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Computational Fluid Dynamics vs. Inverse Dynamics methods to determine passive drag in two breaststroke glide positions

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Abstract

Computational fluid dynamics (CFD) plays an important role to quantify, understand and "observe" the water movements around the human body and its effects on drag (D). We aimed to investigate the flow effects around the swimmer and to compare the drag and drag coefficient (C_D) values obtained from experiments (using cable velocimetry in a swimming pool) with those of CFD simulations for the two ventral gliding positions assumed during the breaststroke underwater cycle (with shoulders flexed and upper limbs extended above the head - GP1; with shoulders in neutral position and upper limbs extended along the trunk - GP2). Six well-trained breaststroke male swimmers (with reasonable homogeneity of body characteristics) participated in the experimental tests; afterwards a 3D swimmer model was created to fit within the limits of the sample body size profile. The standard k-ε turbulent model was used to simulate the fluid flow around the swimmer model. Velocity ranged from 1.30 to 1.70m/s for GP1 and 1.10 to 1.50m/s for GP2. Values found for GP1 and GP2 were lower for CFD than experimental ones. Nevertheless, both CFD and experimental drag/drag coefficient values displayed a tendency to jointly increase/decrease with velocity, except for GP2 C_D where CFD and experimental values display opposite tendencies. Results suggest that CFD values obtained by single model approaches should be considered with caution due to small body shape and dimension differences to real swimmers. For better accuracy of CFD studies, realistic individual 3D models of swimmers are required, and specific kinematics respected.

Introduction

Swimming performance is determined by the combined effect of propulsion, drag and skill (Chatard et al., 1990a; D'Acquisto et al., 1988). Chatard et al. (1990b) indicated passive drag as a reasonable predictor of swimming performance especially during the underwater glide phases of the starts and turns. These phases are an important component of the overall swimming during short distance events. Indeed, the total swimming event time can be divided in start, swim, turn and finish partial times (Haljand & Saagpakk, 1984), having the starts and turns a significant importance (Guimarães & Hay, 1985; Vilas-Boas & Fernandes, 2003) to reduce the time race. For the particular case of the 200m breaststroke event the start might be responsible for 0.5 to ~11% of the total time and the turns for ~39% (Tayer & Hay, 1984). Lyttle et al. (1998), conducted a race analysis, dividing the start section in four phases: leave the block, flight, underwater and above water phases. Complementarily, in breaststroke events, the underwater phase can be divided into four phases (Counsilman, 1986; Maglisho, 2003): (i) ventral position with upper limbs extended above the head and shoulder flexed, with lower limbs together (first gliding position, GP1); (ii) upper limbs action; (iii) ventral position with upper limbs extended along the trunk with lower limbs stretch and together (second gliding position, GP2); and (iv) recovery phase followed by the lower limbs action toward the surface.

In these two gliding positions drag and drag coefficient was only compared by Vilas-Boas et al. (2010) at a common mean velocity of 1.37m/s using inverse dynamics and an analytic/experimental approach based on acceleration and inertia. Other drag gliding related studies were mostly either experimental or numerical, using towing devices (Kolmogorov et al., 1997; Lyttle et al., 2000; Toussaint, 2004) or CFD simulations (Bixler, 2007; Marinho et al., 2009, 2011; Sato and Hino, 2010; Costa et al.,2011, Popa et al., 2011). Experimental approaches may be affected by several drawbacks, both related to the experimental setup and the ability of the swimmer to maintain a stable gliding position throughout time (Bixler et al., 2007). On the other hand, computer simulations seem to rely on the appropriateness of the models and assumptions. Most of the CFD studies in swimming using non-realistic (geometric shapes), quasi-realistic (human body or segment shapes artificially created) and realistic (3D image of real body or segment) models, try to generalize findings to the overall swimmers population. Nevertheless, a question remains: are the numerical conclusions, even if extracted from realistic or quasi-realistic models, able to be generalised, disregarding small differences in body dimensions and shape? Nowadays, with the accessibility of 3D body scanners, CFD related researchers tend to favour realistic and personalised models to test the effects of detailed changes (e.g. in swimsuits). The rationale for this tendency seems mostly determined by scientific believes than by scientific facts as, to the best of our knowledge, no previous studies have analysed the issue above.

