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Hydrodynamic Analysis and Improvement of Pontoon Boats

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Abstract. This study is related to the design features of pontoon boats that enjoy an increasing market share in global recreational boat industry. In this investigation, a representative pontoon boat with three cylindrical buoyancy elements was taken as the model to be studied. Afterwards, the buoyancy elements were improved to optimize hydrodynamic properties using a computational fluid dynamics package. The objective functions were the total hydrodynamic resistance of the boat and the distribution of the turbulence viscosity and total pressure on the hulls. By means of the obtained results, the powering requirements were estimated both for a service speed and for a maximum speed as well as findings were discussed.

1. Introduction

Since pontoon boats generally have simple designs and structural characteristics, they can be manufactured with relatively low hand labour and cost by the use of appropriate materials. For this reason, such boats have significantly increased their market share compared to other segments recently (Fig. 1 and 2). There are approximately over 12 million registered boats in the United States (US), which represents three-quarters of the global recreational boat market. Since 95% of these boats are shorter than 8.00 meters, they can be moved on trailers to the coastal areas and inland waterways and can be moored at marinas with low mooring costs [1, 2]. While speedboats in the US continue to be popular, the pontoon boat segment has taken the first place in the recreational boat industry during the last decade, especially since the 2007-2009 recession [1, 2]. The sales of these boats constitute 33% of total sales and it is estimated that this growth will continue until the end of 2020 [1, 2].

Regardless of the types of drives and engines used, the reason for the rise in the market share of the pontoon boat segment can be explained by the comfort, stability and versatility of these boats as well as their reasonable prices, compared to same-size fiberglass boats. The popularity of the segment also seems to be growing among both elderly generation and entry-level boat owners, since the pontoon boats are easy to acquire, easy to get on and off, easy to dock, and that they mostly use outboard motors. Further sales data show that pontoon owners also own second boats at higher rates than those in many other segments, using the pontoon boats as a mother ship for social occasions. While other boats are more purpose-built, a pontoon yacht is a multi-purpose platform for fishing, skiing and cruising and water sports, thus it can easily be sold on second hand markets (Fig. 1 and 2) [1, 2]. Further properties of these boats are wheelchair-accessibility, maintenance-free buoyancy elements (if especially made of thermoplastic materials), easy-to-maintain single deck layout, great "living room" on the water and super-comfortability with the possibility of installing higher engine powers (Fig. 1-3).

Figure 1. Pontoon boot with three cylindrical buoyancy hulls [3]

Figure 2. Pontoon boot with three cylindrical buoyancy hulls from aluminium [4]

Figure 3. Pontoon boot with three buoyancy hulls from HDPE [5]

They are particularly of interest for buyers who do not need under deck accommodation. Since, when the boat owners were interviewed, it was found that less than 10% of them spend their nights on the boats, and the cabins are used rather for storing goods and tools (Figs. 1-3) [2]. With the latest innovations realized, optional overnight accommodation facilities have been created to meet the needs of some boat owners [2].

This article is aimed to provide the design features of pontoon boats and further computational fluid dynamics (CFD) analysis of a Small Waterplane Area Twin Hull (SWATH) boat model. The validation of the results obtained in these analyses with those of the experiments of the SWATH boat model performed by Begovic et al. in [6] was accomplished as seen in Figures 4-8. After successful conformity of the simulations carried out using the commercial software ANSYS/FLUENT, the developed pontoon models having cylindrical and hydrodynamically improved buoyancy elements were analysed in the same manner and the results obtained were compared to each other.

2. Materials and Method

2.1. Material Selection and Hydrodynamic Design of Pontoon Boats

In the preliminary design phase of the pontoon boats, by means of taking into consideration an initial literature survey and experiences from previous similar boat designs, the following issues were investigated [6-10]:

- Transport possibilities of the pontoon boats in coastal areas and inland waterways on trailers and mooring facilities in marinas,
- Low manufacturing cost potentials,
- Low operating costs.

Then, it was decided that the boat displacement tonnage should be approximately Δ=2.00 tons. Thus, the overall length is L_{OA}=8.25 m and the in-service speed and the top speed vary as $V_{service}$=15−18 knots and V_{max}=35−40 knots, respectively [6-10].

Generally, the first design consideration to be taken into account in this phase is the stability and power requirements of the vehicle considering the mission of the boat and propulsion systems to be equipped before decision of the boat form. These two demands have conflicting characteristics. In order to construct a stable boat, it is necessary to increase the beam of the vehicle during the preliminary design phase; but larger values of the vehicle beam require higher engine power for the same service speeds, due to nonlinear increase of resistance with Froude number.

