

## **EXPERIMENTAL AND CALCULATED VALUES OF MIGRATION VELOCITY AS A PARAMETER OF PRECIPITATION PROCESS IN ELECTROSTATIC PRECIPITATORS**

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### **SUMMARY**

This paper presents results of experimental studies of fly-ash particles migration velocity obtained in a horizontal electrostatic precipitator (ESP) physical model.

The particle migration velocities were recorded and measured by means of photo camera visualization of particle movement trajectories and the ESP model performance effectiveness. Tests were carried out with different parameters of electrical field, different kinds of fly ash and particle size distribution, and for many types of discharge electrode shapes. Substantial influences of discharge electrode shape on the measured migration velocities were found.

The test results shown as graphs and tables, confirm the possibility to utilize the physical ESP model results in the ESP design processes as well as for selection of precipitation process adequate discharge electrodes.

## INTRODUCTION

The famous W. Deutsch equation describing phenomena of electrostatic precipitation is used for more than 80 years. The model, presented in twentieth of the last century by Deutsch (1922), despite of its simplifying assumptions and passing of time, is continuously used for electrostatic precipitator (ESP) operation simulations as well as for sizing purposes. The first equation describing collection efficiency  $h(d)$  of dust particles having diameter  $d$  has been again introduced by White (1963) in fiftieths on the base of probability theory and later modified by Matts & Oenfeld (1963), getting its final shape:

$$h(d) = 1 - \exp \left\{ -w_t(d) \cdot \frac{L}{h \cdot v} \right\} \quad (1)$$

Where:

$w_t(d)$  – is the theoretical migration velocity of particles having diameter  $d$

$L$  – length of electrical field

$h$  – inter-electrode distance.

The total collection efficiency for real particles can be calculated as a sum of fractional collection efficiencies for specific dust size fractional distribution:

$$h(d)_c = \int_{d_{\min}}^{d_{\max}} y_H(d) \cdot h(d) \cdot d(d) = \int_{d_{\min}}^{d_{\max}} \frac{dm}{m \cdot d(d)} h(d) \cdot d(d) = \sum_{d_{\min}}^{d_{\max}} K(d) h(d) \quad (2)$$

Where:

$y_H$  – is the relative loading of respective particle size distribution (size range)

$K(d)$  – the weight of respective particle size.

However very often in practice the dust particle size distribution is not known or it is not taken under consideration and the collection efficiency is calculated according to a more simplified Equation:

$$h_c = 1 - \exp \left\{ -w_{ef} \cdot \frac{L}{h \cdot v} \right\} \quad (3)$$

Where:

$w_{ef}$  – is an ‘effective’ migration velocity.

The  $w_{ef}$  value has not a physical meaning, but it is a parameter calculated from measured collection efficiency of a specific ESP at its working conditions. But using this formula for ESP design (sizing) calculations may lead to serious errors, if some additional parameters will not be taken into account (particle size distribution).

In this paper are presented some attempts to compare a theoretical migration velocity calculated on the base of primary version of Deutch model (it means as a transport of particle matter in electrical field), with experimentally obtained particle migration velocities towards collecting electrode.

## TURBULENT MODEL OF PARTICLE COLLECTION IN AN ESP

In one stage ESP (where charging and collection of particles takes place in the same region) the gas flow is generally turbulent and the so called Reynolds's number is usually higher than 10;  $Re > 10$ .

In order to make a gas flow balance for a controlled area (Fig. 1) several assumptions has to be admitted (White (1963), Parker (1997)):

- i. Entirely and uniform mixing of particles in any cross section of an ESP, as an effect of turbulent gas flow. In that case there is not dust loading gradient in the direction of collecting electrodes,
- ii. Gas velocity has constant value and uniform distribution in the entire ESP except its wall border layer,
- iii. Entering the laminar flow wall border layer particles are collected and transport velocity in the wall border layer is constant for particles of the some diameter. It is the so called theoretical migration velocity  $w$ , calculated from Eq. 6, where the electrical field strength  $E$  pertains to the collecting electrode.
- iv. Particles are charged in very short time and it is assumed that it happens at the moment of entering the collecting region.
- v. Effects disturbing the collection process such as dust reentrainment, back corona, inter collision of particles, non uniform discharge, and so on, were not taken into account there.

