Discussion on the correlations for maximum-efficiency inlet velocity of gas-solid cyclone separators

Qing Wei and Guogang Sun

College of Mechanical and Transportation Engineering

China University of Petroleum-Beijing,

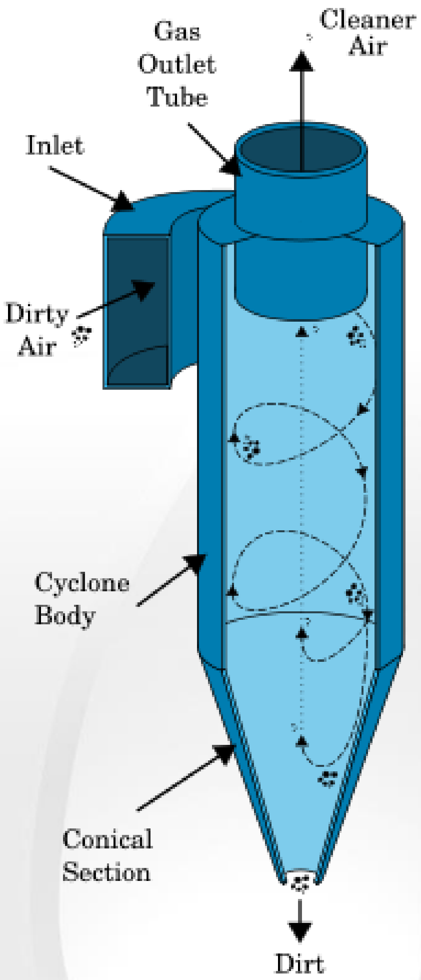
18 Fuxue Road, Changping, Beijing China 102249

Outline

1. Background
2. Correlations for *V*imaxe
3. Comparison of the correlations
4. Summary

Background

A cyclone is a static device that uses centrifugal force to separate particles from gas streams.

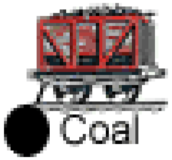


advantages of cyclones:

- can be used under almost any operating conditions, *in particular at high* temperatures and pressures.
- reasonable high efficiency for specially designed cyclones
- *simple structure, low capital investment and maintenance costs in most applications*
- *very robust, no moving parts*