Due to this reason at first, an optimal design decision was made that a pontoon boat with three cylindrical buoyancy hulls was selected as yacht form. This type of construction offers a high transverse stability and requires a lower engine power at the same service speeds due to its very slender hulls, but also providing a large "living" deck area for the arrangement of furniture, equipment and social occasions (Figs. 1-3).

The width of the boat can be increased as required by considering both the stability and the deck area, based on three cylindrical buoyancy elements with a diameter of D = 60 - 90 cm range according to the carrying capacity of respective boats as seen in Figure 4. Since those boat types, in principle, resemble trimaran boats and the water plane width of the individual hulls is constant due to constant diameter of the buoyancy elements, the total waterplane width of the boat is constant, unless the weight of the respective boats changes.

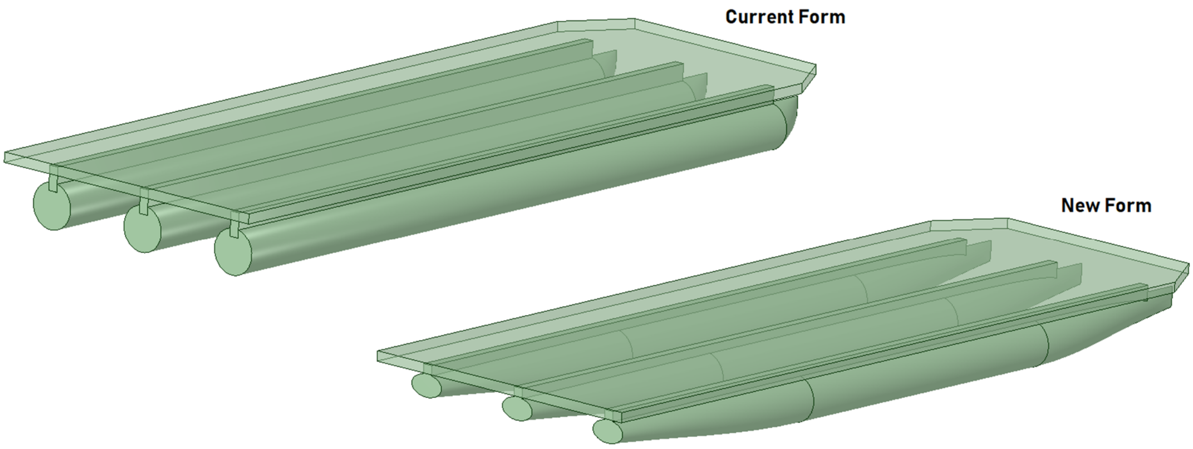


Figure 4. Pontoon boot models with three cylindrical buoyancy hulls (left) and with three hydrodynamically improved buoyancy elements (right)

Furthermore, the manufacturing and workmanship of these types of vehicles have lower costs compared to those of the displacement boats due to simpler boat structure and elements (Figs. 1-4). When considering the form types and the boat sizes mentioned above, the building materials are prevailingly aluminium, composite and thermoplastic materials, which meet the required criteria as follows:

- Low density (weight) and sufficient structural strength,
- Ease of formability and manufacturability,
- Cost-effective components including manufacturing, operation and maintenance-repair,
- Good resistance to corrosion and marine organisms,
- Good resistance to environmental aging conditions (temperature, corrosive and chemical substances, etc.).

The use of high quality aluminium for the design of the vehicle to be constructed results in a very finely slender and light hull form for achieving low resistance values. Nevertheless, this choice will make it relatively costly. In addition, welding of aluminium as well as protection of this material against corrosion always is a problem.

The use of wood in the construction of the vehicle makes the pontoon boat light and relatively cost-effective. However, it requires extremely careful manufacturing and extensive protection measures against severe environmental effects of the sea during its use.

E-glass fibre reinforced polyester material, which started to be used in the production of boats and even in car bodies in the 1950's, is now widely used in boat construction. When working in mass production, with the appropriate mould and equipment support and high-quality workmanship, very good boats are produced from this material. However, a high quality mould production is a factor that always raises costs considerably.

Significant increases in the global scale are expected in the coming years in the production of workboats and yachts with anti-magnetic, anticorrosive, repair-free polyethylene thermoplastic material, which can easy be cut and welded with the same material by the use of heat to create highly strong constructions without any need of costly moulds as in the fiberglass boats.

