DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Simulation-Driven Design Optimization and Automation for Cordwood-Fueled Room Heaters (WBS 3.5.2.605)

April 5, 2023
Systems Development and Integration Session A

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Ohio State University

Project Overview

- Wood-fueled heating systems are a significant source of air pollution during colder months in certain areas of the US
  - This was the specific target of the FOA that funded this award
- Further emissions reductions of the wood-fueled room heater require translation of existing technologies into this sector:
  - Automation: Automatic feedback control systems to monitor and control the combustion process
  - Simulation-Supported Design Optimization: The ability to simulate complex wood combustion processes and evaluate/refine designs virtually rather than through traditional design-build-test processes
- Project High-Level Goals:
  - Develop modeling and automation technology to support simulation-based design of wood stoves
  - Demonstrate the above two technologies through the development of a catalytic and non-catalytic prototype that exceed the targets established in the FOA
  - Transition results into the domestic wood stove industry through engagement and professional development
- Key Risks:
  - Technical Risk: Modeling wood combustion is technically challenging
  - Adoption Risk: The wood stove community generally does not have competency in advanced simulation tools
  - Cost Risk: Automation systems must have low-cost potential to work in the market

1 – Approach

Technical Approach – 1/2

- This is the first peer review of the project
  - Verification period started 1/1/2022 and technical work 4/1/2022
- The project has two technical targets which were consistent with the RFP goals:
  - Demonstrate a catalytic stove with an 8% efficiency improvement and PM emissions at 65% below the 2020 standard
  - Demonstrate a non-catalytic stove with a 7% efficiency improvement and PM emissions 70% below the 2020 standard
- Main Project Thrusts:
  - Flow / Heat Transfer Modeling (Ohio State University)
  - Combustion Modeling (University at Buffalo)
  - PM Modeling (Oak Ridge National Labs)
  - Automation (Ohio State University)
  - Design (Ohio State University)
  - Fabrication (New Buck Corporation)
  - Industry Engagement (NAFEMS / Ohio State University)

1 – Approach

Technical Approach – 2/2

Simulation-Driven Design

- Simulation-driven design is used in every mature engineering field (*e.g.* aerospace, automotive, *etc*.)
- Conducting design optimization in a virtual environment is often less costly and faster than refinement using physical prototypes
- The team is developing modeling techniques capable of predicting efficiency and PM emissions
- These models can be used to explore the design space far more effectively then a traditional design-build-test approach

Automation

- Emissions control in other combustion systems relies upon careful control of the reaction (*i.e.* air-to-fuel ratio for combustion engines)
- Wood burning stoves in the United States are not currently using this technology
- The team is developing algorithms to automatically control the air flow into the wood stove to optimize efficiency and emissions
- This removes potential variability in operator usage of the stove, will be more robust to fuel differences, and will allow potential “smart” integration into home HVAC systems

1 – Approach

Top Challenges

- Challenge 1: Modeling Wood Combustion
  - The process of wood combustion and emission formation is extremely complex
  - University at Buffalo has experience in this area as does Oak Ridge National Labs
  - Alternative methods are also in use that rely on greatly simplified means of representing the wood combustion
- Challenge 2: Technology Transfer into the Wood Stove Industry
  - The domestic wood stove industry does not generally have capability in automation or advanced simulation
  - This will require upskilling existing engineers or hiring of new workers with skills
  - NAFEMS is well-equipped to help facilitate training and connections to simulation resources along with the university partners
  - Automation techniques will also be new to the industry, however, this is more approachable from a training perspective
- Challenge 3: Cost of Automation and Added Development Costs
  - The additional cost of simulation resources (employees, training, software, etc.) could be offset by efficiencies in development timelines and testing/certification
  - The cost of automation systems (*e.g.* embedded controllers, sensors, actuators) will be an additional cost per stove
  - The team is exploring a range of sensor and actuator sets to understand the benefit achieved with each towards the targets
- Challenges encountered thus far have been anticipated by the team and the project was designed to address them

1 – Approach

Go/No-Go Decision Points

- Go/No-Go Decision Point 1: Passing Verification Phase
  - Month 3 (March 2022)
  - Passed
  - The team worked with an independent engineer to provide information for the assessment of the project viability
  - The project was deemed viable and the team was cleared to start the second Budget Period 2

- Go/No-Go Decision Point 2: Successful Testing of the First Prototype
  - Month 24 (December 2023)
  - In-Progress
  - The team will have completed the simulation-based design improvements and deployed the automation system
  - The prototype will be tested at University of Buffalo to compare against the baseline and the performance targets

1 – Approach

Risk Analysis and Mitigation

The following risks were encountered or being actively monitored/mitigated:

- Delayed Project Start:
  - The project was awarded in August of 2020 but was not contracted until January of 2022
  - The team began essential prep work at-risk in summer of 2021 in order to be able to retain critical staff
  - One critical staff member did move on from a partner organization, but another individual was recruited and rapidly onboarded
  - ORNL's start date was delayed due to this which required schedule compression to synchronize the work with other tasks
- Electronic Component Backlogs:
  - The chip shortage delayed some instrumentation purchases
  - These were handled via schedule compression and, once the issue was noted, being proactive in ordering equipment
- Undergraduate/Graduate Student Transitions:
  - A significant amount of the staffing on this overall effort comes from OSU and UB students
  - The PIs are well-versed in managing these potential continuity issues as students move through the system and graduate
  - This is done via recruitment of students and having overlap between incoming and outgoing students

2 – Progress and Outcomes

- Project Start Date: 1/1/2022
  - Budget Period 1 (M1-M3) – Verification Completed and Technical Work Started
  - Budget Period 2 (M4 – M23) – In Progress
  - Budget Period 3 (M24 – M39) – Not Started

- Team held annual review on 12/8/23 with DOE Technology Manager, Project Manager, and Independent Engineers assigned to the project
  - Project was assessed as on track with no major change requests
  - Project team is just beginning to get into the core part of the work with the first major activity being a redesign of the non-catalytic stove, refinement, and testing

- Technical work to date has been focused on capability development in simulation and experimental platform development

