

Hydrodynamic optimization of a Sweptback Stern Foil for resistance reduction in flat-hull ships: A CFD-based extension of the Hull Vane concept


Rahmat Azis Nabawi^{1,*}, Budi Syahri¹, Yogi Dian Alfana¹ and Donny Fernandez²

¹ Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, Indonesia

² Department of Automotive Engineering, Faculty of Engineering, Universitas Negeri Padang, Indonesia

*Corresponding Author: raazna@ft.unp.ac.id

Received: 26 October 2025; Revised: 07 February 2026; Accepted: 12 February 2026

 Cite this <https://doi.org/10.24036/teknomekanik.v9i1.54872>

Abstract: Flat-hull ships are known to have higher resistance than streamlined hulls. Although the Hull Vane[®] concept has been proven effective as a stern-mounted energy-saving device through pressure-field modification and stern-wave interaction, most previous studies have focused on straight-foil configurations (straight planform). The effect of planform shape optimization, particularly the sweptback configuration, on the hydrodynamic performance of flat-hull ships is limited in the literature. This study modifies the geometry of a Hull Vane[®] into a sweptback stern foil and evaluates its performance using Computational Fluid Dynamics simulations. The results show that a 15° sweptback angle yields the greatest reduction in resistance. Velocity contour analysis shows a narrower wake and a more uniform velocity-gradient distribution in the stern area for the 15° swept-back stern-foil configuration compared to other configurations. Meanwhile, the turbulence length distribution shows a tendency toward reduced intensity of large-scale turbulent structures behind the ship, indicating improved wake-flow characteristics. The identified resistance reduction mechanism primarily stems from improved pressure recovery and modified pressure distribution in the stern area, which is consistent with the working principle of Hull Vane[®]. Optimizing the sweptback planform geometry yields more efficient flow interaction than the straight-foil configuration. These findings indicate that planform optimization is an important design parameter in the development of stern foils to improve the hydrodynamic efficiency of medium-to high-speed commercial vessels.

Keywords: flat-hull ship; flow simulation; energy-saving device; affordable and clean energy; ship resistance reduction

1. Introduction

The weakness of flat-hull ships is that they have greater resistance than streamlined hulls [1], [2]. The greater the resistance of the ship, the greater the propulsion power required to maintain operating speed. This increase in power requirements is directly proportional to the main engine's fuel consumption [3]. The impact is an increase in ship operating costs and exhaust emissions due to higher fuel consumption [4]. Flat-hull ships are becoming increasingly popular due to their ease of production and affordability. One approach to reducing resistance is to increase the length-to-width (L/B) ratio to reduce wave-making resistance. However, increasing the L/B ratio can reduce the ship's transverse stability (decrease in GM value), thus increasing safety risks, especially under certain operating conditions. Therefore, innovations to reduce the resistance of flat-hull ships are essential.

Previous research has shown that installing a Hull Vane[®] on a ship's stern can reduce the ship's resistance through a combination of pressure resistance reduction, trim correction, and positive interaction with the stern wave system [5], [6], [7], [8], [9]. Various Computational Fluid Dynamics (CFD)-based studies, model tests in towing tanks, and full-scale sea trials report a potential reduction in resistance of between 5-10% on commercial ships, and more than 20% on medium to high-speed displacement ships with a Froude number (F_n) between 0.2-0.7 [10], [11]. The Hull Vane[®] installed on the stern generates lift due to the interaction between the stern flow and the ship's wave system. This lift and the resistance force of the foil produce a resultant force that can be decomposed into horizontal and vertical components. At certain angles of attack and Froude numbers, the horizontal component of this force can be positive, contributing as an additional thrust. In addition, the vertical component of this force improves trim and reduces pressure resistance due to stern waves [12].

On flat-hull ships, installing a Hull Vane[®] can reduce resistance by 12.44% [13]. However, under comparable operating conditions, flat-hull ships generally have greater resistance than streamlined-hull ships, mainly due to the dominance of pressure resistance and the more pronounced stern-wave formation. Therefore, further innovation in Hull Vane[®] design is needed to further reduce resistance on flat-hull ships. In this study, the shape of the Hull Vane[®] was modified from straight to sweptback. Unlike previous studies that focused on the straight Hull Vane[®] configuration, this study not only created simple geometric modifications but also systematically evaluated the effects of sweptback-angle variations on the resistance characteristics and wake-flow behavior of flat-hull ships. To date, reports on the influence of sweptback planforms on stern-mounted lifting surfaces for flat-hull ships are still very limited, especially in the context of RANS analysis in the medium-to-high Froude number range. Therefore, this study provides a new contribution to understanding the sensitivity of planform geometry to pressure-recovery-based resistance-reduction mechanisms.

2. Material and methods

2.1 Ship model and variations in sweptback stream foil angle

The ship used as a model in this study is a flat-hull ship, which has previously been studied in terms of hull shape [1], [2] and the application of the Hull Vane[®] with a straight configuration using NACA 4012 foil (Figure 1.b). The main innovation in this research lies in modifying the Hull Vane[®] into a swept-back stern-foil configuration (Figure 1.c). The sweptback angle was varied from 5° to 30° in 5° increments to evaluate its effect on hydrodynamic characteristics. This modification is expected to optimize ship performance by reducing ship resistance. The simulation results of the ship equipped with a sweptback stern foil are compared with a ship without a Hull Vane[®] (Figure 1.a) and a ship equipped with a Hull Vane[®]. The main dimensions of the ship are presented in Table 1.

