UDK 533.6.08:535.374:621.375.8:541.182.2/.3

Poenostavljena analiza merilne negotovosti premerov sferičnih delčkov z uporabo standardnega faznega Dopplerjevega anemometra

A Symplified Analysis of Measurement Uncertainty of Spherical Particle Diameters Using a Standard Phase-Doppler Anemometer

BOGDAN BLAGOJEVIĆ - IVAN BAJSIĆ

V prispevku je predstavljena poenostavljena analiza merilne negotovosti velikosti premera delčkov z uporabo faznega Dopplerjevega anemometra (FDA). Za širjenje posameznih vplivov merilnih negotovosti neodvisnih spremenljivk na celotno merilno negotovost velikosti premera delčkov smo za neodvisne izvore pogreškov uporabili Taylorjevo vrsto. Pri tem smo analizirali vplive posameznih neodvisnih spremenljivk in njihovih merilnih negotovosti. Analiza je omejena samo na tiste veličine, ki se uporabljajo pri izračunu velikosti delčkov.

A simplified analysis for the evaluation of measurement uncertainty of spherical particle diameter is presented in this paper. Particle diameter is measured by using the standard Phase-Doppler anemometer (PDA). The effects of propagating uncertainties of individual independent variables on the total uncertainty of the measurement were analysed by employing the Taylor series. This analysis is restricted to quantities which are used in computing the particle size.

0 UVOD

Dvofazni dispergirani tokovi se pojavljajo v mnogih industrijskih procesih. Večina omenjenih procesov je povezana s prenosom snovi, energije in gibalne količine med kontinuitetno in dispergirano fazo. Razumevanje teh pojavov je posebej pomembno pri modeliranju in načrtovanju industrijskih procesov. Razpoložljivi eksperimentalni podatki kažejo, da je poznavanje porazdelitve velikosti, koncentracij in velikosti razpršenih delčkov zelo pomembno za njihovo pravilno fizikalno razumevanje. Kapljičast tok, ki lahko nastane z razpadom tekoče lamele in oblikovanjem kapljic različnih velikosti, je samo eden od primerov dvofaznih dispergiranih tokov. Takšni tokovi se pojavljajo v različnih tehničnih aplikacijah, kakor so ovlaževalniki zraka, razprševanju tekočin v kmetijstvu, hladilnih stolpih [1], [2].

Merjenje velikosti delčkov dispergiranih tokov je posebej težavno, če je koncentracija dispergirane faze v toku plina zelo velika. Velikosti dispergiranih delčkov so se določale z uporabo merilnih sistemov, ki so motili dejanski tok in so s tem vnesli motnje v fizikalno sliko procesa. Razvoj sodobnih optičnih metod, ki ne ovirajo tokov, je omogočil tudi eksperimentalne raziskave dvofaznih dispergiranih tokov. Ena takšnih metod je tudi metoda merjenja s faznim Dopplerjevim anemometrom (FDA), ki je razširitev standardnega laserjevega Dopplerjevega anemometra (LDA) in se zelo uporablja v raziskavah dvofaznih tokov [3] do [10]. Vsaka od teh metod ima omejitve uporabnosti glede na merilno točnost, gostoto razpršenih

0 INTRODUCTION

Two-phase dispersed flows occur in a wide range of industrial processes. Most of these processes involve the transfer of mass, energy and momentum between the dispersed and continuous phases. An understanding of these transfer processes is therefore of paramount importance for modelling and designing industrial processes. The available experimental data indicate that knowing the distributions of velocity, concentration and size of dispersed particles is essential for an accurate physical understanding of the flow. Droplet flow that is caused by the breakup of thin liquid sheets and formation of liquid droplets of different sizes is only one of the two-phase dispersed flows. This particular flow situation occurs in various technical applications such as air humidifiers, atomization in agriculture industry and cooling towers [1], [2].

These particles are highly dispersed in the gas phase, the measurement of their sizes is difficult to execute. Most measurements of particle size were obtained by using measuring system that disturb the flow and therefore introduce some distortion into the physical picture of the flow. The development of optical systems indicated that these systems are non-intrusive and seem to be appropriate for the measurement of two-phase flows. Such method is Phase-Doppler-Anemometry (PDA), which is an extension of Laser-Doppler-Anemometry (LDA) and is one of the optical systems that has been widely used in the examination of two-phase flows [3] to [10]. However, each of these experimental methods has limited usage, with respect to accuracy, particle concentration

delčkov, širino velikosti spektra delčkov in optične lastnosti obeh faz. Mnogo manj pa je znanega o merilni negotovosti takšnega merilnega sistema [11] do [15]. S tem namenom v prispevku podajamo poenostavljeno analizo merilne negotovosti standardnega sistema FDA.

Glavne značilnosti FDA smo povzeli po [10]:

– zagotovljen mora biti optični dostop do merilnega mesta,

– delčki (kapljice, mehurčki ali trdni delci) morajo biti sferične oblike,

– v večini primerov moramo poznati lomna količnika obeh faz,

– velikostni obseg delčkov znaša od nekaj μm do nekaj mm,

– razpršena faza naj bo homogena.

1 MERJENJE VELIKOSTI DELČKOV S FDA

Na sliki 1 je shematično prikazan optični merilni sistem standardnega sistema FDA, ki omogoča merjenje lokalne velikosti, hitrosti in koncentracije delčkov. Oddajno optiko predstavlja standardni dvožarkovni sistem LDA, ki je povezan s sprejemnim sistemom za detekcijo intenzivnosti sipane svetlobe na delčkih. Laserski žarek valovne dolžine λ se v oddajni optiki razdeli na dva koherentna žarka, ki sta med seboj oddaljena za x_S. Zbiralna leča oddajnega sistema z goriščno razdaljo f_S jih ponovno zbere. Merilna kontrolna prostornina (MV) je definirana s presečiščem laserskih žarkov, ki se sekata pod kotom Θ. Laserski žarek ima Gaussovo porazdelitev intenzivnosti, kar je razvidno tudi v MV, ki ima elipsoidno obliko. Sprejemni sistem sestavljata najmanj dva fotodetektorja s sprejemnimi lečami. Za MV veljajo zakonitosti, ki so znane iz standardnega sistema LDA [16] in [17]. Poenostavljeno sliko dogajanja v MV predstavlja model interferenčnih ravnin.

size bandwith, and optical properties of both phases. The analysis of measurement uncertainty of PDA presented in [11] to [15] are still lacking. Therefore the purpose of this paper is to present a simplified analysis of measurement uncertainty of the standard PDA.

The main characteristics of PDA are taken from [10]:

– the optical and mechanical access has to be provided,

– the particles (bubbles, droplets, solid particles) have to be of a spherical shape,

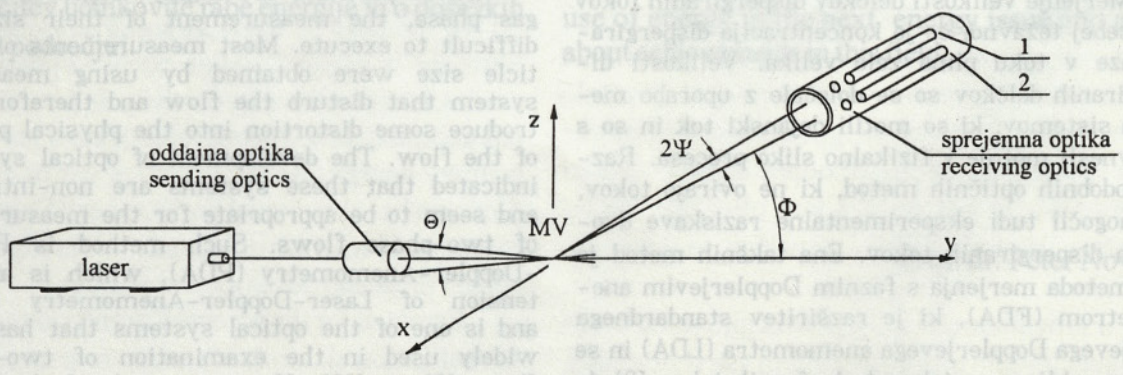
– the refractive indexes of both phases have to be known in most cases,

– the approximate size range is from a few μm to a few mm,

– the dispersed phase has to be homogeneous.

