Promoted Combustion of Metals in a High-Pressure, Flowing Oxygen Environment

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ABSTRACT

Traditional promoted combustion testing has used 0.125 in. dia samples that are ignited in a pressurized, oxygen-enriched environment. Many years of testing this sample size have yielded useful data regarding threshold pressure, or the minimum oxygen pressure required to support self-sustained combustion. However, when a material is tested in a flowing system, the threshold pressure changes. White Sands Test Facility has developed a test system to burn samples in flowing gaseous oxygen. Current sample configurations are 0.5 in. dia rods and 1.25 in. dia pipes with pressures ranging up to 2000 psi and gas velocities reaching 200 ft/s. This paper describes the test apparatus, modifications made as the result of a fire, and a description of the tests currently being performed.

INTRODUCTION

In oxygen systems, metals selection is very important to ensure compatible materials are used for the system's operating conditions. Much data have been collected regarding material flammability versus pressure [1]. Typically, materials burn better as pressure increases. These data provide a good basis for choosing materials based on their flammability. However, these data are based on a material's flammability in a static oxygen environment. When the oxygen is flowing, material flammability can be enhanced or reduced depending on the flow velocity. The NASA White Sands Test Facility (WSTF) has developed a test system that can perform promoted combustion tests in flowing oxygen conditions while controlling pressure and velocity past the test sample. This paper describes the test apparatus, modifications made as the result of a fire, and a description of the tests currently being performed.

BACKGROUND

For years it has been known that materials burn much better at higher oxygen concentrations. As the demand of increased operating pressure in oxygen systems became more acute, particularly in the aerospace industry but also in industrial applications, the incidence of oxygen system fires increased because the normally inflammable metals were flammable at the higher operating pressures. This prompted the area of study known as promoted combustion. The purpose of the present study was to characterize the fire propagation properties of various metals and alloys [1]. Benz, Shaw, and Homa have outlined two major considerations that must be addressed when determining the fire hazards of metals or alloys. "First it must be determined whether the material will ignite, which requires knowledge of the minimum energy rate and temperature for ignition. Second, it must be determined whether the material will support combustion after the stimulus of the ignition source has terminated" [1]. Previous promoted combustion testing typically occurred with 0.125 in. rod configurations that were supported at either the top or bottom of the sample and ignited at the opposite end. The ignition source consisted of a magnesium cylindrical sleeve, or promoter, that was press-fit onto the sample. The promoter was wrapped with nickel-chrome or similar-type wire and ignited electrically. This "kindling chain" was effective for consistently igniting the samples, which could be tested over a wide range of pressures, depending on the chamber design. All chamber designs shared a common feature in that they were capable of producing only static conditions of oxygen before the test and had no way to flow the oxygen at controlled velocities.

Importance of Understanding Velocity

The importance of fluid velocity affecting material flammability is particularly evident when building a campfire, for which the kindling chain of the leaves, twigs, and dead grass catches fire first and in turn ignites sticks, which ignite split logs, and so on. Suppose that the kindling wasn't burning as much as one would like. The usual response is to blow onto the embers. The normally unexcited embers now become more energetic due to the dynamics of the situation. The driving mechanism creating this apparent increase in flammability is the flow velocity. If the velocity is too high, the flames can be blown out. However, gas velocities below this range can increase the potential for fire. Flowing gas produces a forced convection effect that increases the availability of oxygen for consumption at the burning interface. The flowing oxygen also decreases the concentration of inflammable combustion products around the burning interface simply by blowing them away.

Test System Description

The test system is modeled after the static pressure promoted combustion apparatus. It consists of a cylindrical chamber that can be pressurized to 4500psi (Figure 1). The chamber body is made from 304 stainless steel, and the interior is lined with copper to protect it from the burning metal samples. Near the inlet, there is a flow-straightening device made from K500 Monel[1], and directly below it is a copper sample holder. Welded on either side of the chamber are vent ports lined with copper, which protects them from molten debris.