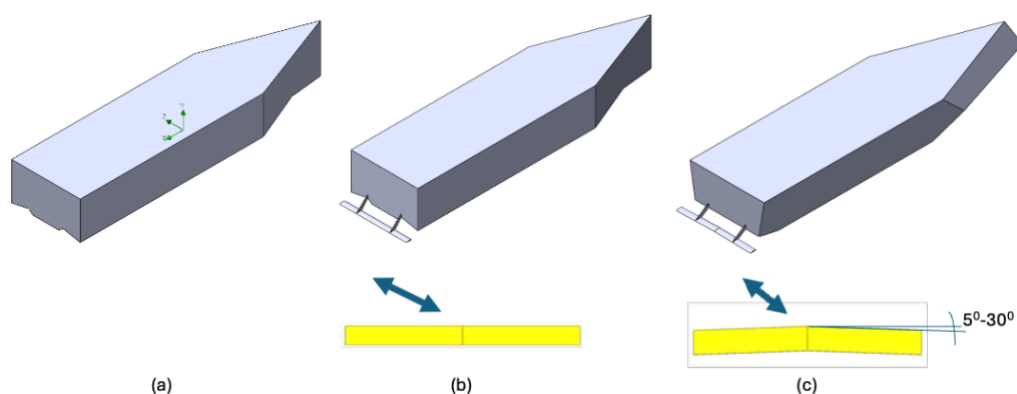


Figure 1. (a) Flat-hull ship without foil, (b) installation of Hull Vane[®] (Straight/Original) [13] and (c) installation of Sweptback stern foil

Table 1. Main dimensions of the ship

Item	Ship	Model	Unit
LoA	12	0.9	m
B	3	0.225	m
H	2.1	0.157	m
T	0.97	0.072	m
Displacement	17609	7.3	kg

2.2 Computational Fluid Dynamics (CFD)

The research was conducted using the CFD method with the SolidWorks Research License from Universitas Negeri Padang. CFD simulations were performed to reveal the resistance and flow phenomena in all research ship models. CFD simulations provided visual data in the form of color illustrations based on fluid pressure [14], [15]. The simulation parameters used in SolidWorks Flow Simulation are presented in Table 2.

Table 2. Parameter condition of the simulation [13]

Analysis type	External
Consider closed cavities	<ul style="list-style-type: none"> - Exclude cavities without flow conditions - Exclude internal space
Time-dependent	<ul style="list-style-type: none"> - Total analysis time: 60 sec. - output time step: 1 sec.
Gravity	Y component: -9.81 m/s^2
Flow analysis type	Free surface
Two immiscible fluids	<ul style="list-style-type: none"> - Air - Water
Velocity parameters	Velocity in X direction
Boundary Condition	<ul style="list-style-type: none"> - Inlet: Velocity with defined Froude Number - Outlet: Constant - Wall: No-slip condition - Hull and Hull Vane: No-slip condition

Numerical simulations were performed on all ship model configurations within a Froude number (Fn) range of 0.5-1.0 to represent medium to high speed operating conditions, where wave resistance and pressure components begin to dominate over frictional resistance. The selection of this Fn range was based on ship hydrodynamics theory, which states that at $Fn > 0.4$, there is a significant increase in wave-making resistance, and flow interaction at the stern becomes more sensitive to additional geometric modifications such as stern foils [16], [17]. The Fn range of 0.5-1.0 was also chosen because flat-hull ships operate within that speed range. The simulation was performed using the Reynolds-Averaged Navier-Stokes (RANS) approach with a two-equation turbulence model commonly used in ship resistance prediction and stern wake analysis. The RANS approach has been proven to reliably represent viscous flow phenomena and pressure distribution in ship resistance studies and energy-saving devices (ESDs) [18], [19].

The computational domain follows ITTC guidelines for CFD simulation [20]. The ship model, foil, and walls were set as slip-free conditions. The inlet was placed 1 L upstream with a flow velocity equal to the ship's speed, while the outlet was located 2 L downstream as an open boundary with constant pressure. The bottom, top, and side walls were each 1 L from the keel, 0.25 L from the deck, and 1 L from the ship's longitudinal axis.

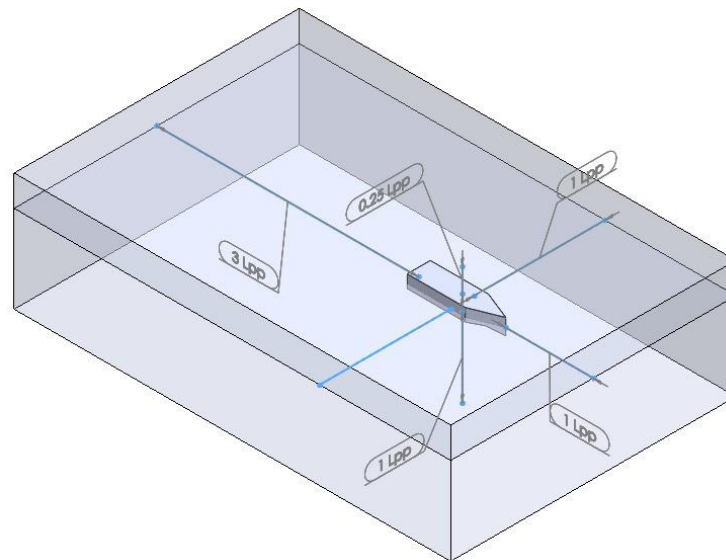


Figure 2. Computational domain [13]