1 PARTICLE SIZE MEASUREMENT BY PDA

The scheme of the basic optical set-up of the PDA system is shown in Figure 1. This system was used for measurements of the local particle sizes, velocities and concentrations of particles. The sending system is represented by the classical two-beam LDA system, that is linked to the receiving system which detects the light scattering from particles. The sending system separates the laser beam with wavelength λ into two coherent beams with separation length x_S. The sending lenses with focal length f_S collect these two laser beams. The measuring control volume (MV) is defined by the intersection of these two laser beams. The beam crossing angle is Θ. Each beam has a Gaussian intensity profile, which is also presented by an ellipsoidal MV. The receiving system is composed of two photodetectors and receiving lenses. The same characteristics are valid for MV as for the LDA [16] and [17]. The interference fringe model presents the processes occurring in the MV.



Sl. 1. *Shematični prikaz optičnega sistema FDA*

Fig. 1. *Schematic presentation of a PDA optical system*

Nastanek vzporednih interferenčnih ravnin in velikosti prostornine sta odvisna od pravilne izbire in namestitve zbiralnih leč laserskega oddajnega sistema. Osnovne geometrijske značilnosti merilne prostornine, ki so dobljene na podlagi geometrijske optike in lastnosti Gaussovih žarkov, povzemamo po [17]:

premer MV:

$$d_e = \frac{4f\lambda}{\pi D_e}, \quad \text{kjer je } D_e \text{ premer Gaussovega žarka}$$

where D_e is beam waist

dolžina MV:

$$l_m = \frac{d_e}{\sin(\theta/2)}$$

širina MV:

$$y = \frac{d_e}{\cos(\theta/2)}$$

višina MV:

$$z = d_e$$

prostornina MV:

$$V_m = \frac{\pi}{6} \frac{d_e^3}{\cos(\theta/2)\sin(\theta/2)}$$

razmik med interferenčnimi ravninami:

$$x_m = \frac{\lambda}{2\sin\theta}$$

število interferenčnih ravnin:

$$N = \frac{d_e}{\lambda}\tan(\theta/2) = \frac{4f}{\pi D_e}\tan(\theta/2)$$

Merilna prostornina je prikazana tudi na sliki 2. Ko delec potuje skozi presečišče laserskih žarkov, sipana svetloba oblikuje interferenčne obroče. To sipano svetlobo zbereta zbiralni leči sprejemne optike z goriščno razdaljo f_r. Sprejemni optični sistem je zasukan okoli navpične osi MV za kot Φ, ki je približno enak kotu sipanja. Dvižni kot med detektorjema je enak ψ. Sprejemne leče preoblikujejo sipano svetlobo v vzporedne žarke. Fokusirana svetloba se zatem prenese na fotodiodi oziroma fotopomnoževalki.

Parallel fringe patterns and the size of the MV depend on the selection and set up of the lenses of the sending laser system. The basic geometrical characteristics of the MV, which are derived from geometrical optics and a Gaussian characteristic of laser beams, are given by [17]:

MV diameter:

MV length:

MV width:

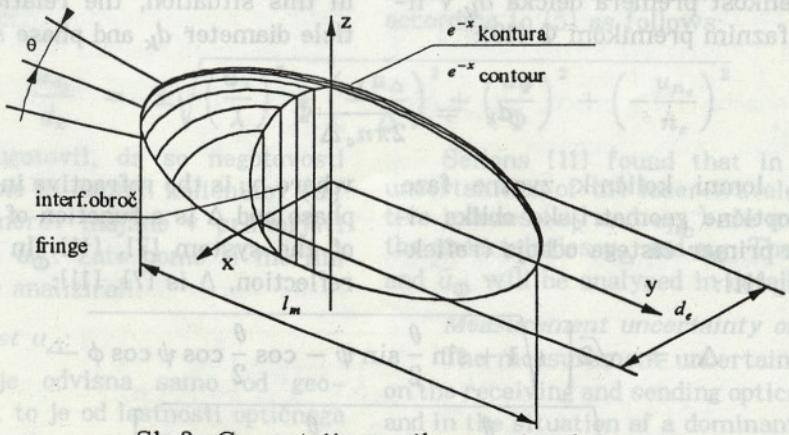
MV height:

MV volume:

length between fringes:

number of fringes:

MV is shown in figure 2. When a particle passes through the intersection of two laser beams, the scattered light forms an interference fringe pattern. This scattered light is then collected by the receiving lenses with focal length f_r. The receiving optics is spaced at off-axis angle Φ, which is approximately equal to the scattering angle. The receiver elevation angle between two detectors is ψ. Receiving lenses transform the scattered light from the particles into parallel beams which are then transferred to two photodiodes or photomultipliers.



Sl. 2. *Geometrija merilne prostornine*
Fig. 2. *Geometry of the measuring volume*

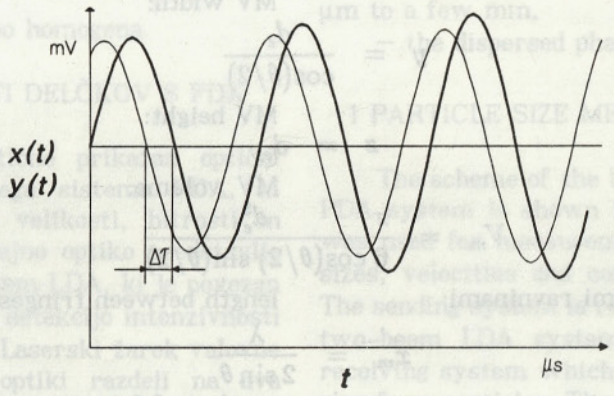
Signali se zatem ustrezno filtrirajo in shranijo v prehodnem zapisovalniku, ki je povezan z osebnim računalnikom (OR). Ta računalnik se uporablja tudi za analizo in procesiranje signalov, ki jih zaznajo fotodiode. Sistem za procesiranje signalov omogoča vrednotenje faznega premika Φ med dvema Dopplerjevima signaloma. Fazni premik je sorazmeren časovni zakasnitvi med Dopplerjevima signaloma $\Delta\tau$:

$$\Phi = \Delta\tau f_D 360° \quad (1),$$

kjer pomeni f_D frekvenco Dopplerjevega signala. Fazni premik Dopplerjevih signalov je prikazan na sliki 3.

The signals from these two photodiodes are filtered and stored in a transient recorder which is linked to a personal computer (PC). This PC is used to analyse and process the signals from the photodiodes. The data processing system evaluates the phase shift Φ between the two Doppler signals which is proportional to the time delay $\Delta\tau$ between the signals:

where f_D is the Doppler frequency of the signal. The phase shift between two Doppler signals is shown in Figure 3.