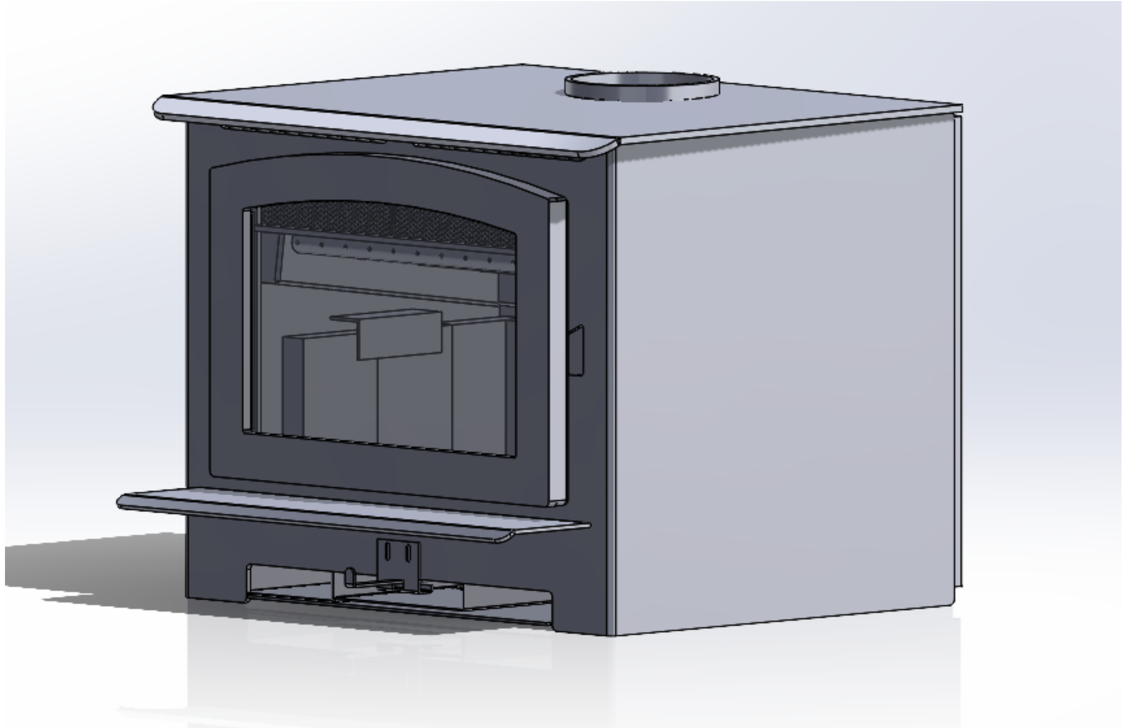
2 – Progress and Outcomes

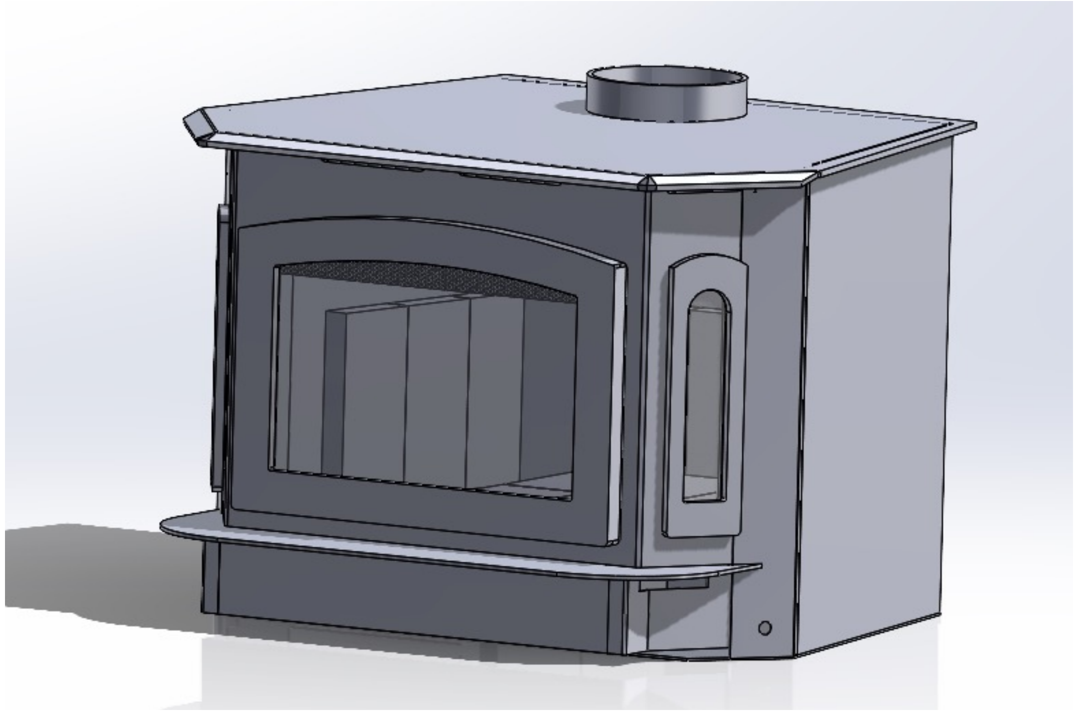
- The following provides high-level summaries from the SOPO defined milestones

- Past Milestone Summary: **All milestones achieved on time**
  - Month 3 (Go/No-Go Decision) – Independent Engineer gives "Go" recommendation
  - Month 6 (Milestone) – OSU can mesh solid models of both stoves in CFD
  - Month 9 (Milestone) – OSU can run CFD models with without errors
  - Month 12 (Milestone) – OSU CFD model with 10% accuracy for non-catalytic stove

- Future Milestone Summary: **Near-term milestones seem achievable**
  - Month 15 (Milestone) – UB has collected appropriate data sets to support (on track at submission for 3/28 completion)
  - Month 18 (Milestone) – OSU to demonstrate automation system for air control
  - Month 21 (Milestone) – UB has received prototype stove
  - Month 25 (Go/No-Go Decision) – UB completes testing of prototype, and it meets project targets

