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(54) **Titre : CYCLONE AGGLOMERATEUR DU TYPE A FLUX INVERSE**
(54) **Title: REVERSE FLOW AGGLOMERATING CYCLONE AND METHOD THEREOF**

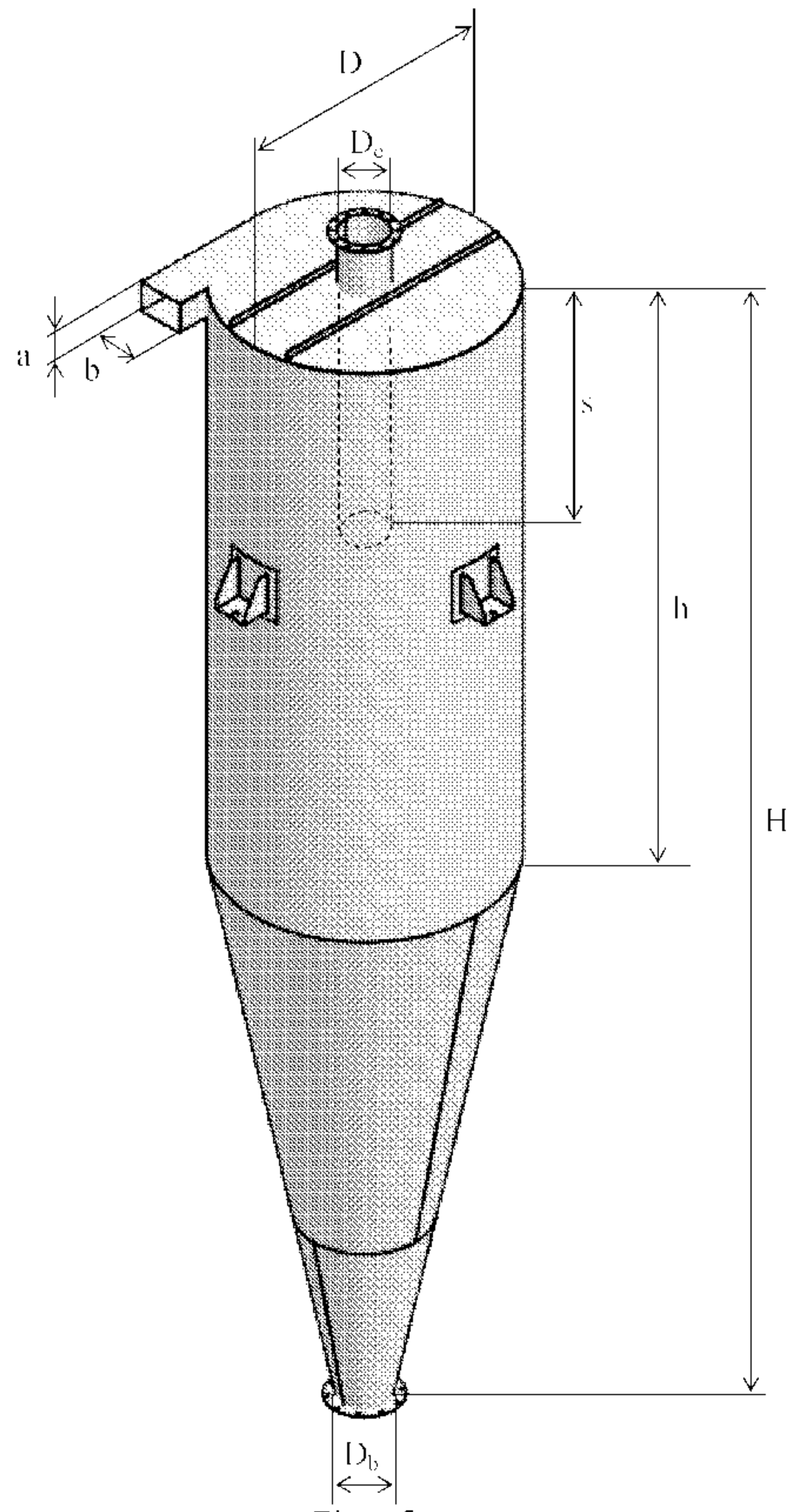

Fig. 2

(57) **Abrégé/Abstract:**
A family of optimised cyclones has been surprisingly detected, when incorporating into cyclone calculation the interparticle agglomeration phenomenon, the main cause of the capture of submicrometric particles by greater particles preferably having

(57) **Abrégé(suite)/Abstract(continued):**
diameters of 10-20 µm, the family of optimised cyclones having a geometry defined by the following non-dimensional parameters: a/D 0.110-0.170; b/D 0.110-0.170; s/D 0.500-0.540; D_e/D 0.100-0.170; h/D 2.200-2.700; H/D 3.900-4.300; D_b/D 0.140-0.180, wherein a and b are the sides of the tangential cyclone entrance, which has a rectangular cross-section, and the first of these sides is parallel to the axis of the cyclone, which has a body of height H with a cylindrical upper section having an inner diameter D and a height h, and a lower section with an inverted truncated cone shape with a minor base having the diameter D_b; and a cylindrical vortex tube of height s and diameter De (inner dimensions). Global efficiency is maximised in that the efficiency for finer and/or less dense particles, which are the most difficult to capture, is maximised.

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(54) Title : AGGLOMERATING CYCLONE OF THE REVERSE-FLOW TYPE

(54) Título : CICLONE AGLOMERADOR DO TIPO DE FLUXO INVERTIDO

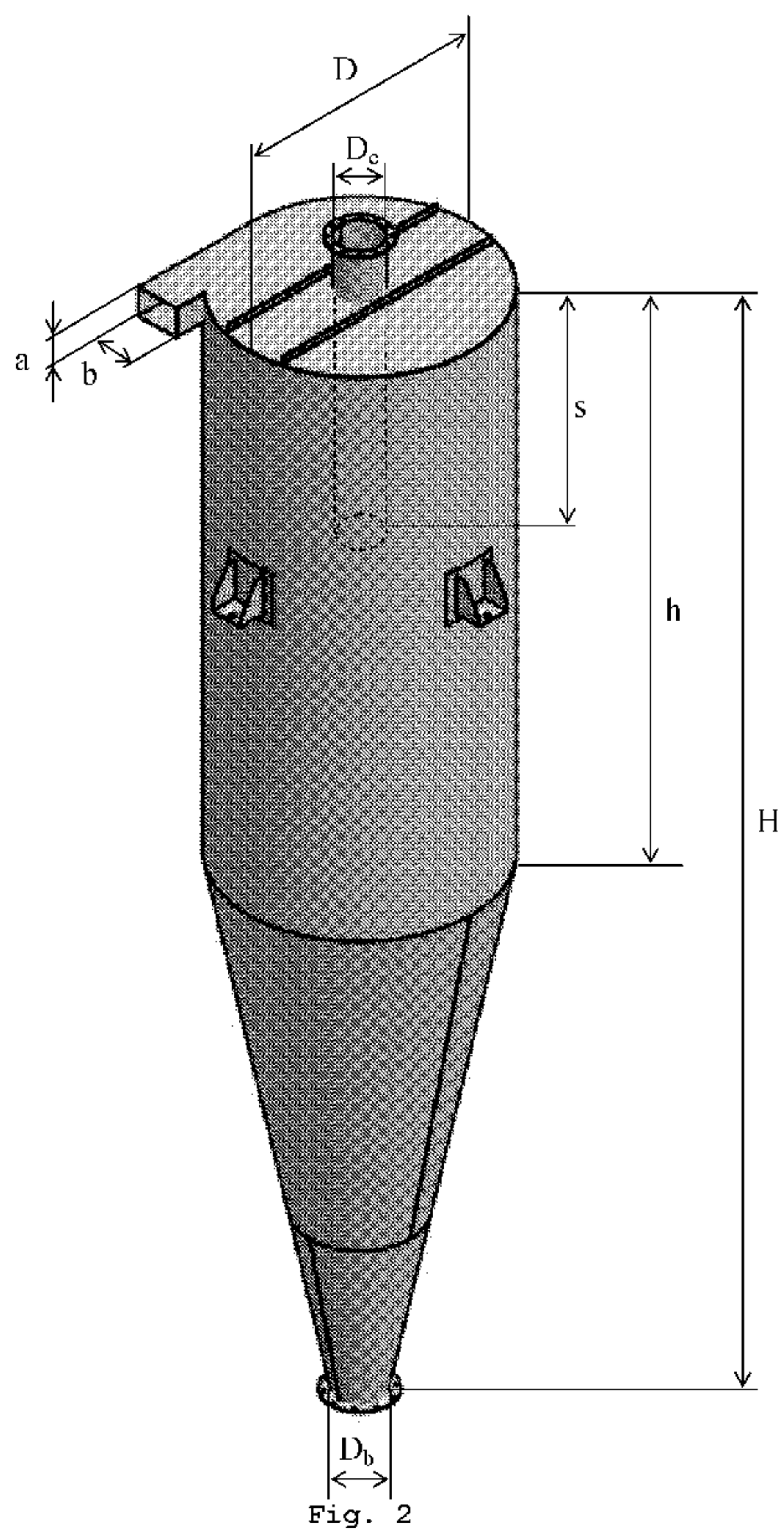

Fig. 2

(57) Abstract : A family of optimised cyclones has been surprisingly detected, when incorporating into cyclone calculation the interparticle agglomeration phenomenon, the main cause of the capture of submicrometric particles by greater particles preferably having diameters of 10-20 µm, the family of optimised cyclones having a geometry defined by the following non-dimensional parameters: *a/D* 0.110-0.170; *b/D* 0.110-0.170; *s/D* 0.500-0.540; D_e/D 0.100-0.170; *h/D* 2.200-2.700; *H/D* 3.900-4.300; D_b/D 0.140-0.180, wherein *a* and *b* are the sides of the tangential cyclone entrance, which has a rectangular cross-section, and the first of these sides is parallel to the axis of the cyclone, which has a body of height *H* with a cylindrical upper section having an inner diameter *D* and a height *h*, and a lower section with an inverted truncated cone shape with a minor base having the diameter D_b; and a cylindrical vortex tube of height *s* and diameter *De* (inner dimensions). Global efficiency is maximised in that the efficiency for finer and/or less dense particles, which are the most difficult to capture, is maximised.

(57) Resumo : Incorporando no cálculo de ciclones o fenómeno de aglomeração interparticular, principal responsável pela captura de partículas submicrométricas por partículas maiores, estas últimas preferencialmente com diâmetros de 10-20 µm, detectouse, com surpresa, uma família de ciclones optimizados de geometria definida pelos

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Declarações sob a Regra 4.17 :

— *relativa à identidade do inventor (Regra 4.17(i))*

— *relativa ao direito do requerente de pedir e obter uma patente (Regra 4.17(ii))*

— *relativa à autoria da invenção (Regra 4.17(iv))*

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seguintes parâmetros adimensionais: *a/D* 0,110-0,170; *b/D* 0,110-0,170; *s/D* 0,500-0,540; D_e/D 0,100-0,170; *h/D* 2,200-2,700; *H/D* 3,900-4,300; D_b/D 0,140-0,180, sendo *a* e *b*, os lados da entrada tangencial de secção rectangular do ciclone, o primeiro deles paralelo ao eixo de tal ciclone, sendo este dotado de um corpo de altura *H* com um troço superior cilíndrico de diâmetro interno *D* e altura *h* e com um troço inferior tronco-cónico invertido de base menor de diâmetro D_b; e de um tubo de vórtice cilíndrico de altura *s* e diâmetro *De* (dimensões internas). Ao maximizar a eficiência para as partículas mais finas e/ou menos densas, as mais difíceis de capturar, maximiza-se a eficiência global.

