DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Swirl Stove: Swirling combustion for efficient wood burning

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Systems Development and Integration

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Project Overview

Wood stoves are a widely used heat source in US homes, which produce air pollution and create health issues.

- ***Goals**: reduce PM emissions to below 0.5 g/hr (down 75%), and increase efficiency to 85%*
- ***Main idea**: leverage swirling combustion (mixing combustion air with gasified wood) to achieve a more complete burn, thereby reducing emissions and increasing efficiency*
- ***Today**: Traditional wood stove geometries and air introduction systems leave pockets of incomplete air/gas fuel mixture leading to incomplete combustion, higher emissions and lower efficiency*
- ***Importance**: Wood heat produces 40% of PM2.5 particulate matter in the US, a leading cause of respiratory illness and lung disease.*
- ***Risks**: 1)Swirling combustion is used in predictable, consistent combustion environments. Wood combustion is inherently inconsistent and swirling combustion has not been achieved in a repeatable consistent way. Project success requires developing a method that can repeatably and consistently achieve sustainable swirling combustion. 2) Creating swirling combustion with wood fuel may not deliver the emission reduction sought.*

1 – Approach

- MF Fire started with a hypothesis based on scientific principle and experienced/observed by its team in other, more consistent fuel combustion environments.
- Modeled the wood combustion process, focused on creating conditions that achieve swirling combustion, and then leveraged Computational Fluid Dynamics (CFD) modeling to evaluate a broad array of potential solutions.
  - In all we tried 14 configurations in an isothermal simulation and 2 in a combustion configuration, before transitioning to real-world prototyping of the most promising configurations.
- Challenges:
  - CFD modeling has limits for modeling the complexities of wood combustion. Favorable simulations do not always translate into real world solutions
  - Swirling combustion, such as a fire tornado, is rarely seen in nature due to the need for multiple conditions to align. It may be that successfully creating a swirling combustion does not lead to a sustainable swirl.
  - Once created, a swirling combustion device may not achieve the targeted goals for emissions reduction.
- The team achieved swirling combustion with solid fuel (cordwood) in its prototypes below the go/no-go threshold of 4.5 g/hr (PM2.5).
- Progress metrics: CFD modeling yielded multiple potential swirl configurations, prototype testing resulted in actual sustained swirling combustion, early lab testing confirms emissions reduction scale.

2 – Impact

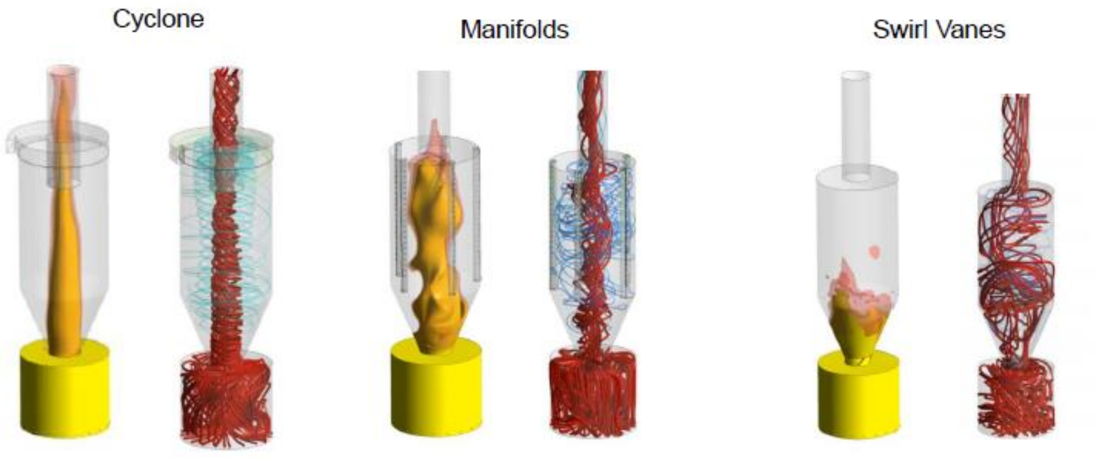
- The biggest challenges facing the industry are the external pressures and regulatory drivers to convert wood heat into a cleaner heat alternative.
- A successful swirl combustion stove has the potential to simplify wood stove design, thus lowering manufacturing costs and making it more affordable, while transforming wood heat into clean energy.
- Once results are known, we will publish articles in the academic and scientific communities while promoting the innovation through popular news outlets.
- The company's patented technology will be made available to the hearth industry to help accelerate the rate of adoption.
- Early customer focus groups have shown very strong consumer interest for both aesthetic and practical reasons.