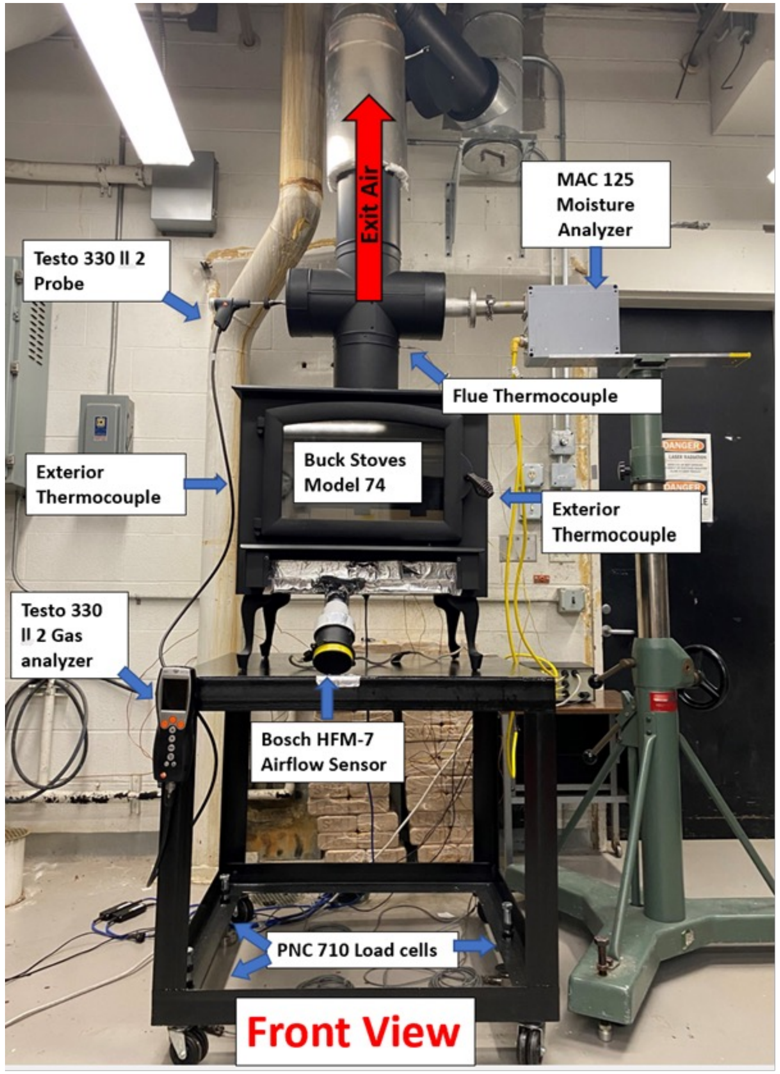
2 – Progress and Outcomes

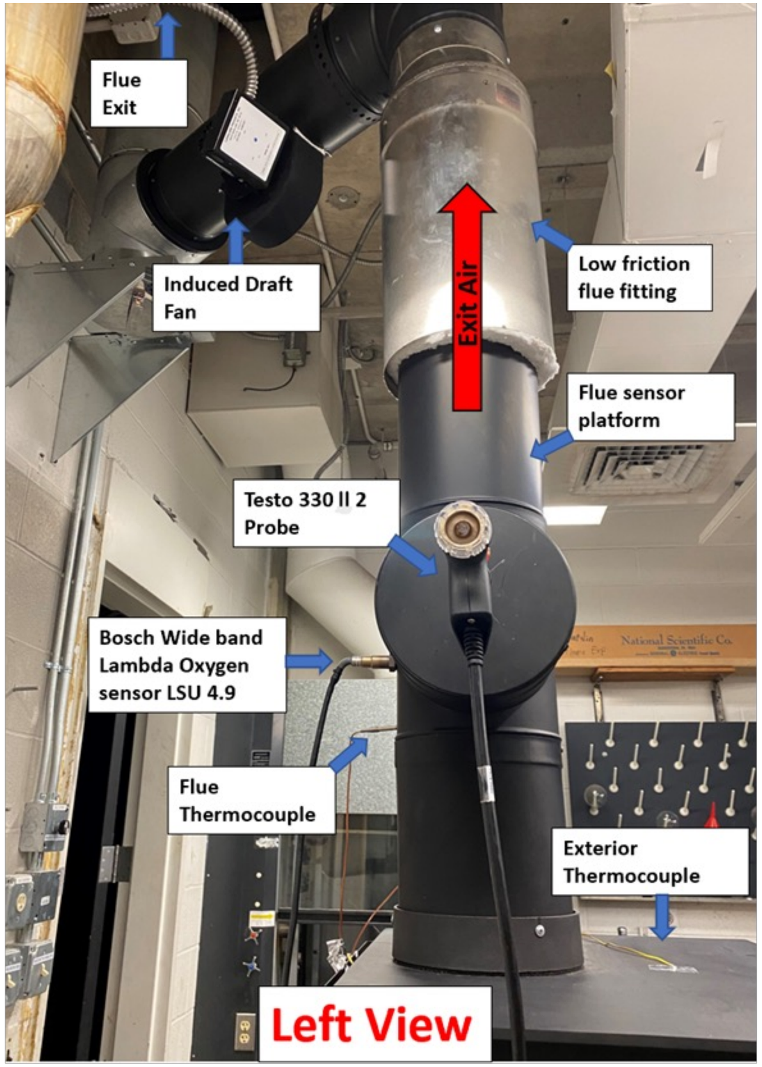


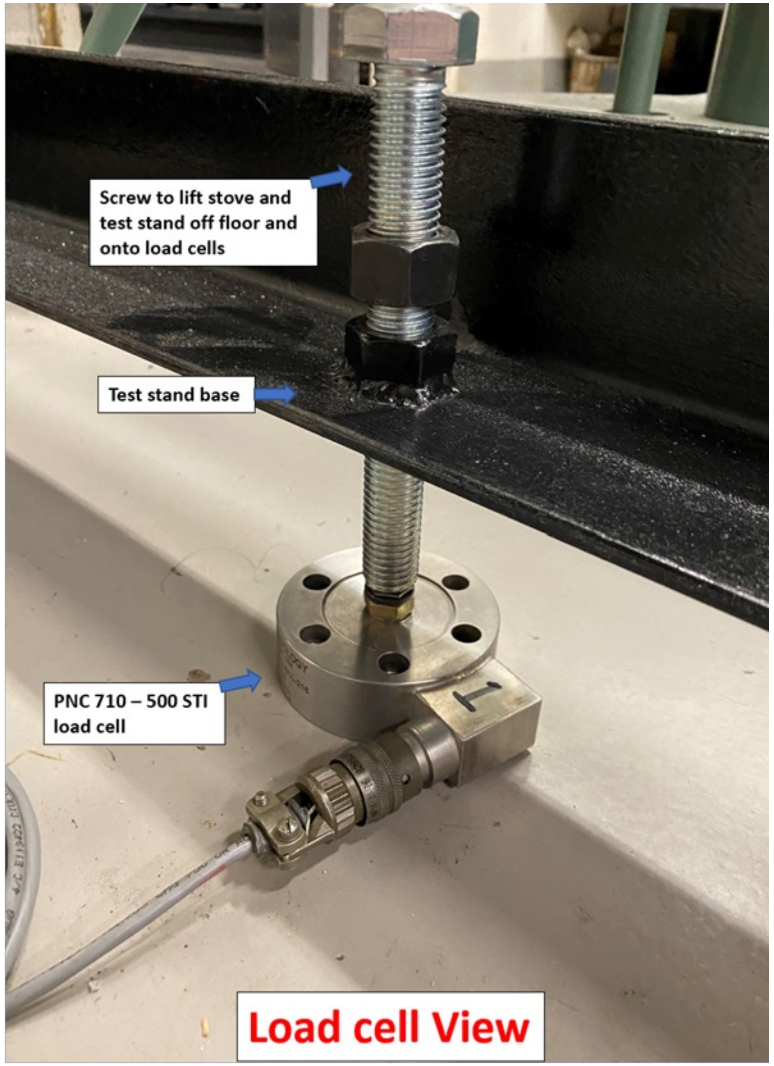


2-D manufacturing drawings of the baseline units from New Buck were used to create solid models of the catalytic and non-catalytic baseline units

