

AN INVESTIGATION OF MILK POWDER DEPOSITION ON PARALLEL FINS

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ABSTRACT

One method to reduce the energy consumption of industrial milk spray dryers is to recover waste heat from the exhaust dryer air. A significant challenge associated with this opportunity is the air contains a small amount of powder that may deposit on the face and surfaces of a recuperator. This paper introduces a novel lab based test that simulates powder deposition on a bank of parallel plate fins at exhaust dryer air conditions. The fin bank acts like the face of a typical finned tube row in a recuperator. The aim of this study is to look at how deposition on the front of fins is affected by the air conditions. Results show similar characteristics to other milk powder deposition studies that exhibit a dramatic increase in deposition once critical stickiness levels are reached. As powder deposits on the face of the fins, the pressure drop across the bank increases until eventually an asymptote occurs, at which point the rates of deposition and removal are similar. For very sticky conditions, deposition on the face of the fins can cause a rise in the pressure drop by as much as 65%. The pressure drop has also been successfully related to the percentage of open frontal area of the fins with and without deposition. Deposition inside and at the rear of the fin bank was found to be minimal.

INTRODUCTION

Spray drying is a highly energy intensive process that is an essential unit operation in several large-scale industries (Masters, 1996). A significant opportunity to reduce the energy consumption of spray drying is to recover low grade waste heat from the exhaust dryer air and use it to heat another process stream (Baker & McKenzie, 2005; Kemp, 2005; Atkins et al., 2011).

In the dairy industry, the path to implementation of exhaust heat recovery systems has several challenges. One particular problem is the exhaust air contains a small amount of powder. At low temperature and high humidity, milk powder is sticky and is likely to deposit on heat exchange surfaces. As a result the heat transfer rate will decrease and the pressure drop will rise, both of which ultimately lead to lower savings and increased costs. The quantity of powder exiting through the exhaust is also an important factor and varies depending on the dryer size and the efficiency of separation operations (e.g. baghouse and/or cyclones) upstream of a recuperator.

Characteristics of milk powder deposition encountered in the primary drying chamber, auxiliary equipment such as fluidized beds and cyclones, and product storage are frequently reported in literature (Chen et al., 1994; Hennigs et al., 2001; Ozkan et al., 2002; Ozmen and Langrish, 2003; Boonyai et al., 2004; Nijdam & Langrish, 2005; Intipunya et al., 2009). Many recent studies have used an impingement jet deposition test (particle gun test) to show that deposition tendencies are strongly affected by air flow dynamics and powder particle size distribution, in addition to air temperature, air humidity and the composition of the particles (Murti et al., 2009, 2010; Walmsley et al., 2010). But studies focusing on characterising milk

powder interaction with complex air flow dynamics around intricate geometries, such as heat exchanger surfaces, are limited at best. In other industries, particulate fouling has been demonstrated to deposit on the face of compact finned tube heat exchangers and is highly detrimental to performance, particularly in terms of an increase in pressure drop (Bell & Groll, 2011; Stehlík, 2011).

The aim of this study focuses on understanding what air conditions lead to fouling and deposition on the front of parallel plate fins. The fins present a similar face as the front of a finned tube heat exchanger. Different air temperatures (constant absolute humidity) are used to mimic various locations within an exhaust heat recovery system. The study introduces a novel lab based test that simulates powder deposition on a bank of parallel plate fins without any tubes at exhaust dryer air conditions. It is essential to understand deposition on fins and extended surfaces that would likely be needed to economically recovery heat from a dryer exhaust air stream.

Characterising the stickiness of dairy powders

Stickiness of milk powder surfaces is intricately related to the concepts of glass transition temperature and viscosity. In amorphous materials the glass transition temperature, T_g , identifies the boundary between the material being in a glassy state, non-sticky, or a rubbery state, sticky. For air temperatures below T_g , the viscosity is high and molecular movements are subdued. Above T_g , the molecular mobility rapidly increases as the surface viscosity lowers. Liquid bridges may then readily form between particles and between particles and solid surfaces. Further temperature increases above T_g continues to lower viscosity. The amount the air temperature is above T_g , i.e. $T - T_g$, is logarithmically related to viscosity as described by the Williams-Landel-Ferry (Williams et al., 1955) equation. Hence, $T - T_g$ is a non-linear measure of stickiness through viscosity.