In this study, the computational grid was created by referring to the meshing strategy used in previous Hull Vane[®] studies to ensure numerical consistency and reliability [13]. Grid independence studies were conducted using three mesh densities (coarse, medium, fine) for the $F_n = 0.7$ configuration as a representative condition. The difference in resistance values between the medium and fine meshes was less than 2%, so a mesh with ± 3.4 million cells was selected as a compromise between accuracy and computational efficiency. In the area around the sweptback stern foil, the mesh was locally refined to more accurately represent the velocity gradient, pressure distribution, and wake structure (Figure 3). Meanwhile, a larger grid size was applied to the area near the computational domain boundary to reduce computational costs and prevent artificial wave reflection at the domain boundary [17], [20], [21]. This meshing strategy strikes a good balance between numerical accuracy and computational efficiency while maintaining the stability of the free-surface simulation. Numerical model validation was performed by comparing the resistance results of the baseline configuration and the conventional Hull Vane[®] with previously published results [13]. The maximum deviation obtained was within an acceptable range for steady-state RANS simulations, so the numerical model was deemed adequate for parametric analysis in this study.

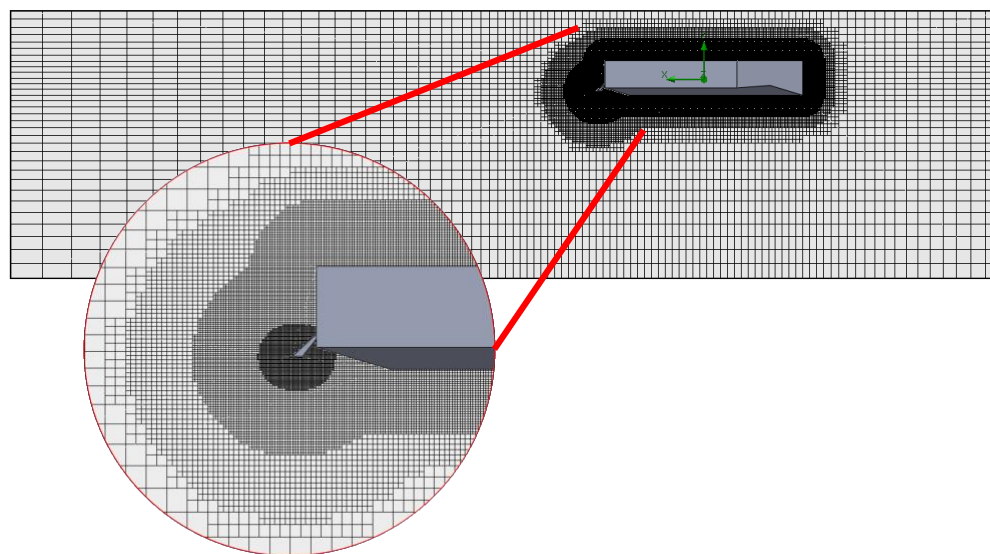


Figure 3. Meshing

3. Results and discussion

The simulation results show that the resistance increases nonlinearly with the increase in F_n for all variations of the sweptback stern foil angle (Figure 4), in line with the hydrodynamic force formulation that depends on the square of the flow velocity [22]. Among all configurations, the 15° angle consistently produced the lowest resistance values across almost the entire tested F_n range tested. At $F_n = 1$, for example, the 15° configuration produced a resistance of 15.13 N, which was lower than the 30° configuration at 16.68 N. At small angles of 5° - 10° , the resistance was relatively higher than at 15° , indicating that the pressure distribution and lift force contribution were not yet optimal. Conversely, at large angles of attack of 20° - 30° , the increase in resistance is more pronounced, especially at high F_n , likely due to increased pressure resistance and three-dimensional flow-separation effects. These findings indicate that there is an optimum angle at which the interaction between the wake flow and the foil produces the most effective pressure recovery mechanism. Overall, the 15° configuration provides the most stable minimum-resistance performance across the entire F_n range, confirming that sweptback-angle optimization is a crucial design parameter in the development of foils to reduce resistance on flat-hull ships.

