Testing of a New Design of a Safe and Efficient Exhaust Thimble

A project by the University of Alaska Fairbanks
Institute of Northern Engineering
Emerging Energy Technology Fund Overview

New technology passes through a variety of phases as it proceeds from development and testing in the laboratory to commercialization in the real world. Emergence is a critical middle phase in the development process of energy technology, linking research and development to the commercialization of energy solutions. Although the Arctic possesses bountiful energy resources, the Arctic also faces unique conditions in terms of climate, environment, population density, energy costs, logistics, and the isolated nature of electrical generation and transmission systems. These conditions, challenging under the best of circumstances, make the Arctic an ideal test bed for energy technology. Emerging energy technology provides a unique opportunity to meet Arctic energy needs, develop energy resources, and create global expertise.

Building on the success of the Emerging Energy Technology Grant, funded by the Denali Commission in 2009, the Alaska State Legislature created the Emerging Energy Technology Fund (EETF) in 2010 to promote the expansion of energy sources available to Alaskans. These grants, partly funded by the Denali Commission and managed by the Alaska Energy Authority, are for demonstration projects of technologies that have a reasonable expectation of becoming commercially viable within five years. Projects can

- test emerging energy technologies or methods of conserving energy;
- improve an existing technology; or
- deploy an existing technology that has not previously been demonstrated in the state.

The funded projects for Round 1 of the EETF include the following:

- Alaska Division of Forestry, Biomass Reforestation of Boreal Forests
- Altaeros Energies, Inc., High Altitude Airborne Wind Turbine
- Arctic Sun, LLC, Arctic Thermal Shutter & Door Development
- Boschma Research, Inc., Cyclo-Hydrokinetic Turbine Energy Production
- Cold Climate Housing Research Center, Cold Climate Ground Source Heat Pump Demonstration
- Genesis Machining and Fabrication, Ultra-Efficient Generators and Diesel-Electric Propulsion
- Hatch, Application of Flywheels for the Integration of Wind–Diesel Hybrid Systems
- Intelligent Energy Systems, Small Community Self Regulating Grid
- Intelligent Energy Systems, Wind Diesel Battery Hybrid System
- Marsh Creek LLC, High Efficiency Diesel Electric Generator for Energy Projects in Alaska
- Oceana Energy Company, In–Stream Hydrokinetic Device Evaluation
- Ocean Renewable Power Corporation, RivGen™ Power System Commercialization Project
- University of Alaska Fairbanks, Safe and Efficient Exhaust Thimble
- University of Alaska Fairbanks, Enhanced Condensation for Organic Rankine Cycle

Award recipients for EETF grants are selected through a competitive application process. Project selection for the EETF program uses a two-stage application process and has a volunteer advisory committee appointed by the governor.

Data Collection

Data collection is a central component of all EETF awards. The recording and careful analysis of high-quality performance data are critical parts of testing new energy technology, to understand how the technology performs and make future refinements. Using this information to support data-driven decisions will continue to prove the value of Alaska as an energy laboratory and ensure that new energy systems are applied appropriately.

Under an agreement with the Alaska Energy Authority, performance data generated by projects are independently verified and analyzed by the Alaska Center for Energy and Power (if a potential conflict of interest arises for any technology, another independent third party is identified). As projects conclude, summary reports and non-sensitive data are made available to the public.

About the Author

The Alaska Center for Energy and Power (ACEP) is an applied energy research group housed under the Institute of Northern Engineering at the University of Alaska Fairbanks.

A key deliverable for each EETF project is a lessons learned report by ACEP. As the projects deal with emerging energy technology, providing lessons learned and recommendations is critical for understanding the future of the technology in Alaska, and the next steps needed in developing energy solutions for Alaska.