Our purpose was to analyse whether passive drag values obtained during GP1 and GP2 may be accurately predicted through CFD. A quasi-realistic model with marginally coherent body dimensions was used throughout a range of ecologically-based selected velocities. It was hypothesised that the lack of personalised models and specific gliding kinematics may compromise the validity of the model results. In addition, we also aimed to compare the drag and C_D values of either GP.

Methods

Experimental Approach

Six well-trained male breaststroke swimmers volunteered to participate and freely signed a written informed consent. The study was approved by the host institution´s ethical committee. Testing sessions were conducted in a 25m pool, 1.90m deep, with water temperature maintained at 27.5ºC ± 0.5ºC. The characteristics of the sample are presented in Table 1. The body cross sectional area was determined through planimetry, using scaled photographs of the subjects, as described in (Vilas-Boas et al., 2010).

The drag was assessed using inverse dynamics based upon inertia and acceleration, obtained through numerical differentiating of the velocity to time (v(t)) curve of each glide phase, acquired by a swim-meter (Swimsensor, Porto University, Portugal; for methodological details see Vilas-Boas et al., 2010). The accuracy of this swim-meter was previously tested for swimming speed fluctuation patterns presenting mean ± SD correlation coefficient values of 0.96±0.028 for hip vs. image-based hip kinematics, and 0.88±0.053 for hip vs. centre of mass (CM) kinematics (Lima et al., 2006). Each swimmer performed three repetitions of the breaststroke underwater cycle at maximal intensity, with a 2min rest interval between trials. During data processing, v(t) curve of each swimmer's best trial was chosen (trial with the better definition of the different gliding phases and with lower noise). It was filtered with a 3Hz low-pass 4th order Butterworth filter and then numerically differentiated to obtain acceleration (a(t)). The velocities common to all swimmers were: 1.3, 1.4, 1.5, 1.6, 1.7m/s in GP1 and 1.1, 1.2, 1.3, 1.4, 1.5m/s in GP2.

The drag force was computed using the following expression:

$$D = m\,a \qquad (1)$$

where m is the swimmer's body mass and a the swimmer's acceleration.

To quantify the drag coefficient, the following equation was used:

$$C_D = \frac{2D}{\rho S v^2} \qquad (2)$$

Where, C_D is the drag coefficient, ρ the water density (998.2kg/m^3), S the swimmer's body cross sectional area while D and v are as referred.

Computational Fluid Dynamics Approach

Three-dimensional model

To obtain the surface geometry of the human body, a 3D body scan of a swimmer within the limits of the sample body size profile was performed. Then, it was further processed in AutoCAD® and GAMBIT® (Figure 1) to finally generate the meshed model, which was imported into FLUENT® (ANSYS®, Hanover, USA) for performing CFD simulations.

CFD Simulation

The CFD simulation was performed on the model fixed in a horizontal position at an angle of attack of 0º (defined between a horizontal line and a line drawn from the tip of the middle finger or the vertex head, depending on the upper limbs position, to the ankle joint). The height of model was 1.87m, with head, chest and waist circumferences of 0.57, 1.04 and 0.85m, respectively. The swimmer model was positioned at a depth of 0.90m from the water surface in rectangular computational domains with 2.50m width, 1.80m depth and 8.00m in pool length for GP1 and 7.55m for GP2. The remaining model and water conditions are presented in Table 2.

Boundary Conditions

The simulation was carried out on the meshed model, consisting of 1 million tetrahedral cells, with a uniform velocity (U_0 – with only x-coordinate direction) equal to 1.30, 1.40, 1.50, 1.60 and 1.70m/s for GP1 and 1.10, 1.20, 1.30, 1.40 and 1.50m/s for GP2. It was ensured that the CFD model would provide accurate results, particularly by refining the grid in areas of high velocity and pressure gradients.