Potentially sticky components of milk powder include primarily lactose and secondarily fats. For these components T_g is a function of water activity (a_w) at the particle's surface. The surface is assumed to be in equilibrium with air relative humidity. An increase in water activity results in a lower T_g and effectively increases stickiness. In many dairy powder stickiness characterisation studies, e.g. Paterson et al. (2007) and Murti et al. (2010), the polynomial empirical model developed by Brooks (2000) for amorphous lactose is applied to calculate T_g .

$$T_g = -530.66(a_w)^3 + 652.06(a_w)^2 - 366.33a_w + 99.458, \quad [0 < a_w < 0.575] \quad (1)$$

Other semi-empirical approaches to relate the T_g to a_w also exist, such as the Gordon-Taylor equation as presented by Hennigs et al. (2001) for skim milk powder.

The $T - T_g$ stickiness measure has been applied to express how deposition and stickiness are related. Fig. 1 is a plot of percentage deposition (sticking) as influenced by $T - T_g$. The data shows that below a critical $T - T_g$ point (about 38 °C), deposition is almost nil; however once the critical $T - T_g$ point is exceeded, the increase in deposition is rapid. A critical $T - T_g$ is often reported and is characteristic of many experimental milk powder deposition studies. It is important to note that the concept of a critical stickiness, $T - T_g$, is not unique, as it is affected by the air flow dynamics and the properties of the surface that the powder attaches to. Results in Fig. 1 have been taken from Paterson et al. (2007) for Whole Milk Powder (WMP) using the particle gun test with the air jet at 20 m/s.

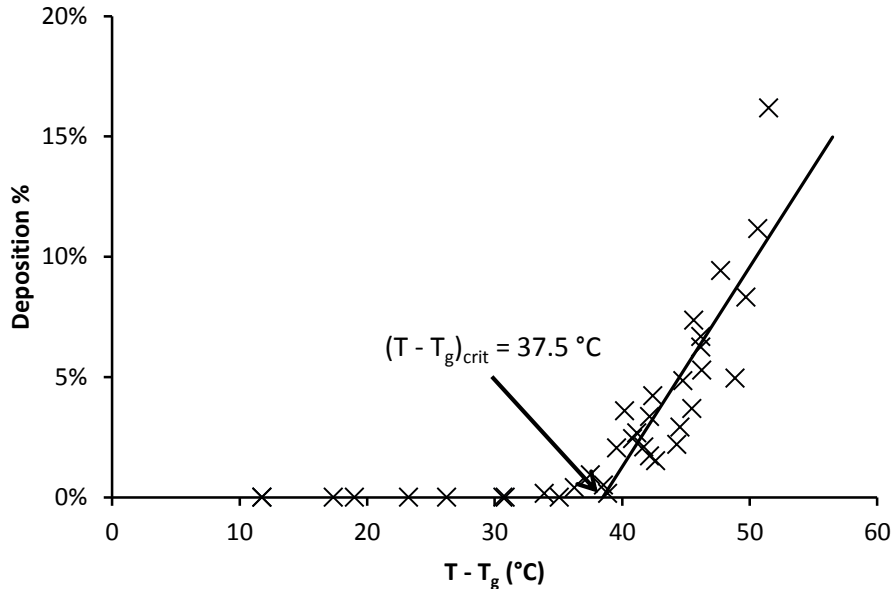


Fig. 1: Effect of particle $T - T_g$ on percentage deposition of WMP particles, obtained using the particle gun test. Data from Paterson et al. (2007).

