A study of heat transfer in fluidized beds using an integrated DIA/PIV/IR technique

Citation for published version (APA):

Document license:
TAVERNE

DOI:
10.1016/j.cej.2014.07.107

Document status and date:
Published: 01/01/2015

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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A study of heat transfer in fluidized beds using an integrated DIA/PIV/IR technique


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A new measuring technique for studying heat transfer in gas–solid fluidized beds is proposed using infrared (IR) thermography. An infrared camera is coupled with a visual camera to simultaneously record images to give instantaneous thermal and hydrodynamic data of a pseudo 2D fluidized bed. The established techniques: digital image analysis (DIA) and particle image velocimetry (PIV) are combined with IR thermography to obtain combined quantitative (i.e. hydrodynamic and thermal) data sets. In this work, the calibration procedure and the methods that are used to combine the data obtained by the different techniques are discussed. The combined technique provides insightful information on the heat transfer in a fluidized bed for varying particle size, aspect ratio and background (or fluidization) gas velocity.

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1. Introduction

Fluidized beds are encountered in a variety of industries because of their favourable mass and heat transfer characteristics. Some of the prominent processing applications include coating, granulation, drying, and synthesis of fuels, base chemicals and polymers. Many of the important applications of fluidized beds involve highly exothermic or endothermic reactions which give rise to a high rate of heat removal or supply to the system. Fluidized catalytic cracking, fluidized bed coal combustion and polymerisation for production of polyethylene (UNIPOL) are some of the well known processes. Under such conditions formation of hot spots or zones is a phenomenon which can severely effect the overall performance of the reactor. Hence in depth knowledge of the heat transfer processes in fluidized beds is highly relevant.

The hydrodynamics of fluidized beds has been investigated by many researchers. Moreover extensive studies of heat transfer in fluidized beds have been reported with many supporting theories proposed on the prevailing heat transfer mechanism [1–7]. Most of the previous heat transfer research on fluidized beds involved the use of temperature probes placed inside or on the walls of fluidized beds [8–10].

In recent years, infrared (IR) technique, a new noninvasive method for measuring temperature in fluidized beds has been developed [11,12]. Tsuji et al. [11] proposed an idea of combining IR with PIV to study heat transfer in fluidized beds. Infrared thermography has been used frequently in process engineering research for heat transfer measurements and studies [13–16]. This measuring technique is quite well known to be reliable for non-in situ measurements. Recent work by Dang et al. [17] demonstrated the suitability of an infrared camera (fitted with spectral filters) for CO₂ concentration measurement in gas voids inside pseudo 2D fluidized beds. This work builds on the measuring method proposed by Tsuji et al. [11] using improved experimental and post processing techniques.

Some of the common techniques known for hydrodynamic studies are electrical capacitance tomography, X-ray tomography,
magnetic resonance particle tracking or positron emission particle tracking and particle image velocimetry (PIV). Among these the PIV technique is specifically used for pseudo 2D beds and has the advantage of being non-intrusive, low cost compared to other techniques and, for our purposes, can be easily coupled with the infrared camera measuring technique for thermographic study. In studies of pseudo 2D fluidized beds digital image analysis (DIA) can be used to determine local solid volume fractions. A combined PIV/DIA analysis as developed by van Buijtenen et al. [18] and de Jong et al. [19] can be used to determine the spatial distribution of the solids mass fluxes.

In our study the infrared technique is coupled with this PIV/DIA method. PIV is performed with a high speed visual camera using two close consecutive instantaneous images. Cross-correlation analysis on such image pairs give velocity field data. DIA on one of the same image pairs provides the solid volume fraction field data in the system. The coupling of DIA and PIV results gives the solids mass fluxes. In this work the IR measurements are coupled with the DIA and PIV measurements of the visual camera to obtain spatial and instantaneous information on both solids motion and solids temperature field in fluidized beds.

The objective of this paper is twofold. First, the technical details such as calibration and data-processing related to combining the three methods: DIA, PIV and IR are communicated. Second, it is shown that this combination of measuring techniques can produce useful data sets to characterize heat-transfer in pseudo-2D fluidized beds. The effects of particle size and fluidization or background gas velocity on the heat transfer characteristics are presented. The generated data sets can be used later for validating CFD models.

2. Experimental set-up and procedures

2.1. Fluidized bed equipment

The experimental study is carried out on a small pseudo 2D fluidized bed. A schematic view of the set up is shown in Fig. 1. The fluidized bed is 8 cm wide, 20 cm high and 1.5 cm in depth. The front wall of the fluidized bed is made up of sapphire glass specifically chosen to give a high transmittance to the infrared light.

The back and side walls consist of aluminium coated from the inside with matt finish black paint to reduce reflection. The aluminium frame was anodized to give the material better adhesion for paints and glue used to attach the sapphire mirror and other accessories to the frame. It also provides corrosion and wear resistance to the whole frame and helps to reduce charging of the particles. The back aluminium frame was fitted with thermocouples to measure its temperature at two different heights.