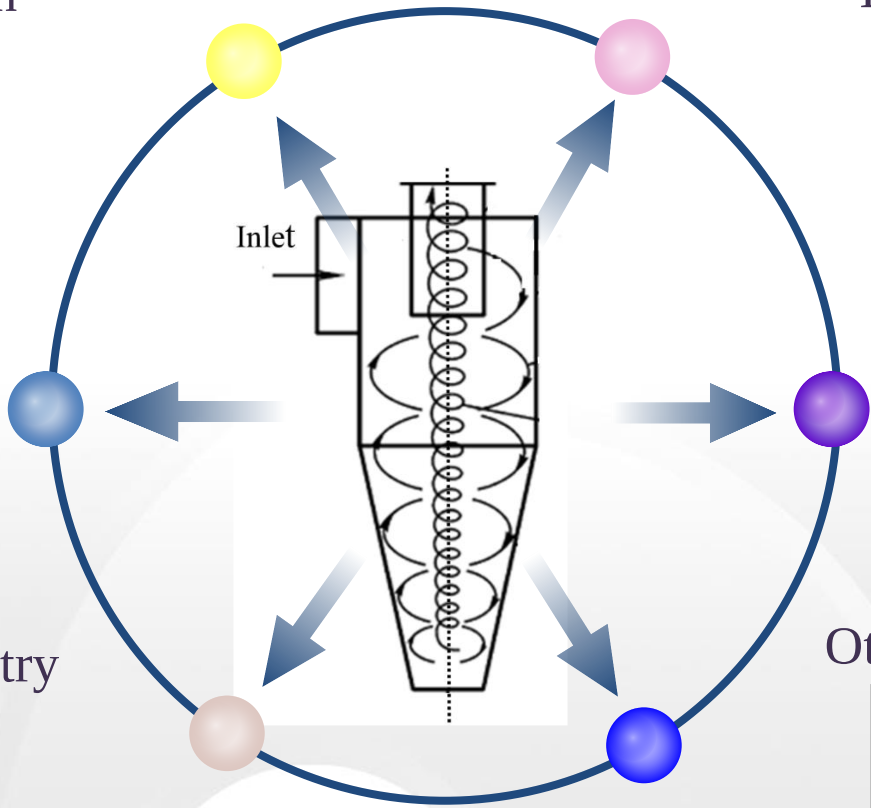
Background

Coal gasification

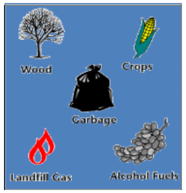


Enviorment

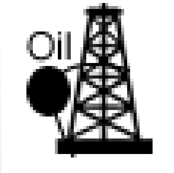
Metallurgical industry



Biomass gasification



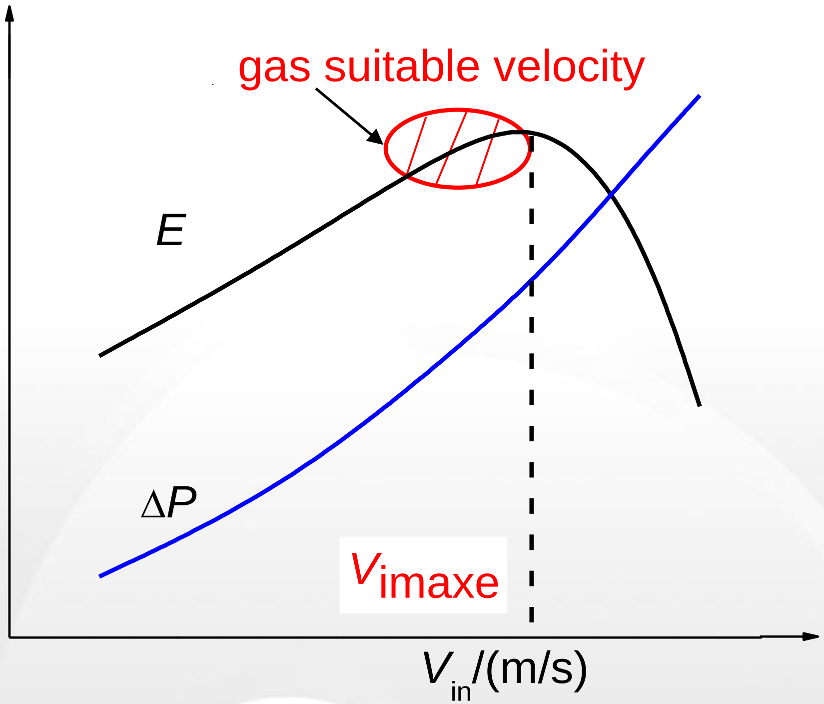
Oil refinery



Other industries

Background

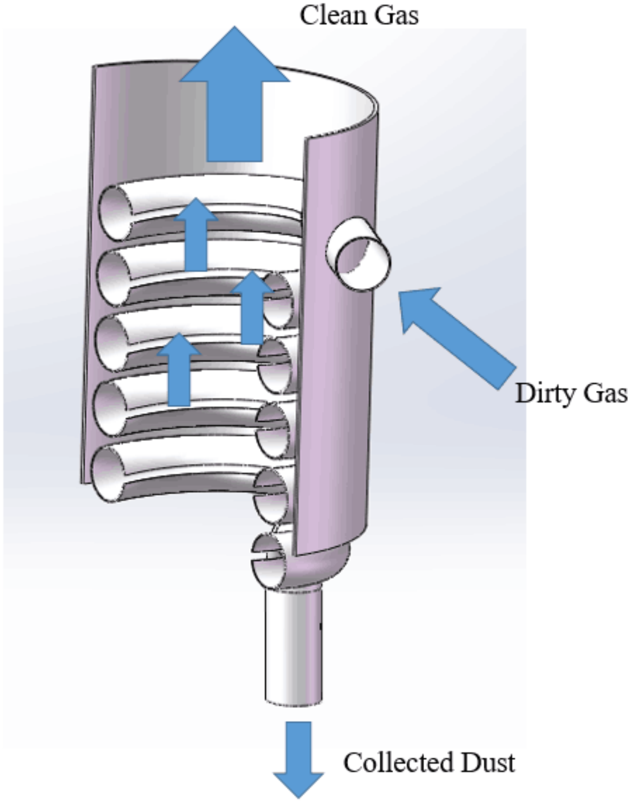
Cyclone performance is mainly characterized by particle separation efficiency and pressure drop between the inlet and outlet, both of which are severely affected by inlet velocity.

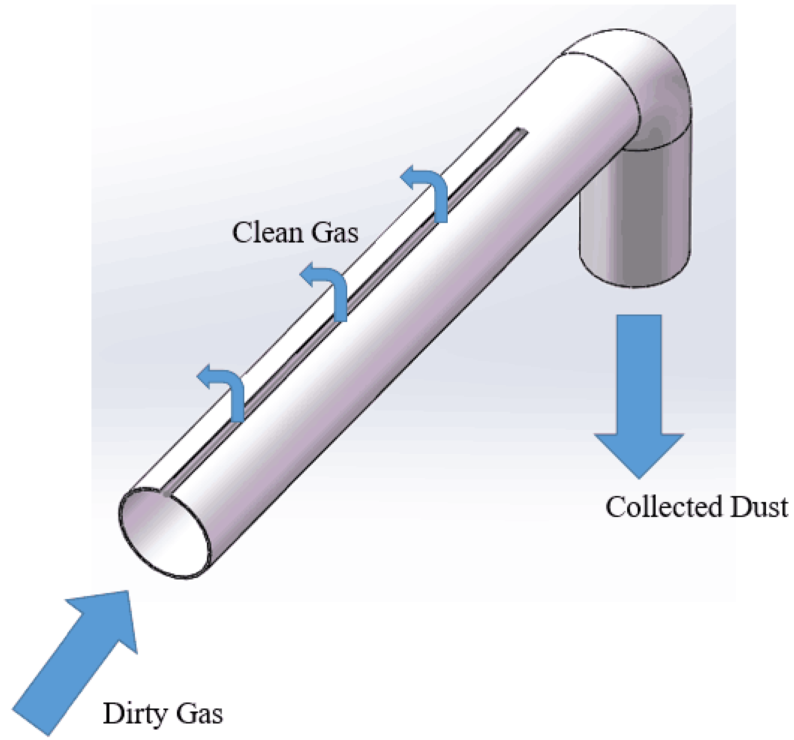


- Separation models, such as Leith-Licht model, Mothes -Löffler model, etc. ✗
- numerical simulations, such as FLUENT. ✗

