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An empirical investigation into the influence of pressure drop on particle behaviour in small scale reverse-flow cyclones

C.W. Haig [a,*], A. Hursthouse [b], S. Mcilwain [a,1], D. Sykes [c,2]

[a] School of Computing & Engineering, University of the West of Scotland, Hamilton ML3 0JB, UK
[b] School of Science & Sport, University of the West of Scotland, Paisley PA1 2BE, UK
[c] Hoover Candy, 1 Forrest Gate, Tannochside Business Park, Glasgow G71 5PG, UK

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ABSTRACT

The operation of small scale reverse-flow cyclones under high flow rates and light solid loadings is poorly understood. This empirical study extends previous investigations into the relationship between particle behaviour and cyclone operating conditions. Previous work concluded that particle agglomeration and attrition occurring in a small scale Stairmand cyclone were heavily dependent on inlet velocity. We report on the performance of two cyclones with similar geometries, but with a 66.2% difference in their vortex finder diameters. Despite inlet velocities that differ by less than 5.7%, the relative pressure drops vary between 96.5 and 105.7% from each other, which contributes to a significant difference in the separation efficiency curves of the two cyclones. The smaller vortex finder diameter produces superior separation efficiency and increased particle attrition. This implies that pressure drop across the cyclone and not inlet velocity is the critical parameter when considering particle behaviour in cyclones of different designs. The study also demonstrates the non-linear relationship between particle cut-size diameter and pressure drop, implying that the cut-size diameter may approach an optimum size. Further to these investigations the study reports near identical separation efficiency curves produced by two geometrically dissimilar cyclones. Although the inlet and vortex finder velocities of the two cyclones differ by 41.0% and 65.3% respectively, there is only a 2.1% difference in pressure drop. This observation prompts the suggestion that the influence of pressure drop on separation efficiency is greater than considerations of cyclone geometry and scale.

1. Introduction

With their simple geometric designs belying complex air flow patterns and particle behaviour, for almost nine decades, cyclonic separators have been a topic of academic and industrial research [1,2]. By utilising the centrifugal force, cyclones separate harmful or nuisance airborne particulates or liquid droplets [3], while their robust structures, inexpensive construction and low maintenance costs contribute to their enduring industrial popularity. Traditionally research has focused on large scale cyclones due to their significance to industrial applications, however small scale cyclones are finding applications in fields as diverse as bioaerosol sampling [4], aerosol drug delivery systems [5], cyclonic vacuum cleaners [6], pre-filtration of dust in automobile ventilation [7] and combustion engines [8,9].

Seeking to increase the understanding of the complex nature of particle behaviour in cyclones and therefore to allow improvement in cyclone design, this empirical study investigates the performance of four small scale reverse-flow cyclones with tangential inlets, operating under high air flow rates and light solid loadings. Three of these cyclones are based on dimensions from commercially available domestic, cyclonic vacuum cleaners, acknowledging the lack of widely available data of such cyclones despite their prevalence in the market place. The general dimensions of two of these cyclones are similar, while the third cyclone, although still classed as small scale, is a little larger and comparable with a Stairmand cyclone of 40 mm body diameter. The Stairmand cyclone is a specific design of a tangential-inlet style cyclone [10] and such a design with a 40 mm body diameter comprises the fourth cyclone in this study.

Previous investigations reported empirical data demonstrating particle agglomeration and attrition occurring in a Stairmand cyclone with a 40 mm body diameter [11]. Specifically the study noted that when the cyclone was operating under light solid loadings and an inlet velocity of 15 m s^{-1}, agglomeration of fine particles occurred solely within the cyclone body and not within the inlet or the associated upstream piping. On increasing the inlet velocity to 30 and 45 m s^{-1}, an increase in the production of fine particles through attrition was observed, while further investigations excluded the re-entrainment of fine particles from the collection bin as a possible source of the greater number of fine particles leaving the cyclone. The study proposed that

* Corresponding author. Tel.: +44 1563 826773.
E-mail address: collette.haig@uws.ac.uk (C.W. Haig).
[1] Current address: Mitsubishi Electric R&D Centre Europe — UK, Livingston EH54 5DJ, UK.
[2] Current address: Ricardo-AEA, 18 Blythswood Square, Glasgow G2 4BG, UK.

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Table 1
Dimensions of the four small scale cyclones investigated in this study (mm).

Cyclone	Inlet depth	Inlet width	Cyclone diameter	Dust outlet	Cyclone height	Cone height	Vortex finder diameter	Vortex finder depth	Vortex finder wall width
	a	b	D	Bc	Ht	Ht-h	D_x	S	Vw
Cyclone A	11	5.5	30	7	70	59	17.5	11	1
Cyclone B	8.9	7.2	29	6.5	73	64	8.8	11	1.4
Cyclone C	25	11	52	13.1	150	75	21.6	29	1.5
Stairmand	20	10	40	10	160	80	20	30	1

the agglomeration of fines was induced by the complex air flow currents occurring in the cyclone body, while the production of fines at higher inlet velocities was caused by attrition through impact with the cyclone walls brought about by the higher kinetic energy of the particles.

