Design of a Laboratory Testbed for Modeling Industrial Exhaust

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Abstract

There are a great many industries in the Kentucky and surrounding areas that utilize natural gas burners in their operation, typically on order of hundreds of thousands of cubic feet per month to liquefy and hold molten aluminum for their die operations. Much of the energy content of this fuel is consumed in plant operation, but a significant amount of heat is released to the outside environment as exhaust. This represents a considerable resource that could be utilized for other outcomes. As a first step toward tapping that potential, a mobile laboratory testbed was developed to simulate industrial exhaust at levels appropriate for prototype development and student engagement. Capable of variable temperatures up to 1800°F, incorporating an insulated exhaust chimney, and outfitted with thermocouples, this testbed provides a flexible resource not only for the targeted research at hand, but the WKU thermofluid laboratories. Details of the testbed will be provided, as well as operational data and initial observations on the nature of the resulting flow.

1.0 Introduction

Engineering students encounter a number of sophisticated technical concepts throughout their college career. Indeed, as their studies delve deeper into upper division courses, matters evolve from conceptually straightforward (i.e., statics) to more sophisticated (deformable) and potentially abstract (thermodynamics). Challenges can arise correcting mistaken preconceptions, and linking perceptually-abstract mathematical formulas to real-world examples. Indeed, studies [1], [2] show that students value real life applications of the material covered, and that such applications contribute to a deep conceptual knowledge.

Western Kentucky University offers programs in civil, electrical and mechanical engineering, presented with a focus on project-based learning. The institution further maintain active relationships with the surrounding industry, and uses real-world experiences as part of the curriculum. Students tour plants to get a sense of the size, scale, and challenges associated with the theories presented in class. Industry partners further interface with our student population by providing in-depth internships that provide practical experiences, and also provide genuine capstone projects utilizing real-world challenges faced by their operations.

Within the mechanical engineering program, laboratories form a key component of the learning experience. These laboratories cover such subjects as: Materials, Instrumentation, Mechanical Systems, Fluid Mechanics, and Heat Transfer. In addition to covering topics germane to the degree, many of the laboratory exercises specifically relate to issues relevant to our industry partners.

An opportunity for exploring the subject of heat transfer lies in the abundance of foundry operations in Kentucky, specifically in the realm of aluminum die-casting. Such operations utilize furnaces of a variety of capacities to hold molten aluminum (or other metals) as part of their manufacturing process; some furnaces exhaust to the outside environment, others exhaust within the facility itself with appropriate ventilation. A representative holding tank and small-scale furnace is shown in Figure 1. The exhaust from these furnaces represents a wealth of energy that is either directly lost to the outside environment, or indirectly after interacting with the facility space. In the summer months, this latter interaction can easily result in temperatures approaching 110°F or higher on the plant floor.

Heat engines hold the possibility of capturing this resource and redirecting the energy to a variety of positive outcomes. Developing appropriate systems, however, can be a challenging task in a manufacturing environment. The target furnaces must run at normal capacity and scheduling, which makes installation and testing of technology complicated. Further, full-scale development can be costly.

Small-scale development is much more appropriate, and lends itself well to practical student experiences in design and application (as well as opening opportunities for expanded heat transfer laboratory experiments). This approach is considered more appropriate to the program culture than pursuing other options such as deploying virtual labs [3] - [5].

This paper describes the initial steps along that path, developing an appropriate small-scale testbed capable of providing a solid foundation for the exploration of thermal systems optimized for the exhaust conditions of aluminum furnaces.

