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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PARTICLE SEPARATION IN A SYMMETRICAL DOUBLE CYCLONE SEPARATOR

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ABSTRACT

The paper presents the results of experimental and numerical investigations of particle separation in symmetrical double cyclone separators. Particle separation rates were measured by Schneider et al. on an experimental test rig at the Flensburg University of Applied Sciences, Germany. The corresponding numerical predictions were performed by Frank et al. using the formerly developed 3–dimensional Lagrangian approach for the prediction of disperse multiphase flows in complex geometries.

The numerical method was applied to the gas–particle flow in different types of symmetrical double cyclone separators. The investigations for the separation of limestone particles from gas flow were carried out for 3 variations of the cyclone separator geometry regarding the cyclone separator inlet and the gap width at the apex cone. Experiments and numerical predictions were carried out for a gas inlet velocity of 25.0 m/s. The numerical predictions were compared with experimental results for the precipitation rates obtained in experimental investigations of Schneider et al. The numerical flow simulations confirmed the expected main vortex structure inside the main body of the cyclone separator and led to new findings about the fluid flow structure near the inlet of the particle settling chamber. Obtained numerical results has to be regarded as a good agreement with the experimentally predicted precipitation rates. Further it was found that particle agglomeration seems to be important for the exact prediction of particle separation in symmetrical double cyclon separators and needs further investigation.

NOMENCLATURE

C_D, C_A coefficients of drag and lift force
d_P particle diameter
g gravitational acceleration
k, f coefficients of restitution and kinetic friction
$\dot{N}_P$ particle flow rate
Re, Re_P Reynolds and particle Reynolds number
$T(d_P)$ particle separation rate
u, v, w velocity in x-, y- and z-direction
v_{rel} absolute value of particle-fluid relative velocity
Ω fluid rotation
ν kinematic viscosity
ρ density
ω_P particle rotational velocity
ω_{rel} absolute value of particle-fluid relative rotational velocity

Subscripts

F fluid phase
P disperse phase

INTRODUCTION

Disperse multiphase flows are very common for processes in mechanical and thermal process technology (e.g.

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gas–particle or gas–droplet flows, coal combustion, pneumatical conveying, erosion phenomena). Furthermore processes for the separation of solid particles from gases or fluids and for the classification and particle size analysis are an important field of interest in process technology.

The main idea of particle removal from gases or fluids by centrifugal forces in a swirling flow like in e.g. cyclone separators is about 100 years old. But in the figurative sense the statement of Feifel (Feifel, 1943) made in 1943 is still valid : "In the field of its applicability the cyclone separator is a gas cleaning equipment of a simplicity and safety in operation which can hardly be exceeded. Investigations of particle separation and the development of cyclones which became known from literature in the past surprisingly lack of a response to the results of fluid mechanics". The well known fact forming the basis for Feifels first statement still today encourages research in the field of cyclone development. Feifels second statement is also valid until nowadays : working methods and latest findings from modern fluid mechanics are rarely applied to cyclone development, although they would have a remarkable potential for construction of efficient cyclones and for improvement of particle separation in cyclone separators.

Based on former work of Feifel (Feifel, 1943) Schneider, LUT GmbH (see publications in (Bachmann, 1996), (Wieck, 1997), (Schneider, 1998)) developed a number of efficient symmetrical double cyclone separators which are able to change the opinions about the limits in operation of cyclone technology. These cyclone developments are based on new findings and investigations on details of the cyclone flow, e.g. about the secondary flows and their effects on particle separation as well as about the mechanisms of particle discharge from the separation chambers of the cyclones to the settling chambers and particle hoppers. From these latest investigations it was found that the secondary flows of a swirling flow like in cyclone separators can be determindely used for an improvement of particle separation efficiency.

The symmetrical double cyclone has been investigated as experimentally by Schneider et al. as well as numerically by Frank et al. The central goal of the investigations was a gain in knowledge about the complex vortex flow in the cyclone, about particle motion and separation efficiency of this special types of symmetrical double cyclone separators. In accordance with the first experimental results such cyclones are able to operate with a cut–off particle diameter of $x_{ae,50} = 50, \ldots, 500\ nm$. These values for the cut–off particle diameter in the submicron range has been measured for cyclone geometries with diameters of the separation chamber of 40 to 230 mm and for circumferential gas velocities in the separation chamber of about $u_F = 10, \ldots, 25\ m/s$. The given particle diameter $x_{ae} = d_P \sqrt{\rho_P / \rho_{P0}}$ with $\rho_{P0} = 1000\ kg/m^3$ is the so called "aerodynamical" particle diameter commonly used for comparison in aerosol technology and corresponds to a particle to fluid density ratio of $\rho_P / \rho_F = 1000\ kg/m^3$.