Sl. 3. *Fazni premik med Dopplerjevima signaloma*
Fig. 3. *Phase shift between two Doppler signals*

V naši analizi se bomo ukvarjali s čistim lomom in čistim odbojem svetlobe. Intenzivnost sipane svetlobe na delčkih lahko določimo numerično po Mieovi teoriji [7]. Bauckhage in Saffmann sta prva izpeljala prenosno funkcijo sistema FDA na podlagi geometrijske optike. Rezultati, dobljeni z numeričnim izračunom na podlagi Mieove teorije sipanja delčkov, se odlično ujemajo z vrednostmi, dobljenimi z uporabo poenostavljene formule za primer čistega odboja (mehurčki) in čistega loma (vodne kapljice) [10], [11] in [7]. V tem primeru je velikost premera delčka d_k v linearni povezavi s faznim premikom Φ [10]:

In the work presented, only a dominant light scattering example of refraction and reflection is analysed. The intensity of the light scattering from particles can be calculated numerically on the basis of the Mie scattering theory [7]. The transfer function of PDA was derived by Bauckhage and Saffmann on the basis of a geometrical optics. An excellent agreement between the numerical calculations of the complete Mie's theory with simplified formula was obtained for dominant light scattering of reflection (bubbles) and refraction (water droplets) [10], [11] and [7]. In this situation, the relationship between particle diameter d_k and phase shift Φ is linear [10]:

$$d_k = \frac{\lambda}{2\pi n_c \Delta}\Phi \quad (2),$$

kjer pomenita n_c lomni količnik zvezne faze, Δ pa je funkcija optične geometrijske oblike sistema [7], [11]. Za primer čistega odboja (refleksija) je Δ enak [7], [11]:

where n_c is the refractive index of the continuous phase and Δ is a function of the optical geometry of the system [7], [11]. In te case of dominant reflection, Δ is [7], [11]:

$$\Delta = \sqrt{2}\left[\sqrt{1+\sin\frac{\theta}{2}\sin\psi-\cos\frac{\theta}{2}\cos\psi\cos\phi}-\sqrt{1-\sin\frac{\theta}{2}\sin\psi-\cos\frac{\theta}{2}\cos\psi\cos\phi}\right] \quad (3).$$

Za primer čistega loma pa je Δ enak:

$$\Delta = 2\left\{\left[1+n'^2-\sqrt{2}n'\sqrt{1+\sin\frac{\theta}{2}\sin\psi+\cos\frac{\theta}{2}\cos\psi\cos\phi}\,\right]^{0.5} - \left[1+n'^2-\sqrt{2}n'\sqrt{1-\sin\frac{\theta}{2}\sin\psi+\cos\frac{\theta}{2}\cos\psi\cos\phi}\,\right]^{0.5}\right\} \quad (4).$$

V enačbi (4) je n' razmerje lomnih količnikov dispergirane tekoče faze n_d in zvezne plinaste faze n_c:

$$n' = \frac{n_d}{n_c}$$

2 MERILNA NEGOTOVOST VELIKOSTI DELČKA

Za širjenje posameznih vplivov merilnih negotovosti neodvisnih spremenljivk na celotno merilno negotovost velikosti premera delčkov smo za neodvisne izvore pogreškov uporabili Taylorjevo vrsto, oziroma upoštevali Gaussovo analizo pogreškov. Če je veličina y odvisna od veličin x_i (i = 1, M), je merilna negotovost enaka:

$$u_y = \pm\sqrt{\sum_{i=1}^{M}\left(\frac{\partial y}{\partial x_i}u_{x_i}\right)^2}$$

oziroma relativno:

$$\frac{u_y}{y} = \pm\sqrt{\sum_{i=1}^{M}\left(\frac{1}{y}\frac{\partial y}{\partial x_i}u_{x_i}\right)^2} \quad (5),$$

kjer sta x in y neposredno in posredno merjeni veličini, M število neposredno merjenih veličin, u_x pa je negotovost neposredno merjene veličine. Člen $\frac{\partial y}{\partial x_i}u_{x_i}$ ali v relativni obliki $\frac{1}{y}\frac{\partial y}{\partial x_i}u_{x_i}$ pomeni vplive neodvisnih spremenljivk x_i na celotno merilno negotovost u_y. Posamezen vpliv smo označili s c_{x_i}.

Iz enačbe (2) je razvidno, da je premer kapljic odvisen od valovne dolžine laserske svetlobe λ, geometrijske funkcije Δ, faznega premika Φ in lomnega količnika zvezne faze n_c. Z upoštevanjem (5) lahko določimo tudi relativno merilno negotovost velikosti kapljic:

$$\frac{u_{d_k}}{d_k} = \pm\sqrt{\left(\frac{u_\lambda}{\lambda}\right)^2+\left(-\frac{u_\Delta}{\Delta}\right)^2+\left(\frac{u_\Phi}{\Phi}\right)^2+\left(-\frac{u_{n_c}}{n_c}\right)^2} \quad (6).$$

Sellens [11] je ugotovil, da so negotovosti laserske valovne dolžine in lomnih količnikov (u_λ in u_{n_c}) v večini primerov majhne v primerjavi z negotovostmi u_Δ in u_Φ. Zato bomo ti merilni negotovosti podrobneje analizirali.

Merilna negotovost u_Δ:

Negotovost u_Δ je odvisna samo od geometrijskh parametrov, to je od lastnosti optičnega sistema oddajne in sprejemne optike, v primeru dominantnosti loma, (npr. vodne kapljice), pa tudi

In the case of dominant refraction, Δ is:

In eq. (4), n' is the ratio between the refractive indexes of the dispersed liquid n_d and continuous gas phase n_c:

2 MEASUREMENT UNCERTAINTY OF PARTICLE SIZE

In the work presented, the effects of individual uncertainties on the total measurement uncertainty were analysed by using the Taylor series (Gaussian error analysis). If a quantity y depends on a number of quantities x_i (i = 1, M), the measurement uncertainty is:

or in relative form:

where x and y are the directly and indirectly measured quantities, respectively. M is the number of directly measured quantities and u_x is the measurement uncertainty of a directly measured quantity. The term $\frac{\partial y}{\partial x_i}u_{x_i}$, or in relative form $\frac{1}{y}\frac{\partial y}{\partial x}u_{x_i}$, shows the effects of the independent variable x_i on the total measurement uncertainty u_y. This single effect is denoted by c_{x_i}.

From (2) it is evident that droplet diameter is a function of beam wavelength λ, geometrical function Δ, phase shift Φ and refractive index of the continuous phase n_c. The relative uncertainty of the measurement of d_k can be evaluated according to (5) as follows:

Sellens [11] found that in most cases the uncertainties of the laser wavelength and refractive indexes (u_λ and u_{n_c}) are much smaller than the uncertainties u_Δ and u_Φ. The uncertainties u_Δ and u_Φ will be analysed in detail.

Measurement uncertainty of u_Δ:

The measurement uncertainty of u_Δ depends on the receiving and sending optical characteristics, and in the situation af a dominant refraction (water droplets), on the ratio of refractive indexes of both the dispersed and continuous phase [7].

od razmerja lomnih količnikov dispergirane in zveznee faze [7]. Na podlagi enačb (3) in (4) lahko ugotovimo, da je funkcija Δ odvisna od razmerja lomnih količnikov n' in kotov Θ, ψ in ϕ. Posamezne veličine so odvisne tudi od drugih merjenih veličin. Npr. kot Θ je odvisen od razdalje med obema žarkoma na oddajni zbiralni leči $x_s \pm u_{xs}$ in od goriščne razdalje oddajne leče $f_s \pm u_{fs}$. Enačba za izračun kota Θ je [11]:

Eqs. (3) and (4) indicate that the function of the optical geometry of the system Δ depends on the refractive index ratio n' and angles Θ, ψ and ϕ. Some of these quantities are a function of the other measured quantities. For example, the angle Θ depends on the beam separation length $x_s \pm u_{xs}$ between two laser beams and on the focal length of sending lenses $f_s \pm u_{fs}$. The equation for Θ [11] is:

$$\theta = 2 \arctan \frac{x_s}{2f_s} \tag{7}.$$

Negotovost u_Θ določimo z enačbo (5):

Uncertainty of u_Θ can be evaluated from (5):

$$u_\theta = \pm \sqrt{\left(\frac{4f_s}{4f_s^2 + x_s^2} u_{xs}\right)^2 + \left(\frac{-4x_s}{4f_s^2 + x_s^2} u_{fs}\right)^2} \tag{8}.$$

Podobno lahko določimo tudi merilno negotovost kota ψ, ki je odvisen od razdalje med žarkoma na sprejemni strani optike $x_r \pm u_{x_r}$ in goriščne razdalje zbiralne leče na sprejemni strani optike $f_r \pm u_{x_r}$. Enačba za izračun kota ψ [11] je:

The uncertainty of the angle ψ can be evaluated in a similar manner. The angle ψ depends on the beam separation length $x_r \pm u_{x_r}$ of the receiving optical system and on the focal length of receiving lenses $f_r \pm u_{x_r}$. The equation for ψ [11] is:

$$\psi = \arctan \frac{x_r}{2f_r} \tag{9}.$$

Merilna negotovost u_ψ je enaka:

The measurement uncertainty of u_ψ is:

$$u_\psi = \pm \sqrt{\left(\frac{2f_r}{4f_r^2 + x_r^2} u_{xr}\right)^2 + \left(\frac{-2x_r}{4f_r^2 + x_r^2} u_{fr}\right)^2} \tag{10}.$$

Merilna negotovost kota ϕ, u_ϕ, je odvisna od tega, kako natančno smo sposobni namestiti fotodetektorja.