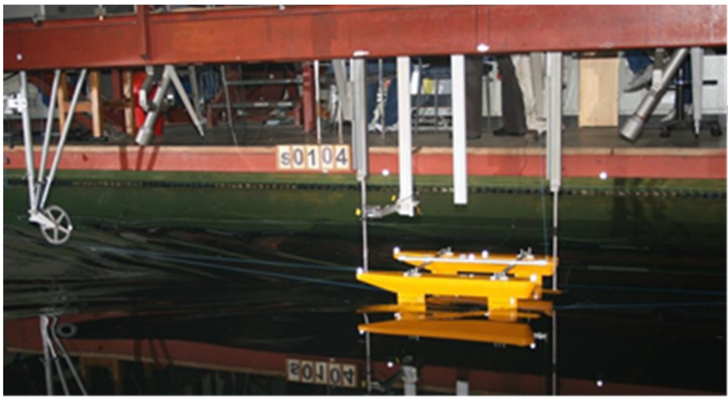
In this study, a pontoon yacht consisting of a platform main deck and three cylindrical buoyancy elements made of polyethylene thermoplastic material was used, and computational hydrodynamic analyses of this design was performed to estimate the hull resistance and consequently the engine power (Figure 4). The three cylindrical buoyancy hulls of high-density polyethylene thermoplastic material will be filled with plastic foam for making the boat unsinkable. In addition, considerable reductions in the manufacturing cost of the boat can be achieved due to further simplicity of its form and construction.

Pontoon boots manufacturers have noted that improvements in outboard engine technology have boosted sales in the segment, while improvements in electric motor technology have also contributed to the continued growth of the category, since electric-powered pontoon boats have been preferred in numerous lakes in the US and Canada due to gasoline engine or engine power restrictions [2]. Pontoon boats having two or three cylindrical buoyancy elements can generally be convenient with drive by electrical energy, owing to their design as well resistance and propulsion characteristics. For this reason, it is expected that demand for electric outboard motors will continue to grow and that these engines will be used in pontoon boats over the next decade in increasing rate.

The most important design factors for both small craft and larger ships are to reduce the hull resistance force and to increase the related thrust force, i.e. increasing the propulsive efficiency. Accurate prediction of the hull resistance of a marine vehicle is the most fundamental factor for determining a specific range of power requirements and hence the operation route of the vehicle. Another design objective is that the hull is to be constructed with a relatively low cost and be mechanically resistant to maximal service loads.

In general, moving objects submerged in a fluid are exposed to viscous drag that can be resolved to two components, i.e. the viscous pressure and frictional resistance components both depending on the Reynolds number. If they are at motion on the free fluid surface, these objects additionally experience wave resistance being a function of the Froude number. Thus both small craft and big ships must possess proper hydrodynamic form and surface characteristics for decreasing their frictional and viscous pressure resistance as well wave resistance components, all depending on vehicle speeds.

Since a Small Waterplane Area Twin Hull (SWATH) boat is at motion on free sea surface, all of the three components of the resistance above-mentioned arise synchronously. Thus this type of analysis is more complicated than the simulations of objects submerged in fluid. In this regard a SWATH boat form consisting of two torpedo shaped boundary elements and four struts was selected for validation of the CFD analyses carried out in this research (Fig. 5). Then a SWATH boat model equivalent to this published in [6] by Begovic et al. was modelled and analysed (Figs. 5-8). After the results obtained from the simulations had been validated with those of the physical towing tank tests of this boat model executed by Begovic et al., numerical hydrodynamic analyses of a pontoon boat consisting of a platform main deck and three cylindrical buoyancy elements made of polyethylene thermoplastic material, were performed to estimate hull resistance accordingly (Figs. 4, 8-13).



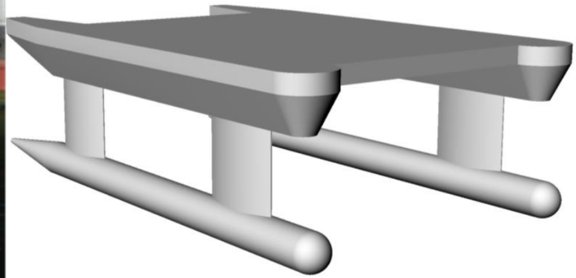


Figure 5. Resistance test of the physical model performed in [6]   Figure 6. SWATH boat model designed in [6]