3 – Progress and Outcomes

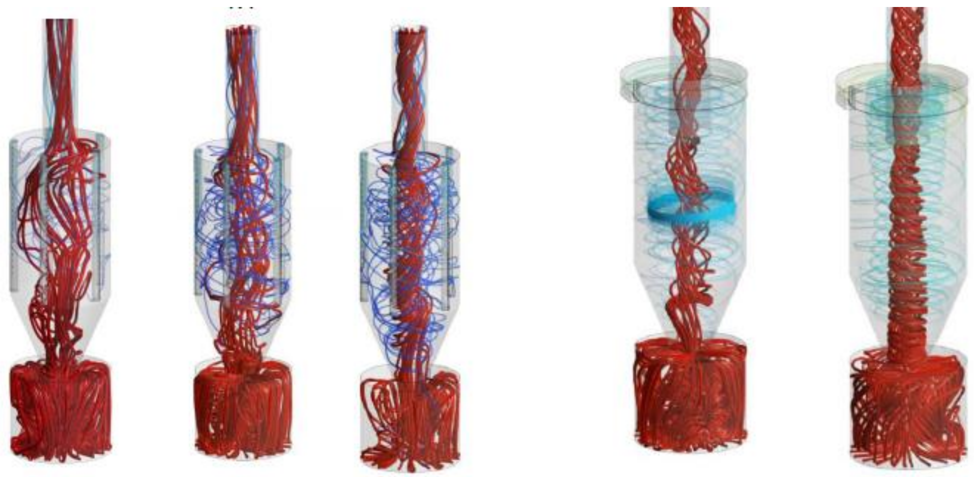
- Met every milestone and on budget. We have completed the major R&D elements leading up to real-world prototype development, the next critical step.
  - Initial design specifications and extensive CFD modeling complete, R1 prototype created and tested
  - R2 prototype complete and undergoing testing
- The company leveraged domain expertise to provide an initial framework to define the project and steps necessary to achieve success.
  - Modeled swirling combustion to identify attributes needed to achieve a theoretic sustained swirl.
  - Built complex CFD models to predict and help visualize outcomes of possible design approaches. 14 configurations in an isothermal simulation and 2 in a combustion configuration.
  - Several rounds of prototypes built to provide early testing of promising approaches
- Learned:
  - Which methods are most effective and necessary for tornado coherence.
  - Ratio of primary to secondary are required to maintain swirl coherence.
- What we don't know yet
  - Can we sustain swirling combustion long enough for consistent consumer acceptance

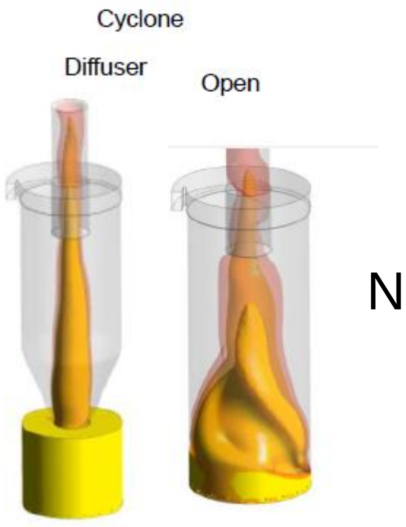
3 – Progress and Outcomes
CFD

Cyclone, Manifolds, or Swirl Vanes

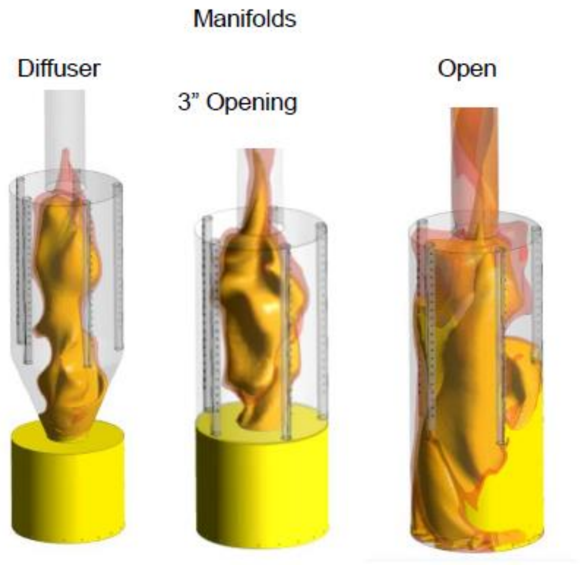


Secondary Air





Nozzle



3 – Progress and Outcomes

Prototype R1

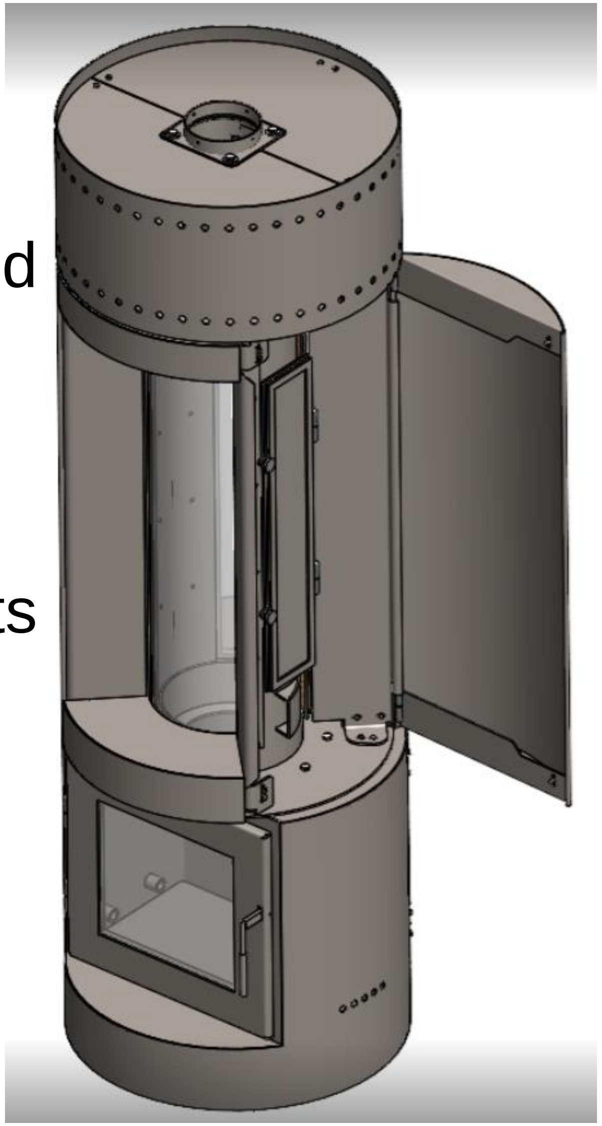
Swirl vane, secondary air

- Modular approach
- Successful swirling combustion with standard consumer fuel - cordwood
- Forced air (negative pressure) & natural convection
  - Both approaches yield swirling combustion
  - Forced air preferable for performance
- Emissions (PM2.5) less than 4.5 g/hr milestone

3 – Progress and Outcomes
Prototype R2

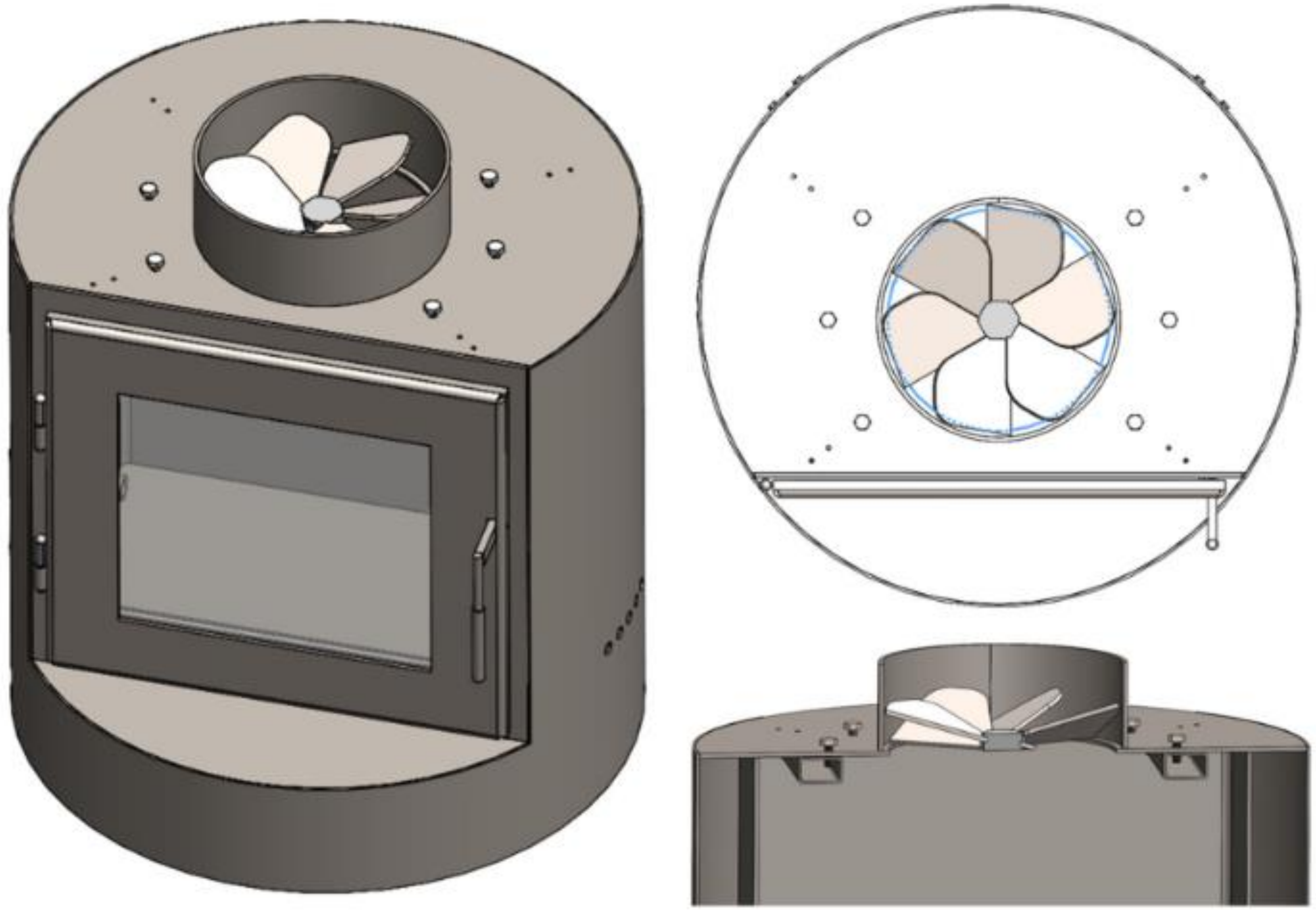
Swirl vane, secondary air

- Same principles as R1, but numerous design improvements
- Modular for access during prototype and beta testing stages
- Curved glass in swirl chamber
  - Greater uniformity in swirl chamber geometry
  - Design change from R1 prototype
- Access doors for maintenance and parts swapping
- Fan chamber
  - Accommodates several fan styles (negative pressure)

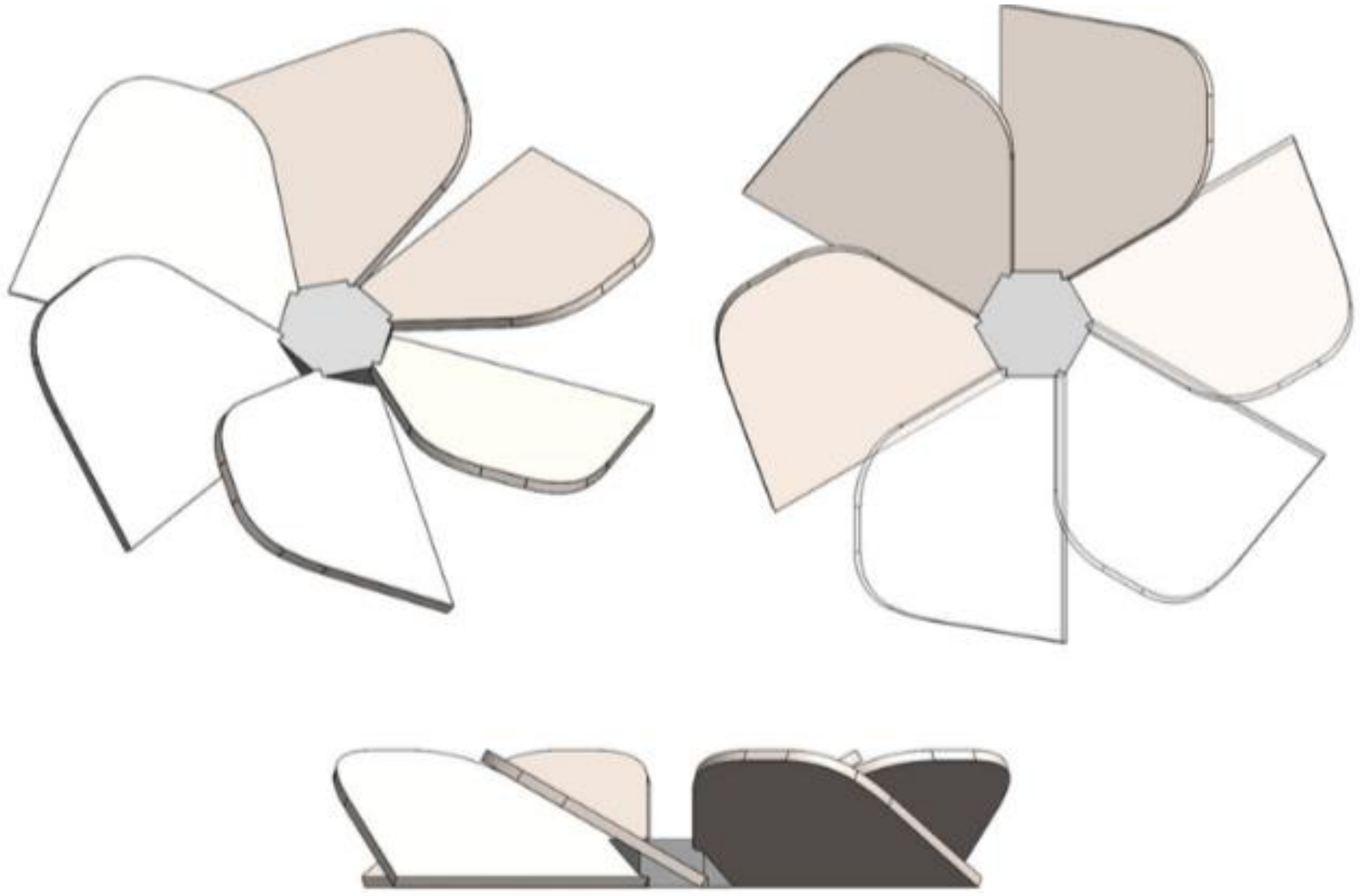


Swirl Vane

- Located above the main burn chamber, below swirl chamber
- Kick starts swirling combustion
- Experimenting with several angle orientations
- Swappable to test and allow for differing use conditions (chimney height, altitude)



Swirl Vane



Work Remaining

- Tighten tolerances between glass and body to improve seal
- Re-establish optimal swirl in prototype R2
  - Changes from R1 to R2 have disrupted swirl from previous version
  - Continue testing of variables including firebox geometry, air introduction pattern in swirl chamber, wood loading
- Improve design for beta test model
  - make install and maintenance easier
- Emissions testing with final version

Plans for the Technology (Commercial)

- Once we achieve a sustainable swirl for a sufficient set of environmental variables, optimize form factor for
  - Easy of install
  - Maintenance and glass cleaning
  - Aesthetic
  - Cost
- Demonstrate swirl technology is an easier-to-use, lower maintenance alternative to catalytic wood stoves

Summary

- Swirling combustion in other (non-wood) fuel sources results in more complete combustion, which results in fewer byproducts and emissions.
- Sustainable swirling combustion of wood fuel with low emissions (PM2.5) can be achieved
- Swirling combustion designs in wood stoves have the potential to advance the state of the art for wood heat emissions and allow for continued improvement to achieve ever-tighter emission targets.

Quad Chart Overview

Timeline

- Oct 1, 2019
- Anticipated June 2024

	FY22 Costed	Total Award
DOE Funding	$197,133	$998,937
Project Cost Share	$49,499	$250,810

Project Partners

- N/A

Project Goal

The goals and objectives for this project are to create a system that:

1. Achieves stable swirling combustion
2. Eliminate remaining 50-75% of emissions
3. Improves the realized efficiency by 10 to 15%
4. Is affordable and can be incorporated into a commercially viable product.

End of Project Milestone

The expected outcomes of this project are:

1. A commercially viable, low emitting wood stove, ready for affordable mass adoption.
2. Passage of UL Safety Tests and EPA Method 28 Emissions Testing with a swirl combustion stove meeting particulate emissions goals of less than 0.5 g/hr
3. A peer reviewed journal article describing the utility of swirling combustion applied to batch loaded wood.

Funding Mechanism

DE-FOA-0002029
FY19 BIOENERGY TECHNOLOGIES OFFICE MULTI-TOPIC, AOI 3: Efficient Wood Heaters

Additional Slides

Management

- Team consists of combustion experts, engineers of varying disciplines and project manager.
- The project is managed using best practices as defined by Project Management Institute.
- Team utilizes weekly formal status meetings as well as daily scrum session to manages progress and key decisions. A separate weekly finance meeting ensures the product adheres to the overall schedule and budget.
- An integrated set of management tools are used to track the project and preserve a record of communication and decisions, such as Slack, Asana, and Google Drive
- The team has successfully worked together on other patented and commercial wood stove technologies for over 8 years.
- Strong collaboration and communication enable the team to keep sight of progress and spot issues early. We utilize a proven, formalized process for product development, which enables the team to work through challenges and test core hypothesis.

(Not a template slide – for information purposes only)

- *The following slides are to be included in your submission for evaluation purposes, but will **not** be part of your oral presentation –*
- *You may refer to them during the Q&A period if they are helpful to you in explaining certain points.*

Responses to Previous Reviewers' Comments

Previous Comments

- **Why develop prototypes before achieving swirl?** Swirling combustion requires precision across many different input variable to be achieved successfully. Device prototyping was critical to achieve sufficient variable control to deliver swirling combustion, which was achieved once we completed the initial prototypes
- **PM vs CO focus.** The BETO FOA objectives are tied to reduction in PM, not CO. This project looks to help with both, but our main success metric is reduction of PM2.5.
- **CFD model validation and expert partner**. CFD modeling is a well-known method for modeling complex systems. Cord wood combustion is a chaotic, constantly changing system – every burn is different. Modeling wood combustion using CFD is new. To achieve the best results, MF Fire defined the scope of the modeling to be performed and enlisted the consulting and CFD engineering assistance from a well-known CFD services organization. MF Fire provided the domain expertise for combustion science that fed into the CFD modeling provided by the outside firm to develop state of the art combustion modeling for swirling combustion conditions.

Publications, Patents, Presentations, Awards, and Commercialization

- Patent awarded 2021-02-16
- US10920987B2
- Abstract

A solid fuel burning device has at least one burn chamber wall, a burn chamber base, and an interior burn chamber. The burn chamber base is capable of supporting a combustible solid fuel thereon. At least one of the burn chamber walls is radially offset with respect to another of the burn chamber walls. At least two longitudinally extending air inlets are formed in the space between a first longitudinal edge of at least one of the burn chamber walls and a second longitudinal edge of another burn chamber wall. Each of the longitudinally extending air inlets tangentially directs an entry of air into the interior burn chamber to induce an interior swirl of air in the interior burn chamber. The interior swirl of air in the interior burn chamber causes a flame of a combusting solid fuel to swirl in the interior burn chamber.