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Enhancing Efficiency in Deep-V Planing Hull Ships: A Study on the Design of Spray Strips to Minimize Resistance

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ABSTRACT

Spray strips are deflectors installed on the hull to decrease the wetted surface area (WSA). By reducing the WSA, the overall resistance of the ship is lowered because it lessens the friction of water flowing against the hull. The purpose of this research is to predict the function of spray strips in an effort to improve ship performance. In this study, the numerical methodology employs the Finite Volume Method (FVM) along with the Reynolds-averaged Navier-Stokes equation (RANS) for resolving fluid dynamics issues. The modeling of the two-phase flow involves the utilization of both the Volume of Fluid (VOF) model and the Eulerian model. The results of this study show that spray strips can reduce the total resistance by about 2.7%. Increasing the number of spray strips can reduce the drag shear value by 3.5%. Spray strips are effective in reducing total drag when the Froude number (Fr) is greater than 1 or when the vessel is in the planing phase. The profile shape of spray strips with dimension 2:1 shows the best performance on ship resistance.

1. Introduction

High-speed craft exhibit distinct attributes, including dynamic pressure along the hull's bottom, phenomena like slamming, and porpoising, as well as trim and heave effects. Studies focused on high-speed planing hulls indicate that a notable spray resistance of 15-20% can manifest along the advancing hull [1]. In the pursuit of fuel reduction for high-speed vessels, endeavors to enhance drag management have led to the identification of several applications. Among these are the Interceptor, hull vane, extended stern, stern flap, Integrated interceptor-stern flap, spray strips and all of which contribute to augmenting performance and minimizing resistance [2-7]. The Spray Strip, a modification for ship hulls, serves to minimize the wetted surface area (WSA), particularly within the spray region. These strips function by redirecting the spray flow ahead of the stagnation line. Accurate identification of the stagnation line holds significance in the application of spray strips.

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Clement performed experimental investigations on the impact of spray rails, revealing a reduction in overall resistance ranging from 6% to 25% at specific Froude displacement numbers. Nevertheless, during displacement and semi-displacement speeds, there is a potential for spray rails to induce a resistance increase of up to 3% [8]. Molchanov *et al.,* [9] conducted the spray rail experiment, which demonstrated a 9% reduction in resistance. Recent research indicates that retrofitted deflectors can lower total resistance by 5% [10].

Fridsma [11] conducted experiments on a planing hull, testing various parameters like displacement, L/B ratio, Longitudinal Center of Gravity, and deadrise angle. These tests were conducted under two conditions: calm water and wavy conditions. The simplicity of the ship's design makes this study a valuable reference for validating subsequent numerical computations. Moreover, the vessel's uncomplicated form contributes to its widespread popularity. The broad spectrum of diverse and influential parameters allows us to thoroughly assess the performance of both mathematical and numerical models [10,12-14]. Numerical validation using the CFD Ship-Iowa code reveals a comparable trend, with an average error rate of 10.6% [13]. Simulations were conducted to prevent ventilation issues, with the goal of achieving favorable outcomes in resistance predictions [15].

The Savitsky method stands as a semi-empirical approach primarily employed to forecast drag on high-speed vessels. It assesses the capabilities of prismatic hulls through computations of running sinkage and trim. Using the Savitsky method allows for the calculation of metrics such as lift, wetted area, drag, and center of pressure for prismatic surfaces featuring hard chines [16]. Bilandi *et al.,* [17] developed method for predicting the calm-water performance of a double-stepped planing hull uses CFD simulations to compare the results of the 2D + T and CFD methodologies. The findings demonstrate a notable similarity in their predictions of heeling resistance, moment, and trim angle. A numerical simulation was executed to forecast the effects of incorporating spray rails. Olin *et al.,* [18] investigated the shape profile employing the 2D concept, achieving a notable 4% reduction in total resistance. Another approach involves using the overset grid method, a mesh manipulation technique that employs donor-acceptor cells. In this method, active cells are located at the boundaries of the overset geometry, acting as intermediaries for donor-acceptor cells, while passive cells remain in the background and are replaced by overset cells. This technique is recommended for complex fluid-structure interactions and has been utilized in research related to planing hulls [14,19,20]. Nevertheless, it's important to consider interpolations between the overset region and the background in the overset method, which occur because of the heightened vorticity computed in the direction of the waves generated beneath the bow of the vessel [21].

This article provides an overview of insights into altering the design of spray strips to reduce resistance in deep-V planing hull ships. The main concept involves rerouting spray along the stagnation line to reduce the extent of the wetted surface. Previously, a spray strip system concept was developed, using computational fluid dynamics models to analyze how deflectors behave in calm water conditions. This analysis could potentially reduce the engine power needed for a given speed. By employing a deflection mechanism that separates the spray sheet from the hull, frictional resistance in the spray rail can be minimized, reducing the wetted area affected by the spray. The effectiveness of spray rails largely hinges on their shape. Nevertheless, challenges can arise if the placement, thickness, or form of the spray rail is not appropriate. In this ongoing research, a novel configuration for the dimensions and positioning of spray strips is explored to investigate their repercussions on ship resistance, trim, and heave.

