A NOVEL EXPERIMENTAL METHOD TO ASSESS INDUSTRIAL AEROSOL DEPOSITION IN IDEALISED POROUS CHANNELS

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ABSTRACT: A novel and economical experimental technique has been developed to assess industrial aerosol deposition in various idealized porous channel configurations. This judicious examination on aerosol penetration in porous channels will assist engineers to better optimize designs for various engineering applications. Deposition patterns differ with porosity due to geometric configurations of the channel and superficial inlet velocities. Interestingly, it is found that two configurations of similar porosity exhibit significantly higher deposition fractions. Inertial impaction is profound at the leading edge of all obstacles, whereas particle build-up is observed at the trailing edge of the obstructions. A qualitative analysis shows that the numerical results are in good agreement with experimental results.

1 INTRODUCTION

The meticulous examination of particle agglomeration and eventual particulate fouling will take great precedence in an array of engineering applications commonly found in heavy engineering industries, in particular air cooled heat exchangers in dusty arid regions. Industries are continuously finding novel and economical ways to enhance heat transfer without compromising the environment. A promising material to enhance heat transfer is open-cell metal foam which exhibits superior qualities ranging from higher effective thermal conductivity to larger exchange area as compared to fin-based heat exchangers (Hooman et al., 2012). Despite these advantages, metal foams and fins are both susceptible to fouling which leads to increase in energy consumption and maintenance costs. For example, in the U.S.A., total annual costs of fouling as of 2010 are estimated to be USD $7 billion, equating to about 0.25% of the Gross National Product of the country (Watkinsin et al., 2005). An increase in fouling, for instance membrane fouling in waste water treatment plants means that more energy will be utilized (Australian Water Recycling Center for Excellence, 2014).
Clearly, fouling is a multi-faceted problem. A comprehension into the mass transport in metal foams on micro and macro scale is of paramount importance in order to judiciously optimize metal foam heat exchanger designs for efficient operation of large scale industrial systems.

Several studies have shown promising details in highlighting particle deposition in plain channels (Peters & Leith, 2004; Wu & Young, 2012; Barth et al., 2013). However, to the best of the author’s knowledge, particle-laden flows in both idealized and realistic 3D metal foam structures and other porous structures are diminutive in literature. There are no numerical or experimental investigations based on multi-dispersed particle laden laminar and turbulent thermophoretic flow in either idealized or realistic metal foam structures. Tamayol et al. (2013) determined an optimal micro-cylinder diameter which minimises pressure drop in an ordered array of cylinders inside microchannels. However, the effects of fluid-filled micron-sized industrial aerosols on pressure drop are not quantitatively known. Yang et al. (2014) numerically studied turbulent flows in 3-dimensional arrays of various porous configurations.

Moreover, most existing experimental studies used complex and very expensive configurations such as neutron activation analysis (Lai, 1998) and fluorescence spectroscopy (Wu & Young, 2012). Abdel-Fattah et al. (2002); Peters & Leith (2004); Sun et al. (2013); Wu & Young (2012) conducted laminar and turbulent particle-laden flows but were restricted to plain channels whilst using expensive hardware. Moreover, particle size range was restricted to 1-200µm.

The first step is to gain a comprehensive outlook of the fluid-particle physics in porous media based on idealized configurations. This research aims to examine the transport of heavy industrial dry aerosol particles and the mechanisms that govern deposition and aggregation of aerosols in idealized porous configurations. This research emblematises the use of a novel and economical experimental setup as a feasibility study to in-situ elucidate macroscopic turbulent particle-laden transport and dust deposition mechanisms in porous channels.

3 EXPERIMENTAL SETUP

It is of the author’s intent to examine macroscopic turbulent particle-laden flows in 5 idealized porous structures with respective porosity $\varepsilon$ as shown in Fig. 1 as a steppingstone to get a more systematic understanding of the particle-laden fluid flow transport phenomenon and propensity of solid aerosol deposition prior utilizing real fibrous metal foams. The porosity of these idealized foams is calculated as a fraction of surface area of the void (fluid) space, $S_T - S_{PR}$, to the total area of a configuration $S_T$. The total area of the obstruction walls (metal foam ligaments) is denoted by $\varepsilon = (S_T - S_{PR})/S_T$. Two superficial inlet velocities ($v_i$) of 20.7 m/s and 28.6 m/s are chosen in this investigation to depict turbulent flows in ventilation duct systems (Peters & Leith, 2004). Wood-dust with a diameter of 500 µm and density of 600 kg/m$^3$ is chosen to simulate heavy industrial dust (Saudi Arabia Patent No. US 20130312794 A1, 2013).
The general assembly of the proposed experimental setup is shown in Fig. 2 to study particle transport and aerosol deposition. The use of this novel set up has several advantages: adaptability of existing Particle Image Velocimetry techniques thanks to mobility and transparency of acrylic rig. This makes it easy to capture particle trajectories at any angle throughout the rig. The inlet and outlet manifolds can easily be removed to modify their diameters. A sieving technique offers flexibility to amass any dry aerosol size in need via sieving method instead of an aerosol generator which is expensive and generates particles of limited size; secondly, acquiring multiple generators is costly.

