Design Optimization of Jet Fuel Pump for Aviation

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Boeing 777[1]

Motivations and Objectives

Jet fuel pumps play a critical role in the safe and efficient operation of commercial aviation. The performance and reliability of these pumps directly impact aircraft operation, fuel consumption, and overall flight safety. As demands for efficiency, reliability, and environmental sustainability continue to increase in the aviation industry, the optimization of jet fuel pump designs becomes paramount.

This report presents a comprehensive study on the optimization of jet fuel pump design utilizing advanced turbomachinery design software, computational fluid dynamics (CFD) simulation tools, and optimization algorithms. CFturbo's integration with SimericsMP and the Sandia National Laboratories' DAKOTA optimizer offers a robust and adaptable framework for meeting the performance requirements and enhancing the efficiency of jet fuel pumps.

CFturbo provides a powerful platform for the rapid and automated design of turbomachinery components, allowing for the generation of geometric models tailored to specific performance requirements and constraints. SimericsMP, a state-of-the-art CFD software package, enables detailed analysis and 3D simulation of fluid flow phenomena within the jet fuel pump, providing valuable insights into flow behavior, pressure distribution, and performance characteristics.

Integrating DAKOTA, a comprehensive and open-source optimization toolkit, further enhances the design process by facilitating the exploration of design parameter space and the identification of optimal solutions. Through the iterative application of design exploration and optimization techniques, this study aims to improve the efficiency and reliability of jet fuel pumps while meeting stringent industry standards and operational performance requirements.

Baseline Design

The jet fuel pump must be strategically designed to meet the performance requirements of the fuel system architecture, providing a consistent delivery of pressurized fuel to the engine. Considering a specified design point [2][3] with a mass flow rate of 2.5 kilograms per second, a total pressure rise of 2 bar, and a rotational speed of 10,000 revolutions per minute, and jet fuel A-1 as the operating fluid, a Baseline design of the centrifugal impeller and outlet volute were generated using CFturbo's automatic design completion feature with minor manual adjustments. A standard leakage flow path was constructed around the impeller's primary flow path and hub and shroud solids, and an inlet and outlet pipe were added to the Baseline design for CFD simulation purposes.

Figure A and **Figure B** show the Baseline design 3D view and meridional view, respectively.