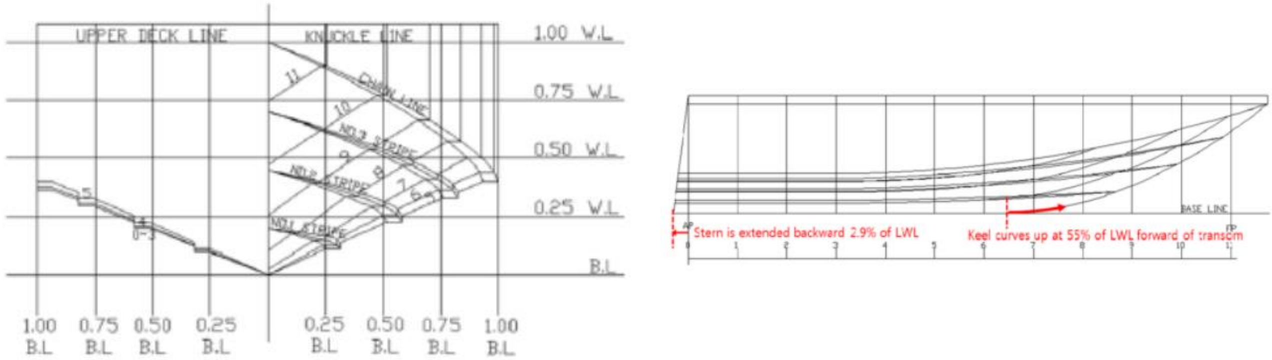
2. Methodology

2.1 Ship Description

This research will use experimental data from Kim *et al.,* [22] is Deep-V Planing Hull Ship called Deep-V Planing Straight. The VPS ship has been experimentally tested using a towing system at Seoul National University in calm water conditions and ITTC standards. Experimental data can be seen in Table 1. The VPS ship's body plan and sheer plan are shown in Figure 1.

Table 1
Principal characteristics of the vessel

Parameter	Unit	Value
Loa	m	0.927
Lwl	m	0.762
B	m	0.308
Draft	m	0.080
LCG from AP	m	0.286
VCG from baseline	m	0.137
Deadrise from AP	Degree	20
Deadrise from midship	Degree	23
Deadrise from FP	Degree	32
Iyy=Izz	$Kg.m^2$	0.186
Δ	Kgf	9.103



(a) (b)

Fig. 1. Vessel 2D (a) Body plan and (b) Sheer plan [22]

2.2 Configuration of Strips

In this study, several tests were carried out to determine the effect of the dimensions of the profile size of the strips and the number of strips. The initial dimensions of the profile are bsr=0.011B and h=0.0044B [22]. bsr is the width of the spray rail and B is beam. Furthermore, the profile dimensions will change into 3 different models with a ratio of bsr : h. Model 1 will use a ratio of bsr : bsr on the profile strips. For model 2 a ratio of bsr : 0.5 bsr is used, while for model 3 using 0.5 bsr : bsr. The three variations of spray strip profiles are shown in Figure 2. Then there are three additional models with variations in the number of strips, namely variations using 1 pair of strips, 2 pairs of strips, and no strips. The three variations in the number of spray strips are shown in Figure 3. In the variation of the number of strips, the profile size of the width and height of the strips use the same dimensions as model 1.

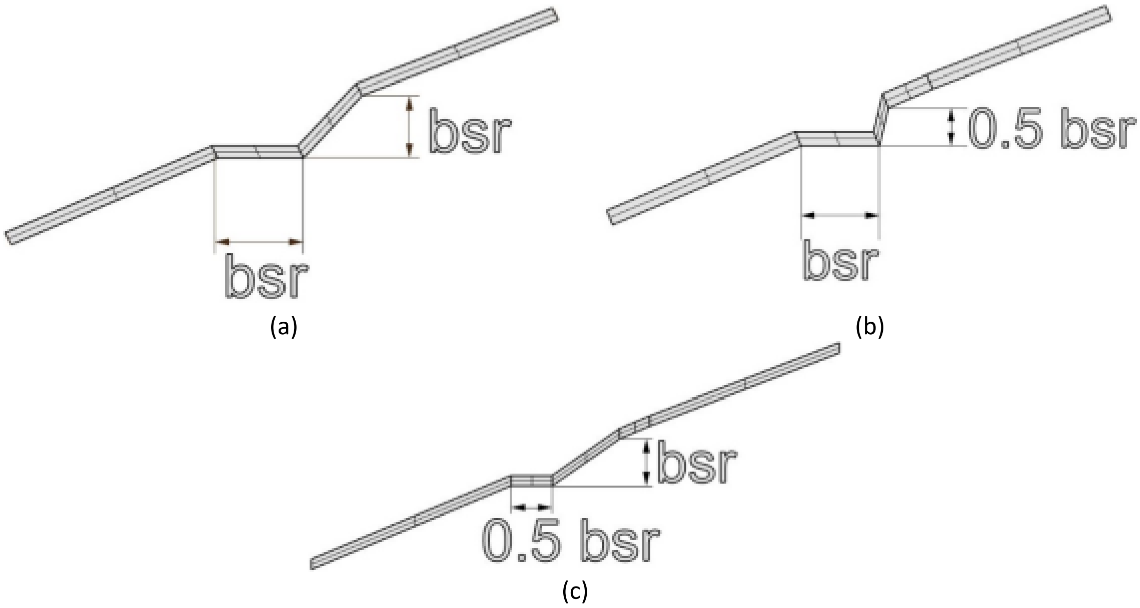


Fig. 2. Profile shape of spray strips (a) Model 1, (b) Model 2 and (c) Model 3

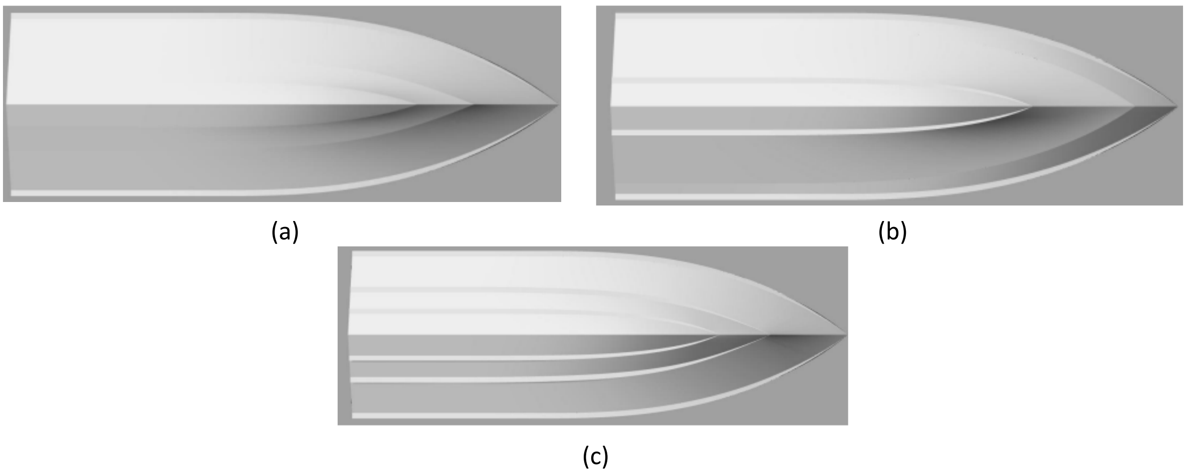


Fig. 3. Configuration strips. (a) No strip, (b) 1 pair strip, and (c) 2 pair strips

