Supplementary material

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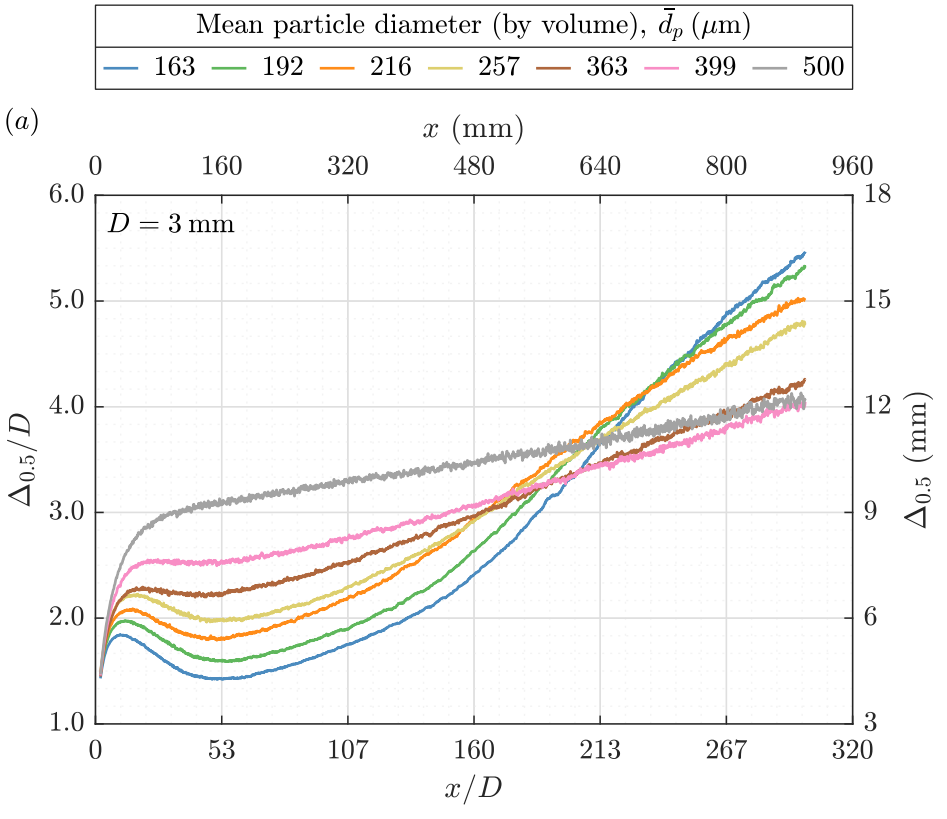
1. Summary of measured particle curtain thickness

1.1. *Curtain thickness for the dense core ($\Delta_{0.5}$)*

The experimental results measured for four different hopper outlet thicknesses, D = 3, 4, 5 and 8 mm, with seven different particle sizes, are presented in panel (*a*), (*b*), (*c*) and (*d*), respectively.