Description

Reverse flow agglomerating cyclone and method thereof

1 - Technical Domain

The present invention relates to a de-duster of the reverse-flow cyclone type. In addition, the invention relates to methods to remove particles from gases, possibly with dry scrubbing of the same gases.

Cyclones are de-dusters used in many types of industries, with two complimentary ends: removal of particles from gases produced by processes before being emitted to the atmosphere, (ex. exhausts from furnaces and ovens), and recovery of fine particles of high-added value (ex. food, chemical and pharmaceutical industries).

Cyclones have the advantages of low investment and operating costs but the disadvantage of low efficiency for particles below 2-3 µm. Hence, to comply with Portuguese and EU legal emission limits, one has frequently to use more costly de-dusters, such as bag filters and electrostatic precipitators.

Thus, the development of cyclones with collection efficiencies much larger than those attainable by cyclones available in the marketplace, especially for particles below 2-3 µm, has a large potential for industrial application. Several industries (wood, iron & steel, cement, chemical - including the production of nanoparticles - food and pharmaceutical) could benefit from low-cost gas-solid separation devices with enough efficiency to prevent the need to use more expensive equipment (both in capital and operation costs), such as bag filters and electrostatic precipitators referred before. In processes at high temperature and pressure, cyclones are presently the only applicable de-dusters.

Industrial cyclones vary in type, but the most used are of the reverse-flow type, shown schematically Fig.1. To briefly describe their functioning, the gas enters at section *ab* and has to describe a descending helical movement, until it reverses direction due to the pressure field (thus the designation of 'reverse-flow') exiting at the top by the vortex pipe of length *s* and diameter D_e. In their descending movement, solid particles are accelerated towards the walls and eventually end up in the cyclone bottom, thus being separated from the gas. In a cyclone, fine particles are those that, in principle, are more difficult to be separated from the transport gas, due to their weaker response to the acceleration imposed by the gas.

Cyclone makers characterize the cyclones by 'families or geometries', characterized in that they present unchanging relations between 7 key dimensions (the ratios of a, b, s, D_e, h, H and D_b relative to the cyclone diameter D).

Recently, it was verified that fine particles will agglomerate with larger particles as long as certain project conditions can be met (Paiva *et al.*, 2010). This clustering is hard to predict, involving quite complex models of solid-solid interaction within turbulent flow fields, and correspondingly highly demanding numerical calculations, even for modern and fast computers.

2 - Previous state of the art

The first cyclones date from the end of the XIX century, while the predictive models for cyclone modelling have evolved from purely empirical to more fundamental ones. Near the frontier of empirical models versus fundamental ones, there is a theory that can adjust fairly well many of the existing data relative to cyclones both at laboratory, pilot or industrial scales, having been developed by Möthes and Loffler (1988).

A disadvantage of this theory is that it is only a diagnostics one (allowing to fit well the observed experimental data), instead of a prognostics one, viz. it is not good at predicting the behaviour of cyclones of arbitrary geometry under arbitrary conditions, because it depends on the knowledge of the particles' turbulent dispersion coefficient, a fundamental parameter for this theory. A second disadvantage is that this theory completely neglects inter-particle agglomeration (clustering) under turbulence, a phenomenon that occurs in practice.

As the turbulent dispersion coefficient is affected by cyclone geometry, operating conditions and particle size distribution, Salcedo and Coelho (1999) could obtain a semi-empirical formula allowing to estimate this parameter from the above conditions. It was the coupling of global optimization algorithms (Salcedo, 1992), to the fundamental model of Möthes and Loffler (1988), and the predictive model of Salcedo and Coelho (1999), which allowed to reach the cyclones as per patent EP0972572. However, until a few years ago (Paiva *et al.*, 2010), it was not possible to estimate the effect of inter-particle agglomeration in the collection efficiency of reverse-flow cyclones.

The problem of obtaining more efficient cyclone geometries has been tackled, from about 25 years ago, both empirically (trial and error), as demonstrated by the few main works in this field (Li *et al.*, 1988; Schmidt, 1993; Molerus and Gluckler, 1996; Ray et al, 1998; Sun *et al.*, 2005), and by global optimization (Salcedo and Campos, 1999; Ravi *et al.*, 2000; Salcedo and Cândido, 2001; Salcedo and Pinho, 2003; Salcedo and Sousa Mendes, 2003; Salcedo *et al.*, 2004) but always neglecting the phenomena of inter-particle agglomeration. The improvements obtained by empirical methods are usually not very significant, and require too much development time and cost. Global optimization, ignoring inter-particle agglomeration, while allowing obtaining significantly better cyclones (for example, those from patent EP0972572), produces large errors in the prediction of the collection for very fine particles.

Summing up, there is not, up to the present date, any warranty that there exists in the marketplace the best reverse-flow cyclones that have included, in their design, the phenomenon of inter-particle agglomeration, as only a few years ago (Paiva *et al.*, 2010) it was possible to begin to understand this phenomenon in a quantitative way, so that agglomeration could be included in predictive models for cyclone design.

3 - Invention basis - a new approach

The present invention is based on the assumption that the comprehension of inter-particle agglomeration in turbulent flows could possibly allow the development of geometries maximizing the collection of fine particles, by maximizing their agglomeration with larger particles, thus maximizing global cyclone efficiency.

The work developed for this invention used the coupling of global optimization techniques, of the type that produced the invention described in patent EP0972572, and in particular those corresponding to the families of cyclones thereof - from now on designated as Cyclop_HE and Cyclop_K - with numerical modelling of inter-particle agglomeration.

With the objective of designing cyclones with much larger collection efficiency than those currently available in the marketplace, including in their design the phenomenon of inter-particle agglomeration, global optimizations were performed in a first phase, simultaneously using the PACyc model (Paiva *et* *al.*, 2010), to model the agglomeration, and the global optimizer MSGA (Salcedo, 1992), to obtain the best possible geometry. The operating conditions used were both at laboratory, pilot and industrial-scales, and the particle size distributions were several, contained in the data base of Advanced Cyclone Systems, S.A. (Portugal) (from now on designated as ACS). Geometrical constraints were imposed on the optimizer so that the numerical solution could be assigned as a buildable cyclone, and maximum pressure drop was fixed at about 2500 Pa (250mm w.g.), as it is usual for industrial applications of cyclones. An additional constraint of low sensitivity of the cyclone geometry to the re-entrainment phenomena was added (to prevent emission to the atmosphere of previously captured particles), using the criterion of Kalen and Zenz (Licht, 1980). Thus, the objective was to obtain optimized cyclones with a predicted (theoretical) efficiency matching as close as possible the experimental one.

In a second phase, ratios of geometrical characteristics were identified, in an attempt to identify common traces possibly allowing to define a family of geometries correctly approaching all the experimental data.

4 - Description of the invention

After detailed analysis of the results, common ratios could be identified that define a new family of reverse-flow cyclones, from now on designated as HR_MK, that maximize efficiency in the presence of inter-particle agglomeration.

The common traces which are characteristic of the cyclones according to the invention are those given by the intervals below, corresponding to each of the seven non-dimensional ratios between the dimensions of the reverse flow cyclones having a tangential entry, of rectangular section of sides *a* and *b*, the first parallel to the main cyclone axis; a body of total height *H* with an upper cylindrical part of internal diameter *D* and height *h* and an inverted inferior cone section with a bottom base diameter D_b; and a cylindrical vortex finder of height *s* and diameter D_e:

a/D	0.110-0.170;
b/D	0.110-0.170;
s/D	0.500-0.540;
D_e/D	0.100-0.170;
h/D	2.200-2.700;
H/D	3.900-4.300;
D_b/D	0.140-0.180.

An example of the geometry of an agglomerating cyclone according to the invention can be seen in Figure 2.

Table 1 below, where the cyclone according to the invention is designated as HR_MK, gives the values of the 7 geometric ratios obtained - such values being defined by means of the intervals given above - and compares them, as an example, with the characteristic ratios of the optimized geometries according to patent EP0972572.

Table 2 shows, for the geometries available in the literature, including some patents related to cyclones, and also from the database of ACS, the values of the corresponding ratios, for a total of 182 different cases. For example, in Ramachandran *et al.* (1991) there are 97 geometries of those in Table 2.

Table 1 - Geometries of optimized families

Ratio	HR_MK(1)	Cyclop_HE(2)	Cyclop_K(2)
a/D	0.110-0.170	0.270-0.360	0.270-0.310
b/D	0.110-0.170	0.270-0.360	0.270-0.310
s/D	0.500-0.540	0.330-0.495	0.330-0.395
D_e/D	0.100-0.170	0.280-0.370	0.405-0.430
h/D	2.200-2.700	1.001-1.300	2.050-2.260
H/D	3.900-4.300	4.050-4.250	3.500-3.700
D_b/D	0.140-0.180	0.200-0.300	0.250-0.300

(1) - Optimized including inter-particle agglomeration
(2) - Optimized excluding inter-particle agglomeration (EP0972572)

Table 2 - Geometries of families available in the literature/marketplace

Model	a/D	b/D	s/D	De/D	h/D	Db/D	H/D	
1	0.270-0.360	0.270-0.360	0.330-0.495	0.280-0.370	1.001-1.300	0.200-0.300	4.050-4.250	(a)
2	0.500	0.200	0.500	0.500	1.500	0.376	4.000	
3	0.353	0.335	0.471	0.400	1.000	0.400	3.353	
4	0.469	0.219	0.500	0.397	1.297	0.397	3.334	
5	0.470	0.220	0.500	0.400	1.300	0.400	3.333	
6	0.271	0.271	0.837	0.360	1.669	0.468	4.259	
7	0.397	0.199	0.608	0.317	0.752	0.206	3.118	
8	0.400	0.200	0.549	0.319	0.797	0.270	3.142	
9	0.453	0.212	0.676	0.500	0.706	0.191	2.529	
10	0.229	0.229	0.516	0.258	0.839	0.484	1.806	
11	0.189	0.189	0.495	0.196	1.030	0.400	2.344	
12	0.685	0.269	0.761	0.514	1.453	0.176	3.272	
13	0.511	0.274	0.756	0.520	1.453	0.255	3.270	
14	0.522	0.273	0.759	0.520	1.455	0.255	3.273	
15	0.608	0.288	0.923	0.615	0.692	0.462	3.385	
16	0.438	0.188	1.000	0.438	1.406	0.250	5.156	
17	0.334	0.167	0.852	0.334	1.325	0.334	3.580	
18	0.665	0.265	1.413	0.604	1.503	0.350	3.000	
19	0.101	0.101	0.333	0.096	1.474	0.439	2.781	
20	0.331	0.166	0.397	0.397	1.414	0.199	2.785	
21	0.319	0.319	0.775	0.206	0.906	0.460	3.969	
22	0.534	0.151	0.732	0.232	0.695	0.332	3.356	
23	0.627	0.247	1.254	0.556	1.530	0.177	3.599	
24	0.500	0.250	0.625	0.500	2.000	0.250	4.000	
25	0.502	0.249	1.505	0.499	2.006	0.371	4.013	
26	0.500	0.250	1.481	0.500	2.000	0.167	4.019	
27	0.500	0.250	1.481	0.500	2.000	0.167	4.019	
28	0.499	0.261	1.502	0.496	4.002	0.235	4.002	
29	0.499	0.261	1.502	0.496	4.002	0.235	4.002	
30	0.445	0.223	1.000	0.444	1.397	0.413	3.905	
31	0.448	0.231	0.996	0.448	1.395	0.403	3.865	
32	0.697	0.250	0.888	0.526	1.224	0.263	4.526	
33	0.471	0.471	0.804	0.358	1.413	0.138	3.139	