The measurement uncertainty of the angle ϕ, u_ϕ depends on the installment precision of photodetectors.

Z upoštevanjem (5) lahko merilno negotovost u_Δ za primer čistega loma in odboja zapišemo kot:

Considering eq. (5), in the case of dominant reflection or refraction, u_Δ is:

$$\frac{u_\Delta}{\Delta} = \pm \frac{1}{\Delta} \sqrt{\left(\frac{\partial \Delta}{\partial \theta} u_\theta\right)^2 + \left(\frac{\partial \Delta}{\partial \psi} u_\psi\right)^2 + \left(\frac{\partial \Delta}{\partial \phi} u_\phi\right)^2 + \left(\frac{\partial \Delta}{\partial n'} u_{n'}\right)^2} \tag{11}.$$

Navadno se za vsak merilni sistem FDA podaja tudi fazni faktor, ki je definiran kot [8], [10] in [11]:

The phase factor, which is usually given for every PDA system, is given by [8], [10] and [11]:

$$K_\Phi = \frac{2\pi n_c}{\lambda} \Delta \tag{12}.$$

Če vstavimo enačbo (12) v enačbo (2), je premer delčka d_k enak:

By putting eq. (12) in (2), the particle diameter d_k is:

$$d_k = \frac{\lambda}{2\pi n_c \Delta} \Phi = \frac{\Phi}{K_\Phi} \tag{13}.$$

Merilno negotovost faznega faktorja lahko izračunamo iz (5):

The measurement uncertainty of the phase factor can be calculated from eq. (5):

$$\frac{u_{K_\Phi}}{K_\Phi} = \pm \sqrt{\left(-\frac{u_\lambda}{\lambda}\right)^2 + \left(\frac{u_\Delta}{\Delta}\right)^2 + \left(\frac{u_{n_c}}{n_c}\right)^2} \tag{14}.$$

Z upoštevanjem enačb (13) in (5), je celotna merilna negotovost velikosti delčka u_{dk} enaka:

Considering the eqs. (13) and (5), the total uncertainty of the particle diameter u_{dk} is:

$$\frac{u_{d_k}}{d_k} = \pm\sqrt{\left(\frac{u_\Phi}{\Phi}\right)^2 + \left(-\frac{u_{K_\Phi}}{K_\Phi}\right)^2} \quad (15).$$

V drugem delu enačbe (15) so zajeti vplivi, ki imajo bolj ali manj stalen vpliv. Odvisni so predvsem od izbire in nastavitve oddajne in sprejemne optike. Večji problem pa pomeni določitev merilne negotovosti merjenja fazne razlike. Ta je odvisna od sistema za procesiranje signalov, ki lahko deluje v časovnem prostoru [11] ali pa frekvenčnem prostoru [10]. V nadaljevanju se bomo omejili na sistem FDA, ki uporablja za metodo procesiranja križno spektralno gostoto. Ta sistem je razvil in podrobno analiziral Domnick [13]. Funkcija križne spektralne gostote signalov $x(t)$ in $y(t)$, ki jih zaznata fotodetektorja, je kompleksna veličina [10], [12], [13] in [15].

Z metodo križnega korelacijskega spektra lahko vrednotimo merilne signale z zelo nizko vrednostjo RSŠ (razmerje med koristnim signalom in šumom), ob tem pa se ohranja dokaj velika točnost [10] in [12].

Merilna negotovost faznega premika Φ:

Domnick [13] je razvrstil naslednje izvore pogreškov, ki vplivajo na določitev merilne negotovsti faznega premika u_Φ:

- fazna zakasnitev na fotodetektorju u_{Φ_1},
- fazna zakasnitev signala v elektroniki u_{Φ_2},
- pogrešek zaradi A/D pretvorbe u_{Φ_3},
- točnost uporabljenega algoritma vrednotenja u_{Φ_4}.

Vsaka od metod vrednotenja signalov terja svojo analizo merilne negotovosti faznega premika Φ, to še posebej velja za negotovost u_{Φ_4}. V nadaljevanju bomo analizirali sisteme, ki uporabljajo metodo križnega korelacijskega spektra. Ocene merilnih negotovosti faznega premika u_{Φ_i}, ki so zbrane v preglednici 1, podajamo na podlagi [13].

Standardni sistem FDA omogoča merjenje fazne zakasnitve Φ do 360^0, zato se vse podane relativne negotovosti v preglednici 1 nanašajo na to vrednost. Z upoštevanjem enačbe (5) je celotna merilna negotovost fazne zakasnitve:

The influences with approximately constant characteristics are involved in the second term of eq. (15). These influences depend on the selection and set-up of the sending and receiving optics. A major problem is the evaluation of the measurement uncertainty of the phase difference between two signals. This uncertainty depends on the signal processing system, which can work in either time [11] or in frequency domain [10]. In following, the cross-spectral density method was taken for the analysis of the data. This signal processing method was developed by Domnick [13]. The cross-spectral density (CSD) function of the two signals $x(t)$ and $y(t)$ detected by photodetectors is a complex quantity [10], [12], [13] and [15].

This method can process signals with very low SNR (Signal-Noise-Ratio) values, while maintaining high accuracy [10] and [12].

Measurement uncertainty of the phase shift Φ:

The sources of the measurement uncertainty of phase shift u_Φ were classified by Domnick [13]:

- phase shift in photodetectors, u_{Φ_1},
- phase shift in the electronics, u_{Φ_2},
- errors in the A/D converter, u_{Φ_3},
- uncertainty of the signal processing algorithm, u_{Φ_4}.

Each of the signal processing methods requires its own measurement uncertainty analysis. This is especially important for u_{Φ_4}. In following, the PDA system with the CSD signal processing method is analysed. The sources of the measurement uncertainty of the phase shift u_{Φ_i} are collected in Table 1, which are taken from [13].

The standard PDA system enables the measurement of the phase shift Φ up to 360^0. All of the relative uncertainties collected in Table 1 refer to this phase angle. Considering eq. (5), the total measurement uncertainty of the phase shift is:

$$\frac{u_\Phi}{\Phi} = \pm\sqrt{\left(\frac{u_{\Phi_1}}{\Phi}\right)^2 + \left(\frac{u_{\Phi_2}}{\Phi}\right)^2 + \left(\frac{u_{\Phi_3}}{\Phi}\right)^2 + \left(\frac{u_{\Phi_4}}{\Phi}\right)^2} \quad (16).$$

Preglednica 1: *Viri merilnih pogreškov faznega premika u_Φ po [13]*
Table 1: *The sources of the measurement uncertainties of the phase shift u_Φ according [13]*

Merilna negotovost Measurement uncertainty	Absolutna vrednost Absolute value	Relativna vrednost Relative value	Opomba Remark
u_{Φ_1}	±0,25°	0,07 %	ocenjen estimated
u_{Φ_2}	±0,5°	0,14 %	izmerjen measured
u_{Φ_3}	±1*digit*	0,04 %	amplituda in hitrost vzorčenja amplitude and sampling velocity
u_{Φ_4}	±1,8°	0,5 %	izmerjen [12] measured [12]

3 ANALIZA MERILNE NEGOTOVOSTI STANDARDNEGA FDA

Na podlagi modela širjenja pogreškov posredno merjenih veličin smo izdelali računalniški algoritem za določitev merilne negotovosti standardnega sistema FDA za merjenje velikosti delčkov. Eno prvih analiz merilne negotovosti sistema FDA je opisal Sellens [11]. Zato smo v naših simuliranjih upoštevali geometrijske parametre sistema FDA, ki jih je pri svojem preizkusu določil Sellens. Ti podatki, zbrani v preglednici 2, so bili dobljeni pri razprševanju vode.