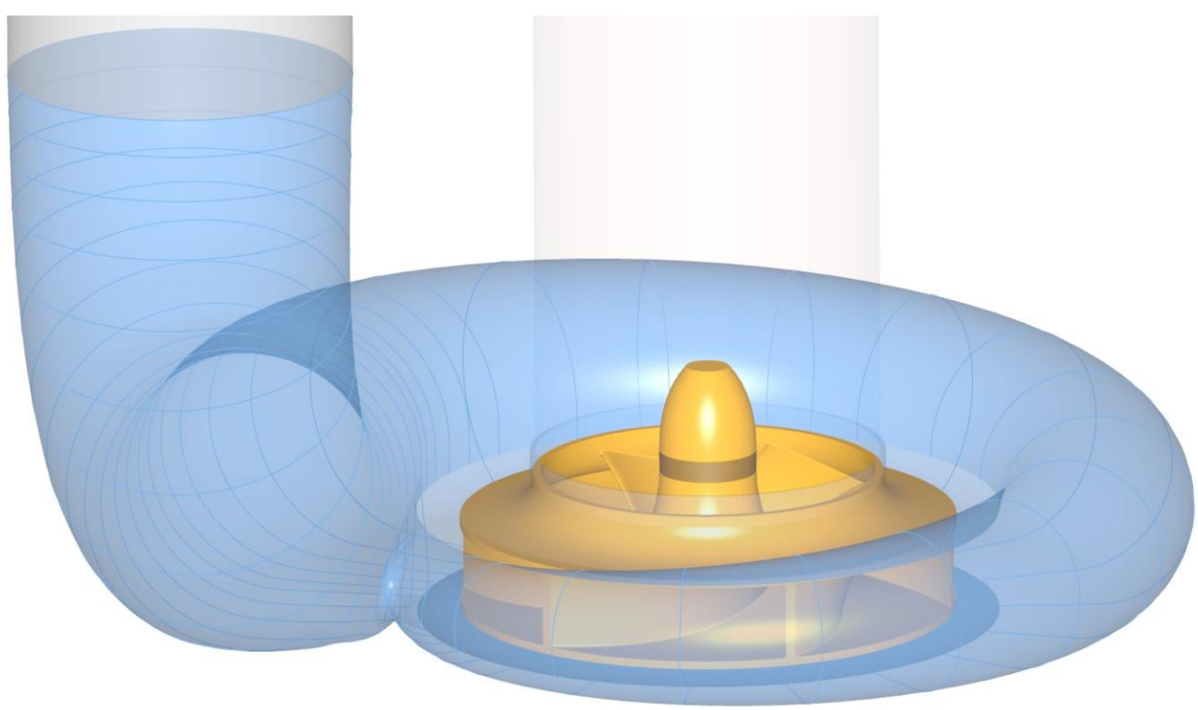

Figure A: Baseline Design – 3D View

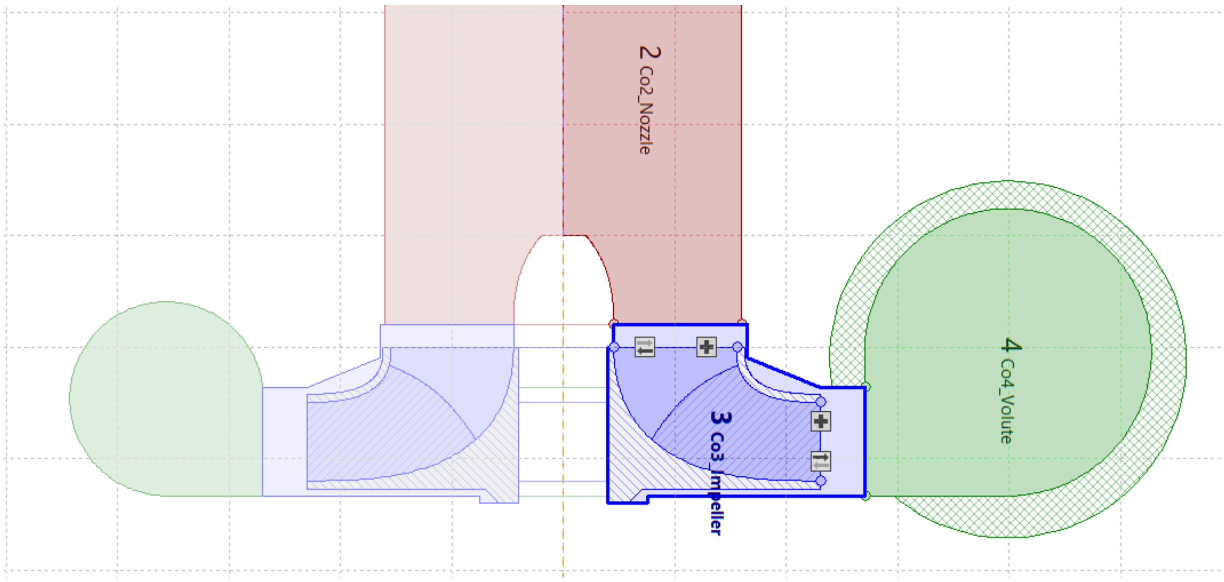

Figure B: Baseline Design – Meridional View

A performance map for the Baseline design, with and without a secondary flow path, was constructed using CFturbo SMP steady-state and transient CFD simulations to see how the pump would operate at varying rotational speeds.

Figure C and **Figure D** show performance curves for 6000, 8000, 10000, and 12000 rpm. We see an excellent initial design for the nominal speed at 10000 rpm. The performance chart highlights the slight yet expected discrepancy between steady-state and transient CFD results, as well as the performance drop with the inclusion of a secondary flow path.

Design Optimization

The DAKOTA design optimization began with a Latin hypercube sampling (LHS) of 300 CFturbo designs excluding secondary flow path to ensure seamless CFturbo geometry creation. Eight continuous design parameters were selected for variation and given a minimum and maximum bound for the sampling to explore.

The blade number, a discrete variable, was also chosen for variation. These design parameters, their initial values, and the minimum and maximum bounds are displayed in **Table A**.