Correlations for *V*imaxe

K-Z model

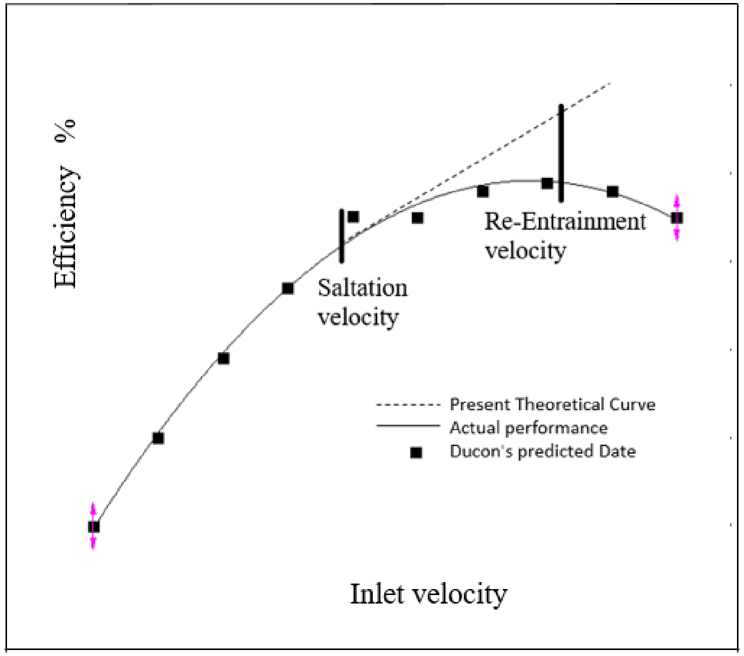




- Gas-solids spiraling flow pattern in cyclone analogous to flow of gas-solids through a coiled pipe provided with a narrow slit along its inner length to permit gradual dissipation of the gas.
- In a direct analogy to horizontal tubes delivering low concentration solids, pipe particle saltation results were applied to the cyclone.

[1] Kalen B., Zenz F.A.,. Theoretical-empirical approach to saltation velocity in cyclone design. AIChE Sgmp. Ser., 1974, 137, 388-396.

Correlations for *V*imaxe



- If gas velocity in the pipe was 1.36 times saltation velocity, particles would be re-entrained and have little chance in terms of remaining on the wall of cyclone.
- However, when inlet velocity was 1.25 times the saltation velocity, separation efficiency would be maximized.

$$V_{\mathrm{imax}e} = 231.6\left(\frac{4g\mu_g\rho_p}{3\rho_g{}^2}\right)\left(\frac{b/D}{1-b/D}\right)b^{0.2}$$

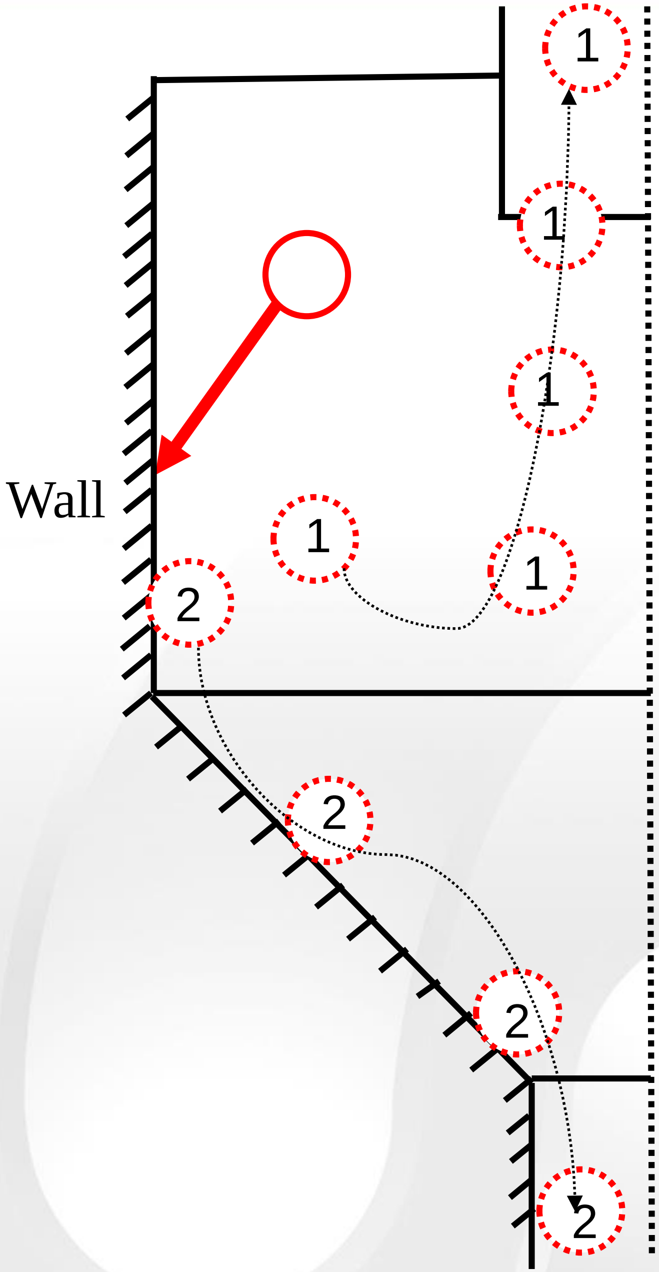
Shi model

Based on K-Z model, the inlet area ratio *K*a and cyclone diameter *D* were substituted with support from their experimental results to create a new expression for *V*imaxe.

$$V_{\mathrm{imax}e} = 19K_a{}^{1.4}\left(\frac{4g\mu_g\rho_p}{3\rho_g{}^2}\right)\left(\frac{b/D}{1-b/D}\right)\left(\frac{b}{D}\right)^{0.2}$$

[1] Shi M., Wu X., An experimental research on the pilot-scale cold model of cyclone separator. Chem. Eng. Mach., 1993, 20 (4), 187–192. (in Chinese)

Correlations for *V*imaxe



Yang model and Wei model

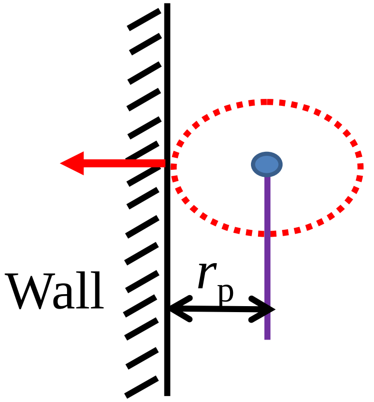
Main theroy：

•Particles centrifuged on the wall are considered captured directly, is rejected in these two models.
•Particles centrifuged on the wall collide the wall and then rebound.
• If the energy in these particles is sufficient, they will rebound into the upward gas flow, and escape from the cyclone. Otherwise, particles are finally collected at the dust box.