CFD Model

The numerical simulation of the fluid flow around the 3D swimmer model was implemented into the ANSYS FLUENT® CFD software. As the current study focused on the global drag and not on the flow turbulences, the closure problem of the turbulence modeling was solved using k–ε model with appropriate wall functions (Bixler & Riewald, 2002; Rouboa et al., 2006). This model is extensively applied and validated in various industrial applications (Raiesi, 2011) and is realistic for free-shear layer flows with relatively small pressure gradients (Bardina, 1997). A second order discretization scheme was applied to limit numerical dissipation. The convergence criterion of 10^{-6} has proved sufficient for this study.

Statistical Analysis

To check the level of agreement between the values of passive drag by experimental and CFD methods we used the Bland & Altman (1996) plots with Confidence Index (CI) of 95%. All statistical tests were made in MedCalc 9.3.2.0 (MedCalc Software, Mariakerke, Belgium).

Results

The results obtained in GP1 and GP2 for both drag and C_D values are presented in Figure 2.

By using the above-referred methods, data evidences that drag increases with velocity in both glide positions, displaying a very strong correlation between both drag determination methods in GP1 (R= 0.95, p= 0.01) and strong correlation for GP2 (R= 0.87, p= 0.05). Drag values derived experimentally were higher than those obtained from the CFD method. The difference of the drag values between both methods was approximately constant for the whole range of studied velocities (Figures 3a and 4a). All points are dispersed within the limits of ±1.96SD from the mean (Figures 3b and 4b).

For GP1 the C_D results showed a very strong correlation between both methods (R = 0.93, p = 0.018, Figure 3c). All points are dispersed within the limits of ±1.96SD around the mean (Figure 3d) and the difference between these limits is 0.10. However, for GP2, the correlation between methods is negative and moderate (Figure 4c) and showed a difference between the ±1.96SD limits around mean of 0.67 (Figure 4d). This difference is not acceptable from a biomechanical point of view. It is possible to conclude that the methods should not be considered consistent for C_D results in GP2.

Discussion

The aim of the present study was to compare experimental and CFD methods by the analysis of drag and C_D for GP1 and GP2 of the breaststroke underwater cycle, verifying if a single-model CFD simulation allows to generalize the results to a sample of swimmers. In this work was found a good and positive correlation of drag and C_D values between numerical and experimental methods for GP1. In GP2 we observed the same trend for drag, however C_D values were not positively correlated between methods. This difference can be attributed to constraints during the experiment, measurement errors and/or errors in the CFD model characteristics. In the current study, the head position and the shoulders elevation varied during the experimental tests, while, the CFD model maintained the best streamline position throughout. It is well known that drag depends on body position (e.g. Karpovich, 1933; Marinho et al. 2009; Vilas-Boas et al., 2010), especially the position of the limbs and the head (Zaidi et al., 2008, Popa et al., 2011).

The drag underestimation produced by CFD is most likely due to a lack of precise control of the swimmer's body position during experimental situations. The current study presents similar variation characteristics as observed in past studies (Lima et al., 2006;

Vilas-Boas et al., 2010; Costa et al., 2010, Marinho et al., 2009-2011). Also, the swimmer had to position himself in a more restrictive position in GP2 than in GP1, leading to areas of high pressure gradients, particularly close to the head and shoulders (Marinho et al., 2009; Costa et al., 2010; Vilas-Boas et al. 2010; Costa et al., 2011).

Nevertheless, since the difference between drag determination by the two methods is approximately constant (as shown by the similar line slopes in Figure 2a and 2c) the CFD results can still be used to predict passive drag values for a given swimmer at a given velocity by adding a suitable constant (16.6N for GP1, Figure 3b; 15.6N for GP2, Figure 4b).