2 – Progress and Outcomes

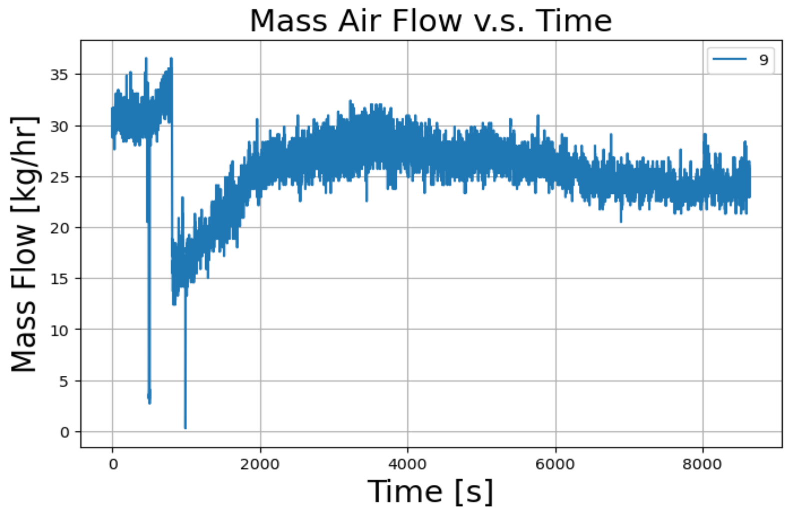


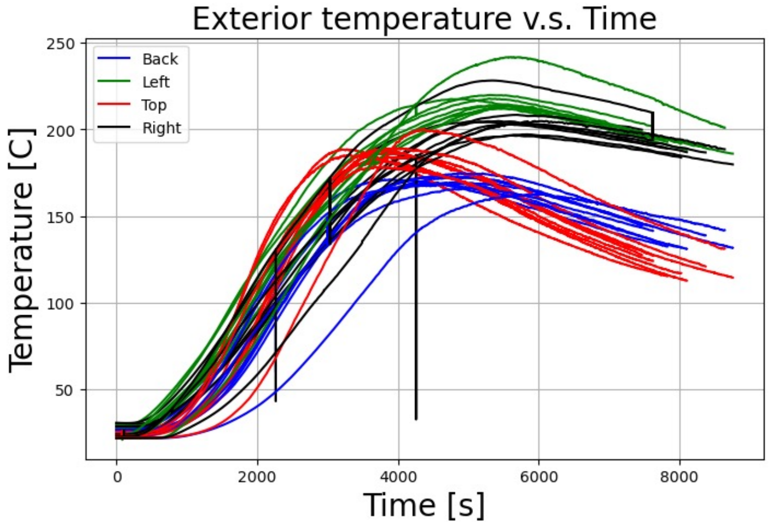


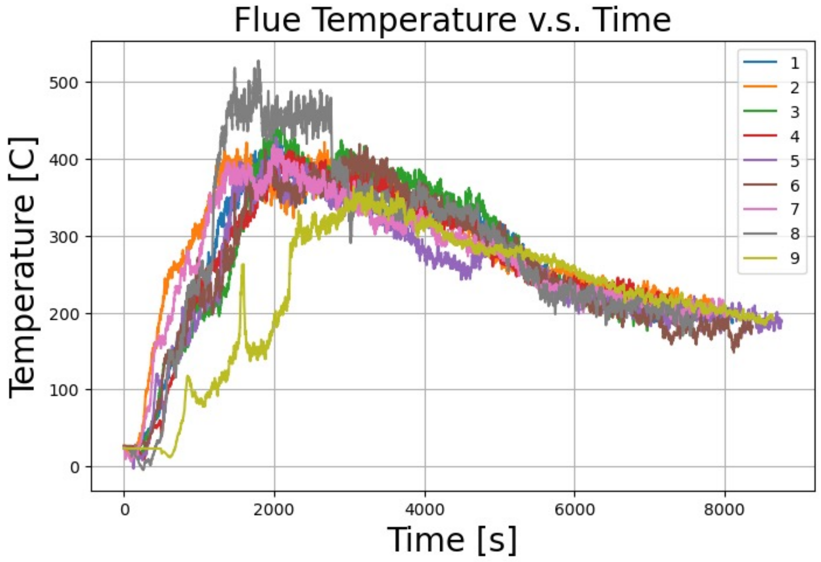


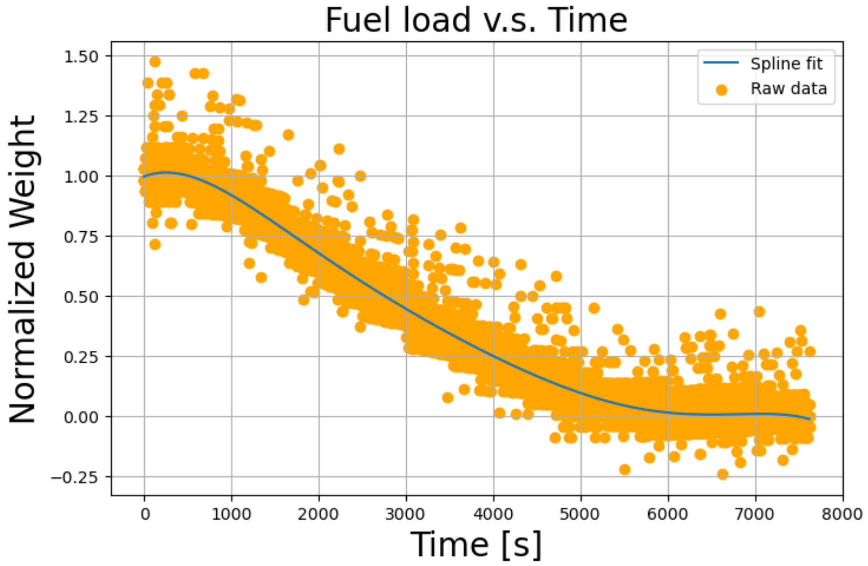
Experimental facilities have been established at UB and OSU per the project plan

2 – Progress and Outcomes



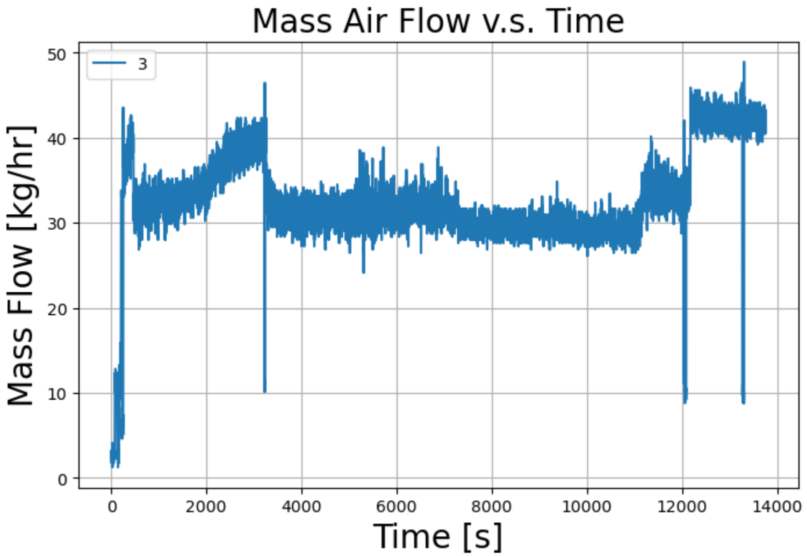


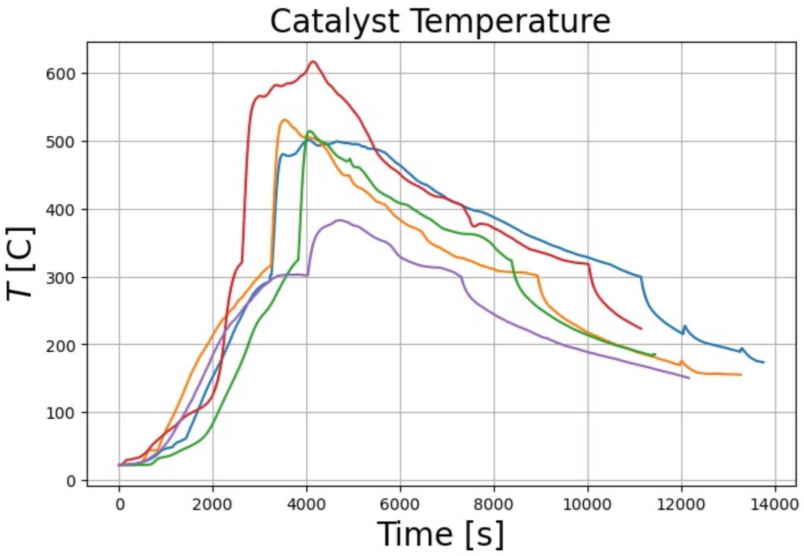


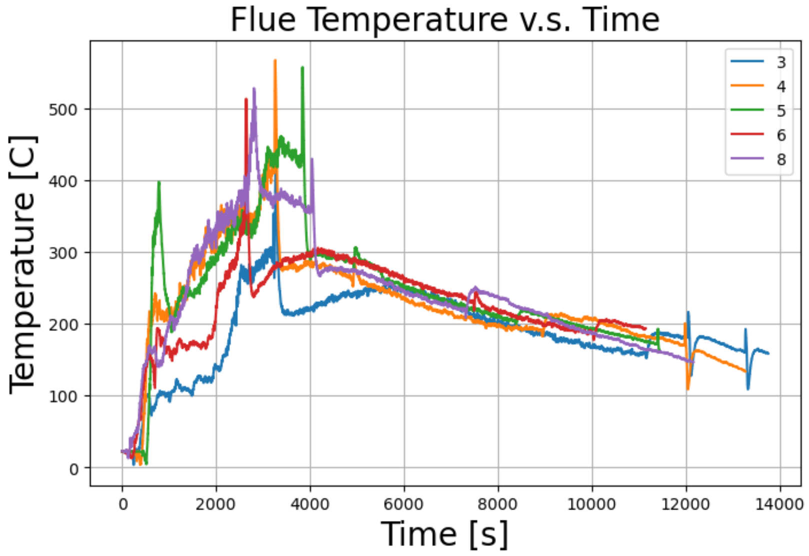


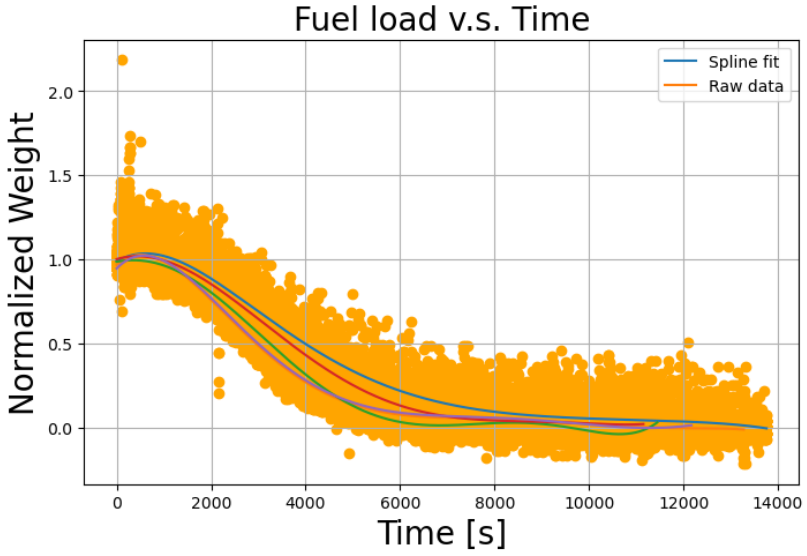
Repeatability runs were conducted on the non-catalytic stove with positive results