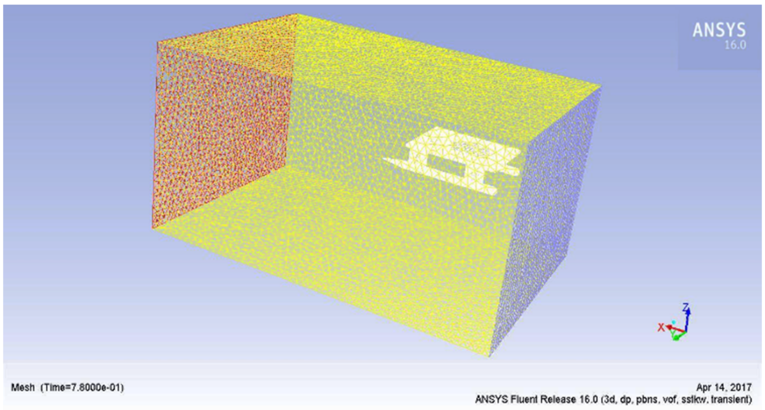


Figure 7. Domain of the model analysed in this study

Figure 6 indicates the model of the SWATH boat while Figure 7 shows the domain of the system analysed. As can be seen in Figure 8, a good agreement between the results of the CFD analyses carried out in this study and the experiments performed by Begovic et al. [6], was achieved.

In all CFD analyses of this study carried out, the turbulence modelling “Shear Stress Transport *k–ω* model (SSTKW) of the software ANSYS/FLUENT was applied [11,12]. The reason for the selection of this algorithm is that it generally gives accurate prediction of the onset and the size of the flow separation under adverse pressure gradient in a floating solid body since SSTKW model contains a modified turbulent viscosity formulation to calculate for the transport effects of the principal turbulent shear stress (Equation 1 and 2) [11,12]. Most of the separations arose close to the sterns of those models at high speeds, as expected.

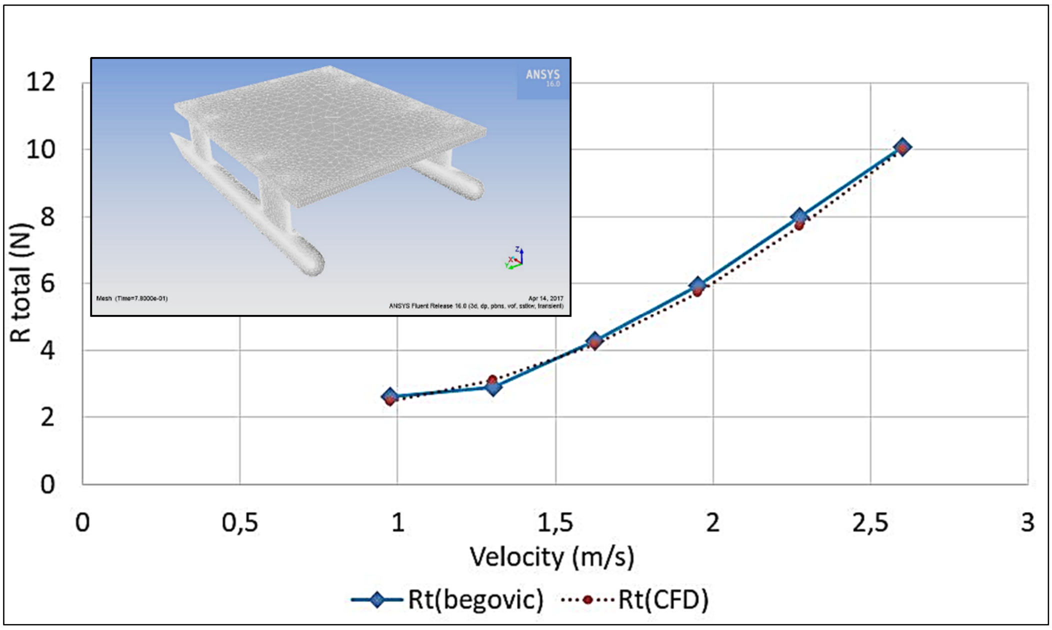


Figure 8. Total resistance values of the SWATH boat model determined by the experiment in [6] and by CFD analyses in this study

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k \quad \text{(Equation 1)}$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_j}(\rho\omega u_j)=\frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega+D_\omega+S_\omega \quad \text{(Equation 2)}$$

Where mean:
k: Turbulence kinetic energy
ω: Specific dissipation rate
ρ : Density
G_k : Generation of turbulence kinetic energy
G_ω : Generation of specific dissipation rate
Γ_k : Effective diffusivity of *k*
Γ_ω : Effective diffusivity of *ω*
S_k ve S_ω : User defined source terms
Y_k ve Y_ω : Dissipation of *k* and *ω* due to turbulence
D_ω : Cross-diffusion term

On the bow of all floating marine vessels in forward motion, a positive pressure field arises due to the basic principles of fluid mechanics, and a negative pressure field in front of the propeller which usually results in trimming by the stern. Thus, an unfavourable condition occurs in terms of resistance and propulsion. However, this state is partially improved by appropriate selection of the longitudinal centre of buoyancy and by conveniently forming the bow and the stern of the marine vehicle. Additionally, the vehicle is navigated with a certain stern trim due to the further improvement of the propulsion characteristics (Figs. 10-12).