The polished aluminium has a low emissivity of 0.09. This helps in reducing any interference that may arise due to heating of the frame. The emissivity of anodized aluminium is 0.77. Hence the internal walls made of anodized aluminium reduces reflection of radiation from hot particles in the system. This gave a good contrast and clarity in observing the particles during fluidization which will be further discussed in the following subsection on the experimental procedure.

In the current set of experiments nitrogen at room temperature is supplied at the bottom through a porous plate gas distributor. The flow rate was 5–7 L/min. The mass flow controller was calibrated to adjust the flow rate to a predefined value. The control of the setup is done using Labview.

2.2. Experimental procedure

The fluidization experiments were performed with glass particles of sizes 0.5 mm and 1 mm. The particle properties are provided in Table 1. Hot particles heated in an oven at 120 °C were charged into the empty bed at room temperature, after which a constant gas stream at 20 °C is supplied through the bottom plate.

Along with fluidizing the particles, the cold gas cools them in time. This was recorded by the two cameras. The recording of the cameras was started before charging of the particles and was continued for about 2–3 min. This was approximately the time required by the fluidizing gas to cool the particles in the system. We choose to cool the particles instead of heating them up, because in this case the contrast between hot particles and cold background is large initially. It was observed that the background effects could be easily filtered and a high quality measurement was possible. This will be discussed in detail later.

The glass particles used in the experiments were properly washed with water and dried in order to make use of well-cleaned particles. To remove any charging of particles during fluidization the particles were rinsed with a Catanac solution. The Catanac...
solution was prepared by dissolving 1 ml of Catanac SP antistatic agent into 100 ml of ethanol. The particles were subsequently dried for one day producing glass particles with a coating of Catanac. Some rinsed particles in this solution were also fluidized in the set up so that small amount of Catanac coated the interior of the fluidized bed.

For this work 2 different particle sizes of 0.5 mm and 1 mm were used, which are Geldart B and Geldart D type particles. For the 1 mm particles two bed-heights corresponding to a bed mass of 75 g and 125 g were considered. Three background gas velocities were used. The properties and settings for the fluidization experiments are summarized in Table 1.

2.3. Camera setup

The fluidization was recorded by a high speed visual camera (La Vision ImagePro, 560 × 1280 resolution) and an infrared camera (FLIR SC7600, 250 × 512 resolution). The IR camera was sensitive in the 1.5–5.1 μm spectral range. The cameras were placed on a tripod in front of the fluidized bed. To minimise the difference in views the cameras were placed as close as possible. The set up was illuminated using a pair of white LED lamps. White LED have blue and yellow peaks in the spectrum, but have very low intensity was illuminated using a pair of white LED lamps. White LED have in views the cameras were placed as close as possible. The set up

<table>
<thead>
<tr>
<th>Particle material</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density $\rho_p$</td>
<td>2500 kg/m$^3$</td>
</tr>
<tr>
<td>Norm. coeff. of resist.</td>
<td>0.97</td>
</tr>
<tr>
<td>Tang. coeff. of resist.</td>
<td>0.33</td>
</tr>
<tr>
<td>Fluid heat capacity $C_p$</td>
<td>1010 J/kg K</td>
</tr>
<tr>
<td>Particle heat capacity $C_{pp}$</td>
<td>840 J/kg K</td>
</tr>
<tr>
<td>$d_p$ (mm)</td>
<td>Geldart type</td>
</tr>
<tr>
<td>0.5</td>
<td>B</td>
</tr>
<tr>
<td>0.5</td>
<td>B</td>
</tr>
<tr>
<td>1.0</td>
<td>D</td>
</tr>
<tr>
<td>1.0</td>
<td>D</td>
</tr>
<tr>
<td>1.0</td>
<td>D</td>
</tr>
</tbody>
</table>

3. Measuring techniques

3.1. Particle image velocimetry (PIV)

The PIV method used here was fairly standard and for example extensively described in literature [18,19]. The visual image has a size of 560 × 1168 pixels. The PIV performed here uses a multi-pass algorithm using an interrogation window of 32 × 32 with 50% overlap for computing the cross correlations. This results in a post processed velocity field on a 35 × 73 grid for the pseudo 2D bed. A standard median filter was used to remove outliers from the vector field.

3.2. Digital image analysis (DIA)

The DIA involved a series of processing steps that was aimed at computing the 3D solids volume fractions. The DIA procedure used was similar to that described by Jong et al. [19]. The raw visual 2D digital image consisted of pixels with different intensities. During DIA this image was subjected to a set of preprocessing steps, namely: background subtraction, elimination of overexposed and underexposed pixels. A raw preprocessed image is shown in Fig. 3a.