EXPERIMENTAL INVESTIGATION OF PARTICLE SEPARATION

The cyclone separator shown in Fig. 2 with a diameter of the separation chamber of 230 mm is one result of cyclone development of Schneider et al. mentioned above. The double cyclon has a rotational symmetric separation chamber which is also symmetrical relating to the center plane between the two conical parts of the separation chamber. The gas–particle flow enters the cyclone by a spiral inflow channel leading to a strong swirling flow and formation of a steady primary vortex in the separation chamber. The swirling flow produces a centrifugal force acting on the particles which causes radial movement of the solid particles towards the wall of the separation chamber. Further, in the conical parts of the cyclone separation chamber two secondary ring vortices of toroidal shape are induced by the radial pressure gradient of the primary vortex. Particles are moved by these secondary vortices to the discharge openings which are formed by the circular edges of the outer casing of the conical separation chamber and by the deflector cone attached to the outer walls of the vortex finder tubes. Particles are moved through these circular slits into the sedimentation chambers by the secondary flow. The continuous phase cleaned from solid particles recirculates along the outer wall of the vortex finder tubes to the clean gas exit and leaves the cyclone through both the vortex finder tubes.

Therefore the separation of solid particles from a gas–particle dispersion in a cyclone separator consists of to stages : 1. the separation of the solid particles from the continuous phase by radial movement of particles and particle agglomerates by centrifugal forces in the separation chamber, and 2. the discharge of particles and particle agglomerates from the separation chamber and further agglomeration and gravitational sedimentation in the range of the sedimentation chamber and particle hopper.

The scheme of the experimental setup for the investigation of particle separation in the symmetrical double cyclone separator is shown in Fig. 1 : The inlet flow for the separator was produced with a fan with speed control delivering a variable volume flow rate of clean gas which was measured by a standard orifice. The necessary amount of solid particles has been dispersed with the RBG 1000 of PALLAS, Karlsruhe/Germany. For the particle phase calcium carbonate particles were used, produced under the trading name OMYACARB 2–GU by OMYA GmbH, Köln/Germany. So the particle phase used in the experiments for investigation

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of particle separation can be characterized by a particle density of $\rho_P = 2700\ kg/m^3$ and a medean of the particle size distribution sum of $x_{50,3} = 2.5\ \mu m$. The gas–particle dispersion is led to the cyclone where phase separation and discharge of the particles into the sedimentation chambers and particle hoppers takes place. The clean gas leaves the cyclone through the vortex finder tubes and is finally processed by a fine–mesh filter.

From both the gas–particle dispersion and the clean gas flow a small amount of the dispersion is separated by isokinetic sampling and processed by the scattered light particle sizer PCS 2000 (PALLAS GmbH, Karlsruhe/Germany). The result of the particle size measurements are the particle size distribution sums $Q_0(x)$ for the gas–particle and the clean gas flow. Particle size distribution sum $Q_3(x)$, particle size density functions $q_3(x)$ and particle separation rates $T(x)$ can be evaluated from these measurments. So Fig. 8 and 9 show experimental results for the investigated symmetrical double cyclon separator for a gas inlet velocity of $u_F = 25\ m/s$ and a particle concentration in the inflow of $800\ mg/m^3$.

NUMERICAL PREDICTION OF GAS–PARTICLE FLOW IN A SYMMETRICAL DOUBLE CYCLONE SEPARATOR

The 3–dimensional Eulerian–Lagrangian approach The experimental results for the particle separation rates in the symmetrical double cyclone separator have been compared with numerical predictions of the gas–particle flow for a number of variations of different cyclone geometries and flow conditions. For these numerical simulations a 3–dimensional Eulerian–Lagrangian approach developed by Frank et al. (Frank, 1992), (Frank, 1997) was used. The 3–dimensional two–phase (gas–particle) flow in the cyclone separator is described by assuming that the particulate phase is dilute and that the particle loading is rather low. This assumption satisfies the neglect of inter–particle effects and contributing source terms in the Navier–Stokes equations due to particle–fluid interaction. Further the two–phase flow is assumed statistically steady, incompressible and isothermal. Then the motion of the fluid phase can be described using the time–averaged form of the Navier–Stokes equations. For consideration of fluid turbulence a standard k–ε turbulence model was used in the present numerical simulations.