3 ANALYSIS OF THE MEASUREMENT UNCERTAINTY OF THE STANDARD PDA

The measurement uncertainty of the standard PDA for particle size measurement was obtained by using a developed computer program. Sellens [11] first analysed his experimental data in a similar manner. In this paper the data were analysed considering the PDA system parameters determined by Sellens. These data are presented in Table 2. In his experimental work, the atomization of water droplets in air was examined.

Preglednica 2: *Geometrijske značilnosti sistema FDA po [11]*
Table 2: *Geometrical characteristics of the PDA by [11]*

Veličina Quantity x_i	Vrednost Value	Merilna negotovost Measurement uncertainty u_{x_i}
n'	1,33	$\simeq 0$
λ	632,8 *nm*	$\simeq 0$
x_s	15 mm	±0,25 mm
f_s	310 mm	±6,2 mm
ϕ	30°	±1°
x_m	40 mm	±0,25 mm
f_r	500 mm	±10 mm
D_e	1,1 mm	

Sellens [11] je pri svojem preizkusu uporabil zbiralne leče, ki so imele merilno negotovost goriščnih razdalj enako ±2 % . Z računalniškim programom smo za vhodne podatke najprej izračunali geometrijske veličine merilne prostornine in nekatere geometrijske parametre sistema FDA (koti Θ in ψ). Rezultati so zbrani v preglednici 3.

The measurement uncertainties of the focal length of optical systems used by Sellens [11] were ±2 %. The calculated geometrical quantities of the measuring volume and some other geometrical parameters of the PDA system (angles Θ and ψ) are determined on the basis of a computer algorithm. The results are shown in the Table 3.

Preglednica 3: *Geometrijske značilnosti merilne prostornine in parametri geometrijske optike*
Table 3: *Geometrical characteristics of measuring volume and other parameters of the geometrical optics*

Veličina Quantity x_i	Vrednost Value
θ	$2{,}77° \pm 0{,}072°$
ψ	$2{,}29° \pm 0{,}05°$
d_e	0,227 mm
l_m	9,388 mm
y	0,227 mm
z	0,227 mm
N	17
x_r	0,013 mm
V_m	0,254 mm^3

Merilne negotovosti funkcije geometrijskih parametrov Δ, faznega faktorja K_Φ in premera kapljic d_k za izbran sistem FDA (pregl. 1, 2 in 3) so prikazane v preglednici 4.

The measurement uncertainty of the function of geometrical parameters Δ, phase factor K_Φ and particle d_k for the chosen PDA system (Tables 1, 2 and 3) are presented in Table 4.

Preglednica 4: *Merilna negotovost velikosti kapljic za izbran merilni sistem FDA*
Table 4: *The measurement uncertainty of particle diameter for the chosen PDA system*

Veličina y in deleži Quantity y, percentage	Vpliv x_1 $c_{x_1} = \frac{\partial y}{\partial x_1} u_{x_1}$ Effect of x_1 c_{x_1}	Vpliv x_2 $c_{x_2} = \frac{\partial y}{\partial x_2} u_{x_2}$ Effect of x_2 c_{x_2}	Vpliv x_3 $c_{x_3} = \frac{\partial y}{\partial x_3} u_{x_3}$ Effect of x_3 c_{x_3}	Vpliv x_4 $c_{x_4} = \frac{\partial y}{\partial x_1} u_{x_4}$ Effect of x_4 c_{x_4}	Merilna negotovost Measur. uncer.
Δ	c_θ=-0,531 $\cdot 10^{-4}$	c_ψ=-0,427 $\cdot 10^{-4}$	c_ϕ=0,105 $\cdot 10^{-4}$	$c_{n'} = \simeq 0$	±3,38 %
Deleži: Percentage:	59,3 %	38,4%	2,3%		
K_Φ	c_Δ=-3,38 %	$c_\lambda = \simeq 0$			±3,38 %
Deleži: Percentage:	100 %				
Φ	c_{Φ_1}= 0,07%	c_{Φ_2}= 0,14 %	c_{Φ_3}= 0,04 %	c_{Φ_4}= 0,5 %	±0,53 %
Deleži: Percentage:	1,8 %	7,1 %	0,6 %	90,5 %	
d_k	c_{K_Φ}= -3,38 %	c_Φ= 0,53 %			±3,42 %
Deleži: Percentage:	97,6 %	2,4 %			

V tej preglednici so prikazani tudi vplivi neodvisnih spremenljivk Δ, K_Φ in d_k, oziroma deleži posameznih spremenljivk v odstotkih glede na celotno merilno negotovost spremenljivk.

Na podlagi rezultatov izračuna merilne negotovosti velikosti kapljic, ki so zbrani v preglednici 4, lahko ugotovimo:

– največji vpliv na u_{d_k} ima fazni faktor K_Φ;

– njegov delež na skupno merilno negotovost znaša kar 97,6 %, medtem ko je delež faznega premika samo 2,4 %;

In this table the effects of independent variables Δ, K_Φ and d_k are shown and the contributions of individual variables to the total measurement uncertainties of dependent variables are also calculated and given in percentages.

From the calculated values of the measurement uncertainties presented in Table 4, it can be concluded that:

– the phase factor K_Φ has the largest effect on u_{d_k};

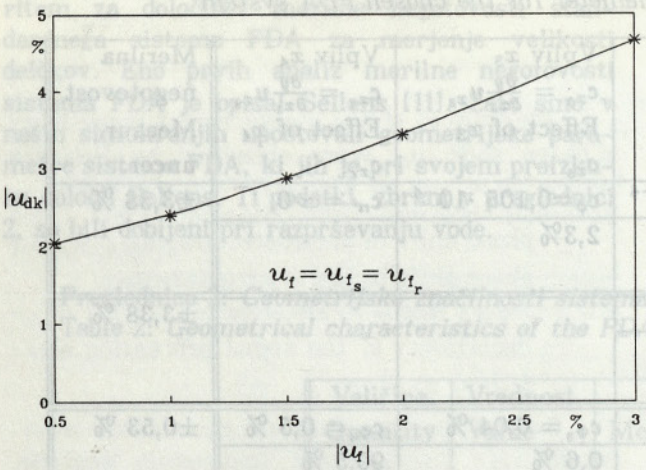
– the contribution of the phase factor to the total measurement uncertainty of the particle diameter is 97,6 %, whereas the contribution of the uncertainty of phase shift is only 2,4 %;

– daleč največji vpliv na celotno merilno negotovost velikosti premera kapljic imata kota Θ in ψ, ker je bil v naših simuliranjih fazni faktor K_Φ odvisen samo od geometrijskih parametrov (lomni količnik vode je dobro znan), zato je $u_{n,} \cong 0$.

Računalniški program omogoča proučevanje posameznih vplivov (geometrijskih parametrov). Pri teh simuliranjih smo upoštevali vhodne podatke, ki so zbrani v preglednicah 1 in 2, vedno pa smo spreminjali samo eno vplivno veličino. Rezultati so zbrani v preglednicah 5 do 7 in prikazani na slikah 4 do 10.

Vpliv merilne negotovosti goriščnih razdalj leč je razviden s slike 4. Ugotovimo lahko, da bo celotna merilna negotovost u_{dk} za različne vrednosti negotovosti u_f manjša od ±3 %, če bo merilna negotovost goriščnih razdalj zbiralnih leč manjša od ±1,7 %.