This digital image was then corrected for inhomogeneity and normalized between 0 and 1. Here 1 is representative of the brightest particle and 0 of the background or no particle. The normalized values of the 2D image were then averaged over an interrogation window (of 32 × 32) to get the apparent 2D volume fraction of the particles (represented by $e_{2D}$). This 2D solid volume fraction was translated to the 3D volume fraction using the correlation,

$$e_{3D} = \begin{cases} A e_{2D} (1 - e_{2D}/B)^{-1} & \text{for } e_{3D} < e_{3D,\text{max}} \\ e_{3D,\text{max}} & \text{for } e_{3D} > e_{3D,\text{max}} \end{cases}$$  \hspace{1cm} (1)
This correlation was proposed by de Jong et al. [19] using results from discrete element method simulations. In this equation we take 
\( e_3^\text{D, max} = 0.6 \) to be the maximum solids volume fraction. According to de Jong et al. [19] the parameter \( A \) is related to the bed depth \( D_z \) and the particle diameter \( d_p \), as 
\[ A = 1.028D_z/d_p. \]
This relation was obtained by using DEM (discrete element method) simulation results to generate images and perform DIA on them. The remaining fitting parameter \( B \) is determined such that the deviation between the computed bed mass and the experimental bed mass is minimal. The computed bed mass was calculated from \( e_3^\text{D} \) by multiplication with the solids density and subsequent integration over the bed volume.

### 3.3. Thermography and IR camera calibration

The fate of incident radiation on an object is determined by three wavelength dependent fractions, namely, absorptance, reflectivity and transmittance. For example, the amount of adsorbed radiation equals the absorptance times the intensity of the incoming radiation at that wavelength. For emitted radiation we have a fourth factor that is of importance, namely, the emissivity. The amount of emitted radiation at a specific wavelength is equal to the emissivity times the black-body radiation intensity corresponding to that wavelength. Kirchhoff’s thermal law of radiation states that emissivity equals absorptance. Details on IR background can be found in literatures [20,21].

Since either the radiation is absorbed or reflected or transmitted we have 
\[ a(\lambda) + r(\lambda) + \tau(\lambda) = 1. \]
For the use of thermography objects of which one wants to determine the temperature should have an emissivity close to 1 in the IR regime. For example for glass we have an emissivity of 0.8–0.95 in the full IR spectrum of our camera. This means that, for these IR wavelengths, already after a few interactions with matter most of this radiation has been absorbed and re-emitted as thermal (i.e. black-body) radiation. If, as in our case, we have hot glass beads then the major part of the radiation coming from these particles is due to the emission of these particles, i.e., the emissivity times the black-body intensity corresponding to the particle temperature.

The remaining radiation coming from a particle is due to reflections of radiation from other sources. Part of this reflected radiation originates from neighboring particles that are similarly hot, and another part comes from the room temperature surroundings. On its way from a glass bead of which we want to measure the temperature to the IR camera the radiation might interact with other matter.

For an object that should be transparent for the IR radiation, like the window of the bed, the transmittance should be close to 1. Clearly using a glass window, with its high absorptance, would ruin the measurement. Therefore we used a sapphire window which has a transmittance of about 0.9. The distance between the fluidized bed and the camera was so small that the air in between was fully IR transparent to very good approximation. In the end, the radiation that enters the IR camera apparently coming...
from a glass bead is composed of thermal radiation coming directly from a particle (say 80%) and the remainder of the radiation is a complicated mixture of radiative contribution from either reflected or emitted by another object.

The used FLIR SC7600 camera was calibrated using perfect black-body radiation. So for black-body objects it can correlate radiation and temperature in a very accurate way. For ‘real’ objects the manufacturer supplied software can perform a correction.
assuming a value of the emissivity of the objects plus the assumption that all other radiation is black-body radiation at room temperature. For both the emissivity and the room temperature the user needs to supply values.

Because the model used by the FLIR software was not a perfect representation of reality we chose to perform our own calibration for our specific situation. For this calibration a glass particle was fitted at the tip of a thermocouple probe. This particle was placed inside the bed very close to the sapphire glass so that it was visible for the IR camera. The calibration started by pouring hot particles into the bed. Immediately after the pouring the colder tracer particle could be easily distinguished from the other hotter particle as seen in the infrared image of the bed. Fig. 4a shows the recorded infrared image where the tracer particle can be easily seen. This image helps us in locating the particle. In a few seconds, however, the tracer particle thermally equilibrated with other surrounding particles and could not be distinguished anymore from the others (see Fig. 4b). Since we already knew the position of the tracer

![Fig. 7. Plot of tracer particle temperature against its distance from the surface of the fixed bed.](image)

![Fig. 8. IR images processing steps showing the raw image (a) which was processed by direct filtering (b) using the threshold Eq. (3). The filter used corrects for wrong temperature readings at particle edges, that in fact are due to partly covered pixels, by filtering these pixels off. The images shown here are from a fluidization run of glass particle size 1 mm, background gas velocity 1.2 m/s and bed mass 75 g.](image)
particle the radiation recorded from the pixels representing the tracer particle position were used to calibrate the digital level signal (DL) of the camera with the standard thermocouple temperature. In this way an accurate calibration is possible.