ACEP’s technical knowledge and objective academic management of the projects, specifically for data collection, analysis, and reporting, are vital components to the intent of the solicitation.
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Executive Summary
Exhaust thimbles are protective sleeves that surround hot metal stovepipes or chimneys to protect a building from dangerously high temperatures. As part of the first round of funding of the Emerging Energy Technology Fund, the Institute of Northern Engineering at UAF designed, modeled, and built several prototypes of an exhaust thimble to improve building efficiency and eliminate uncontrolled airflow between a structure's interior and the outdoor environment. The UAF design improves on current technology, which allows air to pass freely between the interior and exterior of a building through the thimble annulus, the space between the thimble exterior and the hot stovepipe. The new design described in this report does not expose the interior and exterior environments to each other. Instead, cool exterior air circulates in the thimble annulus, which is sealed off from the interior of the building.

Steady-state modeling by UAF was followed by field testing in Fairbanks. Testing showed that with exhaust gas temperatures up to 1000°F, temperatures on the outside surface of the thimble in contact with the roofline stayed well below the 400°F point where pyrolysis begins to occur. The highest temperature measured on the outer thimble surface was 231°F. The thimble was also tested at a variety of ambient temperatures and wind velocities, and with the thimble cooling vents occluded. None of these conditions caused the temperatures at the attachment of the thimble and the roofline to become dangerously high. Future independent third party testing will be needed to verify thimble safety. The UAF researchers have indicated they have no plans to commercialize the technology and think that private industry is best equipped to pursue further development.

Report Overview
This report discusses work undertaken by researchers at the University of Alaska Fairbanks (UAF). The project sought to improve building efficiency by improving the design of an exhaust thimble, used to protect wood and other building materials around chimneys and other high-temperature exhaust stacks. The National Fire Protection Association (NFPA) mandates that exhaust thimbles be installed where high-temperature gasses pass through a building envelope. The conventional design allows airflow between the interior and exterior of the building by maintaining an annular space between the thimble and the exhaust pipe that is open to both the building environment and the ambient conditions (Figure 1).

This report describes the testing of a new design for an exhaust thimble used for wood stoves, furnaces, diesel generators, and other high-temperature exhaust generating sources. The new design would replace the current technology with a passively cooled thimble that utilizes a thermal siphon to draw in cool outside air surrounding the hot exhaust stack and eliminates the open space between the indoor and outdoor environments. This design would prove most beneficial in northern regions, where significant heating loads and high energy prices make efficient building design particularly important. The prototypes were tested in a controlled setting to determine if the design functioned as intended and met necessary safety requirements. An analysis of the testing data is presented in this report along with lessons learned and recommendations for future work.
 Emerging Energy Technology Fund

Project Introduction

Project tasks included:
• modeling of exhaust thimble steady-state operation with COMSOL Multiphysics;
• acquisition and setup of repurposed shipping container as testing lab;
• fabrication of 2-, 4-, 6-, and 10-inch internal diameter thimbles (Figure 2) at UAF shop facility; and
• testing and evaluation of thimble performance over a matrix of conditions including summer and winter ambient conditions, exhaust temperatures ranging from 400–1000°F, and the presence and absence of wind.

The project’s testing activities began in February 2013 with the purchase of the data acquisition system and fabrication of the 2-inch-diameter thimble, used for initial testing. The data acquisition system was tested during the fall of 2013. All remaining thimbles were built and tested between late fall 2013 and the end of 2014.

The following organizations were involved in this project:

University of Alaska Fairbanks,
Institute of Northern Engineering

The Institute of Northern Engineering (INE) is the research arm of the College of Engineering and Mines at UAF. INE conducts a variety of research related to energy efficiency and lowering the cost of energy in Alaska and throughout the Arctic. Dr. Rorik Peterson of INE was the primary researcher of the exhaust thimble prototype. The thimble fabrication also took place at the shop facilities housed at the Institute of Northern Engineering.

Alaska Center for Energy and Power

The Alaska Center for Energy and Power (ACEP), an applied energy research program based at UAF, provided technical support for data collection. In addition, ACEP provided independent project and performance analysis and reporting. This report is the final product of that effort.

Technology Overview

An exhaust thimble is a protective sleeve that surrounds a metal stovepipe or chimney where high-temperature gases pass through a building envelope.