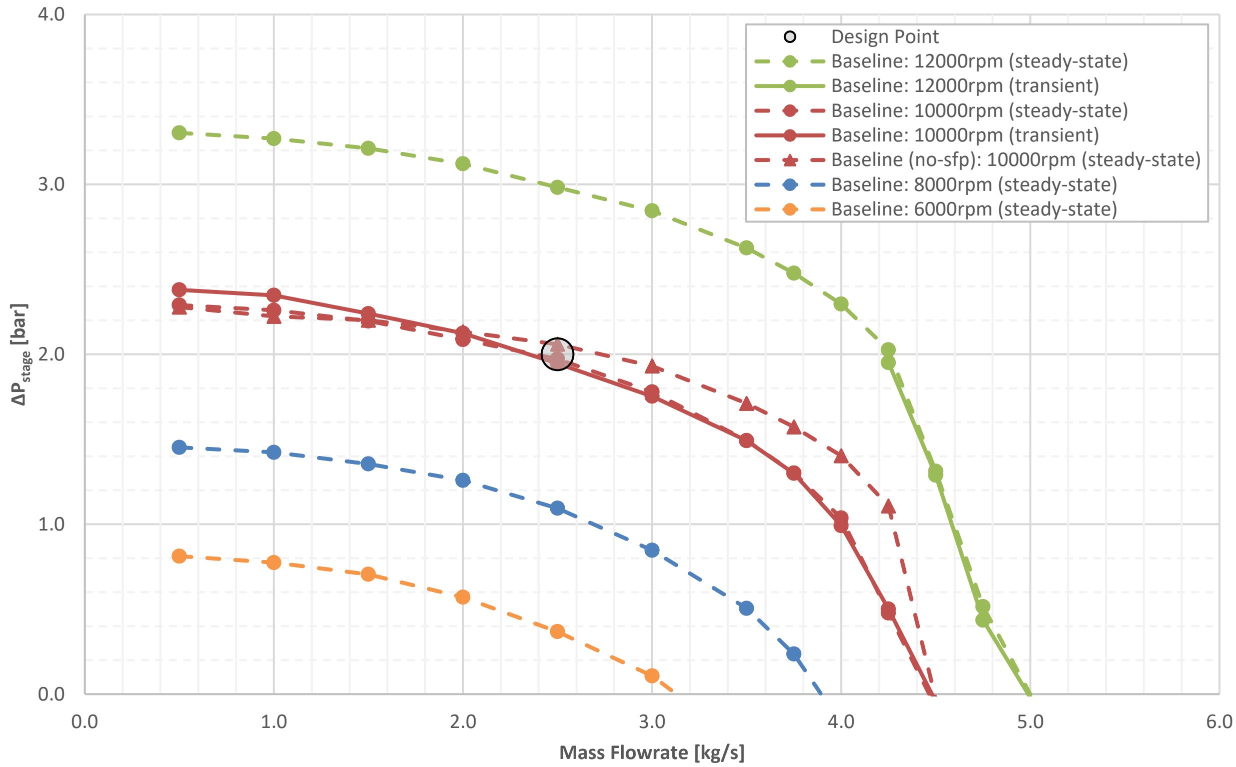

Figure C: Total Pressure Difference Across Stage – Baseline Design

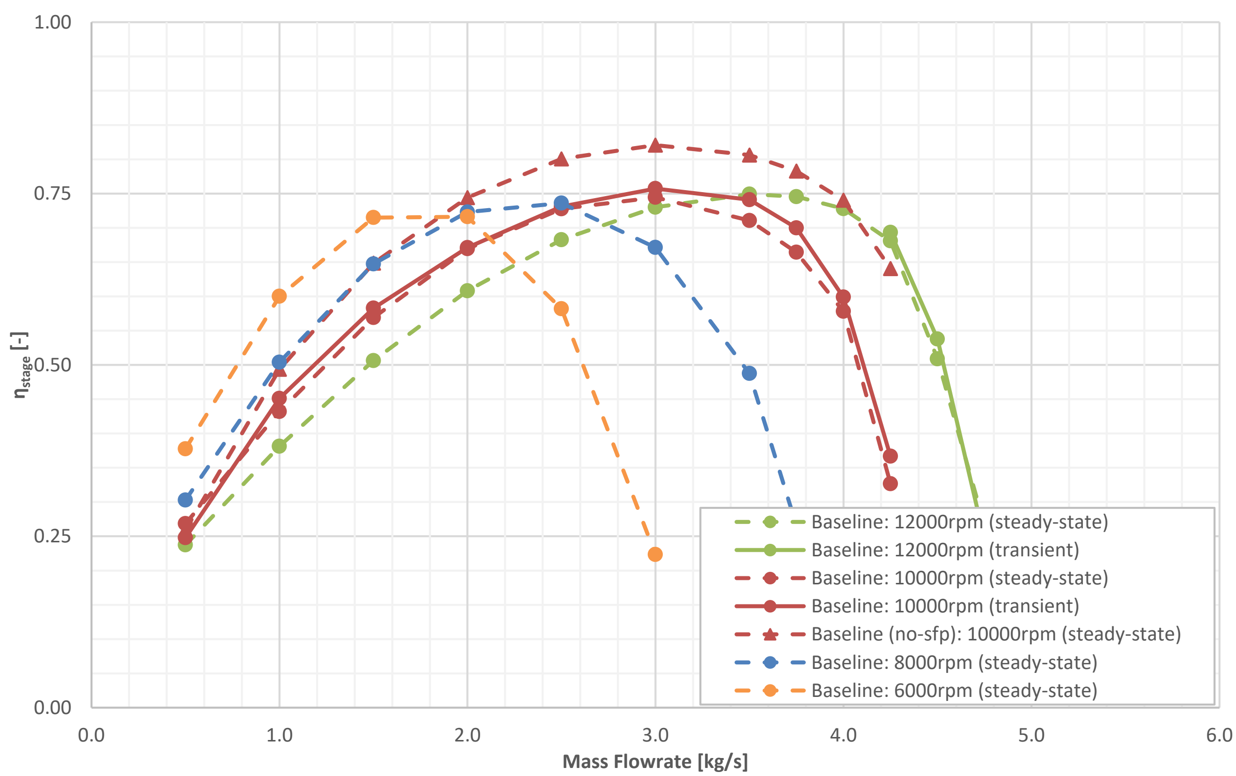

Figure D: Stage Efficiency – Baseline Design

Each LHS design underwent a 500 numerical iteration steady-state simulation using Simerics MP to evaluate performance, each using a mesh with approximately 2 million nodes. After the LHS, the most efficient designs with five blades, six blades, and seven blades underwent a surrogate-based efficient global optimization (EGO) to maximize total-to-total efficiency while staying under a performance range of 2.1 bar.

Design Parameter	Units	Baseline	Minimum	Maximum
Impeller Suction Diameter	mm	31	25	35
Impeller Outlet Width	mm	7	5	10
Impeller Outer Diameter	mm	46	40	60
Impeller Axial Extension	mm	8.5	8.5	15
Impeller Blade Trailing Edge Angle	°	32.6	30	60
Impeller Blade Wrap Angle	°	85.0	80	110
Impeller Blade Number	-	6	5	7
Volute Swirl Exponent	-	1.0	0.0	2.0
Volute Diffuser Outlet Diameter	mm	32	20	40

Table A: Design Parameter Optimization Bounds

Finally, the most efficient design within our performance range went through a gradient-based CONMIN to ensure local optimization. The results from the LHS, EGO, and CONMIN are displayed in **Figure E**.

