HYDROMECHANICS FOR DEVELOPMENT OF SPRINT CANOES FOR THE OLYMPIC GAMES

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ABSTRACT

The current paper focuses on evolution of hull form of sprint canoes from the Olympic Games in Berlin (1936) to the Olympic Games in Beijing (2008) and the influence of hydrodynamics aspects on design of sprint canoes.

The paper describes the process of the Olympic canoes design and optimization, carried out by the Ship Design and Research Centre (CTO, CTO S.A.) in Gdansk and the Plastex Composite PPH (Plastex) in Warsaw –the renowned manufacturer of sport boats. The existing canoes (used as a starting point) and the newly designed ones were analysed with the use of Computational Fluid Dynamics (CFD) methods, simplified potential methods and tested experimentally.

The paper concludes the final results during Olympic Games competitions.

HYDRODYNAMICS OF SPRINT CANOES AS A SEMI –DISPLACEMENT SHIPS

The canoes sprint started to exist on the Olympic Games program in Berlin in 1936. The kayaks and sprint canoes shapes were changing and those changes could be divided to three periods – eras:

- In the first period there were formed the regulations and principles from the ICF formation to the Olympic games in London in 1948.
- The era of boats which were made of the wooden plywood, which also could be named Samson's because of the name of main designer.
- In the third period slender boats were made on the base of carbon-fibre composites.

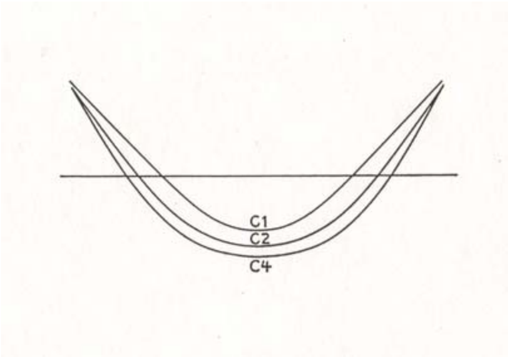
After 1930 in Technischen Hochschule Berlin (THB) the works were carried out on the shapes of the sprint canoes and rowing boats for the Olympic games in Berlin in 1936. Several different projects of boats were designed and tested, what happened in Versuchsanstalt für Wasserbau und Schiffbau (VWS) in Berlin. The elaborated shapes were characteristic for the first era of the Olympic canoe sport - Weitbrecht(1937).

The second era, which started with the gold medal for Karen Hoff in 1948 and ended in 1996 with gold medal for Antonio Rossi, was dominated by the "Struer – like" shapes of kayaks and canoes what is described by Jackson(1995), Lazauskas et.al.(1996, 1997), Rybakowski(2008). In 1988 Ted van Dusen proposed the new kayak's shape and the new technology – the hull made from composites. This modern shape was designed according to the ICF rules (6.2 – the minimum beam limits specified for the different boat categories). Definitely, the second era ended in 1999 when the C1M-Armageddon, the last project of Samson supported by the Danish Maritime Institute (DMI) towing tank tests, could not win with the new Plastex's canoes.

The below table and the figure present the philosophy of the boat shapes developed according to the ICF 6.2 regulations.

Boat category	K1	K2	K4	C1	C2	C4
Beam (minimum) [cm]	51	55	60	75	75	75

Table 1 The ICF 6.2 rule-The limits of beam of the sprint canoes (to be in force to 2003)



Boat category	B_{WL} [mm]	T [mm]	L/B	B/T
C1	382	109	13,61	3,52
C2	477	140	13,63	3,41
C4	533	161	16,88	3,31

Figure 1 (left) Comparison of frames of C1, C2 i C4 boats (Struer)
Table 2 (right) Main factors of canoes shape (Steuer,1980-)

The table 2 is the result of analysing the figure 1. It is precisely shown why the old boats of bigger beams couldn't win with new boats with beams about 32 cm, limited only by human anatomy factors – the intertrochanteric diameter.
The table 3 shows comparison of simple hydromechanics parameters for the model sprint canoes from Berlin (1936) to Athens (2004).

Boat name or symbol	VWS	REGATTA	GAMMA	AMAGEDDON Samson&DMI	STARLIGHT Plastex	OLYMPIA (model 506) Plastex & CTO
Year of design	1936	1952	1987	1999	1998	1999
Boat category	C2/C1	C2/C1	C1	C1	C1	C1
C_B	0,394	-	-	-	0,426	0,482
L/B	7,65	9,61	12,85	14,33	15,61	16,17
B/T	5,23	4,15	3,36	-	2,43	2,57
B_{WL}[m]	0,680	0,540	0,403	0,360	0,331	**0,319**

Table 3.Comparison of selected hydromechanic parameters of the model sprint canoes.