The study of four small scale cyclones described here reveals that the influence of pressure drop across the cyclone on particle behaviour is significantly greater than that of inlet velocity or air flow rate as reported previously. Further these observations suggest that pressure drop has significant influence over the complex air flow patterns within cyclones and subsequently the forces acting on particles undergoing cyclonic separation.

2. Small scale cyclones — applications and cyclone function

Small scale reverse-flow cyclones are increasingly attracting the attention of researchers, with size specific studies being carried out by various authors [5,10,12–20]. A previous study described the class of small scale cyclones as having a body diameter less than 0.1 m and the same upper range limit is applied in the work reported here [5].

2.1. Applications

In common with their industrial scale counterparts small scale cyclones are used to remove harmful or valuable solids from an air flow and can be configured in parallel multi-cyclone clusters [21–23], where the air flow is divided equally between each identically sized cyclone. However the applications and operational conditions of small scale cyclones are arguably more varied than industrial sized cyclones [5].

James Dyson is credited with bringing cyclones to the domestic vacuum cleaner market and during the 1990s various Dyson designs were produced with primary and secondary cyclones [24]. The primary cyclone separated out the larger pieces of dust and debris, with the dust laden air passing through a perforated shroud to be further separated by a relatively large reverse-flow cyclone. Filters were installed downstream to capture any particles that escaped the cyclone system. In further developments the secondary stage was replaced by small multi-cyclones arranged in parallel. On the grounds of this commercial success cyclonic vacuum cleaners are now produced by most domestic vacuum cleaner manufacturers, with one of the main attractions to the consumer being that they no longer need to purchase filter bags as with the original bag vacuum cleaner.

A twin cyclone for use in cyclonic vacuum cleaners has been specifically developed [6] and the study noted that the air flow rates commonly used in vacuum cleaners were between 1.0 and 1.8 $m^3\ min^{-1}$ which resulted in significantly higher inlet velocities than industrial scale cyclones. The body diameters investigated were 0.1, 0.11 and 0.12 m with inlet velocities typically ranging from approximately 20 to 48 $m\ s^{-1}$. The study reported pressure drop and overall efficiency, but not separation grade efficiency. The separation grade efficiency describes the percentage of particles by particle size range, that are collected by the cyclone and defines performance. In particular the particle diameter that corresponds to the particle size that is collected with 50% efficiency, known as the cut-size [3], and the gradient of the separation curve are indicators of cyclone performance and can be used to compare the performance of designs of similar scale, operating under identical conditions of air flow rate and solid loadings.

Small scale reverse-flow cyclones are also used to collect bioaerosol material, such as enzymes, pollen, bacteria, viruses and spores [19,25–27]. Due to the relatively delicate nature of the microbes, as compared to mineral processing, it is essential that bioaerosol material is collected gently to ensure that the microbes are undamaged and can be accurately counted. As such wetted cyclones, which have a film of injected liquid wetting the cyclone walls, have been shown to enhance the efficiency of bioaerosol capture [28–30]. Their application has spread to settings such as agriculture, sewage treatment and general pollution monitoring, as well as food and pharmaceutical industries [31,32]. Personal cyclone samplers are also a growing area of interest, with the sampling targeting viral agents [33], and fungal spores [34]. Inspired by some aspects of previously reported designs [35] these miniature cyclones are designed to be worn on the clothing of people working in potentially hazardous environments, with the collected material being analysed at the end of each day to assess exposure.

The use of cyclone separation technology has also been applied to the field of dry powder inhalers (DPIs) which deliver drugs directly to the patient's lungs. The small scale cyclones are used to separate the drugs from the carrier particles through the impaction and shear forces experienced inside the cyclone [36]. The 3M Conix was the first DPI to utilise the cyclonic effect by incorporating cyclone shaped blisters which enabled the device to deliver a high concentration of drugs [37,38]. An investigation of the potential for cyclones to be used in dry powder inhalers has been previously undertaken and the study concluded that if implemented they would improve drug delivery and eliminate some existing issues with DPIs [5].

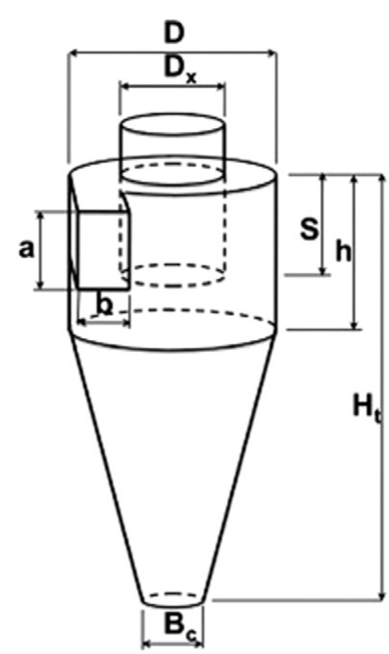

Fig. 1. Tangential cyclone geometry [58].