[1] Yang J., Sun G., Zhan M., 2015. Prediction of the Maximum-Efficiency Inlet Velocity in Cyclones. Powder Tech. 2015, 286 (11), 124-131.
[2]. Wei Q. , Sun G. , Yang J., A model for prediction of maximum-efficiency inlet velocity in a gas-solid cyclone separator. Chemical Engineering Science, 2019, 204, 287-297.

Correlations for *V*imaxe - Yang model

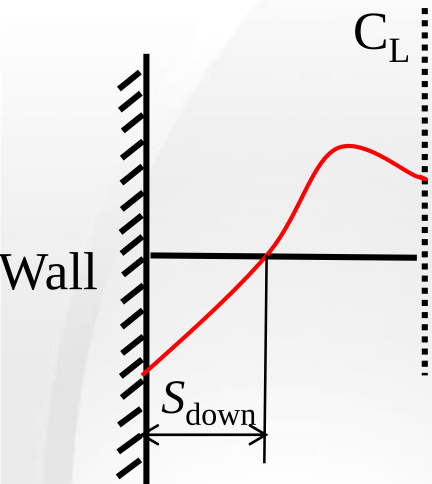
1/Particle-wall collision--The hard sphere model



Particle deformation is neglected so, throughout the collision process, the distance between the particle centers is constant.

$$s_p = 0.5 e^2 v_{rpw}^2 \Big/ \left(-\frac{e v_{\theta w}^2}{R} + \frac{v'^2_{\theta pw}}{R} \right)$$

2/The width S_{down} of the outer downward flow region



There is only a qualitative understanding of the width about the outer downward flow region: the width is slight smaller than that of the vortex finder and is not affected by the axial position.

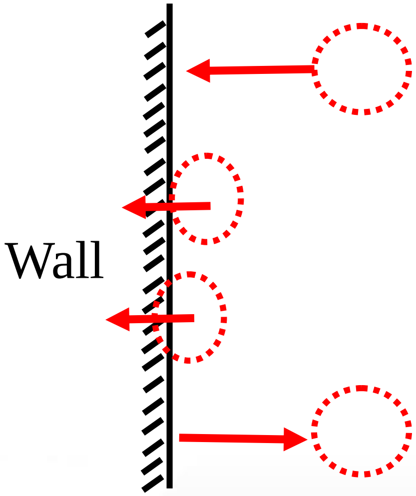
$$S_{down} = S_p$$

$$V_{i\max e} = 18\mu\beta \Big/ \left(d_{pm}^2 \rho_p\right) \left(\sqrt{e f_p^2 (e+1)^2 + (1-e) e^2 R \Big/ \left(2.4 K_a^{0.083} \left(1-\tilde{d}_r\right)^{0.813} b\right)} - f_p (e+1) \right)$$

$$\times \left(e^2 \Big/ \left(2.4 K_a^{0.083} \left(1-\tilde{d}_r\right)^{0.813} b\right) - f_p^2 (e+1)^2 / R \right)^{-1}$$

Correlations for *V*imaxe -Wei model

1/Particle-wall collision--The soft sphere model



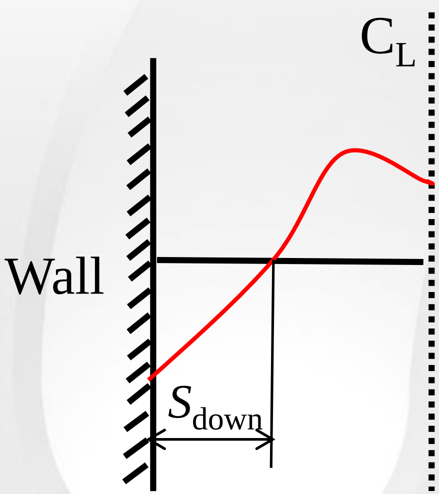
(a) approach

(b) deformation

(c) overlap

$$S_{p}=R-r(t_{0})=\frac{0.5e^{2}u^{2}_{rpw}}{-\frac{18\mu_{g}}{\rho_{p}d_{p}^{2}C_{c}}eu_{rpw}+\frac{u'^{2}_{\theta pW}}{R}}$$

2/The width S_{down} of the outer downward flow region



A face-centered central composite design method and CFD simulation are used to determine the width of the outer downward flow region, which is fit for both normal and high temperature.