Thimbles are designed so that temperatures remain below dangerous levels where the thimble contacts the building shell. Current exhaust thimble technology was developed decades ago and has not been modernized since, as greater emphasis is placed on efficiency and a tight building envelope. Most thimbles in use today cool the exhaust stack by allowing air to pass freely between the interior and exterior of the building through the thimble annulus, the space between the inner and outer layers of the thimble. This open annular space creates a gap in the building envelope and allows conditioned air to escape to the atmosphere.

Regulations

Regulations concerning the clearances surrounding exhaust stacks are described by the National Fire Protection Association (NFPA) in its publications. Standards regarding thimble design and clearances are presented in three different sections:
Exhaust thimbles are used in a variety of applications including wood stoves, oil-fired furnaces, diesel generators, commercial cooking, and other high-temperature exhaust generating sources. The regulations vary for residential, commercial, and industrial use. However, in general, to be NFPA compliant, a thimble must be at least 6 inches larger in diameter than the diameter of the exhaust stack that it surrounds. Specific regulations vary by location. This report is not intended to be a detailed regulatory discussion. Additional details can be obtained in NFPA 54: 12.8.4.6. Most building codes related to this topic are based on the NFPA regulations noted earlier.

The sketches in Figure 1 show conventional thimble designs. Flow is typically driven by thermally induced buoyancy when the hot stack heats the air around it. However, because of pressure differences between the inside and outside of the building, uncontrolled ventilation can occur even when the heat-producing source is not operating. These pressure differences can often result in large energy losses as conditioned air escapes through the building envelope.

In addition to concerns about air leakage and energy efficiency, there are concerns about safety. The cooling effect can be compromised when the thermally driven buoyancy force is balanced by a negative pressure difference between the building interior and exterior. These competing factors can “stall” the airflow across the traditional thimble design, resulting in minimal airflow and dangerous temperatures.

The new design reported on here does not expose the interior and exterior environments to each other, and airflow through the thimble is only dependent on the thermal buoyancy caused by the heat source. The testing described in this report is designed to examine whether safety standards can be maintained and whether the thimble can protect the building envelope from dangerously high temperatures.
ventilation of the annular spaces. In addition, researchers studied the effectiveness of four different sizes of thimbles, which would be designed for different applications. Each thimble had the same design, but with slightly different sizing parameters so that modeling of the size of each chamber could be tested. The different sizes of the thimbles are shown in Table 1.

### Testing Location and Procedure

The thimble prototypes were tested inside a repurposed metal shipping container on the UAF campus. Fairbanks, Alaska, located at 64°N latitude, has extremely large temperature variations between the summer and winter seasons, allowing the thimble to be tested under a variety of ambient conditions ranging from -40°F in the winter to almost 90°F in the summer. A custom-made bracket system was designed to mount the different-size thimbles to the roof of the shipping container. As a heat source, a propane torch, commonly referred to as a weed burner, was inserted into the bottom of the chimney stack, 3 feet below the bottom of the thimble. Exhaust gas temperatures from the propane torch were adjusted depending on the test being performed, but ranged from 400–1000°F. Testing was conducted in 20-minute blocks. When testing started and the torch was ignited, the exhaust gas temperatures rose rapidly. The propane torch was manually adjusted to the proper temperature for the test. The exhaust gas temperature typically equilibrated within a couple minutes. The other thimble temperatures typically equilibrated by the end of the 20-minute test.

Tests were run during calm wind conditions as well as under simulated windy conditions. An industrial fan was aimed at the exterior portion of the thimble above the roof penetration to simulate windy conditions. In addition, a simulated thimble blockage to mimic an animal nest or debris blowing into the device and accumulating in the annular space was tested. These occlusions degraded the airflow by blocking the air channels and impeding the thermal buoyancy process. Testing ensured that the thimble would be safe even if it did not function exactly as designed.

Testing was conducted for each of the thimble sizes using different combinations of exhaust gas temperatures, thimble occlusions, wind conditions, and ambient temperatures. To clearly distinguish these combinations, a testing matrix was created (see Table 2). In total, 256 combinations were tested.

### Instrumentation

To carefully measure thimble temperatures and airflow, thermocouples were placed at nine locations to measure a variety of temperatures on all parts of the thimble and to measure the ambient air temperatures. Data were collected using a data acquisition system running LabVIEW software.