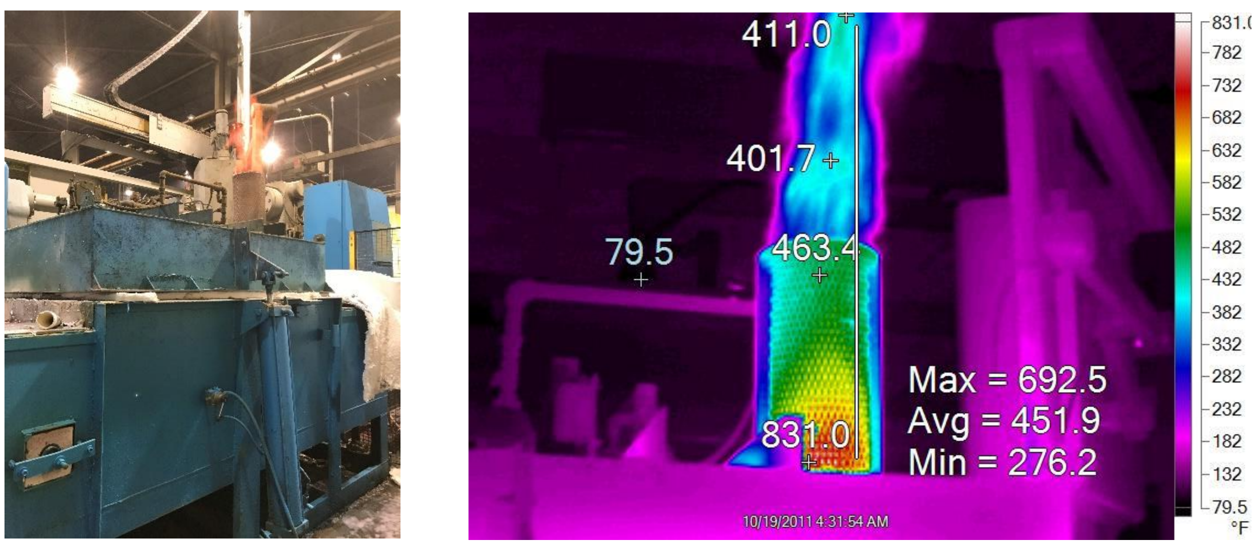

Figure 1. Representative industrial holding tank furnace (left), and thermal imaging of the exhaust stack (right)

2.0 Testbed

Figure 2 shows a schematic of the finished testbed. The system consists of a modified farrier's forge connected to a propane supply tank and an insulated exhaust; all components are mounted to a mobile lab cart, and supported using 80/20 structural members. Ceramic flow straighteners are inserted at the top and bottom of the exhaust pipe to reduce turbulence. The combustion rate is controlled via a pressure regulator, and mass flow is assumed to be steady state (determined by measuring the tank mass before and after experimental runs). Temperatures are obtained via thermocouples placed at various axial and radial locations. All equipment is monitored through a LabVIEW program. To ensure adequate ventilation against combustion byproducts, the testbed is mobile to allow for operation in the outside environment.

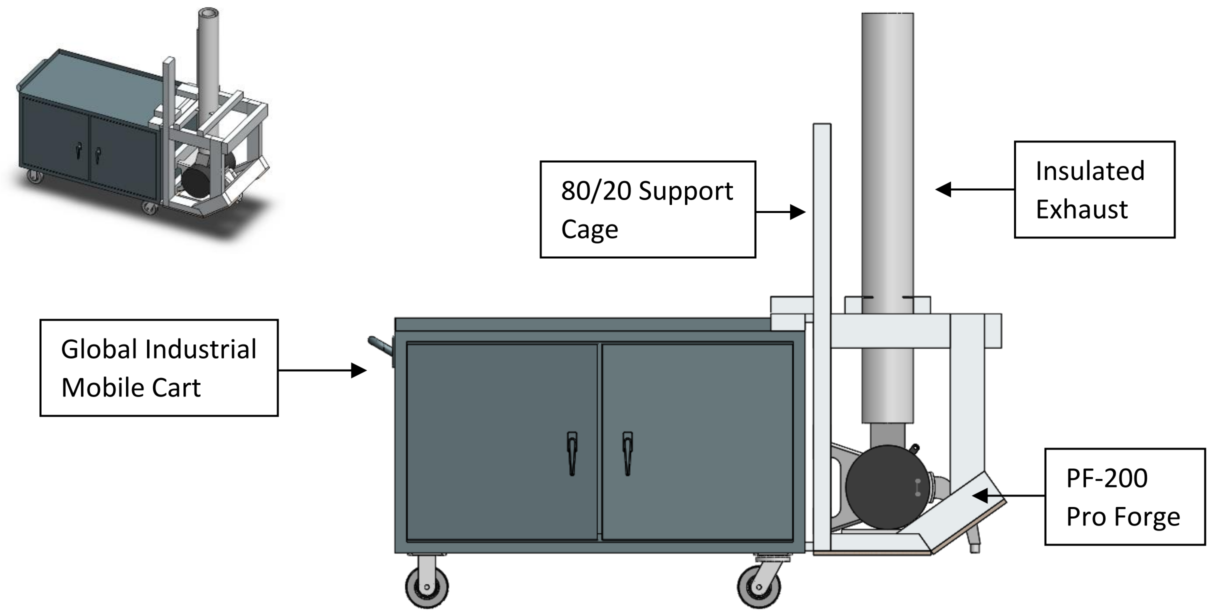

Figure 2. Testbed arrangement

The core of the system is a PF-200 Pro-Forge [6], a portable propane furnace typically used by farriers and blacksmiths (capable of reaching 2450°F at 7psi propane). For this purpose, the furnace is modified to ensure a singular path for exhaust. First, the side barstock and front cast iron door are removed. A relining kit [7] was purchased, and components used to replace the side barstock port insulation panel with a solid side panel (thus removing the access hole). The Pro-Forge is then rotated and installed so that the front opening now faces upward. The base of the Pro-Forge is connected to a support structure fabricated from 80/20 members, and further supported on the bottom using firebricks.