Fig. 5 shows the calibration curve. The shown solid curve is a third order polynomial fit with a least square error of 0.46 °C. This calibration curve is used in the subsequent data processing procedure to convert DL to temperatures.

3.4. Error estimation of the calibration

The calibration method discussed in the previous section was done with the IR camera measuring a fixed bed of particles. However, for the fluidization experiments that were performed the density of the bed varies throughout the pseudo 2D fluidized bed. The current IR camera calibration did not take into account the possible effect on the temperature measurement due to particulate density variation.

To make a rough estimation of this effect a test was performed. In the test a sample glass particle of 2 mm in size was attached to the tip of a straight wire and immersed in a bed of hot particles already poured in the pseudo 2D bed. Once the tracer particle equilibrated with the inside temperature of the bed the tracer particle was quickly pulled out of the bed (with the help of attached wire) to about 1.5 cm above the surface of the bed. Now the particle was lowered quickly back towards the top surface of the bed till it came in contact with the bed. This process was recorded with the IR camera at a high frequency of 100 Hz. A small background gas velocity of 0.1 m/s was maintained so that when the particle is lifted above the bed it is in a gas environment that has a temperature equal to the bulk temperature of the bed. Fig. 6 shows three images that were recorded while lowering the tracer particle. The temperature recorded at the centre of the particle was extracted using the calibration curve. With this data a plot of temperature of the tracer particle against the distance of the particle from the top surface of the bed was made, Fig. 7.

Due to the short duration of the test the change in temperature of the particle is negligible when it moves from an isolated position to the top of the bed. Therefore, the variation in the measurement of the temperature by the IR camera is observed. The plot indicates that the temperature of the particle measured by the camera increased by about 1 °C. This gives a quantification of the error in the temperature measurement of a particle when it moves between dense and isolated regions of the bed.

4. Image processing and data analysis

Here we will focus primarily on the processing of IR images and their coupling with DIA and PIV. For DIA and PIV the reader is referred to the short discussion in Section 3 and the standard references provided there.

4.1. Infrared image preprocessing and filtering

A sample of an image obtained from the infrared camera is shown in Fig. 8a. In this image the particle phase is clearly distinguishable from the background. This is because the experiments were conducted with a cold background wall. The temperature of the anodized aluminium back wall does not rise much and can therefore be easily differentiated from the hot particles for almost the full run of an experiment. In the snapshots the background wall
seems to glow in areas closer to the particle interface. This is due to the reflection of the infrared radiation coming from hot particles. However, this disturbance is not much and is easily distinguishable.

This background effect can be filtered by choosing a suitable threshold temperature. As can be seen in Fig. 8a the hot particles give temperatures well above 65 °C and the cold background is below 45 °C. Thus a filter threshold of about 50 °C should do a good job in this case.

By means of the filtering we determined for a pixel at position \((i,j)\) if it is either part of the particulate phase, where \(1(i,j \in \text{part}) = 1\), or of the background for which \(1(i,j \in \text{part}) = 0\). Using this notation a pixel averages were computed as

\[
(T_p)_{\text{pix}} = \frac{\sum_i 1(i,j \in \text{part}) T_p(i,j)}{\sum_i 1(i,j \in \text{part})}
\]  

(2)

We find that the temperature distribution in the particulate phase is quite narrow. Therefore a threshold closer to the average temperature than to the background temperature, \(T_{bg}\) was used, namely, 

\[
T_{\text{thr}} = 0.25 T_{bg} + 0.75 (T_p)_{\text{pix}}
\]  

(3)

This relation was found to be suited by trial and error experimentation. The background subtraction was found to be insensitive to the precise choice of the parameters for defining the threshold temperature. For example, the combinations of weights: \((0.2, 0.8)\) and \((0.3, 0.7)\) gave nearly the same results.

Since we use the threshold to compute the pixel-averaged temperature Eq. (3) is an implicit definition. However, this average temperature only changes slowly from one snapshot to the next. Therefore we used the average value, \((T_p)_{\text{pix}}\) from the previous time step to compute the threshold temperature.

Fig. 8b shows the filtered image corresponding to Fig. 8a using Eq. (3). Clearly, many of the shades that are present in Fig. 8a at the interface of the particle phase are filtered off. This is due to edge filtering induced by Eq. (3) and is desirable.

This is more clearly illustrated in the following two figures Fig. 8c and d where some particles in flight are shown. The centres of the particles show a high temperature and can be easily differentiated from the background which has a faint glow because of the particles in its vicinity. At the edges of particles, however, there is a signal intensity in between that of the core of a particles and the background. By using the calibration curve this digital level erroneously translated into an in-between temperature. The real cause of the in-between signal was that pixels representing the edges of particles were only partly covered by particles. Since the lower signal does not translate into the correct temperature it was better to filter partly covered pixels off. This was done to a large extent by choosing the threshold relatively close to the average particle temperature as done in Eq. (3).