The changes of B_{WL}, L/B, B/T are a good illustration of the boat shapes evolution.
The below table presents the time records published by ICF and towards to them the mean speeds and the non-dimensional factor - Froude number, for the particular boat categories.

Boat Category	**K1W**	**K2W**	**K4W**	**K1M**	**K2M**	**K4M**	**C1M**	**C2M**	**C4M**
L [m]	5,2	6,5	11,0	5,2	6,5	11,0	5,2	6,5	9,0
Time on 500m	01:47,343	01:37,987	01:30,765	01:36,098	01:26,971	*	01:45,614	01:38,270	*
V_{500} [m/s]	4,660	5,102	5,509	5,202	5,747	-	4,734	5,088	-
Fr_{500}	**0,652**	**0,639**	**0,530**	**0,728**	**0,720**	**-**	**0,593**	**0,637**	**-**
Time on 1000m	*	*	03:13,296	03:24,495	03:09,190	02:49,875	03:46,201	03:28,531	03:15,722
V_{1000} [m/s]	-	-	5,173	4,890	5,286	5,886	4,421	4,795	5,109
Fr_{1000}	-	-	**0,498**	**0,684**	**0,661**	**0,567**	**0,471**	**0,510**	**0,544**

Table 4 The time records published by ICF, the mean speed and the Froude number, for the particular boat categories

In the ship theory, Bertram(2000), Faltinsen(2005), the sprint canoes are considered as semi-displacement ships. The Froude numbers, Fr=V/sort(g*L_{WL}), included between 0,471 and 0,728 show that the hydrodynamic parameters of the sprint canoe are located between high speed crafts and planning boats, (see the tables 4 and 5). During the analysis of the flow and drag for such types of hulls the dynamic changes of displacement and trim must be taken into account.

Boat category	**K1M**	**K1W**	**K2M**	**K2W**	**K4M**	**K4W**	**C1M**	**C2M**
∇ [m3]	0,092	0,078	0,181	0,148	0,362	0,291	0,096	0,190
T [m]	0,123	0,110	0,162	0,142	0,170	0,146	0,124	0,170
Lwl [m]	5,199	5,186	6,486	6,474	10,96	10,74	5,157	6,470
Bwl [m]	0,305	0,296	0,382	0,371	0,380	0,370	0,319	0,323
V200 [m/s]	**5,814**	**5,076**	**6,211**	**5,376**	**6,896**	**5,917**	**5,208**	**5,577**
V/sqrt(Lwl)	2,550	2,229	2,439	2,113	2,083	1,806	2,293	2,193
V/sqrt(gDisp^1/3)	2,752	2,469	2,629	2,353	2,604	2,316	2,448	2,342
V500 [m/s]	**5,202**	**4,66**	**5,747**	**5,102**	**6,273**	**5,495**	**4,735**	**5,088**
V/sqrt(Lwl)	2,281	2,046	2,257	2,005	1,895	1,677	2,085	2,000
V/sqrt(gDisp^1/3)	2,462	2,267	2,433	2,233	2,368	2,151	2,225	2,137
V1000 [m/s]	**4,89**	**4,292**	**5,285**	**4,653**	**5,886**	**5,173**	**4,421**	**4,795**
V/sqrt(Lwl)	2,145	1,885	2,075	1,829	1,778	1,578	1,947	1,885
V/sqrt(g*Disp^1/3)	2,314	2,088	2,237	2,036	2,222	2,025	2,078	2,014

V/sqrt(Lwl) **1.5<semi-displacement craft<2.8**
V/sqrt(gDisp^1/3) **V>=High-Speed-Craft**

Table 5 Hydrodynamics parameters of sprint canoes

Before any important competition the shape of the boat and the mass distribution should be taken into consideration. The paddling technique, the distance, the wind and the waves parameters are also indicators, which can not be forgotten.

„LET'S FORGET ABOUT THE MINIMUM BEAM LIMITS" –PLASTEX'S REVOLUTION

The Plastex Composite – Poland has been actively searching ideas for new solutions in the sprint kayaks and canoes production, developing new shapes and hydrodynamic solutions for the boats for many years. The base for all the hull shapes was the Eagle kayak by T. Van Dusen (USA), whose license was bought by Plastex in 1993, along with the right to produce and modify it. First modifications tended towards improving the "paddling ergonomics", which was achieved by the deck modification – introducing the hollows, allowing the competitor, putting the paddle into water closer to the hull's symmetry plane, both in kayaks and canoes. It was also attempted to improve the performance of the boats by reducing their resistance.

