OpenFOAM Simulation and Validation of Results for Vortex Pumps with Winglets

Symulacje w OpenFOAM i walidacja wyników dla pomp wirowych o swobodnym przepływie z przesłonami

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This research presents OpenFOAM computational fluid dynamics (CFD) simulations used to investigate flow phenomena in SuperVortex pumps—vortex pumps equipped with partial impeller channel shrouds (winglets). The numerical model was developed using the Multiple Reference Frames (MRF) approach combined with the Realizable k-ε turbulence model, which provided the best agreement with experimental data while maintaining reasonable mesh sizes. A comprehensive mesh sensitivity analysis was conducted to determine the optimal balance between accuracy and computational cost. Depending on geometric complexity, the computational mesh contained between 8 and 12 million elements. The simulations showed that shrouds on the suction side of the impeller blades significantly reduced over-tip leakage between impeller channels, thereby enhancing pump performance. At the Best Efficiency Point (BEP), the deviation from experimental data was particularly low—less than 1% for head and approximately 0.5–1% for efficiency. Model validation across the full operating range yielded average deviations of 5.8% for head and 8.4% for efficiency compared to experimental measurements.
Keywords: vortex pump, winglets, OpenFOAM, CFD

W niniejszej pracy przedstawiono symulacje numeryczne przepływu (CFD) wykonane w programie OpenFOAM, mające na celu zbadanie zjawisk przepływowych w pompach Super-Vortex – czyli pompach wirowych o swobodnym przepływie, wyposażonych w częściowe pokrywy kanałów wirnika (winglets). Model numeryczny opracowano z wykorzystaniem metody wielu układów odniesienia (MRF) oraz modelu turbulencji Realizable k-ε który zapewnił najlepszą zgodność z danymi eksperymentalnymi przy zachowaniu rozsądnych rozmiarów siatki obliczeniowej. Przeprowadzono szczegółową analizę czułości siatki w celu określenia optymalnego kompromisu między dokładnością a kosztem obliczeniowym. W zależności od złożoności geometrii siatka obliczeniowa zawierała od 8 do 12 milionów elementów. Symulacje wykazały, że zastosowanie winglets od strony ssawnej łopatek wirnika znacząco ogranicza przeciek międzykanałowy ponad łopatkami, co przyczynia się do poprawy wydajności pompy. W punkcie najlepszej sprawności (BEP) odchylenie od danych eksperymentalnych było szczególnie niskie – poniżej 1% dla podnoszenia oraz około 0,5-1% dla sprawności. Walidacja modelu w pełnym zakresie pracy pompy wykazała średnie odchylenia rzędu 5,8% dla podnoszenia i 8,4% dla sprawności względem wyników pomiarów eksperymentalnych.
Słowa kluczowe: pompa wirowa o swobodnym przepływie, winglety, OpenFOAM, CFD

Introduction to Vortex Pumps

Vortex pumps are specialized centrifugal pumps designed for handling challenging fluids containing solid particles, fibrous materials, or gas inclusions [1, 2]. Their distinctive design features significant clearance between the impeller and pump casing, creating an unobstructed flow path from inlet to outlet.

These pumps serve critical functions in various industries:

- Municipal wastewater management
- Mining and mineral processing
- Food processing and agriculture
- Construction

Despite operating at lower efficiency (30-55%) compared to conventional centrifugal pumps (70-85%), their superior clogging resistance makes them indispensable where reliability is paramount [3, 4]. According to EU projections, the market for vortex pumps is expected to grow approximately 18% by 2030 [5, 6].

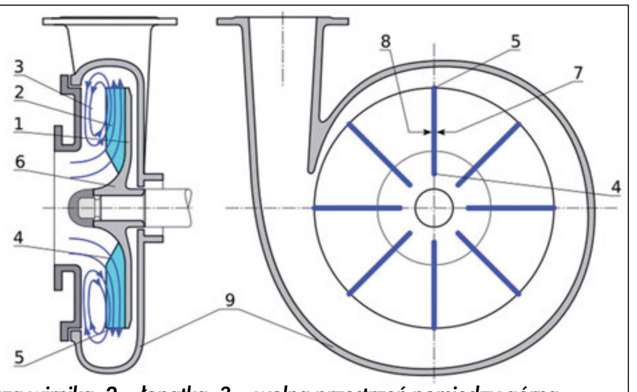

Fig. 1.
Free-flow pumps:
1 – rear disc of the impeller, 2 – blade, 3 – free space between the upper part of the blade and the casing, 4 – leading edge, 5 – trailing edge, 6 – hub, 7 – active surface of the blade, 8 – passive surface of the blade, 9 – spiral casing
Rys. 1. Pompy o swobodnym przepływie: 1 – tylna tarcza wirnika, 2 – łopatka, 3 – wolna przestrzeń pomiędzy górną częścią łopatki a obudową, 4 – krawędź natarcia, 5 – krawędź spływu, 6 – piasta, 7 – powierzchnia czynna łopatki, 8 – powierzchnia bierna łopatki, 9 – obudowa spiralna