The disperse phase is treated by the application of the Lagrangian approach. Each calculated particle represents a large number of physical particles of the same physical properties which is characterized by the particle flow rate $\dot{N}_P$ along each calculated particle trajectory. The prediction of the particle trajectories is carried out by solving the ordinary differential equations for the particle location and velocities. Assuming that the ratio of fluid to particle density is small ($\rho_F/\rho_P \ll 1$) these equations read :

$$\frac{d}{dt}\begin{bmatrix} x_P \\ y_P \\ z_P \end{bmatrix} = \begin{bmatrix} u_P \\ v_P \\ w_P \end{bmatrix} \tag{1}$$

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} u_P \\ v_P \\ w_P \end{bmatrix} = \frac{3}{4}\frac{\rho_F}{(\rho_P + \frac{1}{2}\rho_F)d_P} \Bigg(& v_{rel}\, C_D \begin{bmatrix} u_F - u_P \\ v_F - v_P \\ w_F - w_P \end{bmatrix} \\ & + \frac{2\nu_F^{1/2}}{\pi|\vec{\Omega}|^{1/2}} C_A \begin{bmatrix} (v_F - v_P)\Omega_z - (w_F - w_P)\Omega_y \\ (w_F - w_P)\Omega_x - (u_F - u_P)\Omega_z \\ (u_F - u_P)\Omega_y - (v_F - v_P)\Omega_x \end{bmatrix} \Bigg) \\ & + \frac{\rho_P - \rho_F}{\rho_P + \frac{1}{2}\rho_F} \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} \end{aligned} \tag{2}$$

with

$$\vec{\Omega} = \mathrm{rot}\ \vec{v}_F \quad , \quad Re_P = \frac{d_P\, v_{rel}}{\nu_F}$$

$$v_{rel} = \sqrt{(u_F - u_P)^2 + (v_F - v_P)^2 + (w_F - w_P)^2}$$

These equations of motion of the disperse phase include at the right hand side the drag force, the lift force due to shear in the fluid flow field (Saffman force), the gravitational and added mass force. For the present numerical investigation the Magnus force due to particle rotation is neglected because of their minor importance for the very fine particles in the particle diameter range of interest.

The values for the coefficients C_D and C_A can be found in literature (Frank, 1997), (Sommerfeld, 1996). Additionally for the lift coefficient C_A the correction obtained by Mei (Sommerfeld, 1996) is taken into account. The effect of fluid turbulence on the motion of the disperse phase, which is regarded to be very important for the particle diameter range under investigation, is modelled by the Lagrangian Stochastic–Deterministic (LSD) turbulence model proposed by Schönung and Milojević (Frank, 1992). The particle–wall collisions are treated according to the irregular bouncing model by Sommerfeld (Sommerfeld, 1996) in the modified wall roughness formulation given in (Frank, 1997).

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The time–averaged equations of fluid motion are solved using the program package FAN–3D developed by Perić and Lilek (Perić, 1992). The program FAN–3D was extensively modified by the authors for gas–particle flow computations. Further modifications involve the implementation of a standard k–ε turbulence model and the parallelization of the solution algorithm by application of a domain decomposition method. The most fundamental features of FAN–3D are :

- use of non–orthogonal, boundary fitted, numerical grids with arbitrary hexahedral control volumes,
- use of block structured numerical grids for geometrical approximation of complex flow domains;
- parallelization using domain decomposition method;
- finite volume solution approach of SIMPLE kind with colocated variable arrangement; Cartesian vector and tensor components;

The solution algorithm for the equations of particle motion is based on the program package PartFlow developed by the authors. A detailed description of the 3–dimensional solution algorithm and the developed parallelization methods for the Lagrangian approache can be found in (Frank, 1997), (Frank, 1998b).

Results of the numerical predictions and comparison with experimental data The presented 3–dimensional Eulerian–Lagrangian approach was applied to the gas–particle flow in a symmetrical double cyclone separator as shown in Fig. 2. The calculations were based on experimental investigations carried out by Schneider et al. (Schneider, 1998) at the Flensburg University of Applied Sciences. The geometrical properties of the cyclones investigated in this experiments can be obtained from the following table :

Diameter of the cyclon at symmetry plane	D_1	230 mm
Diameter of the cyclon at the inlet of the settling chamber	D_2	120 mm
Length of the cyclon main section	L	253 mm
Diameter of the clean gas exit	d_T	70 mm
Distance of the clean gas exit from the symmetry plane	l_T	15 mm
Inlet cross section	$a \times b$	$82 \times 100\ mm^2$
Size of the particle settling chamber	$W_c \times H_c \times D_c$	$80 \times 538 \times 276\ mm^3$

Due to the complex flow geometry of the investigated cyclone separators numerical grids with up to 95 different grid blocks and about 350.000 grid cells had to be designed for the numerical calculations of the gas–particle flow.

