected a distance \( \Delta x \). For negligible diffusion, the criterion to be satisfied is \( c < 1 \) [9]. Each time step should also have iterative convergence.
4 CFD Model

4.1 Limitations and assumptions

Following are the assumptions on which the simulation model is based:

- Pellets are regarded as incompressible solid spheres with uniform diameter of 12 mm.
- Moisture content in the bed is not taken into account. Material parameters such as density and conductivity are based on sintered pellets (See Appendix A).
- Since heat in a bed of pellets is up to 90% transferred by convection, all other heat transfer mechanisms will be left out of calculations.
- To account for porosity changes in the bed, two approaches are used. The first describes differences of porosity between fired pellets and green balls. The second accounts for natural variation of porosity in a bed of green balls.
- No regard is taken to thermal- or flow effects coming from outside the bed.
- Only up- draught drying is investigated.
- The air flow is assumed to be incompressible.
- Thermal dissipation is not taken into account.
- Only a small part of the bed is simulated.

A more detailed description of how the porous bed approximations are done is given in the following chapters.

4.1.1 Geometry

The geometry of the bed is simplified in order to save computational time. By using a symmetry condition, only one half of the width of the geometry has to be included. Since simulation of the whole length of the bed would impose a long computational time, a periodic interface condition can be applied at two of the sides when movement of bed in z-direction is neglected. The length of the bed is chosen to 0.5 m and other dimensions are taken from section 2.2. The simplified geometry is presented in Fig. 4.1.

![Figure 4.1: The geometry is oriented such that the y-axis is in direction of height and the z-axis is in direction of length.](image)

Figure 4.1: The geometry is oriented such that the y-axis is in direction of height and the z-axis is in direction of length.
4.1.2 Variation of Porosity

Layers of different porosity are implemented in the model due to differences in size and packing for green balls and fired pellets. The fired pellets layer is approximately 0.1 m of height along wall and bottom, and is assumed to have a fix porosity of 0.39 which is an average porosity calculated from pellet density and bulk density. To account for natural variation, randomly selected values of porosity are interpolated over the whole geometry. It is not known how much the porosity will vary in the bed but to show that it is possible to take such effects into account, the bed porosity is varied between the values 0.40 and 0.45.

An expression named \( N \) is created with aid of step functions in order to implement the variation of porosity in the simulation model (see Appendix B).

4.2 Numerical Setup

4.2.1 Grid

Because of the geometrically simple domain, a structured (regular) hexagonal grid is used. Since a structured grid is equivalent to a Cartesian grid, it is the simplest grid structure. Three grids with different spacing between the nodes are used for a grid convergence test but it is only the grid displayed in Fig. 4.2 that is used in heat transfer simulations.

![Structured mesh with 85064 nodes.](image)

Figure 4.2: Structured mesh with 85064 nodes.

4.2.2 Heat Transfer

The fluid energy equation (Eq. 3.6) is automatically taken into account in CFX 10.0. However, a source term must be added to implement the last term in Eq. 3.13 in order to solve for the convective heat transfer between solid and fluid.

The solid energy equation (Eq. 3.15) is not taken into account automatically, but may be included as a diffusive transport equation by the use of an additional variable. The diffusive transport equation in CFX 10.0 has the appearance
\[
\frac{\partial \phi}{\partial t} = \nabla \bullet \left( \rho D_\phi \nabla \left( \frac{\phi}{\rho} \right) \right) + S_\phi,
\]  

(4.1)

where, in this case, \( \rho \) represents density of air and \( \Phi \) is equal to solid temperature. For Eq. 4.1 to represent Eq. 3.15, density must be excluded and one way to eliminate it is to make it a constant. The additional variable is named \textit{Solid Temperature} and provides a local average temperature in the solid material. A source is added here as well to account for the interaction between solid and fluid. The thermal properties used for pellets (shown in Appendix A) are taken from [1] and earlier work at LKAB.

### 4.2.3 Domain Settings

A porous domain is used as domain type to account for the porous material. In order to include changes of porosity and air in the porous model, two expressions \( LC \) and \( QC \) based on the linear and quadratic coefficients of Eq. 3.11 are used. The expressions are presented in Appendix B. Gravity is neglected in the model.