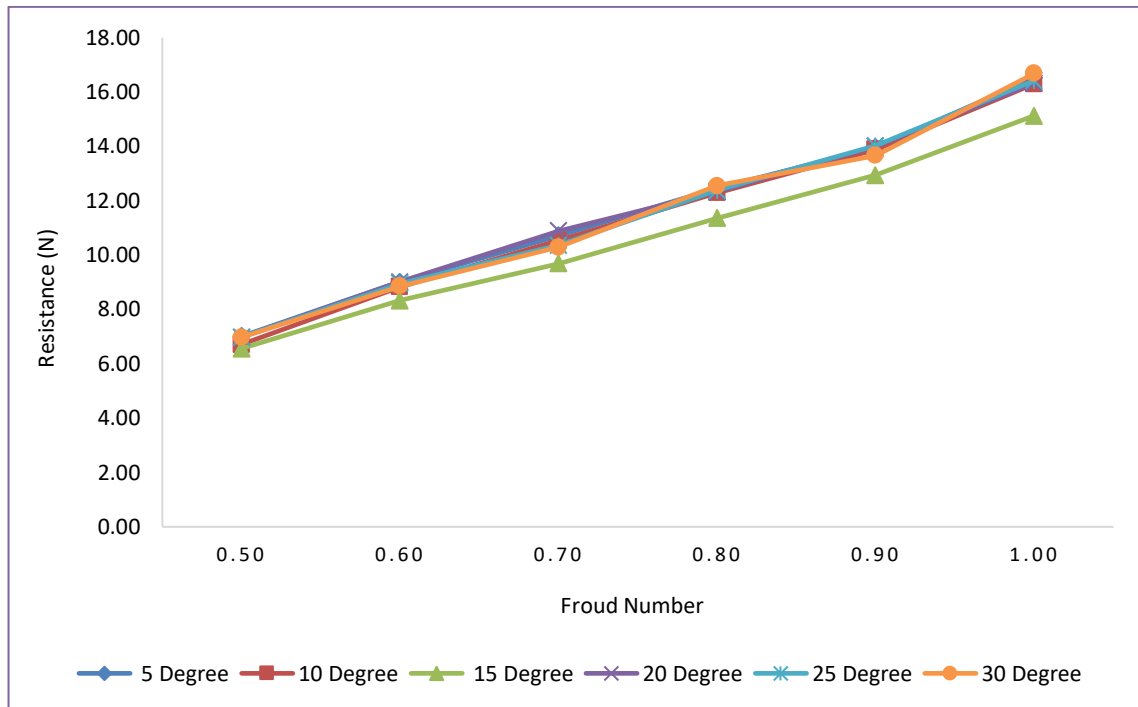


Figure 4. Resistance as a function of F_n for different sweptback stern foil angles

Figure 5 shows a comparison of resistance between a ship without foils, Hull Vane[®], and a 15° sweptback stern foil in the Froude number (F_n) range of 0.5–1. The data for ships without foils and for the Hull Vane[®] refer to results from previous studies, which are used as comparative data to evaluate the development of sweptback stern foil geometry in this study. In general, resistance increases with increasing F_n across all configurations. The ship without foils shows the highest resistance values across the entire F_n range, especially at $F_n \geq 0.7$. Hull Vane[®] consistently reduces resistance compared to ships without foils. The 15° sweptback stern foil configuration in this study resulted in a greater resistance reduction than the Hull Vane[®], especially at F_n 0.8–1. This indicates that planform optimization improves hydrodynamic efficiency by enhancing pressure distribution and wake control at the stern.

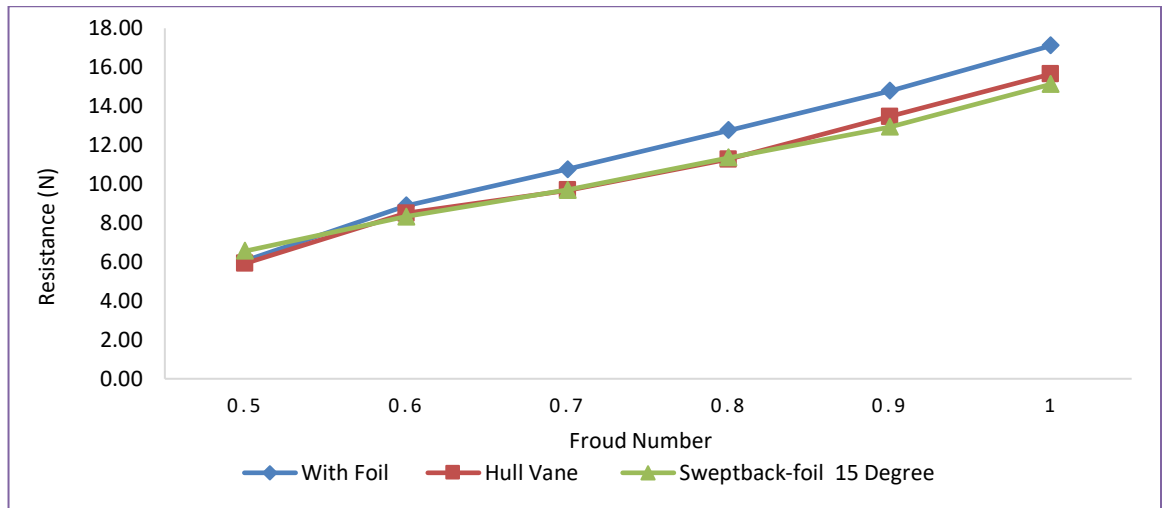


Figure 5. Comparison of resistance total versus Froude number for baseline configuration (without stern foil), conventional Hull Vane, and sweptback stern foil 15°