2 – Progress and Outcomes



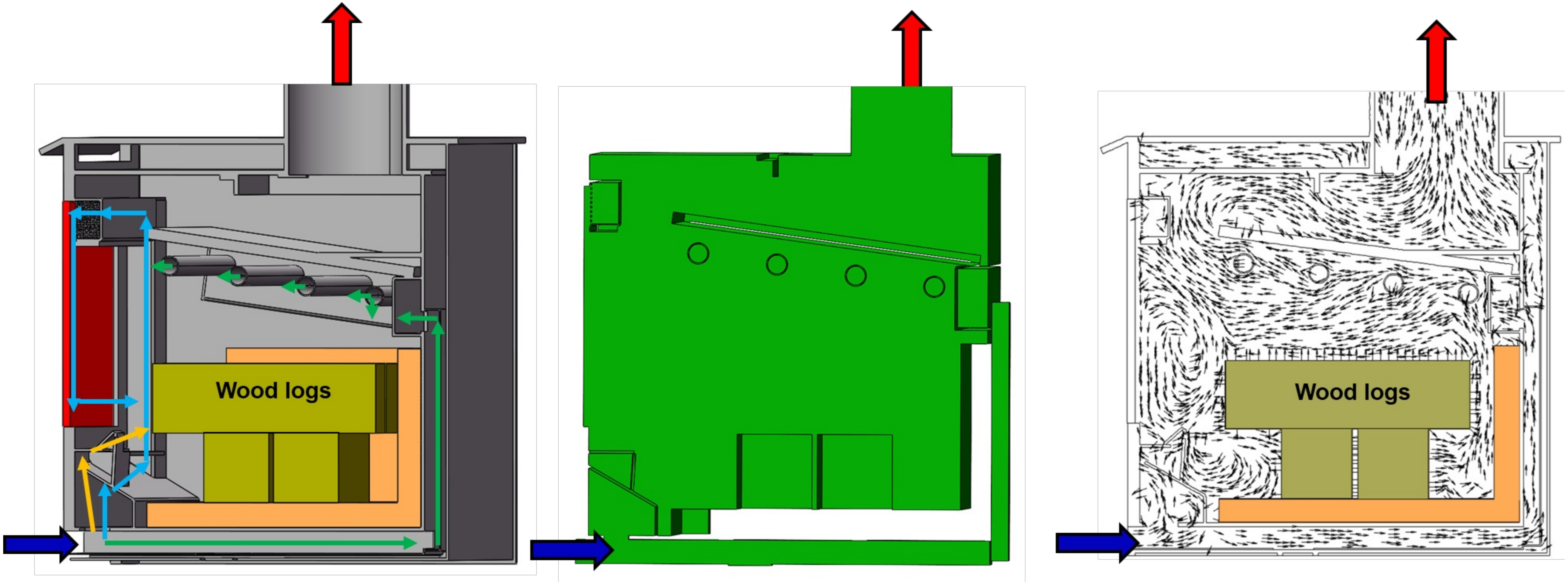






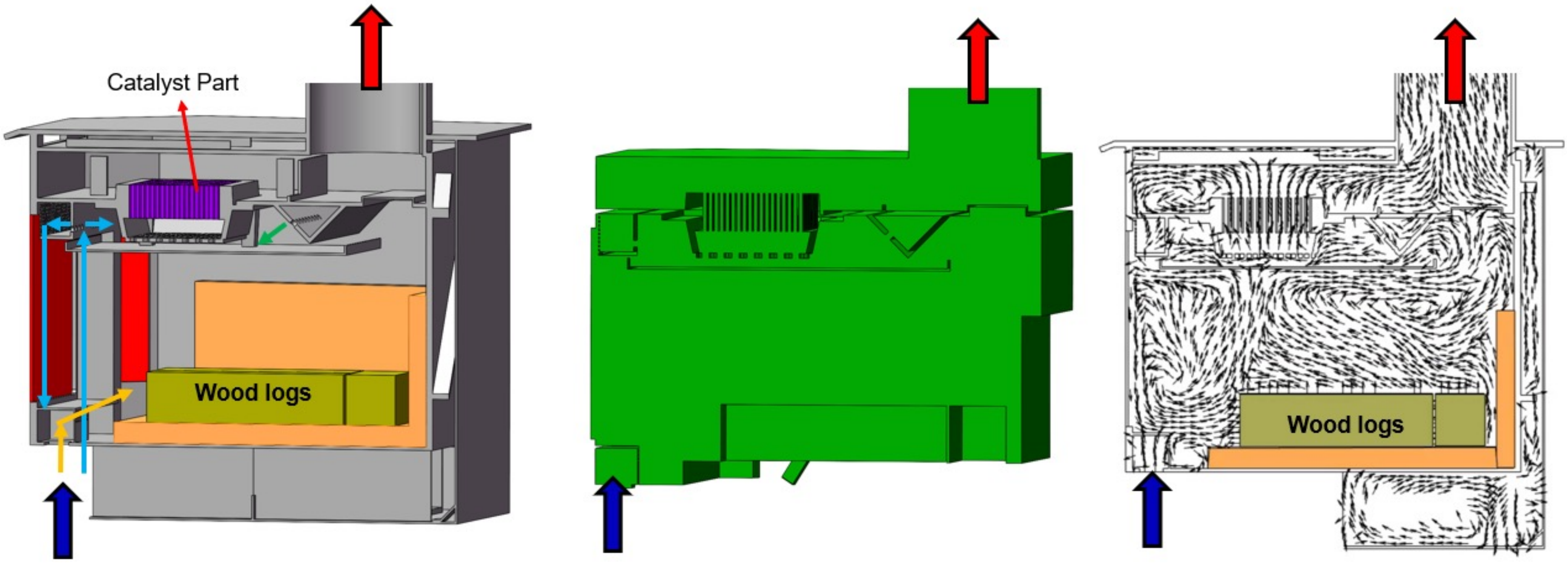
Preliminary runs on the catalytic stove have been conducted as well for later use

2 – Progress and Outcomes



Preliminary models of non-catalytic stove has been created and are being refined to serve as a basis for the design optimization