2.3 Numerical Method

The unsteady fluid-flow equations are discretized and solved using a fully-implicit second-order finite volume method. This method operates on unstructured grids made up of cells with arbitrary shapes. The VOF multiphase model was employed to address challenges concerning immiscible fluid mixtures and free surfaces. A Dynamic Fluid Body Interaction (DFBI) module was used to simulate how the vessel moves under the influence of reactive forces. The vessel's motion was allowed to move freely in heave and trim while being fixed in roll and sway. Reynolds-Averaged Navier-Stokes (RANS) is a technique for solving problems by applying the rules of mass and momentum conservation. The RANS equation is commonly employed for solving hydrodynamic problems involving incompressible flow

$$\nabla . V = 0 \tag{1}$$

$$\rho \frac{\partial V}{\partial t} = -\nabla P + \mu \Delta V + \Delta . T_{re} + S_M \tag{2}$$

where V is an average velocity vector, ∇ is volume, ρ is density, P is the average compressive field, μ is dynamic viscosity, t is time, T_{Re} is a Reynolds stress tensor, Δ is displacement, and SM is a vector of momentum sources. The T_{Re} component is computed using the selected turbulence model, following the Boussinesq hypothesis:

$$\tau_{ij}^{\mathrm{Re}} = \mu_t \left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \tag{3}$$

where k is the turbulent kinetic energy and μt is the turbulent viscosity. Turbulence models are available for addressing hydrodynamic issues within the framework of the RANS method. The prevalent turbulence model in hydrodynamics is the two-equation model, such as SST k−ω and k–ε [20]. To effectively manage body motion, computational cells are categorized as either active or passive based on their location within the computational domain. The dimensions used in this study are shown in Table 2 and Figure 4, where L is the ship's length, H is the ship's height, and B is the ship's width. To save time consumption, the simulation is carried out in half of the hull.

Table 2
Towing Tank Dimension

Dimension	Background	Overset
Length	1L from FP	0.25L from FP
	2.5L from AP	0.25L from AP
Height	1L from Deck	0.75H from Deck
	2L from Keel	0.75H from Keel
Width	1.5L from Symmetry	0.5B from Symmetry

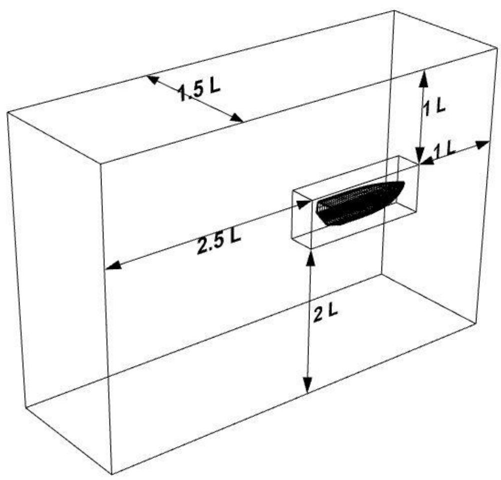
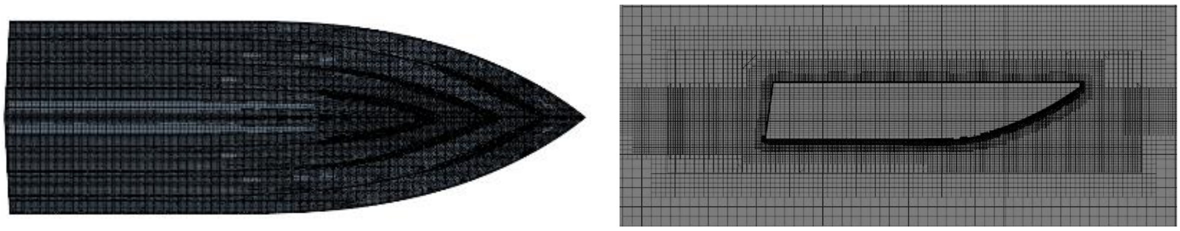


Fig. 4. Towing tank dimension

The number of elements per unit area is focused on both the vessel and the water surface to ensure accurate results. In addition, refinement is carried out on the strips and bottom areas so that the results become more accurate. An anisotropic mesh shape is employed locally, adjusting at the x, y, and z coordinates. The number of elements per unit area is divided into sections as shown in Table 3 and Figure 5.

Table 3
Mesh Density

Section	Mesh Dimensions
Far Field	0.0787 L
Block 1	0.0049 L
Overlap	0.0240 L
Overset	0.0240 L
Hull	0.0062 L
Free Surface	0.0062 L



(a) (b)

Fig. 5. (a) Visualization of mesh density concentrated on the strip profile (b) Mesh density on virtual towing tank