In this configuration, combustion air is drawn in from floor level and combined with propane fuel. After combustion, the Pro-Forge exhaust is directed through an insulated chimney, fabricated from modified truck exhaust components. To accommodate this, the opening of the Pro-Forge mates to a transition shroud, itself welded to a 4-in diameter, 48-in OAL steel exhaust pipe [8]. Flow straighteners are derived from commercially-available honeycomb soldering boards [9] used in jewelry repair, trimmed to fit within the inner exhaust pipe. These provide a grid of square holes, approximately 0.050" to a side, and are placed at either end of the exhaust pipe. For operator safety, a second, 6-in diameter steel exhaust port is coaxially installed, and the intervening space filled with ceramic insulation [10]. The combined arrangement is aligned to the support structure using guide fingers attached to the support structure. The exhaust arrangement is easily and completely replaceable as needed.

The combustion rate is controlled via a pressure regulator attached to a standard propane tank, and mass flow is assumed to be steady state (determined by measuring the tank mass before and after experimental runs). Temperatures are obtained via thermocouples placed at various axial and radial locations. All equipment is monitored through a LabVIEW program.

3.0 Sample Results

Thermocouples were attached to various axial and radial positions on the inner and outer surfaces of the exhaust chimney, points along a radial line from the inner surface to the outer surface, and points along the interior volume of the exhaust itself (Figure 3). A propane tank was attached, and supplied fuel at an 8psi operating pressure. The system was run until steady-state conditions were reached to assess its performance.