Maximum speed of the pontoon boat examined was limited to about 35 knots (18 m/s) due to economic and technical reasons especially for restraining the excessive increase of the resistance values and also preventing the decrease of the longitudinal stability by the increase of the stern trim occurring at high speeds [6, 11, 12].

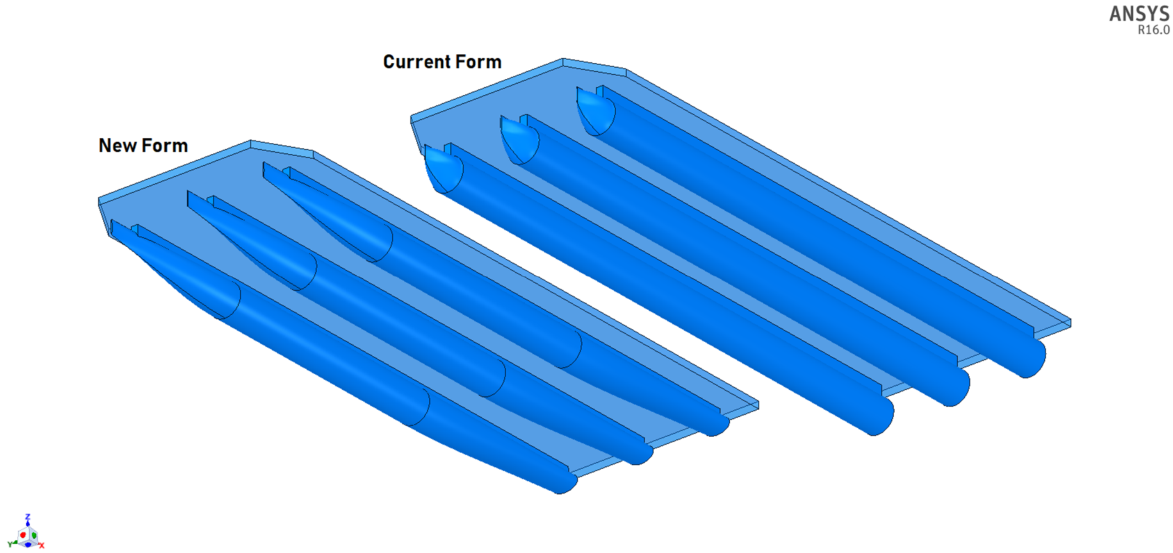


Figure 9. Models of the pontoon boats with cylindrical and hydrodynamically improved buoyancy elements (Current-Form and New-Form).