Celotna merilna negotovost premerov delčkov bo manjša od ±3%, če bo merilna negotovost razdalj med laserskimi žarki za znani sistem FDA manjša od ±0,1 mm. To lahko ugotovimo na podlagi izračunanih vrednosti za različne vrednosti x_s in x_r, prikazane na sliki 5.



Sl. 4. *Vpliv u_f na u_{dk}*
Fig. 4. *The effect of u_f on u_{dk}*

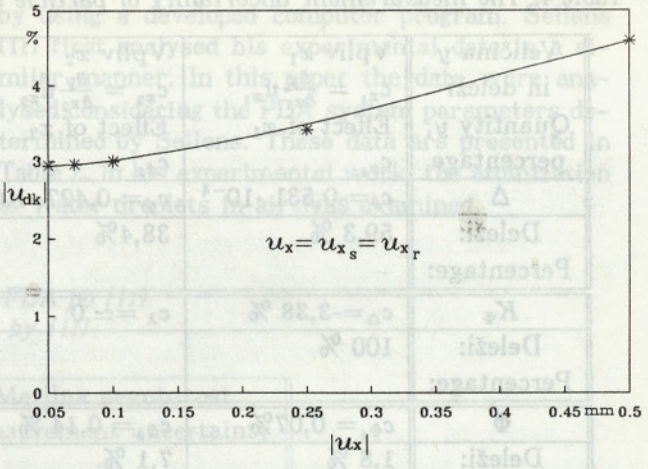
Proučevali smo tudi velikosti kotov Θ in ψ na celotno merilno negotovost velikosti kapljic, tako da smo spreminjali dolžino goriščnih razdalj zbiralnih leč. Za različne vrednosti goriščnih razdalj so izračunane velikosti merilnih prostornin, kotov Θ in ψ, faznih faktorjev in maksimalnih premerov kapljic. Rezultati simuliranj so zbrani v preglednicah 5 in 6 in prikazani na slikah 6 in 7. Velikosti kotov Θ in ψ nimata večjega vpliva na merilno negotovost premerov delčkov. Značilen pa je njun vpliv na fazni faktor K_Φ in s tem tudi na največji premer delčkov d_{kmax}, ki ga je še mogoče zaznati z izbranim sistemom FDA. Na slikah 6 in 7 je prikazana odvisnost največjega premera delčkov, ki se nanašajo na fazni premik 360°, od kotov Θ in ψ. Kot Θ vpliva tudi na velikost merilne prostornine, kar je prav tako razvidno s preglednice 5.

– the uncertainties of the angles Θ and ψ have the largest effect on the total measurement uncertainty of the particle diameter, since in this simulation the phase factor K_Φ depends only on the geometrical parameter (the ratio of the refractive indexes for water is well known), so $u_{n,} \cong 0$.

The computer algorithm enables the examination of the contributions of individual geometric parameters. In these simulations, only one individual variable was varied, while the other input data are taken from Tables 1 and 2. The results of the analysis are collected in Tables 5 to 7 and shown in Figures 4 to 10.

The effect of the measurement uncertainty of the focal length of lenses is evident from Fig. 4. It can be concluded that the total measurement uncertainty u_{dk} will be less than ±3%, if the uncertainties of the focal length are less than ±1,7% for different values of the uncertainty u_f.

The total measurement uncertainty of the particle diameter will be less than ±3%, if the measurement uncertainty of the bea separation lengths between laser beams of the chosen PDA system is less than ±0,1 mm. This conclusion can be made on the basis of the calculated values for different values x_S and x_r. Values are shown in Figure 5.



Sl. 5. *Vpliv u_x na u_{dk}*
Fig. 5. *The effect of u_x on u_{dk}*

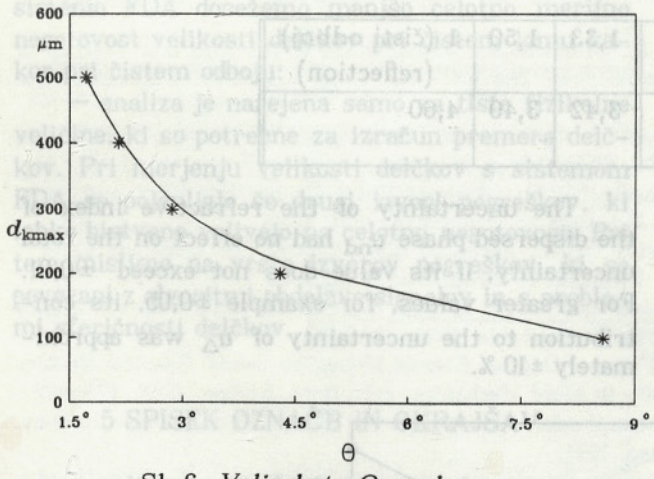
The effect for angles Θ and ψ on the total uncertainty of the particle diameter, with respect to the different focal lengths, were also examined. The calculated values of the size of measuring volume, angles Θ and ψ, phase factor and maximum particle diameter for different values of focal lengths are collected in Tables 5 and 6 and shown in Figures. 6 and 7. Contribution of the angles Θ and ψ to the total measurement uncertainty of the particle diameter is low. Angles have a significant effect on the phase factor K_Φ and on the maximum particle diameter d_{kmax}, which can be measured by the chosen PDA system. The dependency of maximum particle diameters which refer to a phase shift of 360° from angles Θ and ψ is presented in Figs. 6 and 7. The angle Θ has also an effect on the size of the measuring volume, which is evident from Table 5.

Preglednica 5: *Vpliv goriščne razdalje f_s zbiralne oddajne leče*
Table 5: *The effect of the focal length f_s of a collecting sending lens*

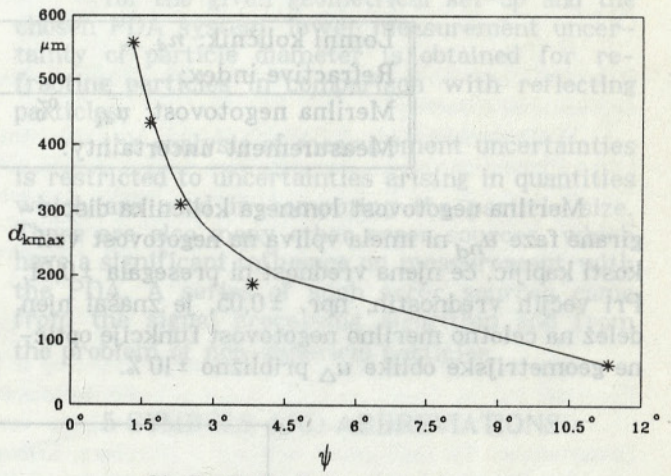
Goriščna razdalja: f_s mm Focal length:	100	200	300	400	500
Prostornina MV: V_m mm^3 Size of MV:	0,003	0,044	0,222	0,703	1,715
Kot: θ ° Angle:	8,58	4,30	2,86	2,15	1,72
Fazni faktor: K_Φ °/μm Phase factor:	-3,59	-1,8	-1,2	-0,9	-0,72
Maks. premer: d_{kmax} μm Max. diameter:	100	200	300	400	500

Preglednica 6: *Vpliv goriščne razdalje f_r zbiralne sprejemne leče*
Table 6: *The effect of the focal length f_r of a collecting receiving lens*

Goriščna razdalja: f_r mm Focal length:	100	300	500	700	900
Kot: ψ ° Angle:	11,31	3,81	2,29	1,64	1,27
Fazni faktor: K_Φ °/μm Phase factor:	-5,69	-1,93	-1,16	-0,83	-0,65
Maks. premer: d_{kmax} μm Max. diameter:	63	186	310	433	557