The wall function $y+$ is used to reduce errors in numerical simulations. Figure 6 illustrates that the y+ value ranges between 30 and 90. Meanwhile, in a study by Avci and Barlas [23], they utilized a y+ value ranging from 45 to 60 to achieve precise outcomes. According to ITTC, the calculation of the y+ value is as follows [24]

$$\frac{y}{L} = \frac{y^+}{Re\sqrt{\frac{C_f}{2}}} \tag{4}$$

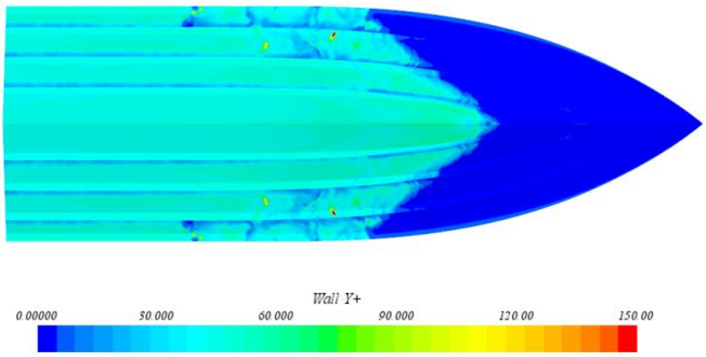


Fig. 6. Visualization of y+ bare hull at Fr 1.806

The ITTC equation is incorporated into the formula employed in the Star-CCM+ code, with y representing the first layer's thickness, L denoting the length of the object, Re indicating the Reynolds number, and Cf estimating the friction coefficient of the object's surface [25].

In unsteady flow simulations, a time step was implemented. This time step signifies the interval between each iterative calculation. A smaller value yields more precise results, while a larger value does the opposite. The CFD calculation's time-step determination is contingent on the ship's velocity; greater ship speed corresponds to a smaller time-step. For this study, a time step of 0.005 seconds was employed. This pertains to the equation as outlined in the ITTC recommendations found in Eq. (5), where U is the speed and L is the length [24].

$$\Delta t\ ITTC = 0.005{\sim}0.01\frac{L}{U} \tag{5}$$

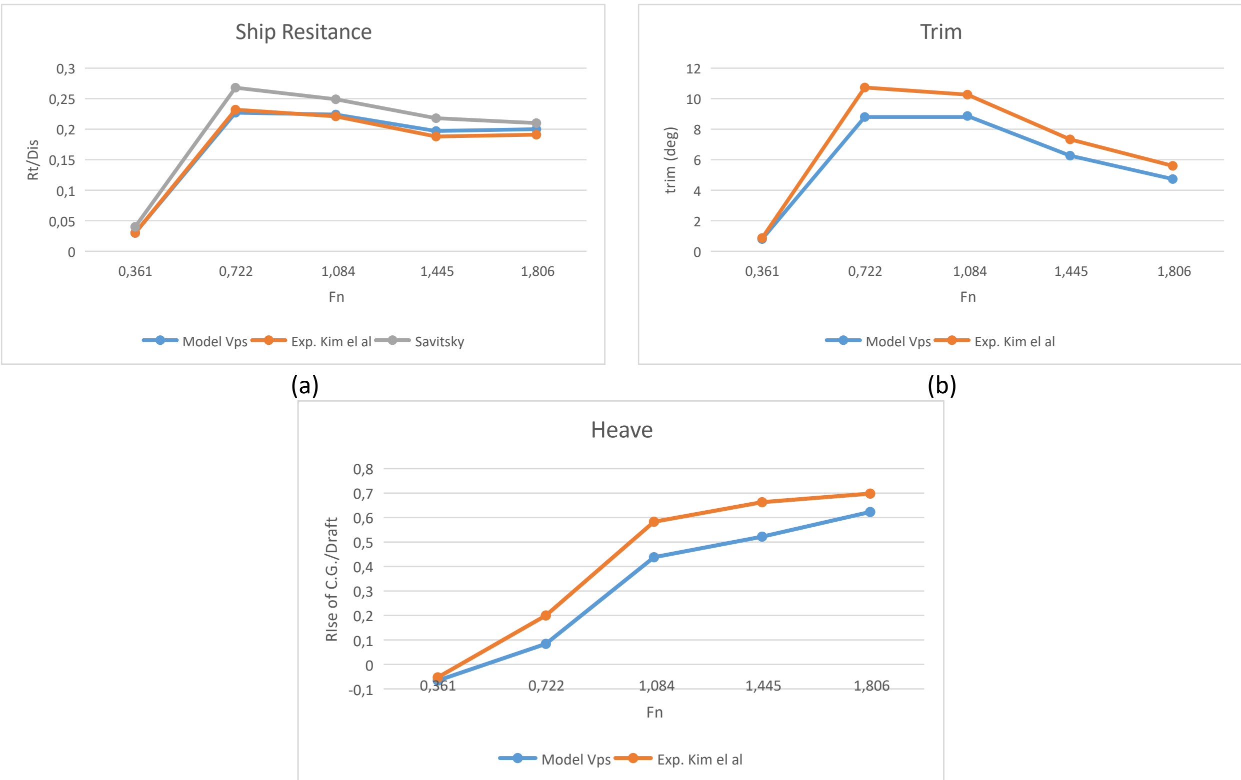
3. Results
3.1 Validation

Kim *et al.,* [22] experimental data on VPS is used as validation for the numerical simulation results. There are 5 velocities based on the Froude number used, namely 0.361, 0.722, 1.084, 1.445, and 1.806. The simulation has a mesh number of around 1400K-1600K which is concentrated on the surface and vessel, especially in the spray strips.

The vertical axis (Y) in the resistance simulation results is a non-dimensional unit of drag denoted by R/Δ, with Newton (R) as the unit of resistance and (Δ) as the unit of displacement, With the horizontal axis (X) being the non-dimensional unit of velocity expressed in Froude Number. For the trim simulation, the vertical axis (Y) is the unit of trim which is degrees (º). The horizontal axis (X) is the non-dimensional unit of velocity expressed in Froude number.

The numerical simulation results of the models obtained show similarities in total drag, but the trim and heave results of the VPS model get lower numbers when compared to the experimental results of Kim *et al.,* [22]. Comparison results between numerical simulations and experiments are shown in Figure 7. Research by Wheeler *et al.,* [26] explains that differences in the location of the center of gravity of the ship can affect numerical results so that the results of total drag, trim, and heave will be different if the location of the center of gravity of the ship moves even slightly.

