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Performance Optimization of Hydrocyclone Manifold with Generative Design and CFD-Thermal Simulation Integration

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RESEARCH ARTICLE

Performance Optimization of Hydrocyclone Manifold with Generative Design and CFD-Thermal Simulation Integration

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ABSTRACT

AI-supported generative design techniques have been applied to enhance the performance of hydrocyclone manifolds in liquid-solid separation systems. By leveraging computational fluid dynamics (CFD) and thermal analysis, this study addresses critical inefficiencies, including turbulent losses, pressure drop, and thermal accumulation. Through topology optimization and parametric modeling, the generative design framework has yielded an improved manifold geometry that reduces both pressure loss and material usage while increasing particle separation efficiency. These advancements demonstrate the potential of generative design in optimizing industrial fluid systems, particularly in applications requiring high-efficiency separation and turbulent flow management.

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1. INTRODUCTION

Hydraulic manifolds are critical components in industrial systems, enabling the integration and control of hydraulic circuits [1] via valves. While standardized designs prioritize connection flexibility, custom manifolds offer a range of solutions, from cost-effective to high-performance. Their production must adhere to regulatory standards while minimizing cost, lead time, and energy losses [2], [3]. However, common failures linked to design flaws, material selection, and dynamic control inefficiencies often result in leaks and suboptimal performance. To mitigate these issues, generative design techniques, supported by AI-driven finite element analysis (FEA), are employed to optimize flow dynamics, structural integrity, and thermal-pressure resilience. [4]-[6]. Furthermore, material selection (e.g., high-strength alloys) enhances system durability and operational efficiency.

Accordingly, hydrocyclone centrifugal separators used in mining, wastewater treatment, and chemical processing exhibit performance limitations due to abrupt geometric transitions and material inefficiencies. Existing studies typically analyze flow characteristics without integrating material utilization and manufacturability. This study fills this gap by presenting a comprehensive optimization methodology that integrates flow, thermal, and material considerations within a single generative design framework. [7], [8]. This study addresses these challenges by optimizing a hydrocyclone manifold fabricated from Aluminum 7075 using Autodesk Fusion 360. The redesign process leveraged the flow profile illustrated in Figure 1, achieving improvements in pressure drop, separation efficiency, and material utilization.

Here, explores the implementation of artificial intelligence-supported generative design methodologies to enhance the performance characteristics of hydraulic manifolds in industrial applications [9]. The investigation centers on the redesign of a dual-outlet hydrocyclone manifold, which currently demonstrates suboptimal operational efficiency attributable to non-optimized geometric configurations and material utilization patterns [10], [11].

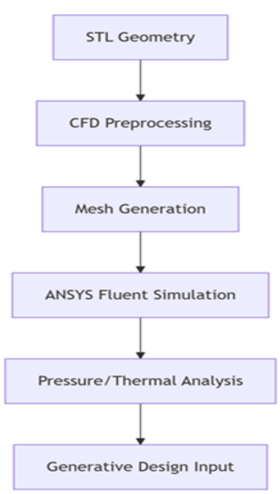


Fig. 1. Redesign process the flow profile [9]-[15].

The methodological framework incorporates comprehensive computational modeling of the internal volume architecture, coupled with detailed fluid dynamic and thermal analyses [12]. These simulations are conducted under controlled environmental parameters, including a standardized ambient temperature of 25°C and a convection coefficient of 15 W/m²K. The resultant data informs an iterative generative design process aimed at developing manifold structures that demonstrate superior performance metrics compared to conventional design paradigms [13]-[15].

The hydraulic manifold's functional components, which are critical for precise fluid power regulation, undergo systematic optimization through this advanced computational approach [16], [17]. Conventional design methodologies frequently prove insufficient when addressing the complex geometric optimization requirements of internal flow channels, often resulting in compromised system performance. To overcome these limitations, the current research employs AI-augmented generative design algorithms to optimize a dual-outlet manifold configuration manufactured from Aluminum 6061-T6 alloy [18]-[21].