EXPERIMENTAL TESTING

Deposition testing

A fin bank has been subjected to conditioned air flow with entrained milk powder and the resulting deposition and its effects are analysed. Tests have been carried at a constant absolute air moisture content of 60 g/kg, which is similar to the exhaust air moisture content of industrial milk powder spray dryers. The air temperature has been varied (49, 52, 55, 59 and 71 °C) to mimic different regions of an exhaust recuperator and to give different levels of powder stickiness ($T - T_g$). The fin bank pitch is 13.5 fins per inch, which is similar to standard air recuperators. The air flow rate in all tests has been kept constant at 28.8 L/s, which is an average face velocity, u_∞ , of 4.5 m/s.

Test operation and method

A lab scale deposition test rig has been developed that is able to test how powder deposits on various surfaces at near dryer exhaust air temperature and humidity conditions (Fig. 2). The test surface reported in this paper is a fin bank. The fin bank is a stack of 0.6 mm parallel aluminium plates that are evenly spaced and act in a similar manner to the fins in a finned tube heat exchanger.

In the test, ambient air is drawn into the rig through a plate-fin heat exchanger that is indirectly heated using steam. The air is then heated further using a 12 kW electric heater controlled by a Variable Speed Drive (VSD). Dry steam is injected to humidify the air. For high humidity conditions, the steam also raised the air temperature by as much as 5 °C. After conditioning, the temperature and humidity of the air is measured and continuously logged. The pressure drop across an orifice plate is measured and the value is used in a PID feedback loop to control the fan speed via a second VSD. The control loop was found to be necessary to maintain a constant air flow rate once deposition on the test surface began.

Immediately after the orifice plate is a powder injection cone. The cone is positioned to take advantage of the low pressure region caused by the orifice plate, and results in a little suction that aids powder injection. Powder is slowly released at an average rate of 2.4 g/min from a container that is mechanically tapped. After being exposed to the conditioned air, water activity at the surface of the powder particles rapidly moves toward equilibrium. The ducting down to the test section is 80 mm square with insulation on the outside to prevent heat loss and powder deposition to the duct walls.

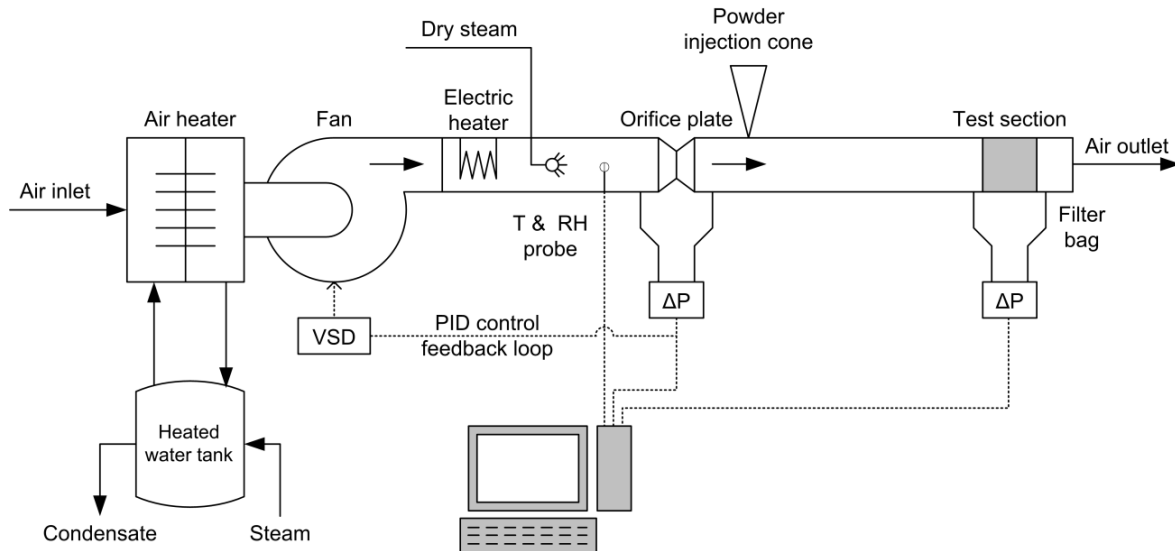


Fig. 2: Deposition test rig schematic.