Calculations were performed for two different locations of the apex cone — a flow guiding equipment which is attached at the lower end of the conical part of the cyclone to the outer diameter of the vortex finder tubes. The gap width between the apex cone and the cyclone wall was varied from $h_{ac} = 18.7\ mm$ (SDC–1) to $h_{ac} = 30.0\ mm$ (SDC–2). For all numerical investigations a constant gas inlet velocity of $u_F = 25.0\ m/s$ was assumed. For comparison with the experimental results the physical properties of the particulate phase were set as for limestone particles ($\rho_P = 2700\ kg/m^3$, $k = 0.5$, $f = 0.45$).

The numerical flow simulations confirm the expected main vortex flow structure known from cyclone theory and from experimental observations. The flow field in the two perpendicular cross sections shown in Fig. 4 and Fig. 6 clearly show the secondary flow from the spiral inlet to the cyclone along the wall of the conical part of the separation chamber towards the inlet cross section of the settling chamber with the attached apex cone. Along the outer wall of the vortex finder tube the gas flow reaches the inlet cross section of the vortex finder tube near the symmetry plane and further exits the cyclone through the clean gas exit. Fig. 5 and Fig. 7 especially show, that there is a secondary flow from the conical separation chamber through the gap at the apex cone into the settling chamber. This secondary flow is led to the walls of the particle sedimentation chamber by the guiding equipment attached to the outer diameter of the vortex finder tubes and allows also for smaller particles to agglomerate and to sedimentate as larger agglomerates in the sedimentation chamber. Therefore this recirculating flow was found to be of particular importance for the process of particle separation in the cyclone separator (see also Fig. 3).

Further numerical investigations were focused on the prediction of the particle separation rates for the cyclone geometries SDC–1 and SDC–2 from particle trajectory calculations. Numerical simulations were carried out for 20 particle diameter classes in the range between $0.5 \ldots 15\ \mu m$. A total number of 670 particle trajectories with random initial conditions in the inlet cross section were calculated for each of the 20 particle diameter classes. Then the separation rate can be predicted as :

$$T(d_P) = 1 - \frac{\dot{N}_{out}(d_P)}{\dot{N}_{in}(d_P)}$$

where $\dot{N}_{in}(d_P)$ and $\dot{N}_{out}(d_P)$ are the particle flow rates for a given particle size in the inlet cross section and clean gas exit cross section respectively. In the numerical prediction particles are assumed to be separated in the cyclone, if :

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1. The particle sticks to the wall of the cyclone (that means the wall normal velocity of the particle after a particle–wall collision is less than $10^{-5}\ m/s$).
2. The particle trajectory reaches the particle settling chamber and exceeds a given maximum residence time inside the cyclone.

Fig. 8 and Fig. 9 show the comparison of the numerically predicted particle separation rates with the experimental results of Schneider et al. (Schneider, 1998), (Bachmann, 1996), (Wieck, 1997) for limestone particles with $\rho_P = 2700\ kg/m^3$. Additionally the numerical results for particle separation for $\rho_P = 1000\ kg/m^3$ are given in the diagrams. Figures show a shift of the particle separation rates and the d_{50} particle diameter ($T(d_{50}) = 0.5$) towards higher particle diameters (for about 2 μm) for the numerical predictions. Under consideration of all uncertainties involved in both the experimental and numerical investigations this has to be regarded as a fairly good agreement. Basically there are two main reasons for the differences in the numerically predicted particle separation rate results :

1. Certainly the complex fluid flow field in the cyclone could not be covered in all quantitative details by the present numerical simulations. Coarse numerical grid resolution in some regions of the flow domain and the used k–ε turbulence model cause some quantitative errors in the fluid flow calculations.
2. The Lagrangian approach used for the prediction of the particle motion does not yet account for the particle agglomeration which seems to be important for the exact prediction of particle separation in this special type of symmetrical double cyclone separators.

Implementation and use of a Reynolds stress turbulence model, improvement of the numerical grid, especially in the region near the apex cone which is important for particle separation processes, together with the development of a particle–particle agglomeration model can substantially improve the numerical results for the prediction of particle separation in cyclone separators.

CONCLUSIONS

The paper presents the results of experimental and numerical investigations of the particle separation from gases in symmetrical double cyclone separators. The experimental results show the excellent performance of this special class of cyclone separator devices especially for fine particles with particle diameters of about $d_P \approx 1\ \mu m$. Furthermore the paper gives the formulation of a 3–dimensional Lagrangian approach applicable to flow domains with complex geometrical boundary conditions. The Lagrangian approach has been applied to the gas–particle flow in the symmetrical double cyclone separator. Geometrical inlet conditions and the location of the apex cone near the inlet of the particle settling chamber has been variied in the numerical predictions. Results for particle precipitation rates and there comparison with the experimental results obtained by Schneider et al. show fairly good agreement and the applicability of the numerical approach to complex 3–dimensional multiphase flows. The effect of particle agglomeration on the particle separation in cyclones needs further investigation.