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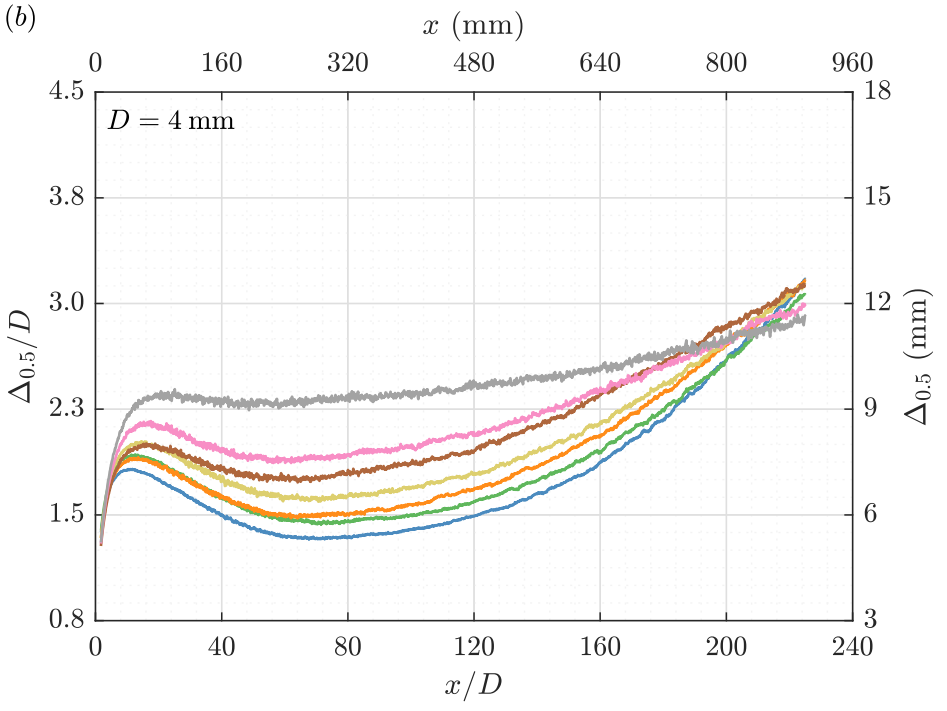
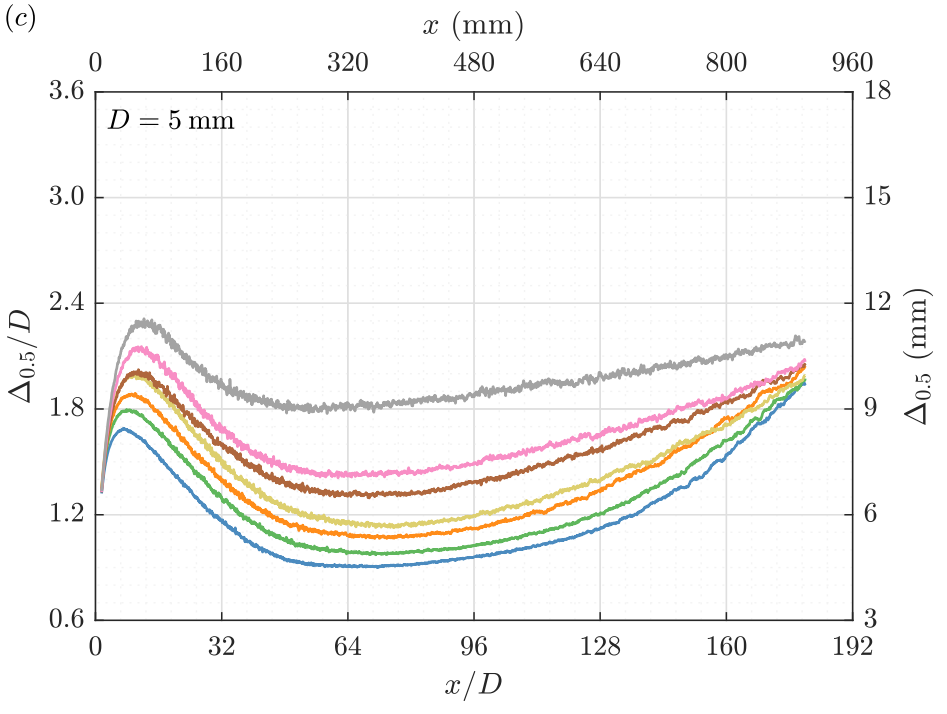
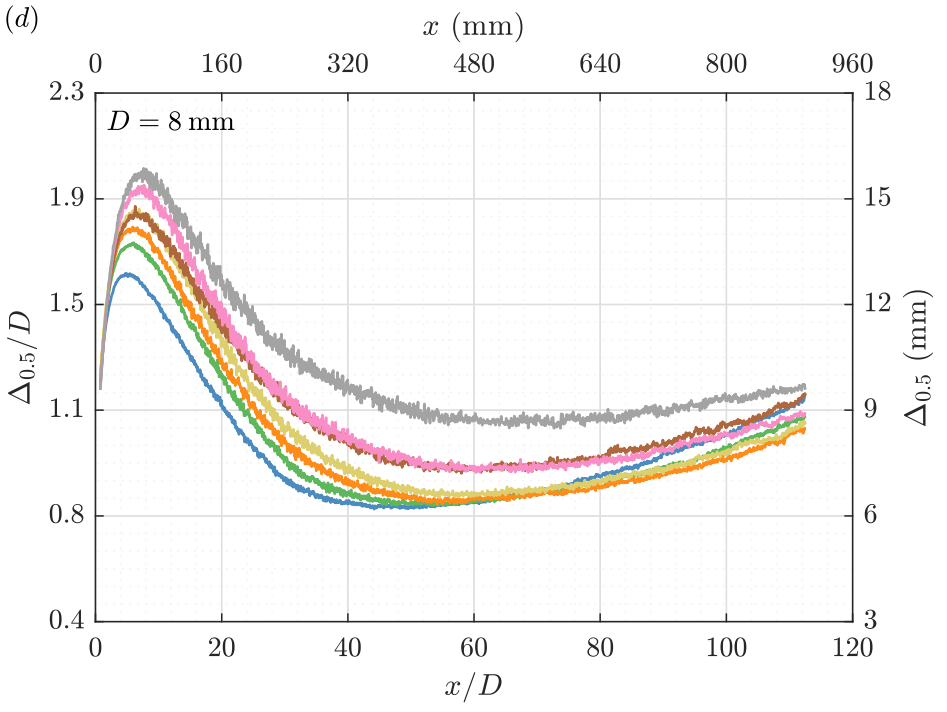
(*b*)