In Fig. 9 the mean pixel temperatures is plotted against time to give the cooling profile for fluidized bed runs with 1 mm particle size and bed mass 75 g for different background gas velocities. The starting point for the recording was taken to be the point in time where the mean pixel temperature falls below 100 °C. The figure gives a closeup view of the region of the temperature interval between 70 and 40 °C.

For each velocity the experiment was repeated 4 times. The repetitions are shown using different symbols but the same colour. The fluctuations between the repeated experiments at the same background velocity are less than the separation of curves corresponding to different background velocities. This plot clearly shows that experiments are reproducible and that the cooling curves for each of the background velocities are distinguishably different.

### 4.2. DIA/IR coupling

The mean pixel temperature calculated in the previous section was not a useful quantity for studying heat transfer. Changes in enthalpy are proportional to the mass times heat capacity times temperature difference. Considering that heat capacities and specific densities are nearly constant a mean temperature that is calculated by a weighted-averaging using solids volume fractions is more appropriate. This quantity can be computed by coupling IR temperature fields with the DIA 3D volume fraction data of the bed.

The DIA process described earlier uses a high resolution 2D image \((560 \times 1168)\) (size = 0.143 mm/pixel) shown in Fig. 3b to get the 3D particle fraction data at a coarse grid \((35 \times 73)\) (size...
2.29 mm/pixel) also called interrogation grid. In order to couple the 3D particle-fraction data of DIA with IR the high resolution filtered IR image (250 × 512) (size = 0.312 mm/pixel) of Fig. 8b was also divided into interrogation areas such that they produce grids of the same size as that of DIA. So, each IR interrogation window has a size of (250/35 × 512/73) pixels. The mean particulate pixel temperature in each of these interrogation grid areas is calculated by using the pixel averaging described in the previous section. This means only the non filtered pixels which represent the particle temperature in interrogation areas are included in the averaging. On performing such an operation the filtered IR image of Fig. 8b transforms to Fig. 11b which has coarse grid data thus producing a less sharp image. This image gives the particle temperature profile data for the 3D particle fraction DIA data of Fig. 3b and hence can be coupled with it. The full image processing scheme is given in Fig. 10. A series of such coupled 3D particle fraction and processed temperature fields are shown in Fig. 11.

The mean particulate pixel temperature in each of these interrogation grid areas was calculated by using the pixel averaging described in the previous section. This means that only the non filtered pixels which represent the particle temperature in interrogation areas are included in the averaging. Not that, as a consequence, even if there are a small number of particles present in an interrogation window that the corresponding coarse pixel gets the temperature corresponding to the average temperature of these particles. This explains why in, e.g., the visual image Fig. 11e a region that contains very little particles still has a high temperature in Fig. 11f.

The temperature distribution obtained from the pseudo 2D bed from the IR images were that of the particles of the few front layers closest to the sapphire window. Since this was a fluidized bed in operation it was expected that in the depth direction the mixing was effective and the temperature was nearly uniform. We know however that the particle distribution within the fluidized bed was not uniform. Throughout the bed the particle fractions will vary in time and space. As said, a temperature that was weighted with the solids volume fraction was essential to understand heat transport phenomena in fluidized beds. The solids-volume-fraction weighted spatial average was computed as

$$\langle T_p \rangle_z = \frac{\sum_{i,j} f_p(i,j) T_p(i,j)}{\sum_{i,j} f_p(i,j)}.$$  \hfill (4)

Because of correlations between voidage and temperature it can be markedly different from a pixel-averaged temperature. In fact the mean temperature of particles computed by Eq. (4) mostly produces a higher value compared to mean pixel temperature of Eq. (2) as the dense regions of the bed are generally at a higher temperature compared to bubble regions or sparse particulate region. This can be observed in the corresponding DIA and IR images of Fig. 11.

Fig. 12 shows the mean temperature plot using both methods for a fluidization experiment where this phenomenon can be clearly seen. Due to the constant expansion and contraction of the bed the mean pixel temperature curve has much more fluctuation compared to solids-fraction weighted mean temperature, which is more stable and smooth. Note also that for low temperatures (below 35 °C in the graph) the mean pixel temperature curve is not smooth and is deviated slightly compared to the DIA coupled mean temperature. The reason is that at low temperatures the particle and background pixels become difficult to distinguish due to which filtering method failed.

4.3. DIA/PIV/IR coupling

Instantaneous spatial mass flux fields, $\Phi_p(t, i, j)$, can be computed by coupling DIA and PIV. This gives useful information on the solids motion in a fluidized bed. For analysing heat transport problems we are also interested in the solid phase convective heat flux.