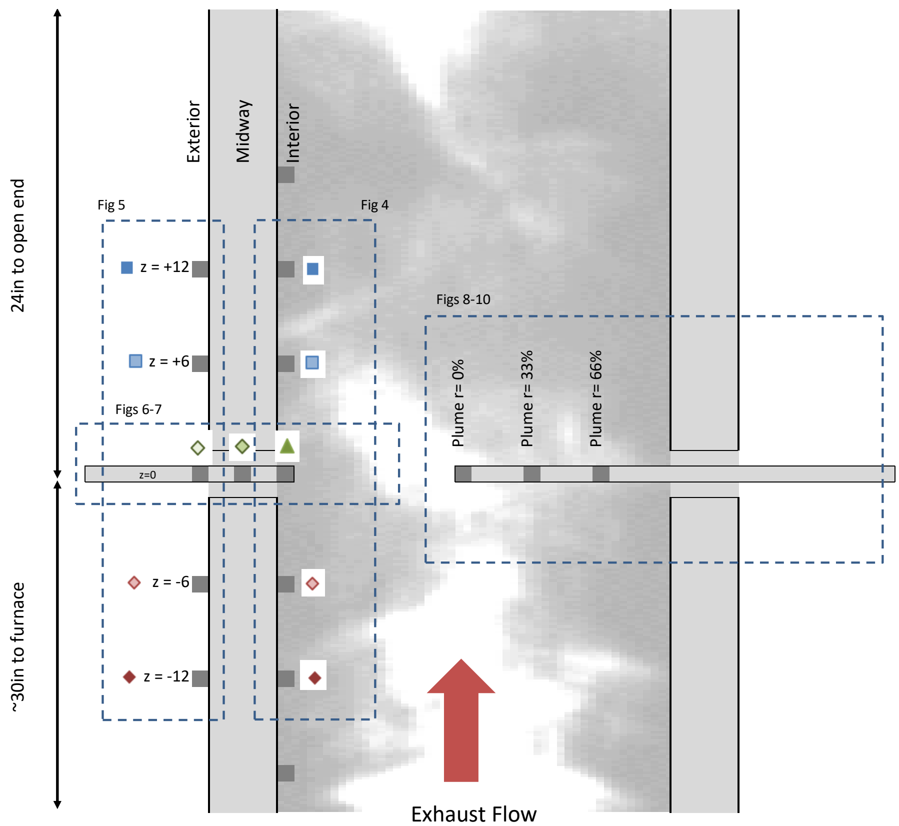

Figure 3. Thermocouple positioning relating to subsequent data plots

<u>3.1 Wall Temperatures</u>

Figure 4 shows the temperature profile along the interior surface of the exhaust chimney as a function of time, measured at steady intervals from 12 inches above the midpoint of the steel pipe (+12) to 12 inches below (-12). Figure 5 shows a similar arrangement along the exterior surface. Steady state conditions are understandably attained faster at closer distances to the furnace, and slower at farther distances. This is consistent with interplays between energy input from the exhaust and differences between axial and radial conduction paths.