10 years after the success of Van Dusen's kayaks during the Olympic Games in Seul (1988) and the World Championship Szeged'98, gold medals in canoe sprint were won by crews using new, composite boats of Plastex Composite– Poland (C1-200 (Doctor), C1-500 (Opalev), C1-1000 (Giles) and C2-1000 (RUS)). The new Plastex boats, announcing the new era in the shapes of sprint canoes, had the narrowest waterlines, which was achieved by highly raised deck in the location where the minimum beam required by ICF rules (75 cm) had to be kept, and monstrously raised front edge of the cockpit, so as to make it the highest part of the deck, according to the rules (see fig.2 and 3). Immediately after this success and before the

Olympic Games in Sydney (2000), Plastex started wide activity tending towards the design of new shapes for boats (both kayaks and canoes) characterized by the minimum resistance.

Figure 2 The canoe of old and new era.

Figure 3 The canoes C1 and C2 STARLIGHT (Plastex, 1999)

The activity included the design of new models basing on the experimental resistance measurements, carried out in the towing tank of the Ship Hydromechanics Centre (a division of the Ship Design and Research Centre, CTO, Gdansk, Poland), providing the hydrodynamical consultation for each new design, and introducing new technologies of manufacturing the boats with the use of composites and carbon fibres

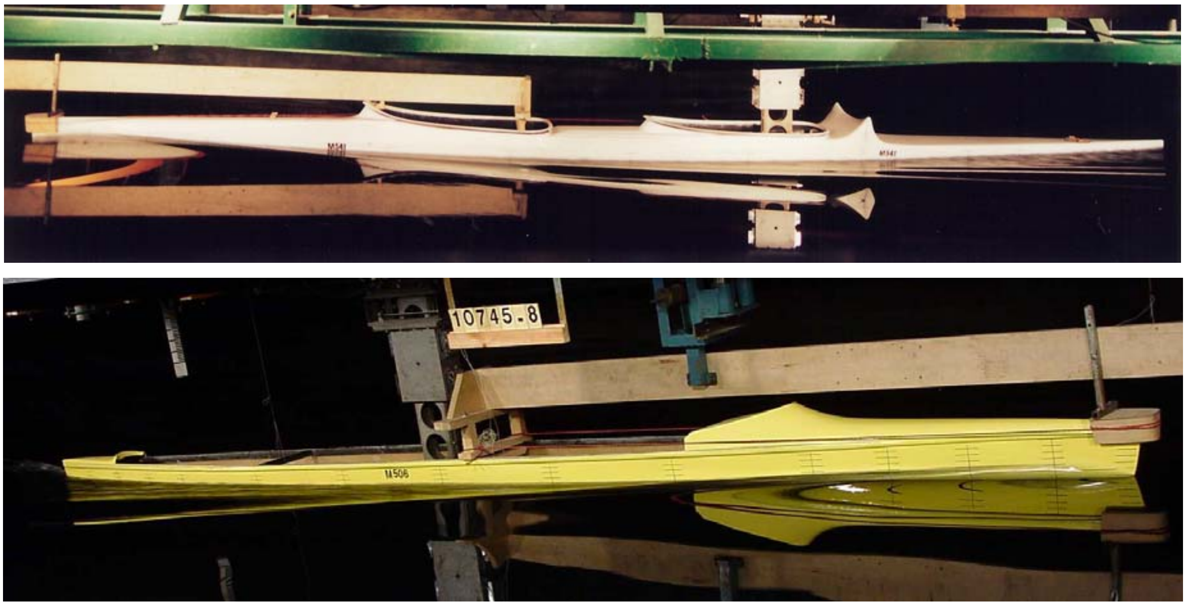


Figure 4 Example of towing tank tests (K2-m541 and C1-m506, CTO, 2000)

In 1999-2000, the wide experimental research was carried out to chose models of kayaks and canoes, supplemented with CFD computations. The shapes of canoes and kayaks underwent the revolution, called „*let’s forget about the minimum beam limits*”, initiated by the main Plastex’s guideline for CTO, concerning the hydrodynamic design of the shapes C1M (model 506) and K2M (model 541). It was the beginning of the era of innovative designs, exceeding the rigid, unimaginative rules. The Plastex boats, designed according to innovative guidelines, where the beam limit was replaced by the anatomical factor – the competitor’s intertrochanteric diameter (*distantia intertrochanterica*) – have dominated the final of the Olympic Games and World Championships of the new Millennium’s first years.