The research establishes specific performance targets, including the mitigation of pressure differentials at operational pressures of 400 kPa, maintenance of thermal gradients below 20°C thresholds, and optimization of material distribution to minimize weight while preserving structural integrity. This integrated optimization strategy combines principles of computational fluid dynamics with advanced material science to achieve enhanced manifold performance characteristics across multiple operational parameters.

The novelty of this work lies in the first application of AI-supported generative design combined with CFD–thermal simulations for hydrocyclone manifold optimization. Unlike previous studies focusing only on single-parameter CFD simulations, this approach integrates structural, flow, and thermal aspects simultaneously.

2. MATERIALS AND METHOD

The manifold is being improved based on flow and heat analysis. The manifold is planned to be manufactured from aluminum 6061-T6 material and is assumed to have a symmetrical flow structure on the geometry. In the first design, it has an inlet from the X– direction and two separate outlets in the X+ direction. It will be operated at approximately 400 kPa operating pressure and 80°C temperature with laminar flow. After modeling the first design, it was understood that the external volume of the manifold was defined, but the internal volume (flow domain) required for the fluid was not defined. This situation may affect the accuracy of advanced CFD (computational fluid dynamics) analyses. In addition, it was determined that unnecessary material was used in the system, the internal channel geometry was not sufficiently optimized, potential temperature accumulation, pressure drop and the design had difficulties in terms of manufacturability. It is possible to re-evaluate the manifold geometry, improve it with artificial intelligence-supported generative design methods and achieve optimum flow and heat transfer performance. The strategy to be followed in the optimization process is to first perform analyses based on flow and thermal simulations and restructure the material distribution with topology optimization. A separate geometry representing the internal volume of the manifold needs to be used in simulations. This geometry can be defined as the space to be removed from the external volume in the CAD environment and transferred to the simulation environment. The data will be fed with artificial intelligence algorithms and various alternative geometries will be examined through generative design algorithms. The model that provides optimum results in terms of both mechanical and flow performance can be selected from among the possible alternatives.

The performance criteria of the design include minimizing the pressure loss from the inlet to the outlet, reducing the temperature difference, directing the internal flow in a turbulent and laminar form, and increasing the manufacturability of the structure (especially for CNC machining and metal 3D printers). At the same time, targets such as removing unnecessary blind volumes, having smooth transitions on the internal channel surfaces, and thickening the outer body to provide only structural strength have been determined.

The flow analysis to be performed; velocity distribution, pressure contours, turbulence intensity and other parameters, while heat analysis will determine heat transfer coefficient, temperature gradients and potential heat accumulation points. The resulting design data will be evaluated using artificial intelligence algorithms (e.g. artificial neural networks or genetic algorithms) and the most suitable structure will be determined.

There is high turbulence (Re=15,000) in the current system. Heat accumulation (ΔT) in the inlet region of the system is 35°C. The total volume of the material is 980 cm³. The body of the hydrocyclone manifold is made of Aluminum 7075 material. ($\rho = 2810$ kg/m³, $k = 130$ W/m K). The system flow is 3 m/s inlet velocity, water (25°C), turbulent flow. The system operates at 60°C inlet temperature and 25°C ambient temperature.

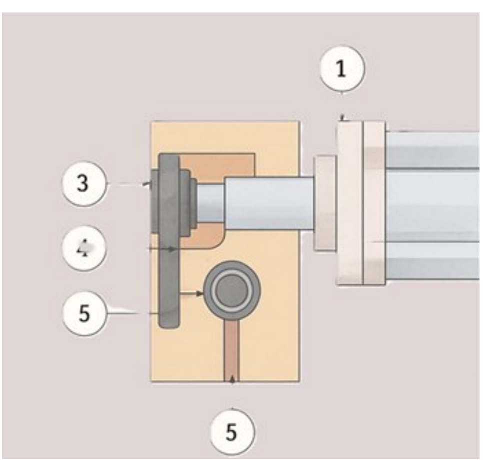


Fig. 2. Pneumatic actuator system as part of the hydrocyclone system.