When all of the above assumptions are taken into consideration then the balance Equation for controlled region with dimensions  $dl \times h$  will take a form:

$$\frac{dS}{S} = -\frac{w}{vh} dl \quad (4)$$

and:

$$S = S_0 \exp\left(-\frac{wL}{vh}\right) \quad (5)$$

Where:  $S$  – dust loading in the specific cross section

$S_0$  – dust loading at the ESP inlet,

and the collection efficiency is described by Eq. 1.

The theoretical migration velocity  $w_t$  in Eq. 1 is calculated according to Eq. 6, after resolving an equation of particle motion in the interelectrode space:

$$w_t = \frac{Q^\infty \cdot E}{3p \cdot h \cdot d} \quad (6)$$

Where:

$Q^\infty$  - saturation charge

$h$  – dynamic coefficient of gas viscosity

The saturation charge  $Q^\infty$  can be calculated from the Cochet Equation (Parker (1997)) with an assumption that the time constant  $t$  is much smaller than the treatment time of particles in the electrical field  $t$  ( $t \ll t$ ):

$$Q = p e_0 \left\{ \left( 1 + \frac{2l}{d} \right) + \frac{2}{1 + \frac{2l}{d}} \cdot \left( \frac{e-1}{e+2} \right) \right\} d^2 E \cdot \frac{t}{t+t} \quad (7)$$

Where:

$l$  - particle free path in the medium

$e$  - dielectric coefficient of vacuum

$e_0$  - particle relative dielectric coefficient.

## EXPERIMENTAL METHODS OF ESTIMATING MIGRATION VELOCITIES

The most popular method in estimating migration velocity in an interelectrode space is a non contact method because of the character and scale of experiments. Analyzing the literature sources it becomes clear that a few scholars only studied directly the migration velocity phenomenon in the last few years.

Leonard *et al.* (1980) in his studies worked out on a solution of convectional diffusion equation and experimental estimated diffusion coefficients for artificially created turbulent gas flow in a two stage ESP model. The profile of dust loading was estimated by means of laser counting device and the migration velocity was determined by laser Doppler anemometer. In that experiment a small droplets of oil with a median diameter of 3.5  $\mu\text{m}$  and geometric standard deviation of  $\sigma = 1,05-1,10$  were used. Those droplets were primarily charged and collected between two opposite polarized plates (positively & negatively) spaced at 5 cm. As a result the measured migration velocities ranged from 0.1 to 0.6 m/s but unfortunately the field potential voltage levels of the electrode system model were not described.

Parker & Hughes (1988) describe their visual studies carried out with several discharge electrode types and oil droplets of the range of 0.1-5.0  $\mu\text{m}$ , when recording with a photo camera the dispersion of fumes trail for different voltage levels of the electrode system  $U=0\div 75\text{kV}$  as well as for different transporting air flow velocities  $v = 0\div 1,5$  m/s. On the base of recorded material the migration velocity was estimated for different types of discharge electrodes, electric parameters and gas velocities. The results were in the range of 0.02-0.7 m/s for barbed tape; 0.04-1.48 m/s for twisted wire of square cross section and 0.03-0.2 m/s for flat plate.

Riehle (1992) presented results of his migration velocity measurements done with laser anemometer method. The maximal values obtained in his work were:  $w=0,1\div 0,3$  m/s for electrical field strength  $E=2.8$  kV/cm and  $0.6\div 0.8$  m/s for  $E=5.0$  kV/cm. The particles in that model were represented by aerosol droplets of median diameter of 1.4  $\mu\text{m}$  transported with a gas flow of  $v = 0.71; 1.41$  m/s. The same Author (Riehle (1993)) presents another results of his studies on agglomeration on grounded (earthed) electrode surface in the corona discharge field, when measuring migration velocities for different particle matter. In that tests the discharge electrode was a single point with a diameter of 0.8 mm fixed at 40 mm from collecting electrode. Moving camera records done under stroboscope light show the following results of migration velocities for different particle size: for graphite particles with a diameter of 34  $\mu\text{m}$  from 0.02 to 0.08 m/s at electrical field strength 0.75 up to 1.5 kV/cm,

for limestone particles with diameter of 36  $\mu\text{m}$  from 0.02 to 0.28 m/s at electrical field strength of 0.75 to 1.5 kV/cm.

