Conference Presentation

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Estimation of the particle concentration in hydraulic liquid by the in-line automatic particle counter based on the CMOS image sensor

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ABSTRACT

Modern hydraulic systems should be monitored on the regular basis. One of the most effective ways to address this task is utilizing in-line automatic particle counters (APC) built inside of the system. The measurement of particle concentration in hydraulic liquid by APC is crucial because increasing numbers of particles should mean functional problems. Existing automatic particle counters have significant limitation for the precise measurement of relatively low concentration of particle in aerospace systems or they are unable to measure higher concentration in industrial ones. Both issues can be addressed by implementation of the CMOS image sensor instead of single photodiode used in the most of APC. CMOS image sensor helps to overcome the problem of the errors in volume measurement caused by inequality of particle speed inside of tube. Correction is based on the determination of the particle position and parabolic velocity distribution profile. Proposed algorithms are also suitable for reducing the errors related to the particles matches in measurement volume. The results of simulation show that the accuracy increased up to 90 per cent and the resolution improved ten times more compared to the single photodiode sensor.

Keywords: CMOS matrix sensor, image processing, automatic particles counters, hydraulic systems, diagnostic, concentration measurement

1. INTRODUCTION

The reliability of hydraulic systems depends on the regular monitoring of their state[1]. One of the most effective ways to address this task is utilizing in-line automatic particle counters (APC) built inside of the system in order to get information about wearing processes inside of it[2, 3, 4]. The information about the state of the system can be obtained by investigation of parameters of particles floating in the hydraulic liquid[1]. The measurement of particle concentration is the crucial part of such monitoring because increasing numbers of particles with particular sizes should mean that some part of hydraulic system does not work properly or is near to break down[2]. In spite of the fact that several automatic particle counters exist, they have significant limitation for the precise measurement of relatively low concentration of particle in case of utilizing it inside of aerospace systems or they are unable to measure highest concentration in industrial ones[5]. Both issues can be addressed by implementation of the CMOS image sensor instead of single photodiode used in the most of modern APC.

Firstly, the accuracy of the particle concentration measurement is influenced by the accuracy of measurement of the volume of liquid to be investigated. Usually, the velocity of the particle is used for determination of the flow rate and the time of analysis whereas the volume is fixed (100 ml). The velocity of the particle is measured by APC using the duration of the electric pulse at the output of the photodiode.

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However, the velocity of the particle varies throughout the tube as in the centre we have got the maximum speed compared to the lower one near to the pipe wall. This issue cannot be resolved by using photodiode as it cannot measures the position of the particle inside of the tube. Generally, the assumption that the average speed is measured by each particle gives sufficient results for high concentrations. Nevertheless, in case of pure systems like aerospace the error of particle concentration estimation cannot be lower than 30 per cent or might be higher[6]. In case of using matrix image sensor the position of the particle in the tube can be determined by image analysis[7] and the real velocity can be calculated. In our study we represent the method and results of particle concentration determination based on assumption that the distribution of particle velocity is parabolic throughout the channel. Calculations based on the proposed algorithm show that the total error in concentration estimation is not exceed 10 per cent and does not depend on liquid viscosity and temperature.

Secondly, the errors of particle concentration estimation are caused by matches of different particles inside of measurement volume[6]. The photodiode measures several particles inside of measurement volume as one. Typically, the restriction of the maximum measured concentration is established for APC based on photodiodes. It is about 1500 particles per cm^3, which is not sufficient for the industrial hydraulic systems. We proposed the algorithm of estimation of the accuracy of the APC based on matrix sensor. Calculations made by using Poisson distribution prove that the improvement of the resolution (or the limit of concentration to be measured) can achieve in average 20 times more compared to the APC with single photodiode.

2. MATERIALS AND METHODS

The general equation to determine particle concentration n is following[2]:

$$n = \frac{N}{V}, \tag{1}$$

Where N stands for the number of particles inside of fixed volume of liquid V . This volume according to the regulation documents should be 100 ml. Therefore, we need to count N particles during the period of time t_a while this fixed volume of liquid goes throughout the sensor.

