Milk Powder Deposition in Cross-Flow Heat Exchangers

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INTRODUCTION

The lack of heat recovery implementation in spray dryer exhausts can be ascribed to difficulties associated with particulate fouling that reduce the thermal performance of these units. The aim of this work is to experimentally characterise the deposition of two brands of skim milk powder (A and B) on a bare tube bank in cross-flow. Results show that the tube powder deposition for powder A reached a maximum at the second row of tubes while for powder B the maximum was at the third row. Analysing the mid diameter of tube deposited particles for powder A showed a separation of particles based on tube row where increasing tube row number into the heat exchanger the deposited particle size was reduced.

METHODS

The test rig allows milk powder to be added to an air stream of controlled temperature and humidity. The powder laden air is then contacted, in cross-flow, with a bank of bare tubes. The tube bank consisted of 48 bare round tubes that were vertically housed in a staggered arrangement. Ambient air is drawn in by a fan, heated and then blown along the test duct. Direct steam injection further increases the air temperature in addition to achieving the target humidity. The fan was set to its maximum output delivering airflow at an average velocity of 0.83 m/s. Air temperature within the duct was maintained by insulating the duct as well as the tube bank. This ensured constant tube and duct characteristics by inhibiting condensation formation.

During the tests the direct steam injection was adjusted to achieve an absolute humidity near 50 g_{H2O}/kg_{Air}. Once the desired values were obtained, powder was manually added by tapping a powder-filled bottle with small holes in its lid. Typically powder was added at 13.5 g/min and test durations ranged from 20 to 140 minutes depending on the quantity of powder added. Throughout the course of a test, pressure drop across the tube bank and air temperature and humidity were monitored. Temperature and relative humidity were logged at one second intervals and $T - T_g$ was calculated for each interval and averaged for the entire test period. At the conclusion of each test the tube assembly was removed from the test duct, photographs taken and deposition collected and weighed for each tube row. Powder deposited on the inside of the test duct was also collected, weighed and recorded.

Two brands of non-agglomerated Skim Milk Powder were tested. The particle size distributions were measured in iso-propanol using a Malvern Mastersizer 2000 according to the method of Pisecky [1]. The lower, mid and upper diameters of each powder were determined by cumulative volume fraction (Table 1).

Table 1 – Particle size distribution for skim milk powder used.

Powder	d(10%), µm	d(50%), µm	d(90%), µm
A	15	51	94
B	39	104	202

RESULTS and DISCUSSION

At a given stickiness, deposition on a tube row was expected to increase to a maximum followed by a reduction with increasing row number. The deposition distribution is dependent on the probability of the particle impacting the tube (tube deposition %) and once impacted adhering to the tube. The tube deposition % was taken as the measured tube deposition as a fraction of the maximum powder passing the tube row. The maximum powder passing the tube row was taken as the difference between the input powder and the sum of powder collected from the duct and any preceding tube row deposition. As the powder laden air travels through the tube bank it becomes depleted in powder particles thereby reducing the possibility of particle impaction. The relative tube row deposition is anticipated to be correlated to the impaction probability. The deposition per tube (Figure 1) as well as the average tube deposition % fitted with 95% confidence intervals have been plotted (Figure 2).

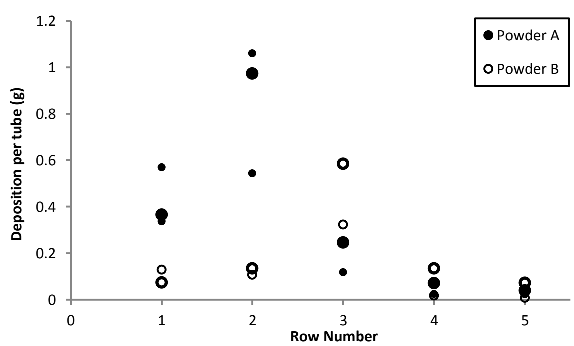

Figure 1 – Deposition per tube plotted against tube row number at a nominal $T\text{-}T_g$ value of 48.4°C for two types of powder.

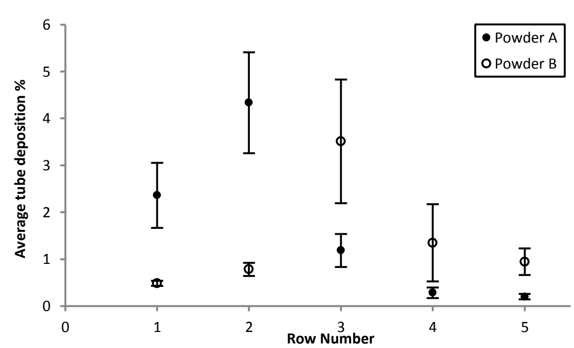

Figure 2 – Average tube deposition % plotted against tube row number at a nominal $T\text{-}T_g$ value of 48.4°C for two types of powder with 95% confidence intervals indicated.