Particle size distribution

A non-agglomerated Skim Milk Powder has been used in all tests. The particle size distribution was measured in iso-propanol using a Malvern Mastersizer 2000 according to the method of Pisecky (1997). By cumulative volume fraction, the mid diameter of the powder, $d(50\%)$, was measured as $104 \mu\text{m}$; $d(10\%) = 39 \mu\text{m}$ and $d(90\%) = 202 \mu\text{m}$.

PRESSURE DROP ANALYSIS OF THE FIN BANK

The pressure drop across the fin bank is related to the average duct air velocity immediately prior to the fin bank, u_∞ , and the fraction of open frontal area, ϕ . To understand this relationship and to form an empirical model, tests have been carried out at high temperatures (about 60°C) using different open area fractions. No powder is injected, rather tape is applied to block off known amounts of frontal area. For the fins alone the open area fraction is 0.67, for a fin pitch of 13.5 fins per inch.

Using the open area fraction and the average duct air velocity, we may define the velocity through the open area of the fins as, $u_\phi = u_\infty / \phi$. Results in Fig. 3 were measured by changing the fan speed, which varied the air flow rate in the duct, and measuring the pressure drop across the fins using a water manometer. The velocity through the open area is calculated from the measured air flow rate and the known open area fraction. Each air flow rate has been tested at least three times.

Fig. 3 shows that the pressure drop is strongly influenced by the velocity through the fin bank and weakly influenced by the fraction of open area. The plot is presented in a log-log form with the trend lines being power-law fits. A slight curve in the data can be seen with the

greatest percentage difference being at the lower velocity range. By assuming the slopes of the power equations in Fig. 3 are the same, an empirical model for the pressure drop can be constructed based on the average face velocity (duct velocity) and the open area fraction.

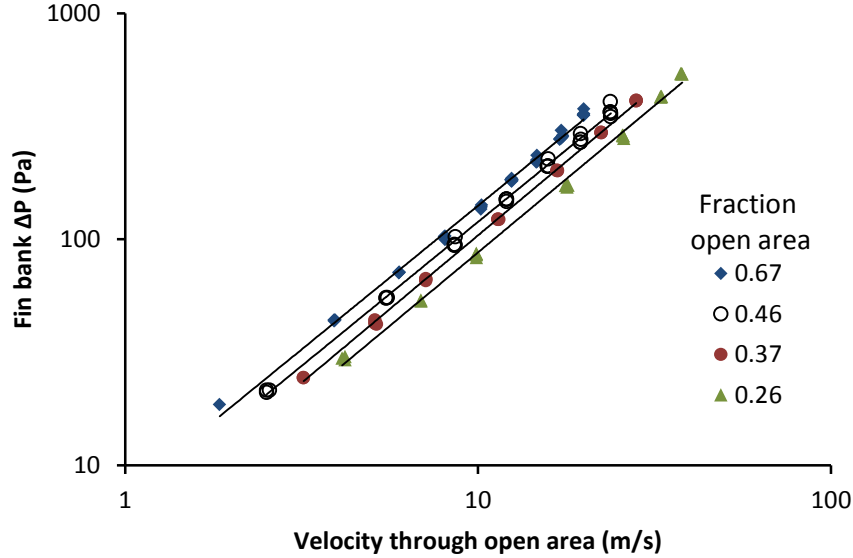


Fig. 3: Pressure drop across the fin bank for different open area fractions.

$$\Delta P = 8.90 \frac{u_{\infty}^{1.29}}{\phi^{0.77}}, \quad [0.26 < \phi < 0.67 \quad \text{and} \quad 1.2 < u_{\infty} < 9.8] \quad (2)$$

Eq. 2 is applied to deposition results, where the pressure drop and face velocity are known, to work out an estimate of the open area fraction and velocity through the open area.

DEPOSITION RESULTS

Powder deposition on the fin bank

Results from the deposition tests presented in Fig. 4 show the pressure drop across the fin bank increased over time as powder deposited. The pressure drop curve followed a typical asymptotic model with the rate of pressure drop increase diminishing over time as suggested in several particulate fouling models (Shah and Sekulić, 2003). Photographs of the frontal deposition on the fin bank at the end of each test are presented in Fig. 5. Open area fractions are estimated using Eq. 2. Deposition mostly occurred in the lower half of the face of the fin bank with very minor deposition inside and at the rear of the fin bank.

