INVESTIGATIONS TOWARDS THE PARTICLE FLOW PATTERN WITHIN SWIRL VANES OF UNIFLOW CYCLONES

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Abstract – The main objective of this study is to shed light on the flow pattern of particles within the swirl vanes of uniflow cyclones. Literature shows hardly any reliable investigations regarding the numerous different geometric designs of the vanes, which details only can be seen in patented prototypes. The typical manufacturers of uniflow cyclones keep their special vane-shape strictly secret, what enforces this study going more into depth. The typical parameters that influence the efficiency of the particle separation within the vanes are the vane angle, the core diameter, the overlap and the vane shape. This work shows the phenomenological influence of different vane designs on the pressure drop and the separation efficiency, which was investigated by numerical simulations validated by empirical dedusting test series and laser-optical flow analysis. The presented results give a deeper understanding onto the flow behavior in-between the vanes and the separation chamber of uniflow cyclones.

INTRODUCTION

Cyclones are widely used in process industry and represent a major device for an effective and reliable operation within dust removal applications. Standard reverse flow cyclones are the mainly used devices, which were investigated by *Barth* (1956) and *Muschelknautz* (1972). The derived findings resulted in well approved calculation models to predict the separation efficiency and the pressure drop, which are probably still the most used tools to design cyclones.

Beside the well investigated standard reverse flow cyclone a second cyclone type exists and is in use since decades. This second cyclone type is called uniflow cyclone and differs mainly in the flow direction of the gas. The uniflow cyclone could be also found in literature by the synonym swirl tube, axial cyclone or uniclone and is designed in a very simple and compact way. A general characterization of swirl tube separators was mentioned by *Peng and Hoffmann* (2004). Simulations regarding the flow field of uniflow cyclones were performed by *Weng* (2003).

The very compact design of this dust removal system allows plant operators an easy implementation in already existing piping systems to reduce dust emissions by a very low fabrication effort, s. Fig. 1.

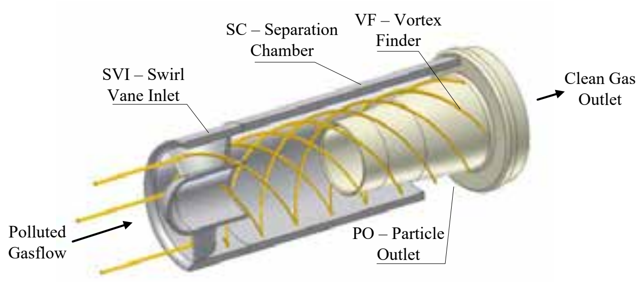

Fig. 1. Depiction of a uniflow cyclone and its flow field pattern.

A very common field of application represents the automotive industry where reliable and compact solutions are absolutely essential. In automotive industry uniflow cyclones could be found as pre-air-cleaning system for the combustion air as well as for the separation of oil droplets from the crankcase exhaust. Petroleum refineries have many cyclones working within FCC-processes, where highest lifetime is required. Erosion within cyclones is the major harassment for operation reliability. Due to this fact *Kraxner et al.* (2013) started research activities to figure out the erosion potential of uniflow cyclones and compared it with the erosion in standard reverse flow cyclones. These results brought up that a uniflow cyclone could be a possible alternative for standard reverse flow cyclones to increase lifetime.

Although this cyclone type also exists since years it is not systematically investigated up to now. There is some literature dealing with the optimization of uniflow cyclones but only for very special applications: *Gauthier et al.* (1990) investigated the design of uniflow cyclones to separate the catalyst in FCC-applications or *Zhang et al.* (1999) investigated this compact dust separator to clean the exhaust air from swine buildings. As these examples show, the existing literature serves information for some special applications but not for an universally valid scope of application for uniflow cyclones. To close this gap the MCI is driving systematical research activities since 2008 to investigate the optimal design of uniflow cyclones for highest separation efficiency at lowest pressure drop for a wide use of applications. Therefor several dedusting units in a size between 0.016m up to 0.3m have been built up to optimize this dust separator system. To manufacture the main components high precisely a rapid prototyping system is used to ensure the repetitious accuracy. The major parts of this cyclone type listed in flow direction are the swirl vane inlet (SVI), the separation chamber (SC), the particle outlet gap (PO) and the gas outlet pipe or often called vortex finder (VF), s. Fig. 2.