In this work its Authors estimated the migration velocity of fly-ash particles by a method of *particle trajectories movement visualization in scattered light*. This method allows a quantified and qualified analysis of the phenomenon of fly-ash particle transport in an interelectrode space (i.e. determining the movement velocity component of particles as well as observation of particles reverberated from collecting electrode – distribution of dispersed phase). The primary studies applied to a fly-ash particle movement in an electrical field of round wire discharge electrodes having diameter of 0.06 mm. The model was lightened with high power halogen lamp, a fly-ash from pulverized hard coal fired boiler having diameter 75÷102  $\mu\text{m}$  and 102÷150  $\mu\text{m}$  was tested. For a gas flowing at 1.0 m/s the following migration velocities were obtained: 0.4÷0.6 m/s at  $E=1.5$  kV/cm and 1.8÷2.2 m/s at  $E=3.0$  kV/cm. The results were reported in few publications (Jedrusik (1982)).

For further studies a laser light was used and a scheme of the enhanced experimental model is shown on Fig. 2. The model had three independent fields in series with collecting electrodes of 300x180 mm and was energized with half-wave rectified (of negative polarity) H.V. supply unit. The model construction allowed replacement of centrally placed discharge electrodes having constant spacing of 60 mm. The gas (air) flow volume was sleeplessly controlled with radial exhaust fan and its velocity measured with constant temperature anemometer type HCA-1. With that model visualization of particle trajectories as well as current-voltage characteristics were measured.

A light beam of argon gas laser was used, emitting uniform path light of 1.5 mm diameter, 514 nm length and 1÷2 W power. The laser beam was directed to the observation region with a system of mirrors and finally shaped as flat beam by means of cylindrical lens and a slot diaphragm. Additionally the laser beam was modulated with electronic stroboscope device connected with an oscilloscope what allows to measure its operating frequency. In that way the length of flash and pause was measured and next the migration velocity estimated.

The ‘knife shaped’ laser flat beam was directed into the interelectrode space parallel to the gas flow on a level of discharge electrode spikes. The observed particle trajectories in scattered light were recorded through a top situated opening with white-and-black photo camera arranged perpendicularly to the gas flow.

The results of that studies were presented in a few reports and publications (Jedrusik et al (1998), Jedrusik et al (2001), Swierczok (1998)). The experiments were carried out with fly-ash from district heating power boiler fired with hard coal and equipped with semidry desulphurization system. Two types of discharge electrodes were used: a barbed tape and round bar with spikes. The gas velocity was stepped for 0.5; 0.8 and 1.0 m/s and supplying voltage was changed from 5 up to 40 (30) kV with 5 kV steps. The resulting migration velocities covered a wide range of recorded values from: 0.07-0.43 m/s for round bar with spikes up to 0.08 to 1.28 m/s for barbed tape.

The results of measured migration velocities by many Authors are summarized and graphically shown on Fig. 3.

## **RESULTS OF THEORETICAL MIGRATION VELOCITY CALCULATION**

The migration velocity  $w_t$  of a single particle with diameter  $d$  may be calculated from formula (6), but some basic assumption have to be introduced:

- i. a particle has its saturation charge  $Q^s$  calculated accordingly to Cochet formula Eq.7,
- ii. the electrical field strength is calculated as  $E=U/h$ ,
- iii. the Eq. 6 should be corrected if a Reynolds's number for a particle is bigger than 0.2.

Some examples of calculated theoretical migration velocities for different supply voltage levels are presented in Table no 1.