Upon powering the vacuum cleaner, the vacuum chamber gets the dust particles into suspension and transports the aerosols directly into the channel via Tube 1 (22.0 mm diameter). Some particles may be collected at the outlet manifold and driven straight into the vacuum cleaner via Tube 2, whilst the remaining are entrained or deposited in the rig. Particle deposition fractions are determined. The process is repeated for other modules. The dust deposition process can be observed and studied via an optical stereo microscope or a digital camera. The deposition rig is shown in Fig 3. All experiments were conducted under standard temperature and pressure conditions. A fluid Reynolds number of 29,361 and 40,567 corresponding to inlet velocity of 20.7 m/s and 28.3 m/s is registered.
2.1 Experimental results

A summary of the experimental results are presented in Tab 1. The tortuosity $\Gamma$ is calculated as a function of the porosity denoted by the Bruggeman relation: $1/\epsilon_m^{0.5}$ (Bruggeman, 1935; Vijayaraghavan et al., 2012). The modified porosity $\epsilon_m$, is calculated using ImageJ (ImageJ, 2014), is based on the inclusion of deposits in the rig in addition to the obstruction walls at a particular time. The particle deposition fraction $\phi_{ave}$ at $t = 5, 15s$ is calculated as the ratio of total mass of particles left in the domain to the total mass of particles injected to the system. The average deposition fraction is based on two readings. It is clear that all 5 configurations are susceptible to particle deposition over time. Fig. 4 shows the amount of deposited particles left in a module at approximately $t = 15s$ based on two inlet velocities. The mass has been measured using a weigh scale (KERN PLS 1200-3A) with $\pm 0.003g$ uncertainty (Kern-Sohn Precision Balances, 2013). Clearly, the deposits increase with decreasing porosity. Increasing the inlet velocity decreases the fraction of deposits in each modules.
According to Figs 5 & 6, it is shown that larger inlet velocity (28.3 m/s) registered lower aerosol mass concentrations in the rig due to the effects of turbulence. Interestingly, when using a maximum critical speed of approximately 45 m/s, particle deposition is negligible; however, there exists a monolithic amount of dust-laden turbulence and inertial impaction between particle and walls attributable to the difference in inlet diameter and cage width. Inertial impaction greatly surpasses sedimentation in this case.

Irrespective of inlet velocity, inertial impaction (particle bounce) is profound at the front face of any obstruction (leading edge) adjacent to the inlet. It is here that inertial impaction play a dominant role over hydrodynamic interactions in particle transport. Particle deposition or build-up is profound at the trailing edge of the obstructions, an area where vortices or wakes are profound. It is evident that increasing the area and number of obstruction walls leads to an increase in particle-wall interactions, thus increasing aggregate formation and deposition fraction. This further leads to more particles entrapped in the cage for longer periods of time.

Modules 3 & 4 show significantly more agglomerated wood-dust pile up near the entrance of the inlet than any other modules. This is attributable to the leading edges of the obstructions being closer to the inlet together with a larger area that covers the leading edges of those obstructions. This increases the particle-wall interactions and deposition of particles at the vicinity of the inlet.

Although module 1 has similar porosity (ε = 93.0%) to module 5 (ε = 91.1%), a notable difference in deposition fraction is observed at both inlet velocities. For example, at \( v_f = 30.7 \) m/s; 0.64% (module 1) and 3.18% (module 5) at t = 5s, and 1.96% (module 1) and 4.68% (module 5) at t = 10s is calculated. This sudden increase in deposition fraction between the two modules is due to the module 5 having a larger perimeter consequently having a greater probability of particles undergoing inertial impaction and striking the objects whereas module 1 with lesser perimeter and curved geometry has a larger swathe of particles bypassing the obstacle towards the outlet. It is noted that the tortuosities decrease with increasing inlet superficial velocity as less agglomerates are formed at larger velocities. An increase in fluid velocity attenuates the fluid turbulence fluctuations thereby minimizing particle deposition.
Table 1: Summary of experimental results for all 5 configurations at 2 different inlet velocities