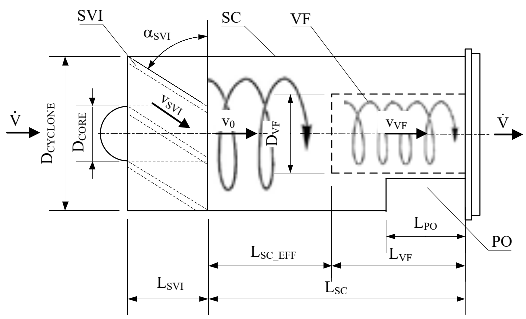

Fig. 2. Major geometric design parameters of a uniflow cyclone.

This work sheds light on the flow behavior inside the swirl vanes, which mainly influences the separation efficiency and pressure drop. The systematic approach, which is aided by laseroptical observations and high speed imaging inside the vane channels, serves phenomenological understanding towards the flow pattern and the separation effects within the swirl vane inlet.

METHODOLOGY AND EXPERIMENTAL SETUP

To investigate the influence of the vane design two separate test stands have been set up. The first set up allows identifying the flow pattern of the particles in an unfolded design of the inlet vane pack, s. Fig. 3.

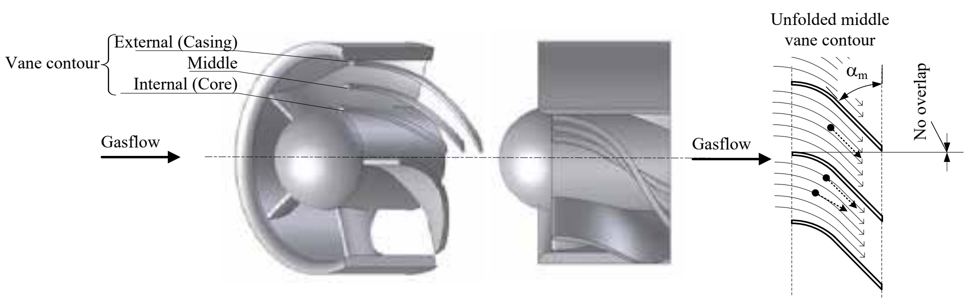

Fig. 3. Depiction an unfolded standard swirl vane inlet (SVI) of a uniflow cyclone.

To track the flow pattern of the particles a test stand with a particle dosing system to ensure a minimal mass flow rate has been designed. The illumination for a valid tracking of the three different particle sizes with a mean diameter of approximately 50µm, 100µm and 200µm (calcium carbonate dust) has been carried out by a high-power LED-array. The particle motion is recorded by a Phantom Miro high-speed imaging camera system.

The second test rig is set up as field test according DIN ISO 5011:2010, to evaluate the performance (separation efficiency and pressure drop) of each investigated swirl vane design. During these tests, all other parameters of a uniflow cyclone have been kept constant to evaluate the influence of the geometric vane parameters properly. During the dedusting tests the separation chamber (SC) is illuminated with a thin laser light sheet to determine the critical sedimentation path (CSP) inside the separation chamber as function of the swirl vane design parameters, s. Fig. 4.