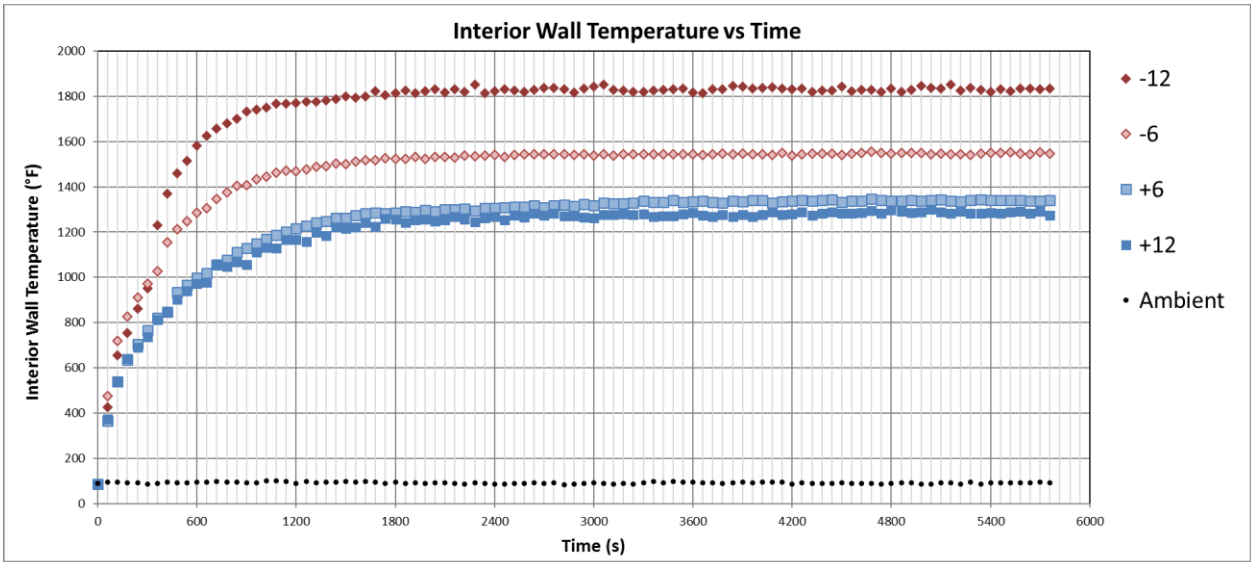

Figure 4. Interior Wall Temperature Development

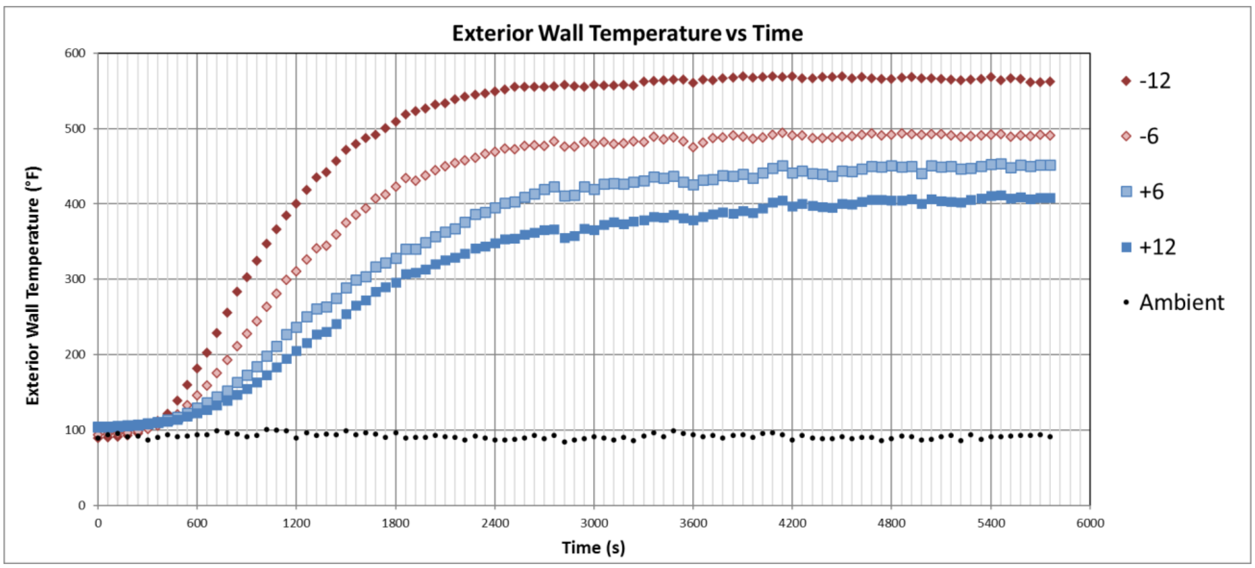

Figure 5. Exterior Wall Temperature Development

Key behavioral observations include:

- Exterior temperatures are broadly comparable with the thermal measurements of the reference industrial furnace.
- Temperature fluctuations in the exterior wall are somewhat larger than the interior wall, but are within normal expectations. Larger variations are observed in the upper (cooler) portions of the exhaust (i.e., as seen at approximately t = 2800s), which were more exposed to wind from the outside environment.
- Three predominant operational modes are observed within the interior wall temperature data. Short term behavior (0-400s) is believed to incorporate effects from the furnace coming up to operational temperature. Mid-term behavior (400s – 2400s) is considered a

transient state where radial and axial conduction effects trade dominance and work to balance out. Long-term behavior (2400s on) attains fairly steady state behavior across all interior regions.

- The interior temperature profiles also show identifiable modes. Short-term behavior (0-300s) is suspected to be due to most of the exhaust heat going to warm up the furnace and interior walls. Mid-term behavior (300-4200s) reflects a transitional state. Long-term behavior (4200s on) attains fairly steady state behavior.

Overall, thermal saturation and steady-state behavior is observed to occur at a system-wide level after approximately 4200s.

3.2 Radial Temperature Profile

Measurements across a radial section of insulation at the midpoint of the exhaust (Figure 6) show a consistent development.