The system is designed so that it is very difficult for debris to make it outside the chamber. A copper slag filter separates the burning sample from the vent outlets. A series of 0.125 in. dia holes has been drilled through the side of the filter at a 15 degree downward angle to minimize slag escape. This filters out any debris larger than 0.125 in. dia. Although debris smaller than this can fit through the holes, the particles must change their direction to travel up the 15 degree incline. Specifically sized orifices can be placed on these vents to control the mass flow rate of oxygen out of the chamber. Below the slag filter is a copper catch cup whose mass is sufficient to conduct the heat from the molten slag away without damage to the cup or chamber body. Two copper terminals that extend down from the top exterior of the chamber ignite the samples. Each terminal is attached to a Kemlon®[2] electrical feedthrough. The terminals have adapters that can be mated with banana-plug type connectors. The pyrofuse wire used to ignite the promoters is attached to the banana plugs. A sapphire crystal view window is mounted onto the chamber wall, with copper crush washers providing the sealing surfaces. The window is housed in a Monel viewport boss flange. A borescope connected to a video camera is mounted to this viewport flange to view and record the burning sample. The chamber is located downstream of a heat exchanger capable of heating the oxygen to 1000 °F. The system supplying the oxygen is capable of producing 6000 psi at a mass flow rate of 8 lb_m/s.

Three pressure transducers and one thermocouple record the test data. One transducer is tapped into the chamber wall opposite the view window to record the chamber pressure, which is also the test article pressure. The other two transducers and thermocouple are located in a four-way block that is connected directly upstream of the chamber inlet. One of these transducers is used as a report-back channel to a pressure control valve, which is computer controlled and regulates itself to achieve the desired pressure.

Test Configuration

Test samples are held vertically and supported at the top from the copper sample holder with setscrews. Oxygen flows into the chamber from top to bottom, and the test samples are ignited at the bottom. Therefore, this testing evaluates material flammability in a counterflow environment.

Currently WSTF is testing two different sample configurations. One configuration is flow in a pipe. Pipes ranging up to 1.25 in. dia schedule XX can be tested at pressures up to 1500 psi, with velocities of 50 ft/s, 100 ft/s, and 200 ft/s. The samples are 5.5 in. long, and the oxygen flows inside the pipe. Depending on the pipe thickness, the promoter is counterbored and either sunk into the wall thickness or attached to the exterior of the pipe.

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[1] Monel® is a registered trademark of Inco Alloys International, Inc.
[2] Kemlon® is a registered trademark of Kemlon Products.