### Data Analysis/Performance Evaluation

Given the variety of individual testing combinations that were performed (Table 2), 256 data sets were created. The challenge for researchers was to determine what information was most significant. Testing had been done with the thimble air chamber occluded and open, with and without wind, during high and low ambient temperatures, etc., and all these testing combinations resulted in large data sets. It was necessary to divide the data into digestible subsets to understand how thimble temperatures reacted under different conditions and to ensure that safety standards were met.

Assessing safe operation of the thimble was the most important goal of the testing, so measuring thimble performance during the hottest exhaust gas temperatures (1000°F) was the most efficient way to assess the thimble safety margin.

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**Table 2. Thimble Testing Combinations**

<table>
<thead>
<tr>
<th>Thimble Size</th>
<th>Exhaust Gas Temperature</th>
<th>Occlusion</th>
<th>Wind Condition</th>
<th>Ambient Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 inch</td>
<td>1000°F</td>
<td>No Occlusion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 inch</td>
<td>800°F</td>
<td>~33%</td>
<td>Calm</td>
<td>Summer</td>
</tr>
<tr>
<td>4 inch</td>
<td>600°F</td>
<td>~66%</td>
<td>Windy</td>
<td>Winter</td>
</tr>
<tr>
<td>2 inch</td>
<td>400°F</td>
<td>Occluded</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3. The Nine Data Channels Defined**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Thermocouple 1 inch below thimble bottom in the exhaust inlet. Measures the temperature of the exhaust gas in the inlet of the stack.</td>
</tr>
<tr>
<td>1</td>
<td>Thermocouple located in the insulation within the roof which surrounds the exterior of the thimble.</td>
</tr>
<tr>
<td>2</td>
<td>Thermocouple at the exhaust exit. Measures the temperature of the exhaust gasses as they exit the stack.</td>
</tr>
<tr>
<td>3</td>
<td>Thermocouple 1 inch above thimble bottom. Measures temperature of air as it is circulated inside thimble air chamber.</td>
</tr>
<tr>
<td>4</td>
<td>Thermocouple 3 inches below air exit. Measures temperature of air as it is circulated out of the thimble air chamber.</td>
</tr>
<tr>
<td>5</td>
<td>Thermocouple 3 inches below air exit. Measures temperature of air as it is circulated out of the thimble air chamber.</td>
</tr>
<tr>
<td>6</td>
<td>Thermocouple 3 inches below air exit. Measures temperature of air as it is circulated out of the thimble air chamber.</td>
</tr>
<tr>
<td>7</td>
<td>Thermocouple 3 inches below air exit. Measures temperature of air as it is circulated out of the thimble air chamber.</td>
</tr>
</tbody>
</table>
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Figure 3. The portion of the thimble above the roofline. The insulation stuffed into the outside air chamber simulates an occluded condition that would block air circulation. The thermocouples shown are referred to as channels 4, 5, 6, and 7 in Figure 2 and Figure 7.

Figure 4. An overhead view of the exhaust stack. The thermocouple shown measures the exhaust gas exit temperature and is referred to as channel 2 in Figure 2 and Figure 7.

Figure 5. The interior portion of the shipping container where the thimbles were tested. The yellow wires connect the thermocouples to the data acquisition system. The propane torch, which simulates a furnace or other heat source and provides hot exhaust gases for testing, is at lower left of photo before it is completely inserted in the exhaust stack.

Figure 6. A large exhaust thimble on top of the roof, after it has been prepared for testing. The top thermocouple is channel 2, and the lower ones are channels 4, 5, 6, and 7.
Figure 8 shows graphs of the data created during a 1000°F exhaust temperature test of the 6-inch thimble in occluded and non-occluded states. The graph shows most of the data channels measured during the test. Each thimble test generated a similar graph. The most interesting item of note on these two graphs is that during the occluded tests, the thimble temperature at the roof was higher than the temperature at the base of the thimble. During the non-occluded test, the thimble temperature at the base stayed above the thimble temperature at the roofline. These temperature differences further help to validate the flow of air through the thimble air chambers. Note, however, that the difference in these temperatures was extremely small, and the data for each thimble size show a similar pattern.