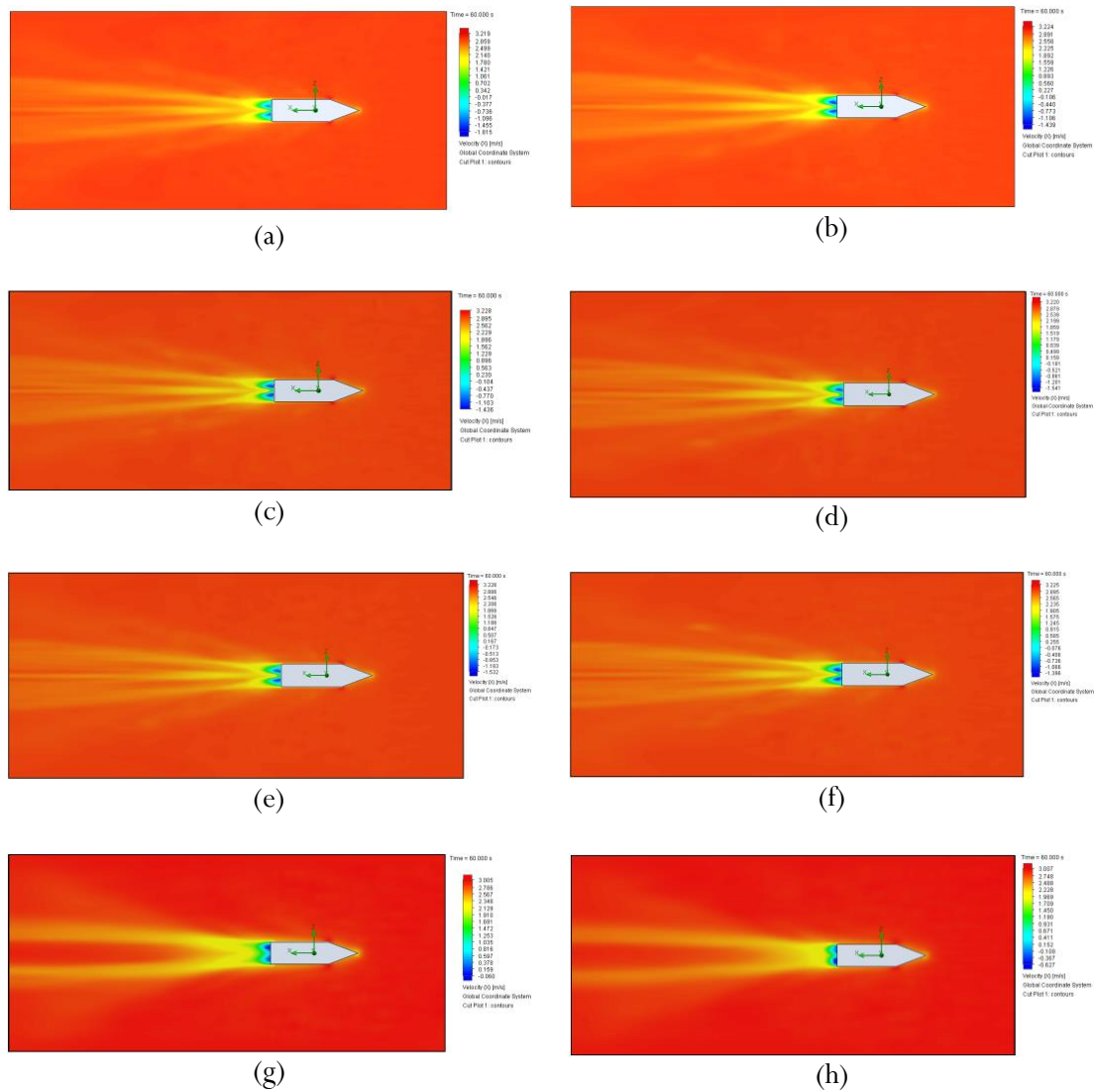


Figure 6. Differences in flow velocity after passing through the ship (a) sweptback-foil 5 degree, (b) sweptback-foil 10 degree, (c) sweptback-foil 15 degree, (d) sweptback-foil 20 degree, (e) sweptback-foil 25 degree, (f) sweptback-foil 30 degree, (g) without foil, and (h) Hull Vane®

CFD simulation results based on velocity contours (Figure 6) show that the installation of sweptback stern foils and Hull Vane[®] significantly modifies the velocity distribution and wake characteristics in the stern area compared to a ship without foils. On ships without foils, a wider, longer velocity-deficit zone is visible behind the ship, indicating a loss of flow momentum and associated with high-pressure resistance due to suboptimal pressure recovery. On ships equipped with Hull Vane[®], the wake zone appears more focused and narrowed, with flow acceleration around the foil, indicating the formation of circulation and a more favorable pressure distribution. Hydrodynamically, this phenomenon is consistent with the working principle of the Hull Vane[®], which modifies the pressure field at the stern, reduces the amplitude of stern waves, and improves pressure recovery, thereby reducing resistance. Ships equipped with a 15° sweptback stern foil show the most stable velocity distribution pattern, with a relatively narrower wake and a smoother velocity gradient transition compared to other angles. This indicates more efficient flow interaction and a potentially more optimal lift-to-resistance ratio. At larger angles (25°-30°), although local acceleration around the foil increases, there is a tendency for the velocity gradient behind the foil to widen, indicating an increase in viscosity losses and the potential for increased induced resistance. Overall, these velocity visualization results support the previous obtained quantitative resistance data and are consistent with the findings of previous Hull Vane[®] CFD studies, which show that resistance reduction is primarily due to wake modification and improved stern pressure distribution, rather than solely due to the addition of direct thrust [23].