*Table 1: Examples of calculated values of theoretical migration velocities.*

Item	Electrical field strength kV/cm	Saturation charge $C \times 10^{-15}$	Migration velocity m/s
1.	0.5	0.82	0.01
2.	1.0	1.63	0.05
3.	1.5	2.45	0.12
4.	2.0	3.27	0.38
5.	2.5	4.08	0.52
6.	3.0	4.90	0.68
7.	3.5	5.72	0.84
8.	4.0	6.53	1.02

The above presented results were obtained for the following constant values:

Particle diameter	18 $\mu\text{m}$
Relative dielectric coefficient	3
Vacuum dielectric coefficient	$8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$
Average free path	$1.0 \times 10^{-7} \text{ m}$
Dynamic viscosity of air	$1.82 \times 10^{-5} \text{ kg/ms}$
Air density	$1.2 \text{ kg/m}^3$

On the base of the same formula a theoretical migration velocity of series of particles can be assessed if its size distribution is known. The assessed value is a weighted average migration velocity calculated as:

$$w_{i_a} = \frac{\sum w_{i_i} \cdot K_i}{\sum K_i} \quad (8)$$

Where:

$w_{i_i}$  – theoretical migration velocity assessed for  $i$ -th size class

$K_i$  – Weight quota for  $i$ -th class

An example of fly-ash particle size distribution is presented in Table 2. The fly-ash comes from a pulverized hard coal fired boiler .

*Table 2: An example of fly-ash size distribution.*

Item	Particle diameter, $\mu\text{m}$	Relative screenings, %	Sum of relative screenings, %
1.	<2	4,8	4,8
2.	2÷4.2	6.9	11.7
3.	4.2÷6.9	15.2	26.9
4.	6.9÷9.6	18.8	45.7
5.	9.6÷16.0	14.3	60.0
6.	16.0÷26.2	9.0	69.0
7.	26.2÷33.2	3.0	72.0
8.	33.2÷38.6	2.0	74.0
9.	38.6÷63.0	12.0	86.0
10.	63÷80	2.4	88.4
11.	80÷100	5.4	93.8
12.	100÷160	6.2	100.0

In a Table 3 are shown calculated average migration velocities accordingly to Eq. 8 for dust having size distribution as per Table 2.

*Table 3: Theoretical average migration velocities*

Item	Electrical field strength kV/cm	Migration velocity m/s
1.	0.5	0.02
2.	1.0	0.07
3.	1.5	0.13
4.	2.0	0.23
5.	2.5	0.36
6.	3.0	0.47
7.	3.5	0.59
8.	4.0	0.72

## COMPARISON OF EXPERIMENTAL AND THEORETICAL VALUES OF MIGRATION VELOCITY

On a drawing Fig. 4 the results of experimental tests are compared with calculated values shown in Table 1. The experimental migration velocity values are estimated by fly-ash particle trajectories visualization method. The particles were in the range of 10-26  $\mu\text{m}$  (mean diameter 18  $\mu\text{m}$ ).

There it is worthy to note that the experimentally assessed values of migration velocity can be either higher (for barbed tape discharge electrodes) as well as lower (for round rod with spikes) than the calculated values. Only in the range of very low electrical field strength values the experimentally assessed values are higher than theoretical –in both cases. This can suggest that the charging process is more efficient then predicted with the Cochet model.

The dependency of average migration velocity (as calculated from Eq. 8) on the electrical field strength in an interelectrode space for the entire set of particle sizes is shown on a Fig. 5.

In work by Swierczok (1998) some efforts were undertaken to show the dependency of migration velocity on particle diameter which appears -from analysis of formulas on particle saturation charge and its migration velocity - to have nearly exponential character. Unfortunately, because of technical reasons, no satisfying proves were obtained (Fig. 6). The

most probably reason was an uncontrolled agglomeration of particles introduced to the interelectrode region of the ESP model.