The C1M-OLYMPIA, based on the m506 design, still remains the slenderest sprint boat and allows many competitors winning the highest awards of the World Championships and Olympic Games.

Figure 5 The canoe -C1 OLYMPIA (2003-) (Plastex)

The Plastex canoes of C1 and C2 type (OLYMPIA, OLYMPIA SPRINT, OLYMPIA MAXIMA, DOMINATOR) represent the entire range of shapes, allowing choosing the appropriate boat for the competitor’s characteristics (mass, style of paddling), water region and weather conditions. The appearance of the new Plastex canoe of C4 type in 2003 brought numerous successes in the World Cup and the World Championships. The low and slender hull of this canoe allows it to maximize the paddling efficiency of all the crew. The straight line of the keel allows minimizing the course instability. The uniform distribution of the volume along the hull length and shifting the additional buoyancy to stern considerably reduces the unfavourable dipping of the stern.

The appearance of new boats (both kayaks and canoes) in Plastex’s offer, constructed so as to overcome the strict ICF rules in a tricky way (table 2), and immediate copying of their ideas by other manufacturers, resulted in changing these rules and definitive abandoning the minimum beam requirement in 2003.The regulations changes caused that few sport boats factories produce kayaks with the convex parties on the hull surfaces. The boat control eliminate this problem in the year time, Bugalski for ICF(2004).

NEW LINE OF OLYMPIC KAYAKS –RESULTS OF RESEARCH PROJECT

Before the Beijing Olympic Games appeared the publications abort the research projects, which were developing the new shapes of kayaks: Crotti et al.(2005), Warzecha et al.(2007)…In Spring 2007, Plastex and CTO S.A. began to work on the shape of new line of the sprint canoes for the Olympic Games in Beijing, Bugalski(2008), Bugalski& Kraskowski(2008). The optimization of the new design started with extensive investigation of the existing hull shapes in CTO's model basin, with the principal aim of determining the dependency of the canoe's performance on the basic design parameters and initial trim. Although such experiments provide a large amount of reliable data in a short timescale, they do not always illuminate the physical mechanisms that affect the performance of the hull.

For this reason, the experimental research was widely supported with extensive CFD simulation, which is more suited to a detailed comparison of the influence of flow properties such as the wave elevation and the pressure distribution on the hull for different designs.

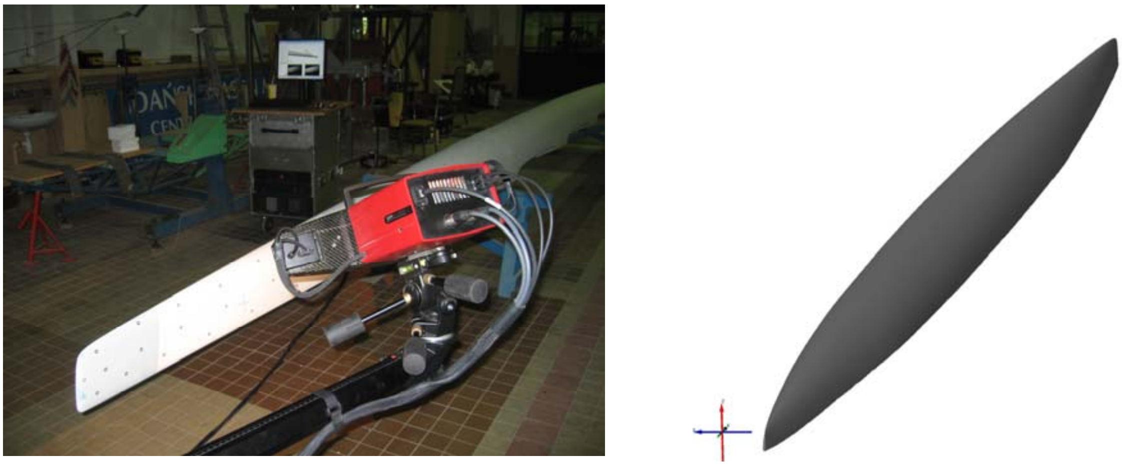


Figure 6 The digital scanning of the hulls, carried out using an ATOS II scanner (CTO S.A., 2007)

The surface models of the existing canoes were obtained by digitally scanning the hulls, carried out using an ATOS II optical scanner and a TRIPOD photogrammetric system provided by GOM GmbH.