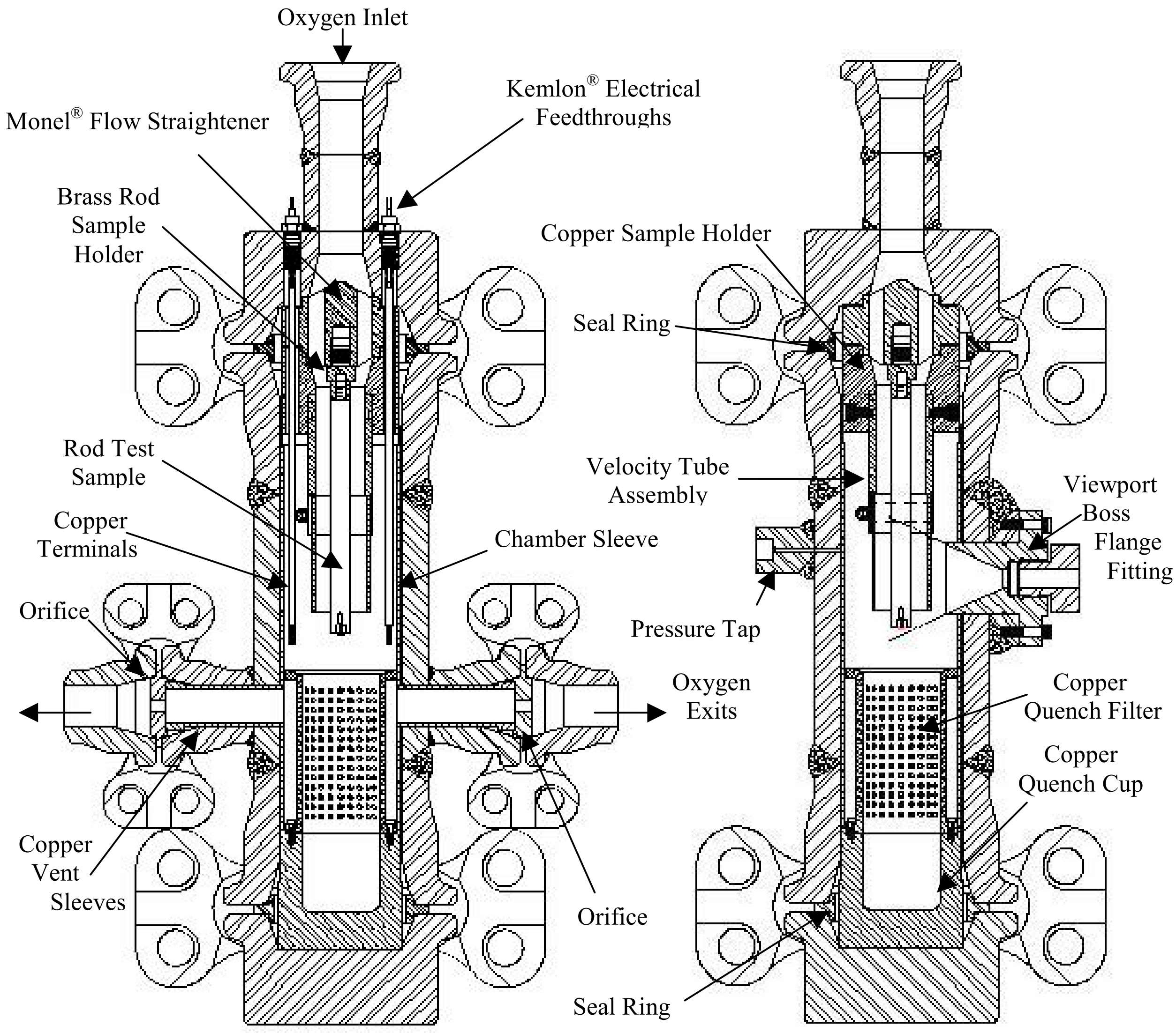

Figure 1
First Test Apparatus, Front View (left) and Side View (right)

The other configuration is a 0.5 in. dia rod. A 1.378 in. ID mock pipe called the velocity tube, consisting of a copper upper section and a quartz lower section, is clamped into the sample holder. The quartz tube slides into a countersunk region in the copper tube, and the two are connected by a worm clamp that compresses petals on the copper tube against the exterior of the quartz tube. Quartz is used because of its extremely low coefficient of thermal expansion, which keeps it from cracking or breaking if it comes into contact with molten metal; the molten metal simply quenches onto the quartz. The 0.5 in. rod is screwed onto a brass sample holder, and the test article assembly is then screwed into the bottom of the Monel flow straightener. Similar to the pipes, the rods have been tested at pressures ranging up to 1500 psi at velocities of 50 ft/s, 100 ft/s, and 200 ft/s. Flowing oxygen passes over the sample but within the velocity tube. By knowing the cross-sectional flow areas and the mass flow rate, gas velocity can be calculated.

RESULTS

The original intent of this paper was to present combustion data for 0.5 in. dia aluminum, carbon steel, and 304 stainless rod samples. However, during testing of a 1.25 in. dia schedule XX pipe sample at a 500 psi, 200 ft/s flow velocity, an event occurred that resulted in destruction the test chamber. Therefore, no test data were collected.

The remainder of this paper will discuss the results of the fire and modifications that have been performed to rebuild a better chamber.