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Module¹</th>
<th>εᵣ (%)</th>
<th>Γ</th>
<th>φave (%)</th>
<th>Module²</th>
<th>εᵣ (%)</th>
<th>Γ</th>
<th>φave (%)</th>
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<td>1.24</td>
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<td>87.6</td>
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<tr>
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<td>0.76</td>
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<tr>
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<tr>
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<td>5</td>
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<td>4.68</td>
<td>5</td>
<td>93.6</td>
<td>1.03</td>
<td>2.98</td>
</tr>
</tbody>
</table>

¹Experiments conducted with inlet velocity of 20.7 m/s; ²Experiments conducted with inlet velocity of 28.6 m/s

Module 1

(a) t = 5s
(b) t = 15s

Module 2

(a) t = 5s
(b) t = 15s

Module 3

(a) t = 5s
(b) t = 15s

Module 4

(a) t = 5s
(b) t = 15s
Module 5

(a) $t = 5\, s$

(b) $t = 15\, s$

Figure 5: Deposition patterns for five configurations at $t = 5, 15\, s$ with inlet velocity ($v_i$) of 20.7 m/s
[flow direction: left (inlet) to right (outlet)]
Figure 6: Deposition patterns for five configurations at \( t = 5s, 15s \) with inlet velocity of \( (v_f) = 28.6 \text{ m/s} \) [flow direction: left (inlet) to right (outlet)]

Modules 2, 3, 4 have a greater amount of particle agglomerates accumulating in between the obstructions and cage wall. Module 3 has a more profound build-up between the cage wall due to a lesser distance between the wall and obstruction as compared to module 2. A spoiler could be introduced to a configuration to mitigate dust deposition (Zhang et al., 1992); however, the effects of heat transfer performance remain to be seen.

It is anticipated that heavier dust such as sandstone with density of 2600 kg/m\(^3\) with the same diameter as wood-dust will have larger deposition fractions. This is primarily due to the sandstone has a higher mass and relaxation time (Stokes number of 1469) than wood-dust (Stokes number of 495) is able to withstand the hydrodynamic effects thus requiring more force to drive the concrete or sandstone aerosols towards the outlet.

Preferential deposition zones are discerned by taking into account the fluid wakes or vortices that are clearly visible behind the obstruction walls, opposite the outlet face. The zero fluid velocities in this zone are primarily responsible for particles being quiescent in nature (Fig. 7). Additionally, the large wakes are also responsible for entraining a significant swathe of aerosols behind the obstruction walls. A numerical assessment using ANSYS (ANSYS, 2015) showing incompressible, isothermal, Newtonian fluid (air) velocity vectors confirms this observation as shown in Fig. 7. Due to page limitation, numerical results for \( v_f = 20.7 \text{ m/s} \) is shown only.

For the numerical assessment, a velocity inlet, pressure outlet, and no-slip wall boundary conditions were assigned. A R.A.N.S. Shear Stress Transport k-\( \omega \) (S.S.T. k-\( \omega \)) model is used. The turbulence intensity of 5% and hydraulic diameter of 0.02m is used to directly specify turbulence parameters which is the norm for internal flows (ANSYS Fluent Modeling Turbulent Flows, 2006). The turbulence intensity of 5% for both Reynolds number is assigned as magnitudes ranging from 1-5% is commonly found in relatively simple geometries such as duct flows or pipes (Using Flow Boundary Conditions, 2015). Moreover, a S.I.M.P.L.E. algorithm is used for the pressure-velocity coupling in this steady-state numerical simulation. The following spatial discretization schemes were applied:

- Gradient: least squares cell
- Pressure: second order
- Momentum: second order upwind
- Turbulent kinetic energy: first order upwind
- Turbulent dissipation rate: first order upwind
4 CONCLUSIONS

A novel and economical experimental approach is used to examine macroscopic turbulent particle-laden flow and to better comprehend the mechanisms of particulate deposition in various porous channels. The average particle deposition fraction, modified porosities, tortuosities is evaluated. Evidently, all configurations are susceptible to fouling with particle bounce being significant at the leading edge and particle agglomeration and deposition prevalent at the trailing edge of all obstructions in all 5 modules. Modules 1 and 5 have very similar porosities but their respective deposition fractions differ significantly largely

Figure 7: Comparative study of numerical and experimental results showing fluid (air) velocity vectors
attributable to the geometric configurations of the obstructions. This synergistic approach is part of a long term research project to numerically and experimentally examine industrial aerosol deposition in idealized and real 3D metal foams, and its effect when coupled with heat transfer. The authors will soon replace the idealized obstructions and insert real metal foam of various porosities in order to measure the pressure drop. Moreover, the authors will induct numerical assessment of particle deposition in real and idealized metal foam heat exchangers.

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