The most important temperature combinations recorded during the thimble testing were the exhaust gas temperatures and the exterior thimble temperature at the roofline. These two data points are shown independently of each other in the graphs in Figure 8; however, graphing the temperatures against one another (Figure 9) reveals how the thimble exterior temperatures react to high exhaust gas temperatures. It is extremely important to prove that despite long-term high exhaust gas temperatures, the thimble temperature at the roofline will stay low so that there is no risk of fire. If temperatures at the exterior of the thimble, where it contacts wood and other building materials, get too high, the building materials could undergo pyrolysis; that is, thermal degradation into flammable liquids and vapors. Pyrolysis generally begins to occur at temperatures above 400°F. During testing, when the exhaust gas temperatures were set at 1000°F, temperatures never approached the 400°F danger threshold. In fact, the highest temperature recorded during the thimble testing was 231°F. This temperature was recorded during summer testing of the 6-inch thimble in occluded condition. Figure 9 shows graphs generated from the data that compare the exhaust gas temperatures to the thimble temperatures measured at the roofline, where the thimble contacts the insulation. Figure 9 shows that the 6-inch thimble consistently had the highest temperatures. It is unknown exactly why this was the case, but the consistency of these high temperatures suggests that a physical trait of the 6-inch thimble affects annular airflow.

Measured Airflow

One unexpected challenge during thimble testing was the struggle to accurately and consistently measure the airflow velocity through the thimble annular vent channels. While the temperature monitoring described earlier showed that temperatures at the intersection of the thimble and the roofline stayed low enough to prevent pyrolysis, consistent airflow readings that matched model predictions would add an additional layer of confidence that the thimble design was functioning as intended.

Initially, a hot-wire anemometer was used in the thimble vent channel, but readings were inconsistent (R. Peterson, personal communication, December 12, 2013). After attempting to troubleshoot this method without much success, researchers changed course and settled on a manual process. To acquire readings, researchers waited until the temperature measurements had reached a pseudo-steady state. At this point, one of the operators made several readings using a handheld pinwheel anemometer around the outside of the thimble vent inlet. The average value was manually recorded, and the process was repeated several times throughout a 5- to 10-minute interval. In general, about a 20% variation in flow velocity recordings was observed each time the temperature was measured. Airflow data are presented in Figure 10. Although the 4- and 10-inch test results are not shown, they look very similar to the 2-inch and 6-inch data that are shown. It is unclear why the velocities increase with exhaust gas temperature in the summer, yet decrease as exhaust gas temperatures increase in the winter.

Manufacturing and Cost

Because of the use of in-house services at UAF, the actual cost of construction was minimal; hence, it is not considered an accurate estimation of future manufacturing costs. Researchers consulted with Holaday-Parks, a sheet metal fabrication facility in Fairbanks, Alaska, to get cost estimations for thimble manufacturing. These cost estimates for 10-foot long thimbles of varying dimensions and
quantities are shown in Table 4. Researchers acknowledge that these costs are likely higher than what actual costs would be. Future thimble manufacturing would probably take place either in Anchorage or in the Lower 48, where manufacturing costs are lower. In addition, developers would work with the fabrication shop to make design modifications that simplify the manufacturing process. For example, determining what types of cuts and welds are easiest could simplify the manufacturing process and reduce costs. The prices given by Holaday-Parks are a starting point and serve as a ceiling for what future costs could be.
Additional to the empirical testing described in this report, numerical modeling of the steady-state operation of the thimble was performed by project researchers using COMSOL Multiphysics. The modeling was intended to approximate the observed thermal behavior of the thimble and test different thimble dimensions without having to build physical prototypes. The models show the airflow velocity and temperatures in different parts of the thimbles (Figure 11). The following explanation is given in the final report by UAF researchers: “the predominant heat transfer cooling effect of the thimble occurs at the inner channel boundary with the exhaust gas.” This is where fluid makes a 180° turn coming into contact with the exhaust gas chimney and

Figure 9. The highest recorded thimble temperatures at roof level (CH1) are graphed against the exhaust gas temperatures (CH0) for each thimble size during the summer and winter occluded and non-occluded tests. Since wind did not appear to significantly affect testing, all tests occurred in the absence of wind. The highest thimble roofline temperatures occurred during the summertime occluded testing of the 6-inch thimble.