For high temperatures and low relative humidity, the amount of deposition was minimal (A). As the air temperature was reduced, the amount of fouling slowly increased (B and C). A decrease in air temperature resulted in an increase in particle stickiness due to a significant increase in the air relative humidity and a subsequent fall in T_g . The net effect on $T - T_g$ was an increase in temperature difference. A further drop in the air temperature resulted in a rapid rise in pressure drop and reduction in open frontal area. The concept of a critical stickiness as illustrated in Fig. 1 can also be seen for the fouling of the fin bank considered in this study.

Particularly apparent in tests D and E is the distinctive asymptotic pressure drop. At this equilibrium, the rate of deposition and the rate of removal are similar, which indicates the amount of open area remains fairly constant. Powder may deposit on top or over powder, but

the open area to the flow is unchanged. The reduction in frontal free flow area results in high velocities through the open sections of the fin bank. The increase in velocity simultaneously causes an increase in the rate of deposit removal. Blocked areas of the fin bank may then temporarily reopen. This dynamic deposit/removal process is one contributor to the oscillations in pressure drop in Fig. 4.

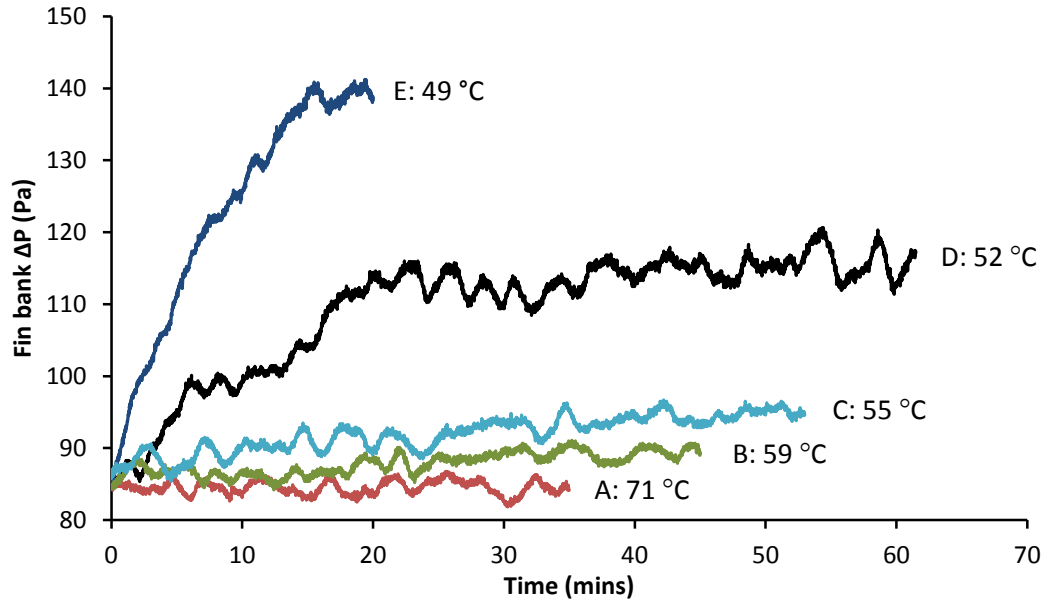


Fig. 4: Pressure drop across the fin bank over time. Air temperatures as labelled with air moisture content constant at 60 g/kg.

