Picosecond laser surface micro-texturing for the modification of aerodynamic and dust distribution characteristics in a multi-cyclone system

Omonigho B. Otanocha1*, Li Lin1, Yuanye Zhou1, Shan Zhong1 and Liu Zhu2

Abstract: Aerodynamic flow control in a cyclone is critical to its performance. Dust accumulation in a multi-cyclone is undesirable. This research investigated, the effects of laser-patterned Ethylene-Propylene-Diene Monomer (EPDM) roof in a commercial multi-cyclone system on its aerodynamic and dust accumulation characteristics. Our experimental data show that strategically designed concentric micro-dimples on the cyclone roof can improve both the aerodynamic performance and dust separation capability in the multi-cyclone system. With specific laser-patterned cyclone roof, up to 78% reduction in dust adhesion was demonstrated in one of the cones (cone 9). With the 315-μm diameter micro-dimples on EPDM roof, it was observed that dimples located close to the vortex finder caused an increase in the reverse airflows in the cyclone, thereby effecting entrainment of dust. The overall dust separation efficiency of the multi-cyclone system was at an average of 99.9% with the laser-textured roof, hence no adverse effect on the original cyclone system, in spite of the reported improvements in dust adhesion reduction.

Subjects: Machine Science & Technology; Mechanical Engineering; Technology

Keywords: laser surface modification; multi-cyclone; dust adhesion; aerodynamics; environmental sustainability engineering

ABOUT THE AUTHOR

Omonigho B. Otanocha received his PhD degree from The University of Manchester, School of Mechanical, Aerospace and Civil Engineering (MACE), Laser Processing Research Centre (LPRC). His research involved laser micropatterning, with interests in sustainable manufacture, mechanical design and enterprise development. Omonigho holds an M Eng in Manufacturing Engineering and B Eng in Production Engineering.

The research team at LPRC is part of the innovative manufacturing group at the University of Manchester, with the focus on fundamental research in laser technology applications. Lin Li is the head of the group and chair at the LPRC.

PUBLIC INTEREST STATEMENT

In attending to demands for better livelihood, sustainable product development and the ever-increasing need for corporate social responsibility, innovative approach to the provision of state-of-the-art technologies is imperative. Dust adhesion has been indentified to adversely affect cyclones when operated under certain conditions (e.g. when dealing with fine dust particles with an average size of 1.2 μm). This research endeavour explored surface engineering for operational improvements in cyclones which primarily function in air media, to reduce dust adhesion. Advancements in the laser surface engineering were applied to modify the roof of an existing cyclone system, which brought about improvements that can be translated to energy savings of up to 5%. Dust adhesion which is undesirable in cyclone operation was demonstrably reduced up to 78% in one of the worst cones (cone 9).

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1. Introduction

A cyclonic system is actuated by a high-speed motor (e.g. 37,000 RPM), which generates a “vacuum” condition at approximately -20 kPa. Dust collection within the cyclone is consequent upon the resultant of various forces, which shove the particulate matter to cyclone walls, which is then collected in a container. The centrifugal force generated ensured that the dust is collected on the inner wall surfaces of the container and then finally conveyed to its base (Cortes & Gil, 2007; Zhu & Lee, 1999), while the ‘clean’ air exits via an outlet tube in a reversed air stream (Hoffmann & Stein, 2008). Figure 1 illustrates basic airflows in a gas cyclone system.

Despite the very high dust separation efficiency achievable with cyclone systems, there are situations where dust adheres to the cyclone walls. When processing very fine dust particles, the lower parts of the cyclone units are prone to dust accumulation, leading to clogging during prolonged usage (as highlighted in Figure 2) leading to increased energy consumption and reduced efficiency. These effects are evidently connected to a complex interplay of aerodynamic instabilities within the cyclone separation system involving particulate matter.

In the cyclone system considered in this investigation (and most cyclones), as shown in Figure 1, the top of the inlet is preferably located somewhat beneath the roof, hence any substantial interference occasioned at the roof boundary layer will affect the net air stream and tangential velocity at the conical wall regions. Therefore, a marginal increase in tangential velocity at cyclone conical walls would effectively reduce dust entrainment and improve dust flow downwards towards collection at the exit.