ACKNOWLEDGMENT

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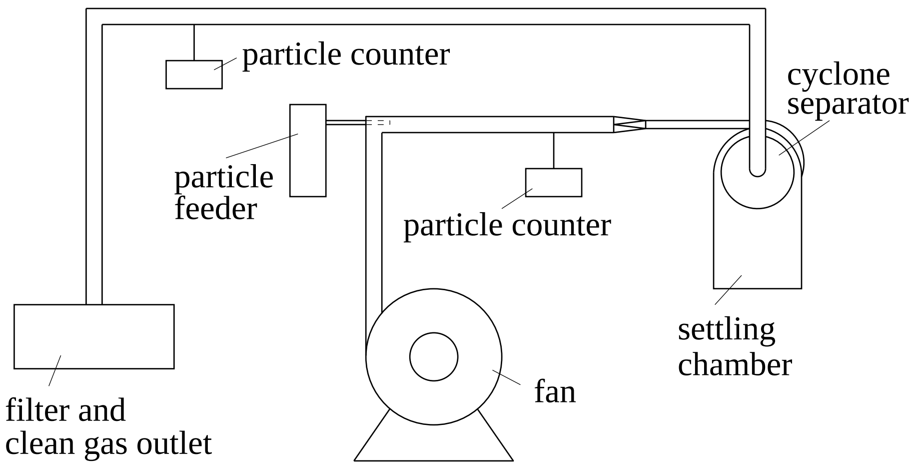

Figure 1. SCHEME OF THE EXPERIMENTAL TEST RIG WITH THE SYMMETRICAL DOUBLE CYCLONE SEPARATOR.

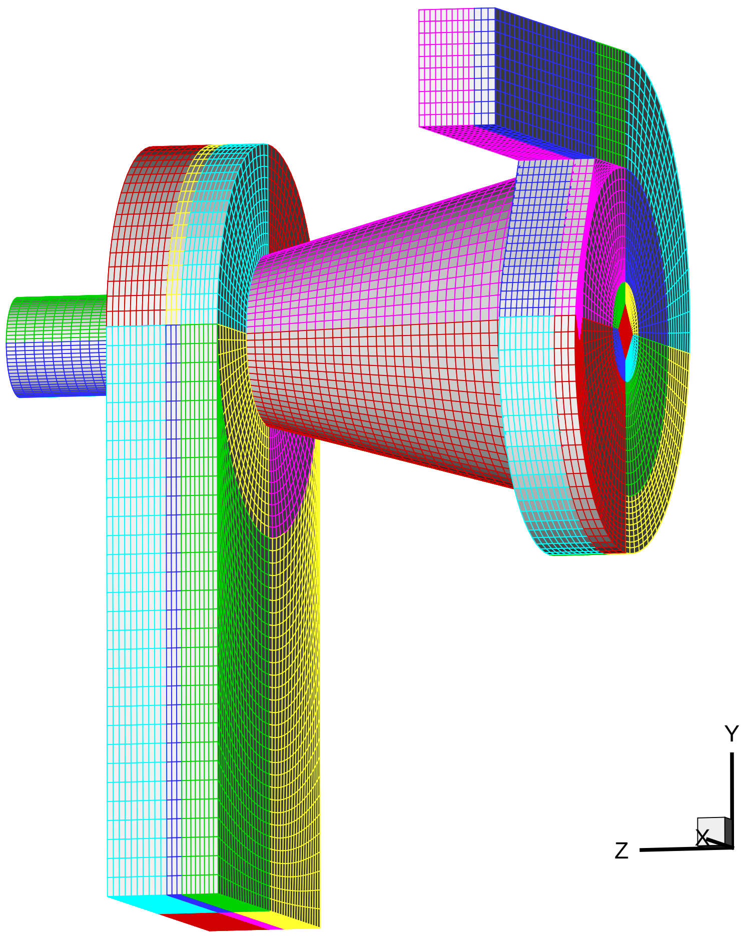

Figure 2. GRID STRUCTURE FOR THE SYMMETRICAL DOUBLE CYCLONE (LEFT HALF).