Since the temperature of the fluid will vary between the values 35 °C and 300 °C, a material is created in order to let the air properties vary with temperature. However, due to the diffusive transport equation (Eq. 4.1), variation of density is not possible at the moment. This implies constant density and specific heat while dynamic viscosity and thermal conductivity is varied as functions of temperature. The new material is named \textit{Air} and its properties are presented in Appendix A.

Since the particle based Reynolds number for the conditions just described becomes well over 300, the flow is assumed to be turbulent, based on the theory in chapter 3.1.1. A standard \( k-\epsilon \) turbulence model is used with default intensity and length scale and automatic eddy dissipation.

Thermal energy is used as heat transfer model. Thermal energy differs from Total Energy model in that the effects of the mean flow kinetic energy are not included and it is therefore adequate for low speed flows where kinetic effects are negligible. Total energy should be used for gas flows where the Mach number exceeds 0.2.

### 4.2.4 BC for Constant Inlet Velocity

An value of normal speed is applied at the inlet for stability reasons. The magnitude of the inlet velocity is approximated from an available inlet pressure value of approximately 4548 Pa which represents the average pressure of the inlet drying zone. The approximation is based on a steady simulation without heat transfer, and with air properties corresponding to 160 °C.

The value of outlet pressure is unknown but can be approximated to zero, since it is expected to be of a smaller magnitude than the inlet pressure. The inlet superficial velocity is from this approximation given a value of 3.3 m/s and the outlet boundary condition is set to static pressure with zero as relative pressure.

By taking the transfer coefficient as zero for the solid temperature inlet boundary condition, the only heat transfer between solid and fluid is done by the convective term in Eq. 3.15.
A no slip boundary wall condition is imposed at the leaning wall and all other boundary conditions are stated as in chapter 4.1.1.

4.2.5 BC for Varying Inlet Velocity

In reality, the bed is moving with a velocity of approximately 3m/min in the z-direction. The inlet velocity is therefore varied with aid of an inlet velocity function named \textit{Veloc} (presented in Appendix B), in order to give a more realistic picture of thermal- and flow effects when the bed enters the drying zone. Influences from other zones of the pelletizing process are unknown and are therefore neglected at the moment.

All boundary conditions are the same as for the case of constant velocity except that the periodic interface condition is replaced by symmetry conditions.
4.3 Results

4.3.1 Grid Convergence
A grid convergence test based on results from three grids is done in order to estimate the magnitude of the discretization error. Numerical settings for the steady grid test simulations are the same as stated in Chapter 4, except that air at 25°C is used as fluid and heat transfer is not taken into account. The RMS residual target is set to $1e^{-7}$ as convergence criteria, which in this case represents a reduction of error with at least 2-3 orders of magnitude. Results from simulations are presented in Table 4.1.

<table>
<thead>
<tr>
<th>No. of nodes</th>
<th>85064</th>
<th>180000</th>
<th>343980</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave Inlet Pressure [Pa]</td>
<td>6475.5</td>
<td>6544.2</td>
<td>6586.8</td>
</tr>
</tbody>
</table>

Table 4.1: Results from steady simulations made on the geometry presented in 4.1.1.

A discretization error analysis is performed by calculation of $p$ from values of average inlet pressure with aid of Eq. 3.19. The extrapolated value of the average inlet pressure and the estimated errors are presented in Table 5.2.

<table>
<thead>
<tr>
<th>Value</th>
<th>p</th>
<th>$f$[exact] [Pa]</th>
<th>Error coarsest grid</th>
<th>Error finest grid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4201</td>
<td>6705.5</td>
<td>0.0343</td>
<td>0.0177</td>
</tr>
</tbody>
</table>

Table 4.2: Results from discretization error analysis.

4.3.2 Temperature and Velocity Distribution
The result of the porosity distribution in the bed is presented in Fig. 4.3.

A simulation with constant velocity is made with convergence criteria for courant number and iterative convergence fulfilled. Iterative convergence is achieved since a reduction of RMS residuals of at least three decades and a courant number of 0.95 is obtained.

To illustrate changes in solid and fluid temperature, a sequence of results from six time steps is presented in Fig. 4.4 and 4.5. The pictures show a cross section of the XY-plane (See figure 4.1), and only the initial stage of heating is considered due to temporary limitations in computer capacity.