The effect of the roof on the axial position and natural turning length of the vortex as an important cyclone operational parameter for a cyclone was highlighted by Hoffman et al. (Derksen, 2003; Hoffmann & Stein, 2008) who have shown that it is the influence of the vortex finder diameter, rather than its length that would have an important influence on the aerodynamic performance of the cyclone. Suffice it to mention that there are conflicting data and lack of agreement on the complex issue of predicting the natural length of vortex in a cyclone (Cortes & Gil, 2007). In addition to observed dust accumulation at the exit end of a Stairmand high-efficiency cyclone, there were confined concentrations of dust on the cyclone roof during operation (Derksen, 2003).

There is paucity of information concerning dust adhesion and accumulation in literature, notwithstanding the tremendous industrial applications and research interests in cyclone systems for the better part of past 120 years (Bohnet, Gottschalk, & Morweiser, 1997; Enliang & Yingmin, 1989; Hoffmann & Stein, 2008). These include the study of particle/wall interaction dynamics (Cortes & Gil, 2007), pressure losses within the cyclone during operation (Shepherd & Lapple, 1939), effect of dust...
particle sizes and loading rate (Leith & Mehta, 1973; Wan, Sun, Xue, & Shi, 2008), and vortex core instabilities (Ivanov, Dumnov, Muslaev, & Popov, 2013; O’Doherty, Griffiths, Syred, Bowen, & Fick, 1999; Syred, 2006). However, there is a knowledge gap on the understanding the effect of surface structure of the cyclone roof on cyclone aerodynamic behaviour and dust distribution/accumulation.

This paper reports an investigation on the effect of laser-patterned cyclone roof on the system aerodynamics and dust accumulation characteristics, in a commercial multi-cyclone, for the first time.

2. Experimental materials and procedures

2.1. The experimental rig

The cyclone test rig consisted of a dust feeder (to provide continuous dust feed via an incorporated sieve), connected to a multi-cyclone system (Figures 3 and 4).

Pre-measured portions of dust (5 g) particles were fed into the dust feeder, which has an attached voltage-induced vibrator, which ensured that lumps of dust were loosely detached. Dust was introduced into the systems at 5 g/min for 20 min for a standard experimental run. Pressure tapping sensors were located at the air inlet pipe, and connected to a designed ‘LabView’ flow rate data acquisition programme.

After the dust flow experiments, the multi-cyclone pack was carefully de-coupled for dust build-up analysis. Digital optical images were captured with a Canon® PowerShot Pro1 digital camera.
positioned on a tripod overlooking a jig to accommodate the cones to be inspected. Nine shots of images at three different focal positions of specimen were taken per set, while maintaining same dimensional camera location and lighting ‘conditions’, with an autofocus image acquisition setting. An Adobe Photoshop CS5 software package was used to align and blend the images in layers for a qualitative image analysis of the cones inspected. Thereafter, the dust built-up was characterised by collecting dust accumulated within cones of interest. This was done by carefully collecting the retained dust within the each cone of interest into pre-weighed plastic vials to measure differential weights. The bottom opening was similarly measured to evaluate dust adhesion at the smaller exit end of the cone.

Four sets of repeated dust adhesion experiments were carried out for each case study.

An illustration of a multi-cyclone is as shown in Figure 3. Red arrows indicate airstream path feeding the individual cones at their inlet ducts, while the multi-cyclone test rig for dust adhesion experiments is presented in Figure 4.

2.2. Dust particles
Gypsum® plaster—Thistle DuraFinish was used in this research work as the dust. Particle size analysis carried out with a Aerodynamic Particle Sizer (APS) Spectrometer 3,321, ranged between 1 and 1.2 μm in diameter, for 15 different sets of 3 measurements within 5 s intervals. The results for dust aerodynamic diameter are as presented in Figure 5.

The dust specimens were placed within a miniature compartment in a standard kit aerosol dispenser, and ejected using a jet of compressed air into a holding volume (a metallic cylinder, approximately 1.5 m in height and 0.5 m in diameter) that had been purged with particle-free air. This volume was subsequently sampled using a TSI Inc. (Shoreview, MN, USA) model 3,321 APS, through a network of sheathed airflow, the airborne dust particles were accelerated through laser optical detectors (utilising light-scattering intensity in the optics chamber), which generate high-resolution,
instantaneous aerodynamic measurements of particle size data, from the aggregate time-of-flight of distinct particles for interpretation by the device software (aerosol instrument manager). Controlled airflow made possible by a combination of flow pumps and the pressure drop across an accelerating orifice nozzle ensured that the particles travelled along the centre-line of the flow stream.