Based on research conducted by Sukas *et al.,* [27] shows more accurate resistance results but trim results show significant differences. Therefore, the VPS model simulation can be accepted as a reference in comparing several variations in the dimensions of the strips and variations in the number of strips that will be used in this study.

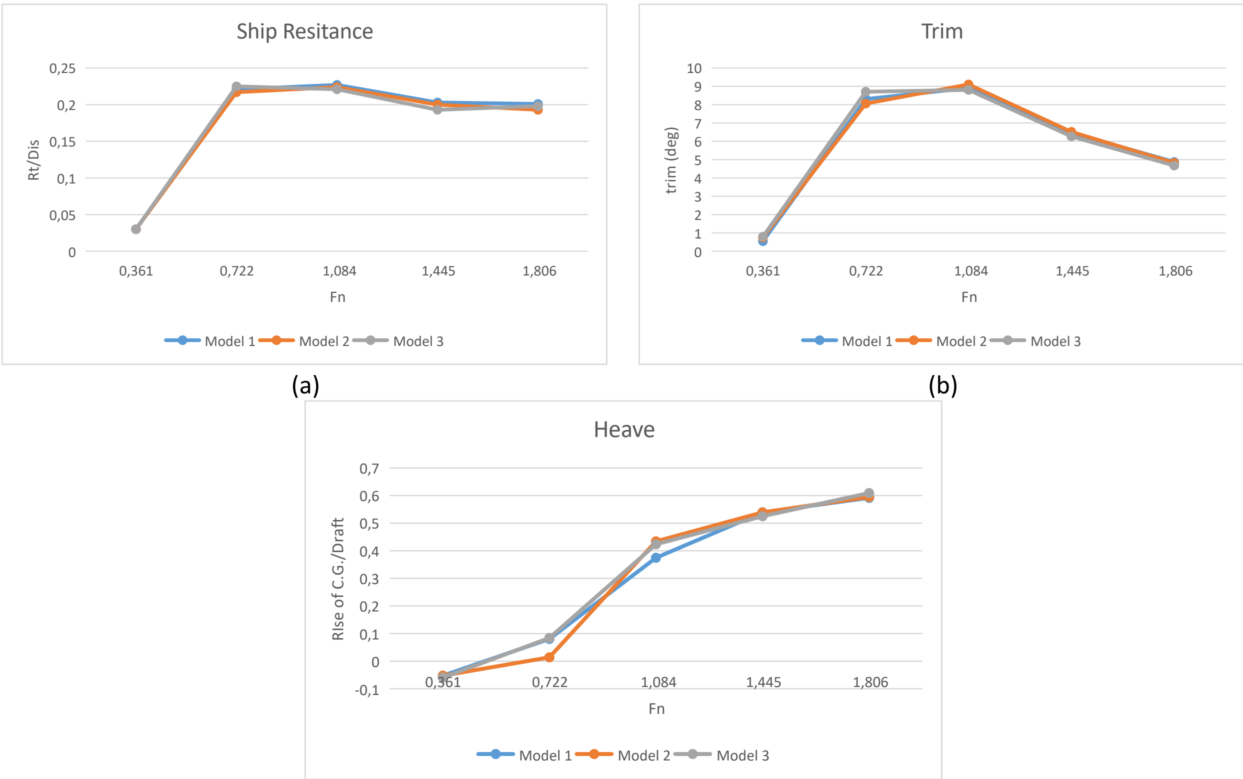


(a) (b) (c)

Fig. 7. Numerical simulation results of (a) total drag, (b) trim, and (c) heave vs. experiments

3.2 Effect of Variation of Spray Strip Dimensions

The simulation in this study is designed to conduct a comparison to know the effect of different dimensions (Figure 2) on the application of spray strips on the resistance of planing hull ships, especially deep-V planing hulls. The total drag, trim, and heave for the three-dimensional variations can be seen in Figure 8. The drag is described by the non-dimensional unit R/ Δ, with R as the resistance and Δ as the displacement/weight of the ship. The trim graph is described in units of degrees, while the heave is shown in units of non-dimensional Rise of CG/draft.



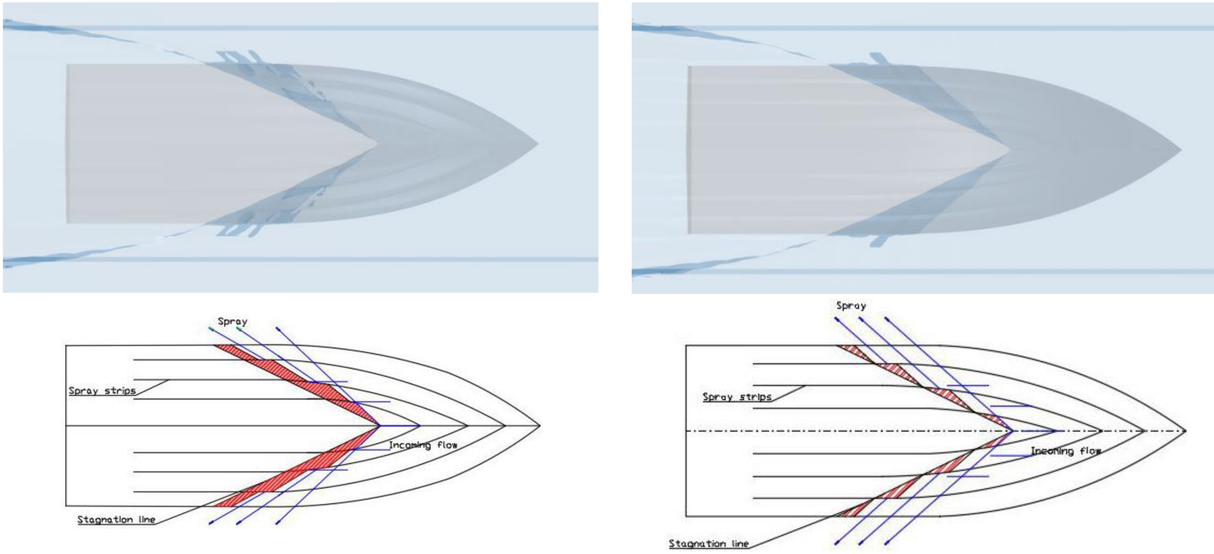
(c)