34	0.447	0.096	0.500	0.367	0.545	0.100	1.469
35	0.400	0.200	0.875	0.436	0.875	0.125	3.500
36	0.300	0.200	0.783	0.444	0.800	0.083	3.333
37	0.302	0.198	0.710	0.400	0.794	0.317	2.825
38	0.461	0.202	0.459	0.279	1.303	0.401	3.353
39	0.636	0.275	0.630	0.472	1.195	0.398	2.635
40	0.223	0.223	1.000	0.500	2.167	0.333	3.083
41	0.208	0.208	0.900	0.318	0.900	0.381	2.790
42	0.653	0.286	1.735	0.510	1.806	0.408	3.949
43	0.638	0.320	0.637	0.477	1.326	0.387	2.643
44	0.271	0.271	0.750	0.471	0.833	0.233	3.000
45	0.270	0.270	0.747	0.470	0.798	0.295	2.904
46	0.249	0.249	0.852	0.391	0.899	0.280	2.937
47	0.198	0.198	2.009	0.670	2.232	0.670	3.125
48	0.301	0.301	0.508	0.340	1.347	0.340	3.640
49	0.167	0.083	0.417	0.167	1.500	0.500	3.531
50	0.139	0.139	0.993	0.235	2.085	0.118	3.623
51	0.390	0.300	0.496	0.390	1.000	0.400	3.000
52	0.500	0.250	1.090	0.300	1.090	0.381	3.000
53	0.247	0.247	0.447	0.282	4.124	0.182	5.000
54	0.222	0.222	0.328	0.333	0.853	0.500	2.723
55	0.994	0.147	1.123	0.448	3.241	0.376	5.562
56	0.394	0.303	0.571	0.394	0.861	0.429	1.858
57	0.322	0.201	0.503	0.497	1.678	0.658	2.852
58	0.548	0.246	1.173	0.550	2.173	0.533	3.573
59	0.816	0.204	1.259	0.646	1.895	0.204	3.799
60	0.408	0.282	0.652	0.565	1.013	0.392	2.922
61	0.501	0.232	0.626	0.357	1.376	0.429	4.252
62	0.461	0.257	1.122	0.498	1.146	0.024	2.580
63	0.704	0.306	0.822	0.593	1.375	0.407	2.699
64	0.500	0.250	0.625	0.500	2.000	0.250	4.000
65	0.500	0.200	0.500	0.500	1.500	0.375	4.000
66	0.440	0.210	0.500	0.400	1.400	0.400	3.900
67	0.500	0.230	0.654	0.523	0.654	0.317	3.164
68	0.400	0.150	0.400	0.400	1.100	0.325	4.500
69	0.333	0.167	0.752	0.333	1.333	0.333	3.333
70	0.350	0.300	0.350	0.390	1.500	0.375	5.000
71	0.750	0.380	0.880	0.750	1.500	0.380	4.000
72	0.270-0.310	0.270-0.310	0.330-0.395	0.405-0.430	2.050-2.260	0.250-0.300	3.500-3.700 (a)
73	0.265	0.265	0.332	0.349	2.500	0.349	5.000
74	0.208	0.208	0.900	0.318	0.900	0.381	2.790
75	0.394	0.303	0.571	0.394	0.861	0.429	1.858
76	0.304	0.184	0.814	0.259	1.019	0.250	4.779
77	0.533	0.133	0.733	0.333	0.693	0.333	2.580

78	0.400	0.100	0.733	0.333	0.693	0.333	2.580
79	0.500	0.250	1.060	0.500	1.990	0.250	3.980
80	0.380	0.190	1.130	0.310	1.810	0.380	4.310
81	0.533	0.233	1.600	0.500	2.133	0.267	4.267
82	0.533	0.156	1.600	0.500	2.133	0.267	4.267
83	0.533	0.111	1.600	0.500	2.133	0.267	4.267
84	0.500	0.148	0.500	0.313	1.625	0.313	2.375
85	0.500	0.148	0.500	0.500	1.625	0.313	2.375
86	1.000	0.250	0.500	0.313	1.125	0.313	1.688
87	1.000	0.250	0.500	0.500	1.125	0.313	1.688
88	0.250	0.125	1.500	0.500	2.000	0.250	4.000
89	0.500	0.250	1.500	0.500	2.000	0.250	4.000
90	0.600	0.250	1.500	0.500	2.000	0.250	4.000
91	0.667	0.133	0.400	0.333	1.133	0.250	1.967
92	0.367	0.117	0.733	0.250	0.950	0.250	2.200
93	0.283	0.150	0.600	0.500	0.700	0.200	1.450
94	0.288	0.151	0.613	0.500	0.700	0.200	1.463
95	0.293	0.150	0.600	0.500	0.700	0.200	1.475
96	0.283	0.067	0.600	0.500	0.700	0.200	1.450
97	0.142	0.150	0.600	0.500	0.700	0.200	1.450
98	0.283	0.150	0.600	0.667	0.700	0.200	1.450
99	0.283	0.067	0.600	0.333	0.700	0.200	1.450
100	0.283	0.150	0.600	0.500	0.700	0.200	1.158
101	0.283	0.094	0.600	0.500	0.700	0.200	1.158
102	0.283	0.094	0.600	0.667	0.700	0.200	1.158
103	0.283	0.150	0.600	0.333	0.700	0.200	1.158
104	0.283	0.150	0.600	0.667	0.700	0.200	1.158
105	0.283	0.150	0.600	0.333	0.700	0.200	1.450
106	0.113	0.150	0.600	0.500	0.700	0.200	1.450
107	0.208	0.150	0.600	0.500	0.700	0.200	1.450
108	0.283	0.094	0.600	0.500	0.700	0.200	1.450
109	0.283	0.067	0.400	0.333	0.700	0.200	1.450
110	0.292	0.208	0.556	0.417	0.667	0.140	2.056
111	0.393	0.119	0.667	0.476	0.655	0.141	1.607
112	0.500	0.200	0.500	0.500	1.500	0.375	4.000
113	0.620	0.230	1.170	0.500	1.330	0.250	3.180
114	0.667	0.333	0.893	0.573	1.307	0.250	3.280
115	0.609	0.318	0.909	0.564	1.364	0.250	2.727
116	0.561	0.211	0.763	0.513	0.561	0.531	2.666
117	0.526	0.156	0.632	0.434	0.632	0.316	3.579
118	0.538	0.162	0.673	0.435	0.681	0.404	3.373
119	0.527	0.149	0.636	0.400	0.636	0.345	2.909
120	0.486	0.268	0.568	0.405	0.649	0.405	2.335
121	0.267	0.267	0.390	0.300	0.501	0.300	2.486
122	0.900	0.100	0.967	0.500	1.035	0.500	2.217

123	0.900	0.100	0.967	0.500	1.035	0.500	3.467
124	0.900	0.100	0.967	0.500	1.035	0.500	5.967
125	0.900	0.100	0.967	0.500	1.035	0.500	10.970
126	0.900	0.200	0.967	0.500	1.035	0.500	2.217
127	0.900	0.200	0.967	0.500	1.035	0.500	3.467
128	0.900	0.200	0.967	0.500	1.035	0.500	5.967
129	0.900	0.200	0.967	0.500	1.035	0.500	10.970
130	0.900	0.300	0.967	0.500	1.035	0.500	2.217
131	0.900	0.300	0.967	0.500	1.035	0.500	3.467
132	0.900	0.300	0.967	0.500	1.035	0.500	5.967
133	0.900	0.300	0.967	0.500	1.035	0.500	10.970
134	0.900	0.400	0.967	0.500	1.035	0.500	2.217
135	0.900	0.400	0.967	0.500	1.035	0.500	3.467
136	0.900	0.400	0.967	0.500	1.035	0.500	5.967
137	0.900	0.400	0.967	0.500	1.035	0.500	10.970
138	0.900	0.100	0.967	0.333	1.035	0.333	1.801
139	0.900	0.100	0.967	0.333	1.035	0.333	2.634
140	0.900	0.100	0.967	0.333	1.035	0.333	4.301
141	0.900	0.200	0.967	0.333	1.035	0.333	1.801
142	0.900	0.200	0.967	0.333	1.035	0.333	2.634
143	0.900	0.200	0.967	0.333	1.035	0.333	4.301
144	0.900	0.300	0.967	0.333	1.035	0.333	1.801
145	0.900	0.300	0.967	0.333	1.035	0.333	2.634
146	0.900	0.300	0.967	0.333	1.035	0.333	4.301
147	0.900	0.400	0.967	0.333	1.035	0.333	1.801
148	0.900	0.400	0.967	0.333	1.035	0.333	2.634
149	0.900	0.400	0.967	0.333	1.035	0.333	4.301
150	0.900	0.100	0.967	0.250	1.035	0.250	1.592
151	0.900	0.100	0.967	0.250	1.035	0.250	2.217
152	0.900	0.100	0.967	0.250	1.035	0.250	3.467
153	0.900	0.200	0.967	0.250	1.035	0.250	1.592
154	0.900	0.200	0.967	0.250	1.035	0.250	2.217
155	0.900	0.200	0.967	0.250	1.035	0.250	3.467
156	0.900	0.300	0.967	0.250	1.035	0.250	1.592
157	0.900	0.300	0.967	0.250	1.035	0.250	2.217
158	0.900	0.300	0.967	0.250	1.035	0.250	3.467
159	0.900	0.400	0.967	0.250	1.035	0.250	1.592
160	0.900	0.400	0.967	0.250	1.035	0.250	2.217
161	0.555	0.400	0.967	0.250	1.035	0.250	3.467
162	0.553	0.162	0.543	0.433	0.684	0.384	3.263
163	0.553	0.161	0.552	0.431	0.681	0.383	3.245
164	0.553	0.161	0.561	0.432	0.682	0.382	3.255
165	0.440	0.210	0.500	0.400	1.400	0.400	3.900
166	0.500	0.250	0.600	0.500	1.750	0.400	3.750
167	0.557	0.331	0.962	0.541	3.350	0.287	5.939