2.3. Cyclone roofs
Ethylene-Propylene-Diene Monomer (EPDM) and 50-μm thick stainless steel foils (as inserts on the EPDM roof) were the materials used in this investigation. EPDM is a commercially available multipurpose sheet rubber, usually black in appearance. They find considerable applications as sealing accessories in mechanical components and most gaskets, with operational temperature ranges from -65 to +220 °C, and a mass density of 1,180.8 kg/m³ mm (Blackley, 1983; Marlier, 2010; Plaček, Kohout, Hnát, & Bartoniček, 2009).

Plain EPDM sheets of 1.4 ± 0.1 mm thickness (with inner and outer diameters of 8 mm and 36 mm, respectively) as shown in Figure 6(A), and an Ra = 4.4 μm used as the sealing component within the multi-cyclone assembly (formed as rims over individual cyclone upper edges, around the vortex finder) were used in this investigation. The EPDM roofs were surface patterned using a picosecond laser to create dimensionally identical micro-dimples arranged in a concentric manner along the various circumferences (Figure 6(B)). Stainless steel (Ra = 13 nm) inserts of 50 μm thickness were similarly laser patterned and care was taken to avoid air leakages in order to maintain vacuum conditions within the cyclone by permanently attaching the stainless steel inserts well within the cone roof, as with the plain EPDM roof, with the vortex finder centre used as concentric reference.

The circular patterns for the cyclone roof were of two different diameters, 1.5 mm (Figure 7(A)) and 315 μm (Figure 7(B)), respectively. These circular patterns were separately populated close to and away from the vortex finder, in twenty one, three and two rings respectively, to investigate their effects on dust dynamics at the upper region of the cyclone. These patterns were machined on the EPDM roof components and stainless steel inserts, with various depths ranging from 0.05–1.4 mm.
The EPDM sheets and stainless steel foils were patterned with a picosecond laser. The EPDM was laser patterned at a 80-mJ/cm² laser energy density (fluence) a 300-mm/s scanning speed, with varying number of passes (maximum of 5 scans) to achieve an increased depth of pattern, while the stainless steel foils were laser textured at a 330-mJ/cm² laser fluence and a 400-mm/s scanning speed. As indicated in Figure 4, between 48–63 shapes and adjoining perimeter rings (12 and 32 mm diameters) were patterned sequentially.

An Edgewave picosecond laser machine (Model: QX; SN 0416) was used for micro-fabrication processes in this research work. The laser is a diode-pumped system (oscillator: Nd:YVO4) with an optical emission wavelength of 1,064 nm (infrared, invisible) at a pulse length of 10 ps operating at a repetition rate of 102 kHz–19.2 MHz. The laser was operated with an average output power up to 100 W, with pulse energy up to 1 mJ and maximum peak power at 100 MW. The beam quality factor M² = 1.2 and pulse energy stability < 4% rms variation. Laser beam was diverted by several mirrors into a galvo scanning mirror, then focused by an F-theta lens. The incorporated galvo (Scanlab Curryscan 20) scanning system had scan rates up to 10 m/s. This was located on a PRO 165 Aerotech vertical Z-axis: 400 mm traverse range, 0.5 μm resolution, 1 μm repeatability, 2 μm accuracy, 150 mm/s maximum velocity. The specimen stage was an Aerotech high dynamic XY-linear motor table: 400 mm × 400 mm traverse, 20 nm resolution, 2 μm accuracy, maximum velocity 500 mm/s, maximum acceleration 0.5 g, maximum load 75 kg. Control unit includes a computer and display (G &M codes) and Windows-based software to control the laser, the translation tables and the scanner, for the fabrication of patterns on the injection moulding tools. The experimental set-up for the laser surface modification of EPDM cyclone sealing sheets is as shown in Figure 8.

Figure 7. Illustration of circular patterns on the cyclone roof to be generated in this investigation: (A) patterns close to vortex finder and (B) micro-patterns in two rings away from vortex finder.

Figure 8. Schematic for picosecond (PS) laser micro-patterning of EPDM sheet, with Galvo scans.
The various concentric circular micro-patterns and main surface materials used as roof in the multi-cyclone for this enquiry are presented in Table 1.

### 3. Results

Different depths of micro-patterns from 50 μm up to 1.4 mm (through hole) were produced with the picosecond laser on the EPDM roof to form 48 micro-conical structures (tapered circular blind holes) by varying the beam scanning speed while maintaining other laser processing parameters (power, frequency and number of scans) as shown in Figure 9.