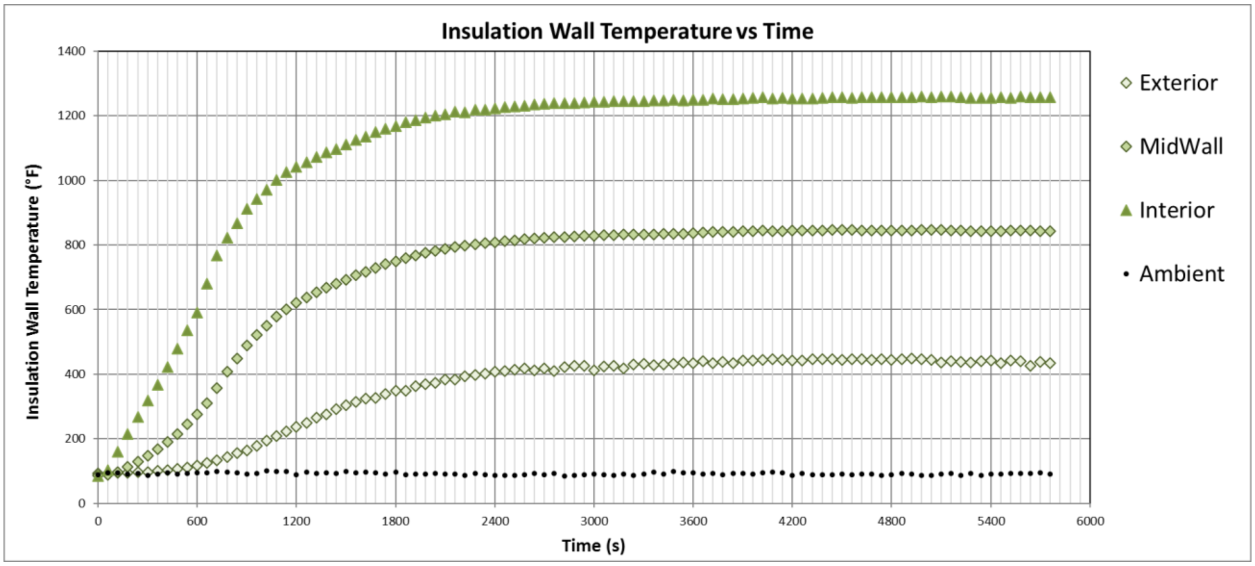

Figure 6. Radial Temperature Development

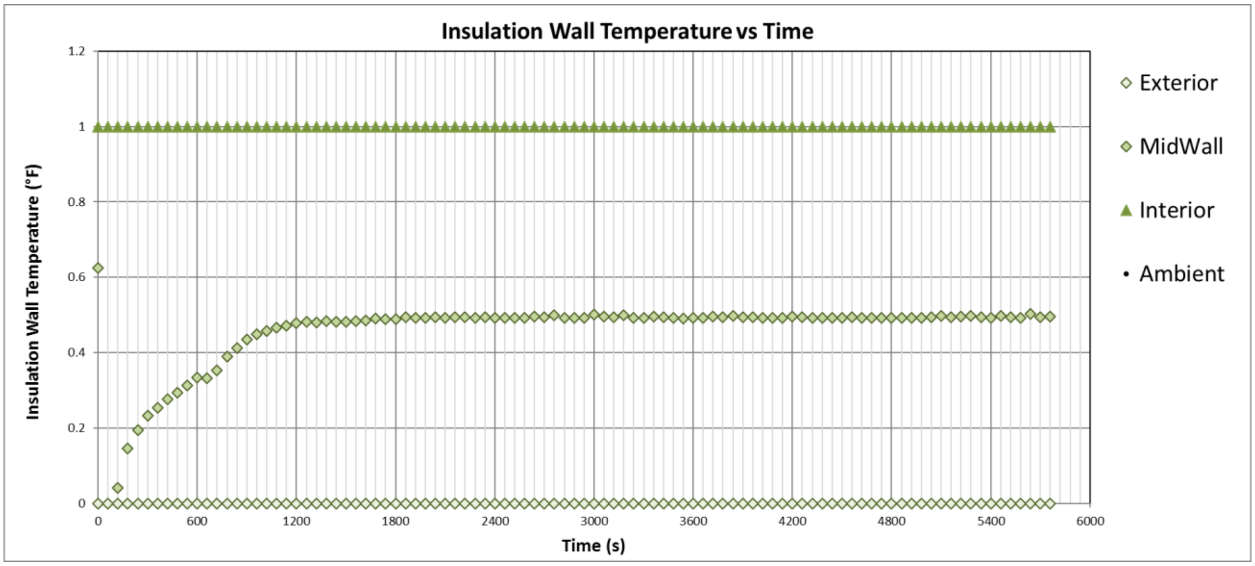

Figure 7. Radial Temperature Development, scaled to temperature difference between interior and exterior walls

Key behavioral observations include:

- The interior wall temperature develops in a predominantly linear fashion in the short term (0- 600s). The behavior changes thereafter, suggesting a change in the dominant means of heat transport.
- Scaling these measurements in terms of the temperature differential (Figure 7) reinforces the shift in behavior in the interior wall temperature at 600s, smoothly transitioning to steady-state after approximately 1200s. This suggests that the heat transfer dominance starts with a primarily convective mode from the exhaust at the start, transitions to an axially-dominant conductive mode, and settles out to a radially-dominant conductive mode.

3.3 Exhaust Plume Development

Measurements across the radius of the exhaust plume also are well-behaved, and are shown in Figures 8-10.