The key operating principle of vortex pumps (Figure 1) involves the semi-open impeller creating strong rotational flow in the space between impeller and pump casing, generating a pressure gradient that transports fluid and solids through the volute [7, 8]. This

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indirect energy transfer mechanism trades efficiency for superior handling of challenging media.

The primary design challenge lies in balancing free passage for solid handling with energy efficiency [9]. Recent developments include the SuperVortex concept with partial channel shrouds (winglets) aimed at reducing over-blade flow energy losses while maintaining adequate passage [10].

Computational Methodology

Numerical simulations were performed using OpenFOAM to investigate flow behavior in vortex pumps equipped with different winglet configurations. A detailed three-dimensional model was constructed, comprising rotating (impeller) and stationary (volute and pipe sections) domains, representing realistic pump operating conditions (Figure 2).

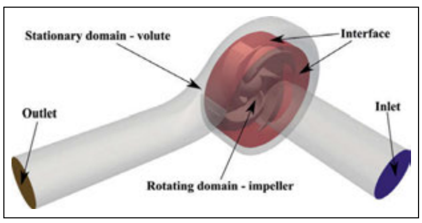

Fig. 2.
Computational model of vortex pump showing boundary conditions and domain divisions
Rys. 2. Model obliczeniowy pompy wirowej o swobodnym przepływie z zaznaczonymi warunkami brzegowymi i podziałem obszaru obliczeniowego

Simplifications were introduced to reduce geometric complexity while preserving hydraulic accuracy:

- The impeller fastening screw was replaced by a streamlined fairing.
- The clearance between the rear impeller disk and pump casing was omitted, as it mainly affects mechanical rather than hydraulic losses.

Inlet and outlet pipes, each four diameters long, ensured fully developed velocity profiles and minimized boundary condition effects.

The computational domain was divided into:

- A rotating zone containing the impeller.
- A stationary zone including the volute and connected pipes.

The interface between these zones was positioned near the pump suction side, following the guidance of Krishtop et al. [11], enhancing accuracy in pumps with large impeller-to-casing clearances.

All simulations used the steady-state Multiple Reference Frame (MRF) method, implemented through the modified `MRFSimpleFoam` solver, which is based on the SIMPLE algorithm. This approach captures rotational effects without resorting to transient modeling, offering a good balance between accuracy and computational cost.

Water was used as the working fluid, with a density ρ = 998.2 kg/m^3 and dynamic viscosity μ = 0.001003 Pa·s. Wall roughness was neglected, as its influence is minimal in vortex pumps with significant clearance.

Boundary conditions:

- Inlet: Uniform velocity, 5% turbulence intensity.
- Outlet: Fixed static pressure (0 Pa gauge).
- Rotating region: 2890 rpm.
- Walls: No-slip.
- Interface: Conservative flux interpolation.

Convergence was assessed by stabilization of total pressure, flow rate, and torque over at least 2000 iterations with residuals below 10^{-4}.

Results and Discussion

Mesh Generation and Independence Study

The computational grid was generated using OpenFOAM's SnappyHexMesh utility. It consisted predominantly of hexahedral and polyhedral elements in central flow regions, with refined tetrahedral and prismatic layers adjacent to walls to accurately capture boundary layer effects.

A thorough mesh sensitivity analysis was conducted to determine mesh independence, assessing stability of key performance parameters (head, efficiency) for meshes ranging from 0.5 to 14 million cells. Results were compared with experimental data obtained from our specialized test rig [12], demonstrating that approximately 6 million cells achieved mesh independence, with relative errors below 0.5% for head and approximately 4% for efficiency (Figure 3).