#### 3.1. Multi-cyclone roof patterns—dust adhesion experiments

Graphical plots (Figure 10) of the respective airflow rates for the baselines (plain and patterned) of EPDM roof sheets used in the dust experiments consistently show a fluctuation between 1975 and 2,200 L/min, for the 20 min of dust adhesion test duration.

The dust retained within the cones (5–10) was carefully collected with fine brush and weighed in an enclosed digital scale. Cones 1–4 and 11–14 were comparatively ‘clean’, since there were negligible amounts of dust retained (≤ 15 mg) within these cones after repeated trials. The enclosure ensured minimal external interference with the sensitive scale measurements. With the EPDM roof, the dust retained was an aggregate of weight of roof before and after the dust experiments.

The amount retained within the cones with patterned and plain EPDM (baselines), after dust adhesion experiments (tests were repeated 4 times) are presented in Table 2. The results show clearly an

| Name             | Material | Top diameter (μm) | Deepest depth (μm) | Base shape     | Note               |
|------------------|----------|-------------------|--------------------|----------------|--------------------|
| Micro-dimple     | EPDM     | 314               | 315                | Bell shaped    | Shallow etching    |
| Deep micro-dimple| EPDM     | 314               | 719                | Conical        | Blind deep etching |
| Micro-frustum    | EPDM     | 380               | 1,200              | Conical        | Cut through        |
| SS insert        | SS       | 50 μm             | 1,100              | Flat           | Stainless steel    |

Figure 9. Microscopic images of picosecond laser-perforated EPDM roof material.
Up to 78% reduction in dust adhesion is shown in Cone 9. The effects of patterned roof were compared with plain EPDM (control) by linear measurements of the corresponding exit opening diameters of individual cones in the multi-cyclone. Four diametric lines from a common central point at different angular rotations were employed. For each cone, an average of the diameters was calculated for the 4 repeated dust experiments, as shown in Figure 11, with particular interests in cones 8, 9 and 10. Results for four repeated dust adhesion experiments comparing bottom opening diameters of picosecond laser-patterned EPDM (micro-dimples) cyclone roof with baseline cases are presented in Figure 12.

The bottom opening diameters for dust adhesion experiments with the picosecond laser-patterned 50-μm stainless steel roof inserts are compared with those of the plain EPDM roofs shown in Figure 13. The results show that, with the laser-textured roof, dust accumulation at the cyclone exit opening was reduced consistently for all the cones tested.
Initial experimental results from dust experiments with PS laser-patterned concentric and continuous micro-grooves (average kerf width of 103 μm and 55 μm depth) on the cyclone roof, to mimic the radial airflow pattern (Figure 14(A)), show dust accumulation within the micro-grooves. This worsened the dust adhesion problem as the expected effects of the micro-grooves on the roof boundary layer created more room for the incoming airborne dust to be trapped within the grooves on the EPDM roof (Figure 14(B)).

Following the standard experimental procedure described, other EPDM roofs with different depths (200 μm–1.4 mm) and largest surface diameter of 315 μm, arranged in 2 and 3 concentric rings away from the vortex finder, were tried to observed effects on airflow within the cyclones. Figure 15 explains EPDM roof with 3 rings of circular micro-patterns of 715 μm depth, while a comparison of dust retention in the cone with baseline, is displayed in Figure 16.

To investigate if the effect of the circular micro-pattern depth on the airflow near the EDPM roof was material dependent, stainless steel sheets of 50 μm thickness were similarly laser patterned (cut through) and fixed as inserts on the EPDM roof, and dust experiments performed as described in procedure. The stainless steel inserts on the EPDM roof provided baseline depths of 50 μm, before attachment to the EPDM roof. Flat dimples were formed when the 50-μm stainless steel foils with cut through circular patterns, were fixed to the EPDM roof material. The circular cuts had an average of

![Figure 12. Graph comparing bottom opening diameters of picosecond laser-patterned EPDM (micro-dimples) cyclone roof with baseline cases—four repeated dust adhesion experiments. Here, the baseline is the case with the plain roof without patterns.](image)

![Figure 13. Cyclone bottom openings for laser-patterned 50-μm stainless steel foils (with cut through two rings of concentric circular patterns of 1.2 mm diameter) attached to EPDM cyclone roof.](image)

![Figure 14. PS laser-patterned cyclone ‘roof’ (cone 5) with concentric circular micro-grooves with 103 μm kerf width and 55 μm depth: (A) before, and (B) after, dust adhesion test.](image)
3.6 mm as surface circumference, forming 24-μm flat dimple depth on the EPDM base. The inter-patter spacing was 1.8 mm in the radial direction, and 1.9 mm in the transverse direction (Figure 17).