168	0.575	0.230	0.584	0.575	0.750	0.480	3.510	
169	0.573	0.223	0.580	0.575	0.750	0.477	3.460	
170	0.372	0.186	0.541	0.514	0.743	0.253	2.095	
171	0.494	0.247	0.740	0.407	2.662	0.586	3.961	
172	0.375	0.188	1.125	0.313	1.813	0.375	4.313	
173	0.500	0.200	0.500	0.500	1.500	0.375	4.000	
174	0.500	0.300	0.558	0.333	3.500	0.375	6.000	
175	0.375	0.200	3.052	0.583	3.500	1.000	6.000	
176	0.375	0.200	2.865	0.583	3.500	0.688	6.000	
177	0.500	0.300	2.073	0.333	3.500	1.000	6.000	
178	0.500	0.202	0.623	0.500	2.623	0.447	4.018	(b)
179	1.000	0.201	0.467	0.375	2.007	0.336	4.013	(b)
180	0.513	0.201	0.526	0.375	2.007	0.336	4.013	(b)
181	0.513	0.201	0.526	0.375	3.007	0.336	5.013	(b)
182	0.274-0.500	0.141-0.258	0.250-0.750	0.300-0.700	0.160-1.000	>0.640	0.800-2.000	(c)

(a) EP0972572; (b) EP1487588; (c) EP0564992

After a detailed statistical analysis on the occurrence of violations to the ratios imposed in Tab.1 for the geometry HR_MK, on can see that there are 37% (67 geometries) that violate a single ratio and 14% (25 geometries) that violate exactly two ratios, as it can be seen in Tables 3 and 4. By violation of a ratio, it is understood, in the present patent specification, that there exists at least one cyclone from the previous state of the art, which, for that ratio (or non-dimensional parameter), has at least one value that belongs to the characteristic interval specified in Table 1 for the cyclones according to the invention (HR_MK), with respect to that ratio.

There is no geometry that violates more than 2 ratios, which makes the family HR_MK quite different from the cyclones previously known. This is not astonishing, because no optimized reverse-flow cyclones were ever obtained before including in their design the phenomenon of inter-particle agglomeration. Surprising, yes, was the fact that common traces (traits) could be recognized for this new family, because nothing would guarantee that such a possibility existed, given that the high complexity of inter-particle interaction could be so closely related to each concrete case (geometry included), that it would be impossible to obtain links of general traces.

As main characteristics that distinguish the optimized family according to the present invention, from the other families, one can point out the following ones:

- Gas entry, vortex tube and solids discharge more narrow;
- Longer cylindrical upper body and shorter cone lower body.

Table 3 - Identification of geometries that violate a single ratio of HR_MK

Number of violated ratios = 1							
Ratio/Geometry	a/D	b/D	s/D	De/D	h/D	Db/D	H/D
4			X				
5			X				
6							X
10			X				
11			X				
12						X	
17		X					
19				X			
20		X					
21							X
22		X					
23						X	
24							X
25							X
28							X
29							X
30							X
31							X
33						X	
34			X				
40					X		
42							X
47					X		
48			X				
51			X				
53						X	

55		X					
57			X				
58					X		
61							X
64							X
68		X					
69		X					
71							X
72					X		
73					X		
77		X					
79							X
81							X
83							X
86			X				
87			X				
89							X
90							X
91		X					
92		X					
93		X					
94		X					
95		X					
98		X					
100		X					
103		X					
104		X					
105		X					
107		X					
117		X					
118		X					
119		X					
140							X
143							X
146							X
149							X
163		X					
164		X					
170			X				
179							X
181			X				

X = violation of a single ratio

Table 4 - Identification of geometries that violate two ratios of HR_MK

Number of violated ratios = 2							
Ratio/Geometry	a/D	b/D	s/D	De/D	h/D	Db/D	H/D
1			X				X
2			X				X
26						X	X
27						X	X
49	X			X			
50	X	X					
65			X				X
66			X				X
82		X					X
83		X					X
84		X	X				
85		X	X				
88		X					X
97	X	X					
106	X	X					
111		X				X	
112			X				X
162		X	X				
165			X				X
171					X		X
173			X				X
178					X		X
180			X				X
182		X	X				

X = violation of one ratio

The present patent application refers to a geometry of reverse-flow cyclones that was numerically optimized simultaneously considering inter-particle agglomeration and global optimization. As it can be seen from the above, the family of cyclones according to the invention is quite distinct from those existing in the marketplace and in the scientific literature, having for that being analysed 182 different geometries. The cyclone family according to the invention is of maximum efficiency significantly larger than the one of the cyclones disclosed in patent EP0972572, which had already been demonstrated to be significantly more efficient than other reverse-flow cyclones usually referred to as being of the high-efficiency type.

The present invention also relates to a de-dusting method where the flue gases pass through a cyclone according to the present invention.

According to a particular embodiment, de-dusting can be accompanied by the dry removal of gases, by introducing an appropriate reactant (sorbent) in powder form, upstream of the cyclone according to the invention.

The invention also relates to the use of the method and of the cyclone, according to the invention, for the cleaning of acid gases. According to a particular embodiment, the acid gases, are HCl (hydrogen chloride), HF (hydrogen fluoride), SO_2 (sulphur dioxide) and/or NO_x (nitrogen oxides).

Following another particular embodiment, the invention is also related to the use of the disclosed method and cyclone, for the removal of fine particulate matter from diesel exhaust fumes.

5 - Brief description of figures

Figure 1 represents a reverse-flow cyclone and shows the linear dimensions that are the basis for calculating the non-dimensional ratios referred before, dimensions which were already described in detail, as well as the flows entering and exiting the cyclone, respectively the dirty gas (GS) the cleaned gas (GL) and the captured particles (P).

Figure 2 represents a typical agglomerating cyclone according to the invention (HR_MK).

Figure 3 represents a graph with the particle size distribution used in a small cyclone according to the invention (HR_MK) of 135mm internal diameter (D) for a very low particle density (ρ_p) of 450 kg/m^3. The ordinate axis represents the cumulative undersize frequency (FC) in percentage (by Volume) and the abscissa axis the diameter (ϕ) of the particles, in microns.

Figure 4 represents a graph where the grade-efficiencies are compared for the geometry of the invention (HR_MK) and for the geometry Cyclop_HE (for the particles of Fig. 3). The ordinate axis represents the efficiency (η) and the abscissa axis the diameter (ϕ) of the particles, in microns.

Figure 5 represents a graph with the particle size distribution used in a cyclone according to the invention (HR_MK) of 460mm internal diameter (D) for a particle density (ρ_p) of 906 kg/m^3. The axes are identical to those of Figure 3.

Figure 6 represents a graph where the grade-efficiencies are compared for the geometry of the invention (HR_MK) and for the geometry Cyclop_HE (for the particles of Fig. 5). The axes are identical to those of Figure 4.

Figure 7 represents a graph with the particle size distribution used in a cyclone according to the invention (HR_MK) of 700mm internal diameter (D) for a very low particle density (ρ_p) of 310 kg/m^3. The axes are identical to those of Figure 3.

Figure 8 represents a graph where the grade-efficiencies are compared for the geometry of the invention (HR_MK) and for the geometry Cyclop_HE (for the particles of Fig. 7). The axes are identical to those of Figure 4.

Figure 9 represents a graph with the particle size distribution used in a cyclone according to the invention (HR_MK) of 1400mm internal diameter (D) for a large particle density (ρ_p) of 1450 kg/m^3. The axes are identical to those of Figure 3.

Figure 10 represents a graph where the grade-efficiencies are compared for the geometry of the invention (HR_MK) and for the geometry Cyclop_HE (for the particles of Fig. 9). The axes are identical to those of Figure 4.

6 - Specific examples

To confirm the simulation results obtained, four different sized cyclones were tested according to the invention (HR_MK), with diameters of 135, 460, 700 and 1400mm. The obtained efficiencies with different particles and particle size distributions were compared with those obtained with similar sized cyclones of the type Cyclop_HE (the best numerically optimized prior to the present invention), for the capture of very fine powders, with very low density or with both of these characteristics. In all cases, a significant increase in the capture efficiencies of fine particles was observed, and consequently, of the global efficiency.

The comparison between the geometries HR_MK and Cyclop_HE was also done for a case of denser particles and without any appreciable size fraction below 1 micron, end even below 10 micron, where, in this case, the geometry Cyclop_HE was better.

6a - HR_MK of 135mm

Fig. 3 shows the test particle size distribution for a cyclone of the present invention (HR_MK) of 135mm diameter, for non-porous particles but of very low density (true density, obtained by helium pycnometry, of 450 kg/m^3). The remaining operating conditions were: gas flow-rate of 40m^3/h@165°C and inlet concentration of 530 mg/m^3. Fig. 4 compares the performance of the cyclones HR_MK and Cyclop_HE (EP0972572), for an equivalent pressure drop (2.6 kPa). It should be noted that low particle density enhances inter-particle agglomeration by producing cohesive particle collisions (Paiva *et al.*, 2010). Global efficiencies were respectively of 57 and 76% for the geometry Cyclop_HE and for the optimized HR_MK, i.e., emissions of the optimized cyclone according to the present invention are about 56% lower than those of the Cyclop_HE.

6b - HR_MK of 460mm

Fig. 5 shows the test particle size distribution for a cyclone of the present invention (HR_MK) of 460mm de diameter, for particles with a skeletal density (including the intra-particle pores) obtained by mercury pycnometry, of 906 kg/m^3)(for non-porous particles the true density coincides with the skeletal density, but for porous particles the skeletal density is always lower than the true density and is the one that should be used in cyclone modelling). The remaining operating conditions were: gas flow-rate of $310m^3/h@30°C$ and inlet concentration of 430 mg/m^3. Fig. 6 compares the performance of the cyclones HR_MK and Cyclop_HE (EP0972572), for an equivalent pressure drop (1.8 kPa). Global efficiencies were respectively of 62 and 92% for the geometry Cyclop_HE and for the optimized HR_MK, i.e., emissions of the optimized cyclone according to the present invention are about 78% lower than those of the Cyclop_HE.

6c - HR _MK of 700mm

Fig. 7 shows the test particle size distribution for a cyclone of the present invention (HR_MK) of 700mm de diameter, for particles with a skeletal density of 310 kg/m^3. The remaining operating conditions were: gas flow-rate of $640m^3/h@20°C$ and inlet concentration of 360 mg/m^3. Fig. 8 compares the performance of the cyclones HR_MK and Cyclop_HE, for an equivalent pressure drop (1.9 kPa). The emissions of the optimized cyclone according to the present invention are about 75% lower than those of the Cyclop_HE.

6d - HR_MK of 1400mm

In this case (figures 9 and 10), the particles used were denser and without an appreciable sub-micrometer fraction, with only 20% below 10 μm, thus with a lower tendency for agglomeration as compared to less dense and finer particles. The geometry according to the present invention (HR_MK) is not superior to the geometry Cyclop_HE, for equivalent pressure drops (1.2 kPa), for particles with density 1450 kg/m^3, gas flow-rate of 72000m^3/h@88°C and an inlet concentration of 460 mg/m^3.

7 - Final comments

The geometry HR_MK is the one that maximizes efficiency, considering inter-particle agglomeration and minimizing particle re-entrainment. The geometry HR_MK was tested at pilot and industrial-scales, showing significantly higher efficiencies (emissions, on average, 70% lower) than those from a very high efficiency cyclone available in the literature and in the marketplace and patented (EP0972572).