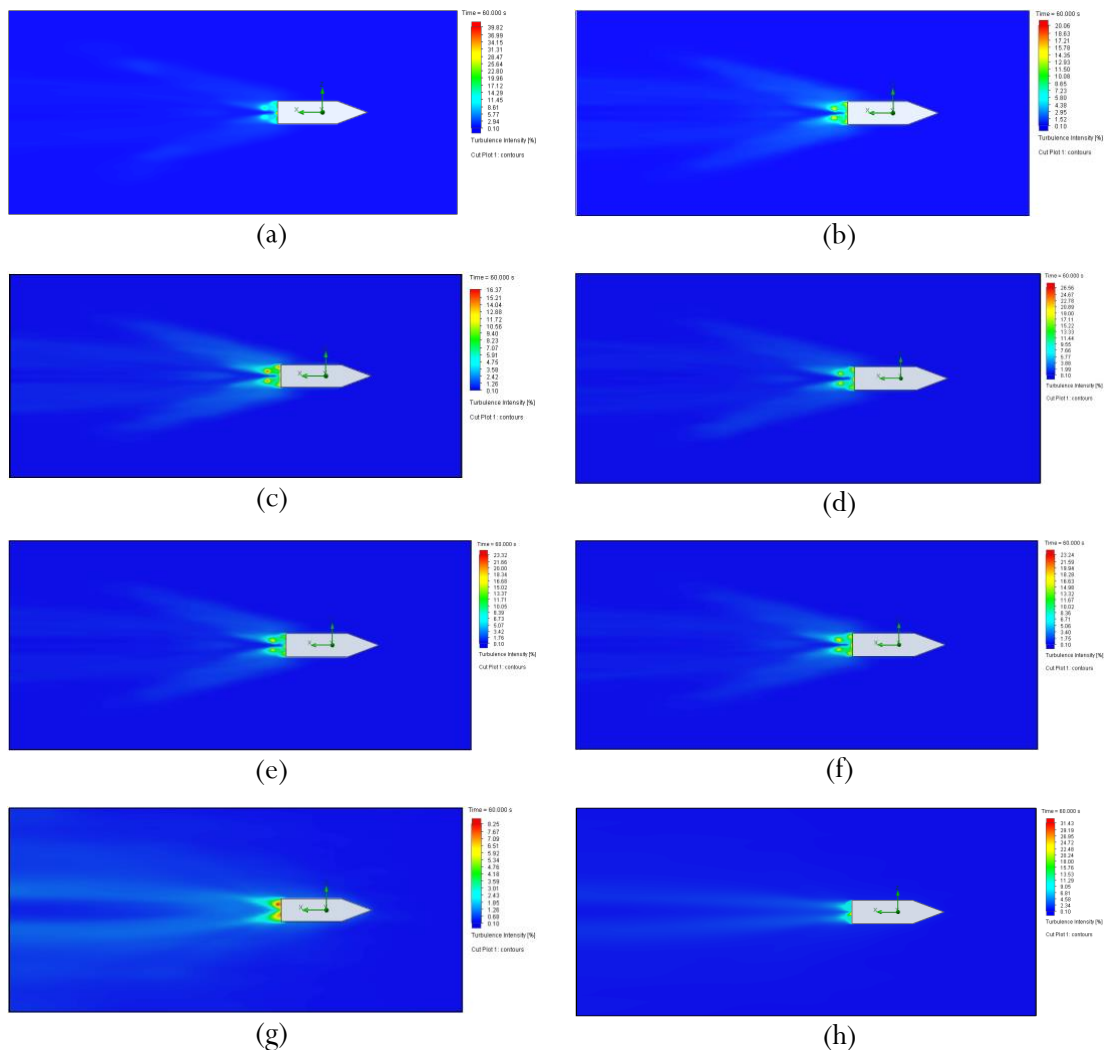


Figure 7. Differences in turbulence length (a) sweptback-foil 5 degree, (b) sweptback-foil 10 degree, (c) sweptback-foil 15 degree, (d) sweptback-foil 20 degree, (e) sweptback-foil 25 degree, (f) sweptback-foil 30 degree, (g) without foil, and (h) Hull Vane[®]

On ships without foils, the wake area has a greater turbulence length and extends behind the stern. This indicates the development of a larger turbulence scale and a less effective pressure recovery process, resulting in less controlled flow in the stern area and contributing to increased pressure resistance. Conversely, on a 15° sweptback stern foil, the high turbulence length zone is more localized around the trailing edge of the foil, and the wake appears narrower and dissipates more quickly. This pattern shows that flow modification by the foil can control turbulence development and reduce the formation of large vortex structures at the stern. These findings are in line with the resistance graph results, which show the greatest reduction at an angle of 15°. They are consistent with the velocity contours, which show a more focused wake and a more stable velocity gradient distribution. Thus, based on the consistent quantitative data (resistance graphs) and CFD visualizations (velocity and turbulence length), the 15° sweptback stern foil configuration provides the most efficient flow interaction, with improved pressure recovery and better control of turbulence development behind the ship.