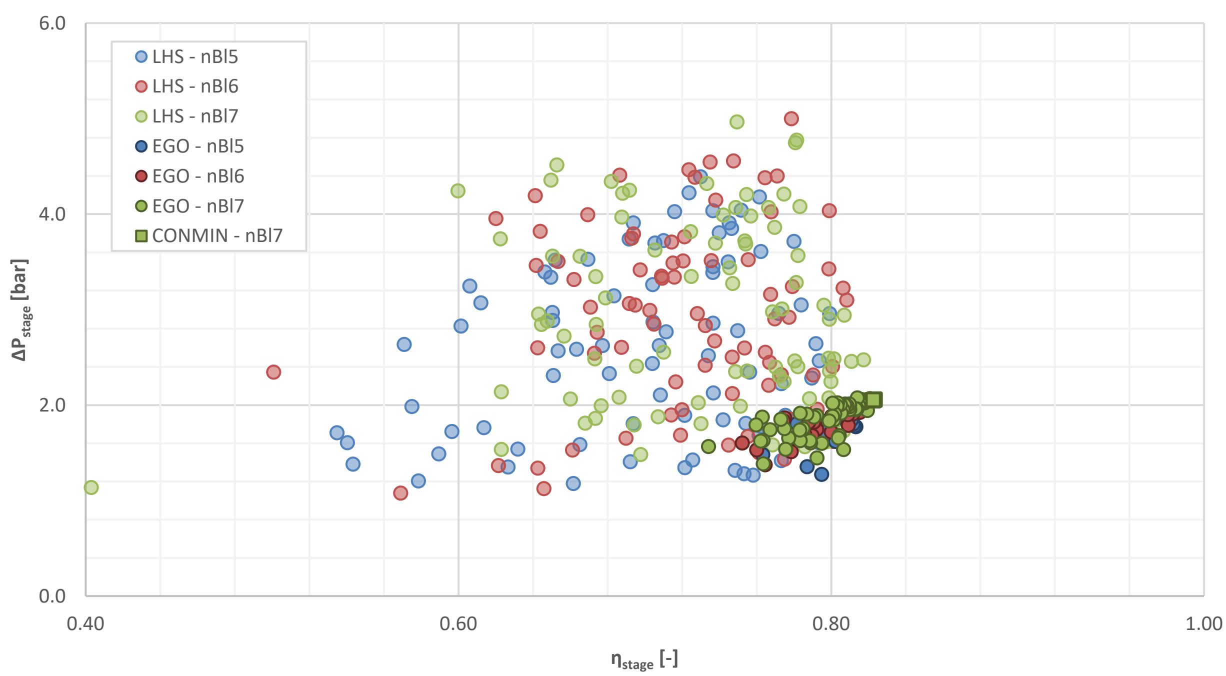

Figure E: LHS, EGO, CONMIN Performance Results

Key Results

After the optimization, four highly efficient, feasible designs were selected, and transient simulations were performed to provide a more accurate performance approximation. The transient simulations utilized a total of 360 timesteps, a second-order upwind scheme for the velocity calculation, and a first-order upwind scheme for the pressure calculation. Out of the optimized designs, the ***Optimized4*** design met the performance requirement and had the broadest operating range for optimal efficiency.

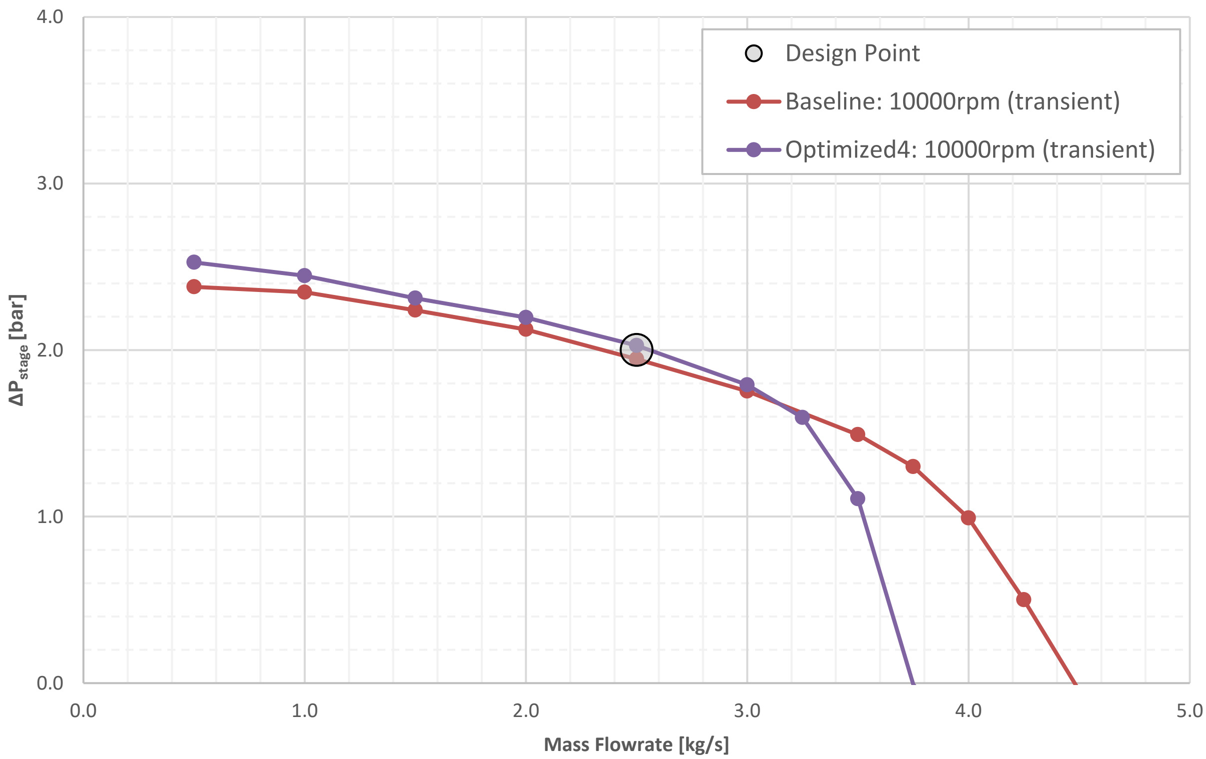

Figure F: Total Pressure Difference Across Stage – **Optimized4** vs. **Baseline**