The geometry HR_MK is significantly different from high efficiency geometries available in the marketplace, being the only one, to the knowledge of the inventorsl, which was numerically optimized taking inter-particle agglomeration into account.

Predicted behaviour for industrial-scale situations show that the proposed geometry will have significantly higher efficiencies than those of the most efficient cyclones available in the marketplace, as long as particles to be captured have low densities and with a significant sub-micrometer fraction and also below about 10-20 µm, with expected emission reductions, on average of 70% relative to the Cyclop_HE geometry.

The method and the cyclone according to the invention are particularly preferential for the capture of particles with true densities below 1000 kg/m^3' when transported in a gas.

The method and the cyclone according to the invention are particularly preferential for the capture of particles from flue gases where the sub-micrometric fraction ranges from 20% to 30%.

The method and the cyclone according to the invention are particularly preferential for the capture from flue gases where particles below 10-20 µm range from 90% to 100%.

The method and the cyclone according to the invention are even more preferential for the de-dusting of flue gases where particles have any two of the three characteristics given in the three precedent paragraphs, being most preferential for de-dusting of flue gases where the particles combine the three given characteristics.

Considering that the inter-particle agglomeration/clustering promoted by the cyclone according to the invention and respective method is temporary, namely in the cases of the four paragraphs above (specially in the cases of examples 6a to 6c in the preceding section) occurring in the interior of the cyclone and ending when the particles are deposited at its outlet (namely when the particles are collected in any hopper) - being such agglomeration a temporary clustering - it was found that such cyclone and method are particularly indicated for the recovery of powdery material carried in gaseous streams. According to a particular embodiment of the invention, after the method of particle capture according to the invention, thus comprising the agglomerates (clusters) of particles formed inside the cyclone, these, after their removal from the cyclone bottom, are subjected to an additional stage of de-agglomeration (clusters' destruction), that complements the natural separation. According to a particular embodiment, the additional de-agglomeration stage can be done dispersing the clusters in a liquid medium.

The geometry of the cyclones according to the invention is substantially different from those existing in the marketplace, as well as from those referred to in the specialized literature, as it only shares, in the worst case, two of the seven ratios that define the cyclone geometry.

The cross section of the entry is preferably of a square configuration, the dimensions *a* and *b* being equal.

Although the entry should be of a tangential type, it may be volute, if the size justifies, without invalidating any of the above considerations.

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Claims

1 - Agglomerating cyclone of the reverse-flow type - comprising a tangential entry of rectangular cross section, of sides *a* and *b*, the first parallel to the main cyclone axis; a body of total height *H* with an upper cylindrical part of internal diameter *D* and height *h* and with a bottom inverted conical part whose smaller base has the smaller diameter D_b; and one cylindrical vortex tube of height *s* and diameter D_e - **characterized in that** presents a geometry, defined in terms of ratios of the internal dimensions of the referred sides, heights and diameters to the internal diameter *D* of the cyclone body, according to the following set of intervals of values, relative to the following non-dimensional ratios:

a/D	0.110-0.170;
b/D	0.110-0.170;
s/D	0.500-0.540;
D_e/D	0.100-0.170;
h/D	2.200-2.700;
H/D	3.900-4.300;
D_b/D	0.140-0.180.

2 - Cyclone according to claim 1, **characterized in that** the dimension of the sides a and b are equal, such that the entry section is squared.

3 - Cyclone according to claims 1 or 2, **characterized in that** the entry section is of a volute type.

4 - De-dusting method of a gaseous stream, **characterized in that** the gaseous stream circulates through a device according to claim 1.

5 - De-dusting method according to claim 4, **characterized in that** a gaseous stream carrying particles with true density below 1000 kg/m^3 circulates through a device according to claim 1.

6 - De-dusting method according to claims 4 or 5, **characterized in that** a gaseous stream carrying particles with

a cumulative fraction (mass or volume) below 10-20 µm in the range of 90% to 100% circulates through a device according to claim 1.

7 - De-dusting method according to claims 4, 5 or 6, **characterized in that** a gaseous stream carrying particles with a sub-micrometric cumulative fraction (mass or volume) in the range of 20% to 30% circulates through a device according to claim 1.

8 - De-dusting and acid gas dry cleaning method, from a gaseous stream, according to claim 4, **characterized in that**, upstream to the cyclone, is injected an appropriate reactant in powder form for acid gas removal.

9 - Use **characterized in that** the device of claim 1 and corresponding method of claim 8 are employed for de-dusting and cleaning of acid gases.

10 - Use according to claim 9, **characterized in that** the acid gases are HCl (hydrogen chloride), HF (hydrogen fluoride), SO_2 (sulphur dioxide) and/or NOx (nitrogen oxides).

11 - Use **characterized in that** the device of claim 1 and the corresponding method of claim 4 are employed for de-dusting of flue gases from diesel engines.