## SUMMARY AND FINAL CONCLUSIONS

A final analysis of theoretically and practically obtained results of migration velocity allowed us to formulate some general remarks:

- i. the Deutsch's mathematical model meets the conditions of our experimental studies,
- ii. for experimental proposes a visualization method of particle trajectories movement in an inter electrode space for estimation its migration came out to be very appropriate,
- iii. a visual method of estimating particle migration velocities can be very helpful in comparative studies on different discharge and collecting electrode effectiveness in particle collection efficiency.

The differences between theoretically and experimentally estimated migration velocities are nearly of the same order and they come basically from the admitted assumptions. Better understanding of specific processes influencing the dust particle collection on collecting electrode (i.e. particle charging intensity, agglomeration processes, particle surface character and shape) should restrain differences and secure a more accurate and realistic migration velocity estimation.

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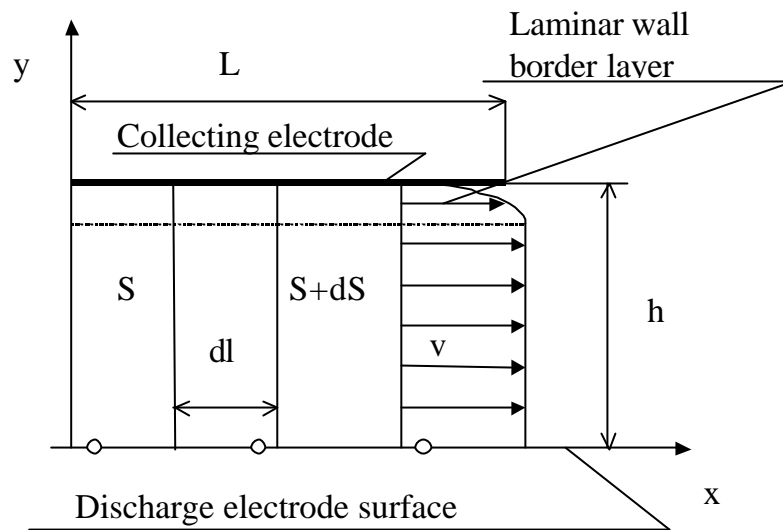


Figure 1: Particle matter separation process according to Deutsch model (Parker (1997))

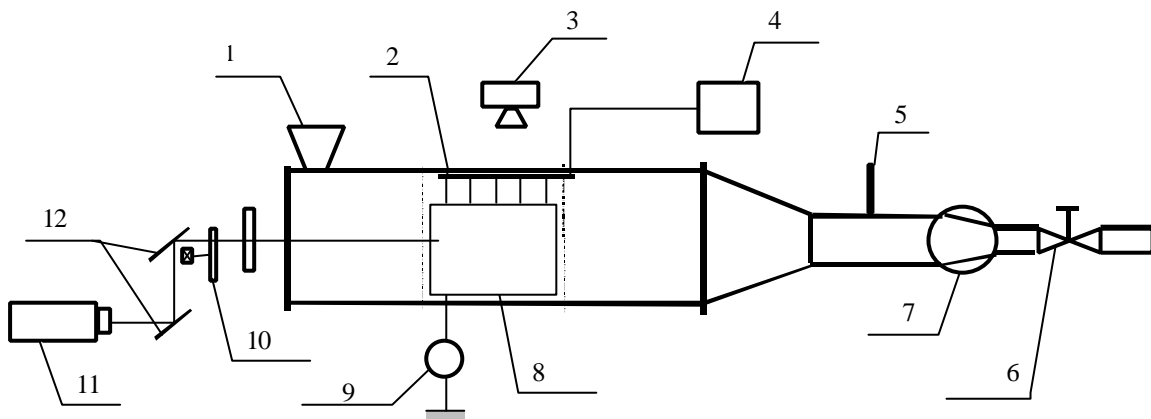


Figure 2: Scheme of testing bench for migration velocity measurement  
 1- dust feeder, 2 discharge electrodes, 3 camera, 4 HV supply, 5 thermoanemometer,  
 6- gas flow control, 7- exhaust fan, 8- collection electrodes, 9- microammeter,  
 10- stroboscope, 11-Ar laser, 12- mirrors