The total pressure difference across the stage, from the inlet of *Co2_Nozzle* to the outlet *of Co4_Volute* in **Figure B**, is displayed above in **Figure F**. There is a tradeoff in performance range when maximizing the stage efficiency at a singular operating point (in this case, the design point); the Baseline design maintains a positive total pressure difference at higher mass flowrates. More optimization constraints may be applied to mitigate this loss in performance, but the study's computational requirement would increase significantly.

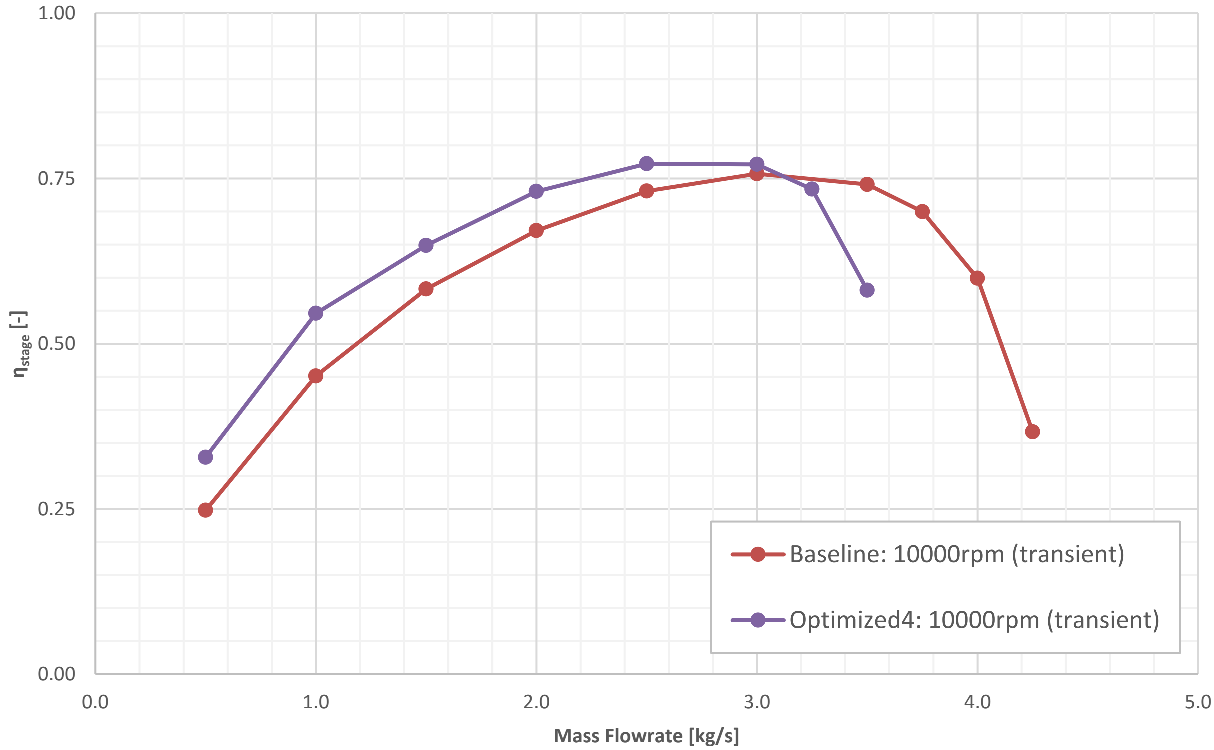

Figure G: Stage Efficiency – **Optimized4** vs. **Baseline**

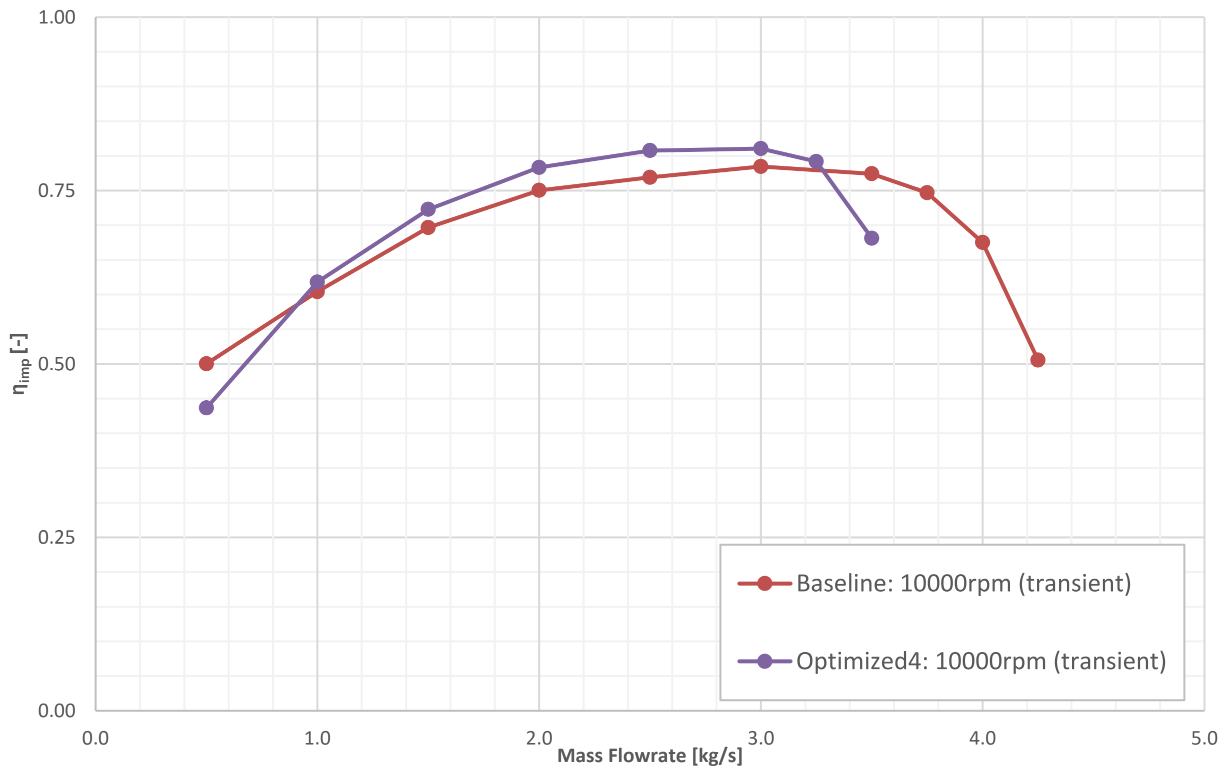

Figure H: Impeller Efficiency – **Optimized4** vs. **Baseline**

The stage efficiency and impeller efficiency of both the Baseline design and the Optimized4 design are displayed in **Figure G** and **Figure