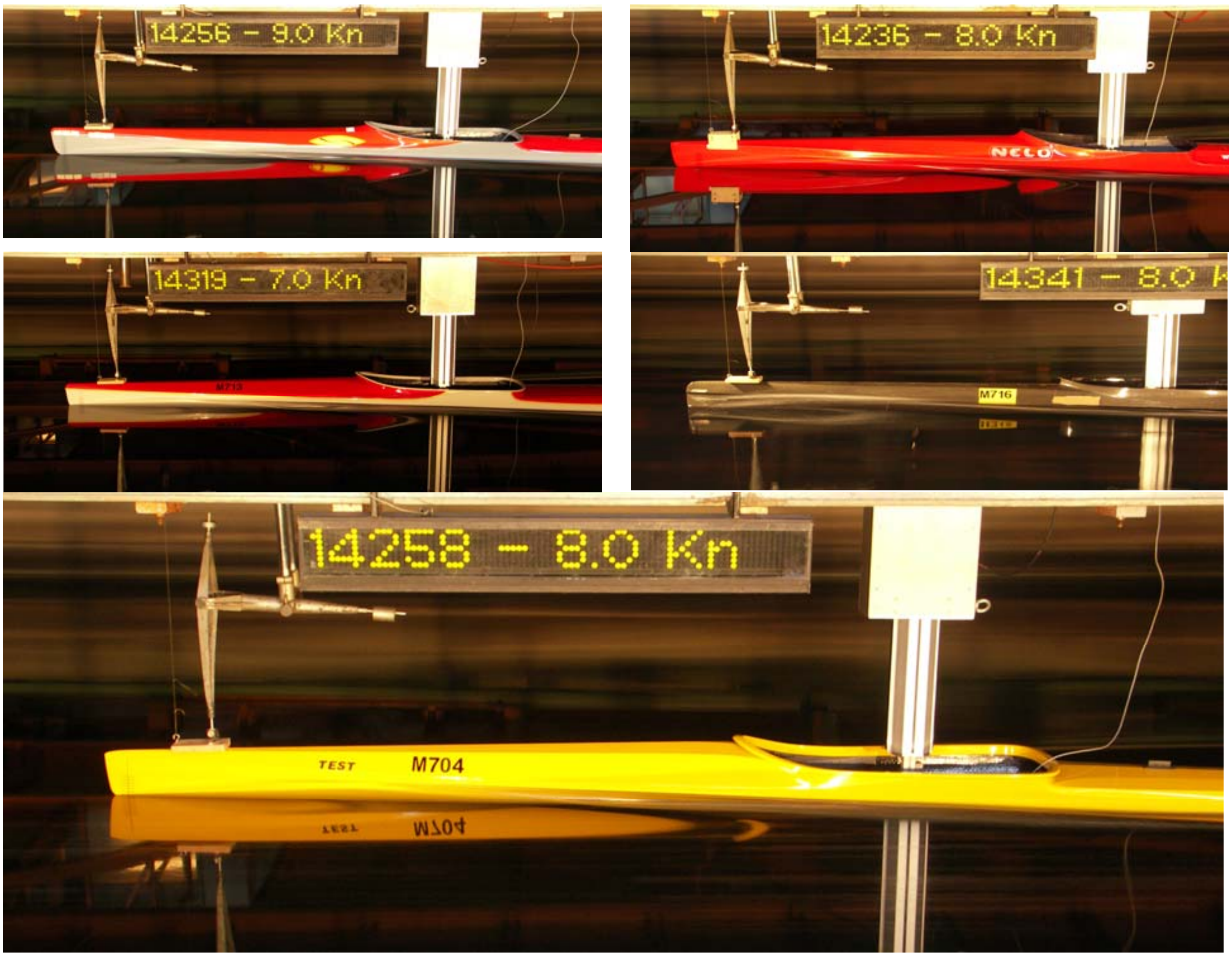


Figure 7 The example of resistance tests of K1, K2, K4 kayaks (CTO S.A., 2007)

Each CFD simulation considered a canoe hull towed at the constant speed through calm water. The computational analyses yielded numerical data, such as the hull resistance, as well as allowing the design team to visualize the flow field around the hulls, thereby helping them identify the mechanisms behind variations in physical performance, e.g. the bow and stern wave height or the wave interaction.