The results of this study show that the sweptback stern foil configuration at a 15° angle provides the greatest reduction in resistance compared to ships without foils or a conventional Hull Vane® (straight foil). The trend of resistance reduction obtained is consistent with the working principle of Hull Vane® as described by van Oossanen and Uithof [10] that the main mechanism of resistance reduction is not solely due to additional direct thrust, but mainly through modification of the pressure distribution at the stern, reduction of stern wave amplitude, and increased pressure recovery. The CFD velocity contour results in this study show that the configuration without foils produces a wider, longer velocity-deficit zone in the stern wake, indicating a loss of flow momentum and a greater contribution to pressure resistance. In contrast, the 15° swept-back stern foil configuration produces a narrower wake and a more stable velocity-gradient distribution. This phenomenon is in line with the results of research reported by Tripathi and Vijayakumar [24] that installation of stern foils can reduce residual resistance through constructive interaction with the stern wave system and improved pressure field behind the ship. The turbulence length distribution shows a tendency for a reduction in the characteristic turbulence scale in the wake region at a 15° sweptback configuration, indicating a more controlled pressure recovery process compared to the baseline configuration. However, a detailed analysis of vortex structures was not performed in this study. The simulation was performed under steady-state and static trim conditions. The effects of trim dynamics and sinkage were not accounted for in this study, so the results obtained represent hydrodynamic trends under ideal conditions. Evaluation under free-to-trim conditions warrants further research.

4. Conclusion

This study confirms that the installation of stern foil devices is effective in reducing a ship's resistance through pressure field modification and wake control, as described in previous Hull Vane® studies. Based on CFD simulation results, the sweptback stern foil configuration at 15° showed the best performance compared to configurations without foils or Hull Vane®, as indicated by lower resistance, a narrower wake, a more stable velocity distribution, and better control of turbulence length in the stern area. These findings are consistent with the theory that, in the medium-to high-Froude-number range, pressure and wave-resistance components become dominant, so that lifting-surface-based devices contribute significantly to improving hydrodynamic efficiency. Compared to previous research on Hull Vane®, this study shows that optimizing the planform geometry through a sweptback design can increase resistance-reduction effectiveness without changing the basic working principle. Thus, this study not only reinforces the validity of the stern foil concept as an energy-saving device but also makes a new contribution to the development of designs that optimize planform angles and shapes for ships with a dominant pressure resistance. These findings have practical implications for improving energy efficiency and reducing fuel consumption in medium-to high-speed operational ships.

Author's declaration

Author contribution

Rahmat Azis Nabawi: Conceptualization, methodology, validation, formal analysis, writing-original draft, and writing – review & editing. **Budi Syahri:** Software, formal analysis, and writing – review & editing. **Yogi Dian Alfana:** Software, formal analysis, and writing – review & editing. **Donny Fernandez:** Software, formal analysis, and writing – review & editing.

Funding statement

The authors would like to thank Lembaga Penelitian dan Pengabdian Masyarakat Universitas Negeri Padang for funding this work under the contract number: 1826/UN35.15/LT/2024.

Data availability

The design of the ship and sweptback stern foil can be requested by readers for further research through an official request to the corresponding author.

Acknowledgements

The authors would like to thank the Manufacturing Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang for granting permission to use its facilities for CFD simulations.

Competing interest

The authors declare that there are no conflicts of interest in the research and publication of this article.

Ethical clearance

Not applicable.

AI statement

This article is the original work of the author without using AI tools for writing sentences and/or creating/editing tables and figures in this manuscript.

Publisher's and Journal's note

Universitas Negeri Padang as the publisher, and Editor of Teknomekanik state that there is no conflict of interest towards this article publication.

References

- [1] R. A. Nabawi, S. Syahril, and S. Salmat, "Stability Study of Flat Hull Ship for Fishing Tourism," *Teknomekanik*, vol. 3, no. 2, pp. 80–85, Dec. 2020, <https://doi.org/10.24036/teknomekanik.v3i2.9272>
- [2] R. A. Nabawi, S. Syahril, and R. Refdinal, "The Study of Shape Flat Hull Ship Toward Resistance," *TEM Journal*, pp. 1669–1673, Nov. 2022, <https://doi.org/10.18421/TEM114-30>