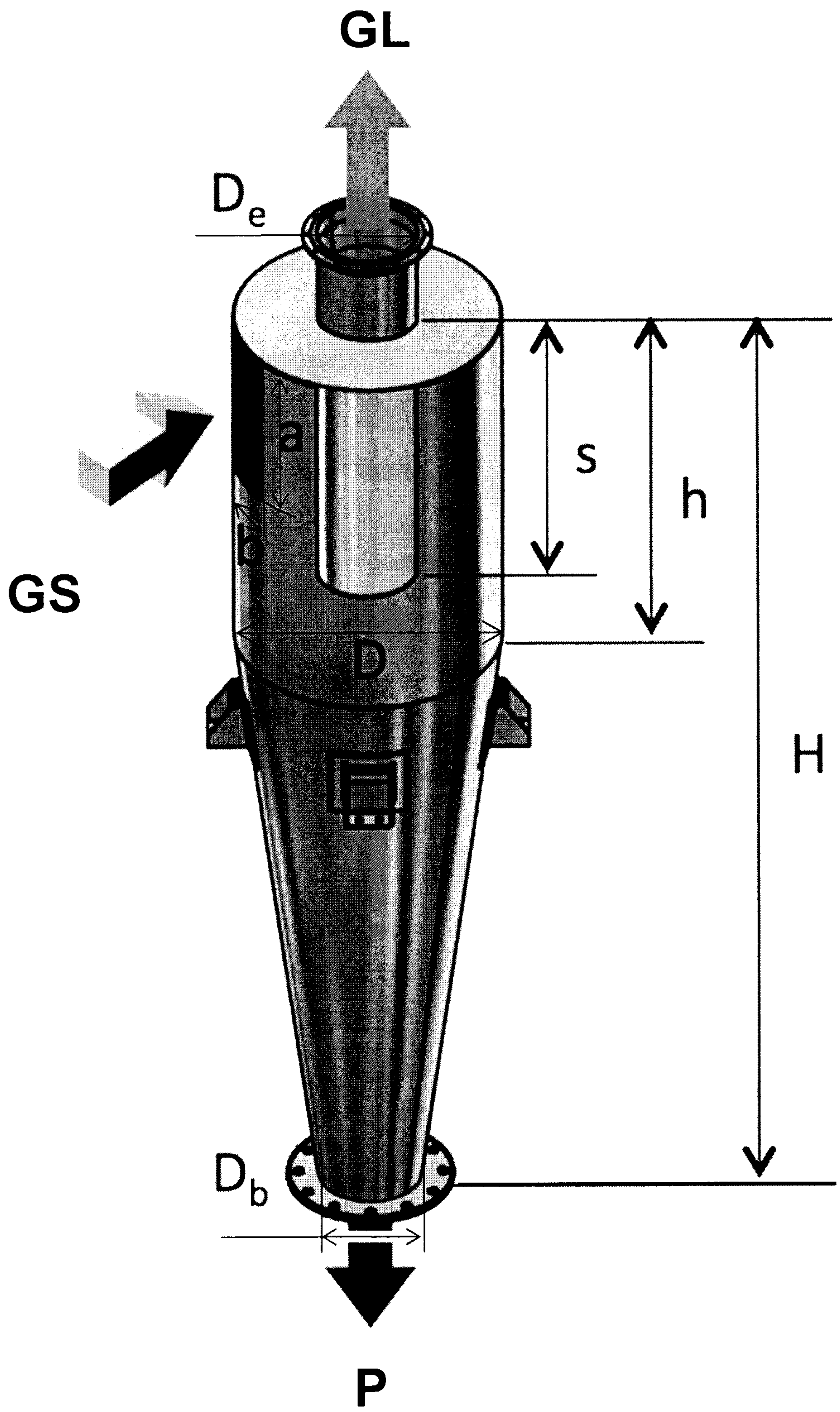

Fig. 1

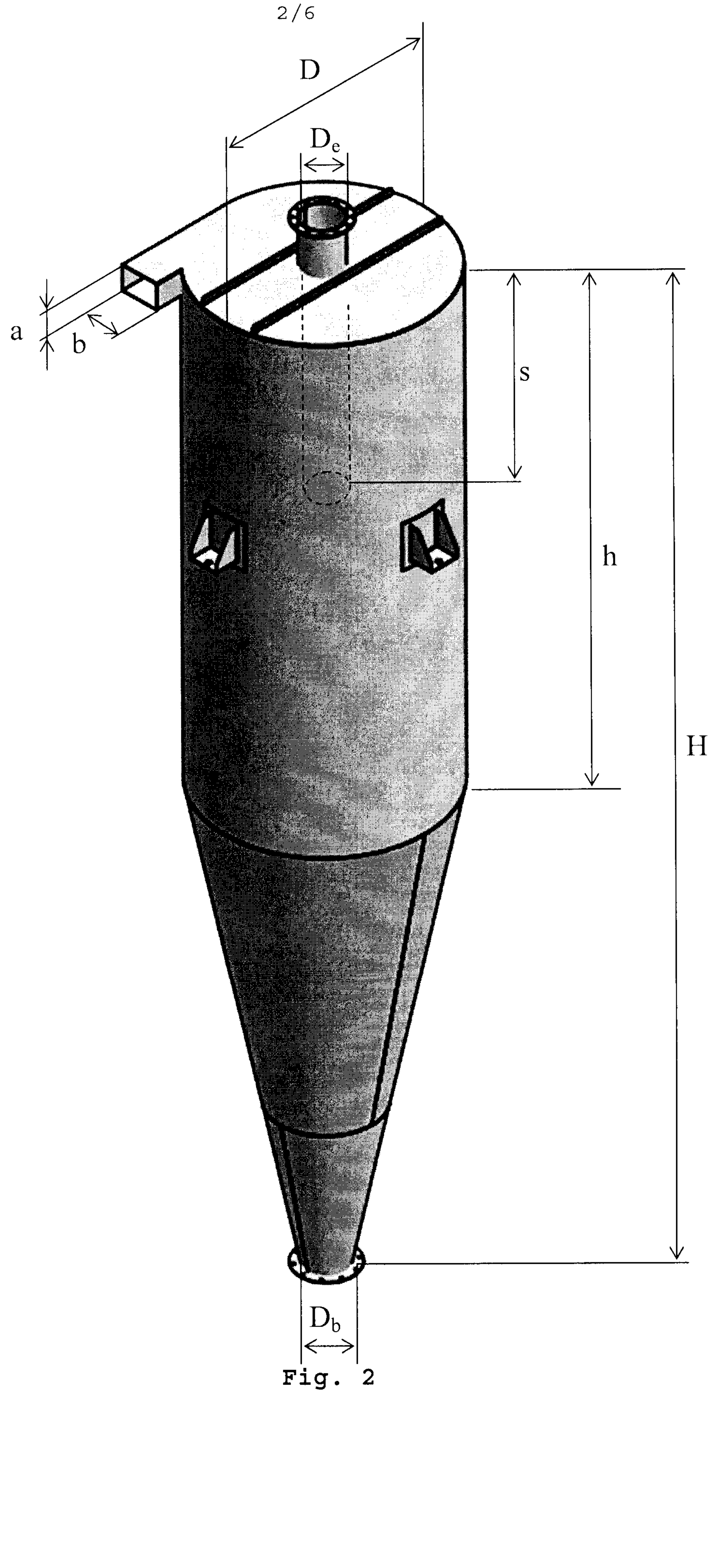

Fig. 2

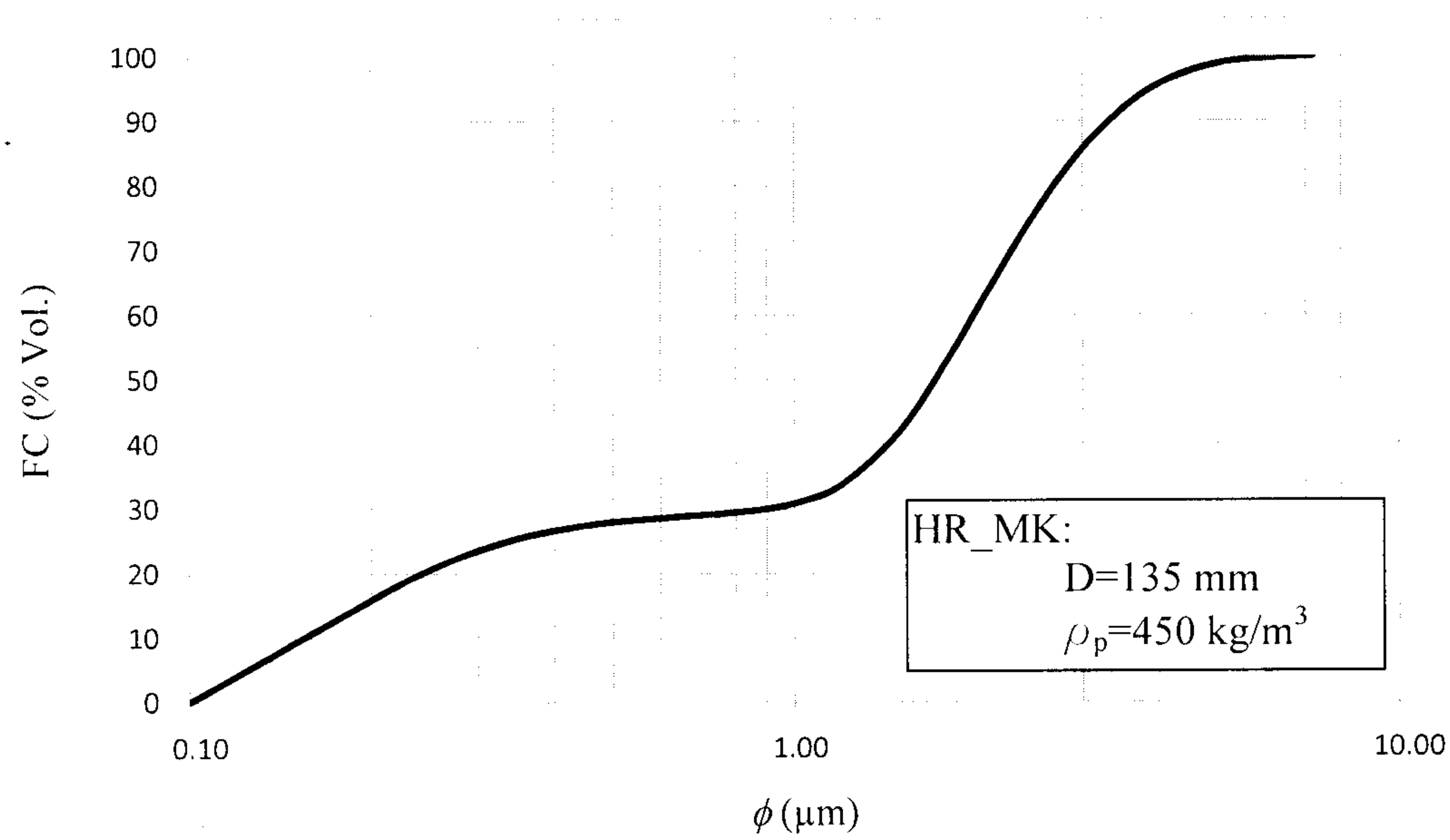
100
90
80
70
60
50
40
30
20
10
0
FC (% Vol.)
0.10
1.00
10.00
ϕ (µm)
HR_MK:
D=135 mm
ρ_p=450 kg/m^3

Fig. 3

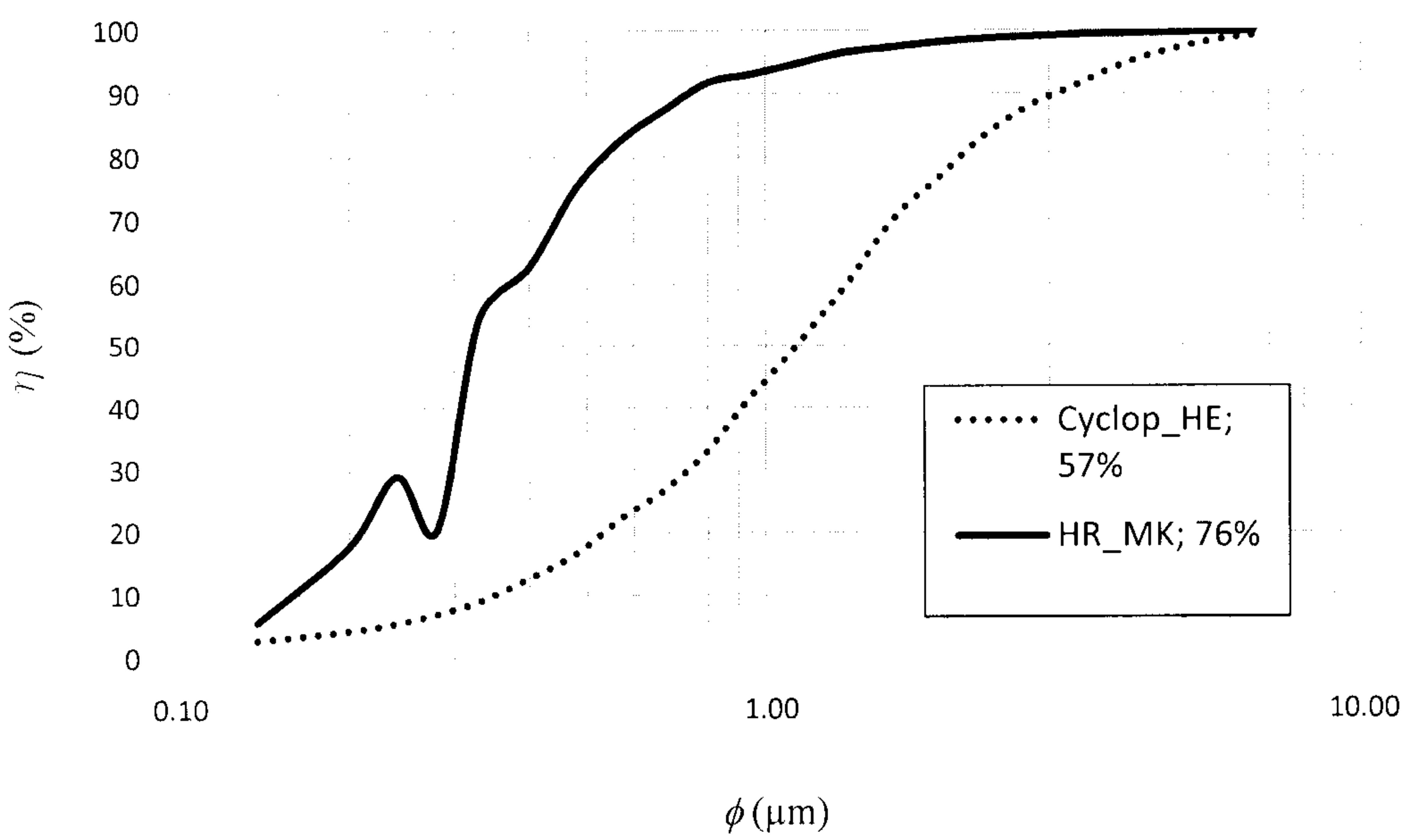
100
90
80
70
60
50
40
30
20
10
0
η (%)
0.10
1.00
10.00
ϕ (µm)
Cyclop_HE; 57%
HR_MK; 76%

