Apparatus for Characterizing Hot Surface Ignition of Aviation Fuels

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In this paper, we describe the development of a hot surface ignition (HSI) test apparatus, designed to evaluate the ignition behavior of leaking flammable liquids that come in contact with hot surfaces aboard aircraft. HSI events occur when a flammable liquid impinges on a hot surface, evaporates/boils, and mixes with the surrounding air. A hot surface capable of providing a controlled environment for HSI testing was developed using vapor chamber-based technology. The ability of the hot surface to ignite fuels in static air was investigated for common fuels like n-decane, n-heptane, IPA, and JP-8, to ensure repeatability of controlled experiments. Subsequently, an HSI apparatus with expanded capabilities was designed and fabricated to simulate aircraft operating conditions by providing control over the airflow, degree of enclosedness, hot surface geometry, pressure, and inlet air temperature. The HSI apparatus was then utilized to investigate ignition behavior of Jet-A fuel in conditions relevant to aircraft environments. In addition to the research and development efforts, we describe the preliminary results that demonstrate the applicability of HSI test apparatus developed by Advanced Cooling Technologies, Inc. (ACT) under an Air Force funded Small Business Innovation Research (SBIR) contract FA2487-15-C-0326.

I. Introduction

Leaking of flammable liquids within an aircraft engine bay may lead to direct contact with hot surfaces. These liquids can then ignite, which creates serious risks to on-board personnel and the aircraft itself. Mitigation of these fire hazards requires an understanding of the hot surface ignition (HSI) behavior of the fuel. While ASTM standards exist for assessment of combustion characteristics like flammability, auto ignition temperature (AIT), and flash point no such protocols exist for assessment of HSI characteristics of flammable liquid fuels. Much of the published literature stems from Air Force research programs in the 1970s and 1980 on aviation fuels, which are less susceptible to ignition. Current aviation fuels are more susceptible to HSI and the ignition characteristics are dependent on hot surface geometries, fluid sprays/drips, and environmental conditions (like airflow and stagnation zones).

HSI occurs when a flammable liquid comes into contact with a hot surface. As the liquid impinges on to the surface, heat is transferred from the hot surface to the liquid resulting in an increase of the liquid temperature and eventual evaporation. The flammable vapor then mixes with air and the temperature of the fuel/air mixture increases as the heat is transferred from the hot surface to the gas phase mixture. Ignition occurs when the fuel/air mixture reaches its flammability limit and AIT, as outlined in Figure 1. This complex process of fluid dynamics, heat transfer, and chemistry is further complicated by the buoyancy of the flammable vapor and the presence of wind across the hot surface [1].

However, literature values of the minimum HSI temperature of flammable liquids have been associated with large variability due to inconsistent sets of test conditions and non-isothermal hot surfaces.

Motivated by the need to develop an HSI apparatus and test protocol, Advanced Cooling Technologies, Inc. (ACT) developed a hot surface ignition test apparatus under an Air Force Phase II SBIR program [2]. This paper summarizes

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the developed HSI apparatus and the capability of the system to be used for providing controlled environment for investigation of the HSI characteristics of aviation fuels. The test apparatus provides a high degree of control over the testing parameters, including humidity, wall temperature, surface temperature, air temperature, and air flow rate.

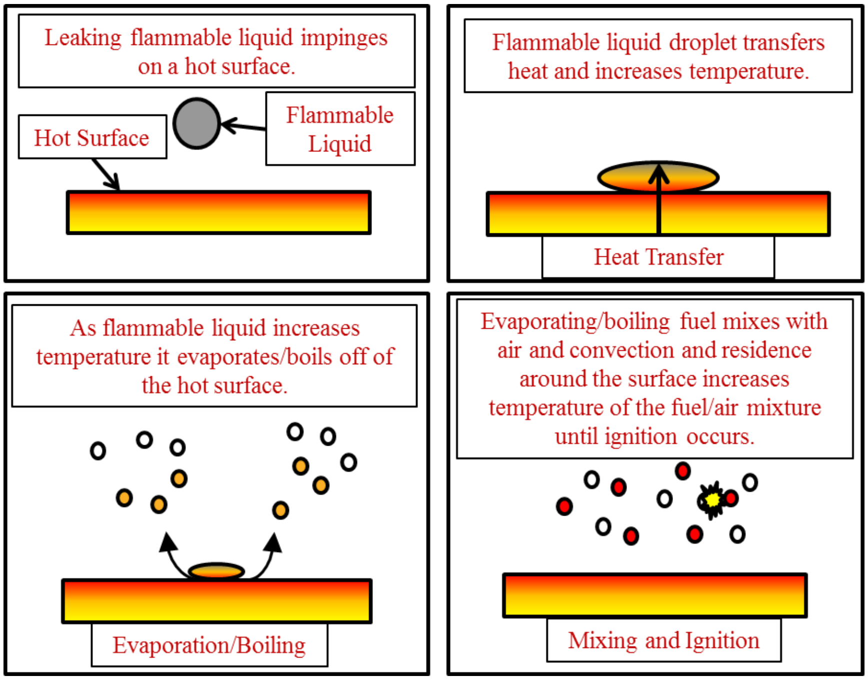


Figure 1. Illustration of the hot surface ignition process outlining the steps leading to ignition.