For C_D values the predictive potential of CFD single model approach is not adequate, particularly for GP2. This may be caused mainly by the referred “misalignment” of the swimmers and consequent change in S which directly implicates on the computation of C_D (Eq. 2) while the CFD swimmer model is always the same, although being compared against several swimmers.

Therefore, we conclude that the one to one correlation of swimmer body position during experiment and CFD simulations is essential. In particular, for the experimental side, the head, limbs and body alignment affect the angle of attack and the depth of glide. Therefore, to have the CFD simulations as close as possible to the actual experimental conditions, it is necessary: 1) to control the position, alignment and orientation of the swimmer during the experimental situation; 2) or to feed the experimental position and attitude of the swimmer to the CFD simulations which is not straightforward and poses severe constraints.

It is evident from the current study that CFD method might be a good tool choice due to the offered precision, accuracy and flexibility. However, it is necessary to use individualized models and specific kinematics for the simulations.

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Conflict Of Interest Statement

None of the authors of the above manuscript has declared any conflict of interest which may arise from being named as an author on the manuscript at present and in future.

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Tables Legends

Table 1. Characteristics of the sample (mean; n=6).

Table 2. Characteristics for the model surface, turbulence and water.

Tables

			Body cross sectional area (cm^2)	
Age (years old)	**Height (m)**	**Body mass (kg)**	**GP1**	**GP2**
18.2 ± 4.0	1.78 ± 0.09	64.4 ± 11.4	759.95±124.12	814.46±111.23

Table 1. Characteristics of the sample (mean; n=6)

Model's roughness	0	**Water Temperature**	28ºC
Surface model´s viscosity	0.5	**Water Density**	998.2 kg m^{-3}
Turbulence	1%	**Water Viscosity**	0.001 kg m s^{-1}
Scale of turbulence	0.10 m		

Table 2. Characteristics for the model surface, turbulence and water.

Figure Captions

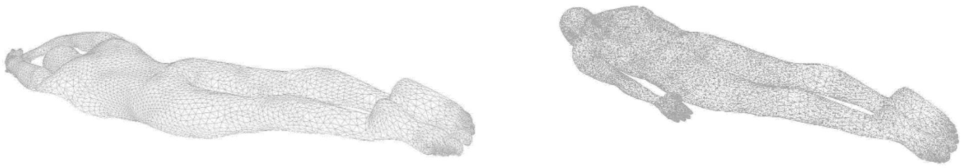
Figure 1: Swimmer's model after its formation through surfacing and meshing software's in two respective glide positions: (a) GP1 (b) GP2.

Figure 2: Drag and drag coefficient values for GP1 (a and b, respectively) and GP2 (c and d, respectively) obtained through experimental method (mean; n= 6) and CFD for all velocities tested.

Figure 3: Correlation between Experimental method and CFD in GP1 for passive drag (a), and drag coefficient values (c) for 1.30, 1.40, 1.50, 1.60 and 1.7m/s flow velocities; Bland & Altman plot: comparing the passive drag (b) and drag coefficient values (d) obtained by inverse dynamic and CFD, in GP1 for all velocities tested.