The period of time for liquid analysis t_a depends on the flow rate inside of the sensor Q according to the formula[2]:

$$t_a = \frac{V}{Q}, \tag{2}$$

Generally, the flow rate depends on the type of liquid and varied from analysis to analysis. Therefore, the sensor should determine Q automatically. Q depends also on the velocity of the liquid inside of sensor sample tube. The distribution of the velocities is shown in Figure 1.

2.1 Time of analysis for automatic particle counter based on photodiode

Usually, the flow rate in in-line photodiode sensors is estimated by the average velocity of liquid v_{avg} in the sensor sample tube using following relation[8]:

$$Q = 4 \cdot \chi \cdot h^2 \cdot v_{avg}, \tag{3}$$

where χ represents the size of the channel along with y axis divided by the size of channel along with x axis, h denotes the half of the channel size along with x axis.

The average velocity v_{avg} is determined theoretically using equation[8]:

$$v_{avg} = \frac{\Delta p \cdot h^2}{16 \cdot \mu \cdot l} \cdot \left[\frac{16}{3} - \frac{1024}{\pi^5 \cdot \chi} \cdot \left(th \frac{\pi \cdot \chi}{2} + \frac{1}{3^3} \cdot th \frac{3 \cdot \pi \cdot \chi}{2} + \ldots \right) \right], \tag{4}$$

where Δp stands for pressure difference on the sample tube, l denotes the width of diaphragm[6, 7]; μ is kinematic viscosity of the liquid.

Utilizing equation (4) for determination of v_{avg} cases problems because of complication in measurement of Δp and μ during the time of analysis.

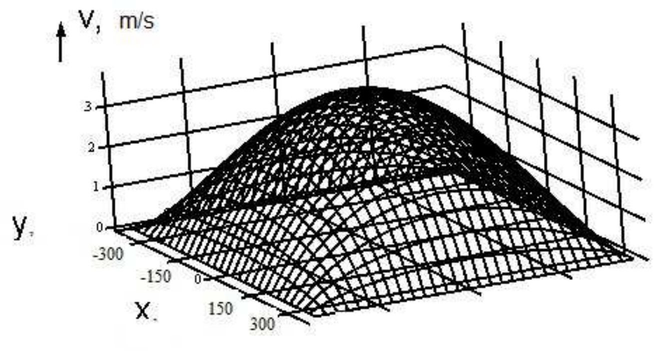


Figure 1. The distribution of velocities inside of the sensor sample tube. The distribution was calculated for the dimension of the sample tube section with sizes 700 μm along with *x* axis and 1000 μm along with *y* axis.

This measurement also requires some additional and very specific instruments. Thus, the v_{avg} is estimated by particle velocity v_{avg}' in the channel which can be measured by the pulse duration at the output of the photodiode[6]:

$$v_{avg}' = \frac{l+d}{\tau}, \qquad (5)$$

where d denotes particle size and τ stands for the pulse duration.

However, measurement according relation (5) causes additional error because v_{avg}' relates to the instantaneous speed of liquid v inside of sample tube and this speed varies significantly in the slice of the tube. This instantaneous speed v can be calculated using following equation in case of laminar flow[8]:

$$v = \frac{16\cdot\chi^2}{\pi^3}\cdot\frac{h^2\cdot\Delta p}{\mu\cdot l}\cdot\sum_{n=0}^{\infty}\frac{(-1)^n}{(2\cdot n+1)^3}\left[1-\frac{ch(\frac{2\cdot n+1}{2}\cdot\frac{\pi\cdot x}{\chi\cdot h})}{ch(\frac{2\cdot n+1}{2}\cdot\frac{\pi}{\chi})}\right]\cdot\cos(\frac{2\cdot n+1}{2}\cdot\frac{\pi\cdot y}{\chi\cdot h}), \qquad (6)$$

This velocity is shown in Figure 1. Eventually, time of the analysis measured by automatic particle counter based on photodiode is determined utilizing relation:

$$t_a = \frac{V}{4\cdot\chi\cdot h^2\cdot v}, \qquad (7)$$

where $v \approx v_{avg}'$.