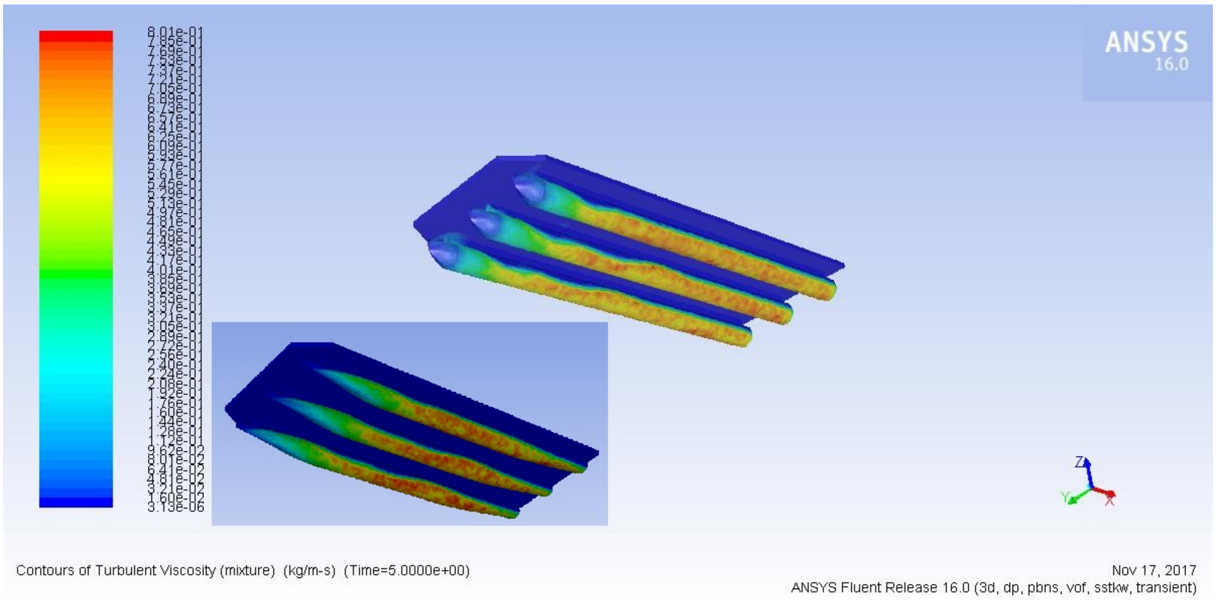


Figure 10. Turbulent viscosity alongside the buoyancy elements of the both forms at v=3 m/s.

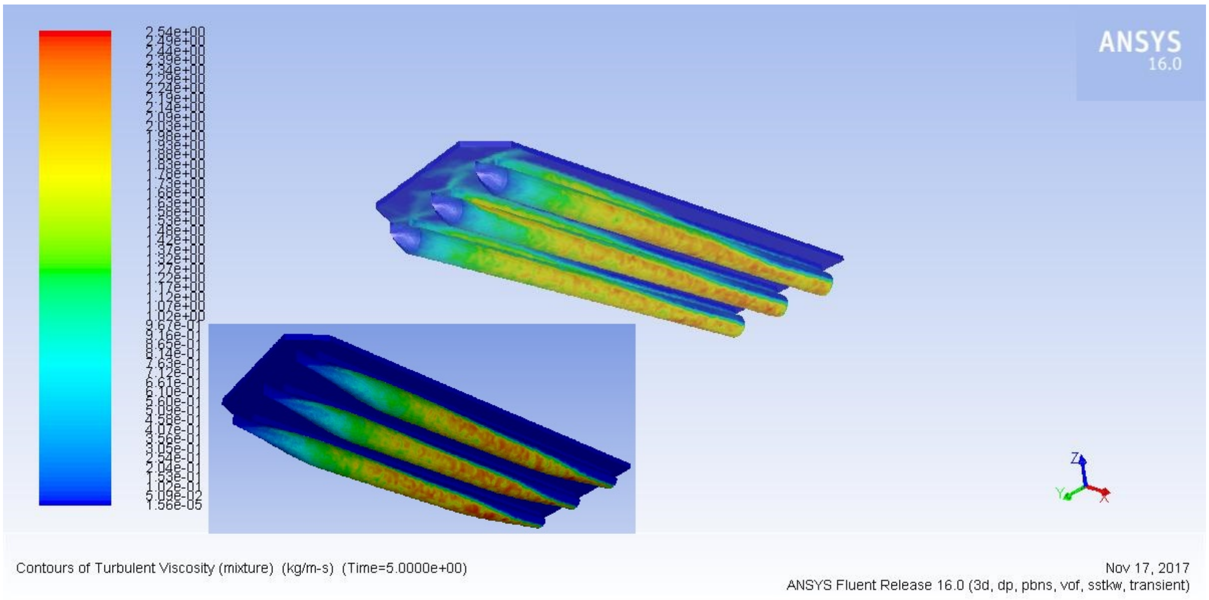


Figure 11. Turbulent viscosity alongside the buoyancy elements of the both forms at v=10 m/s.