This quantity can be obtained by complete coupling of the DIA data (particle fraction), PIV data (particle velocity) and IR data (particle temperature). The enthalpy change of a particle when its temperature changes equals $m_p C_{pp} \Delta T_p$. So, when analysing heat transport the convective transport of $T_p$ can provide valuable information. We define an instantaneous ‘heat’ flux for each coarse grid position (i.e., interrogation window) as

$$H_p(t, i, j) = \varepsilon_p(t, i, j) \rho_p C_{pp} \mathbf{v}_p(t, i, j) T_p(t, i, j).$$  \hfill (5)

4.4. Temperature distribution of particles

The infrared image observations that were made during a sample run are shown in Fig. 13 together with temperature histograms. These distributions have a well defined single peak. It was observed that the distribution spread tended to become narrow as the cooling proceeded. This is expected because at higher particle temperatures the difference between particles and inlet gas is larger, which causes the temperature differences between mixing particles to be also larger.

Besides the mean temperature, Eq. (4), the width of the distributions can be characterized from the standard deviation, $\sigma_p$, which equals the square root of the variance,
\[ \sigma_p^2 = \left( \langle T_p \rangle - \langle T_{p,c} \rangle \right)^2 = \frac{\sum_{i,j} \rho_p(1,j) (T_p(i,j) - \langle T_p \rangle)^2}{\sum_{i,j} \rho_p(i,j)} \] (6)

To obtain an impression of the relation between the bed temperature and the width of the temperature distribution \( \sigma_p \) was plotted against the mean particle temperature in Fig. 14a in an absolute and a relative way. These plots clearly demonstrate the decreasing standard deviation as the bed cools down.

In the relative plot the standard deviation is normalized by the thermal 'driving force' for the cooling process: \( \frac{\langle T_p \rangle - T_{g,m} \} Fig. 14b shows that this normalized standard deviation is more or less constant. These results also show a large fluctuation in the standard deviation when the driving force is high.

Fig. 13. Raw IR images and their corresponding temperature distribution of a cooling bed with particle size 1 mm, background gas velocity 1.2 m/s and bed mass 75 g.
Fig. 14. Plots showing standard deviation of particle temperature distribution against mean particle temperature with and without non-dimensionalization. This is obtained from the processing of data from bed mass 75 g, particle size 1 mm and background gas velocity 1.2 m/s.

(a) Spatial standard deviation of the particle temperature.

(b) Non-dimensionalised standard deviation for the same data points as shown in (a).

Fig. 15. Instantaneous DIA, PIV and IR processed results giving the particle fraction field, temperature field, mass flux field and heat flux field. This data is for an instantaneous image from a fluidized bed run of particle size 1 mm, background gas velocity 1.2 m/s and bed mass 125 g.
temperature differences. It therefore makes sense to look at temperature differences and for three flow conditions. It can be seen that close to the inlet also increases. This is expected because the temperature gradient at the inlet also increases. This is expected because the heat transfer coefficient increases as the gas velocity increases.

It is observed from these plots that at higher mean temperatures of the bed the temperature profile increases more sharply at the inlet. As the background gas velocity increases the temperature gradient at the inlet also increases. This is expected because the heat transfer coefficient increases as the gas velocity increases. By comparing Fig. 17c, which shows 0.5 mm particle data, with plots 17a and b, which show 1 mm data, it is seen that the temperature profile at the inlet is sharper for the smaller particle size. As 0.5 mm particles are smaller they have a larger specific area causing a higher bed heat transfer coefficient even for background velocities that are smaller than in case of the 1 mm particles.

5.2. Time-averaged data results

The temperature distribution of particles in the fluidized bed depends on the solidity density distribution and the flow pattern temperature profiles. In the second subsection we show time-averaged spatial distribution profiles that were obtained for a series of standard runs. Finally we show the DIA/IR coupled mean temperature plot with respect to time for different conditions. With these sets of results we summarize a new development in the field of non-invasive hydrodynamic/thermal monitoring in gas fluidized beds.

5.1. Instantaneous image profiles

In Figs. 15 and 16 instantaneous DIA/PIV and DIA/PIV/IR results are shown for two bed masses (125 g and 75 g). By coupling the visual images with IR data for each of the snapshots the solids volume fractions and temperature fields can be observed along with the instantaneous solids mass and convective heat fluxes. Because the temperatures within the domain does not vary too much the heat flux vector plots (see Figs. 15d and 16d) look quite similar to the mass flux plots (see Figs. 15c and 16c). The mean difference is in the bottom section where the cold gas enters. In this region the temperature changes are most significant.

To investigate the temperature profile in the bottom section more thoroughly we have used the high resolution IR data. In Fig. 17 axial temperature profiles along the central axis of the pseudo 2D fluidized bed are shown for several instants in time and for three flow conditions. It can be seen that close to $z = 0$ m, where the gas enters the bed, the temperature increases sharply. After moving along the height for, say, 5 mm the temperature of the bed remains constant with only minor variation.

This quantity is analysed for runs of varying particle sizes, background velocity and bed mass in the next section. The number of images used for each of the time averaging was 150.