H**, respectively. The optimization resulted in a 4.1-point increase in the efficiency of the stage and a 3.9-point increase in impeller efficiency at the targeted design point. The Optimized4 design showed better stage and impeller efficiency than that of the Baseline design in the lower to medium operating range. To improve the efficiencies for the higher mass flow rates, a multi-constraint optimization must be performed. The increase in efficiency is paired with a decrease in shaft power required, as seen below in **Figure I**; specifically, the optimization resulted in a 21-W decrease in required shaft power.

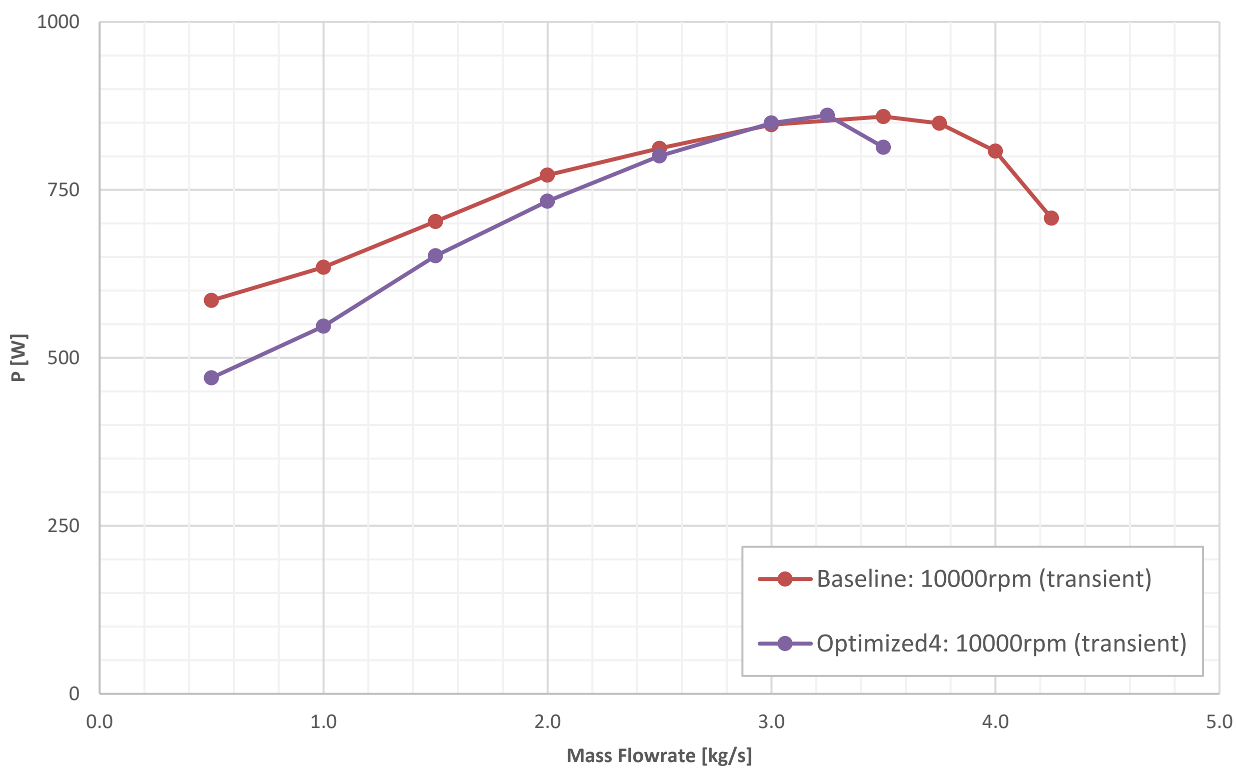

Figure I: Shaft Power – **Optimized4** vs. **Baseline**

The *Optimized4* design parameter values are displayed below in **Table B** and a meridional view comparison of the Optimized4 design, and the Baseline design is seen in **Figure J**.