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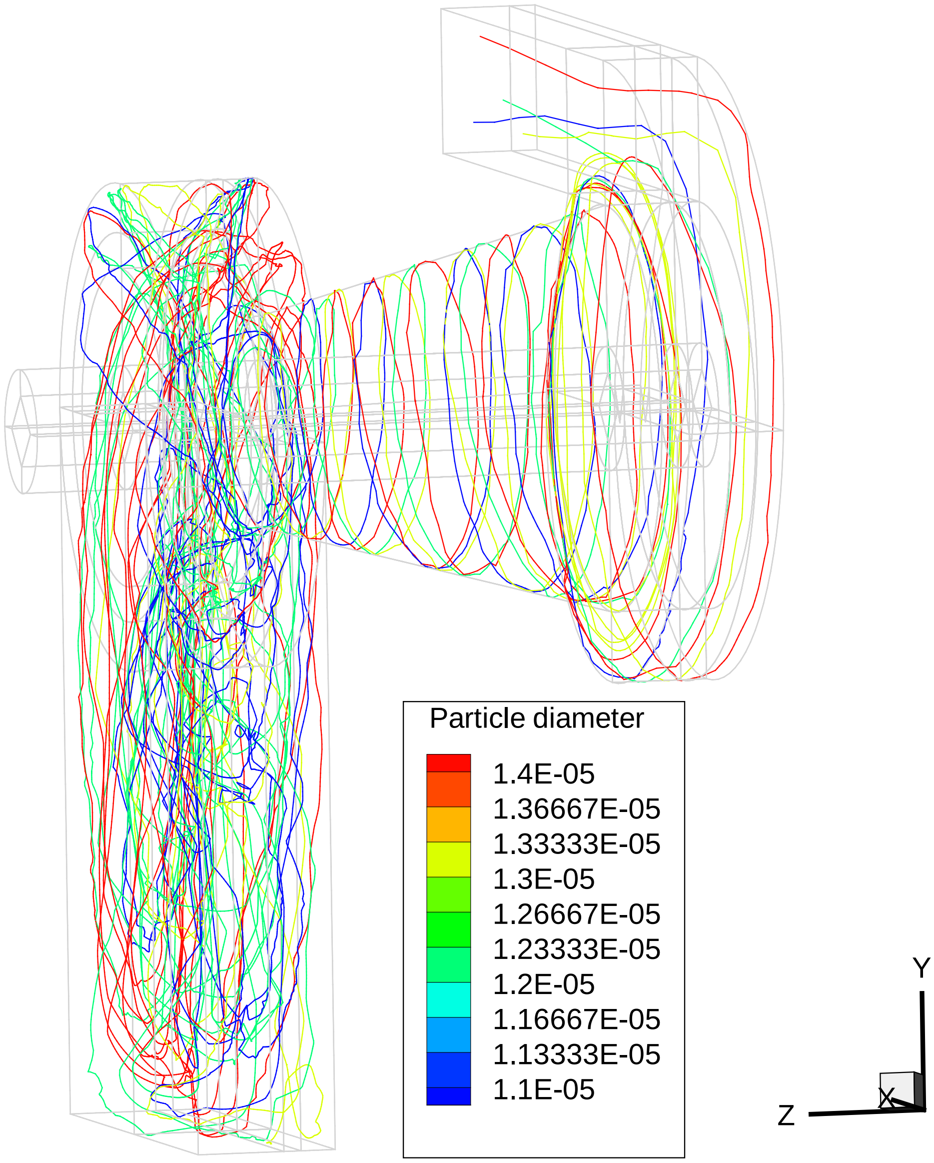

Figure 3. PARTICLE TRAJECTORIES IN THE SYMMETRICAL DOUBLE CYCLONE (LEFT HALF).

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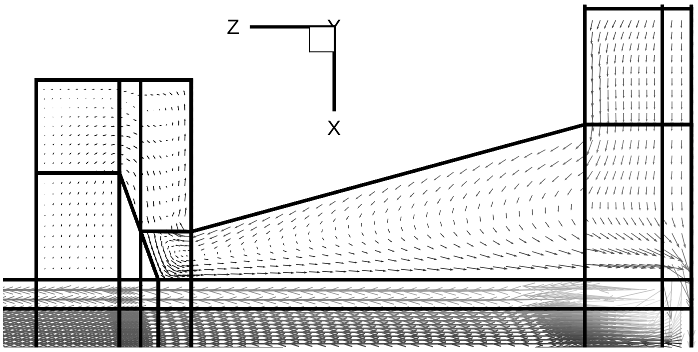

Figure 4. GAS FLOW FIELD IN THE x–z–PLANE.