Fig. 8. Numerical simulation results of (a) total drag, (b) trim, and (c) heave of VPS model and experiment on variation of spray strip dimensions

Numerical simulation results show almost identical total drag results for all model variations and experiments. The difference in numerical results has a range of 0.5 to 7 percent difference to experimental results [22]. Numerical results at Fr 1.45 show that the profiles of model 1 and model 2 increase the total drag when compared to the comparison model by 2.8% and 2.1%, but model 3 is able to reduce the drag by 1.4%. At Froude number 0.72, the results show the largest total drag compared to other Froude numbers. The strip profile in model 3 can reduce drag better at high Froude numbers.

For the trim result, there is no significant difference, but in the heave result, the value that appears has a significant difference in value at Froude numbers 0.72 and 1.08. Trim and heave from numerical simulation results show less accurate results at low Froude numbers. It is explained by Sukas *et al.,* [14] that Savitsky's empirical approach causes large pressure differences to drag at low Froude number. Savitsky predicts high dynamic forces at trim angles even at low speeds, which can be an improvement in the prediction of total drag.

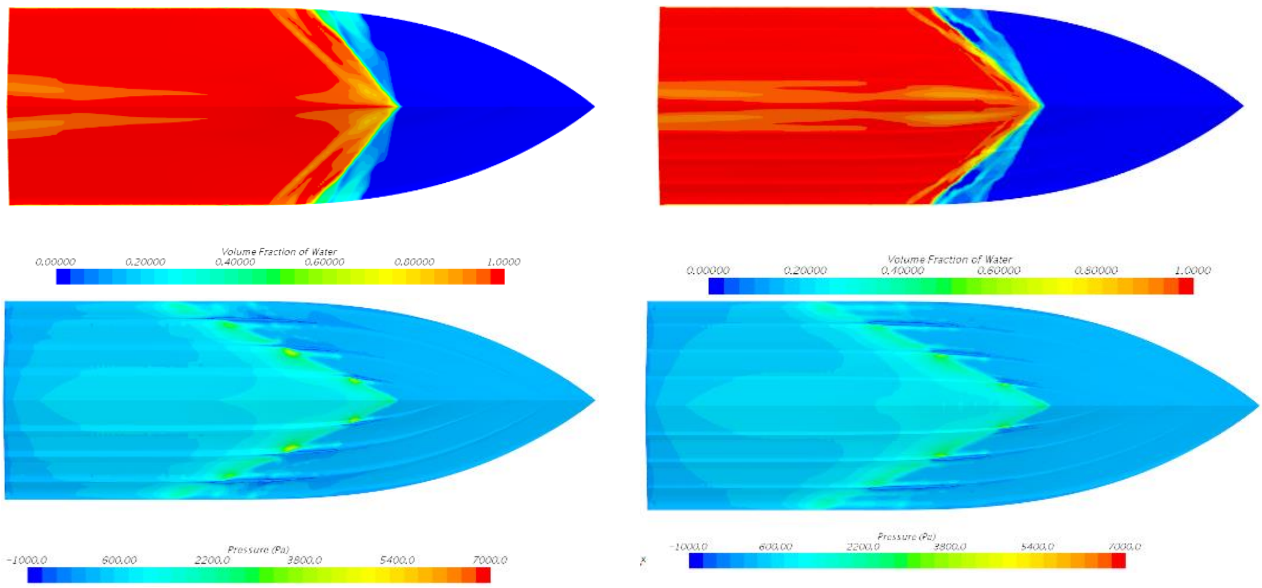
Visualization of the wetted surface area on the hull can be seen in Figure 9. Spray reduction can also be seen in Figure 9. There is spray deflection and spray reduction experienced by model 1 and model 3. Model 3 shows a better reduction than model 1.



(a) (b)

Fig. 9. Comparison results of spray area reduced due to deflection by spray strips at Fr 1.806 for (a) Model 1 and (b) Model 3

For the depiction of WSA, it can be seen through the "Volume Fraction of Water" in Figure 10. The position of the stagnation line is in the area with the greatest pressure. As seen in Figure 10, a comparison of the stagnation line position at Fr 1.806. Each horizontal base of the strip profile shows the greatest pressure shown in red. While the lower pressure is found at the vertical base of the profile strips. That area is the part where there is no water flow because of the deflection that occurs due to the strips.



(a) (b)

Fig. 10. Visualization of Volume Fraction of Water and Pressure at Fr 1.806 for (a) Model 1 and (b) Model 3

Figure 11 shows the components of total drag, namely drag shear and drag pressure expressed in non-dimensional units R/Δ. The drag shear in Kim's experiment shows the largest drag value at high speed. A reduction in drag shear occurred in model 2 and model 3. Model 3 experienced a reduction in frictional resistance of 4% and model 2 by 4.7%.