Most portions of the micro-dimple (1.2 mm base diameter) created by the steel foil edges with EPDM on the background were largely free of dust, except the steel foil edges with minute dust on the airflow radial direction as observed in Figure 18.

The surface roughness values for both the EPDM (average Ra = 4.4 μm) and the 50-μm stainless steel roof inserts (Ra of 13 nm), were analysed for wall surface–dust particle adhesion effects.

The efficiency was calculated by dividing the aggregate weight of dust collected within the cyclone pack (without the post filter), by the total dust accumulated (for the entire cyclone assembly—both cyclone pack and post filter). The dust portion trapped in the post filter unit represents ‘emissions’, being dust escaping (or entrained) in the reverse swirl flow through the top section of the multi-cyclone system. Table 3 gives a sample calculation of the efficiency of separation for the multi-cyclone system. The dust retained in the post-filter (located at the exit airflow upper chamber)
was trapped from being emitted into the environment. Table 4 is a summary of separation efficiency for four repeated multi-cyclone dust experiments.

It is worth noting that an average of 8% dust unaccounted for within the multi-cyclones pack is lost within the dust feeder and connecting hose (Figure 4). Also, dust observed within the post-filter
was counted as emissions, since they are borne by the reverse air stream exiting the multi-cyclone system.

4. Effects of patterned EPDM roof on multi-cyclone aerodynamics

Experiments were carried out on the multi-cyclone system without dust introduction, to compare plain EPDM roof (control) and two separately patterned EPDM roof sheets (each of the 14 cones with similar patterns). This was done to observe possible effects of the patterned roof on the cyclone system aerodynamics. Results are shown in Figure 19. For each experimental run, the multi-cyclone was run for 4 min and 12,000 data points (for inlet velocity and dynamic pressure measured by a Pitot tube) were collected using digital acquisition cards and LabView programme. Averages and error values over 1,000 batches of the data were analysed and presented in Figure 19.

Table 4. Summary of the separation efficiency for patterns (2 concentric rings) on cyclone roof, after 4 repeated experiments

| Cyclone overall separation efficiency (%) | Plain EPDM roof | Laser-patterned EPDM Roof | Laser-patterned 50-μm SS Insert Roof |
|------------------------------------------|-----------------|---------------------------|--------------------------------------|
| Ave                                      | Std. dev        | Ave                       | Std. dev                             |
| 100                                      | 0.0             | 99.9                      | 0.14                                 |
| 99.9                                     | 0.12            |                           |                                      |

Figure 19. Comparative aerodynamic data for experiments without dust input; for plain EPDM roof (control) and patterned EPDM roof: dimples and micro-frustum.
As shown in Table 5, comparatively, there was approximately 3% reduction in inlet velocity and 5% reduction in the dynamic pressure across the cyclone, when dimple patterns were applied on EPDM roof.

### Discussion

Laser-patterned roof has resulted in improved dust adhesion in the multi-cone cyclone system. The patterned roof has resulted in an alteration of the cyclone aerodynamics. In this research, particular attention was given to cones 5–10, due to preliminary dust adhesion experiments which had consistently shown that cones 1–4 and 11–14 were least affected. This could be due to their positions, since dust-laden air comes into the multi-cyclone near the region where cone 1 is located, and flows round (counter clock-wise, Figure 7) with the ‘steepest’ bend around cones 7, 8 and 9. This indicated the possible reasons for large volumes of dust deposits in these cones, as observed in this investigation.

The circular micro-dimples on EPDM cyclone roof proved effective in moving the dust particles farthest downwards to the exit. In spite of other complex factors, for example: charge effects and pressure fluctuation, at play within the cyclone yet to be fully understood in this research, possible reasons for this occurrence may be the formation of turbulent bursts of minute reversing flows within the circular micro-dimples. This action would invariably lead to a shift in the boundary layer in the radial flow across the roof to cause increased swirl flow, hence an improved tangential flow of the fluidised bed to the exit bottom end of cone, hence effect less dust accumulation.

The micro-dimples arranged along the radial flow path of the main airflow direction create turbulence near its walls, as indicated in Figure 19. These localised, short-duration, intermittent dynamic fluctuations of the instantaneous velocity profile near the walls, act not to alter the mean field flow, but rather to sustain it. One possible explanation is that the roof patterns change the roof flow in a manner that the particle trajectory is affected afterwards. Since the particle trajectory changes, the condition for build-up is different, which may lead to the reduction.