x (mm)
0
160
320
480
640
800
960
$D = 4$ mm
4.5
3.8
3.0
2.3
1.5
0.8
18
15
12
9
6
3
$\Delta_{0.5}/D$
$\Delta_{0.5}$ (mm)
0
40
80
120
160
200
240
x/D

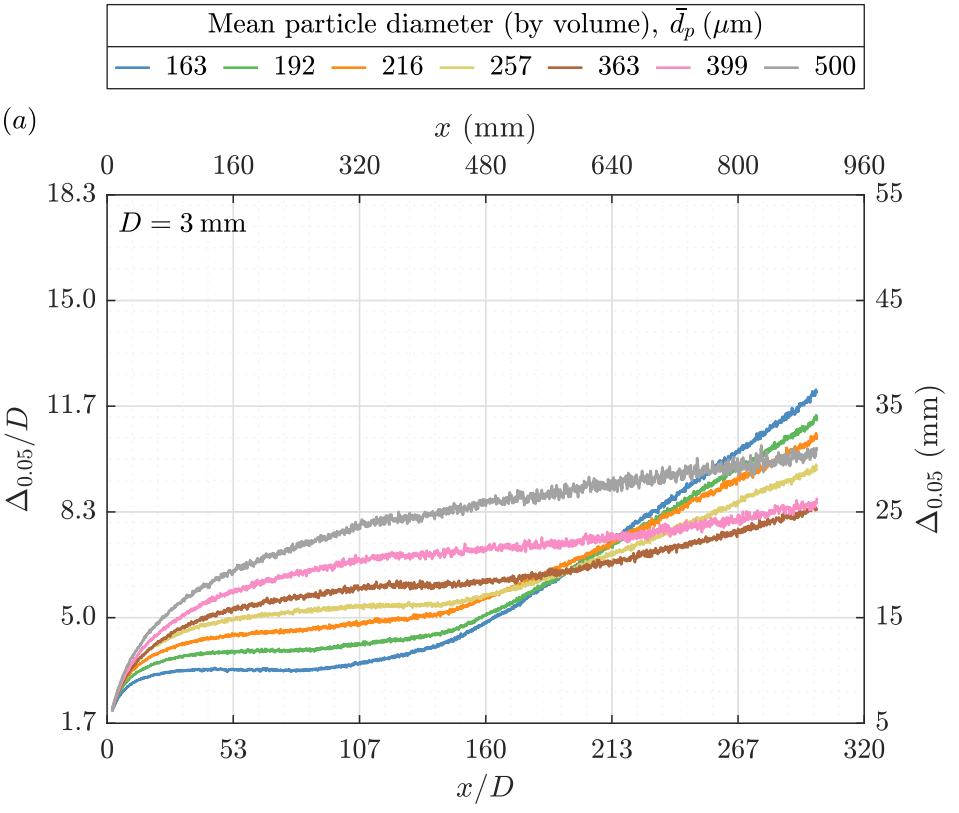
(*c*)


x (mm)
0
160
320
480
640
800
960
$D = 5$ mm
3.6
3.0
2.4
1.8
1.2
0.6
18
15
12
9
6
3
$\Delta_{0.5}/D$
$\Delta_{0.5}$ (mm)
0
32
64
96
128
160
192
x/D