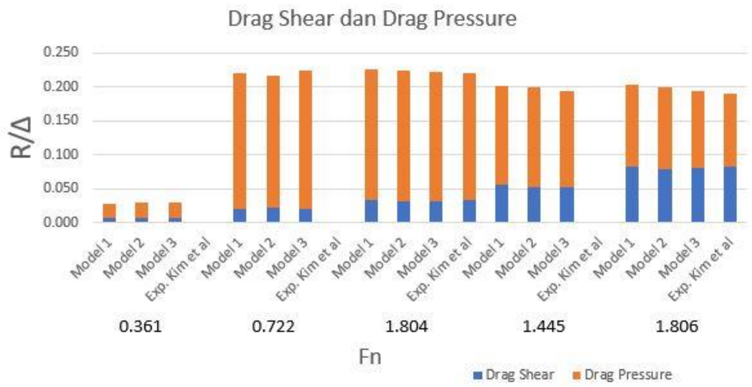
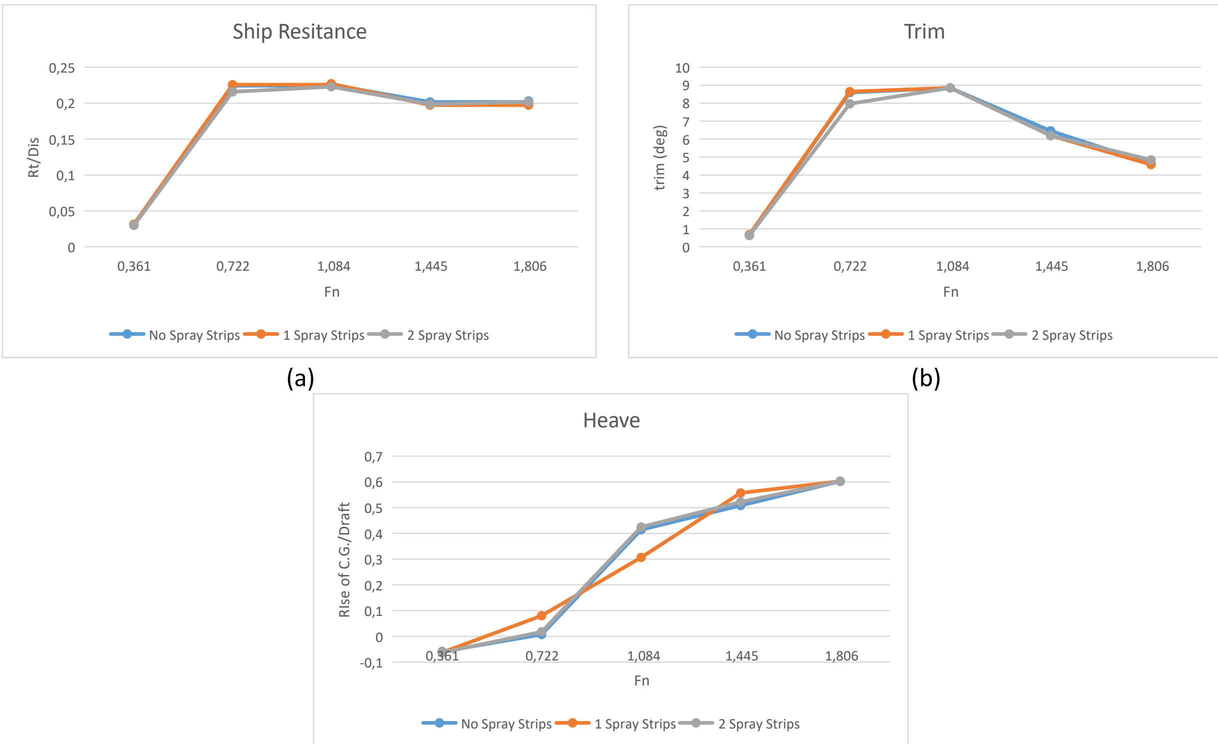


Fig. 11. Comparison of drag shear and drag pressure results

3.3 Effect of Different Number of Strips on the Hull

This study will compare the number of strips to be used on the hull. The profile size of the strips will follow Model 1. So, the model formed in the variation of the number of strips is 1 pair of strips, 2 pairs of strips, and without using strips. The drag, trim, and heave results are shown in Figure 12.

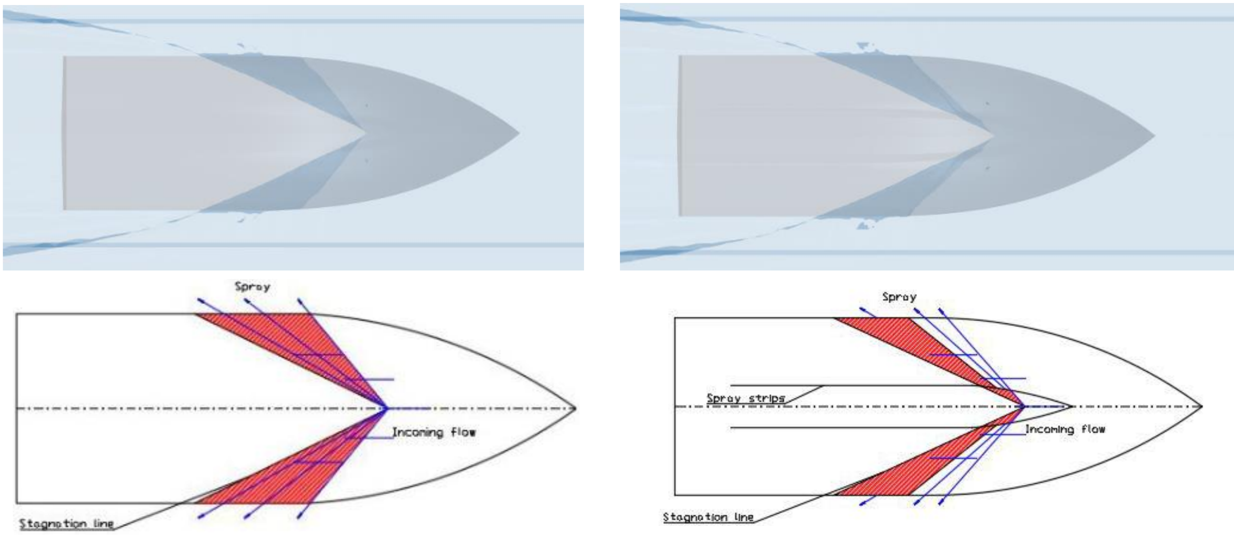


(c)

Fig. 12. Comparison results of numerical simulations on the number of strips variation model (a) total drag, (b) trim, and (c) heave

Reducing the number of strips does not give the same results as reducing drag. As seen from Froude number 0.361 to 1.084, 1 pair of strips has the largest number compared to other models. At Froude Number 0.72, the addition of 1 pair of strips increases drag by 0.8%. While in the planing phase, Fr 1.45, there is a reduction in drag of 2.8% for the addition of 1 pair of strips and 1.5% for 2 pairs of strips. The difference in resistance using 3 pairs of strips and other variations in the number of strips only ranges from 0.3 to 2.7 percent. Therefore, the difference in the number of strips is not too influential on this Deep-V planning hull ship. However, when viewed through the heave graph the results shown are the opposite. It can be seen that there is a considerable range of numbers at Fr 0.722 to 1.084.