The shallow dimples helped in the establishment of sustained near-wall turbulences through localised, short bursts of intermittent dynamic fluxes of instantaneous velocity, at the cyclone roof. These dynamic fluxes rather than alter the mean field flow acted to maintain it, as demonstrated in Figure 20, by discharge of minute volumes of fluid from the micro-dimple, hence less dust deposits.

Despite the variation in the base diameters between the patterned EDPM and steel foil inserts, there were considerable reductions of dust adhesions within the cyclones, for dimples located approximately 6.5 mm from the outer edge of the vortex finder.

The effects of regular micro-dimples on the cyclone roof in promoting axial velocity component of the swirling air stream is the primary reason for the observed dust adhesion reduction. This agrees with the experimental observation by Hoffmann and Stein (Hoffmann & Stein, 2008). The finer particles (≤ 1.2 μm) are effectively collected due to the high efficiency of the multi-cyclone assembly.
instance by the associated very high-volume flow rate, hence highly reduced recirculation within
the cyclone.

As observed by some researchers (Karagoz & Avci, 2005; Kaya, Karagoz, & Avci, 2011), the inten-
sity of the swirl flow and the pressure drop across the cyclone are adversely affected by wall friction.
This is most prominent in cyclones with high inlet velocities, hence, with the evidence from this re-
search, when the boundary layer is effectively triggered by minute turbulence within the designed
micro-depth dimples; the radial flow on the roof is sustained to drive the swirl flow with an increase
in the axial velocity component which translates to more dust getting to the exit for collection. The
consequences of having tangential and axial velocities well sustained are better particle separation
processes and a minimisation in the inlet-to-outlet pressure drop in the cyclone.

To explain and understand these phenomena, the following analyses are given. Considering an
individual cone within the multi-cyclone pack, the terminal settling velocity (the air velocity at which
dust particles will just begin to ascend with the airflow) of the dust particle follows Stokes’ law and
is represented by (Hinds, 2012; Weiner & Matthews, 2003):

\[ V_t = \frac{g d_p^2 (\rho_p - \rho_g)}{18 \mu_g} \]  

(1)

where:

- \( V_t \): terminal or settling velocity of particle
- \( g \): acceleration of particle due to gravity (980 cm/s²)
- \( d_p \): physical diameter of the particle (cm)
- \( \rho_g \): gas density (g/cm³),
- \( \rho_p \): particle density (g/cm³), and
- \( \mu_g \): gas viscosity (g/(cm . s))

Due to the consequence of ‘slip’, the formula of settling velocity is modified by a slip correction
factor \( C_c \),

where \( C_c \) (a non-dimensional number) is the slip correction factor, and

\[ C_c = 1 + \frac{\lambda}{d_p} \left[ 2.34 + 1.05 e^{(-0.39 \frac{d_p}{\lambda})} \right] \]  

(2)
For air, $\lambda$ (the mean free path of the gas) is 0.066 μm at standard temperature and pressure (Agranovski, 2011; Jennings, 1988; Kulkarni, Baron, & Willeke, 2011).

By substituting values:

$$C_C = 1 + \frac{0.066}{1.2} \left[ 2.34 + 1.05e^{-0.39 \frac{1.2}{2.34}} \right]$$

$$C_C = 1.129$$

Therefore,

$$V_t = \frac{gd_p^2(\rho_p - \rho_g)C_C}{18 \mu_g}$$

(4)

By substituting in values for

$$g = 980 \text{ cm/s}^2; \ d_p = 1.2 \times 10^{-4} \text{ cm}; \ \rho_p = 2.3 \text{ g/cm}^3; \ \mu_g = 1.85 \times 10^{-3} \text{ g/cm} \cdot \text{s};$$

$$V_t = \frac{(980)(1.2 \times 10^{-4})^2(2.3)}{18(1.85 \times 10^{-3})}$$

Thus,

$$V_t = 9.75 \times 10^{-4} \text{ cm/s}$$

With average particle diameter ($d_p$) measurements at $1.2 \times 10^{-4}$ cm, the volume of the dust particle is:

$$Vol_p = \frac{\pi (1.2 \times 10^{-4})^3}{6}$$

$$= 9.05 \times 10^{-13} \text{ cm}^3$$

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Table 6. Data for the volume of cut through circular patterns (conical micro-frustums) on EDPM roof

| $R_1$ (mm) | $R_2$ (mm) | $h$ (mm) | $V$ (mm$^3$) |
|------------|------------|--------|-------------|
| 0.38       | 0.35       | 1.48   | 0.62        |