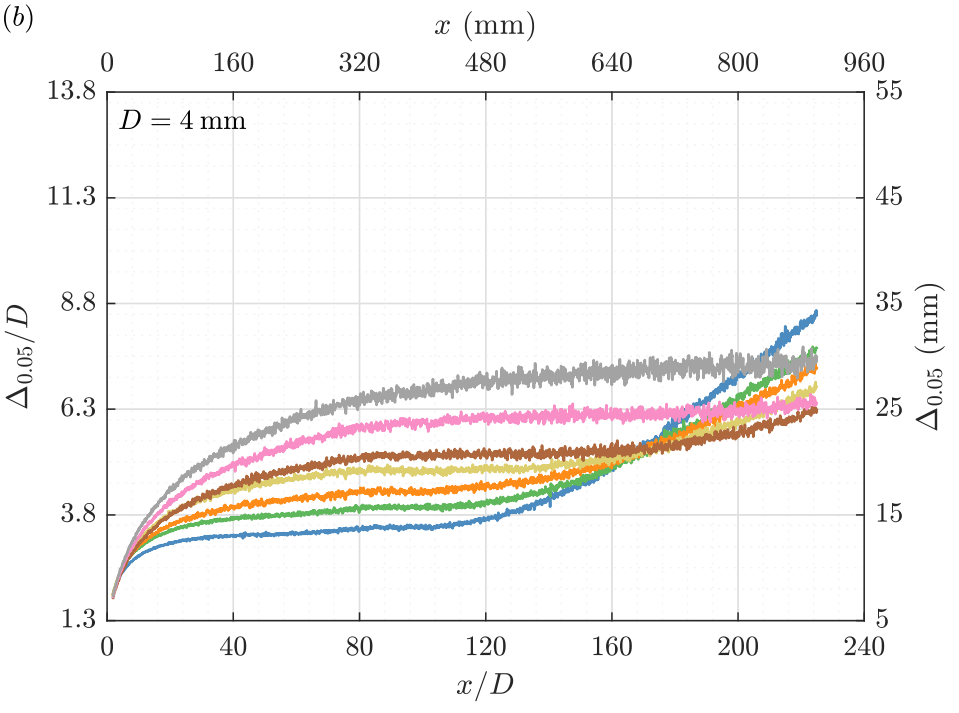

(d)
x (mm)
0
160
320
480
640
800
960
$D = 8$ mm
2.3
1.9
1.5
1.1
0.8
0.4
$\Delta_{0.5}/D$
18
15
12
9
6
3
$\Delta_{0.5}$ (mm)
0
20
40
60
80
100
120
x/D

1.2. *Curtain thickness for the dilute region with the dense core included ($\Delta_{0.05}$)*