Fig. 4

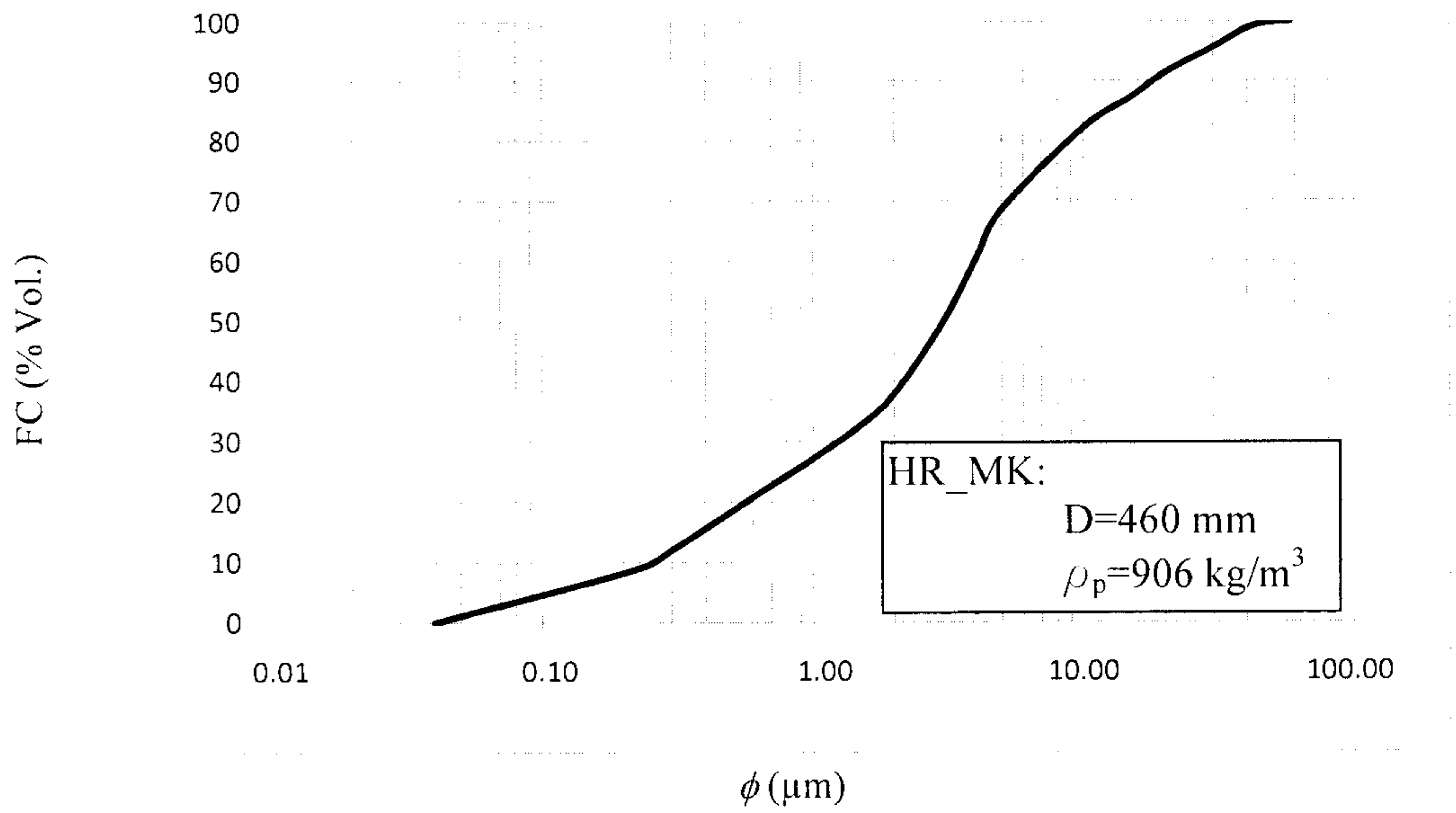
100
90
80
70
60
50
40
30
20
10
0
FC (% Vol.)
0.01
0.10
1.00
10.00
100.00
ϕ (μm)
HR_MK:
D=460 mm
ρp=906 kg/m3

Fig. 5

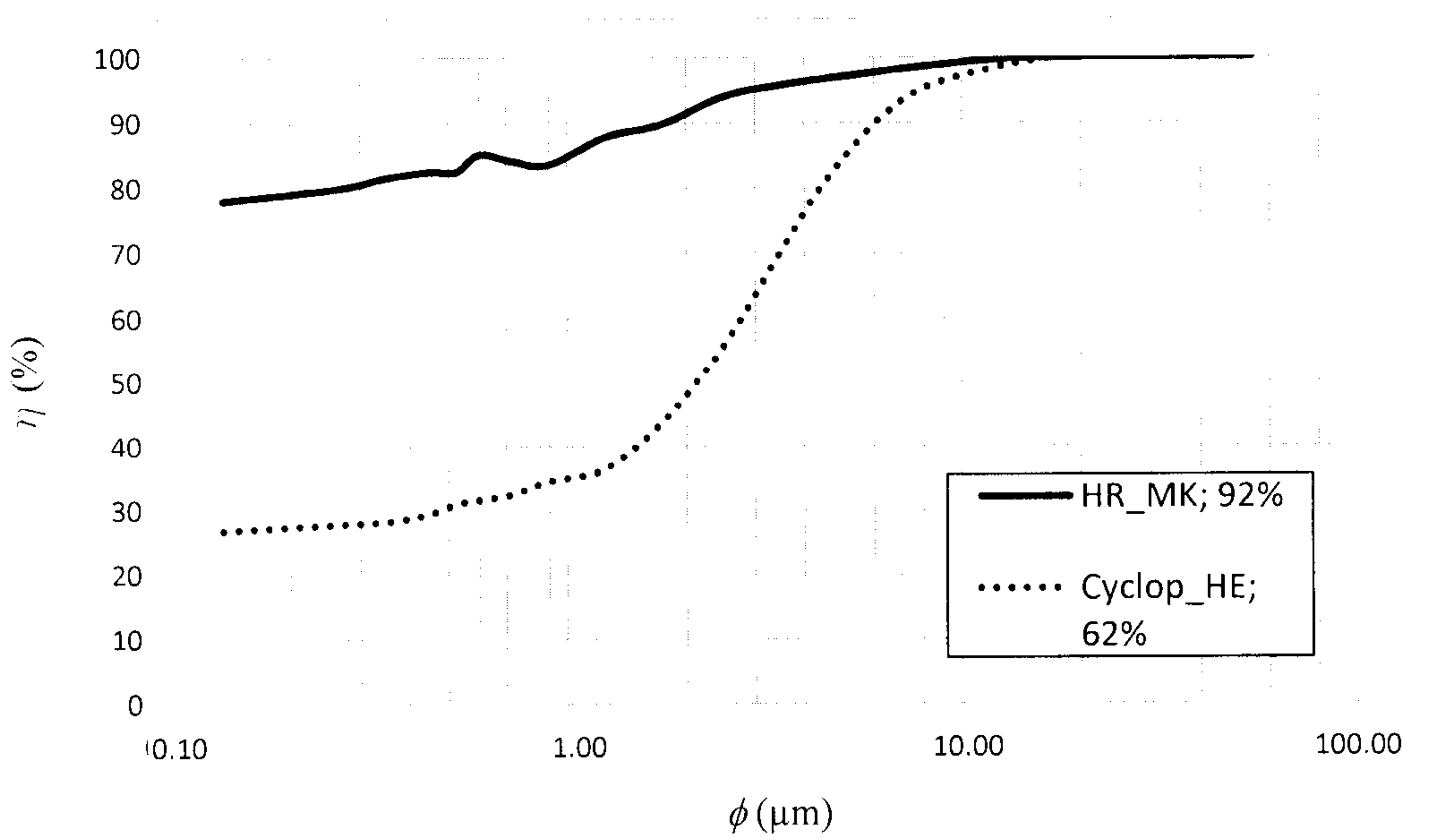
100
90
80
70
60
50
40
30
20
10
0
η (%)
0.10
1.00
10.00
100.00
ϕ (μm)
HR_MK; 92%
Cyclop_HE; 62%

Fig. 6

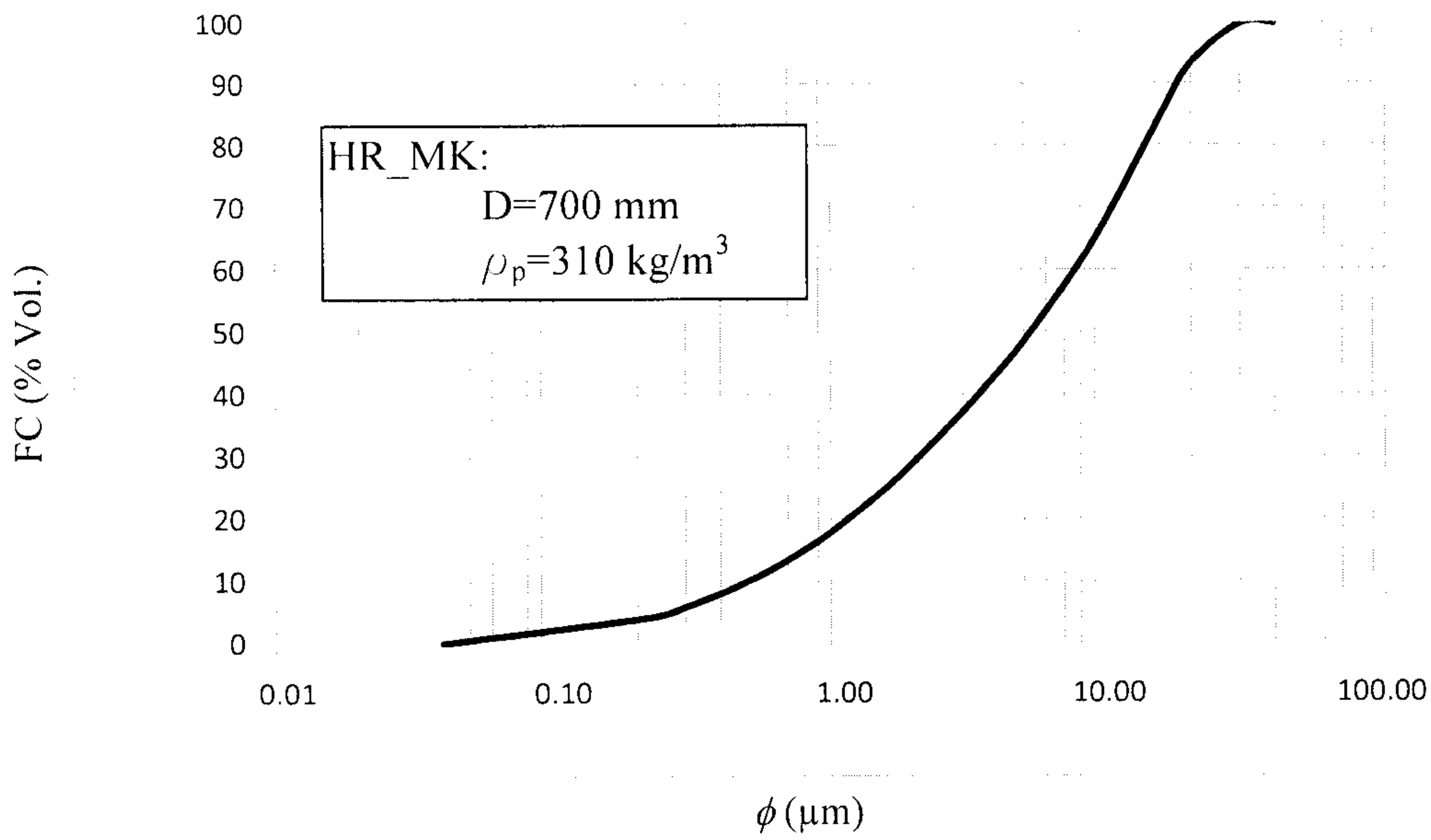
100
90
80
70
60
50
40
30
20
10
0
FC (% Vol.)
HR_MK:
D=700 mm
ρp=310 kg/m3
0.01
0.10
1.00
10.00
100.00
ϕ (μm)