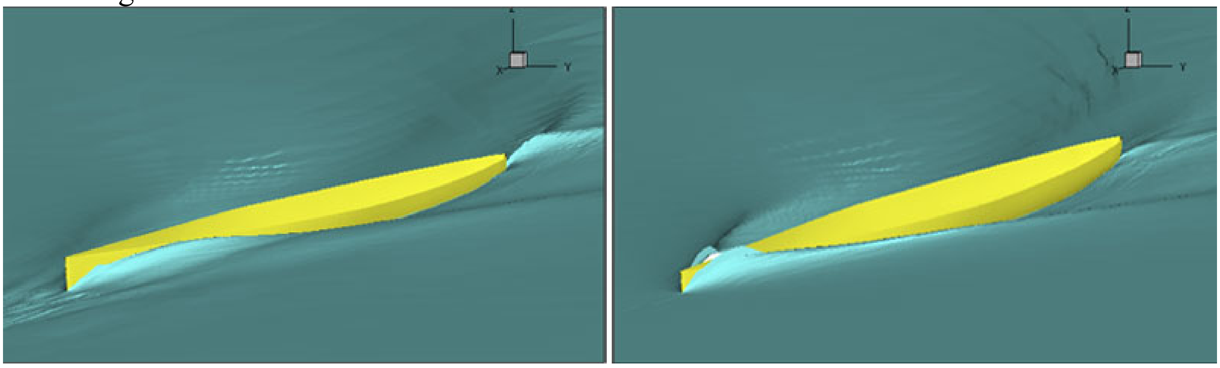


Figure 8 The canoe hull in its static (left) and dynamic position (right) in the flow.

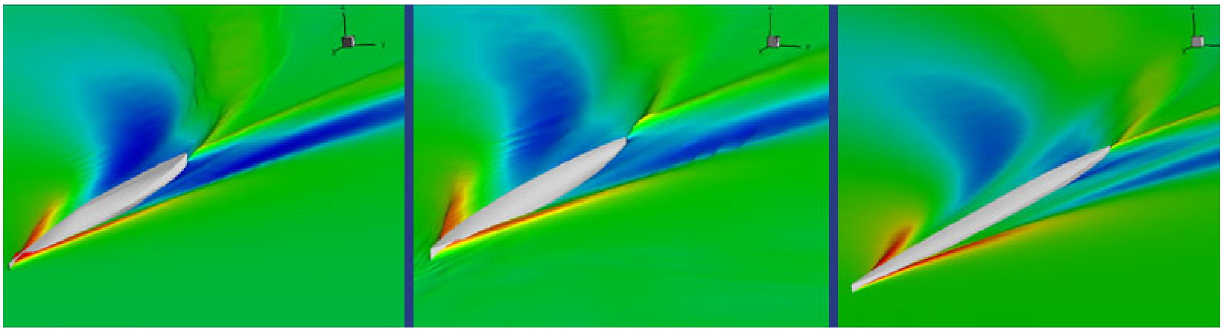


Figure 9 K1, K2 and K4 canoes – free surface elevation.

After testing the existing boats, the best design was chosen based on analysis results and works on new designs began. By implementing CFD into the design process, timescales and costs have been significantly reduced.

The CFD simulations were carried out using the Volume Of Fluid (VOF) model for multiphase flows and the RNG k-epsilon turbulence model using specially constructed 1.5 million cell hexahedral meshes.

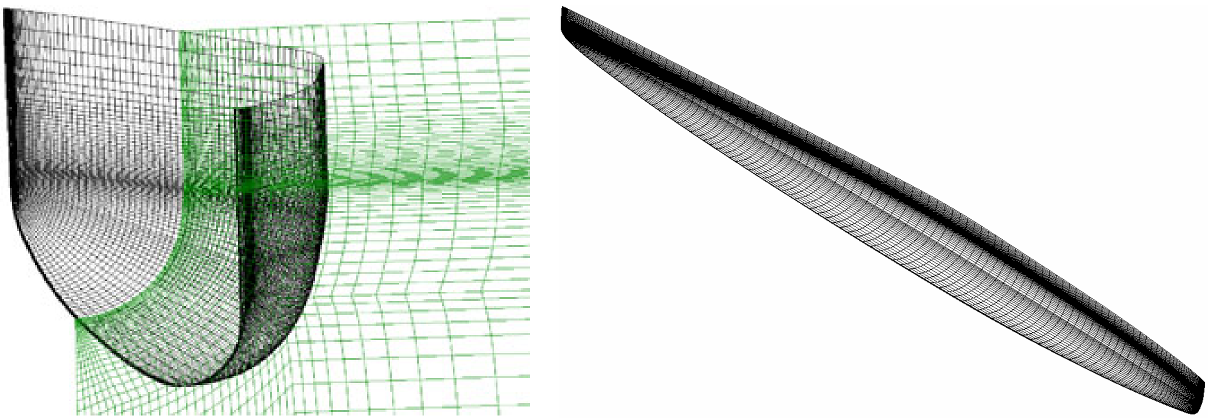


Figure 10 Examples of the computational mesh.