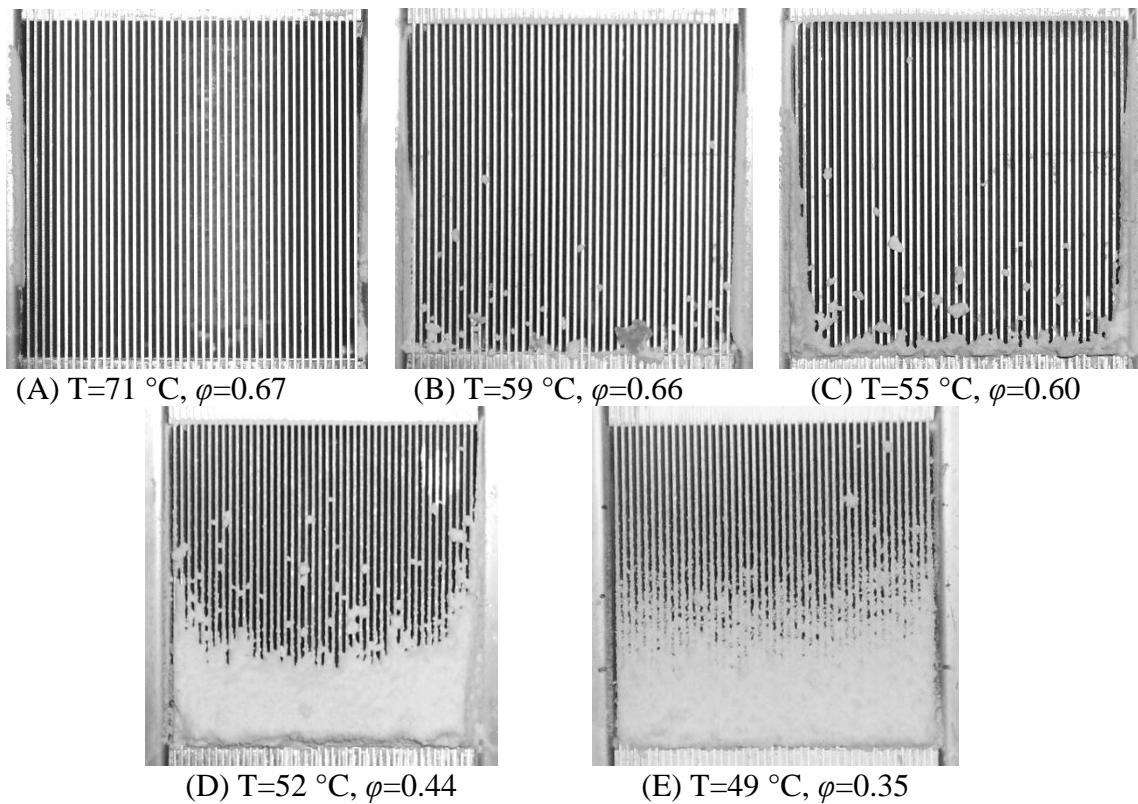


Fig. 5: Photographs of frontal fouling for various air temperatures and a constant air moisture content of 60 g/kg. Photos were taken at the end of each test.

Deposition favoured the bottom half of the fin bank (Fig. 5). This affinity is due to gravity causing particles to settle out of the air flow. As a result a greater share of the injected powder passes through the bottom half of the fin bank. Deposition and blocking tended to initiate at the bottom of the fin bank face before moving up the face until the net deposition rate was close to zero.

Critical pressure drop, velocity and stickiness

The pressure drop asymptotes from Fig. 4 can be plotted against powder stickiness, $T - T_g$, as shown in Fig. 6. The pressure drop results of the fin bank test have similar characteristics to literature results for the Particle Gun test shown in Fig. 1. The critical $T - T_g$ value after which deposition initiates is identified as $(T - T_g)_{crit}$ and has a value of 37 °C. This $(T - T_g)_{crit}$ value is very close to the Particle Gun test results of Patterson et al., where $(T - T_g)_{crit}$ was 37.5 °C, although the reported velocity of the Particle Gun air jet was considerably higher at 20 m/s and the powder tested was Whole Milk Powder. The closeness of $(T - T_g)_{crit}$ values may therefore be mere coincidence.