A simulation with varying inlet velocity is made with the same convergence criteria as for constant velocity. The same time steps are used as for constant inlet velocity and the result is presented in Fig. 4.6 and 4.7. The pictures show a cross section of the YZ-plane (See figure 4.1).
Figure 4.3: Porosity variation in a section of the bed. Porosity is interpolated from 15 randomly selected points.
Fig 4.4: Fluid temperature distribution for constant inlet velocity

\[ \text{Temperature} \quad \text{Plane 1} \]

- \( t = 0 \text{ s} \)
- \( t = 0.2 \text{ s} \)
- \( t = 0.4 \text{ s} \)
- \( t = 0.6 \text{ s} \)
- \( t = 0.8 \text{ s} \)
- \( t = 1 \text{ s} \)
Fig 4.5: Solid temperature distribution for constant inlet velocity

- t=0 s
- t=0.2 s
- t=0.4 s
- t=0.6 s
- t=0.8 s
- t=1 s
Figure 4.6: Velocity distribution for varying inlet velocity

$t=0 \text{ s}$

$t=0.2 \text{ s}$

$t=0.4 \text{ s}$

$t=0.6 \text{ s}$

$t=0.8 \text{ s}$

$t=1 \text{ s}$
Figure 4.7: Solid temperature distribution for varying inlet velocity
5 Experiments

5.1 Introduction

Experiments are performed at the Metallurgical Research Institute AB (MEFOS) with aid of an oven created for porous media measurements. The equipment is designed by Sten Ångström at MEFOS and measures for example pressure drop and fluid temperature for a test sample. The charge container (S in Fig. 5.1) is cylindrical with a diameter of 10 cm. The goal is to use the equipment to define unknown material parameters and for validation of simulations.

Within the frames of this thesis, two sets of experiments are carried out. The first set has the aim to secure the equipment from possible measuring errors. In the second set of experiments, flow through pellets of different sizes and packing is investigated and compared with available equations. Only cold gas is used since the validating experiments should be performed under isothermal conditions in order to allow comparison with theory.

![Figure 5.1: The presented equipment is available at MEFOS for measurements of flow through a packed bed.](image-url)
5.2 Validation of Equipment

For validation of the experimental equipment, a couple of measurements are performed under isothermal conditions. The intention is to discover eventual measurement errors by comparing result of the experiments with theoretical results calculated from Darcy’s law (Eq. 3.7) and Ergun’s equation (Eq. 3.11). To be able to measure pressure drop at low volume flows, almost spherical glass beads with a diameter of 2 mm are used. Another reason why it convenient to perform experiments on small beads is that uncertainties still exist when calculating pressure drop for packed tubes with low and medium tube to particle ratio since the increased porosity near the wall results in an increased wall permeability which leads to changes in flow distribution [12]. Additionally, the viscous friction at the wall may not be negligible in comparison to that caused by particles [12]. Result from [12], [13] shows that if the condition

\[
\frac{\text{Diameter of experimental equipment}}{\text{Diameter of beads}} > 10
\]

is fulfilled, the boundary wall-effects should be negligible. Since the tube to particle ratio in this set of experiments is 50, the effects described above should not have to be taken into account. The fluid used in the experiments is Nitrogen gas.

In order to investigate measurement errors, three experiments are carried out with a different height for each experiment. Measurements of pressure drop from seven different volume flows at each height are analysed. The experiments are carried out under isothermal conditions (bed and fluid temperature of approximately 20°C). Random packing of the beads is assumed.

5.2.1 Results

Table 5.1 represents values of porosity adjusted from Ergun’s equation (Eq. 3.11) for the three experiments. The results indicate decrease in packing with increase in bed height. The porosity values in brackets shows the confidence bound.

<table>
<thead>
<tr>
<th>Height [m]</th>
<th>Porosity</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.155</td>
<td>0.3713 (0.3693, 0.3733)</td>
<td>0.9988</td>
</tr>
<tr>
<td>0.2</td>
<td>0.377 (0.3745, 0.3795)</td>
<td>0.9982</td>
</tr>
<tr>
<td>0.255</td>
<td>0.3836 (0.3808, 0.3864)</td>
<td>0.9978</td>
</tr>
</tbody>
</table>

Table 5.1: Adjusted porosity.