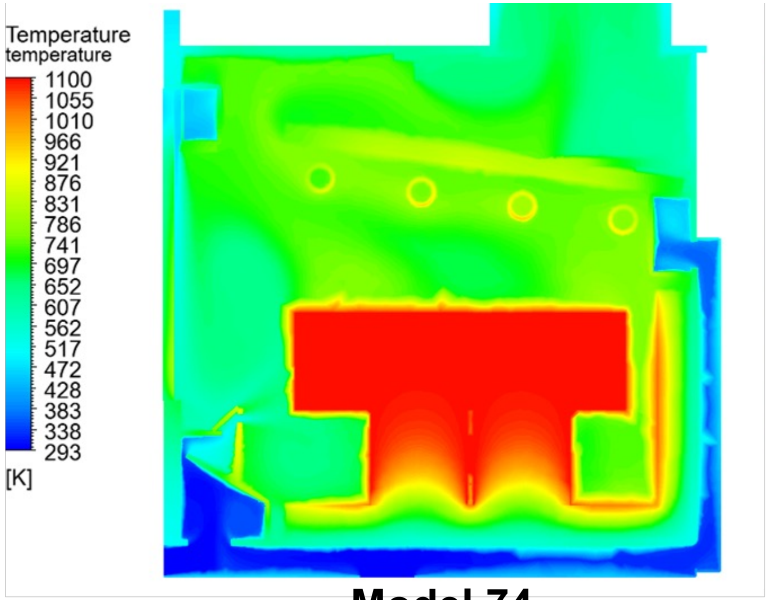
2 – Progress and Outcomes



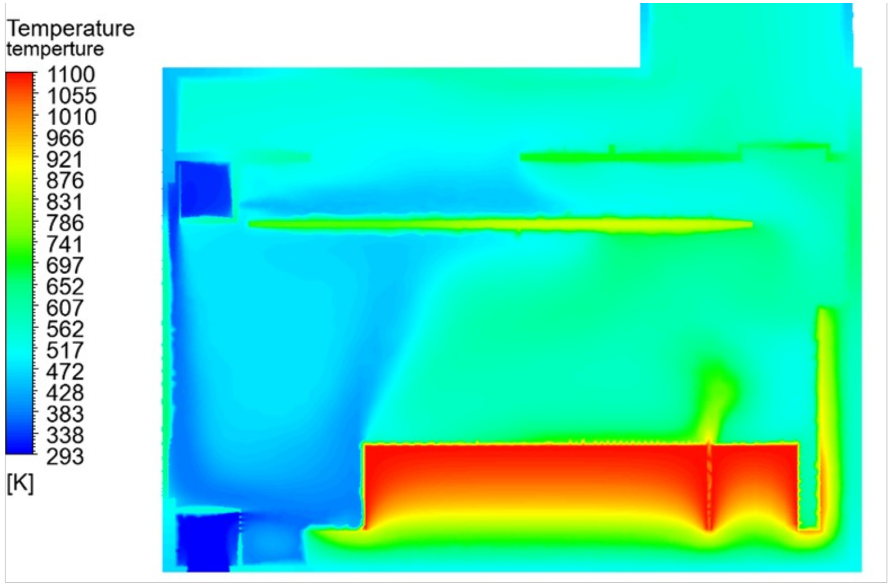
Model 91 Solid Domain | Model 91 Fluid Domain | Model 91 Vector Distribution

Preliminary models of catalytic stove has been created – these will be used later in the project when the focus is on the catalytic prototype development

2 – Progress and Outcomes



Model 74

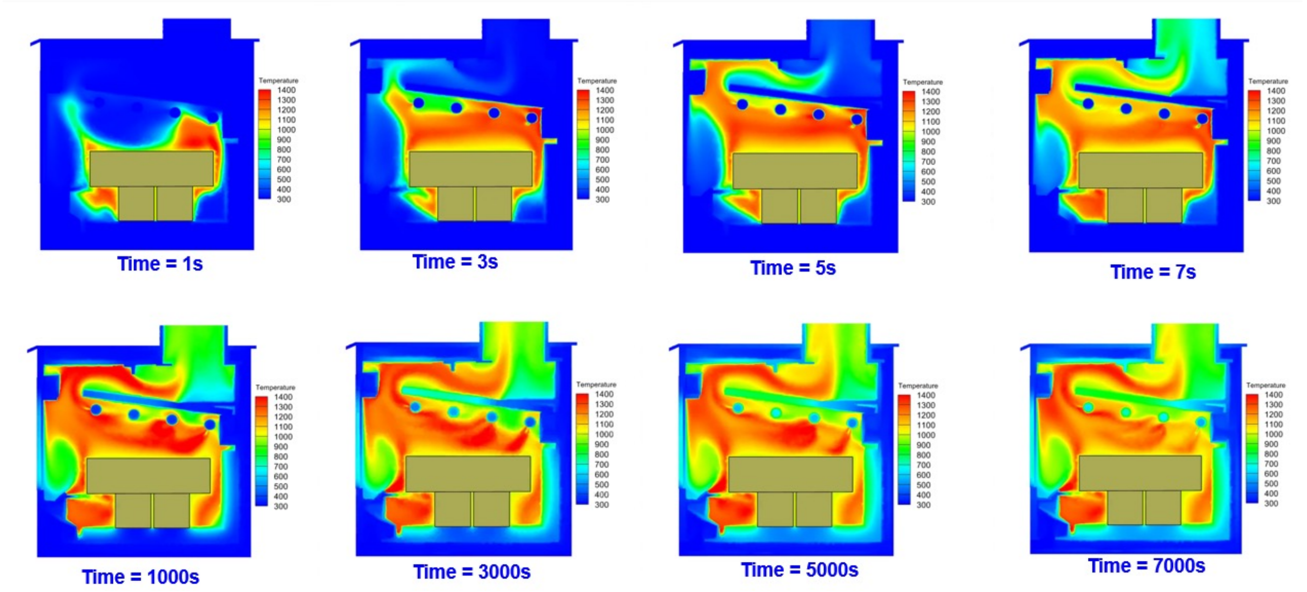


Model 91

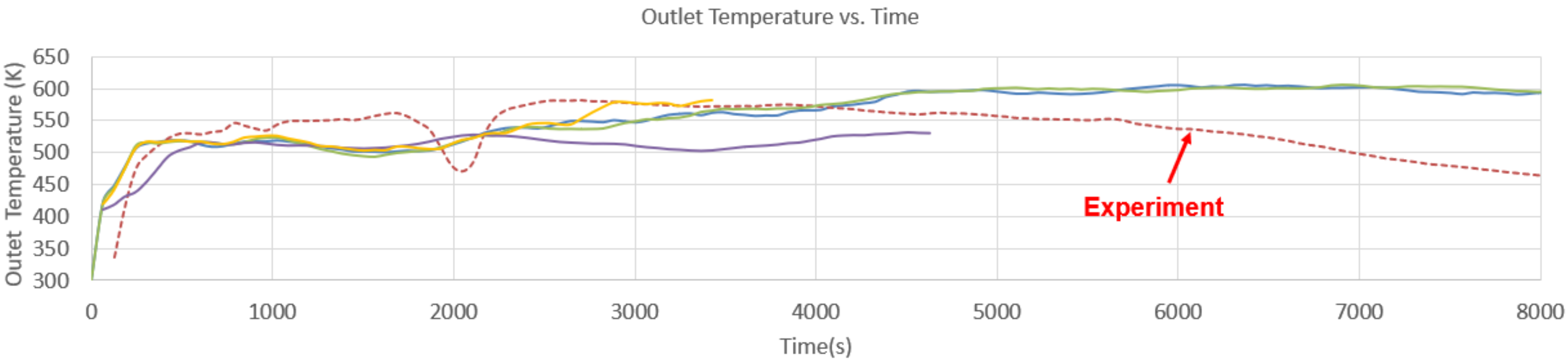
	Experimental heat output	CFD heat output	Error
Model 74	15.35 kw	13.60 kw	-11.4%
Model 91	18.38 kw	12.54 kw	-31.8%

The Model 74 model (non-catalytic) at the first release nearly met the 10% accuracy target. The Model 91 (catalytic) at first release was less accurate due lack of information on the catalytic combustor at the time