Final simulations used meshes ranging from 8–12 million cells depending on geometry complexity, representing a compromise between precision and computational effort. Mesh quality metrics were carefully monitored throughout the domain to ensure simulation stability and accuracy. The maximum orthogonality was maintained below 75, minimum volume ratio was kept above 0.01, and maximum skewness remained under 4, adhering to OpenFOAM's best practices for complex turbomachinery simulations.

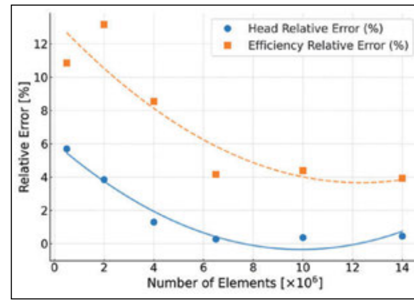

Fig. 3.
Mesh sensitivity analysis demonstrating independence for head and efficiency
Rys. 3. Analiza czułości siatki wykazująca niezależność wyników wysokości podnoszenia i sprawności od liczby elementów siatki

Turbulence Model Selection and Validation

Three RANS turbulence models were evaluated: Standard k–ε, Realizable k–ε, and k–ω SST. The Realizable k–ε model demonstrated the best agreement with experimental data, particularly near the Best Efficiency Point (BEP), as illustrated in Fig. 4. This model was especially advantageous for the current application because maintaining y+ values close to 1 throughout the entire domain proved challenging with the complex pump geometry when using SnappyHexMesh. The Realizable k–ε model's wall functions provided more consistent results in these conditions compared to the k–ω SST model, which typically requires finer near-wall resolution.

Comparative analysis revealed that the Realizable k–ε model achieved deviations below 1% for head and efficiency at BEP conditions, while Standard k–ε showed deviations of approximately 3.2% for head and 4.5% for efficiency. The k–ω SST model performed intermediately with deviations of 2.1% for head and 3.2% for efficiency. As shown in Fig. 4a, larger discrepancies appeared at flow rates far from optimal points, especially at low flows—a common issue in CFD pump modeling. The efficiency predictions followed similar trends (Fig. 4b), with all models showing greater deviation at the extremes of the operating range.

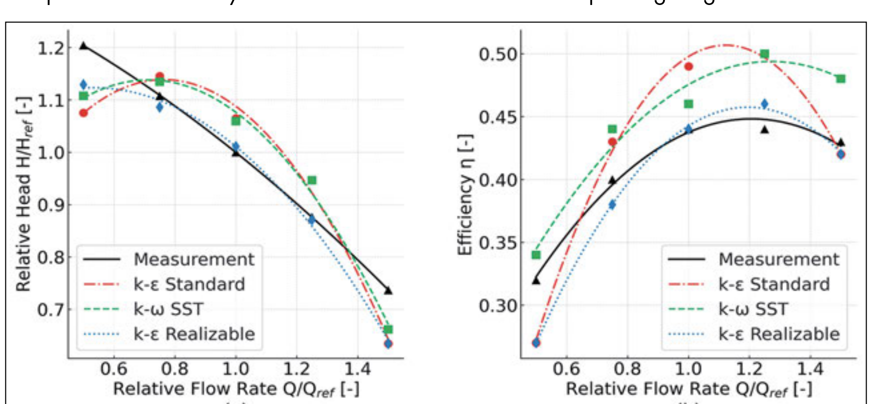

Fig.4.
Comparison between experimental measurements and CFD predictions using different turbulence models: (a) Relative head curves (H/H_{opt} vs. Q/Q_{opt}); (b) Efficiency curves (η vs. Q/Q_{opt})
Rys. 4. Porównanie wyników pomiarów eksperymentalnych i predykcji CFD przy użyciu różnych modeli turbulencji: (a) Krzywe względnej wysokości podnoszenia (H/H_{opt} względem Q/Q_{opt}); (b) Krzywe sprawności (η względem Q/Q_{opt})

This validated numerical model ensured accurate predictions of pump performance within the recommended operating range (0.8Q to 1.2Q), providing a reliable foundation for analyzing flow phenomena in vortex pumps with various winglet configurations. Given its minimal deviation at BEP and acceptable accuracy across the range, the Realizable k–ε model was deemed sufficiently reliable for further analysis.

Flow Structure Analysis

The validated CFD model revealed key flow patterns explaining performance differences between standard and SuperVortex impellers. Two representative cases were analyzed: the reference impeller without winglets and the optimized impeller with suction side winglets.