2.2 Time of analysis for automatic particle counter based on CMOS image sensor

In case of using matrix CMOS image sensor we have additional information about coordinate of particle flown inside of the sample tube. This coordinate can be used for proper determination of the average velocity of the liquid inside of the tube.

Combining relation (3) and (4), we also getting the Δp from equation (6), we can calculate the time of analysis as following:

$$t_a = \frac{64}{\pi^3} \cdot \frac{\chi}{h^2} \cdot \frac{V}{v} \cdot \frac{\sum_{n=0}^{\infty} \frac{(-1)^n}{(2 \cdot n+1)^3} \left[1 - \frac{ch(\frac{2 \cdot n+1}{2} \cdot \frac{\pi \cdot x}{\chi \cdot h})}{ch(\frac{2 \cdot n+1}{2} \cdot \frac{\pi}{\chi})} \right] \cdot \cos(\frac{2 \cdot n+1}{2} \cdot \frac{\pi \cdot y}{\chi \cdot h})}{\left[\frac{16}{3} - \frac{1024}{\pi^5 \cdot \chi} \cdot (th\frac{\pi \cdot \chi}{2} + \frac{1}{3^3} \cdot th\frac{3 \cdot \pi \cdot \chi}{2} + ...) \right]}, \quad (8)$$

This equation is more suitable for matrix CMOS image sensor because it might be possible to determine x and y coordinates of particle track and make some correction for known velocities distribution according to the (6). We also need to know the channel size h that is constant and can be measured.

The velocity of the liquid can be measured by the velocity of the particle inside of sample tube utilizing this relation:

$$v = \frac{N_z \cdot p}{t_{\exp}}, \quad (9)$$

where N_z stands for the size of particle track on the image in number of pixels [San Diego], p is pixel size and t_{exp} denotes exposure time of CMOS image sensor.

Let $F(x, y, \chi)$ stands for the last part of equation (8) and m for the first one. Then $F(x, y, \chi)$ reflects the velocity distribution inside the channel and m represents the sizes of channel. Thus from (8) and (9) we get the following:

$$t_a = \frac{m \cdot t_{\exp}}{N_z \cdot p} \cdot V \cdot F(x, y, \chi), \quad (10)$$

Eventually, we need to know the sizes of channel m, exposure time of CMOS sensor, the size of particle track and pixel size in order to estimate the time of analysis for the predefined volume V.

2.3 Accuracy of estimation of particle concentration

In accordance with (1), the absolute error of particle concentration measurement is determined by the error of indirect measurement:

$$\Delta n = \sqrt{\left(-\frac{N}{V^2} \Delta V \right)^2 + \left(\frac{1}{V} \Delta N \right)^2}, \quad (11)$$

Therefore, we need to determine the absolute error of measurement of volume ΔV and absolute error of measurement of the particle number counting ΔN.

2.4 Accuracy of volume measurement

If we propose that the flow rate is constant value, we can obtain the ΔV from equation (2):

$$\Delta V = Q \cdot \Delta t_a, \quad (12)$$

As follows from the equations (12) and (2), the relative error of volume determination is equal to the relative error of measurement of analysis time:

$$\frac{\Delta V}{V} = \frac{\Delta t_a}{V / Q} = \frac{\Delta t_a}{t_a}, \quad (13)$$

The absolute error of analysis time determination for CMOS image sensor consists of the errors of measurement particle velocities Δv_y, Δv_x and error in measuring particle track coordinate Δx, Δy:

$$\Delta t_a = \sqrt{\left(\frac{\partial t_a}{\partial v_y}\Delta v_y\right)^2 + \left(\frac{\partial t_a}{\partial v_x}\Delta v_x\right)^2 + \left(\frac{\partial t_a}{\partial x}\Delta x\right)^2 + \left(\frac{\partial t_a}{\partial y}\Delta y\right)^2}, \quad (14)$$

where t_a should be calculated according to the equation (10). The absolute error of particle velocity measurement is calculated utilizing formula (9) as following:

$$\Delta v = \frac{p}{t_{\exp}}\Delta N_z, \quad (15)$$

where ΔN_z stands for the absolute error of particle track measurement. The maximum value of ΔN_z is two pixels because when particle track consists of only two pixels, the true length of track can be less than one pixel and up to two pixels. In addition, the total influence of the error in measuring particle track coordinate Δx, Δy are significantly lower than errors of measurement particle velocities Δv_y, Δv_x because there are ten times more pixels along with measurement volume than in particle track. Therefore, the equation (14) can be rewritten as following:

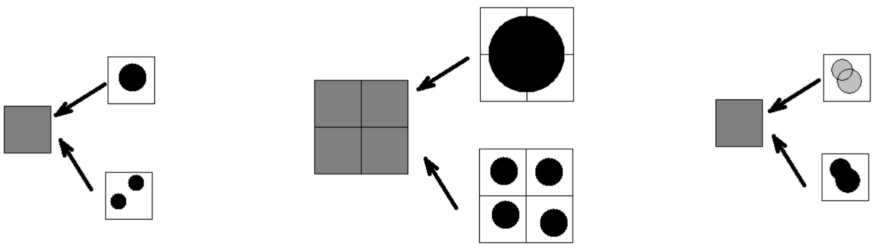
$$\frac{\Delta t_a}{t_a} = \sqrt{\left(\frac{2\cdot p}{v_y \cdot t_э}\right)^2 + \left(\frac{2\cdot p}{v_x \cdot t_э}\right)^2}, \quad (16)$$

Using relation (9) and propose the equal velocities along with both axes, equation (16) can be rewritten as following:

$$\frac{\Delta t_a}{t_a} = \frac{2\sqrt{2}}{N_z}, \quad (17)$$

2.5 Accuracy of particle counting

The absolute error of counting particles ΔN in volume is caused by the particle matches inside of measurement volume. Three cases are possible for particle matches shown in Figure 2.



a) b) c)

Figure 2. Different cases of matches particles inside of measurement volume. In this cases several particles are not distinguished from the one particle. Case a) represents situation when two particles can be counted as one by one pixel, case b) shows the situation of matches several particles above several pixels and c) reflects the case when particles projections are crossing

The probability of particle matches P_{err} means that two or more particles are in the predetermined volume. Let V_{eq} stands for such volume. P_{err} can be calculated on the basis of the Poisson law. The Poisson law estimates the probability P_m of particle numbers presence inside of volume V[9]:

$$P_m = \frac{a^m}{m!}\cdot e^{-a}, \quad (18)$$

where m denotes the number of particles, a stands for the average number of particle in the volume V. a should be calculated as following[9]:

$$a = nV\,, \qquad (19)$$

Thus, P_{err} can be calculated as following:

$$P_{err} = 1 - P_0 - P_1\,, \qquad (20)$$

where P_0 and P_1 stands for the probability of absence of any particle and presence only one particle in the volume respectively.

Using relations (20) and (18) we can obtain for the P_{err} following equation:

$$P_{err} = 1 - \frac{a^0}{0!}e^{-a} - \frac{a^1}{1!}e^{-a} = 1 - e^{-a} - ae^{-a} = 1 - e^{-nV_{eq}}(1 + nV_{eq})\,, \qquad (21)$$

Therefore, P_{err} should depend on V_{eq} in case of constant concentration n. The estimation of the volume is based on drawing in Figure 3. As the CMOS sensor is flat, the V_{eq} can be calculated as product of the channel width h and the area on the surface of the matrix S_{eq}. We can consider two-dimensional case. S_{eq} is presented in Figure 3.