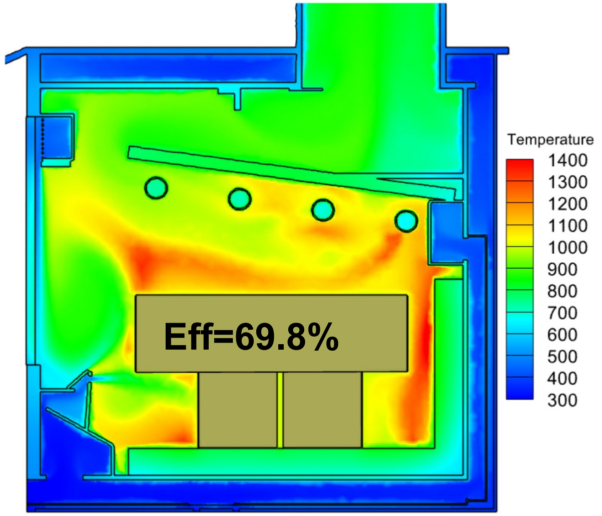
2 – Progress and Outcomes



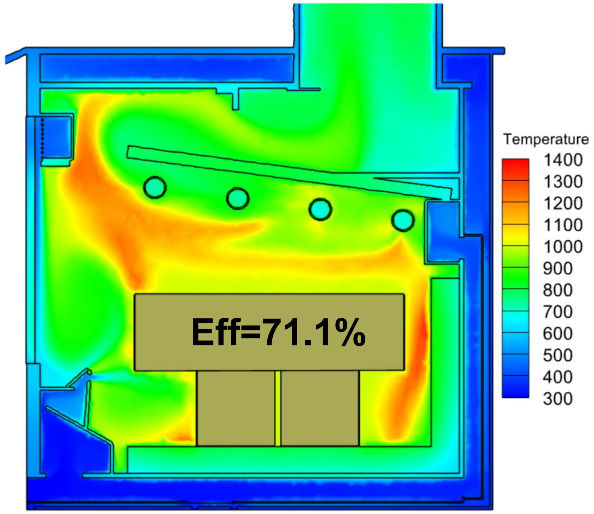
Transient results for full-duration burns are possible and correlate well with experiments until char combustion is dominant latter in the burn (this is work in progress)



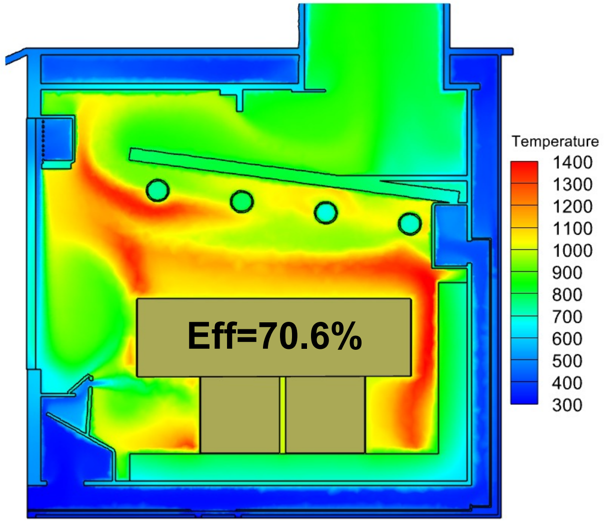
2 – Progress and Outcomes



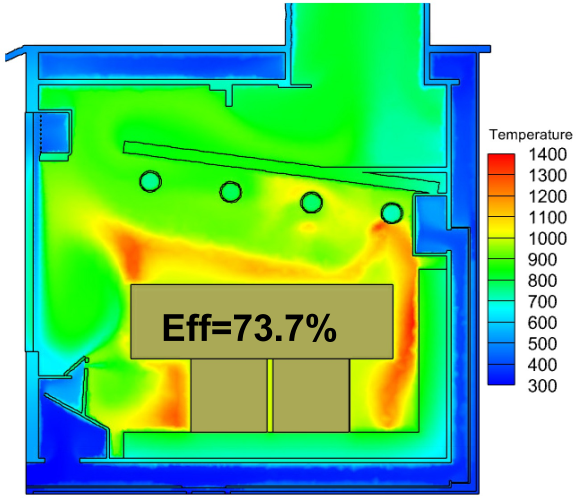
Baseline



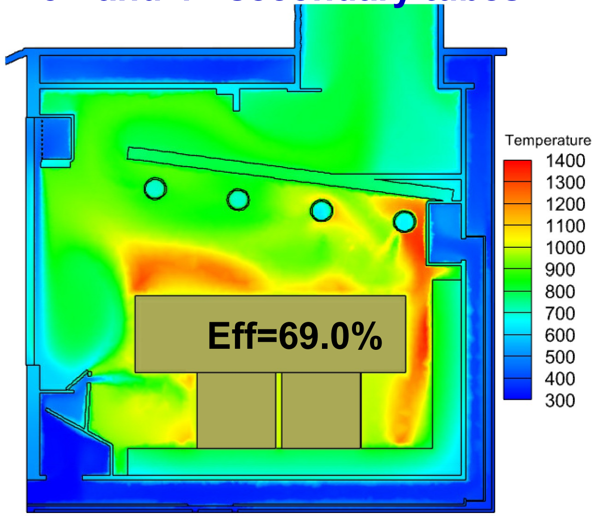
Case 1- Larger front holes of 3rd and 4th secondary tubes



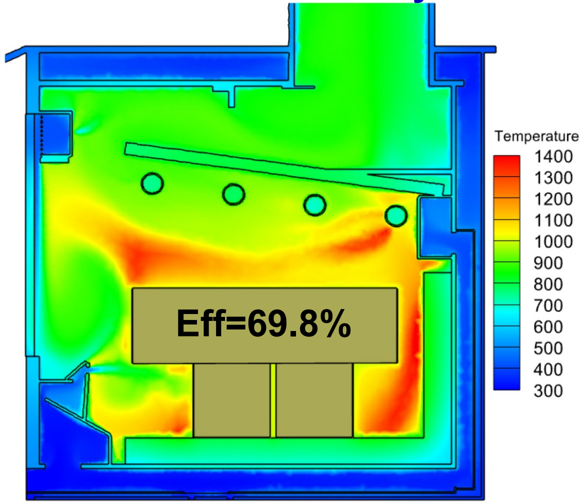
Case 4 - Smaller downward holes of 3rd and 4th secondary tubes