Note that the DAKOTA optimization creates a wide range of viable designs that can be used for ever-changing manufacturing constraints or performance requirements**. Figure K** shows the three-dimensional flow behavior as static pressure streamlines in SimericsMP on the Optimized4 design.

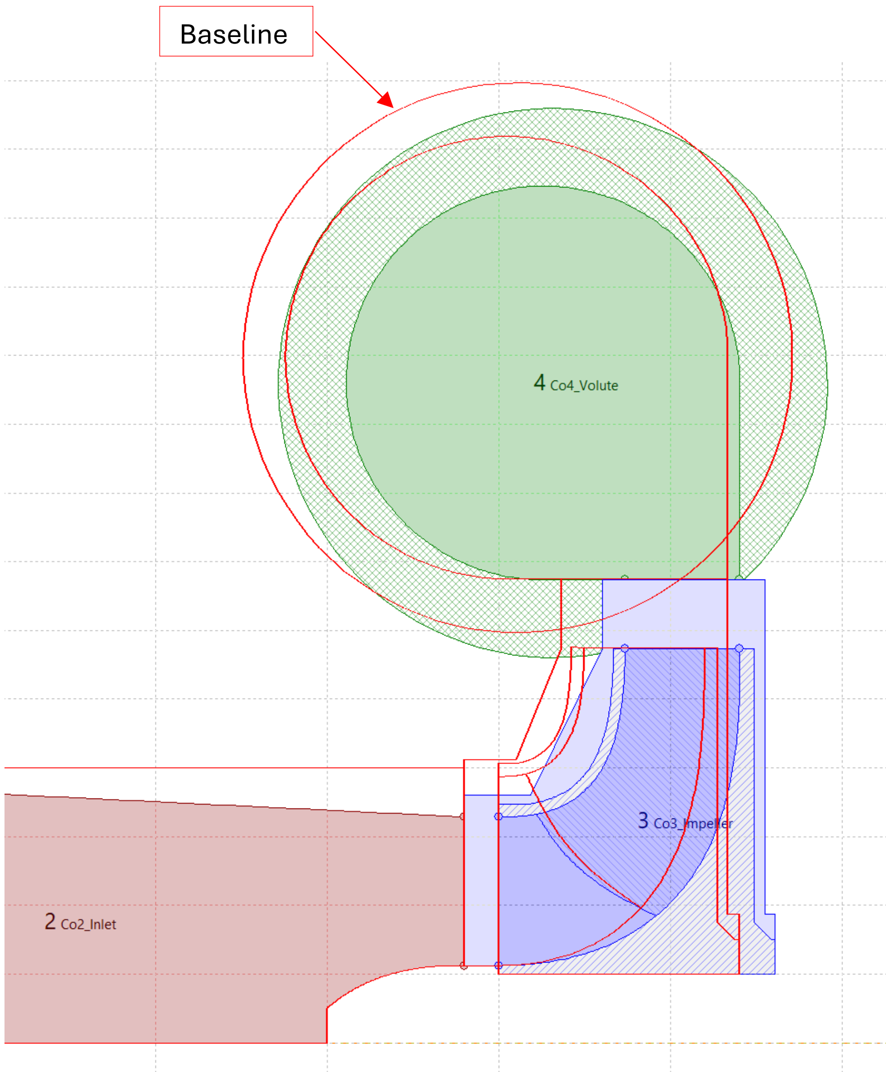

Figure J: Meridional View Comparison – Optimized4 vs. Baseline

Design Parameter	Units	Baseline	Minimum	Maximum	Optimized4
Impeller Suction Diameter	mm	31	25	35	26.3
Impeller Outlet Width	mm	7	5	10	6.68
Impeller Outer Diameter	mm	46	40	60	45.89
Impeller Axial Extension	mm	8.5	8.5	15	10.7
Impeller Blade Trailing Edge Angle	°	32.6	30	60	36.5
Impeller Blade Wrap Angle	°	85.0	80	110	95.1
Impeller Blade Number	-	6	5	7	5
Volute Swirl Exponent	-	1	0	2	1.33
Volute Diffuser Outlet Diameter	mm	32	20	40	31.98