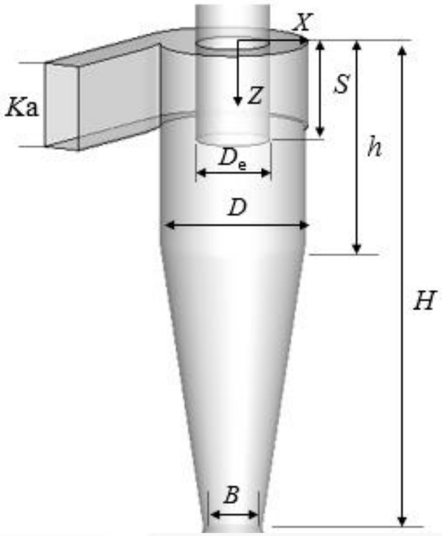
$$S_{down}=0.4095\cdot Der^{-0.5494}\cdot K_{a}^{0.1482}\cdot\left(\frac{T_{0}}{T}\right)^{0.183}$$

$S_{down}=S_{p}$ ⇒

$$V_{imaxe}=\frac{0.378\mu}{d_{50}^{2}\rho_{p}eD^{0.5}}K_{a}^{1.4961}Der^{0.2253}b^{0.5}\left(\frac{T_{0}}{T}\right)^{0.183}\sqrt{\left(\frac{5}{7}-\frac{2}{7}\beta\right)^{2}-e}$$

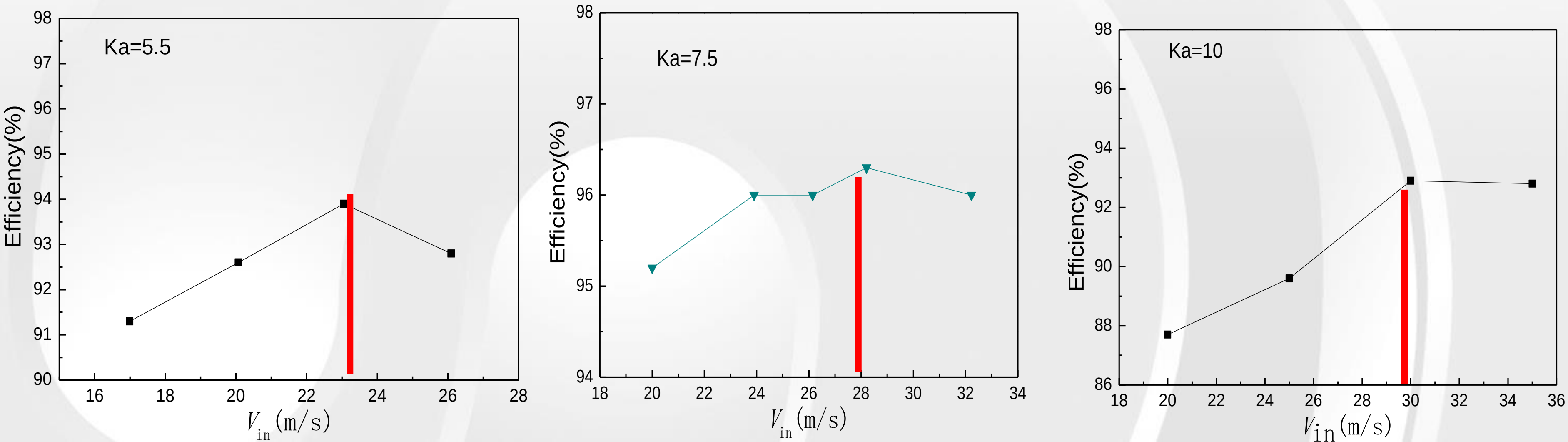
Comparison of the correlations

Inlet dimension:



Dimension	Value
Cyclone diameter, *D*	300 mm
Vortex finder, D_e	120 mm
Inlet area ratio, *K*a	5.5, 7.5, 10
Cyclone height, *H*	1080 mm
Cylindrical body height, *h*	420 mm
Cone tip-diameter, *B*	120 mm

The solid particles used were silica powder with a physical density of 2650 kg/m^3 and a volume median diameter of 13.7 μm.



Comparison of the correlations

Inlet dimension：

Ka	Exp.	K-Z	Shi	Yang	Wei
5.5	23m/s	16.6m/s	18.8m/s	18.4m/s	18.4m/s
7.5	28m/s	13.3m/s	23.3m/s	18.1m/s	27.1m/s
10	30m/s	11.2m/s	29.4m/s	17.8m/s	39.3m/s

It only include particle entrainment while neglecting centrifugal force effects in cyclone separator.

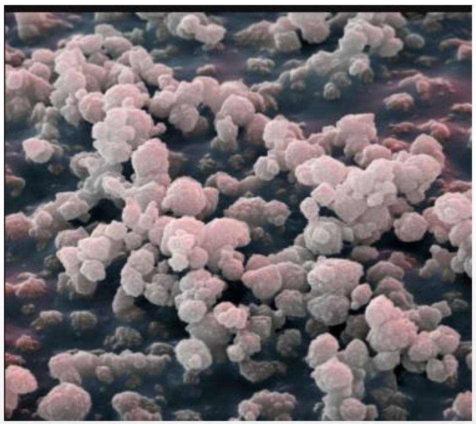
The hard sphere model is based on probability to determine is collision of particle occurs or not, which is not fit for particle deposition at the wall of cyclone. So the soft sphere model is better for the flow field of cyclone.