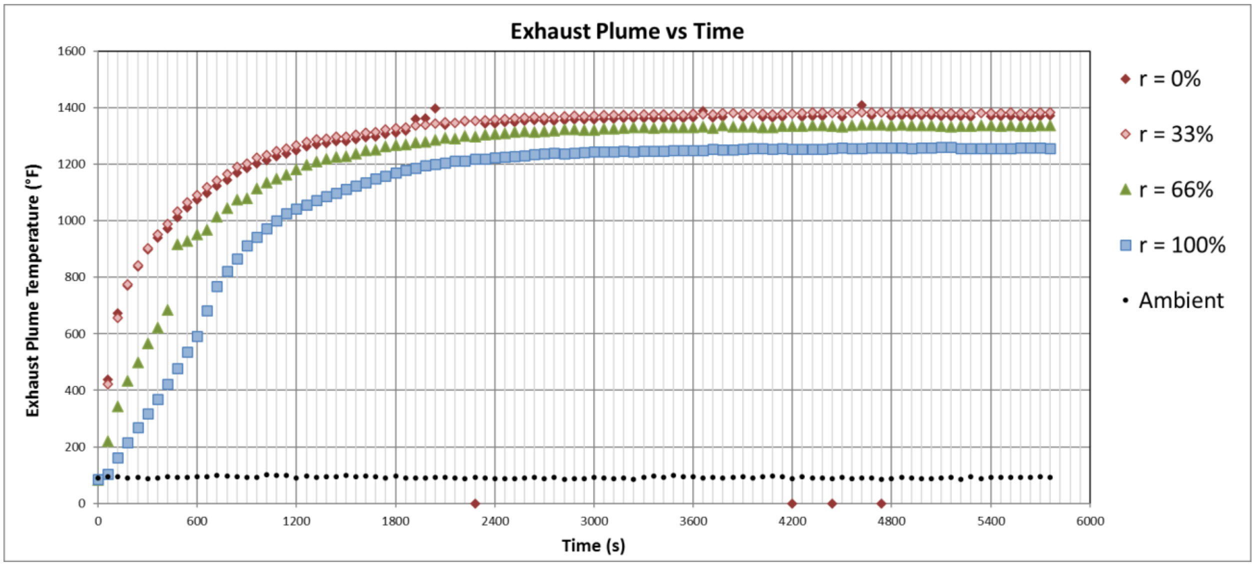

Figure 8. Exhaust Plume Temperature Development

Key behavioral observations include:

- The centerline behavior (r=0% and 33%) is fairly well-behaved and consistent. Occasional discrepancies are believed to stem from short-term variations in byproducts carried up from the furnace, or other variations in combustion behavior.
- Initial behavior (0-600s) at r=66% follows the wall behavior, reinforcing the belief that convective transfer (initially warming the interior wall) dominates in the short term. The discontinuity at approximately 400s is believed to be from a short-term instability in the exhaust stream, pushing the centerline over into the r=66% region.

In an attempt to better characterize the plume behavior, the temperature profiles were scaled to the centerline temperature (Figure 9) and plotted against radial position (Figure 10).