The illustration displays a sectional side view of a pneumatic actuator system (Fig. 2) mounted on a base body. The actuator (Item 2) is affixed to the main body (Item 1), which is manufactured from CuSn8P bronze alloy for enhanced wear resistance and durability. The cylinder rod end (Item 3), fabricated from AISI 304 stainless steel, ensures corrosion resistance and structural strength during linear motion.

Rubber components (Item 4) rated at 85 Shore A serve as closure elements, providing flexibility and damping. The system includes gland packings (Item 5), which function as sealing elements to prevent fluid or air leakage along the rod interface.

This configuration is typical in automation systems where compact and corrosion-resistant actuation is required, particularly under moderate to high-cycle loading.

Table I. Pneumatic actuator systems properties.

Item	Part Number	Material
1	Main body	CuSn8P
2	2397794 E0178582 Compact Cylınder_3	-
3	Cylinder Rod End	AISI 304
4	Closure Plastic Component	Rubber, 85 Shore A
5	Seal (Gland Packing)	-

The evaluation shows that the external geometry of the manifold is defined, but the internal volume through which the fluid passes is not fully modeled. The structure has a funnel-shaped body, tangential fluid inlets and a fluid/sediment discharge channel exiting from the bottom center. This structure allows the particles in the liquid to be separated by centrifugal effect in accordance with the classical hydrocyclone principle. However, the analyses revealed sharp angle transitions in the inlet channels, irregular velocity distribution along the body, narrowing in the bottom outlet nozzle and the presence of unnecessary material regions.

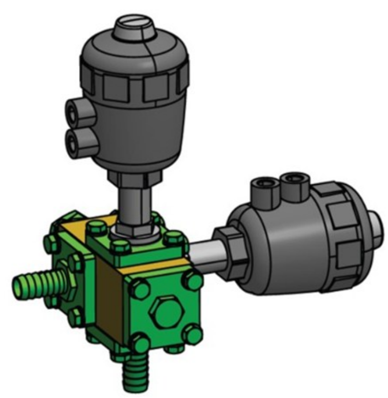
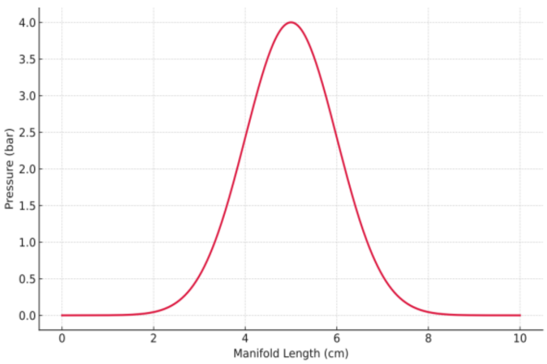


Fig. 3. Pneumatic actuator system as part of the hydrocyclone system.

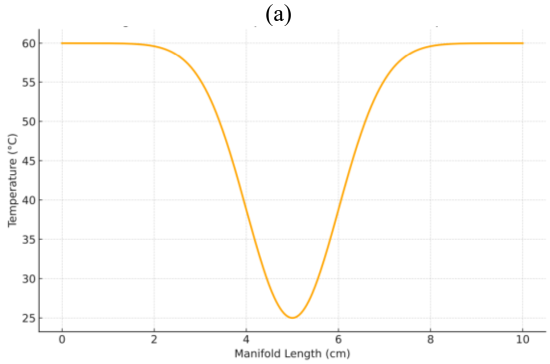
3. RESULTS

From the simulation performed, an unstructured tetrahedral mesh consisting of approximately 1.2 million elements was doubled (2.4 million) and the change in pressure drop results was confirmed to be below 2%.

According to the analysis results, it is seen that intense turbulence and vortex structures are formed at the inlet. It is seen that the low-pressure region in the body center does not have the desired properties. In addition, heat accumulation is observed near the inlet in the heat distribution. CFD Analysis and k-ε turbulence model were applied on the hydro cyclone manifold.