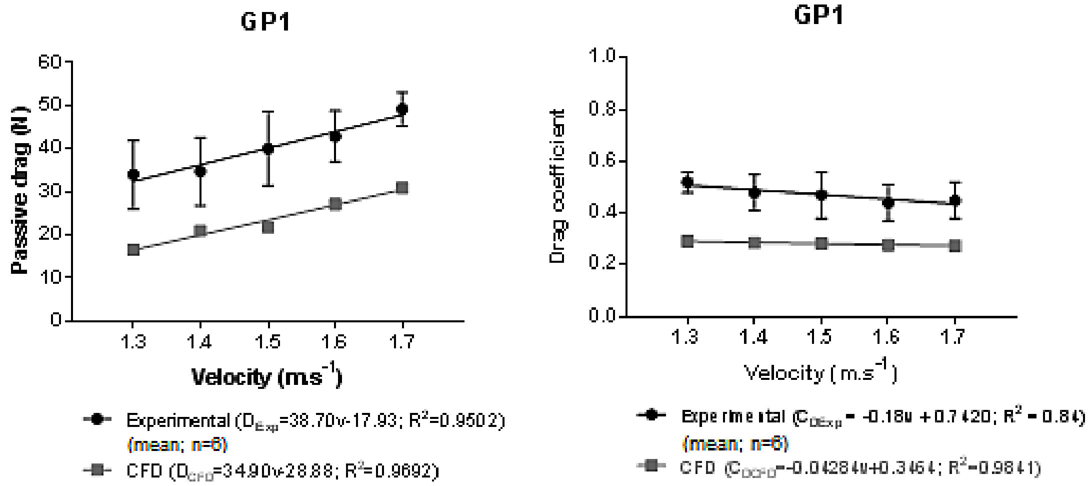
Figure 4: Correlation between Experimental method and CFD in GP2 for passive drag (a) and drag coefficient values (c) for 1.10, 1.20, 1.30, 1.40 and 1.50m/s flow velocities; Bland & Altman plot: comparing the passive drag (b) and drag coefficient values (d) obtained by inverse dynamic and CFD, for GP2 for all velocities tested.

Figures

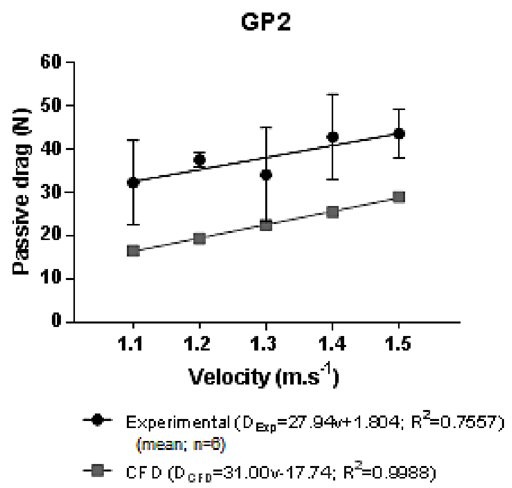


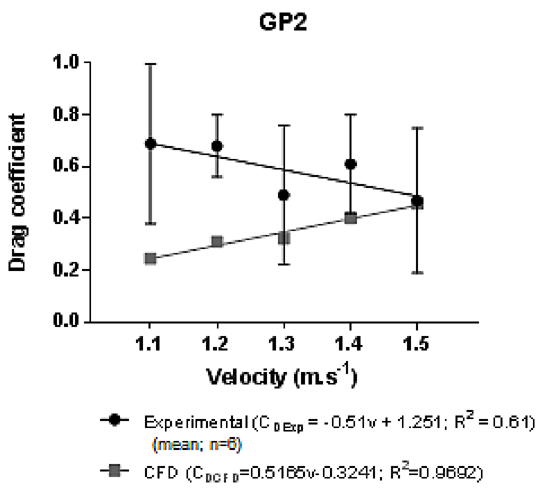
(a) (b)