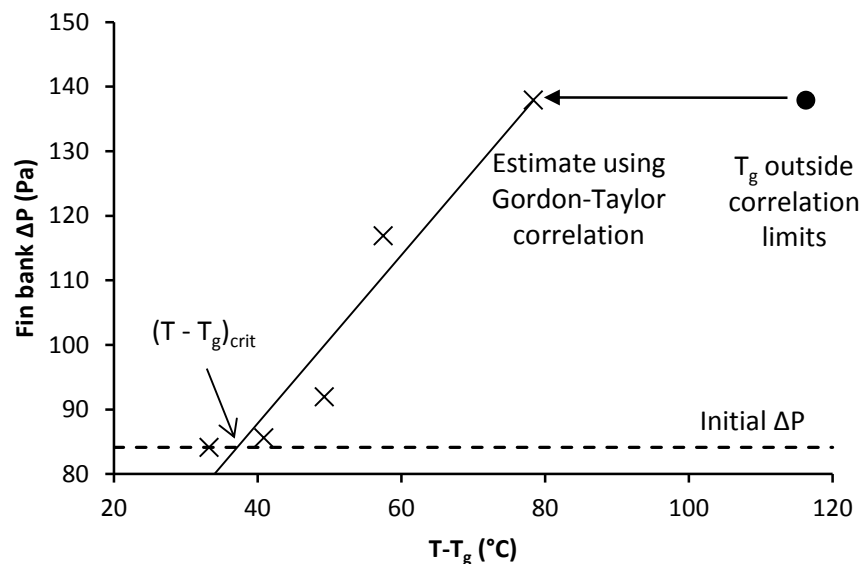


Fig. 6: The relationship of fin bank pressure drop and particle stickiness, $T - T_g$.

Applying Eq. 2, estimates for the velocity through the open area of the partially fouled fin bank are plotted against particle stickiness, $T - T_g$, in Fig. 7. Previous milk powder deposition studies have demonstrated the affect velocity has on critical $T - T_g$ values (Zhao, 2009; Murti et al., 2010). In essence, Fig. 7 represents an equilibrium and critical condition, where the u_ϕ is a function of $T - T_g$. For a given face velocity, the curve in Fig. 7 can be used to predict a critical $T - T_g$ above which deposition will begin to close off small sections of the fin bank. For example, if the face velocity was 6.7 m/s instead of 4.5 m/s as in the tests, then the initial velocity through the open area would be 10 m/s as indicated by u_{ϕ^*} and the expectation would be that significant deposition would not occur until $T - T_g$ is greater than 60 °C. Future work is expected to focus on repeating the tests at different velocities to investigate whether the curve in Fig. 7 may be generalised for all face velocities.

T_g has been calculated using Eq. 1. However the low temperature, high humidity air condition fell outside the valid water activity range of the correlation. Instead a Gordon-Taylor equation (Hennigs et al., 2001) is used to produce a second estimate of T_g and, therefore, $T - T_g$. Both

points are included in Figs. 6 and 7. In this study only one average face velocity has been considered.

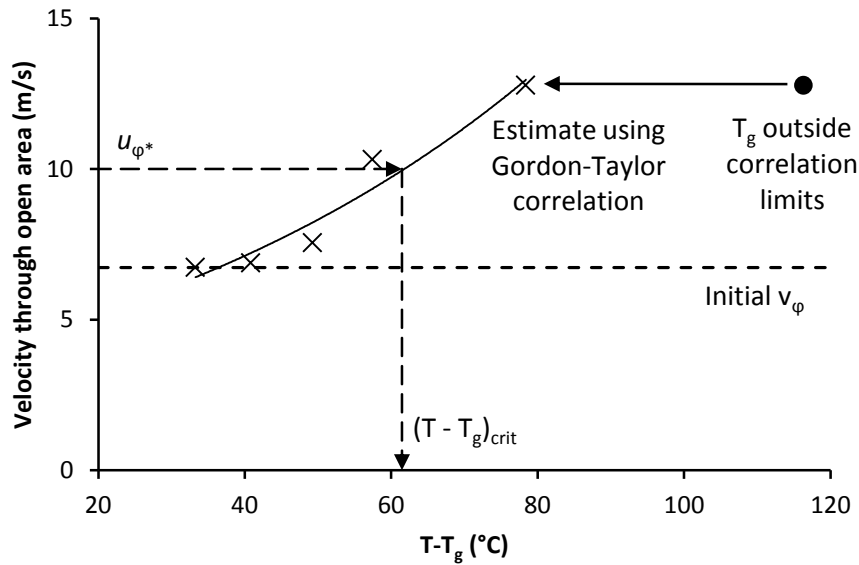


Fig. 7: The impact of particle stickiness, $T - T_g$, on the equilibrium velocity through the open area of the fin bank.