Fig. 7

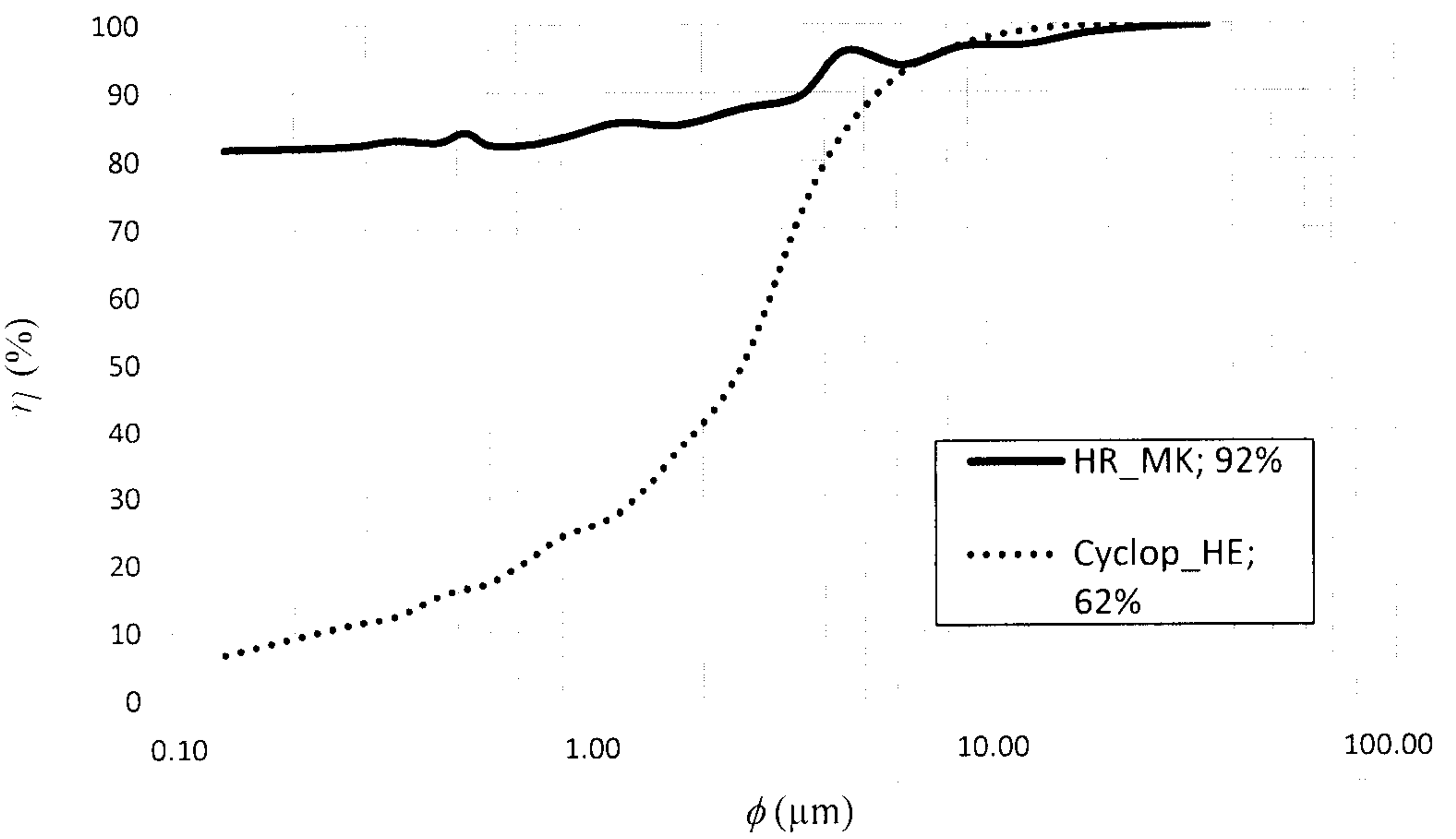
100
90
80
70
60
50
40
30
20
10
0
η (%)
HR_MK; 92%
Cyclop_HE; 62%
0.10
1.00
10.00
100.00
ϕ (μm)

Fig. 8

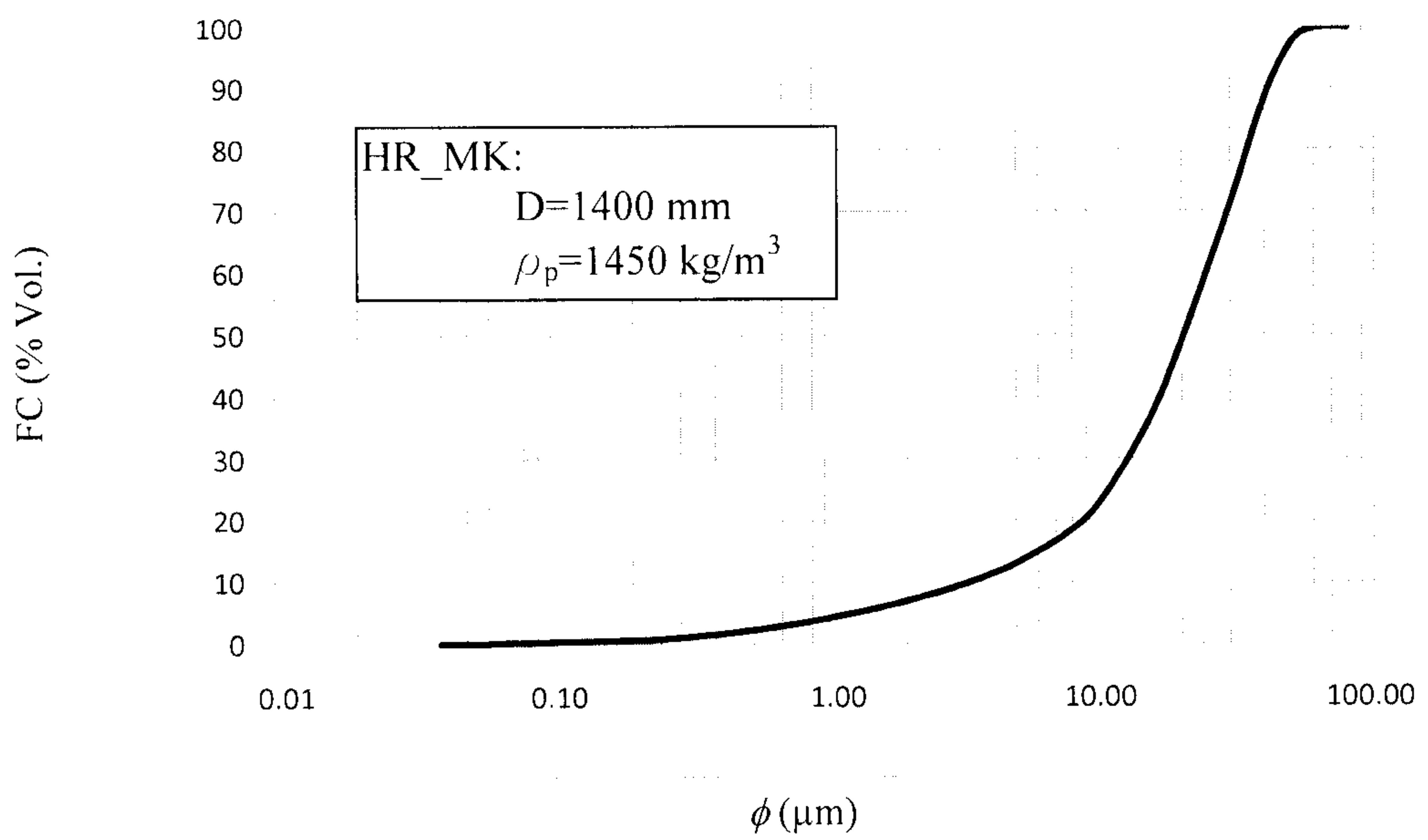
100
90
80
70
60
50
40
30
20
10
0
FC (% Vol.)
HR_MK:
D=1400 mm
ρp=1450 kg/m3
0.01
0.10
1.00
10.00
100.00
ϕ (µm)

Fig. 9

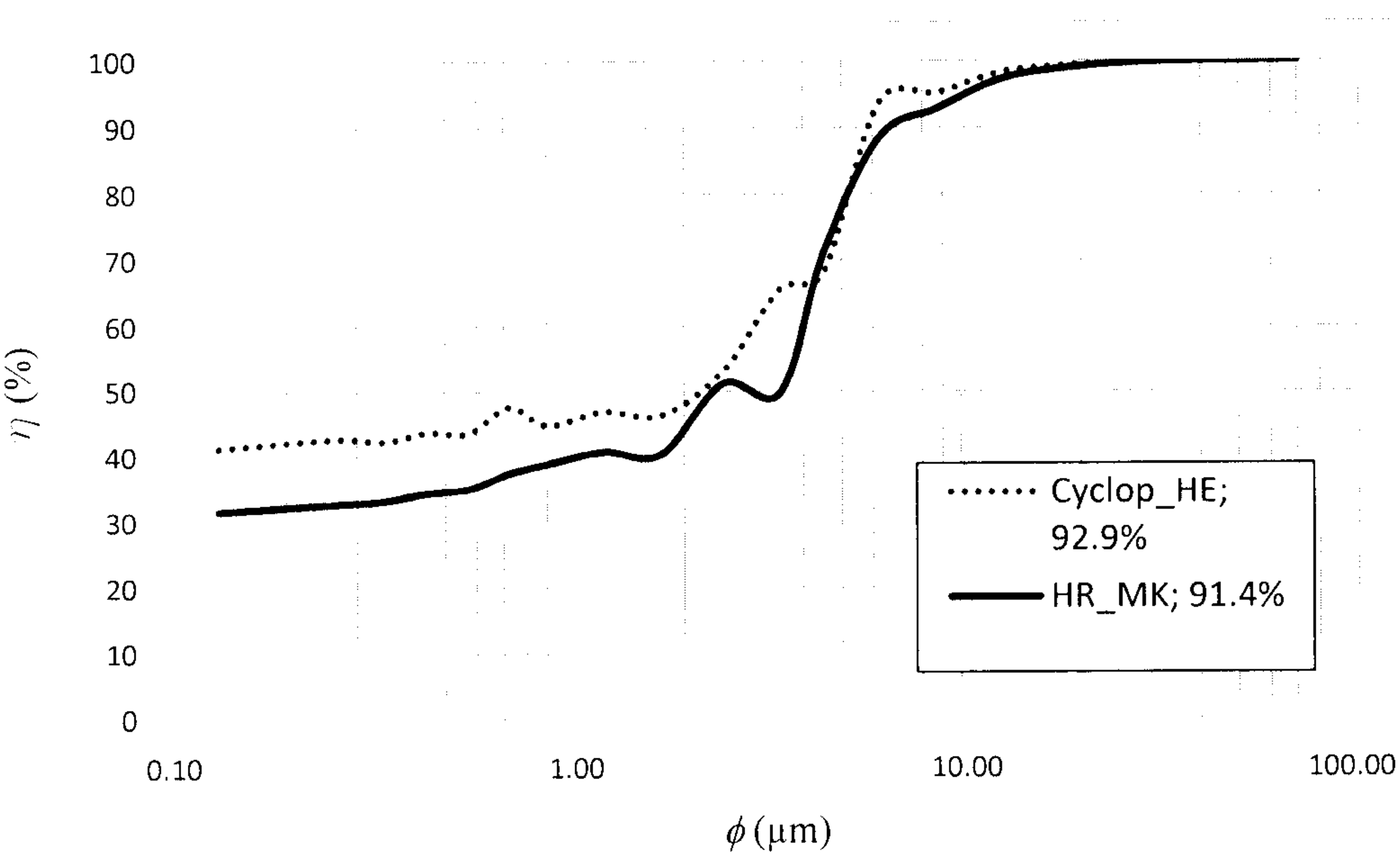
100
90
80
70
60
50
40
30
20
10
0
η (%)
Cyclop_HE; 92.9%
HR_MK; 91.4%
0.10
1.00
10.00
100.00
ϕ (µm)

Fig. 10

Fig. 2