Porosity for randomly packed spheres lies in the interval 0.36 to 0.40 [9]. To compare results with Ergun’s equation, a graph with specific pressure is constructed. Since specific pressure presents the pressure difference without regard to bed height, all curves should be the same (provided that all batches have the same average porosity). The results are shown in Fig. 5.2. Theoretical values calculated from Ergun’s equation are plotted for the two bounding porosities.
Values of apparent permeability calculated from experimental results are compared to permeability calculated from Eq. 3.8. The porosities in Table 5.1 are used to calculate $Re_p$ and the results are shown in Fig. 5.3. Provided that the average porosity is the same for each height, permeability should have the same constant value.
5.3 Variation of Packing

The aim with the second set of experiments is to investigate random packing of pellets and how well Ergun’s equation represents fluid flow through a bed of pellets. Since the tube to particle ratio is less in this case, it is important to investigate how boundary effects might interfere with the result. To study the effects, experiments are carried out on glass beads ($D_p = 10$ mm), screened pellets ($D_p = 9-10$ mm) and with three bed heights of pellets of natural size distribution.

All experiments are carried out under isothermal conditions with nitrogen as fluid. Pressure difference for five gas flows are measured for every batch. Ten gas rates are measured for the first measurement series of each material. In Table 5.2, a list of the performed experiments is presented.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Material</th>
<th>Height [m]</th>
<th>Weight [Kg]</th>
<th>Calculated porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>Glass</td>
<td>0.165</td>
<td>2</td>
<td>0.375</td>
</tr>
<tr>
<td>2:2</td>
<td>''</td>
<td>0.163</td>
<td>2</td>
<td>0.368</td>
</tr>
<tr>
<td>2:3</td>
<td>''</td>
<td>0.161</td>
<td>2</td>
<td>0.360</td>
</tr>
<tr>
<td>2:4</td>
<td>''</td>
<td>0.161</td>
<td>2</td>
<td>0.360</td>
</tr>
<tr>
<td>2:5</td>
<td>''</td>
<td>0.161</td>
<td>2</td>
<td>0.360</td>
</tr>
<tr>
<td>2:6</td>
<td>Screened Pellets</td>
<td>0.116</td>
<td>2</td>
<td>0.407</td>
</tr>
<tr>
<td>2:7</td>
<td>''</td>
<td>0.117</td>
<td>2</td>
<td>0.412</td>
</tr>
<tr>
<td>2:8</td>
<td>''</td>
<td>0.113</td>
<td>2</td>
<td>0.391</td>
</tr>
<tr>
<td>2:9</td>
<td>''</td>
<td>0.115</td>
<td>2</td>
<td>0.402</td>
</tr>
<tr>
<td>2:10</td>
<td>''</td>
<td>0.116</td>
<td>2</td>
<td>0.407</td>
</tr>
<tr>
<td>2:11</td>
<td>Pellets</td>
<td>0.111</td>
<td>2</td>
<td>0.380</td>
</tr>
<tr>
<td>2:12</td>
<td>''</td>
<td>0.113</td>
<td>2</td>
<td>0.391</td>
</tr>
<tr>
<td>2:13</td>
<td>''</td>
<td>0.112</td>
<td>2</td>
<td>0.386</td>
</tr>
<tr>
<td>2:14</td>
<td>''</td>
<td>0.113</td>
<td>2</td>
<td>0.391</td>
</tr>
<tr>
<td>2:15</td>
<td>''</td>
<td>0.111</td>
<td>2</td>
<td>0.380</td>
</tr>
<tr>
<td>2:16</td>
<td>''</td>
<td>0.142</td>
<td>2.5</td>
<td>0.394</td>
</tr>
<tr>
<td>2:17</td>
<td>''</td>
<td>0.163</td>
<td>3</td>
<td>0.367</td>
</tr>
</tbody>
</table>

Table 5.2: Measurement arrangement.

5.3.1 Results

Fig. 5.4 -5.7 illustrates variations due to packing.
Figure 5.4: Result from experiments with glass beads.

Figure 5.5: Result from experiments with screened pellets.
Figure 5.6: Result from experiments with natural size distribution of pellets.