Sl. 6. *Vpliv kota Θ na d_{kmax}*
Fig. 6. *The effect of angle Θ on d_{kmax}*



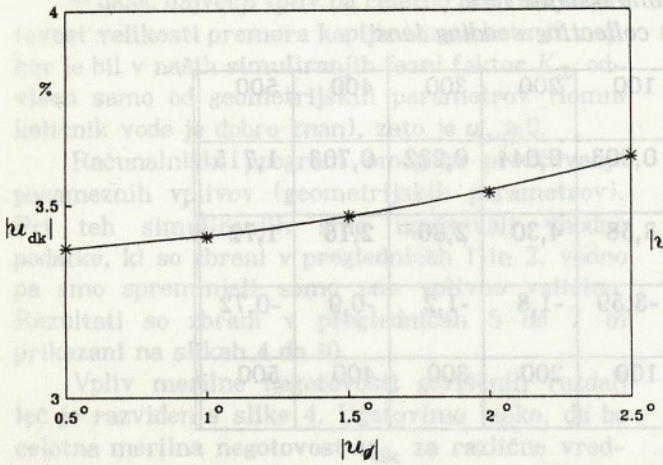
Sl. 7. *Vpliv kota ψ na d_{kmax}*
Fig. 7. *The effect of angle ψ on d_{kmax}*

S slik 8 in 9 lahko ugotovimo, da imata velikost kota Φ in njegova negotovost u_Φ majhen vpliv na merilno negotovost velikosti kapljic. Če so vrednosti kota Φ med 30° in 70°, ne moremo pretirano izboljšati ali poslabšati celotne merilne negotovosti. Natančneje ko bomo izmerili kot Φ, manjša bo celotna negotovost premerov delčkov.

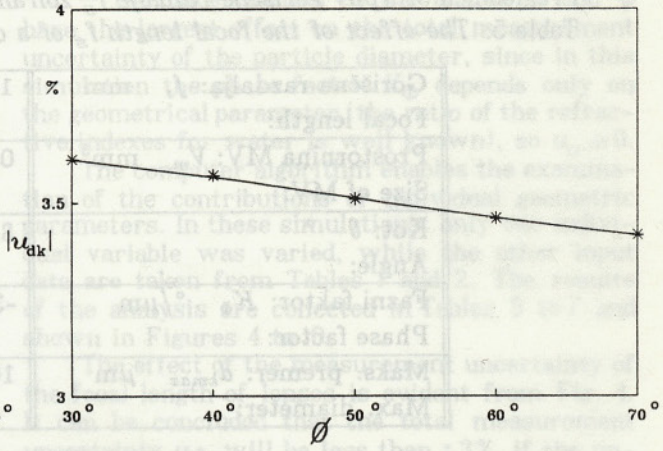
Analizirali smo tudi vpliv merilne negotovosti valovne dolžine laserskega žarka, ki pa nima večjega vpliva na celotno merilno negotovost glede na druge vplive. Vrednosti u_λ smo spreminjali od ± 0,05 nm do ±1 nm.

Figures 8 and 9 indicate that the value of Φ and uncertainty u_Φ have a minor effect on the measurement uncertainty of droplet size. The total uncertainty can not be made considerably better or worse, if the angle Φ is between 30° and 70°. The total uncertainty of particle diameter can decrease, if the angle Φ is measured with higher accuracy.

The effect of the uncertainty of the laser wavelength u_λ, which varies from ±0,05 nm to ±1 nm, was also examined. This effect can be neglected in comparison with the other influences.



Sl. 8. *Vpliv* u_ϕ *na* u_{dk}
Fig. 8. *The effect of* u_ϕ *on* u_{dk}



Sl. 9. *Vpliv kota* Ø *na* u_{dk}
Fig. 9. *The effect of the angle* Ø *on* u_{dk}

Proučevali smo tudi vpliv lomnih količnikov Rezultati so zbrani v preglednici 7. Celotna merilna negotovost premerov delčkov bo manjša, če bo razmerje lomnih količnikov večje. Opazimo tudi, da je za isto geometrijsko obliko sistema FDA negotovost velikosti delčkov pri čistem odboju večja kakor pa pri čistem lomu.

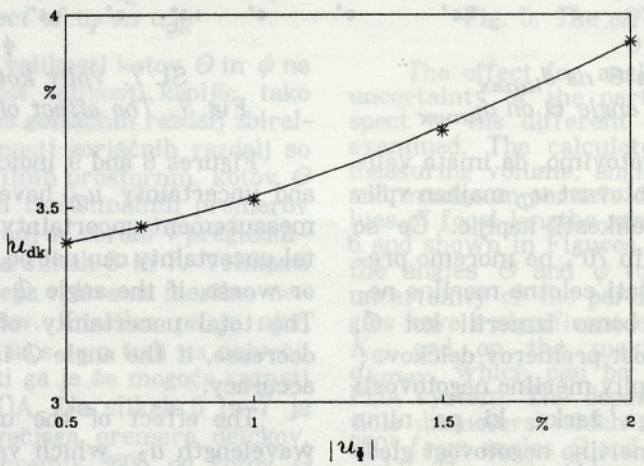
Table 7 shows that the total uncertainty of particle diameter decreased, if the ratio of the refraction index is increased. The measurement uncertainty of particle diameter for the same geometry of PDA system in case of dominant reflection is greater than in a situation where refraction is dominant.

Preglednica 7: *Vpliv velikosti lomnih količnikov*
Table 7: *The effect of refractive indexes*

Lomni količnik: n_d Refractive index:	1,33	1,50	1 (čisti odboj) (reflection)
Merilna negotovost: u_{d_k} % Measurement uncertainty:	3,42	3,40	4,60

Merilna negotovost lomnega količnika dispergirane faze u_{nd} ni imela vpliva na negotovost velikosti kapljic, če njena vrednost ni presegala ±0,01. Pri večjih vrednostih, npr. ±0,05, je znašal njen delež na celotno merilno negotovost funkcije optične geometrijske oblike u_Δ približno ±10 %.

The uncertainty of the refractive index of the dispersed phase u_{nd} had no effect on the total uncertainty, if its value does not exceed ±0,01. For greater values, for example ±0,05, its contribution to the uncertainty of u_Δ was approximately ±10 %.



Sl. 10. *Vpliv* u_Φ *na* u_{dk}
Fig. 10. *The effect of* u_Φ *on* u_{dk}

Prav tako smo analizirali vpliv merilne negotovosti faznega premika Φ. Merilno negotovost smo spreminjali v mejah od ±0,5 % do ±2 %. Njen vpliv postane značilen, če je u_Φ večja od ±1 %. Njen odstotni delež na celotno merilno negotovost premera delčkov je manjši od ±10%, če je u_Φ manjša od ±1%. Izračunane vrednosti so prikazane na sliki 10.

4 SKLEP

Na podlagi opisanega algoritma in opravljene analize lahko povzamemo:

– analiza, ki izhaja iz poenostavljene prenosne funkcije sistema FDA za sferične delčke, se odlično ujema z numeričnim izračunom sipanja delcev po Mieovi teoriji;

– poenostavljen algoritem merilne negotovosti sistema FDA je lahko koristen pripomoček pri izbiri in nastavitvi oddajne in sprejemne optike;

– na celotno merilno negotovost velikosti delčkov (premerov) imata največji vpliv merilni negotovosti kotov med žarki oddajne in sprejemne optike Θ in ψ, ki sta odvisna od goriščnih razdalj zbiralnih leč in medsebojnih razdalj laserskih žarkov;

– za znano geometrijsko obliko in nastavitev sistema FDA dosežemo manjšo celotno merilno negotovost velikosti delčkov pri čistem lomu kakor pri čistem odboju:

– analiza je narejena samo za tiste fizikalne veličine, ki so potrebne za izračun premera delčkov. Pri merjenju velikosti delčkov s sistemom FDA se pojavljajo še drugi izvori pogreškov, ki lahko bistveno vplivajo na celotno negotovost. Pri tem mislimo na vrsto izvorov pogreškov, ki so povezani z algoritmi obdelave signalov in s problemi sferičnosti delčkov.