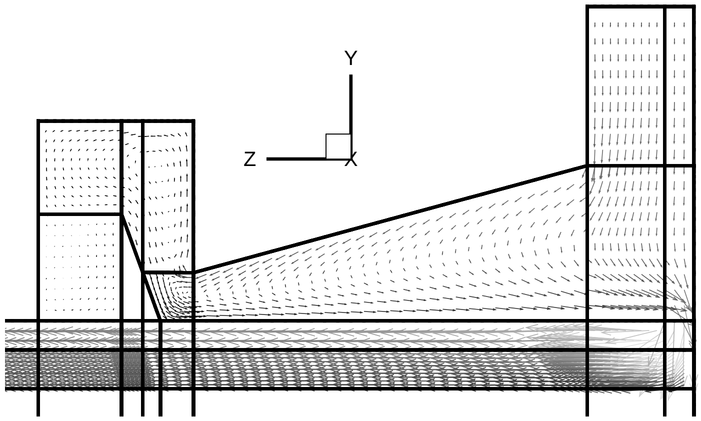

Figure 6. GAS FLOW FIELD IN THE y–z–PLANE.

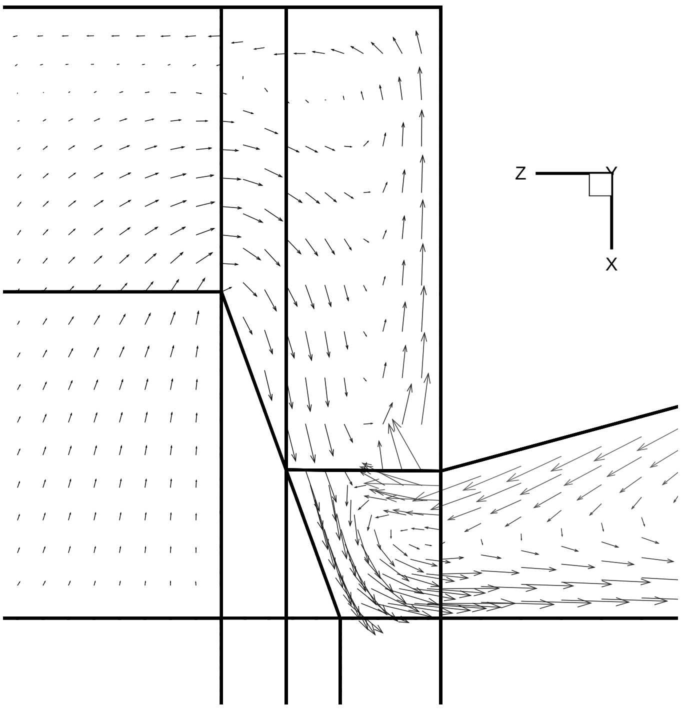

Figure 5. DETAIL OF THE FLUID VELOCITY FIELD IN THE VICINITY OF THE APEX CONE (x–z–PLANE).

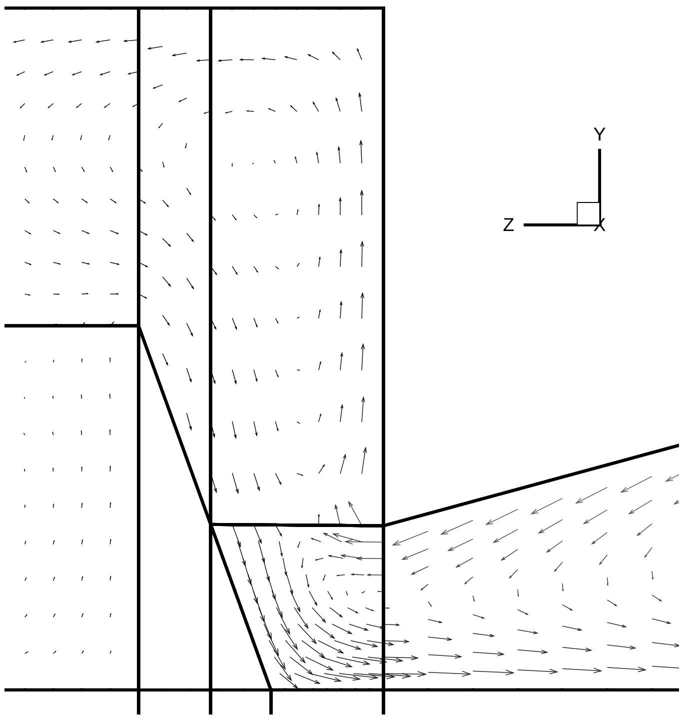

Figure 7. DETAIL OF THE FLUID VELOCITY FIELD IN THE VICINITY OF THE APEX CONE (y–z–PLANE).