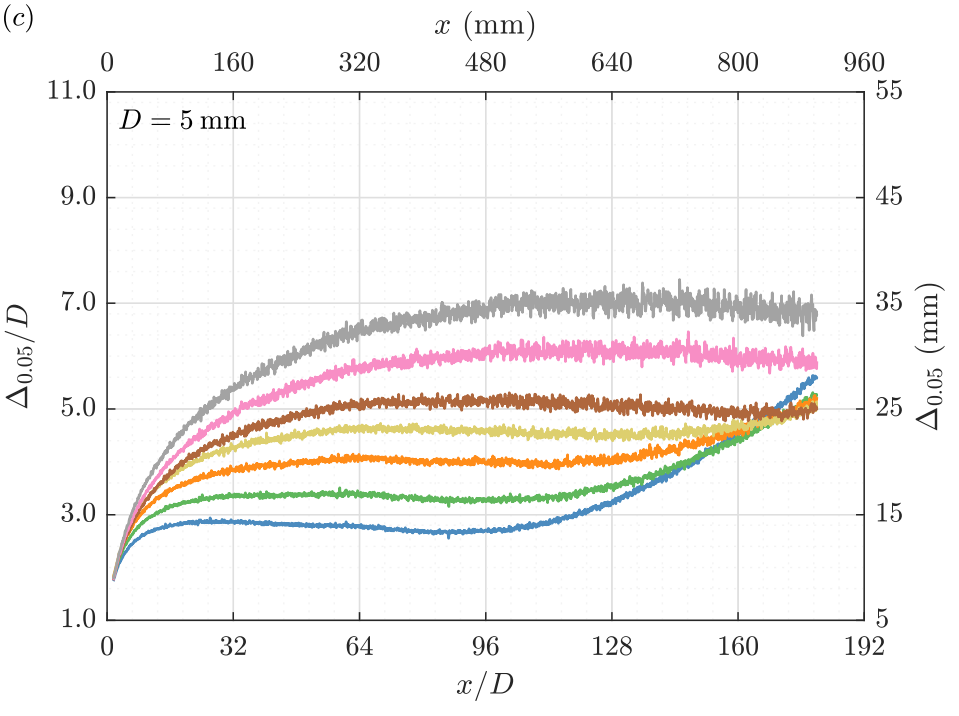
The experimental results measured for four different hopper outlet thicknesses, D = 3, 4, 5 and 8 mm, with seven different particle sizes, are presented in panel (*a*), (*b*), (*c*) and (*d*), respectively.

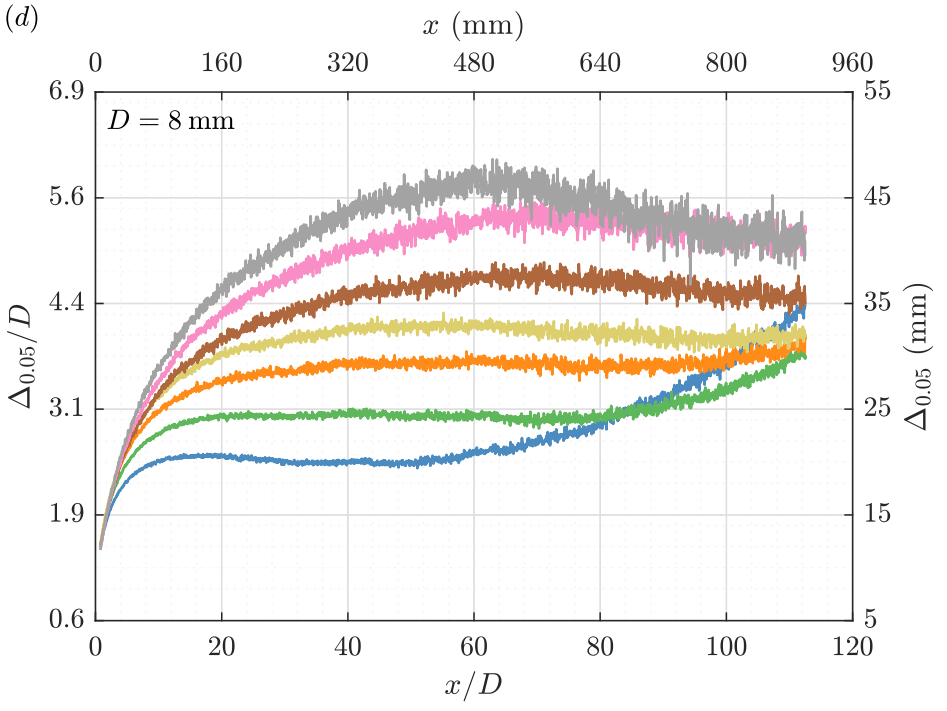


(*b*)


x (mm)
0
160
320
480
640
800
960
D = 4 mm
13.8
11.3
8.8
6.3
3.8
1.3
Δ0.05/D
55
45
35
25
15
5
Δ0.05 (mm)
0
40
80
120
160
200
240
x/D