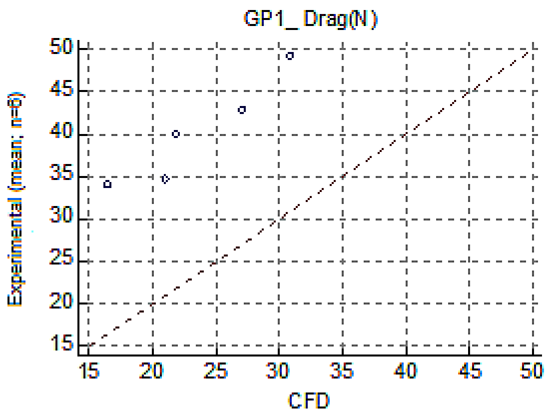
Figure 1



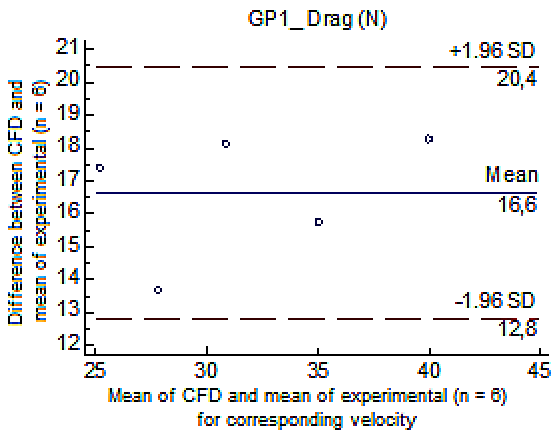
(a) (b)


GP2
Passive drag (N)
Velocity (m.s-1)
Experimental (DExp=27.94v+1.804; R2=0.7557)
(mean; n=6)
CFD (DCFD=31.00v-17.74; R2=0.9988)

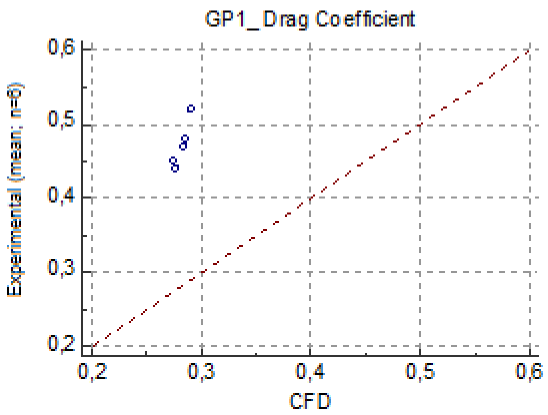

GP2
Drag coefficient
Velocity (m.s-1)
Experimental (CDExp = -0.51v + 1.251; R2 = 0.61)
(mean; n=6)
CFD (CDCFD=0.5165v-0.3241; R2=0.9692)


GP1_ Drag(N)
Experimental (mean; n=6)
CFD

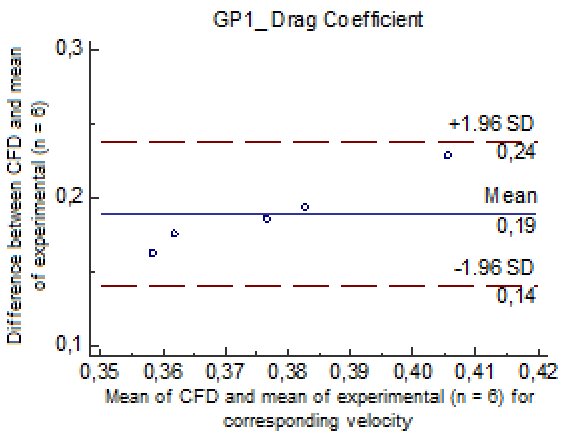
(a)


GP1_ Drag (N)
+1.96 SD
20,4
Mean
16,6
-1.96 SD
12,8
Difference between CFD and mean of experimental (n = 6)
Mean of CFD and mean of experimental (n = 6) for corresponding velocity