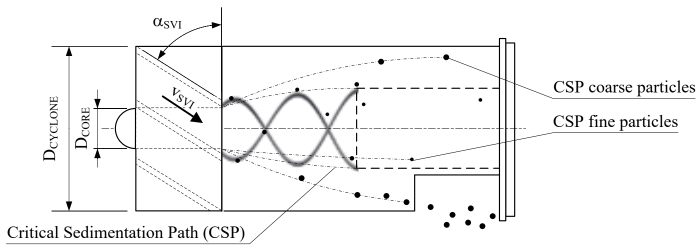

Fig. 4. Setup for dedusting tests and determination of the critical sedimentation path (CSP) inside the separation chamber (SC).

RESULTS

The investigations onto the particle flow pattern inside the vanes show significant bouncing effects and particles which pass the swirl vanes without significant change of its flow direction. These observations are mainly caused by the vane design, the particle properties (shape, sphericity, density), the particle and gas velocity.

The bouncing of the particles when hitting the vane in the SVI can be significantly reduced by an alternating vane shortening. This design suffers turbulences on the backside of the un-shortened vanes, which reduces the cross-section area for the flow and lifts the gas-velocity, respectively. This phenomenon was further investigated by *Pillei et al.* (2014). The shortened vanes lead to an overlap in-between the SVI, which could allow particles leaving the SVI without significant change of its flow-direction. So, especially coarse particles which are mainly influenced by inertial forces, suffer a momentum-change, the shortened vane needs to be elongated downstream, so that no overlap remains.

The investigated optimizations towards the SVI (vane angle α_{SVI}, core diameter D_{CORE}) have also been carried out in dedusting tests. These phenomenological observations represent the backscattered light of the particle-movement inside the separation chamber and give a deeper understanding of the sedimentation path of particles within the centrifugal field.

Fig. 5 shows the flow pattern of the dust strand and single particles inside the separation chamber with three different core diameters at a constant vane angle of 45°. The recorded critical sedimentation path shows obviously coherent dependencies to the separation efficiency, s. Fig. 6. Compared to the characteristics of the cyclone with a core/cyclone ratio of 0.5 a bigger core diameter raises the separation efficiency and the pressure drop significantly.

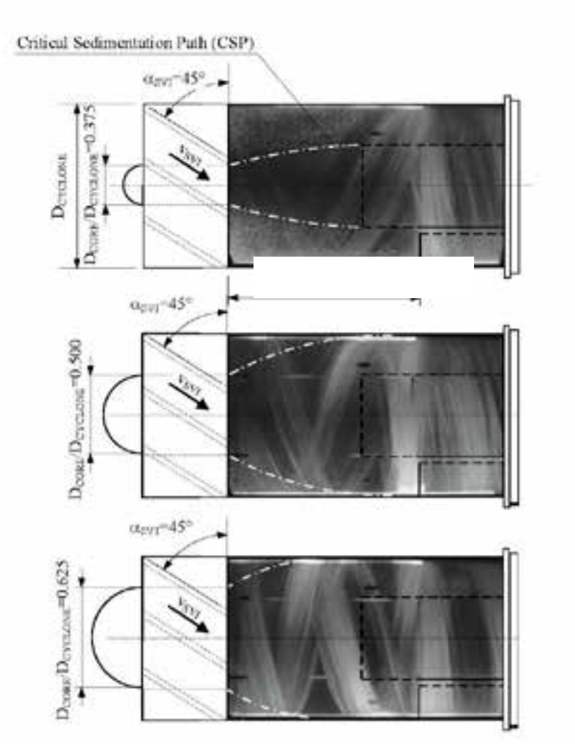

Fig. 5. Particle flow patterns inside the separation chamber of a uniflow cyclone with three different core diameter

The reduction of the core diameter bears much more interesting opportunities due to the fact that the pressure drop reduces nearby 40% what opens potential for a steeper vane angle leading to higher separation efficiency respectively according to *Kraxner* (2013), s. Fig. 7.