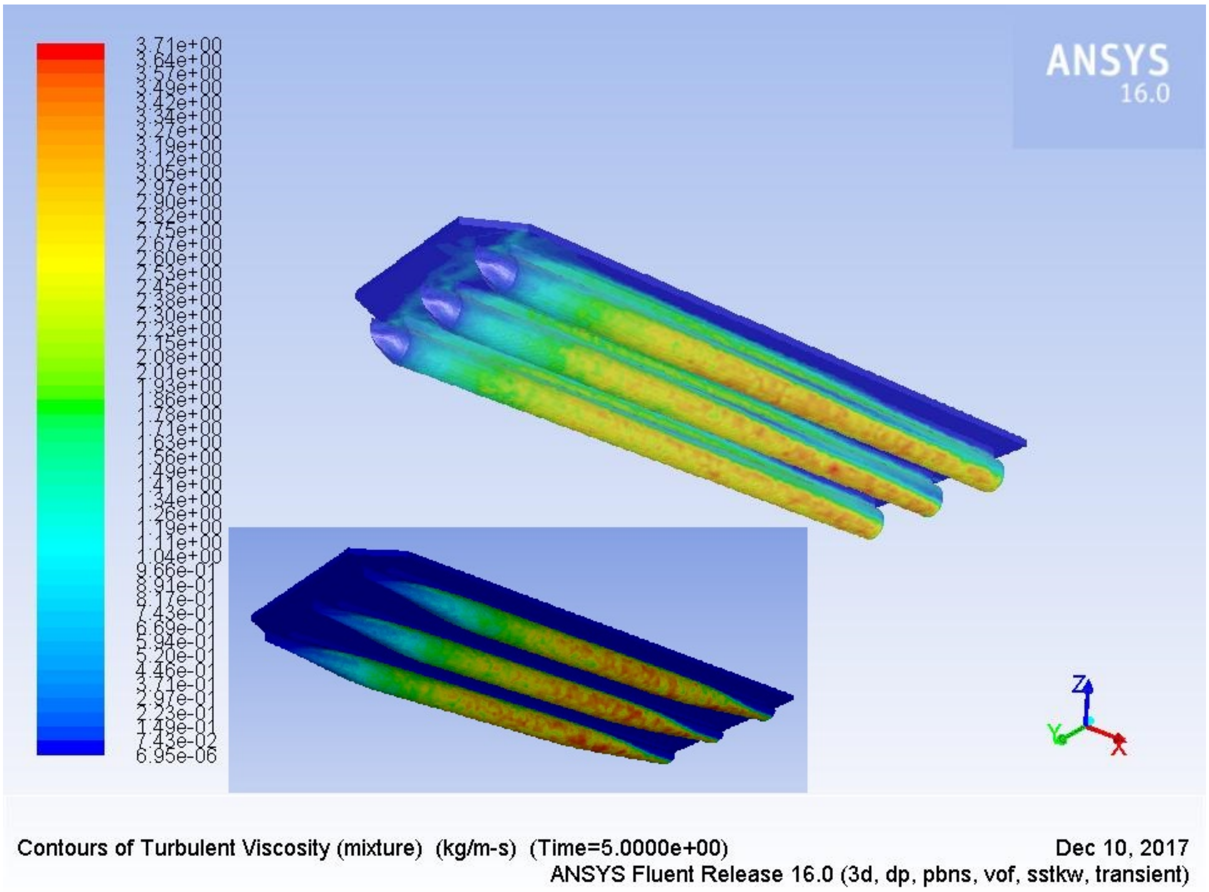


Figure 12. Turbulent viscosity alongside the buoyancy elements of the both forms at v=15 m/s.

2.2 Pontoon Boats Having Cylindrical and Hydrodynamically Improved Buoyancy Elements

Using the validated algorithm and simulation system above-mentioned, the pontoon boat with three cylindrical buoyancy elements (Current-Form) was subjected to CFD analyses at a speed range of 1-20 m/s, and total resistance values and required engine powers related to respective velocities were determined (Figs. 4 and 9-13). Furthermore, it was found out that the increase in resistance is not proportional to the second power of velocities but rather lower and bilinear up to 19 m/s, which was unexpected. Also, the limited increases in resistance values can be explained by the limited increase in turbulent viscosity alongside the buoyancy element forms as seen in Figures10-12.

In second part of the study, the cylindrical buoyancy elements of the boat were improved to optimize the hydrodynamic properties of the floating members at the bottom parts of the bow and the stern of the hull (New-Form) (Figs. 4 and 9-13).The model of New-Form was analysed in the same manner as the model of the Current-Form, and it was found out that resistance values obtained were significantly lower than those of the Current-Form (Fig. 13). This can result in significant fuel savings for the same service speeds or higher speeds with a smaller engine. Finally, engine powers of the boats with typical characteristics of this segment were calculated for service and maximum speeds by estimating their resistance values using the software ANSYS/FLUENT.

The propulsion estimation was made for three hull members, while the general propulsion efficiency was accepted to be $\eta_D = 0.5$, ranging from $0.4 < \eta_D < 0.65$. The power in the engine shaft (Brake Power) was calculated by Equation 3, using the total resistance (R_T [N]), speed (v [m/s]) and general propulsion efficiency (η_D) of the pontoon boat as well assuming transmission losses as $\eta_{tr}=0.97$.