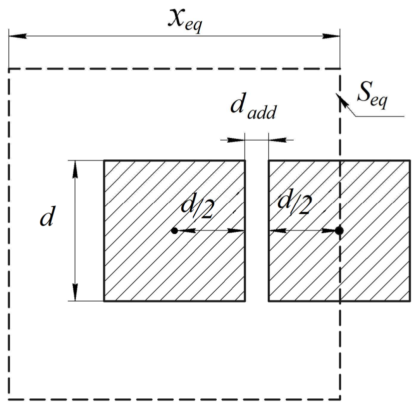


Figure 3. Determination of the equivalent area S_{eq} on the surface of the matrix CMOS image sensor. d stands for particle diameter, x_{eq} is the side of S_{eq} , d_{add} denotes additional interval for particles to be differentiated by image processing.

As follows from Figure 3, the side of the S_{eq} can be calculated utilizing this equation:

$$x_{eq} = 2 \cdot (d + d_{add})\,, \qquad (22)$$

Therefore, the V_{eq} should be determined as following:

$$V_{eq} = h \cdot S_{eq} = 4 \cdot h \cdot (d + d_{add})^2\,, \qquad (23)$$

By substitution of relation (23) in (21) we obtain the equation for P_{err} :

$$P_{err} = 1 - e^{-n \cdot 4 \cdot h \cdot (d + d_{add})^2}(1 + n \cdot 4 \cdot h \cdot (d + d_{add})^2)\,, \qquad (24)$$

3. RESULTS AND DUSCUSSION

3.1 Accuracy of volume and analysis time measurement

Generally, if we have the fixed volume of liquid to be investigated and fixed flow rate we should get the constant time of analysis as follows from the relation (2). However, this time depends on the method of the flow rate determination as was shown in the methods section. The result of calculation of the time of analysis in case of using single photodiode utilizing equation (7) is shown in Figure 4.

As follows from the Figure 4, t_a varies significantly from the value of roughly 45 seconds in centre of channel up to uncertain value near to the tube wall. Theoretically, if the particle goes through the channel on the wall, the error can be infinite. The particle counter can be recalibrated to determine the maximum velocity in the centre of tube though. Consequently, it leads to less error especially when the most of the particle goes through the centre.

However, the error is still depends on the coordinate of the particle and can be significant when the total number of particle in the volume V less than 100.

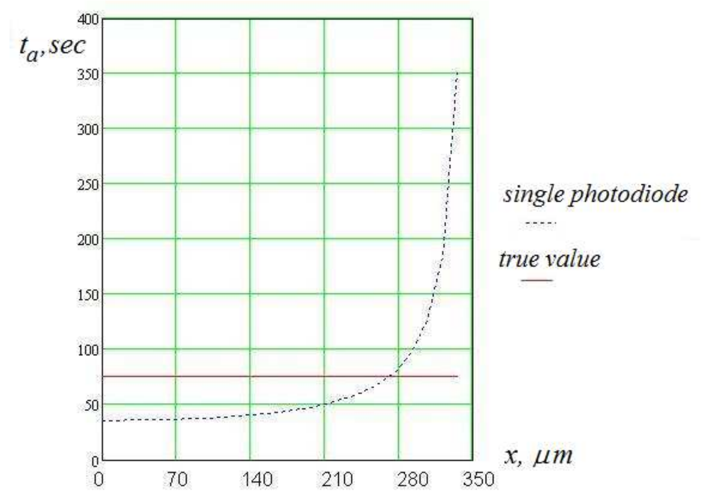


Figure 4. The time of analysis in relation with particle coordinate inside of sample tube. The true value of time of analysis is 75 seconds. The line denotes the true value of t_a , the dotted line is the t_a , determined by single photodiode sensor.

In case of using single photodiode the relative error of volume determination can be calculated according to the relation (13) and (7). We can also obtain the relative accuracy of volume measurement δV in relation with the particle coordinate. This error can easily reach the value of 100 per cent and more for particles flown near to the wall of the tube.

Utilizing equations (17) and (13) we can show the relation between relative error of volume measurement and the size of particle track[7] shown in Figure 5.