As the powder laden air travels through the tube bank a portion of the particles will bypass the first row, but collide with the second row at both normal and oblique impaction angles due to tube geometry and path taken by the particle. In addition some particles are pulled in by the turbulent wake of the first tube row, which may cause these particles to miss impacting the second row. This transport and deposition regime is repeated for the remaining tube rows although the total amount of powder particles available to deposit is reduced after each row giving a reduction in deposition with increasing row number.

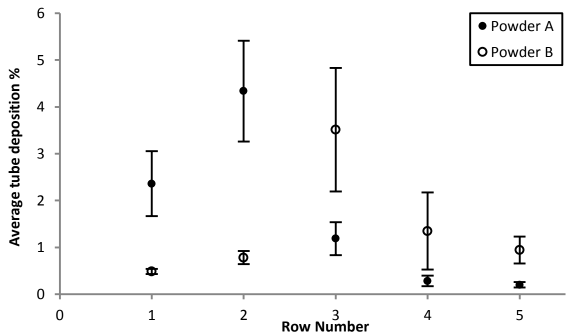

Figure 3 – Average tube deposition % plotted against tube row number at a nominal T-T_g value of 48.4°C for two types of powder with 95% confidence intervals indicated.

The change in row number at which peak tube deposition is measured for the two powders may be related to the difference in bulk particle sizes. One possibility is that the smaller particles of powder A are prone to agglomeration resulting in the formation of larger agglomerated particles that are sluggish to respond to sudden flow changes. The larger particles of powder B inhibit particle agglomeration and as a result particles that reach the tube bank are smaller compared to the agglomerated particles of powder A. Smaller particles are more responsive to changes in flow.

It was noticed that for powder A the first row's deposition appears more spread around the front half of the tube whereas the second row's deposition is significantly more protruding with reduced spread around the tube. The remaining rows' foulant layers had similar patterns to that of the second row but significantly less protruding and the layer thickness gradually reduced with increasing row number. The deposition distribution and spread are the result of the changed air flow patterns as the powder laden air travels through the tube bank. When the particles impact the first tube row, particles are travelling at approximately the air face velocity whereas particles impacting the second row are moving at about twice the speed of the face velocity due to the restriction of the air flow by the tube row. Walmsley et al [2] studied a single tube and found a negative correlation between deposition coverage around a tube and the velocity of particle impacts. Higher velocity collisions resulted in less coverage in a similar manner as has been observed in the tube bank for tube rows one and two. The combination of increased particle impaction probability and flow velocity result in the narrow protruding deposition layer of the second row. For the remaining rows the velocity increase is maintained, however with increasing row number the probability of particle impaction appears to decrease.

The deposited particle size distribution for powder A was determined for each tube row (Figure 4). With increasing row number the cumulative volume fraction curve is translated left indicating an overall reduction in the median particle diameter. Again the particle size separation can be assigned to the slow responding larger agglomerated particles that collide and adhere to the front most tubes while the smaller particles can easily respond to changes in air flow and can therefore travel further in to the tube bank. There is a separation of particle size distribution curves for the tube deposition from that of the bulk powder which suggests that the bulk powder particles are smaller compared to any of the deposited particles. This confirms the occurrence of the hypothesised particle agglomeration.

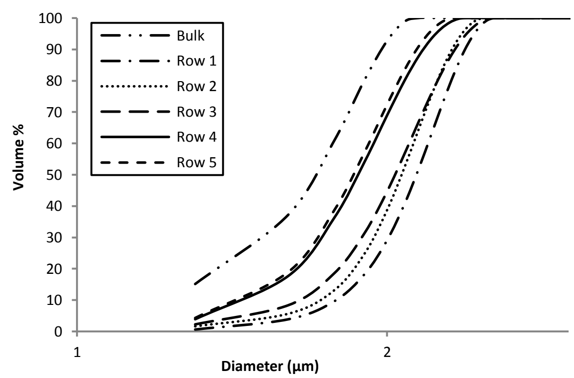

Figure 4 – Particle size distribution for powder A of the bulk powder and deposition collected from the five rows in the tube bank.

CONCLUSIONS

The key conclusions from the work presented are summarised as follow: The average tube deposition for powder A reached a maximum at the second tube row while the maximum for powder B occurred at the third tube row. The deposition distribution is the result of change in air flow patterns as it travels through the tube bank. The front most tubes in the bank were fouled by particles having a larger mid diameter compared to those that were deposited on the rearmost tubes.

ACKNOWLEDGMENTS

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REFERENCES

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