5 SPISEK OZNAČB IN OKRAJŠAV

c_{x_i} – vpliv spremenljivke x_i na celotno negotovost u_y.
D_e – premer laserskega žarka,
d_e – premer MV,
d_k – premer delčka,
f_s – goriščna razdalja oddajne leče,
f_r – goriščna razdalja sprejemne leče,
f_D – Dopplerjeva frekvenca,
K_Φ – fazni faktor,
l_m – dolžina MV,
MP – merilna prostornina,
N – število interferenčnih obročev v MV,
n_c – lomni količnik zvezne faze,
n_d – lomni količnik dispergirane tekoče faze,
n' – razmerje lomnih količnikov,

The contribution of the measurement uncertainty of the phase shift Φ was also analysed. The measurement uncertainty is varied from ±0,5% to ±2%. The contribution of u_Φ becomes characteristic if u_Φ has a value greater than ±1 %. Its contribution to the total uncertainty of the particle diameter is less than ±10 %, if u_Φ is smaller than ±1%. Calculated values are presented in Fig. 10.

4 CONCLUSION

From the obtained values and described algorithm it can be concluded:

– the analysis, proceeding from a simplified algebraic formula for a PDA system for a spherical particle, is in excellent agreement with the results obtained on the basis of the Mie scattering theory;

– a simplified algorithm of measurement uncertainty of the PDA system can be a useful tool to choose and set-up a receiving and sending optical system;

– the measurement uncertainties of sending and receiving optics angles Θ and ψ, which depend on the focal length of the collecting lenses and the separation lengths between laser beams have the greatest effect on the total measurement uncertainty of the particle size (diameter);

– for the given geometrical set-up and the chosen PDA system, lower measurement uncertainty of particle diameter is obtained for refracting particles in comparison with reflecting particles;

– the analysis of measurement uncertainties is restricted to uncertainties arising in quantities which are used in computing the particle size. There are also many other error sources, which have a significant influence on measurement with the PDA. A series of such error sources came from the signal processing algorithm and from the problem of non-spherical particles.

5 SYMBOLS AND ABBREVIATIONS

c_{x_i} – effects of variable x_i on total uncertainty u_y,
D_e – laser beam diameter,
d_e – MV diameter,
d_k – particle diameter,
f_s – focal length of the sending lens,
f_r – focal lenght of the receiving lens,
f_D – Doppler frequency,
K_Φ – phase factor,
l_m – MV length,
MP – measuring control volume,
N – number of fringes in MV
n_c – refractive index of the continuous phase,
n_d – refractive index of the dispersed liquid phase,
n' – ratio between the refraction indexes,

u – merilna negotovost,
V_m – prostornina MV,
x_i – neposredno merjena veličina,
x_m – razmik med ravninami,
x_r – razdalja med žarki oddajne optike
x_s – razdalja med žarki sprejemne optike,
y – širina MV,
z – višina MV,
Δ – funkcija geometrijske optike sistema,
$\Delta\tau$ – časovni premik,
Θ – kot med žarki oddajne optike,
λ – valovna dolžina,
$\emptyset$ – dvižni kot,
Φ – fazni odmik,
ψ – kot med žarki sprejemne optike.

u – measurement uncertainty,
V_m – MV volume,
x_i – independent measured quantity,
x_m – length between fringes,
x_r – receiver separation,
x_s – beam separation,
y – MV width,
z – MV height,
Δ – a function of optical geometry of the system,
$\Delta\tau$ – time delay,
Θ – beam crossing angle,
λ – wavelength,
$\emptyset$ – off-axis angle,
Φ – phase shift,
ψ – receiver elevation angle.

6 LITERATURA
6 REFERENCES

[1] Bajsić, I.–Blagojević, B.: Razpad ploščatega curka, SV (39) 1993/3–4, 75–93.

[2] Bajsić, I.–Blagojević, B.–Pertot, B.: Porazdelitvene funkcije za velikost kapljic in trdnih delcev pri razpršenvanju fluidov in drugih materialov, SV (38) 1992/1–3, 7–18.

[3] Durst, F.–Zare, M.: Laser–Doppler Measurement in Two-Phase Flows. Proc. DDA - Symp. Copenhagen, 1975, 403–429.

[4] Bachalo, W.D.: The Evolution of Particle Size and Velocity Measurement Technology. Proc. 2nd Int. Conf. Laser Anemometry Advances and Applications, Strathclyde, 1987/75–98.

[5] Bathia, J.C.–Domnick, J.–Durst, F.–Tropea, C.: Phase Doppler Anemometry and the Log-Hyperbolic Distribution Applied to Liquid Sprays. Part. and Part. Syst. Charact., (5), 1988, 153–164.

[6] Wriedt, T.: Einfluß der Parameter eines Phasen –Doppler– Anemometrie Prozessors auf die gemessenen Größverteilungen. Technisches Messen (60), 1993, 278–282.

[7] Bauckhage, K.–Flögel, H.H.–Fritsching, U.–Hiller, R.: Simultaneous Measurement of the Size and Velocity of Spherical Metal Particles Using the Phase - Doppler - Method. Proc. 2nd Int. Conf. Laser Anemometry Advances and Applications, Strathclyde, 1987, 347–354.

[8] Sommerfeld, M.: A Reliable Method for Determining the Measurement Volume Size and Particle Mass Fluxes Using Phase-Doppler Anemometry. Exp. in Fluids (13), 1992, 393–404.

[9] Tropea, C.: Principles of Laser Doppler Anemometry (LDA), Advanced Short Course Hot-Wire and Laser Doppler Anemometry. Turboinštitut, Univerza v Ljubljani, Fakulteta za strojništvo, junij 1992.

[10] Tropea, C.: Principles of Phase Doppler Anemometry (PDA). Advanced Short Course Hot-Wire and Laser – Doppler Anemometry. Turboinštitut, Univerza v Ljubljani, Fakulteta za strojništvo, junij 1992.

[11] Sellens, R.W.: Phase - Doppler Measurements Near the Nozzle in Low - Pressure Water Spray. Liquid Particle Size Measurement Techniques, (2), ASTM.STP 1083, Philadelphia, 1990, 193–208.

[12] Domnick, J.–Ertel, H.–Tropea, C.: Processing of Phase - Doppler Signals Using the Cross. Spectral Density Function. 4th Int. Symp. on Applications of Laser Anemometry to Fluid Mechanics, July 11–14, Lisbon, 1988, 473–483.

[13] Domnick, J.: Experimentelle Untersuchung verdampfender Strömungen an einer Querschnittsverengung, Dissertataion, TF Universität Erlangen - Nürnberg, Erlangen, 1991.

[14] Czarske, J.–Hock, F.–Müller, H.: Processing of Phase - Doppler Signals Using the Cross - Spectral Density Function, Technisches Messen (61), 1994/4, 168–182.

[15] Qiu, H.H.–Sommerfeld, M.–Durst, F.: High-Resolution Data Processing for Phase-Doppler Measurements in a Complex Two - Phase Flow. Meas. Sci. Technol., (2), 1991, 455–463.

[16] Oberdank, K.: Laserska Dopplerjeva anemometrija. Zbornik referatov: Kuhljevi dnevi, 1989.

[17] Adrian, R.J.: Laser Velocimetry, Fluid Mechanics Measurement by Goldstein, R.J., Hemisphere, 1988.

[18] INVENT Gmbh: Streu, A Computational Code for the Light Scattering Properties of Spherical Particles. Instruction Manual, September, 1991.

Naslov avtorjev: mag. Bogdan Blagojević, dipl. inž.
doc. dr. Ivan Bajsić, dipl. inž.
Fakulteta za strojništvo
Univerze v Ljubljani
Aškerčeva 6
1000 Ljubljana

Authors' Address: Mag. Bogdan Blagojević, Dipl. Ing.
Doc. Dr. Ivan Bajsić, Dipl. Ing.
Faculty of Mechanical Engineering
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia

Prejeto: 22.5.1996
Received:

Sprejeto: 28.6.1996
Accepted: