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# A Performance Study of Fuel Cells with Novel Channel Cross-Section Configuration

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**Abstract:** The cross-sectional design of the flow channel is the subject of many studies aimed at improving fuel cell(s) performance in a different condition. These studies include laboratory experiments and simulations to understand how design affects performance under different pressures and temperatures. This research demonstrates the importance of collaboration between scientists and engineers to improve fuel cell technologies to meet the needs of multiple applications. The design approach of cross-sectional in flow-channel is a key element in improving fuel cell performance. As technology advances and new materials and advanced manufacturing techniques emerge, we can expect to see more efficient and innovative designs in the future. These developments will not only improve fuel cell efficiency but will also help reduce reliance on fossil fuels and promote the transition to a sustainable, clean energy economy. Mixed-configuration design is used based on taking the advantages of the rectangular, circle and triangle cross-section shapes. For performance analysis, flexible and reliable fuel flow and current density rate are used to analyze performance in this article and effective comparison is shown an effective and accepted results.

**Keywords:** fuel cell, flow channel, channel cross-section, current density, fuel cell performance

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## 1. Introduction

The flow channel basic design of cross-sectional and its significant impact on the performance characteristics is one of the most prominent topics of interest to researchers and specialists in the field of sustainable energy technology. With the global trend towards reducing dependence on traditional polluting energy sources, fuel cells, especially those based on hydrogen, have become a promising option for providing clean and efficient energy. In order to gaining a good possible performance of the mentioned cells, all their components and designs must be carefully considered, and among these components comes the flow channel [1, 2].

Mainly, flow channel expressed as most sensitive and powerful part of any fuel cell system design to distribute the fuel and oxidizer (mostly hydrogen and oxygen, respectively) evenly across the surface of the electrode [3]. In addition, the channel contributes to the disposal of reaction products, such as water, thus preventing blockages that may affect the resulted performance of the fuel system. However, the design of it is not just a simple technical element; rather, it is a complex process that requires a careful balance between many factors to achieve high efficiency [4].

One of the most important considerations in the design of it is the geometric shape of the transformation channel itself. These kinds of designs may range from straight, helical, zigzag, to even grid-type patterns. All these kinds of designs directly impact the fuel and oxidizer distribution in the cell. For example, straight designs are simple and easy to manufacture, but suffer from the drawback of inferior fuel and oxidizer distribution, resulting in dead areas in the cell where chemical reaction is limited. Conversely, zigzag or helical patterns can enhance the fuel distribution but will have higher resistance to flow, which will use more energy in pumping the fuel and the oxidizer [5, 6]. Moreover, the cross-sectional area plays a significant role in cell performance design. Narrow channels can be clogged using water produced through the reaction, reducing cell efficiency [7]. On the other hand, if the channel is wide, it can contribute to poor fuel and oxidizer flow, reducing resource utilization and increasing energy loss. Therefore, the design needs to be optimized to increase fuel and oxidizer distribution and reduce hydraulic resistance [8]. The design surpasses distribution alone but also serves a specific function on cell temperature. Fuel cells produce heat through chemical reactions that occur within it, and without regulation, this can lead to a decrease in cell efficiency or even to component damage of the fuel cell [9]. An effective flow channel helps to remove excess heat from the cell, which is the cause of its stable operation. New designs, such as spiral or lattice-pattern-based designs, enhance heat transfer from hot spots. The biggest challenge in the design of flow channels is to provide the optimum possible compromise between the proper distribution of effective fuel and oxidizer on the one hand, and by-product evacuation on the other, and reducing loss of energy by virtue of thermal or hydraulic resistance on the other. To optimize this best, engineers are reliant on computer and simulation modelling techniques to model the performance of potential designs before they are carried out [10]. The second area of flow channel design to be addressed is the material that will be used to build the channel. The material must be resistant to corrosion and chemical reaction since the condition inside a fuel cell is normally harsh due to high temperatures and high humidity. In addition, the material must possess sufficient thermal and electrical conductivity to aid in improving the performance of the cell as a whole [11]. Another major component is the environmental impact of channel design. As wonderful as fuel cells are as a green technology, their design and manufacturing must take into account the environmental impact of the materials and production costs. Designs that require rare materials or complex manufacturing processes can increase the environmental and cost factor of this technology. For these reasons, researchers are looking to utilize green materials and environmentally friendly manufacturing processes [12].

Recently, 3D channel design(s) initialized and become the hot topic behind building of fuel cell to performance gain. These designs help to make better use of space and distribute fuel and oxidizer more efficiently. 3D printing technologies are a promising tool in this field, as they allow the implementation of complex designs that could not be achieved using conventional methods. For example, channels with very fine mesh designs can be implemented, ensuring optimal fuel distribution and reducing resistance [13], [14],15].

## 2. Materials and Methods

Literature review

In this section, an important previous studies are briefly reviews which relevant to the objectives, core components, and parameters needed to develop the proposed channel cross-section configuration and performance analysis.

***Kaplan et al.*** [16] employs a 3D single-phase computational-fluid-dynamic(s) (CFD) approach for analyzing the impact of flow channel cross-section dimensions on Proton-Exchange-Membrane-Fuel-Cell (PEMFC) total performance. Rectangular cross-sections with varying widths and depths were simulated to optimize performance. The model demonstrates a 57% current density improvement at (0.4) V with minimal channel sizes (0.2) × (0.1) mm, but this increases pressure drops significantly. The most efficient design, balancing performance and pressure, is a 0.8 × 1 mm channel, achieving a (2.5%) in density improvements if it is compared to the baseline. Limitations include assumptions of single-phase flow and steady-state conditions.

***Abdulla*** et al. [17] employ a detailed 3D 2-phase of (CFD) approach to analyze the Enhanced Cross-Flow-Split-Serpentine-Flow-Field (ECSSFF) system-design for square-cross-sectional PEMFCs). The optimal configuration, with a 1:1 rib-to-channel width ratio, achieves good performance, even at active areas up to 200 cm². Maximum efficiency is achieved at 70 °C and 200 kPa, with humidified anode and cathode reactants at 100% and 50%, respectively. The design enhances fuel distribution and performance but requires precise stoichiometry control and high computational resources for evaluation.

***Cao et al.*** [18] uses Volume-of-Fluid (VOF) approach for modeling 2-phase in PEM fuel cell channels, optimizing gas channel geometry for improved clearance of (GDL) and liquid residence-time. Among analyzed geometries, triangular channels reduce the Area-Coverage-Ratio (ACR) by (64%) at (0.5) m/s air velocity and demonstrate stable two-phase pressure drop. However, hexagonal channels rank best for liquid residence time, followed by pentagonal, rectangular, and triangular designs. Efficiency is influenced by channel cross-section and wall wettability, with contact angles of 85°–120° improving performance. Limitations include variability in two-phase flow stability and computational complexity.

***Jałowiecka et al.*** [19] employs computational fluid dynamics (CFD) modeling to address the basic transportation mass challenges in the Direct-Formic-Acid-Fuel-Cells (DFAFCs). A new channel design with right-angled trapezoidal baffles improves formic acid concentration uniformity and convective flux in serpentine flow fields, mitigating fuel starvation zones. The design achieved a (711.11%) rising in the max. of power density at about (1) ml/min of the value (9.00 M formic acid compared to prior hydrogen PEMFC studies. This approach enhances efficiency but may introduce complexity in channel fabrication and flow management.

***Babay et al.*** [20] used numerical analysis method for ANSYS Fluent based to compare Serpentine-Flow-Field and the approach of straight channel (PEM) fuel cells. Key system parameters such as reactant, velocity, temperature polarization behavior were analyzed, showing a 5% performance advantage for the straight-channel design. However, Serpentine Flow-Field designs demonstrated greater efficiency and durability. Optimization of the membrane electrode assembly (MEA) was highlighted as critical for cost-effectiveness. Limitations include minor performance differences and trade-offs in cost and durability between designs. Both configurations proved sustainable and viable for future applications.

An effective comparison between the proposed model in this article and the previous studied studies in terms of: method, findings, channel configuration, fuel flow rate and limitations as shown in Table (1) below:

**Table (1):** Comparative Analysis of proposed model and the literature review studies.

| Study | Method | Findings | Channel Configuration | Fuel Flow Rate | Limitations |
|---|---|---|---|---|---|
| **Proposed** | Laboratory experiments and simulations. | Mixed configuration of rectangular, circular, and triangular shapes shows effective and reliable results. | Mixed rectangular, circular, triangular | Flexible for analysis | Requires advanced materials and manufacturing for optimization. |
| **Kaplan et al. [16]** | 3D single-phase CFD modeling. | 57% current density improvement for smallest dimensions (0.2 × 0.1 mm), best performance at 0.8 × 1 mm channel. | Rectangular with varying widths and depths | Not specified | Assumes single-phase flow and steady-state conditions; increased pressure drop for small channels. |

| | | | | | |
|---|---|---|---|---|---|
| **Abdulla et al. [17]** | 3D two-phase CFD modeling of ECSSFF design. | 1:1 rib-to-channel ratio performance enhancement, works at active areas up to 200 cm². | Cross-Flow-Split-Serpentine (ECSSFF) improving | Not specified | High computational resource demand; precise stoichiometry control needed. |
| **Cao et al. [18]** | Volume of Fluid (VOF) model for two-phase flow simulation. | Triangular channels reduce ACR by 64%, while hexagonal channels rank best for liquid residence time. | Triangular, hexagonal, pentagonal, rectangular | Superficial air velocity (0.5–2.5 m/s) | Stability issues for two-phase flow; complex computational setup. |
| **Jałowiecka et al. [19]** | CFD modeling for mass transport in DFAFCs. | Trapezoidal baffle design increases power density by 711.11% compared to hydrogen PEMFCs. | Serpentine with trapezoidal baffles | 1 ml/min of 9.0 M formic acid | Channel fabrication complexity; increased flow management challenges. |
| **Babay et al. [20]** | Numerical analysis with finite element method and ANSYS Fluent. | Straight channel outperforms Serpentine Flow-Field by 5% in production; Serpentine is more durable. | Straight and Serpentine Flow-Field | Not specified | Minor performance differences; trade-offs between cost and durability. |

**Methodology**

This section contains two main sub-sections which are channel cross-section configuration and performance analysis as shown in Figure (1)

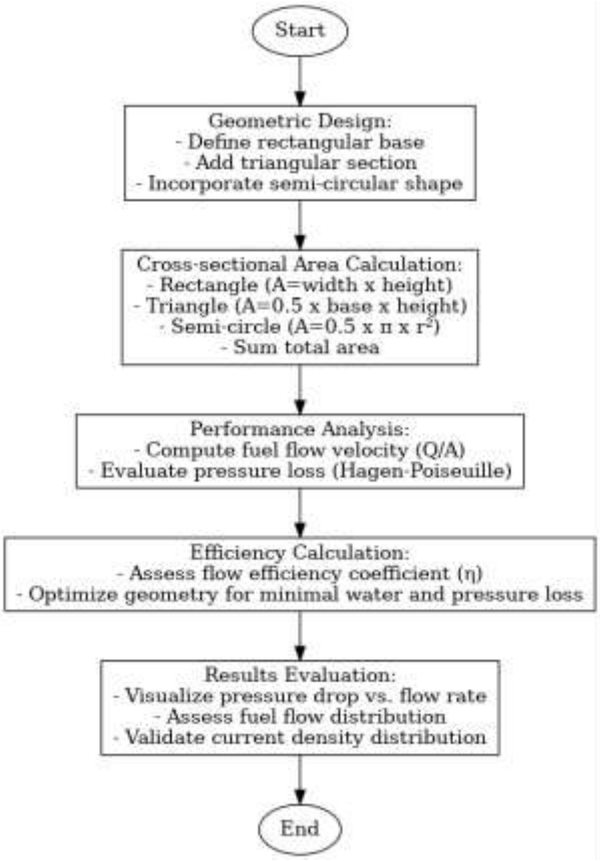


**Figure 1.** Proposed Model Analysis Process Design

## 1.1 Channel cross-section configuration

Cross-section of fuel-cell channel act as critical element in fuel cell design, controlling the even distribution of reactant gases, such as hydrogen or oxygen, across the electrode surface.. The design of the channel cross-section includes many geometric factors that take into account performance and efficiency.

The geometric shape of the channel is a key factor in its design, as the channel can be rectangular, triangular, circular, or trapezoidal. The rectangular channel is most utilized because it is easy to produce and sustains stable gas flow, while triangular channels stand out in terms of low pressure loss and high electrochemical reaction. Trapezoidal and circular channels stand out for low water accumulation due to the reaction and high gas distribution. The channel size is selected with care to provide the ideal balance between flow and gas distribution. The width and depth are selected to allow for balanced distribution and minimize pressure loss. The ratio of width to depth is a critical parameter to ensure control over gas pressure and the flow rate because increasing it decreases the flow resistance but doing it too excessively results in the improper distribution of gases. Channels are linearly or zigzag distributed, for instance, spiral or parallel arrangements. The distributions aid in the enhancement of gas flow and water handling in consideration of zigzag distribution usually being efficient at draining water.

Microchannels are a new feature in the design of small-sized fuel cells, which enhance the efficiency of the reaction by reducing congestion of water and improving gas utilization. The channels are well-designed with precise dimensions that allow water tension surface reduction, which assists in improving its expulsion from the channel. The properties of the inner channel surface are quite critical to its operation. The inner surface would ideally be non-stick to water and corrosion-resistant. These properties help in reducing water accumulation and improving the continuity of gas flow.

Reaction water management is an essential part of the channel design. Some channels are designed to be slanted or tortuous to remove water better than linear channels. The effects of gravity and surface tension are taken into account in managing water within the channel, as water accumulation can flood the membrane and reduce reaction efficiency.

As for the materials used, they are designed according to the functional requirements of the cell. Common materials include graphite, stainless steel, and highly conductive polymers, which combine durability with the ability to withstand harsh conditions.

The main goals and objectives in this study is designing the cross-section of a fuel-cell channel and then be summarized as achieving a homogeneous distribution of gases, improving heat and moisture management, and reducing pressure loss. For example, the pressure loss within the channel can be calculated using the Hagen-Poiseuille law:

$$\Delta P = \frac{8\mu L Q}{r\pi^4} \qquad (1)$$

Where:

$\Delta P$: are the pressure loos.

$\mu$: is the gas viscosity.

L: is the channel length.

Q: is the flow rate.

r: is the channel radius

The cross-sectional-area (A) is the crucial parameters that affect the gas flow inside the channel. It can be calculated based on the geometric channel shape. Since cross-section channel designed in this article was made by a mix of rectangular, circular and triangular shapes, the method of calculating the areas of the three geometric shapes mentioned will be known as follows:

**A) Rectangle:**

**Forms the base of the mixed channel, providing structural stability and a straightforward flow path. The rectangle dimensions are width (channel width) and height (channel height). Formula (2) is shown how the area calculation:**

$$A_{rect} = Width \times Height \quad (2)$$

**B) Triangle (on top of the rectangle)**

**The triangle is used to** enhance the channel's ability to distribute reactant gases uniformly and improves flow distribution without significantly increasing the channel size. This shape contains two main dimensions: base (channel width) and height (triangle height). **Formula (3) is shown how the area calculation:**

$$A_{tri} = \frac{1}{2} \times Base \times Height \quad (3)$$

**C) Semicircle (below the rectangle):**

**The main role of circle shape is to** add extra volume for gas storage and improves water drainage. One dimension is used is that radius (channel radius). This part is so important to complete the mixed configuration because it has smooth curve minimizes flow resistance and natural water drainage due to the curvature. Formula (4) shows the circle (semi-circle) calculation

$$A_{semi} = \frac{1}{2}\pi \times Radius^2 \quad (4)$$

The total area of the mixed configuration is the linear sum of the areas of areas of rectangle, triangle, and semicircle as shown in formula (5):

$$A_{mixed} = A_{rect} + A_{tri} + A_{semi} \quad (5)$$

**1.2 Performance analysis**

Two main parameterized measurements are studied and analyzed based on this project requirements and objectives these are: fuel flow and measure the performance of channel cross-section. Formula (6) shows flow speed ($v$) inside the channel by utilizing the continuity equation which is connect between two rate of volume flow ($Q$) and channel cross-section area ($A$).

$$v = \frac{Q}{A} \quad (6)$$

Where:

$v$: is the fuel flow speed (m/s).

$Q$: is the volume flow rate ($m^3/s$).

A: is the channel cross-section area ($m^2$).

This interaction is essential to offer an adequate flow rate to ensure maximum electrochemical reaction and pressure loss or water accumulation in the channel.

In addition, the laws are embedded in a comprehensive design that harmonizes flow, homogeneous distribution, and water surface as well as heat management. Through this, the fuel cell channel cross-section is designed to maximize power generation performance. To quantity the effectiveness of the fuel transference frequency in a fuel cell, the flow productivity coefficient ($\eta$) can be used, which expresses how effectively the channel can transport and distribute the fuel while minimizing pressure loss and managing resulted water. The coefficient of flow efficiency is calculated as in equation (7) using the following relation:

$$\eta = \frac{Q_{useful}}{Q_{total}} \quad (7)$$

Where:

η: Channel effectiveness (ranging from 0 to 1, unitless number,).

$Q_{useful}$: Fuel flow rate actually used in the electrochemical reaction ($m^3/s$).

$Q_{total}$: Total fuel flow rate passing through the channel ($m^3/s$)

There are many factors affecting efficiency such as homogeneous gas distribution, water management and pressure loss. If the channel distributes the fuel evenly over the electrode surface, this increases homogeneous gas distribution. While water accumulation reduces the area available for fuel flow, resulting in decreased efficiency. Channels with a design that minimizes pressure loss ensure better flow and increased efficiency. And in order to improving efficiency, optimizing channel dimensions (depth and width) to achieve a balance between fuel flow and water removal and selecting the optimal geometry that minimizes water accumulation (such as inclined or zigzag channels). Finally, using materials with appropriate properties (corrosion resistance and water resistance). Formulas (6) and (7) are used as an evaluation criterion during the design and testing of fuel cell channels to ensure optimal performance.

## 3. Results

Figure (2) shows the channel cross-section proposed configuration and how to take the advantages of the three main basic shapes for reliable and flexible fuel flow.

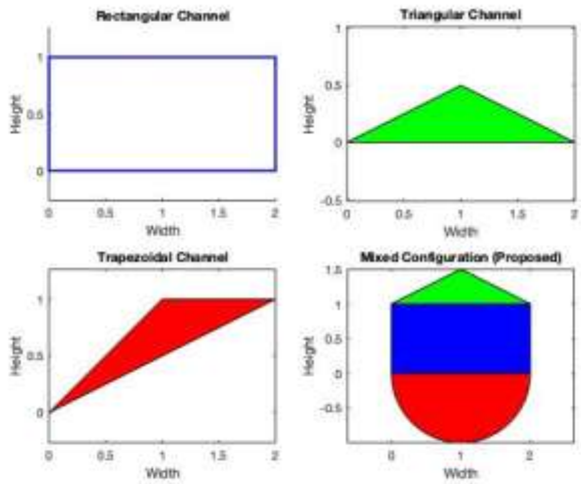


**Figure 2.** Channel Cross-Section Configuration.

## 4. Discussion

Below are three figures representing different performance parameters of a fuel cell channel: **pressure drop, fuel flow distribution**, and **current fuel density Distribution**. These are typical performance metrics for analyzing fuel cell channels. The basic assumptions for the parameters and visualizations based on idealized fuel cell channel characteristics. These visualizations can be extended or refined depending on specific experimental or simulation setups.

Figure (3) represents the idealized relationship between the pressure-drop across fuel-cell channel and also rate of fuel flow. Flow rate increases, the pressure drop also typically increases. This can help identify the efficiency of the channel design and flow resistance.

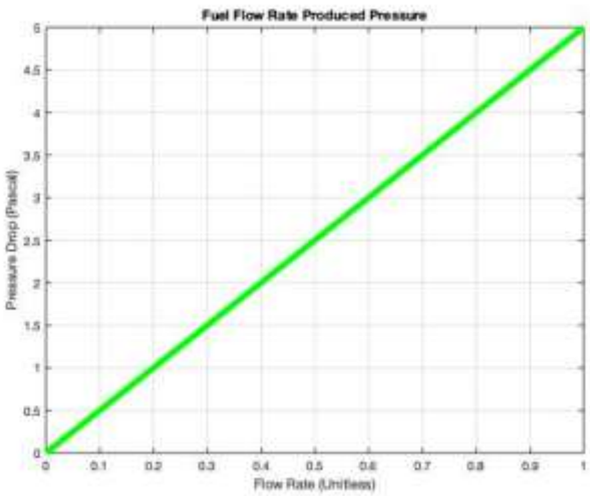


**Figure 3.** Pressure Drop vs. Flow Rate.

Figure (4) visualizes how the fuel is distributed across the fuel cell channel. Here, a Gaussian distribution is used to simulate the uniformity of flow. In a real fuel cell, this would vary depending on the channel geometry, such as a rectangle, triangle, or semicircle.

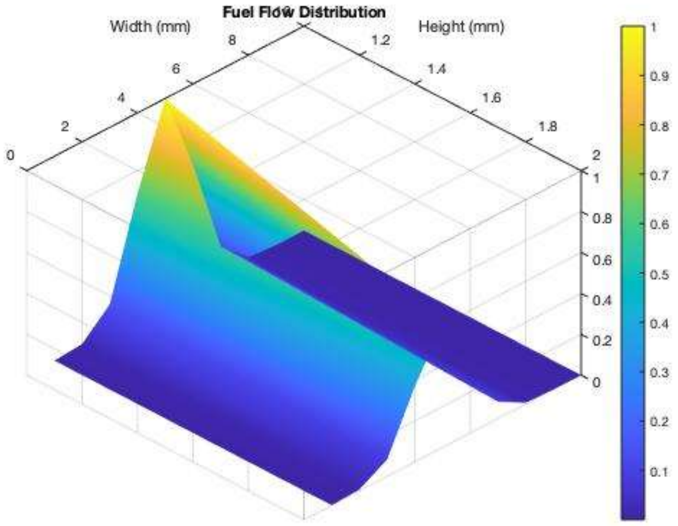


**Figure 4.** Fuel Flow Distribution Across the Channel

Figure (5) represents the current density distribution across the channel. Typically, areas closer to the center of the channel have higher current densities due to better gas distribution. The exponential decay replicates a non-uniform current density distribution, which is typical in fuel cells.

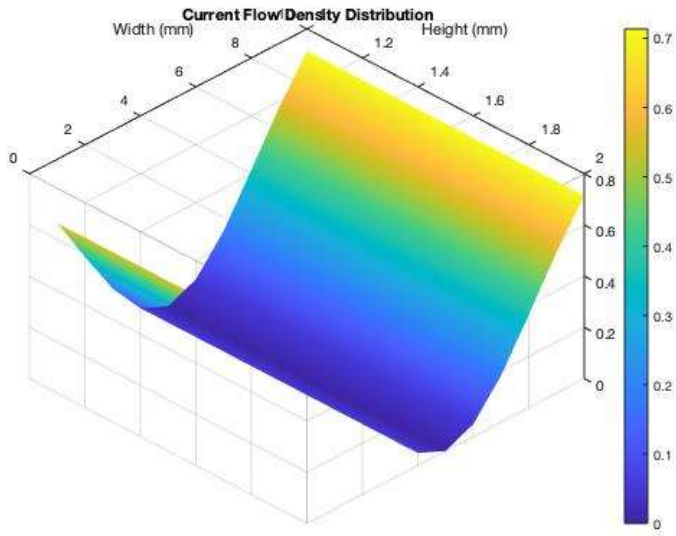


**Figure 5.** Current Fuel Density Distribution.

## 5. Conclusion

The fuel channel design process requires a high understanding of fluid behavior and engineering mechanics concepts. The process of developing was focused on creating a new cross-section combining the strengths of the basic shapes: rectangle, circle, and triangle. The final design focused on combining the shapes to generate a cross-section that benefits from their combined strength. For example, the rectangle base was used as the major space for stable flow, the circle was incorporated to reduce resistance, and the triangle was incorporated to improve pressure distribution. Once the channel was designed, efficiency was measured through two sub-stages: flow rate measurement, where the quantity of fuel transferred during a period is determined, in which results showed that the designed channel can achieve a more stable flow compared to conventional designs.

In addition to the measurement of error rate (fuel lost), the fuel lost in transferring was considered because the channel showed a lower loss rate compared to previous designs. The study validated that innovation in fuel transfer channel design through the combination of different geometric shapes has the potential to achieve high operational efficiency. This study contributed to the precision of outcomes and provided pragmatic solutions toward improving channel performance. This was an important move toward creating more sustainable and efficient fuel transfer technology. Application of such designs provides broad opportunities for improvement of industrial systems and reduction of the environmental burden created during fuel loss during transport.

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