Industrial application

Fouling on the front of compact finned tube heat exchangers applied to exhaust heat recovery in industrial spray dryers is demonstrated to be an important issue. The pressure drop across the lab scale fin bank was shown to increase by as much as 65 %. A similar percentage increase in pressure drop for an industrial heat recovery system may be expected if the exhaust air is driven below 49 °C in the recuperator and sufficient time passes for powder to deposit.

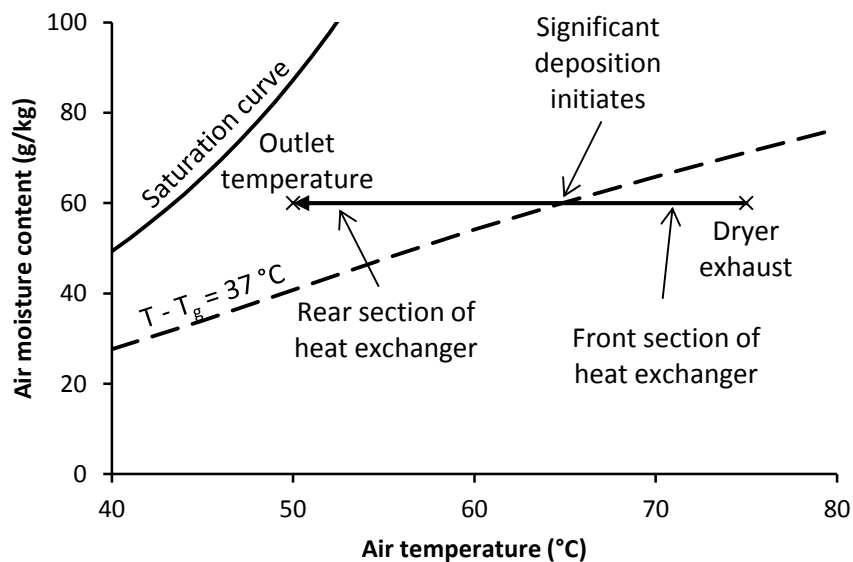


Fig. 8: Psychrometric plot of exhaust heat exchanger.

Fig. 8 shows the relationship between exhaust heat recovery and stickiness, $T - T_g$, using a psychrometric plot. As heat from the exhaust dryer air (75 °C) is recovered, air conditions

cross the stickiness line, $T - T_g = 37$ °C, at an air temperature of 65 °C. Recovering 10 °C of heat from the exhaust is not likely to be uneconomic and so allowances for fouling in the heat exchanger need to be made. In particular, Fig. 8 highlights that the front of the finned tube rows at the rear of the recuperator is likely to encounter deposition issues due to the sticky conditions that exist.

Fouling in an exhaust heat recovery system may be limited by intentionally avoiding critically low temperatures. For example results suggest the exhaust air may be taken down to 55 °C with a relatively manageable level of deposition and pressure drop increase. Other approaches to limiting fouling may include reducing the fin pitch, removing fins completely or operating at a higher average air face velocity. Varying the fin pitch and fin temperature will be investigated in future work.

CONCLUSION

Results show that milk powder deposition can cause a rise in the pressure drop across the fin bank by as much as 65%. The pressure drop across the fin bank is strongly related to the fraction of open area available for air to pass through and the average face velocity. The stickiness level of milk powder is a determining factor in the severity of deposition and pressure drop increase. Application of the results to industry may inform the design of a recuperator to intentionally limit the amount of heat recovery to avoid sticky conditions and prevent high levels of fouling.

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