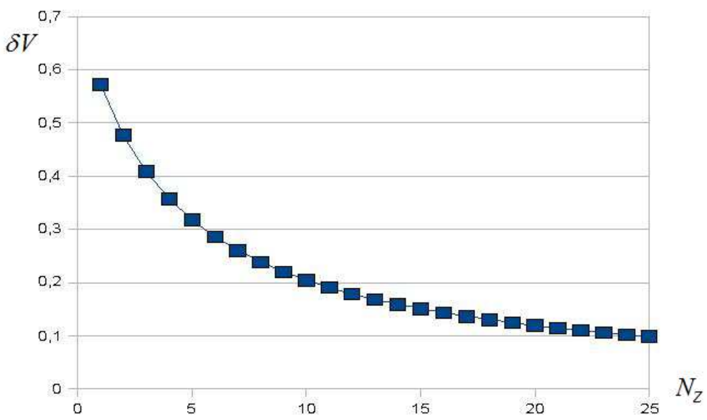


Figure 5. The influence of the length of particle track on the relative error of volume measurement. Pixel size is 6 μm.

According to Figure 5 the length of track should not be less than 20 pixels in order to achieve the accuracy 90 per cent.

Comparison of the results represented in Figures 4 and 5 shows that the implementation of CMOS image matrix sensor reduces the error of volume measurement down to 10 per cent, whereas sensor based on single photodiode has significant error up to infinite value.

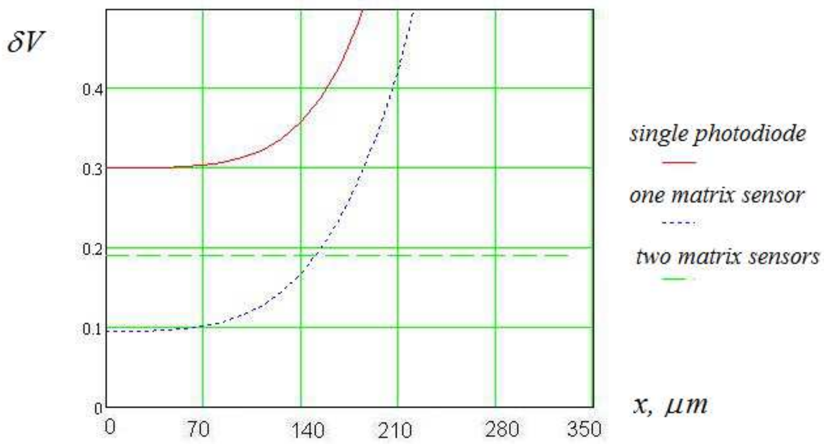


Figure 6. The relative error of volume measurement in relation of the particle coordinate for single photodiode sensor (line), one CMOS image sensor (dotted line) and two CMOS image sensors (dashed line).

However, this error decrease is possible in case of utilizing two matrix sensors along with the *x* and *y* axes of the sample tube. In practice, only one matrix can be easily integrated inside of sample tube and potential error reduction is not complete. Figure 6 represents the relative error of volume measurement in relation of the particle coordinate for single photodiode sensor, one CMOS image sensor and two CMOS image sensors.

In case of using two matrix sensors the error does not depend on the particle track coordinate because both coordinate are determined and the measurement volume is corrected. Sensor with only one matrix sensor has lower error near to the centre of channel because of only one measurement error related to only one matrix. However, the error in this case also depends on the particle track coordinate. The error of the sensor with single photodiode three times higher as the velocity of particle determination is not as effective as in matrix sensor.

3.2 Accuracy of particle counting

As revealed by formula (24), the error in particle counting caused by particle matches depend on the size of sensor channel, the particle concentration and sizes. Let us choose the interval of d_{add} equal to the size of pixel. The results of calculation for particle sizes of 2 μm and 200 μm are represented in Figure 7.