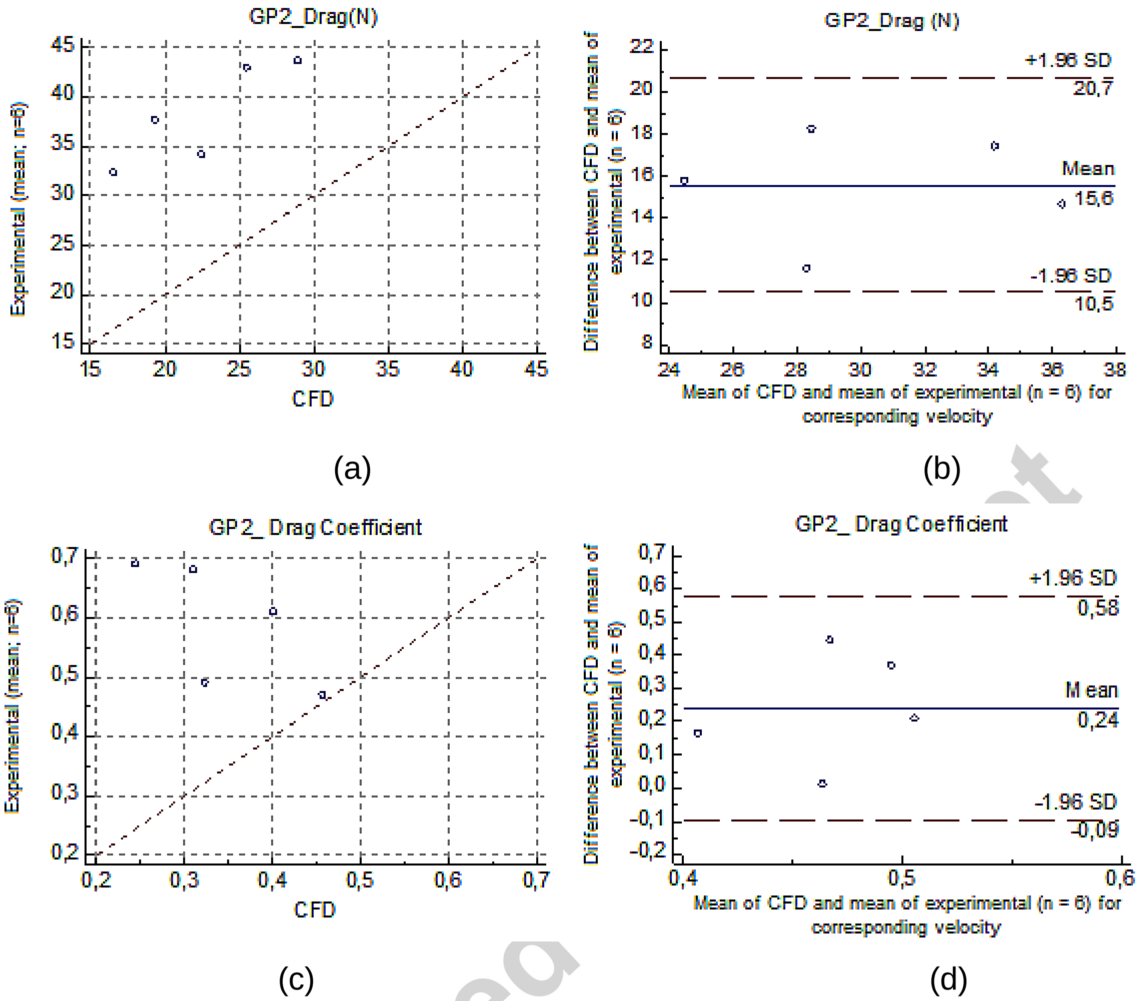
(b)


GP1_ Drag Coefficient
Experimental (mean; n=6)
CFD

(c)


GP1_ Drag Coefficient
+1.96 SD
0,24
Mean
0,19
-1.96 SD
0,14
Difference between CFD and mean of experimental (n = 6)
Mean of CFD and mean of experimental (n = 6) for corresponding velocity

(d)



GP2_Drag(N)
Experimental (mean; n=6)
CFD
GP2_Drag (N)
Difference between CFD and mean of experimental (n = 6)
+1.96 SD
20,7
Mean
15,6
-1.96 SD
10,5
Mean of CFD and mean of experimental (n = 6) for corresponding velocity
(a)
(b)
GP2_ Drag Coefficient
Experimental (mean; n=6)
CFD
GP2_ Drag Coefficient
Difference between CFD and mean of experimental (n = 6)
+1.96 SD
0,58
Mean
0,24
-1.96 SD
-0,09
Mean of CFD and mean of experimental (n = 6) for corresponding velocity
(c)
(d)

Figure 4