II. Approach and Apparatus

In this work, ACT developed a test apparatus that can accurately determine the minimum HSI temperature of flammable liquid used aboard aircraft by controlling and reproducing sets of test conditions and variables that contribute to HSI. A controlled test chamber capable of temperatures in the range of 500 to 700°C was developed, using high temperature vapor chambers that isolate the hot surface from the environment. Surfaces of different geometries were developed using custom designed vapor chambers capable of producing an isothermal hot surface. Furthermore, the test apparatus has controlled gas flow into the chamber which enables the air currents over the hot surface to be controlled. The flammable liquid is delivered to the test chamber by a syringe pump which can accurately control the volume and flow rate of the flammable liquid which can be injected onto the hot surface in a droplet, stream, or spray pattern.

A versatile test apparatus has been developed that can evaluate the minimum HSI temperature in various conditions and has the following features:

- *Isothermal Hot Surface*: Utilizing vapor chambers as the hot surface increases the accuracy of determining the minimum HSI temperature (within ±5 °C) of flammable liquids by creating an isothermal surface and removing uncertainties due to temperature gradients.
- *Hot Surface Geometry Customization*: Vapor chambers can be made in flat, concave, and convex geometries and still provide isothermality. Thus, they provide the ability to accurately simulate the surface geometries within hazardous operating conditions.
- *Versatile Testing*: The test apparatus allows the user to have control over the hot surface temperature, hot surface geometry, test fluid injection parameters, test fluid temperature, and air flow; thereby giving the user the versatility to evaluate minimum hot surface ignition temperatures under custom conditions.
- *Turnkey System*: The HSI test apparatus is integrated with a human-machine interface enabling the user to easily choose and control the desired testing conditions.

To develop a HSI test apparatus we first investigated the viability of a HSI testing chamber using a vapor chamber based design in static air and subsequently developed a flow bench apparatus to enable HSI testing of aviation fuels in different environments. In the following we briefly discuss the design of these two prototypes: HSI testing chamber, and HSI test apparatus.

II.A Vapor Chamber for HSI Testing Chamber

The HSI process includes complex fluid dynamics, heat transfer, and chemical processes which provide significant challenges when evaluating the minimum hot surface ignition temperature (MHSIT) of flammable liquids used aboard aircraft. During experimental determination of the MHSIT, it is important to precisely control all test conditions in order to obtain accurate and repeatable results. One of the conditions that must be controlled is the isothermality of the hot surface temperature within ±10°C. Metal surfaces with embedded resistance heaters have been used and documented in published literature, however, these test apparatuses do not maintain the isothermality of the hot surface to the aforementioned specifications. In order to provide an isothermal hot surface that meets the aforementioned specifications, we first developed a high temperature vapor chamber, which is a heat pipe in a planar form factor, to provide an isothermal surface. For information on heat pipes and vapor chambers refer to [3] and [4], respectively.

Figure 2, shows the prototype design developed to assess the viability of vapor chamber based HSI testing. It includes a removable isothermal vapor chamber that is bolted via the bottom flange (as shown in Figure 2-b), flammable liquid delivery by syringe pump, and inlet and outlet ports for controlling pressure of the chamber. This set-up was equipped with a fluid injection system that can deliver flammable liquids to the hot surface in either a stream, spray, or droplet. In addition, the set-up was outfitted with a photodiode and an exposed thermocouple to measure response to the ignition process and the time to ignition (i.e. the time required for ignition to occur after delivery of the flammable liquid) of various types of fuel.