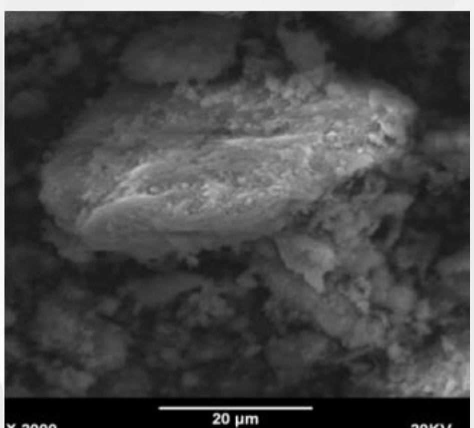
Comparison of the correlations

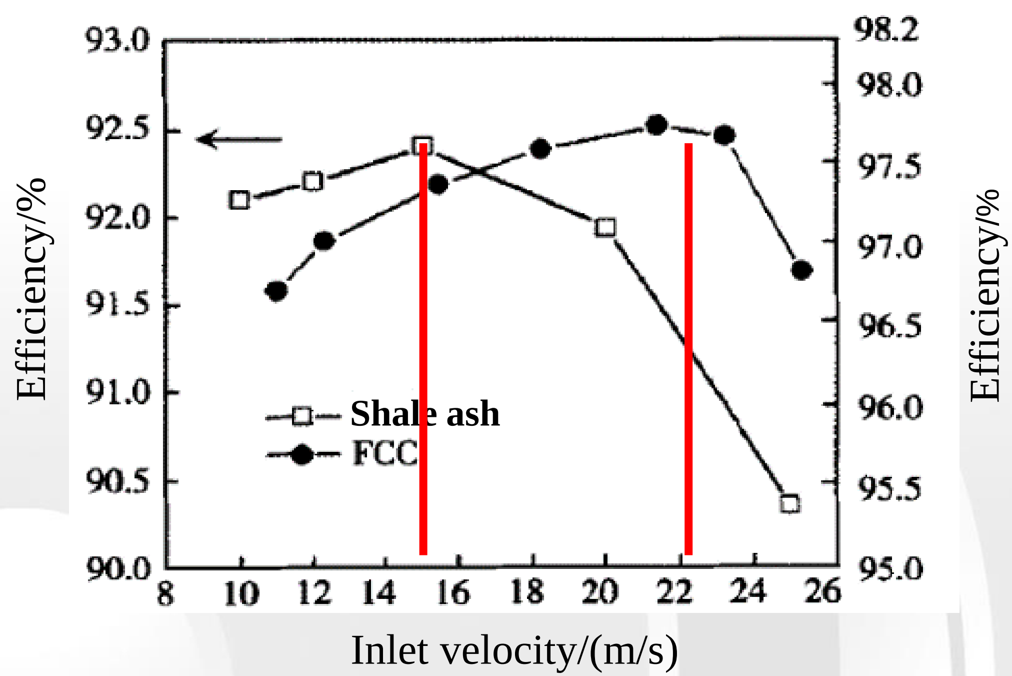
Particle properties：

The solid particles used were FCC powder with a physical density of 1500 kg/m^3 and a volume median diameter of 13 μm.

The solid particles used were shale ash with a physical density of 1350 kg/m^3 and a volume median diameter of 21.7μm.







[1]Wang W., Wang Y., Ma Q., Sun G., Contrast experiments on cyclone separator performances of shale ash and FCC fine catalysts. China Powder Sci. Technol. 2012, 18 (4), 70–72 (in Chinese).

Comparison of the correlations

Particle properties：

Powder	Exp.	K-Z	Shi	Yang	Wei
FCC	22m/s	16.6m/s	18.8m/s	18.4m/s	18.4m/s
Shale ash	15m/s	9.8m/s	11.1m/s	15.5m/s	17.8m/s

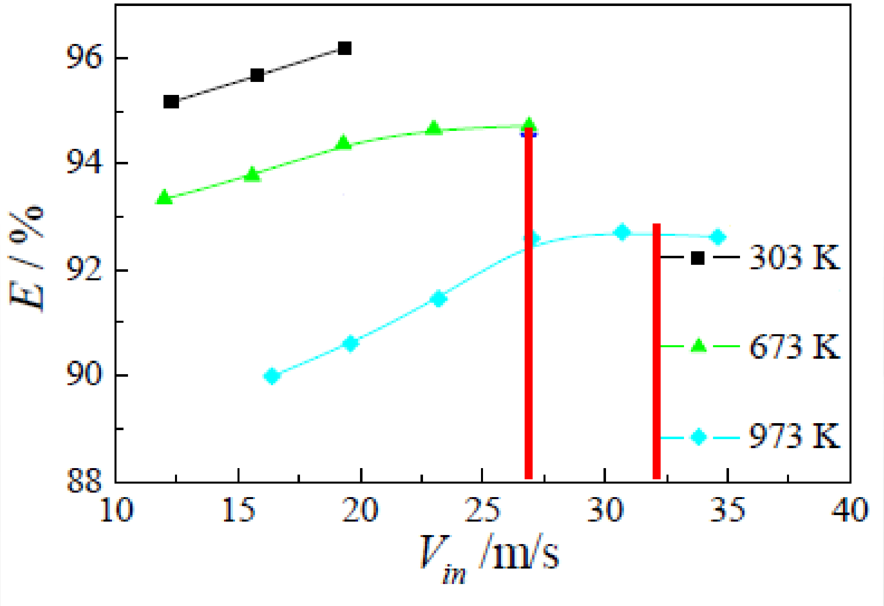
For K-Z model, according to the data of sand and salt, particle shape is not considered.

For Yang model and Wei model, various particle characteristics are encompassed in the radial motions of particles.

Comparison of the correlations

Temperature：

The solid particles used were silica powder with a physical density of 2650 kg/m^3 and a volume median diameter of 10 μm.



[1] Walton O.R., Braun R.L., Journal of Rheology ,1985. 30 (5), 949-980.
[2] Alexander R. M., Proceedings of the Australian Institute of Mining Metals,1949, 152-153, 203-228.
[3] Li W., Chen J., Journal of China University of Petroleum,2006, 30 (3), 97-100.