---

Figure 23. Close-up inspection of cone 8 with patterned SS insert roof.
Therefore, \( m_p = \rho_p \cdot V_{ol_p} = 2.3 \times 9.05E-13 = 2.08 \times 10^{-12} \) g

Dust particle density \( (\rho_p) \) is assumed at 2.3 g/cm\(^3\) (particle density for Gypsum = 2,300 kg/m\(^3\)).

The dust adhesion dynamics observed around the (plastic) vortex finder where it connects with the EPDM roof layer, suggest that surface electrical charges could play a significant role in how well (charged) dust attaches to plastic surfaces. This effect has been studied and will be presented in a separate paper, as it was not the main focus of the research findings herein reported.

The choice of the 50-μm stainless steel foils as an insert on the EPDM cyclone roof was designed to provide an even surface geometry and equal depth for the patterns machined with the picosecond laser. With the plain EPDM material, the ability to scale up the base diameter of laser-fabricated dimples was limited to an average of 315 μm due to the delicate nature of the material as revealed with the extremely high material etch rate (5,760 mm3/min) with a single pass at focused position. Attempts to increase the base diameter for cyclone dust distribution assessment purposes, by a defocused laser beam, compromised the desired average depths (230–315 μm) which were noticeably better with preliminary EPDM roof cyclone dust dynamics. Hence, the 50-μm stainless steel foils as inserts provided the platform for consistent 50 μm depths with all cut through patterns, before being attached to the cyclone roof.

With the 315-μm diameter micro-dimples on EPDM roof, it was observed that dimples located close to the vortex finder caused an increase in the reverse airflows in the cyclone, thereby effecting entrainment of dust, and affected dust accumulation in the vortex finder as indicated in Figures (11 and 16). For the EPDM roof with cut through circular patterns (conical micro-frustums), the hollows were filled with dust through the action of dust-laden radial airflow at the roof. Micro-spiral offsets from the main flow are responsible for this filling activity, these dust residues were well formed within the conical micro-frustum that they remained when the EDPM roof layer was carefully lifted, as shown in Figure 20.

As observed (Tables 3 and 4) with all the patterns investigated, the overall separation efficiency of the multi-cyclone system was at an average of 99.9%.

For the EDPM roof with cut through circular patterns (conical micro-frustums), the volume filled with dust is calculated by putting values into equation (5), as presented in Table 6.

The volume of a conical micro-frustum can be deduced from the equation of a conical frustum thus (Weisstein, 2015):

\[
V = \frac{1}{3} \pi h \left( R_1^2 + R_1 R_2 + R_2^2 \right) \tag{5}
\]

| Table 7. Evaluation of dust retained within various cones of picosecond patterned 50-μm stainless steel insert on roof |
|---------------------------------------------------------------|
| Dust retained in cone (mg)                                      |
| Cone 5 | Cone 6 | Cone 7 | Cone 8 | Cone 9 | Cone 10 |
|--------|--------|--------|--------|--------|--------|
| Control (plain EPDM)             | 244.7  | 136.6  | 101.8  | **159.6** | 122.1  | 128.5  |
| Std. dev.                        | 17     | 5.7    | 5.7    | **15.9** | 16.2   | 9.2    |
| Patterned 50 μm SS (2 rings)     | 192.7  | 127.1  | 94.3   | **161.9** | 95.8   | 117.8  |
| Std. dev.                        | 3.8    | 4      | 4      | 3.4     | 4.4    | 7.8    |
| Difference                       | 52.0   | 9.5    | 7.5    | **−2.3** | 26.3   | 10.7   |
| Percentage Reduction (%)         | 21     | 7      | 7      | **−1**  | 22     | 8      |
where:

\[ R_1 \text{ (large radius on the surface in contact with the cyclone inner space) and } R_2 \text{ (at the base, in contact with the supporting roof assembly) are the respective radii of a conical micro-frustum on the EPDM roof. } \]

\[ h \text{ is the thickness of the cut through EPDM roof (i.e. height of a conical micro-frustum).} \]

Therefore, each conical micro-frustum on the EPDM roof had 0.62 mm\(^3\) capacity to retain dust during the particular experiments. This was not desirable for the proper operation of the cyclone, since the dust was meant to be separated at the cyclone walls and transported to the exit for collection. Also, with the dust being collected at the roof, the tendency for increased emissions was high due to reverse flows and aerodynamic effects associated with the laser-patterned micro-frustums. Shown in Figure 21 are dust residues retained within micro-frustum EDPM roof.