After test sample ignition, a larger fire began on the right side of the chamber. Most of the right vent port (Figure 2, front view) was consumed during the fire. The chamber fire was extinguished by shutting off the oxygen flow. A 3 in. dia hole remained where the vent hub was welded to the chamber, and 75 to 90 percent of the clamp and right exterior hub were consumed in the fire. Internally, the thinnest sections of the copper quench filter and most of the chamber sleeve were melted or eroded away on the right side. This was the first test conducted on schedule XX pipes in this chamber at this flow velocity. Schedule XX pipes had been tested in this chamber at higher pressures and slower velocities of up to 1500 psi and 50 ft/s. After investigation of this incident, it was determined that a dimensioning tolerance exposed a 0.04 in. annular ring of chamber wall around each copper vent sleeve. The vent sleeves and the Monel viewport boss flange protruded through the copper chamber sleeve as a means of eliminating exposure of molten metal to the chamber wall. This of course was dependent on machining tolerances being tight enough to seal around the protruding pieces. Recall that the chamber was made of 304 stainless steel, for which data show the lower flammability threshold to be around 500 psi. It is believed the 200 ft/s flow was more efficient at distributing molten slag into crevices leading to the chamber wall. The conditions between the copper liner and the chamber wall produced a condition favorable to combustion of a nominal 4.5 in. dia stainless steel pipe with a wall thickness of 0.674 in.

Figure 2
Burnthrough of First Test Apparatus, Right Vent Port

Test Apparatus Modifications

The test apparatus has since been modified and rebuilt (Figure 3), which does not show the entire assembly as in Figure 1. Instead, it shows the major modifications which includes enlarging the inner diameter of the chamber to increase the thickness of the copper liner. This increased thickness allows for a sufficient counterbore to be drilled to accommodate the vent sleeves. The sleeves no longer protrude into the flow; instead, they extend just to the inner diameter of the chamber sleeve. The sleeves now have a recessed lip that exactly fits the counterbore depth. Also, the vent sleeves have been made thicker to provide more protection to the vent walls. Another modification was to eliminate the protruding edge of the viewport flange. The overall length of flange was shortened, and one end was "fishmouthed" to the exact radius of the outer diameter of the inner sleeve. When bolted down, the edge of this fishmouth cuts into the chamber sleeve, thereby producing a sealing surface. To protect the resulting cavity, another modification was made to the chamber sleeve. The top 4 in. of the sleeve now has a counterbore to fit large quartz sleeves. The inner diameter of these quartz sleeves matches the inner diameter of the lower portion of the chamber sleeve. Once again, quartz is used because the molten metal quenches onto the quartz sleeve without any damage to the chamber. In addition to the modifications made, another component was added to further fireproof this new chamber. A quench ring that is press-fit into the inner diameter of the chamber sleeve directly above the quench filter has been added. This quench ring is simply a thick ring of copper to act as a heat sink to protect the upper lip of the quench filter.