Due to the fact that the Olympic canoes travel at the relatively high speed (Fr=0,47-0,73), it is absolutely necessary to take into account the dynamic trim and sinkage of the hull in the numerical analysis of the flow around it, requiring either experiment data, or if it is not available, adjusting the hull position during the CFD simulation until the force and moment equilibrium is reached, Kraskowski(2005), Bugalski&Kraskowski(2005). Although this can

be done iteratively, based on the hull hydrostatics, CTO S.A. uses an in-house, automated procedure for coupling the flow solver to the hull motion equations, allowing for accurate evaluation of the canoe's position. The computational mesh in this approach remains rigid - it moves together with the hull without relative motion of the nodes, which proved to be sufficiently accurate, robust and very simple - no re-meshing is required when the hull changes its position.
At present, the CFD analyses and model tests of the canoe's performance are limited to steady-state analyses - the hull is towed with the constant speed and fixed centre of mass. Such a simplified approach allowed the effective optimization of the hull shapes based upon resistance with an identified 1% reduction - which could easily be the difference between Olympic Glory and the ignominious defeat. The use of CFD methods allowed reduction in costs by limiting the number of designs tested and also reducing the need to manufacture many hull shapes. Further move the identification of the flow phenomena by CFD allowed optimization to be carried out far quicker than previously possible.
It is very likely that the present shapes of the Olympic canoes are already very close to the absolute minimum resistance obtainable in steady flow. In the future, significant further development will only occur by optimizing the dynamic behaviour of the hull, which means taking into account all the phenomena encountered during a race - motion of the competitor and unsteady forces exerted on the hull.