Figure 10. Thimble cooling vent average channel airflow velocities are shown with corresponding exhaust gas temperatures (CH0) during the (a) 2-inch thimble summer test, (b) 6-inch thimble summer test, (c) 2-inch thimble winter test, and (d) 6-inch thimble winter test. For each thimble size, there is a clear trend towards air velocity increasing as exhaust temperatures get hotter in the summer and airflow velocity decreasing as exhaust gas temperatures get higher in the winter.

Modeling

In addition to the empirical testing described in this report, numerical modeling of the steady-state operation of the thimble was performed by project researchers using COMSOL Multiphysics. The modeling was intended to approximate the observed thermal behavior of the thimble and test different thimble dimensions without having to build physical prototypes. The models show the airflow velocity and temperatures in different parts of the thimbles (Figure 11). The following explanation is given in the final report by UAF researchers: “the predominant heat transfer cooling effect of the thimble occurs at the inner channel boundary with the exhaust gas.” This is where fluid makes a 180° turn coming into contact with the exhaust gas chimney and...
increases in temperature, making it more buoyant than the cooler ambient air (Figure 11). In the model, the fluid velocity quickly increases as it rises in the inner chamber, reaching 9 feet per second as it exits the thimble. The scale on the right represents fluid velocity in feet per second while the x-axis and y-axis represent dimensions in inches.

The modeling efforts indicated that the large vertical dimension of the thimble could be modified from 75 inches to as little as 25 inches and result in a reduction in material costs, while still maintaining safe temperatures. A 25-inch thimble would use about one-third the material as its 75-inch counterpart, which would affect the cost of manufacturing. The actual reduction in the minimum vertical size of the thimble would depend on the individual installation and would be limited by engineering constraints. The model also showed areas of stagnant flow (bottom right of Figure 11). Slight design modifications to create a curved thimble base might remove the stagnant recirculation zone. This design change, however, might increase the cost of manufacturing. With little likely improvement in safety, the economics do not support the modification.

Differences Between Model and Empirical Testing

Researchers spent significant time and resources attempting to collect accurate annular flow velocity data. The primary purpose of collecting flow velocity data had been to confirm the accuracy of the modeling described here. Given the lack
of consistent flow velocity data, there is little that one can say about the performance of the model compared with empirical testing. Despite this, the temperature data collected show that the exterior of the thimble that makes contact with the building envelope maintained safe temperatures throughout all testing. From a safety perspective, this result was the most important aspect of the testing.

Summary

Testing Conclusions

- All thimble temperatures remained below the 400°F pyrolysis danger level where the thimble intersects the roofline.
- Wind had limited effect on thimble performance.
- Airflow velocity was measured with very limited success during testing. To better understand air circulation within and around the thimble, successful velocity measurements obtained throughout the entire testing process would be useful.
- Thimble annular occlusion limited air circulation, but temperatures still remained at safe levels.
- The 6-inch thimble had the highest temperatures at the roof intersection, followed by the 10-inch, 4-inch, and 2-inch thimbles.

Testing at UAF has provided a good first step towards product development. The testing conducted during this study showed that during the testing conditions replicated in the laboratory with exhaust gas temperatures up to 1000°F, the temperatures where the thimble made contact with building materials stayed below 400°F, the critical temperature at which pyrolysis starts to occur.

Future independent third party testing would be required before the exhaust thimble could be installed in homes and businesses. Discussions with UAF researchers revealed that they do not intend to develop the product. They think that private industry is best equipped to commercialize the UAF design and pursue further development.

Future testing should include data collection and analysis with a focus on the following:

- Thimble temperatures.
- Air velocities measured at various places in the thimble cooling chamber during a variety of exhaust gas temperatures. These measurements will verify the modeling that has been performed to date.
- A more in-depth look at thimble costs and the economics of replacing existing exhaust thimbles with this new and improved exhaust thimble.

References and Notes

i From: http://www.akenergyauthority.org/Programs/EETF