Figure 13 illustrates the reduction in spray area due to variations in the number of strips. Increasing the number of strips can reduce the spray area, it can be seen that increasing the number of strips reduces the wetted surface area in the spray area. Changes in spray area that occur with the addition of spray strips are also related to changes in the total resistance that occurs.



(a) (b)

Fig. 13. Comparison results of spray area reduced due to deflection by spray strips at Fr 1.806 for (a) Model without strips and (b) Model with 1 pair of strips

For visualization of Volume Fraction of Water can be seen in Figure 14, it is shown that the spray area that appears is getting narrower with the addition of the number of spray strips. The addition of strips shows a reduction in drag shear. As can be seen in Figure 15, at high speeds the drag shear of the model without strips has a greater value than the model using strips. The addition of strips to the model of 1 pair of strips reduced the drag shear by 2.4% and the drag shear of the model of 2 pairs of strips reduced by 3.5%.

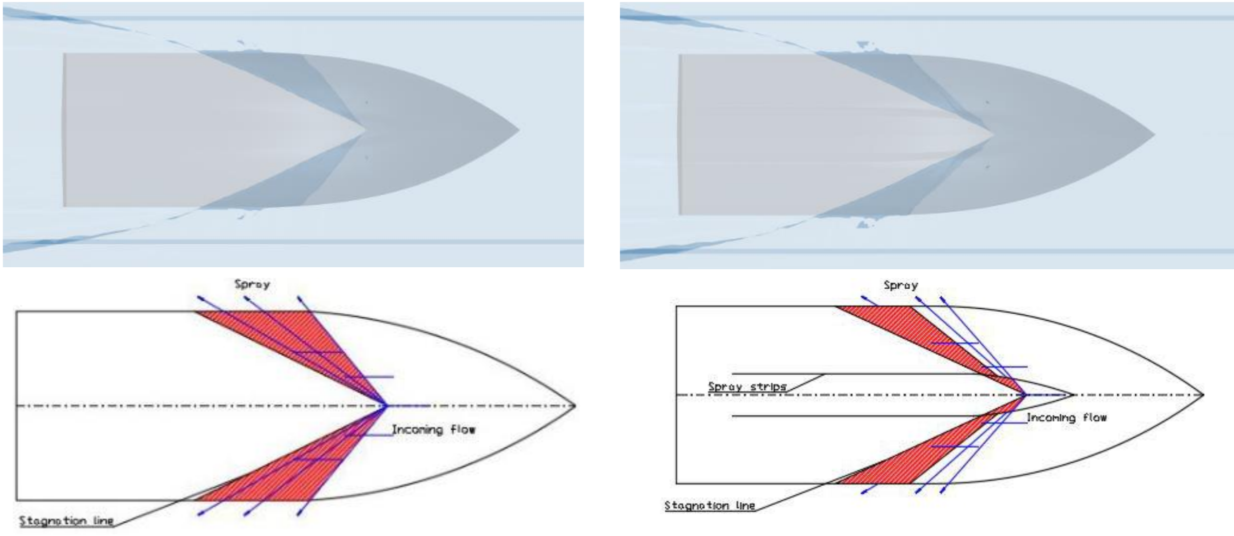


Fig. 14. Visualization of Volume Fraction of Water and Pressure at Fr 1.806 for (a) no strips and (b) 1 pair of strips

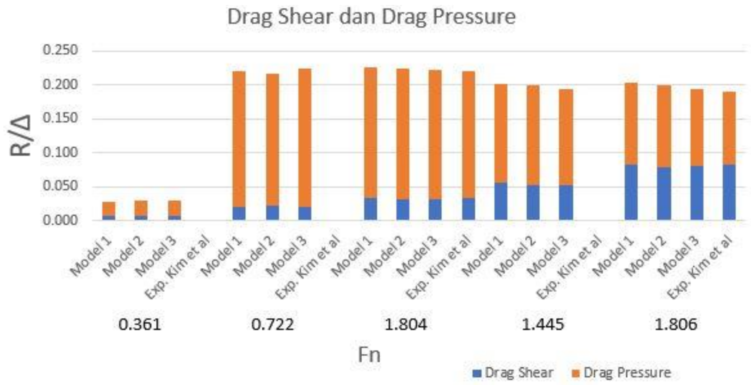


Fig. 15. Comparison of the results of drag shear and drag pressure on ship models with variations in the number of strips

4. Conclusions

The results of CFD research using the overset mesh method are able to provide values that are close to Kim *et al.,*'s [22] research by conducting mesh studies. The results of the calculation of the total resistance produced show a small error value of about 0.96 - 4.37 percent against the experimental data of Kim *et al.,* [22].

In the variation of dimensions, it is found that the best strip profile in reducing total drag is a profile with a size of 0.5 bsr : 1 bsr. This profile is applied to model 3. Model 3 is able to reduce total drag by 3.54 percent against model 2 and 4.29 percent against model 1 at Froude number 1.44. However, when looking at the trim results, it does not show significant differences or values that tend to be similar.

In the study of the variation of the number of strips, a strip profile with a size of 1 bsr : 1 bsr as used in model 1 was used. At Froude number 1.44, the application of 2 pairs of strips can reduce drag by 0.30 percent against deep-v planing hull ships that do not use additional strips on the hull and 1.42 percent against 1 pair of strips. The trim value produced in the study of the variation in the number of strips did not show a significant difference.

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