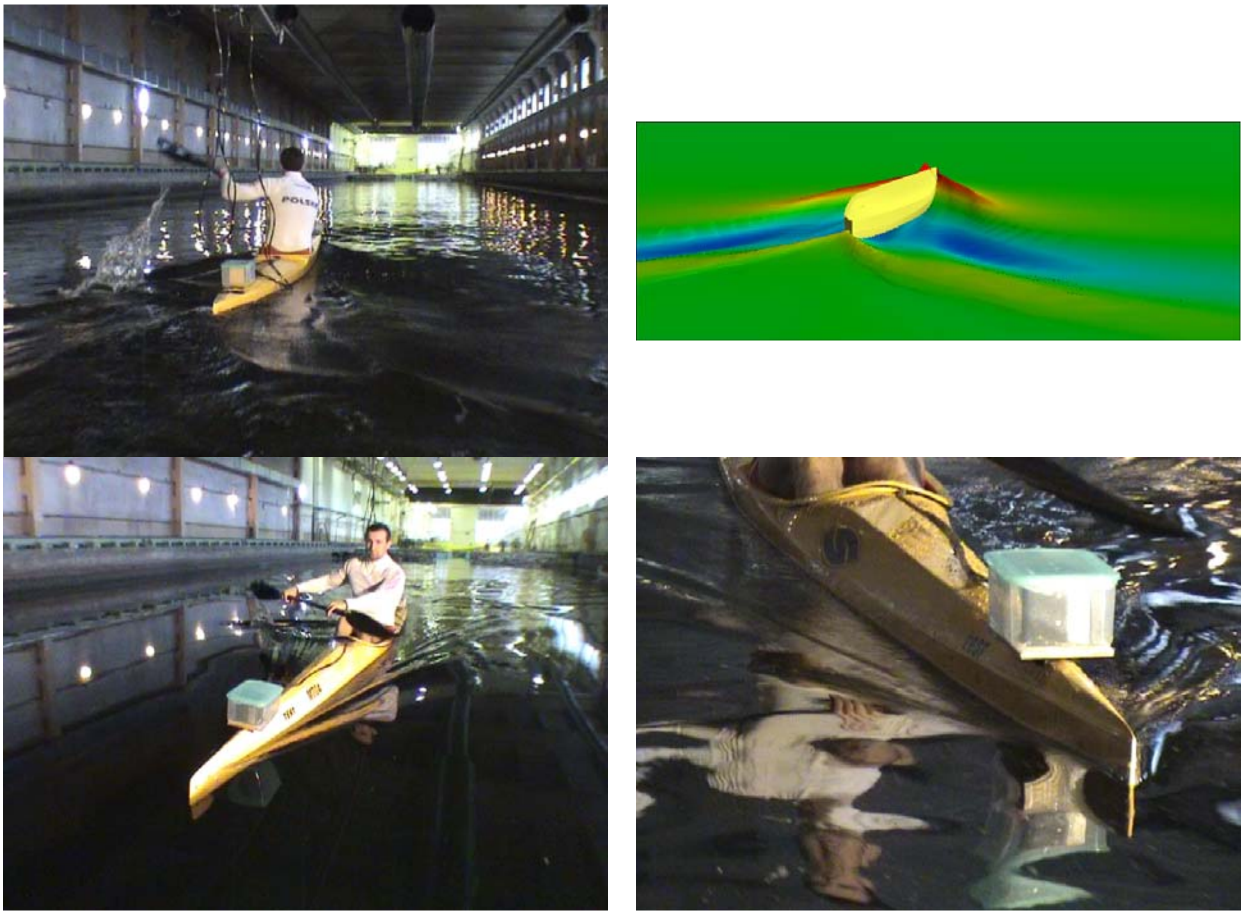


Figure 11 The complex test of K1kayak performance before Olympic Games (CTO S.A., 2008)

New shapes of the Plastex's sprint canoes are developed on the way of successive modifications of existing shapes. The alterations are supported by CAD systems (NAPA, Maxsurf, Rhino, FreeSHIP, MasterCAM) connected with Experimental and Computational

Fluid Dynamics methods. The forms of new kayaks and canoes are prepared with CNC technology. The most modern materials, which are widely applied for the aircrafts production by Airbus and Boeing companies, are used to manufacture boats. Recently, Plastex has introduced „vacuum infusion" and the remote control heating whole boats. Because of the above innovations the Plastex makes boats of the highest quality.

The viability of each new design was first tested numerically, so that only a small number of optimized designs were selected for manufacturing and testing in the model basin. Final tests were carried out in to the real conditions - with the professional competitor rowing along the basin.

The new line of flatwater kayaks –final results of the complex work described in this paper had been verified during Beijing 2008 Olympic Games. The Plastex had shown 4 of 8 new boats from the new sprint canoes line. The results had been as follow:

- C1M 500m –Gold (Maxim Opalev RUS 1:47.140)
- C2M 500m –Gold (CHN 1:41.025), Silver (RUS 1:41.282), Bronze (GER 1:41.964)
- K4M 1000m –Gold (BLR 2:55.714), Silver (SVK 2:56.593), VI (POL 2:59.505)
- K2M 1000m –IV (POL), V (HUN).

Aknowledgement

The part of research presented in this paper has been financially supported by Polish Ministry of Science and Higher Education, Research Grant No. 6ZR6 2006 C/06811. The author would like to express his gratitude for this support.

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CTO RH-2007/T-075 The experimental test of 13 sprint model canoes,
CTO RH-2007/T-092 The hydrodynamic optimization of New line of Olympic sprint canoes using CFD methods,
CTO RH-2007/T-106 & T-025 The execution of 8 new sprint canoe prototypes on CNC machine. The hull shape data,
CTO RH-2007/T-107 The towing tank experimental test of new sprint canoe prototypes,
CTO RH-2008/T-101 The pitch and roll influence on performance of sprint canoes. The towing tank tests of kayak powered by human.

Symbols and Definitions[1]:

B	*(ships, hull geometry)* Beam or breadth, moulded, of sprint canoes hull
B_{WL}	*(ships, hull geometry)* Maximum moulded breadth at design waterline
∇	*(ships, hull geometry)* Displacement volume
L	*(ships, hull geometry)* Length of sprint canoe
L_{WL}	*(ships, hull geometry)* Length of waterline
T	*(ships, hull geometry)* Draft, moulded, of sprint canoe hull
V	*(ships, hull resistance)* Speed of the model or the sprint canoe
C_B	Block coefficient, $C_B = \nabla / (L \cdot B \cdot T)$
Fr	*(fluid mechanics, flow parameter)* Froude number, $Fr = V / \sqrt{g \cdot L}$
g	*(ships, basic quantities)* Acceleration of gravity
WL	waterline, design waterline, a line corresponding to the surface of the water when the canoe is afloat

[1] ITTC Symbols and Terminology List, Version 2008