Figure 5.7: Result from experiments with natural size distribution of pellets and three bed heights.
Values for the percentage change of specific pressure are presented in Table 5.3 and values of mean, standard deviation and coefficient of variation are presented in Table 5.4. The results show greater variation and standard deviation in specific pressure for natural distributed pellets than for glass beads and screened pellets.

<table>
<thead>
<tr>
<th>Material</th>
<th>Variation %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 l/min</td>
</tr>
<tr>
<td>Glass beads</td>
<td>6.77</td>
</tr>
<tr>
<td>Screened Pellets</td>
<td>10.16</td>
</tr>
<tr>
<td>Pellets</td>
<td>12.26</td>
</tr>
</tbody>
</table>

Table 5.3: Variation of specific pressure.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean Value of Specific Pressure [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 l/min</td>
</tr>
<tr>
<td>Glass beads</td>
<td>134.18</td>
</tr>
<tr>
<td>Screened Pellets</td>
<td>130.49</td>
</tr>
<tr>
<td>Pellets</td>
<td>133.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Standard Deviation of Specific Pressure [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass beads</td>
<td>3.73</td>
</tr>
<tr>
<td>Screened Pellets</td>
<td>5.81</td>
</tr>
<tr>
<td>Pellets</td>
<td>6.74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Coefficient of Variation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass beads</td>
<td>2.78</td>
</tr>
<tr>
<td>Screened Pellets</td>
<td>4.45</td>
</tr>
<tr>
<td>Pellets</td>
<td>5.04</td>
</tr>
</tbody>
</table>

Table 5.4: Mean value, standard deviation and coefficient of variation of specific pressure.

Results of the experiments performed with gas flows between 100 and 1000 l/min are presented in Fig. 5.8. The graph shows that the difference between theoretical values and experimental values increases with Reₚ.
Figure 5.8: Specific pressure for gas flows of 100-1000 l/min.
6 Conclusions and Discussion

It is in CFX 10.0 possible to make a heat transfer model which calculates solid and fluid temperature. There is however important to solve the problem of varying air density in order to get a proper estimation of heat and velocity distribution in the bed of pellets. It should also be noted that this kind of model only gives an average temperature and velocity since small scale effects are not taken into account. Flow effects due to movement of the bed and other influences from the process need further investigation.

Since the permeability of the bed is very complex, it is important to use appropriate approximations of the bed porosity in order to make the permeability a function of both time and location. In the established CFD model, an investigation of how it is possible to vary this parameter is made. It is however important to stress that the main work is focused on what can be done and not how it should be done. This work, however, facilitates further investigations on how to describe the bed in a proper way. The material parameters used are only estimations and might not be valid in future simulation with moisture included.

Both iteration errors and discretization errors should be negligible in comparison to modelling errors, since the assumptions in the model are arbitrary and convergence is achieved in all simulations.

The experimental equipment at MEFOS is reliable for experiments made on small particles if results are to be implemented in a simulation model. The difference in result between experiment and Darcy’s Eq. might arise from inertia effects since Re_p>10. Further investigation is needed regarding how analyse measurements for particles in the same size range as pellets and gas flows of higher magnitude (Re_p>200-300). Phenomena like turbulence and boundary effects might arise and effect comparison with theory for higher gas flows. Uncertainties might also occur from variations in size and form factor since Ergun’s equation is strongly dependent on both particle size and porosity. Error estimations for measurement values of temperature, pressure difference, and height measurements have not been made and might need more investigation depending on future concerns.
7 Future Work

Future research can be made either on a macro level on the whole bed or on meso and micro level where heat and moisture transport is investigated on a smaller scale.

**Macro level**
In future work on a macro level, it is important to improve approximations of the porous bed and to do further investigations on what values of the material parameters are appropriate to use. It is important to have moisture content in mind when estimating properties of the bed, since moisture will have mayor affect on size, shape and packing. To save computational time, optimization of the geometry, time step and convergence criteria should be made. It is also of high importance to make validating experiments of the simulation model.