Comparison of the correlations

Temperature:

T/K	Exp.	K-Z	Shi	Yang	Wei ✓
673	27.5m/s	191.6m/s	217.5m/s	52.9m/s	37.7m/s
973	32.5m/s	508.4m/s	577.2m/s	67.0m/s	41.8m/s

It is based on experimental data at room temperature without considering the effect of temperature on equivalent velocity.

It is based on at room temperature. Although the trend is the same with experiment, the error is reaching more than 70%.

It considers the effect of temperature on tangential velocity, gas density and viscosity.
But it does not account for changes in turbulence characteristics with temperature, which leads to some error.

Discussion

1 K-Z model

2 Shi model

3 Yang model

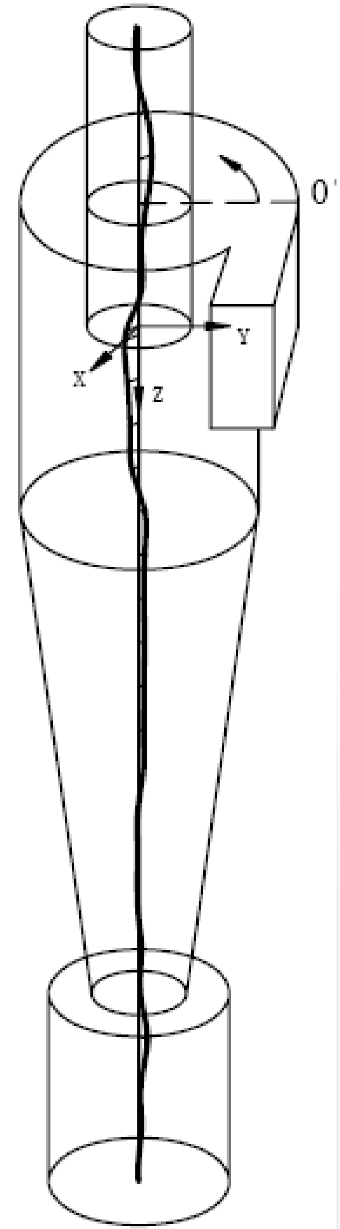
4 Wei model

*V*in ↑ *V*t ↑ *F*c ↑

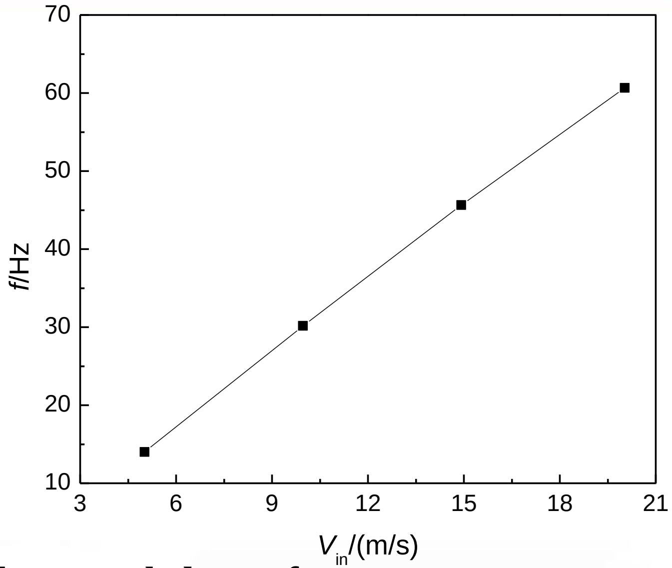
*V*in ↑ *t*res ↓

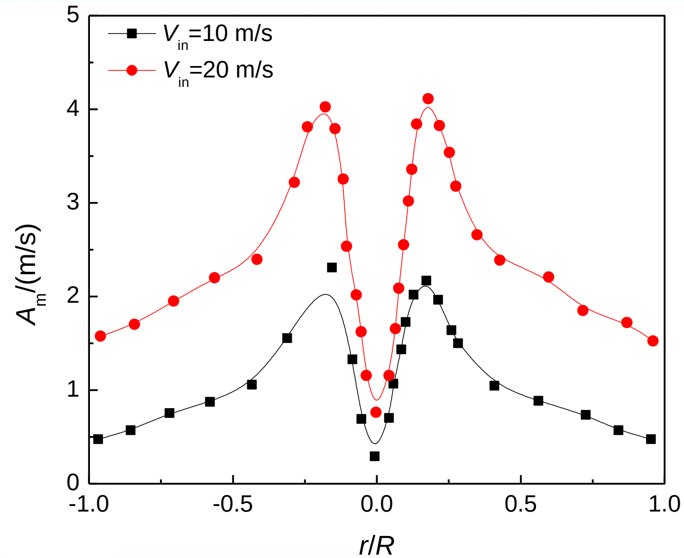
*V*in ↑ → Bounce and backmixing

The flow field of cyclone separator is unstable, that is, the rotation center of vortex core is different from the center of cyclone separator. The rotation center line of vortex core is an oscillating curve and procession movement around a certain spiral line (usually called processing vortex core)