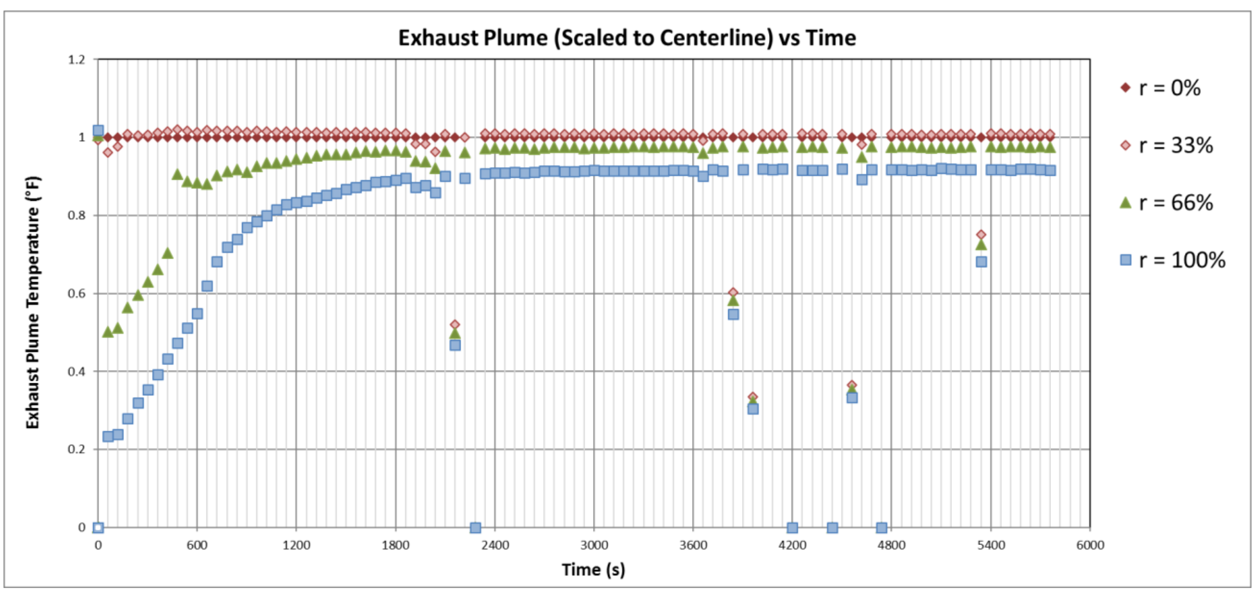

Figure 9. Exhaust Plume Temperature Development, scaled to centerline value

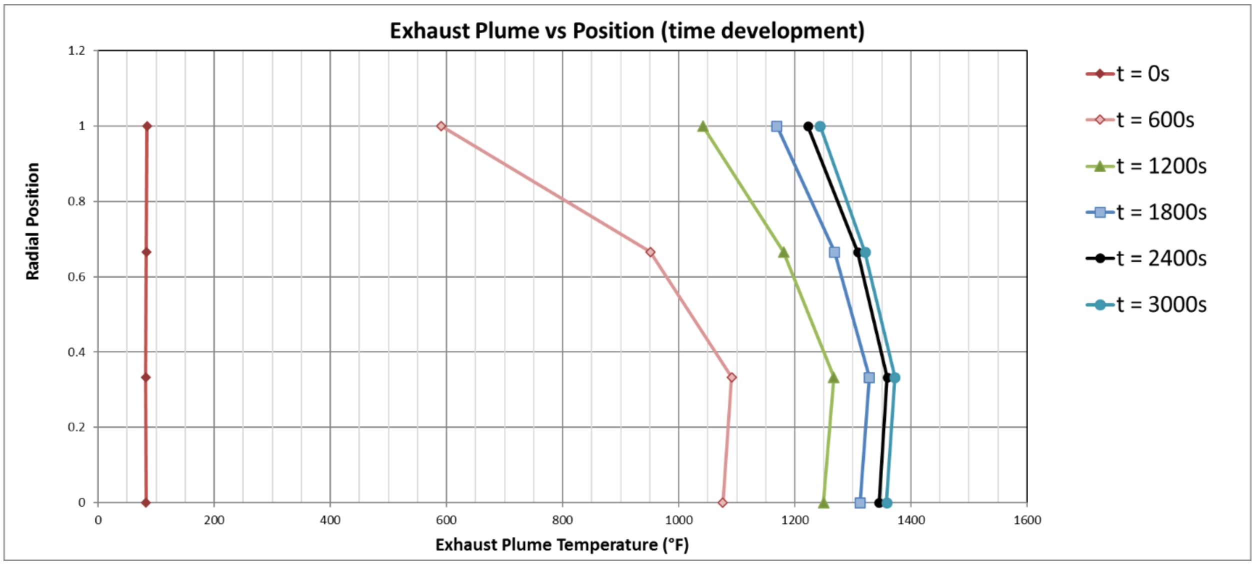

Figure 10. Exhaust Plume Temperature Development at z=0 as a function of scaled radius

Key behavioral observations further include:

- The scaled plot emphasizes the discrepancies observed in the raw data shown before, making them easier to identify
- The temperature structure is fairly stable, suggesting largely laminar flow.

4.0 Planned Laboratory Exercises

With the qualitative and broadly quantified understanding of the furnace performance, many interesting questions and opportunities arise for student laboratory explorations. At this time, the planned activities (depending on future funding and available students for development) include:

- Schlieren visualization of exhaust flow
- Heat exchanger development and testing
- Modelling of steady-state heat transfer from exhaust to chimney walls and exterior environment
- Modeling of transient heat transfer from exhaust to chimney walls and exterior environment
- Modelling of transient and steady-state heat transfer from exhaust to immersed objects
- Exploring flow variations and efficiencies due to incomplete combustion

The effectiveness of this testbed as a learning tool is still being assessed, but it is clear that the flexibility of the system is a key benefit. By changing a singular, inexpensive assembly of the exhaust shroud and steel pipes, each of these experiments (and possibly more) are attainable. Further, the experimental operating temperatures can be adjusted by changing the lengths of the pipe and/or where measurements are taken, as well as adjusting the flow rate of the propane fuel supply.

5.0 Conclusions

This paper presents a laboratory-scale testbed intended to explore opportunities within industrial furnace exhaust. The resulting testbed provides comparable temperatures and conditions that facilitate future development. This initial work positions us well for further technology and laboratory development, and has provided rewarding opportunities for senior project students. In addition to developing a valuable research asset, our students have specifically mentioned feeling a deep sense of pride in undertaking a project with a larger-than-normal design component; their work involved developing a variety of mathematical models used to derive reasonable design requirements before considering (and realizing) solutions.

The general details and operating data are presented in the hopes that they will be sufficient for similar development at other institutions.

Acknowledgements

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