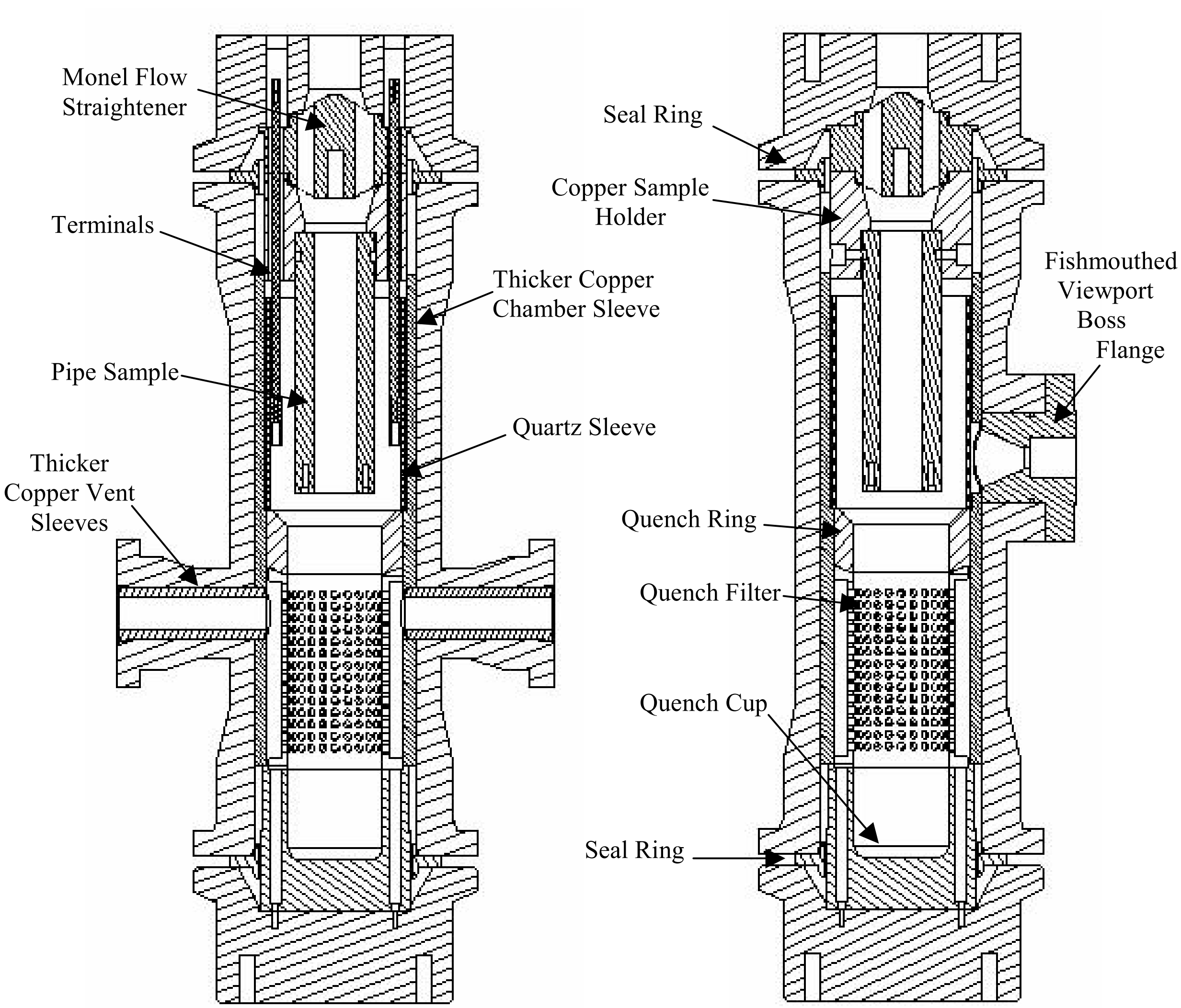

Figure 3
Second Test Apparatus after Improvements, Front View (left) and Side View (right)

CONCLUSIONS

The remaining 1.25 in. dia samples have been tested at the same flow velocities that destroyed the first chamber. The modifications performed have proved to be effective in eliminating the problems that existed in the first test chamber. Tests that have been performed to date include 0.5 in. dia rods and 1.25 in. dia pipes at 500 psi, 1000 psi, and 1500 psi with velocities 50 ft/s, 100 ft/s, and 200 ft/s. Flammabilities are increased with flow velocity, but there exists a point at which the velocity is too great for a material to sustain combustion. WSTF now has the capability to test metals flammability in flowing conditions. A new realm of data can and should be obtained for materials in flowing oxygen. Perhaps there are conditions that materials exhibit increased flammability with pressures lower than current threshold data shows when the oxygen is flowing. To a systems engineer, this type of data would be very useful to improve the design of oxygen systems.

REFERENCES

[*1*] Benz, F. J., Shaw, R. C., Homa, J. M. "Burn Propagation Rates of Metals and Alloys in Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Second Volume,* ASTM STP 910*,* M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, PA, 1986, pp. 135-152.