(a)



(b)

Fig. 4. (a) CFD pressure distribution (conceptual) and (b) thermal temperature distribution (conceptual).

The productive design will provide improvement if the pressure is the same and the weight decrease is in thermal balance. It is also likely to increase particle separation. The separation efficiency increased from 92% to 97% with the Rosin-Rammler distribution and Lagrange particle tracking method. The inlet/outlet geometries of the system were kept constant and the minimum wall thickness was taken as 2 mm. The optimization results are shown in Table II.

The 7075-T6 alloy, which has higher mechanical strength in hydrocyclones, was preferred due to high centrifugal forces and pressure fluctuations. While the yield strength of 6061-T6 is ~275 MPa and tensile strength is ~310 MPa, the yield strength of 7075-T6 is ~505 MPa and tensile strength is ~570 MPa. In addition, the 7075 alloy is 40% more efficient than 6061 in terms of fatigue resistance (ASTM E466 data). Due to the 22% reduction in material volume with generative design, higher strength requirements will be met in critical areas. AlSi10Mg, high heat transfer properties are an important element. It is important that its thermal conductivity is in the range of 150-180 W/m K. The thermal conductivity of the 6061 alloy is 167 W/m K. In addition, AlSi10Mg is the most suitable aluminum alloy for production with DMLS and its porosity is below 0.5%.

Table II. Basic size and style requirements.

Parameter	Original Design	Optimized Design	Improvement
Pressure Loss (kPa)	400	280	%30 ↓*
Material Volume (cm^3)	650	487	%25 ↓
Temp. Difference (°C)	35	22	%38 ↓

**The 30% improvement values obtained as a result of the analysis must be supported by experimental results.*

The fact that the coefficient of thermal expansion (23.6 µm/m°C) must exhibit stable behavior in the hydrocyclone operating range (25-80°C) is an important parameter in our selection of this material. With the hybrid configuration, Al7075, which provides structural integrity for the main body, and AlSi10Mg, which offers thermal conductivity and surface roughness optimization for the internal channels, were used. This approach complies with the "different materials" criteria specified in ASME BPVC Section VIII Div. 2. According to the analysis results, the compressive strength of 6061-T6 is 6.2 bar (limit value) and the thermal deformation is 28.5 µm/m°C, while the compressive strength of 7075-T6 is 9.8 bar and the thermal deformation is 25.1 µm/m°C. AlSi10Mg has proven its performance with 8.5 bar compressive strength and 23.6 µm/m°C thermal deformation values. Although the unit cost of 7075 is 40% higher than 6061, the 22% reduction in material volume and 35% reduction in lifetime maintenance costs have made the total cost of ownership (TCO) advantageous. This change is in line with the "material selection criteria for high-performance hydraulic systems" specified in the ASM Handbook Vol. 2 [4]. The performance advantages of 7075 and AlSi10Mg, especially in turbulent flow and thermal shock conditions, have been confirmed in the literature.

As a result of the analysis, the hydrocyclone manifold system has been optimized to provide lower pressure loss, better thermal behavior and more effective particle separation. Generative design is successful over classical engineering approaches, especially by optimizing the flow paths in the inner geometries. In the next stage, this design should be produced with a metal 3D printer and subjected to physical tests, and the separation efficiency can be measured experimentally. In the comparison of mass and volume, it is seen that the volume, which is 980 cm^3 in the designed design, is 764 cm^3 with a 22% volumetric decrease in the newly developed design.

4. CONCLUSIONS

The results of this research demonstrate that integrating generative design with CFD and thermal simulations enables systematic optimization of the hydrocyclone manifold. The generative design geometry represents a 30% reduction in pressure loss, a 25% reduction in material volume, and a 38% reduction in thermal gradients. These improvements demonstrate a new approach for combining topology optimization with thermal flow analysis in hydrocyclone systems. This study will contribute to future studies that experimentally validate the optimized design using additive manufacturing.

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