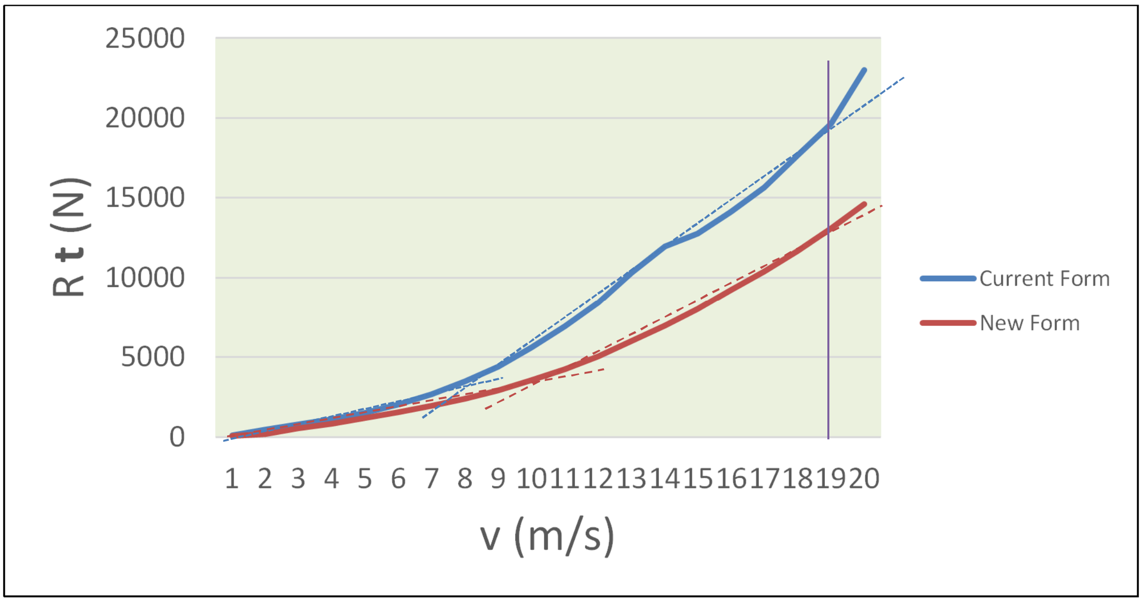


Figure 13. Total resistance values of the both models estimated at speed range of 1-20 m/s (2−38,9 kn)

$$P_B = \frac{R_T \cdot v}{\eta_D \cdot \eta_{tr}} = 2.062 \cdot 10^{-3} \cdot R_T \cdot v \qquad [kW] \qquad \text{(Equation 3)}$$

Conclusively, the pontoon boat of New-Form needs a relatively smaller engine capable of providing $P_{service}$ = 113 kW and P_{max}= 433 kW at the service and maximum cruising speeds, yielding $V_{service}$ = 22.5 knots and V_{max} = 35 knots, respectively (instead of $P_{service}$=183 kW; P_{max}=655 kW).

3. Conclusions

According to recent studies publicly available, the global recreational boat market is expected to reach an estimated 30.0 billion USD by 2022, and it is forecast to grow at a Compound Annual Growth Rate of 3.8% from 2017 to 2022. It is also expected that the pontoon boat type will gain a significant share in the world boat market and in the US market that represents a share of three-quarters of this global market.

Pontoon boats can conveniently and cost-efficiently be manufactured from E-glass fibre reinforced polyester, aluminium and high-density polyethylene material. With the choice of appropriate materials, a single easy-to-care deck layout, comfortable furnishings, large areas and affordable prices, pontoon boats have increased their market share against other categories. Additionally, due to their versatility, such as cruising, fishing and water sports, and easy sales in second-hand markets, they are consistently capturing market share from other boat segments.

This study was aimed to develop a proper buoyancy hull form to utilize hydrodynamic innovation potential of the pontoon boats. Therefore, in order to exactly apply the CFD method to hydrodynamic analyses, a selected SWATH boat was modelled and analysed. After the successful validation of the results obtained in these CFD analyses by those of the experiments of this boat model performed by Begovic et al. [6], the simulations carried out on the developed models of the pontoon boat having cylindrical buoyancy elements with the length of 8.25 m, were performed in the same manner using the commercial software ANSYS/FLUENT.

Subsequently, the pontoon boat with improved buoyancy elements having modifications on bottom parts of the bow and the stern (New-Form) were analysed, and the results obtained were compared to each other. The new form of the improved buoyancy elements appears to possess considerably better hydrodynamic characteristics than the cylindrical ones, since it shows lower turbulence viscosity alongside the buoyancy elements (Fig. 10-12).

Conclusively, the results of the performed analyses of this boat has indicated that the resistance and power requirements of New-Form decrease by up to 34-38% compared to those of the Current-Form. Based on the results of this research, it was found out that:

- the pontoon boats have appropriate improvement characteristics in terms of the hydrodynamic design of their buoyancy hulls, and
- they are suitable for mass production with low man-hours as well
- they can be produced in a way to appeal to both entry and advanced level boaters, who are interested in yachts in the middle or high speed category.

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