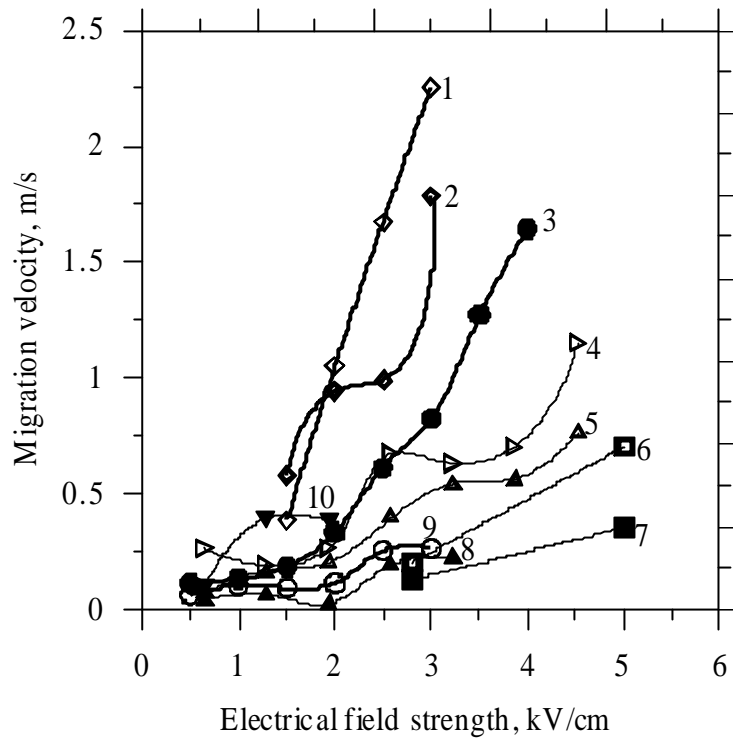


Figure 3: Summarized presentation of measured migration velocities by different Authors. Curves: 4, 5, 8, 10 are as per Parker & Hughes (1998), 1 & 2 are as per Jedrusik (1982); 6 & 7 are as per Riehle (1992) and 3 & 9 are as per Jedrusik (1998)

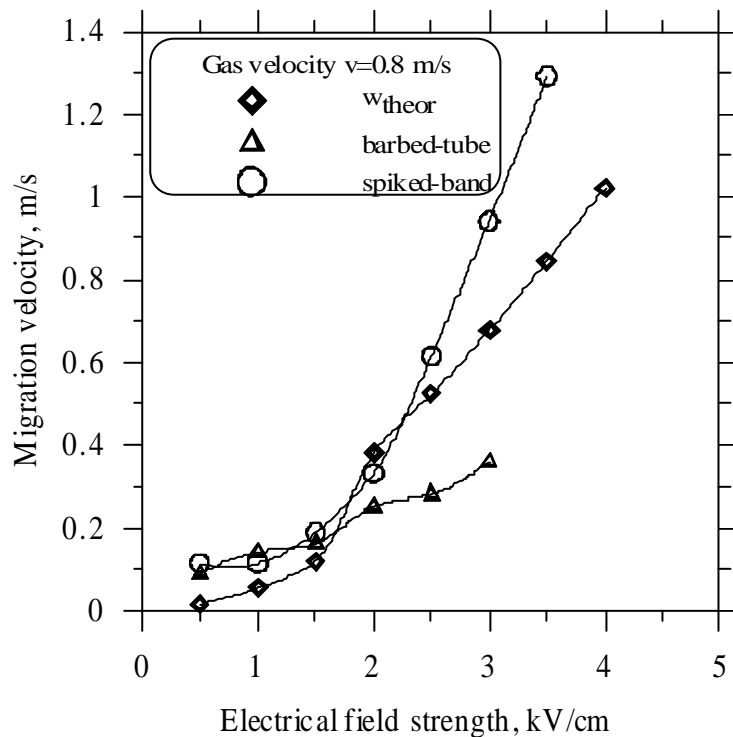


Figure 4: Comparison of mathematically assessed migration velocities and measured values, for the same particle size diameter