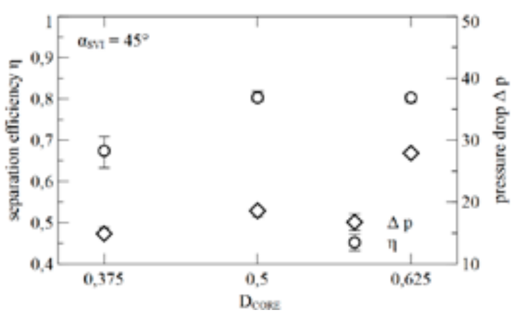

Fig. 6. Correlation of vane angle and separator performance

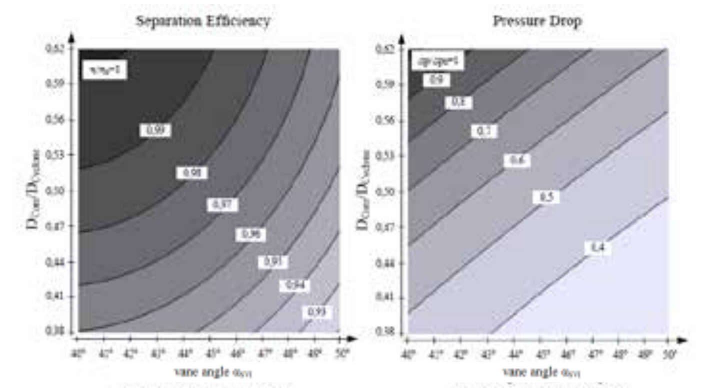

Fig. 7. Correlation of vane angle and separator performance, s. *Kraxner* (2013)

Further investigations with steeper vane angles at a constant $D_{CORE}/D_{CYCLONE}$ ratio of 0,375 show a significant raise in separation efficiency with minor increases in pressure drop up to a vane angle of 30°, s. Fig 8. A steeper vane angle leads to an oversized pressure drop leaving the possibility to reduce the $D_{CORE}/D_{CYCLONE}$ ratio to a lower level to reduce the velocity inside the vane channel for lower energy consumption.

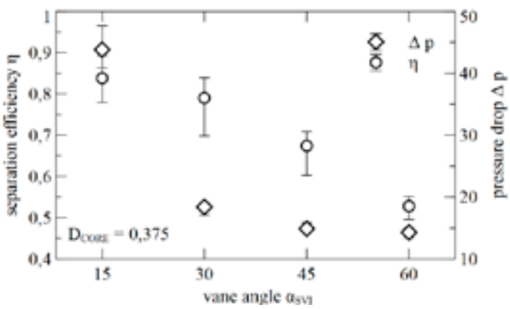

Fig. 8. Influence of swirl intensity to separator performance

SUMMARY AND OUTLOOK

The interacting bundle of geometric parameters in the design of uniflow cyclones, opens a wide field for investigations. The presented results should give a phenomenological impression of the systematically driven research work at MCI. Up to now, uniflow cyclones could serve as an alternative to standard reverse flow cyclones if low pressure drop or limited space is required. Uniflow cyclones can be built approximately $^2/_3$ smaller by volume than standard reverse flow cyclones and have its biggest advantage in a parallel arrangement, due to the small cyclone diameter of a single cell and therefore high circumferential forces and separation efficiency, respectively.

ACKNOWLEDGEMENT

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NOTATION

CSP	critical sedimentation path	L_{SC}	separation chamber length, m
PO	particle outlet gap	L_{SC_EFF}	effective sep. chamber length, m
SC	separation chamber	L_{SVI}	swirl vane inlet length, m
SVI	swirl vane inlet	L_{VF}	vortex finder length, m
VF	vortex finder	v	superficial velocity, m/s
D_{CORE}	core diameter SVI, m	v_{SVI}	velocity inside vane channel, m/s
$D_{CYCLONE}$	cyclone diameter, m	v_{VF}	superficial velocity i. D_{VF}, m/s
D_{VF}	vortex finder diameter, m	α_m	midlle vane angle, deg
L_{PO}	particle outlet length, m	η	separation efficiency,

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