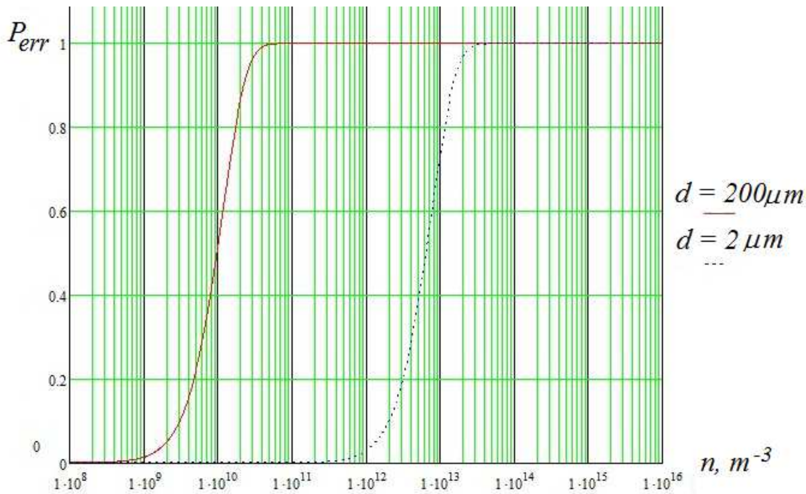


Figure 7. The probability of error in particle counting caused by particle matches in dependence of particle concentration. The error for particle sizes 2 μm shown by dotted line and for 200 μm represented by line.

As can be seen in Figure 7, the maximum concentration to be measured for 2 µm particles significantly higher compared to the 200 µm particles. If we set up the probability of error on the level of 10 per cent, the maximum concentration will be approximately $2 \cdot 10^{12}$ particles in m^3, whereas for 200 µm particles it will be roughly $3 \cdot 10^9$. The resolution of sensors based on CMOS matrix sensor is more than of single photodiode sensors. This fact is also represented in Figure 8.

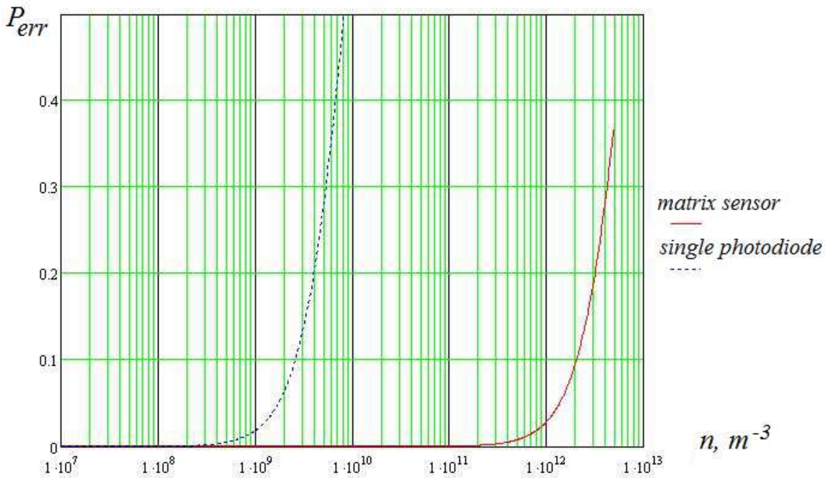


Figure 8. Comparison of the probability of error in particle counting caused by particle matches in dependence of particle concentration for single photodiode sensor (dotted line) and CMOS image sensor (line). Pixel size is 6 µm, the photodiode diaphragm is 140 µm x 700 µm.

As revealed in Figure 8, the resolution of CMOS image sensor is at least 1000 times higher than resolution of single photodiode sensor. This fact can be predictable by comparison of the size of pixel 6 µm and the size of sensitive area in single photodiode sensor with dimensions 140 µm x 700 µm. In addition, we also should consider the length of particle track in case of using CMOS image sensor, therefore the resolution will be at least 100 times more than in single photodiode sensor.

4. CONCLUSION

This article provides the theoretical basis and some results for the estimation of the maximum concentration to be measured by inline automatic particle counter based on CMOS image sensor. The comparisons made shows that this sensor has significant benefits than single photodiode sensors. In methods section presented the algorithm of reducing error caused by the different particle velocities inside of measuring channel of the sensor to be implemented in CMOS image sensors. The method of choosing proper parameters of CMOS image particle sensor like pixel size, exposure time is also provided. The materials in this article can also be used for the accuracy estimation for both single photodiode and CMOS image particle sensors.

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