Figure 22 shows the laser-patterned EPDM roof with 21 rings of 2,903 concentric micro-dimples 710 μm deep and with top surface diameter of 326 μm, conical circular micro-patterns, before and after dust experiment. This was the worst case of dust accumulation on the cyclone roof (on cones 5, 6, 7, 8, 9, 10) observed in this research, indicating the most emission and dust entrainments through the reverse flows within the cyclone.

The observed difference between the surface roughness values for both materials used for the cyclone roof might have affected their dust adhesion capacity. Comparatively, under similar test conditions, the EPDM sheets with an average \(Ra = 4.4 \mu m\) had more dust accumulation than the 50-μm stainless steel roof inserts (\(Ra of 13 \text{ nm}\)). Also, as can be noticed with Figure 22, the micro-dimples in 21 rings saturated round the vortex finder accumulated the most dust in this research. This corroborated other research evidence which demonstrated that as dust particles adhere to the wall...
surfaces, wall roughness increases (Hoffmann & Stein, 2008), thereby promoting more dust accumulation.

As highlighted in Table 7, there was comparative increase (1.4%) in the weight of dust retained in cone 8, while the other cones had reductions. This was peculiar to the patterned steel foil inserts. There was noticeably more dust agglomeration as evidenced by the numerous dust spatters round the cone rim and within the cone (Figure 23). This occurrence could be related to charge effects and the increased dynamics in the radial flow at the roof, due to the flat dimples created by the picosecond patterned SS inserts.

Results in Figure 19 and Table 5 indicate that without dust introduction, there is a 3% reduction in inlet velocity and 5% reduction in the dynamic pressure across the cyclone, when dimple patterns are applied on EPDM roof. These effects could have introduced flow resistance in the radial airflow at the roof, hence reducing the inlet flow going directly into the vortex finder. With the introduction of dust, the entire aerodynamics in the multi-cyclone is changed, these results support the improved dust separation reported with patterned dimpled roof. Hence, without any significant compromise in over cyclone system separation efficiency, reduction in pressure across the cyclone would translate to decrease in energy usage.

6. Conclusion
The following conclusions can be drawn from the experimental findings:

• Cyclone roof with picosecond laser micro-patterned ‘shallow dimple’ (with an average depth of 315 μm and top diameter of 315 μm) effected up to a 78% reduction in dust accumulation within the multi-cyclone system.

• The overall separation efficiency of the multi-cyclone was consistent at an average of 99% during all the cases of dust experiments, in this research.

• Concentric circular patterns located 6.5 mm from the vortex finder walls gave best results. It was observed that finer dust (≤ 1.2 μm) get accumulated on the roof with patterns located closer the vortex finder tube. Also, results indicate that shallower dimples on the roof caused less dust accumulation on roof, with similar values for the exit opening diameters.

• The reasons responsible could be a result of ‘opportunistic’ small vortices generated within the individual patterns (further investigations needed).

• It was observed that material surface roughness of the cyclone roof affected its dust adhesion capacity. Under similar test conditions, the EPDM sheets with an average Ra = 4.4 μm had more dust accumulation than the 50-μm stainless steel roof inserts with an Ra of 13 nm. Though, the likely effects of charge need to be further investigated.

• The picosecond patterned steel inserts on cyclone roof, generally improved dust exit opening diameter of cones, but consistently caused an average 1% more dust adhesion within the cone 8 in the multi-cyclone system.

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Author details
Omonigho B. Otanocha1
E-mail: Omonigho.Otanocha@postgrad.manchester.ac.uk

ORCID ID: http://orcid.org/0000-0002-9816-6011
Li Lin1
E-mail: lin.li@manchester.ac.uk
ORCID ID: http://orcid.org/0000-0002-4465-0342
Yuanye Zhou1
E-mail: yuanye.zhou@manchester.ac.uk
Shan Zhong1
E-mail: shan.zhong@manchester.ac.uk
Liu Zhu2
E-mail: Zhu.Liu@manchester.ac.uk

1 School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK.
2 School of Materials, The University of Manchester, Manchester M13 9PL, UK.
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