5. Results and discussion

The visual/IR coupling has led to various kinds of processing possibilities that give a wide range of result output types. We have tried to classify and present these in three separate subsections as individual achievements of the developed technique. First, we present data on individual time instant images of DIA and IR giving instantaneous mass and heat flux profiles and instantaneous axial velocity can be computed using Eq. (8).

\[ \overline{P}(t, j) = \frac{1}{N_t} \sum_{i} \overline{e_p}(t, i, j) \]  

\[ \overline{Q_p}(t, j) = \frac{1}{N_t} \sum_{i} e_p(t, i, j) \overline{v_p}(t, i, j) \]  

\[ \overline{v_p}(t, j) = \frac{\sum_{i} e_p(t, i, j) \overline{v_p}(t, i, j)}{\sum_{i} e_p(t, i, j)} \]  

Besides spatial averaging also time-averages per pixel give valuable information. We will use an overbar-notation to distinguish time-averaging from spatial averaging.

Temperature distribution of particles in the fluidized bed run of particle size 1 mm, background gas velocity 1.2 m/s and bed mass 75 g.

4.5. Time-averaging

\[ T_{g}(t) - T_{g, in} \] is a good quantifier for the internal temperature differences. It therefore makes sense to look at temperature differences that are made dimensionless using this thermal driving force. This leads to the definition of a time-averaged dimensionless temperature difference.

\[ \overline{T_p}(t, j) = \frac{1}{\sum_{i} e_p(t, i, j)} \sum_{i} e_p(t, i, j) \frac{T_p(t, i, j) - T_{g, in}(t)}{T_p(t, i, j) - T_{g, in}(t)} \]  

Here Eq. (8) gives the time-averaged mass flux. To obtain this quantity solids-volume-fraction data from DIA needs to be combined with velocity data from PIV. This is similar to the hydrodynamic data processing previously presented in van Buijtenen et al. [18], de Jong et al. [19]. From the mass flux a mass-averaged particle velocity can be computed using Eq. (8).

Since the bed is cooling down it does not make much sense to time-average the temperature. The analysis of the standard deviation in the previous section suggests that the thermal driving, \( (T_p) - T_{g, in} \), is a good quantifier for the internal temperature differences. It therefore makes sense to look at temperature differences that are made dimensionless using this thermal driving force. This leads to the definition of a time-averaged dimensionless temperature difference.
that exists in the beds. Fig. 18 and 19 show time-averaged fields of the solids-volume fractions, mass flux and dimensionless temperature. Fig. 18 is for a bed mass of 75 g with a particle size of 1 mm, which corresponds to a bed aspect ratio of 0.5, and Fig. 19 is for a bed mass of 125 g with the same particle size of 1 mm, which corresponds to an aspect ratio of 0.8.

Let us first consider the time-averaged results of 1 mm particle size and 75 g bed mass. The DIA analysis provides the time-averaged results of 1 mm particle size and 75 g bed mass. The DIA analysis provides the time-averaged results of 1 mm particle size and 75 g bed mass. The DIA analysis provides the time-averaged results of 1 mm particle size and 75 g bed mass. The DIA analysis provides the time-averaged results of 1 mm particle size and 75 g bed mass.
aged particle density distribution of the bed. These data are given in Fig. 18a–c for background gas velocities 1.2 m/s, 1.54 m/s and 1.71 m/s respectively.

The DIA/PIV coupling provides mass fluxes that are plotted in Fig. 18d–f for the same three gas velocities. The influence of the background gas velocity is noticeable in the circulation pattern of the particulate phase. The increase in the background gas velocity causes a more pronounced circulation and back mixing of particles in the bed. This can be observed more closely in the Fig. 20a that shows the cross-sectional profile of the mass flux for these three background gas velocities at a height of 2.3 mm above the bottom plate.

A typical instantaneous IR image was shown earlier in Fig. 2. Here one sees a small jet of cold particles issuing into the bed from the bottom-centre of the bed. This is a typical narrow cold zone created along the axial direction from the bottom that tends to diminish as it propagates into the bed. This narrow cold zone (‘jet’) of particles is created due to the circulation pattern of the particles which moves from the sides of the bed to centre from the bottom. During this process the particles come into contact with fresh cold gas and exchange more heat before moving upward from the centre. During fluidization runs, the jet oscillates in the bed with a relatively stable base.

It was observed that at the lower background gas velocity of 1.2 m/s the narrow cold zone is more stable compared to higher background gas velocity. Thus when a time-average of the dimensionless temperature distribution is computed, using Eq. (10), we obtain a distribution as shown in Fig. 18g. In this figure at the centre bottom the narrow cold zone leaves its mark. This causes relatively hotter zones to appear on the sides of the bed.

At higher background gas velocities the narrow cold zone tends to oscillate more as well as move around the bottom of the bed. Thus when a time-averaging is performed the resulting field is more uniform. This can be observed for background gas velocities 1.54 and 1.71 m/s in Fig. 18h and 18i, respectively. Also the hotter zones forming at the sides of the pseudo 2D bed tend to diminish at higher background gas velocity.