Case 2 - Smaller holes of shotgun air



Case 3 - Larger downward holes of 3rd and 4th secondary tubes



Case 5 - Adding holes for primary air channel

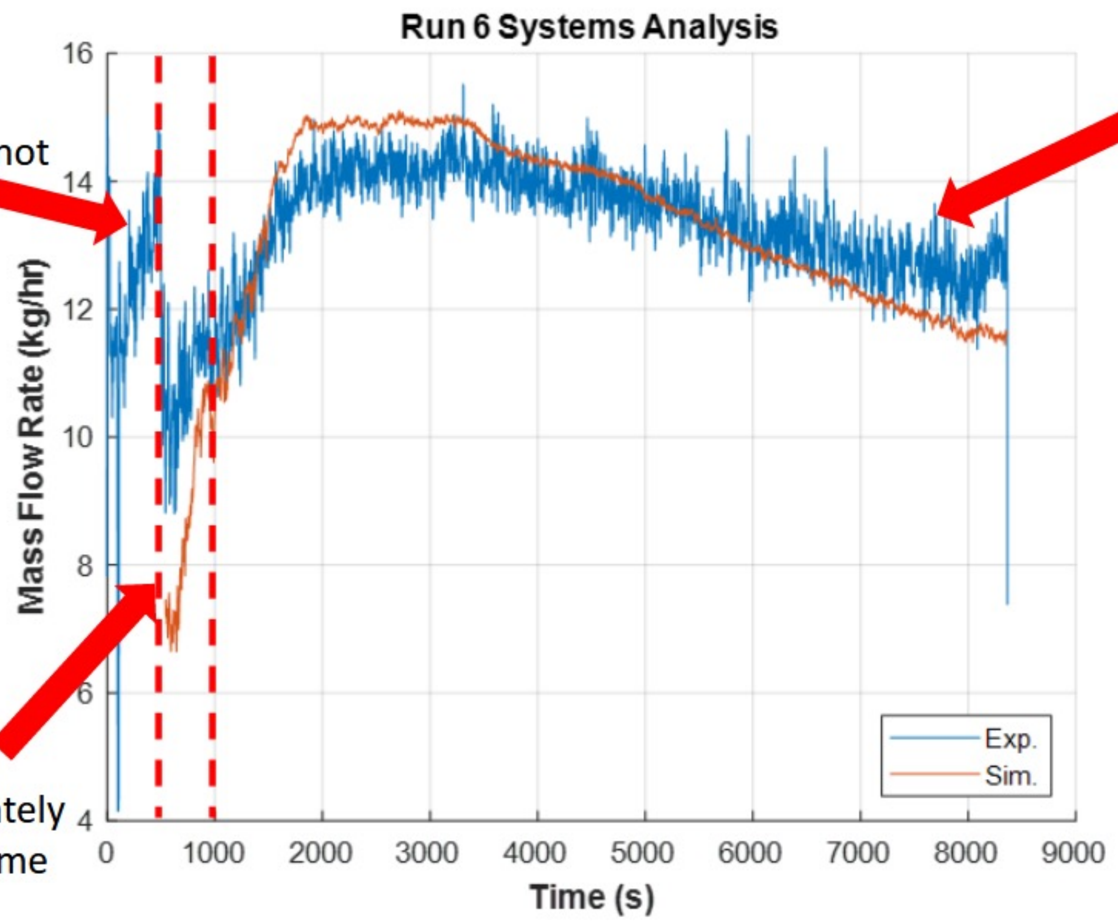
Major Successes

Preliminary design studies showing efficiency improvements as the team refines the process and accuracy of the modeling activity

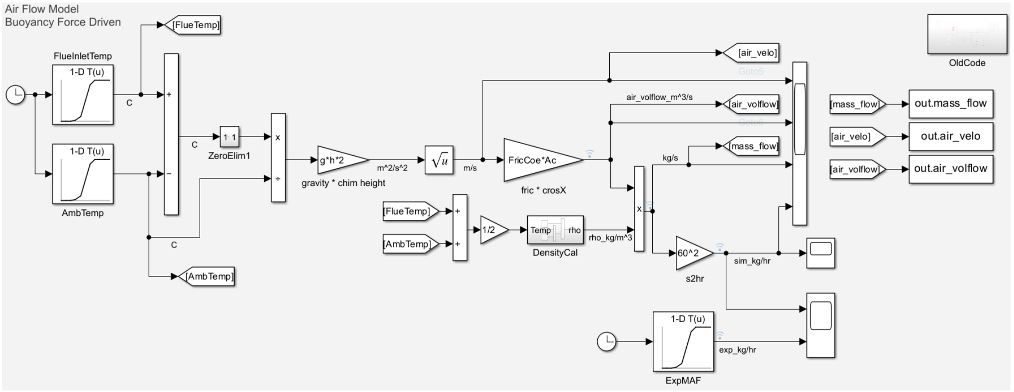
2 – Progress and Outcomes

Blower active, not modeled

Low temperature region, not accurately modeled at this time



High temperature operating region. Current optimization method reasonably matches results



Systems modelling to support automation development is progressing according to schedule

3 – Impact

- The project is aimed at developing improved capabilities and translating those directly into the wood burning stove industry

- These tools will give the industry the ability to innovate their products in new ways and be responsive to potential future regulations in efficiency or emissions

- The project is focused on the modification of existing stoves rather than the development of entirely new designs:
  - This is the most likely path that manufacturers would take in order to reuse existing designs
  - This is the current path most manufactures have taken in order to update designs to new emissions regulations

- These design tools also open the door to explore radical changes in designs without the time-consuming process of physical builds and testing

- The processes developed will be transferred into the wood stove community via publications, training, and engagement via conferences where the industry attends

Summary

- The technical work officially started April of 2022
  - Largely focused on capability development
  - Work to date has occurred largely as planned
  - Issues that have been encountered have been mitigated effectively
  - The December review with the DOE Technology Manager, Project Manager, and Independent Engineers assigned to the project was deemed successful

- The team is currently transitioning into the use of these capabilities to redesign the first stove to meet the efficiency and PM targets
  - This stage will be critical as the team transitions from focusing solely on capability to undertaking a newly developed virtual design process as well as deploys new automation systems

- Overall, the work to date has fell in line with the expectations so the team is excited to continue developing and demonstrating the approach

- The next year of work will be critical to the success of the project and the current trajectory looks positive

Quad Chart Overview

Timeline
- *Start: 1/1/2022*
- *End: 4/1/2025*

	FY22 Costed	Total Award
DOE Funding	*$419k*	*$2.2M*
Project Cost Share *	$174k	$643k

TRL at Project Start: 3
TRL at Project End: 7

Project Goal:
- Develop modeling technology and automation technology to support development of cleaner and more efficient wood stoves
- Demonstrate the above two technologies through the development of a catalytic and non-catalytic prototype that exceed the targets established in the FOA
- Transition results into the domestic wood stove industry through engagement with the industry and creation of targeted professional development

End of Project Milestone:
- Demonstrate a catalytic stove with an 8% efficiency improvement and PM emissions at 65% below the 2020 standard
- Demonstrate a non-catalytic stove with a 7% efficiency improvement and PM emissions 70% below the 2020 standard

Funding Mechanism
- FY20 Bioenergy Technologies Multi-Topic FOA (DE-FOA-0002203)

Project Partners
- Ohio State University, University at Buffalo, Oak Ridge National Labs, New Buck Corporation, and NAFEMs

Additional Slides

Responses to Previous Reviewers' Comments

- N/A - This is the first review

Publications, Patents, Presentations, Awards, and Commercialization

- Publications in Progress – Technical work started in April 2023

Prime Applicant: Ohio State University
Project Title: Simulation-Driven Design Optimization and Automation for Cordwood-Fueled Room Heaters

Principal Investigator:	Prof. Shawn Midlam-Mohler
Key Partners:	The Ohio State University (Prime), University at Buffalo, Oak Ridge National Laboratory, New Buck Corporation, and NAFEMS
Proposed Duration:	39 months

Technical Targets: With typical commercial stoves as baselines, develop design changes and automation strategies that:

- Demonstrate a catalytic stove with a 8% efficiency improvement and PM emissions at 65% below the 2020 standard
- Demonstrate a non-catalytic stove with a 7% efficiency improvement and PM emissions 70% below the 2020 standard

	Federal Share	Recipient Share
Total Project Cost	**$3,143,161**	
Total Shares (Prime+FFRDCs+Subcontractors)	**$2,500,000**	**$643,161**
Prime	**$1,268,396**	**$310,689**
FFRDCs Total	**$300,000**	**$0**
ORNL	$300,000	$0
Subcontractors Total	**$931,604**	**$332,472**
University at Buffalo	$749,393	$299,999
New Buck Corporation	$132,211	$32,473
NAFEMS	$50,000	$0

Application Area:

- Catalytic and Non-Catalytic Cordwood-Fueled Room Heaters

Technology Summary:

- Automation: Automation has played a key role in improving efficiency and emissions in many product sectors. The proposed work will develop automation systems for catalytic and non-catalytic stoves using the same approaches used in the automotive industry. This system will utilize low-cost sensors and actuators to control primary and secondary air to improve wood stove performance.
- Simulation-Driven Design: The use of simulation as a "digital twin" has allowed other industry sectors to make major advances in product design. In this approach, simulations are used to support the design activity as early proxies for traditional prototype-driven design processes. The team will refine existing simulation methods for use in wood stove design and apply these to develop improved designs for a catalytic and non-catalytic stove. This will result in improved combustion chamber designs, improved mixing of combustion air with gasification products, improved baffling, and improved insulation strategies.

Project Goals:

- Develop modeling technology to support simulation-based design of wood stoves
- Develop automation technology for application to catalytic and non-catalytic wood room heaters
- Demonstrate the above two technologies through the development of a catalytic and non-catalytic prototype that exceed the targets established in the FOA
- Transition results into the domestic wood stove industry through engagement with the industry and creation of targeted professional development

Key Takeaway:

- The proposed work aims to move the state-of-the forward while simultaneously increasing the technical competency of the domestic wood stove industry. This joint approach will allow the industry to adopt simulation and automation such that their in-house R&D capability is able to deliver products that can meet current and future efficiency and emissions targets.