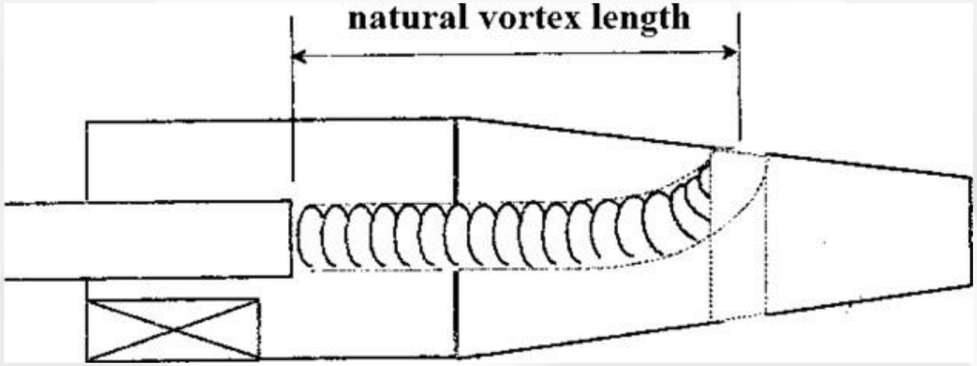


Discussion



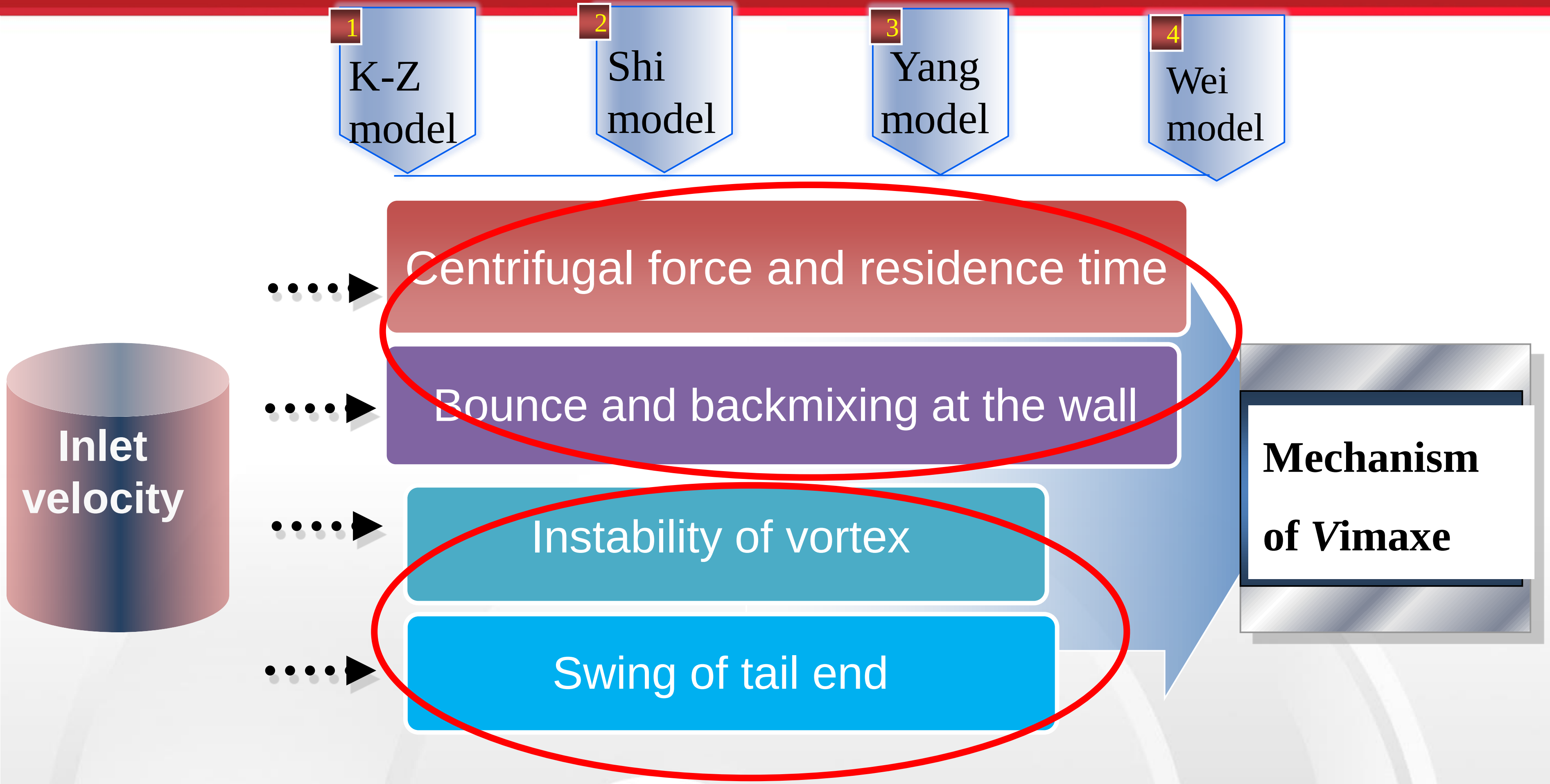


The instability of vortex increases, which leads to the re-entrainment of particles collected at the wall in the flow field. As a result, separation efficiency is reduced.



The vortex in cyclone separator would end at a certain position, which is called tail end. It would bend and collide with the wall, causing a large amount of particles backmixing and reducing separation efficiency.

Discussion


1
K-Z model
2
Shi model
3
Yang model
4
Wei model
Inlet velocity
Centrifugal force and residence time
Bounce and backmixing at the wall
Instability of vortex
Swing of tail end
Mechanism of *V*imaxe

Summary

1. Accurate prediction of *V*imaxe in the gas-solid cyclone is of great importance and urgent demand in research areas related to gas solid separation.
2. The four models about *V*imaxe were evaluated from the inlet size, particle characteristics and temperature. The prediction trend of Wei model is in good agreement with the experimental data, but there is still error. The reasons are that it does not account for changes in turbulence characteristics with temperature and ignores the cone section of cyclone.
3. Higher inlet velocity creates greater centrifugal force on the particle, which enhances the cyclone's separation efficiency. However, excessive gas velocity will not only cause particles deposited on the wall surface to be lifted up, but also lead to backmixing of particles due to the instability of vortex and the swing of tail end, which results in a reduction of particle separation efficiency.

Thanks for attention ！