In the reference impeller without winglets (Fig. 5), fluid flows substantially over blade tips from pressure to suction side of adjacent channels. This cross-channel leakage causes significant energy losses as demonstrated by Gerlach [14], resulting in reduced head generation and lower hydraulic efficiency.

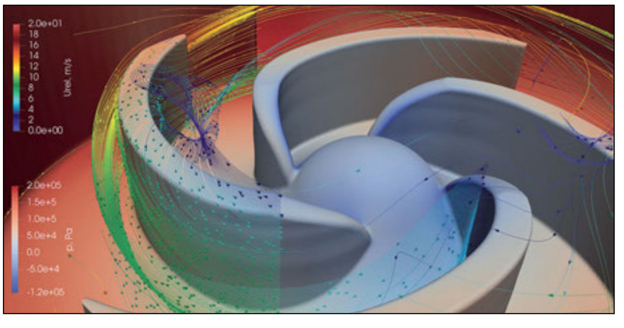

Fig. 5. Streamlines in reference impeller without winglets
Rys. 5. Linie prądu w wirniku referencyjnym bez wingletów

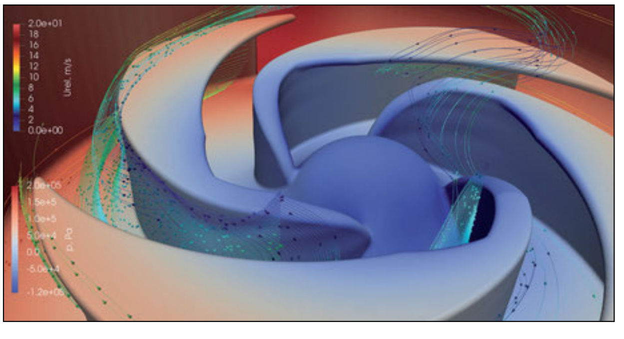

Fig. 6. Streamlines in impeller with suction side winglets
Rys. 6. Linie prądu w wirniku z wingletami po stronie ssawnej

The impeller with suction side winglets (Fig. 6) effectively reduces this cross-channel flow, directing more energy into useful work. The winglets create a partial barrier that guides flow through the intended path while maintaining adequate clearance for solid particles, intercepting leakage flow without compromising the pump's solid-handling capabilities.

Quantitative analysis confirmed this observation. The internal flow coefficient (ratio of pump outlet flow to impeller outlet flow) increased from 39.2% for the reference impeller to 52.6% for the optimized winglet design, indicating reduced recirculation losses. Pressure side winglets proved ineffective (36.1%), while dual-sided winglets showed only moderate improvement (42.8%).

These flow structures align with theoretical descriptions in literature [13, 14, 10], confirming that suction side winglets provide the optimal balance between maintaining solid-handling capabilities while mitigating efficiency disadvantages inherent to vortex pump designs.

Conclusions

This study demonstrated that OpenFOAM provides an effective framework for simulating complex flow phenomena in vortex pumps with winglets. The following conclusions can be drawn:

1. The Realizable k–ε turbulence model achieved sufficient accuracy for capturing the dominant vortical structures in SuperVortex pumps, with deviations below 1% for head and efficiency at BEP conditions.
2. Mesh sensitivity analysis established that approximately 8-12 million elements provide an optimal balance between computational cost and solution accuracy, with relative errors stabilizing below 0.5% for head and approximately 4% for efficiency.
3. Steady-state MRF simulations proved adequate for comparative analysis, though transient approaches could offer higher fidelity for time-dependent phenomena as noted by Krishtop et al. [11].
4. Quantitative flow analysis confirmed experimental findings, revealing that the internal flow coefficient (ratio of pump outlet flow to impeller outlet flow) increased from 39.2% for the reference impeller to 52.6% for the optimized suction-side winglet design.
5. Flow visualizations clearly demonstrated that winglets on the suction side effectively reduce cross-channel flow, while pressure-side winglets proved ineffective (36.1% internal flow coefficient) and dual-sided winglets showed only moderate improvement (42.8%).

The developed numerical methodology provides a reliable foundation for future optimization studies. Potential directions for future work include: (1) transient simulations to capture time-dependent vortical structures, (2) integration of automatic optimization algorithms for winglet geometry, (3) extension to two-phase flow modeling for realistic solid-liquid mixtures, and (4) investigation of scale effects for industrial applications. The present work confirms that computational approaches can effectively guide the design of more efficient vortex pumps while maintaining their critical solid-handling capabilities.

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