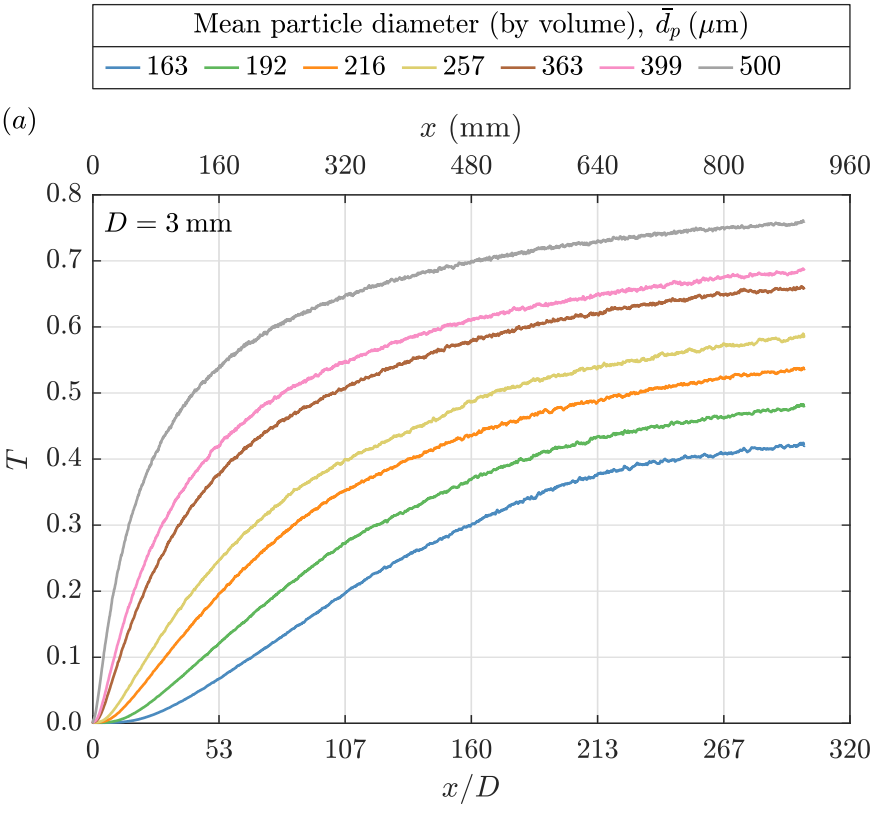
(*c*)