- [3] Y. Xue *et al.*, “A combined experimental and numerical approach to predict ship resistance and power demand in broken ice,” *Ocean Engineering*, vol. 292, p. 116476, Jan. 2024, <https://doi.org/10.1016/j.oceaneng.2023.116476>
- [4] L. Bilgili, “Determination of the weights of external conditions for ship resistance,” *Ocean Engineering*, vol. 276, p. 114141, May 2023, <https://doi.org/10.1016/j.oceaneng.2023.114141>
- [5] A. G. Avci and B. Barlas, “An experimental investigation of interceptors for a high speed hull,” *International Journal of Naval Architecture and Ocean Engineering*, vol. 11, no. 1, pp. 256–273, Jan. 2019, <https://doi.org/10.1016/j.ijnaoe.2018.05.001>
- [6] C. Celik, D. B. Danisman, P. Kaklis, and S. Khan, “An investigation into the effect of the hull vane on the ship resistance in openfoam,” *Sustainable Development and Innovations in Marine Technologies - Proceedings of the 18th International Congress of the International Maritime Association of the Mediterranean, IMAM 2019*, pp. 136–141, 2020, <https://doi.org/10.1201/9780367810085-17>
- [7] M. A. Murdianto, M. A. Budiyanoto, and M. F. Syahrudin, “Application of stern foil on full draft patrol vessel at high speed condition using computational fluid dynamics (CFD) method,” in *AIP Conference Proceedings*, 2020, pp. 1–6. <https://doi.org/10.1063/5.0013750>
- [8] M. A. Budiyanoto, M. F. Syahrudin, and M. A. Murdianto, “Investigation of the effectiveness of a stern foil on a patrol boat by experiment and simulation,” *Cogent Eng.*, vol. 7, no. 1, pp. 1–17, Jan. 2020, <https://doi.org/10.1080/23311916.2020.1716925>
- [9] H. Dwiputera, N. Y. Prawira, M. A. Budiyanoto, and M. Arif, “Effect of Angle of Attack Variation of Stern Foil on High-Speed Craft on Various Speed with Computational Fluid Dynamics Method,” *International Journal of Technology*, vol. 11, no. 7, pp. 1359–1369, 2020, <https://doi.org/10.14716/ijtech.v11i7.4467>
- [10] K. Uithof, P. Van Oossanen, N. Moerke, P. G. Van Oossanen, and K. S. Zaaijer, “an Update on the Development of the Hull Vane ®,” *9th International Conference on High-Performance Marine Vehicles (HIPER)*, Athens, 2014.
- [11] K. Uithof, N. Hagemester, B. Bouckaert, P. G. Van Oossanen, N. Moerke, and B. V. Hull Vane, “A systematic comparison of the influence of the hull Vane®, interceptors, trim wedges, and ballasting on the performance of the 50M amercr series #13 patrol vessel,” in *RINA, Royal Institution of Naval Architects - Warship 2016: Advanced Technologies in Naval Design, Construction, and Operation*, 2016.
- [12] P. Van Oossanen, “Vessel provided with a foil situated below the waterline,” 2006
- [13] R. A. Nabawi, Syahril, and Primawati, “Study Reduction of Resistance on The Flat Hull Ship of The Semi-Trimaran Model: Hull Vane Vs Stern Foil,” *CFD Letters*, vol. 13, no. 12, pp. 32–44, Dec. 2021, <https://doi.org/10.37934/CFDL.13.12.3244>
- [14] Y. K. Demirel, O. Turan, and A. Incecik, “Predicting the effect of biofouling on ship resistance using CFD,” *Applied Ocean Research*, vol. 62, pp. 100–118, 2017, <https://doi.org/10.1016/j.apor.2016.12.003>
- [15] Muhammad Arif Budiyanoto, Naufal Yudha Prawira, and Haekal Dwiputra, “Lift-to-Drag Ratio of the Application of Hydrofoil With Variation Mounted Position on High-Speed Patrol Vessel,” *CFD Letters*, vol. 13, no. 5, pp. 1–9, Jun. 2021, <https://doi.org/10.37934/cfdl.13.5.19>
- [16] O. M. Faltinsen, *Hydrodynamics of High-Speed Marine Vehicles*. Cambridge University Press, 2006. <https://doi.org/10.1017/CBO9780511546068>
- [17] ITTC, “Recommended Procedures and Guidelines: Practical Guidelines for Ship CFD,” in *International Towing Tank Conference*, 2011, pp. 1–18.
- [18] F. Stern, R. V. Wilson, H. W. Coleman, and E. G. Paterson, “Comprehensive Approach to Verification and Validation of CFD Simulations—Part 1: Methodology and Procedures,” *J. Fluids Eng.*, vol. 123, no. 4, pp. 793–802, Dec. 2001, <https://doi.org/10.1115/1.1412235>
- [19] L. Larsson and E. Baba, *Ship resistance and flow computations*, vol. 5. 1996.

- [20] ITTC, “Report 7.5-03-02-04: Practical Guidelines for Ship Resistance CFD,” in *ITTC Quality System Manual - Recommended Procedures and Guidelines*, 2014, pp. 1–10.
- [21] ITTC, “Report 7.5-03-02-03: Practical Guidelines for Ship CFD Applications,” in *ITTC – Recommended Procedures and Guidelines*, 2011, pp. 1–18.
- [22] S. Oyuela, H. R. D. Ojeda, F. P. Arribas, A. D. Otero, and R. Sosa, “Investigating Fishing Vessel Hydrodynamics by Using EFD and CFD Tools, with Focus on Total Ship Resistance and Its Components,” *J. Mar. Sci. Eng.*, vol. 12, no. 4, p. 622, Apr. 2024, <https://doi.org/10.3390/jmse12040622>
- [23] H. Ferré, P. Goubault, C. Yvin, and B. Bouckaert, “Improving the nautical performance of a surface ship with the Hull Vane[®] appendage,” *ATMA*, vol. 2738, no. 1, 2019.
- [24] S. Tripathi and R. Vijayakumar, “Numerical and experimental study of stern flaps impact on resistance and propulsion of high–speed displacement ships,” *Ocean Engineering*, vol. 292, p. 116483, Jan. 2024, <https://doi.org/10.1016/j.oceaneng.2023.116483>