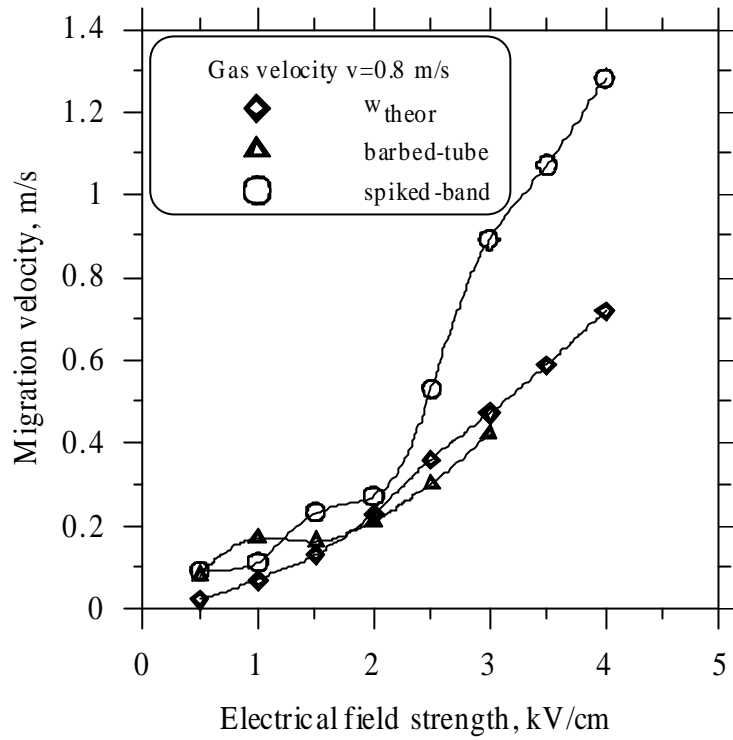


Figure 5: Comparison of theoretical average and measured migration velocities for entire set of particle size classes

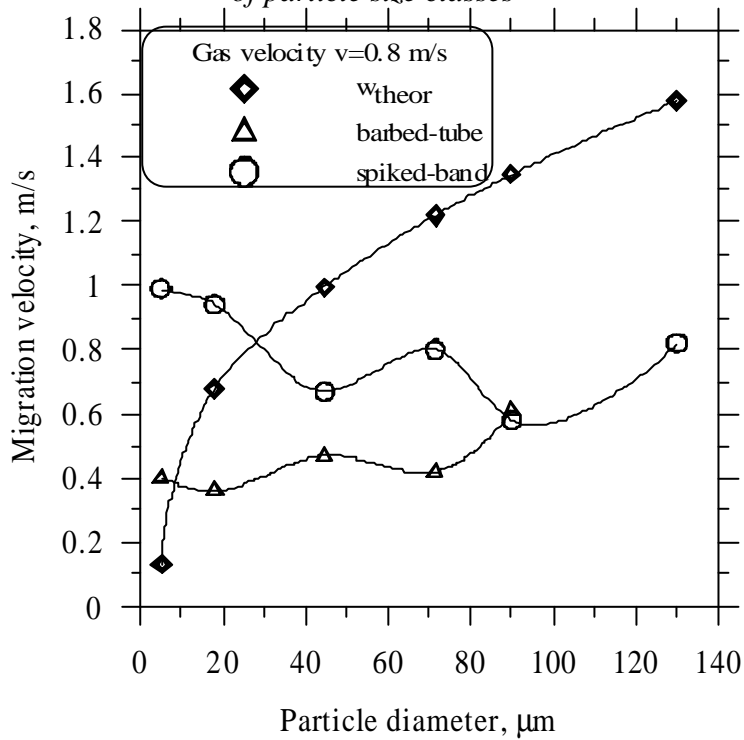


Figure 6: Migration velocity dependency on particle diameter