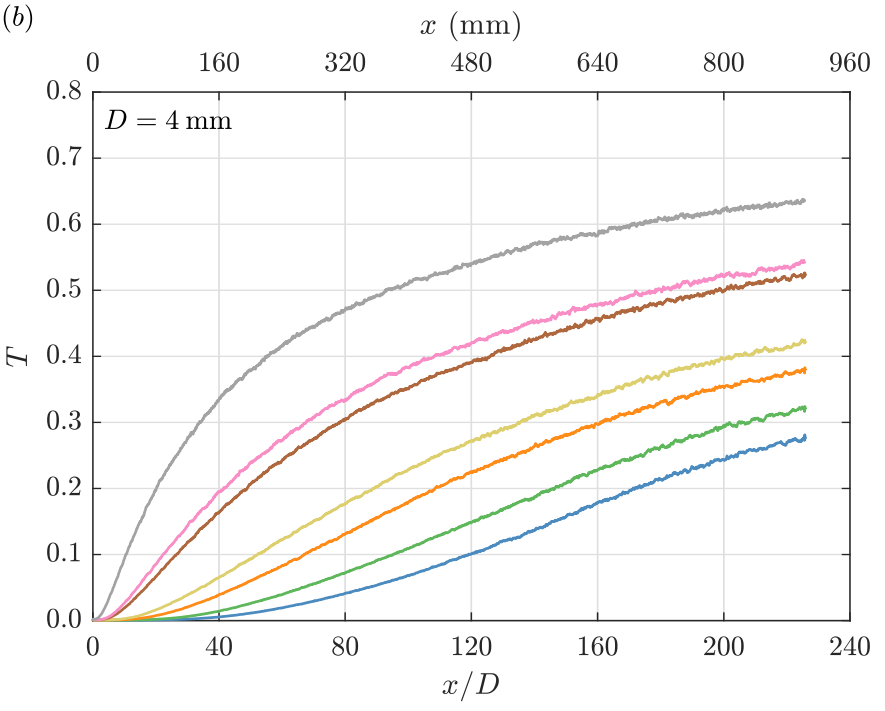

x (mm)
0
160
320
480
640
800
960
D = 5 mm
11.0
9.0
7.0
5.0
3.0
1.0
Δ0.05/D
55
45
35
25
15
5
Δ0.05 (mm)
0
32
64
96
128
160
192
x/D

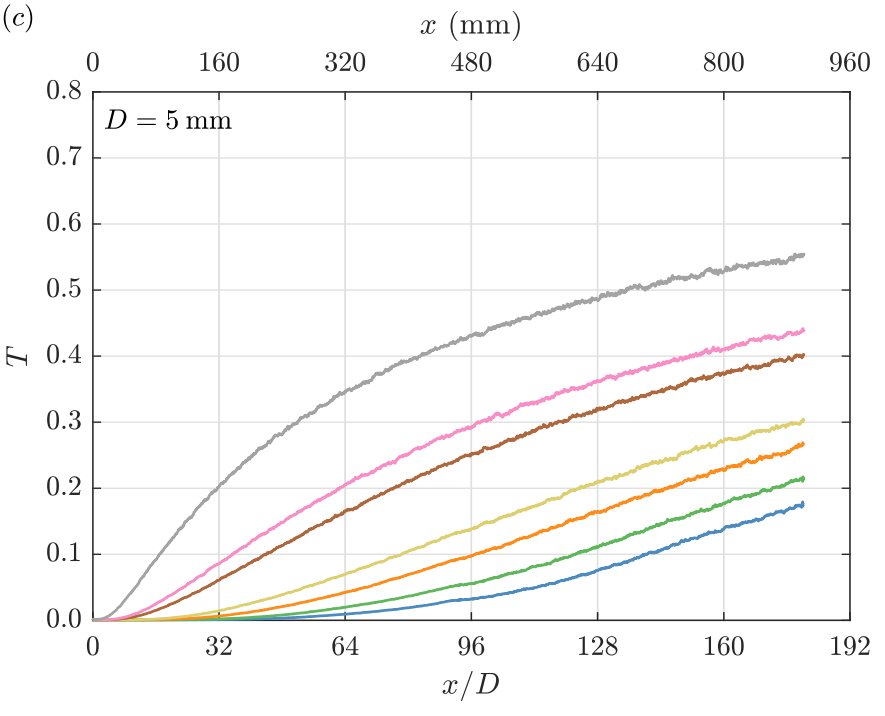

(d)
x (mm)
0
160
320
480
640
800
960
$D = 8$ mm
6.9
5.6
4.4
3.1
1.9
0.6
$\Delta_{0.05}/D$
55
45
35
25
15
5
$\Delta_{0.05}$ (mm)
0
20
40
60
80
100
120
x/D