Now let us consider and analyse the distribution profiles for higher bed mass of 125 g and bed aspect ratio of 0.8 with the same particle size of 1 mm. Here background gas velocities of 1.2 m/s and 1.54 m/s are considered for which various plots and profiles are shown in Fig. 19. The time-averaged particle fraction data are
shown in Fig. 19a and b for runs at background gas velocities of 1.2 m/s and 1.54 m/s respectively. Following this the mass flux profile giving the flow pattern is shown in Fig. 19c and d. The axial component of the mass flux at a bed height of 2.3 mm is shown in Fig. 20b. Here it can be seen that, as the background gas velocity increases from 1.2 m/s to 1.54 m/s, the mass flux also increase causing greater circulation of particles. The narrow cold zone created in the 75 g bed for background gas velocity 1.2 m/s is not that pronounced in the system with bed mass 125 g. Therefore the hot zone tend to stay in the centre as shown in Fig. 19e. However, for the higher background gas velocity of 1.54 m/s the hot zone formation is again towards to the sides with cold zones forming at the centre bottom. This indicate that the narrow cold zone forming at the bottom is affected by the bed aspect ratio as well.

5.3. Position averaged data results

The DIA/IR image processing detailed in the Section 4.2 was applied to all the fluidized bed runs listed in Table 1. By means of these procedures the mean particle temperature was calculated as function of time and plotted together for comparison. Fig. 21 shows a plot of the mean particle temperature change with respect to time for the bed mass of 75 g and particle sizes 1 mm and 0.5 mm. There are two important observations that can be made from this plot. For one particle size of 1 mm or 0.5 mm, as the background gas velocity increases from 1.2 m/s to 1.54 m/s, the mass flux also increase causing greater circulation of particles. The narrow cold zone created in the 75 g bed for background gas velocity 1.2 m/s is not that pronounced in the system with bed mass 125 g. Therefore the hot zone tend to stay in the centre as shown in Fig. 19e. However, for the higher background gas velocity of 1.54 m/s the hot zone formation is again towards to the sides with cold zones forming at the centre bottom. This indicate that the narrow cold zone forming at the bottom is affected by the bed aspect ratio as well.

Fig. 19. Time-averaged fields for particle size \(d_p = 1\) mm and bed mass 125 g. The two columns present data for different background gas velocities, namely, \(u_{bg} = 1.2\) m/s and 1.54 m/s. The first row of plots shows the solids volume fraction in the bed obtained from DIA. The second row shows mass flux fields obtained by DIA/PIV coupling. The third row shows the time-averaged dimensionless particle temperature, Eq. (10), obtained by DIA/IR coupling.
Similarly, the background gas velocity for 0.5 mm particles is 0.51 m/s and 0.86 m/s, which are 2.83 and 4.78 times the minimum fluidization velocity ($u_{mf} = 0.18$ m/s).

All curves in Fig. 21 are for the same bed mass of 75 g. In Fig. 22 we present a comparison between the cooling rate for two bed masses, namely, 75 g and 125 g with otherwise the same 1 mm particle size and two background velocities. The higher bed mass gives a slower rate of cooling of the bed as expected.

These plots accurately give the rate of heat loss of the particles. This heat loss is the sum of heat exchange between particles and gas due to multiphase flow, heat radiating from the particles to the surrounding and heat exchange between the gas phase and surrounding walls by means of heat conduction. In this paper we do not try to quantify these quantities but using DEM some of these heat exchange types have been quantified in the literature [6,5]. Using some direct measurements shown in this work these
quantities can be validated. The plot in Fig. 22 can quantify gas particle convective heat transfer as it is a plot for the same particle size and background gas velocity but different bed mass. As the gas flowing through the particles becomes thermally saturated the remaining heat will be lost due to other transfer mechanisms like radiation.

6. Conclusion

A measuring technique involving the use of visual and infrared images has been developed. The visual and IR recordings were successfully synchronized and combined by a high resolution image mapping. The mean temperature of particles in the bed was calculated with respect to time for different particle sizes, background gas velocity and bed mass (aspect ratio). With these plots the varying exchange rate between particles and gas can be calculated. Time averaged temperature distribution fields of the fluidised bed were calculated and presented for various configurations. They were compared and analysed with their respective particle volume fraction and also mass and heat flux data was computed.

With this work processed measurements of four important synchronized parameters of multiphase flow in non-isothermal pseudo 2D fluidized beds are made available, namely, solids volume fractions, temperature fields and mass- and heat-flux fields. This has produced a data sets that can be used to analyse the heat transfer mechanisms inside a fluidized bed in more detail, e.g., by comparison with CFD computations.

Acknowledgements

The authors would like to thank the European Research Council – Belgium for its financial support, under its Advanced Investigator Grant scheme, contract number 247298 (Multiscale Flows). This research was also supported by the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Ministry of Economic Affairs in The Netherlands. The authors would also like to acknowledge the Dutch polymer institute (DPI) which had supported the building of the set up. The technicians Lee McAlpine and Paul Aendenroomer (TNO) are specially thanked for helping and suggestions at various stages during the development of the set up and measurement method.

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