Table B: Design Parameter Optimization Bounds and Final Values

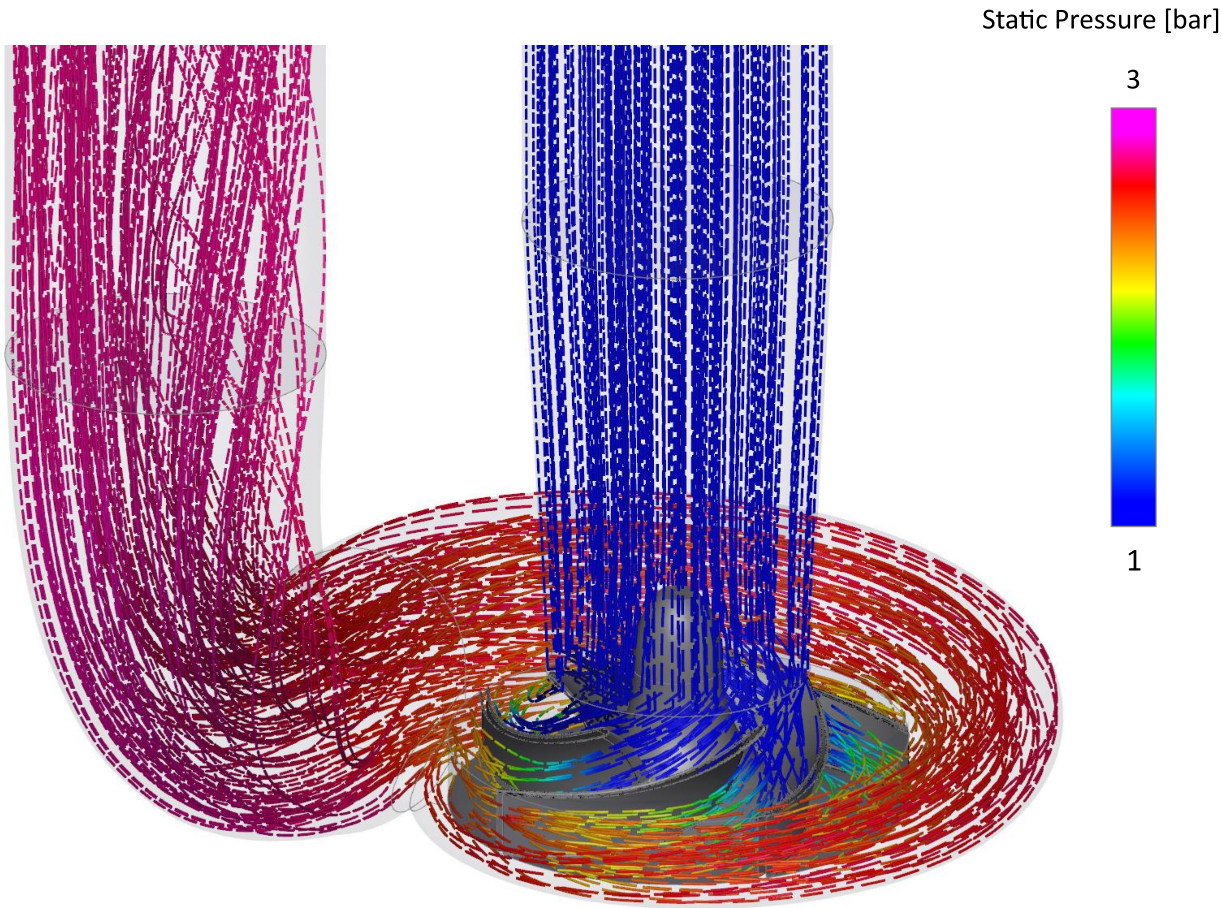

Figure K: Static Pressure Streamlines – Optimized4 Design

Conclusion

Integrating CFturbo with Simerics MP and the DAKOTA optimizer provides a robust framework for achieving optimal performance and efficiency in Turbomachinery designs like jet fuel pumps. CFturbo facilitates rapid and automated design generation, while Simerics MP allows detailed analysis and 3D simulation of fluid flow phenomena within the pump. The DAKOTA optimization process yielded highly efficient and feasible designs. The selected *Optimized4* design demonstrated superior performance, meeting the specified targets and exhibiting enhanced efficiency at the design point. The study highlights the tradeoff in performance range when maximizing stage efficiency at a singular operating point, which can be reduced with further, more computationally expensive optimization.

After approximately 48 hours of consecutive running time, the optimization produced a design with a notable 4.1-point increase in stage efficiency, a 3.9-point increase in impeller efficiency, and a 21-W decrease in required shaft power at the targeted design point. With sufficient computational resources, such a project can be finished within one week. In summary, this study demonstrates the effectiveness of an integrated approach for jet fuel pump design optimization, showcasing improved efficiency and reliability. The findings contribute to the ongoing pursuit of enhanced performance, meeting industry standards, and addressing high-efficiency requirements in the aviation sector.

Works Cited

[1] J. Mahot, "Boeing 777: The Heavy Check", https://www.amazon.com/Boeing-777-Heavy-Josselin-Mahot/dp/B07NDH49BD, 2016

[2] Eaton Corporation. (2013). Eaton Type 9106 Fuel Boost Pump for B777. [Online]. Available: https://www.eaton.com/content/dam/eaton/products/pumps/aerospace-fuel-pumps/documents/eaton-type9106-fuel-boost-pump-b777-datasheet-ds600-2a-en-us.pdf. Accessed: February, 2024.

[3] This case study we created using original CFturbo designs only. There is no reference to customer 3D CAD data or any other specification.

About CFturbo

CFturbo (est. 2008) is headquartered in Dresden, Germany, with a significant office in New York City, New York. Over the last decade, the company has gained worldwide respect within the Turbomachinery community. CFturbo is dedicated to Turbomachinery design and engineering services in designing rotating machinery components and solving fluid flow and heat transfer problems.

Our conceptual design software CFturbo is the most user-friendly system available on the market. Through its unrivaled, intuitive, and user-friendly design process, CFturbo software empowers every user, regardless of experience. The software can be used to design various turbomachinery-related devices, including pumps, fans, blowers, compressors, turbines, stators, and volutes.

CFturbo, Inc. offers various Turbomachinery engineering services, including aerodynamic and hydraulic designs, CFD and FEA simulation, rotating machinery optimization, mechanical design, prototyping, and testing. For more information, visit cfturbo.com.