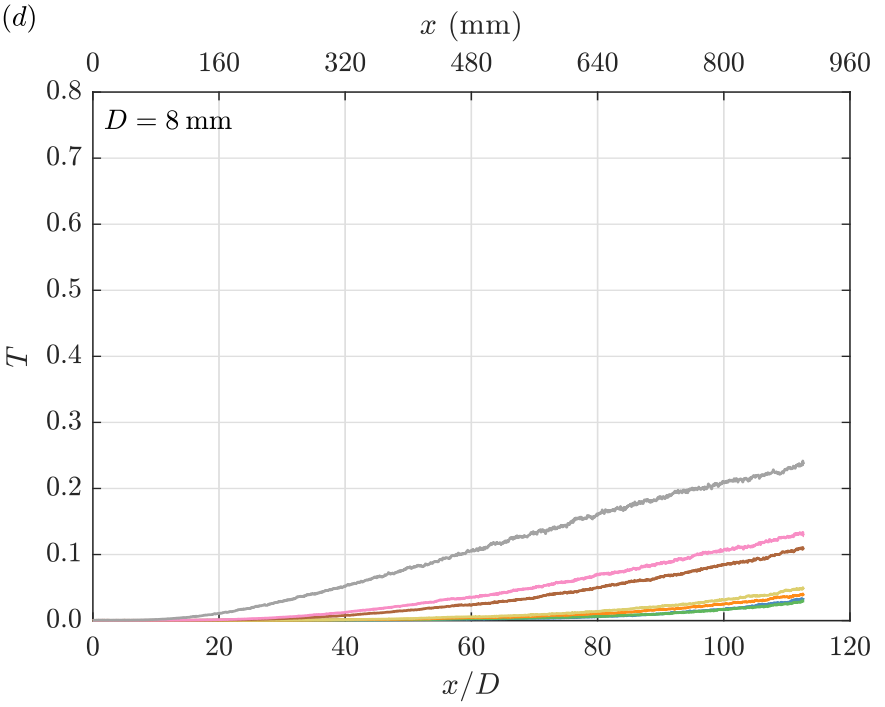
2. Summary of measured particle curtain transmittance (T)

The experimental results measured for four different hopper outlet thicknesses, D = 3, 4, 5 and 8 mm, with seven different particle sizes, are presented in panel (a), (b), (c) and (d), respectively.



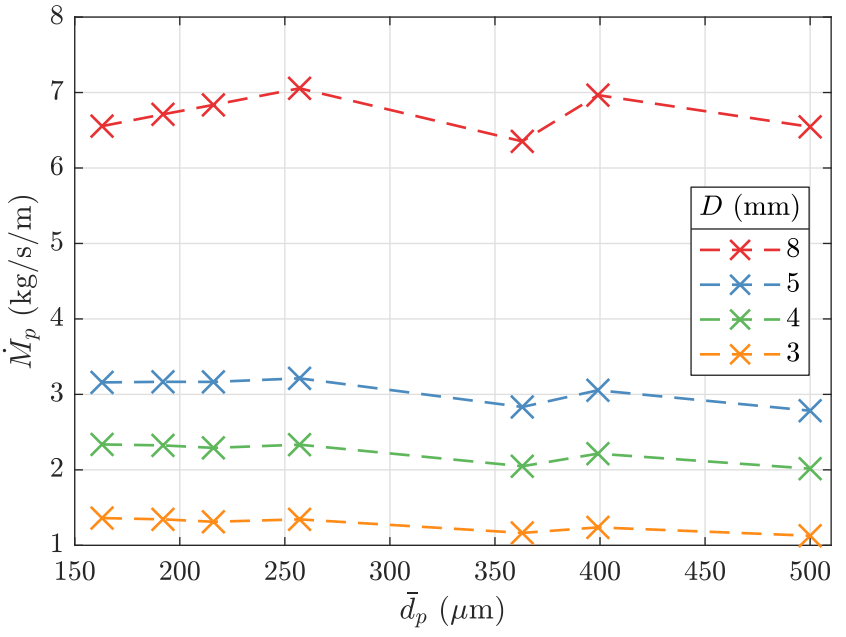

(b)
x (mm)
0
160
320
480
640
800
960
D = 4 mm
T
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
40
80
120
160
200
240
x/D


(c)
x (mm)
0
160
320
480
640
800
960
D = 5 mm
T
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
32
64
96
128
160
192
x/D


(d)
x (mm)
0
160
320
480
640
800
960
D = 8 mm
T
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
x/D

3. Summary of measured mass flow rates ($\dot{M}_p$)

Here, the mass flow rate, $\dot{M}_p$, is based on per unit width of the hopper outlet.



4. Drawings of the metal hoppers

The hopper dimensions are presented in the following figure. The actual particle filling height was maintained at 3 times the hopper height. This was achieved by connecting extra two vertical channels (each has the same height as the hopper) to the top of the hopper, both with the same internal cross section as the top part of the hopper.