**Mesos and Micro level**
In order to fully clarify drying of pellets, heat and moisture transport must be investigated on a smaller scale. This could be done by making a model of one pellet together with a model of convective heat transfer that includes interaction between pellets.
References


A Properties of Pellets and Air

Table A.1 presents the material constants used for pellets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>3700</td>
<td>Kg m(^{-3})</td>
</tr>
<tr>
<td>Bulk density</td>
<td>2200</td>
<td>Kg m(^{-3})</td>
</tr>
<tr>
<td>Convection heat transfer</td>
<td>190</td>
<td>W m(^{-2}) K</td>
</tr>
<tr>
<td>Average diameter</td>
<td>0.012</td>
<td>M</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>560</td>
<td>J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.4</td>
<td>W m(^{-1}) K(^{-1})</td>
</tr>
</tbody>
</table>

Table A.1: Parameters based on fired pellets

Density, dynamic viscosity, specific heat capacity and thermal conductivity for air are dependent on temperature and/or pressure and should therefore be varied accordingly. A new material named Air is created in order to account for property changes and the material parameters used are shown in Table A.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molar mass</td>
<td>28.96</td>
<td>kg kmol(^{-1})</td>
</tr>
<tr>
<td>Density</td>
<td>0.815(^1)</td>
<td>Kg m(^{-3})</td>
</tr>
<tr>
<td>Specific heat capacity, (C_p)</td>
<td>1017(^2)</td>
<td>J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Reference temperature ((C_p))</td>
<td>180</td>
<td>C</td>
</tr>
<tr>
<td>Ref. spec. enthalpy</td>
<td>0</td>
<td>J kg(^{-1})</td>
</tr>
<tr>
<td>Ref. spec. Entropy</td>
<td>0</td>
<td>J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>3(^3)</td>
<td>N s m(^{-2})</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>3(^3)</td>
<td>W m(^{-1}) K(^{-1})</td>
</tr>
</tbody>
</table>

Table A.2: Air properties.

\(^1\) A constant value of density is used based on an average between 35 C and 300 C.

\(^2\) Specific heat capacity is dependent on temperature and pressure but is here used as a constant approximated in the same way as density.

\(^3\) The dynamic viscosity is strongly temperature dependent and increases with temperature for gases. The dynamic viscosity of air is therefore computed using Sutherland's formula

\[
\mu = \mu_{ref}\left(\frac{T}{T_{ref}}\right)^{\frac{3\gamma}{2}}\frac{T_{ref} + S}{T + S}
\]  

(A.1)

Where the constants are for air [14]
\[ T_{\text{ref}} = 273.1 \text{ K} \]
\[ S = 111 \text{ K} \]
\[ \mu_{\text{ref}} = 1.7160 \cdot 10^{-5} \text{ N s/m}^2. \]

Thermal conductivity is also computed using Sutherland’s formula with constants

\[ T_{\text{ref}} = 25 \text{ C} \]
\[ S = 111 \text{ K} \]
\[ k_{\text{ref}} = 0.0261 \text{ W/mK}. \]
B Expressions

The expressions used in the heat transfer model are shown in Table B.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>$150 \frac{(1-n)^2 \mu}{n^3 D_p^2}$</td>
</tr>
<tr>
<td>QC</td>
<td>$1.75 \frac{(1-n) \rho}{n^3 D_p}$</td>
</tr>
<tr>
<td>N</td>
<td>$0.39(A<em>C+B</em>D+A*D)+MyFunction(x,y,z)<em>B</em>C$</td>
</tr>
<tr>
<td>A</td>
<td>$(1-step((y-0.1[m])/1[m]))$</td>
</tr>
<tr>
<td>B</td>
<td>$step((y-0.1[m])/1[m])$</td>
</tr>
<tr>
<td>C</td>
<td>$1-step((x-1.65[m]-0.1400*y)/1[m])$</td>
</tr>
<tr>
<td>D</td>
<td>$step((x-1.65[m]-0.1400*y)/1[m])$</td>
</tr>
<tr>
<td>Veloc</td>
<td>$Vconst*((1-step((t-10[s])/1[s]))<em>step(z/1[m]-(0.25-0.05</em>t/1[s]))+step((t-10[s])/1[s]))$</td>
</tr>
<tr>
<td>Vconst</td>
<td>3.3 m/s</td>
</tr>
</tbody>
</table>

Table B.1: Expressions.