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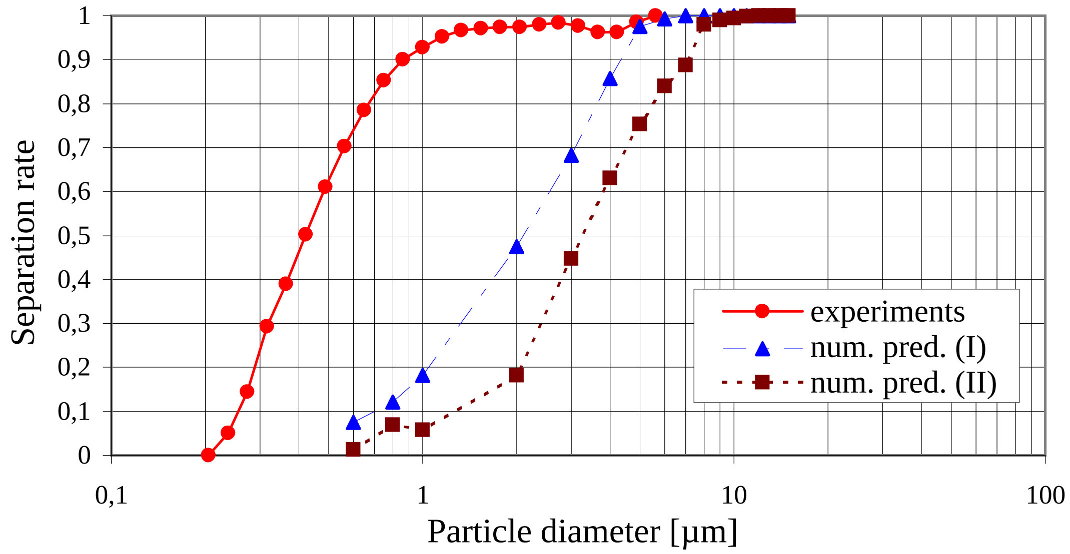

Figure 8. COMPARISON OF PARTICLE SEPARATION RATES FOR THE SDC–1 CYCLONE SEPARATOR ($h_{ac} = 18.7\ mm$) FOR $u_F = 25.0\ m/s$ (I – $\rho_P = 2700.0\ kg/m^3$, II – $\rho_P = 1000.0\ kg/m^3$).

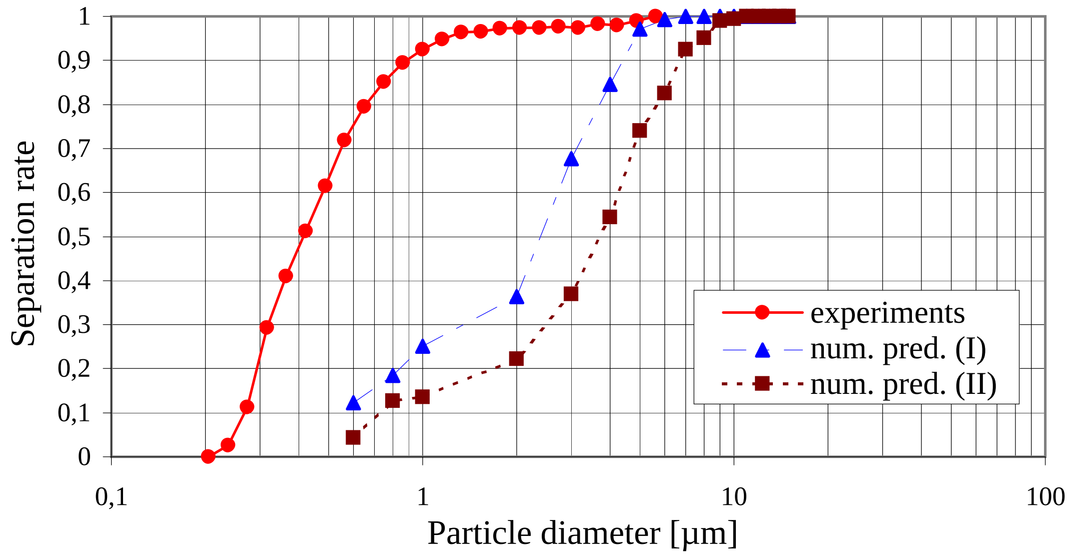

Figure 9. COMPARISON OF PARTICLE SEPARATION RATES FOR THE SDC–2 CYCLONE SEPARATOR ($h_{ac} = 30.0\ mm$) FOR $u_F = 25.0\ m/s$ (I – $\rho_P = 2700.0\ kg/m^3$, II – $\rho_P = 1000.0\ kg/m^3$).

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