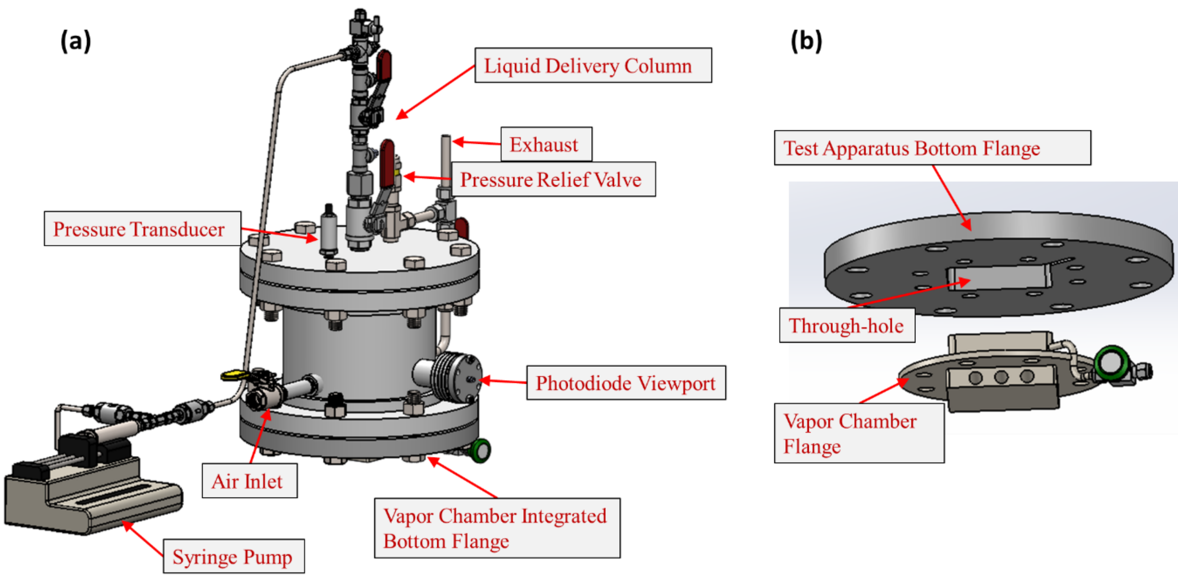
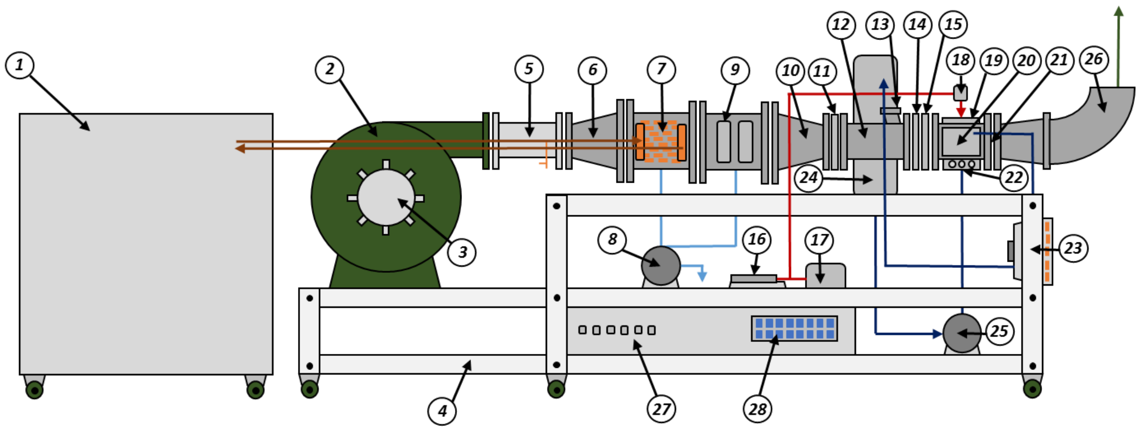


Figure 2. Prototype Design of vapor chamber based HSI testing chamber: (a) Overall apparatus used for testing, (b) Vapor chamber integrated into the bottom flange.

II.B Development of HSI Test Apparatus

The HSI test apparatus is comprised of four subsystems that are required to work together to produce the operating conditions for testing that are needed to investigate the causal relationships for hot surface ignition. The overall system is comprised of (1) an inlet air conditioning system, (2) hot section, (3) fuel delivery system, and (4) associated instrumentation. The diagram in Figure 3 labels many of the important components within the four subsystems. Items numbered 1 through 12 are all part of the air conditioning system. Items numbered 19 through 26 are components of the hot section subsystem. Items numbered 16 through 18 comprise the fuel delivery subsystem. Lastly, items 13, 14, 15, 27, and 28 are some of the components of the instrumentation and data collection subsystem. Figure 5 provides more details of all the sensors in the data collection subsystem which are recording measurements during testing. The photo in Figure 4 also shows the 4 subsystems after fabrication.



1. Chiller
2. Blower
3. Blower Motor
4. Test Cart
5. Air Flow Meter
6. Diffuser Duct Section 1
7. Cooling Coil Duct Section
8. Condensate Pump
9. Heating Coil Duct Section
10. Reducer Duct Section
11. Flow Distributor
12. Entrance Duct
13. Viewports
14. Pitot-Static Tube Array Flange
15. Thermocouple Array Flange
16. Fuel Injection Pump
17. Fuel Reservoir
18. Fuel Injection Valve
19. Top Wall Heat Exchanger
20. Side Wall Heat Exchanger
21. Ignition Chamber Duct Section
22. Vapor Chamber, Isothermal Heat Exchanger
23. Ignition Chamber Cooler
24. Ignition Chamber Coolant Reservoir
25. Ignition Chamber Coolant Pump
26. Diffuser Section 2 and Exit Bend
27. Electronics Enclosure
28. Instrument Output Panel

Fuel Flow:
Air Precooling Coolant Flow:
Ignition Chamber Coolant Flow:
Condensate Flow:
Air Flow:
Annotation:

Figure 3. Schematic of the HSI test apparatus design outlining the major components.

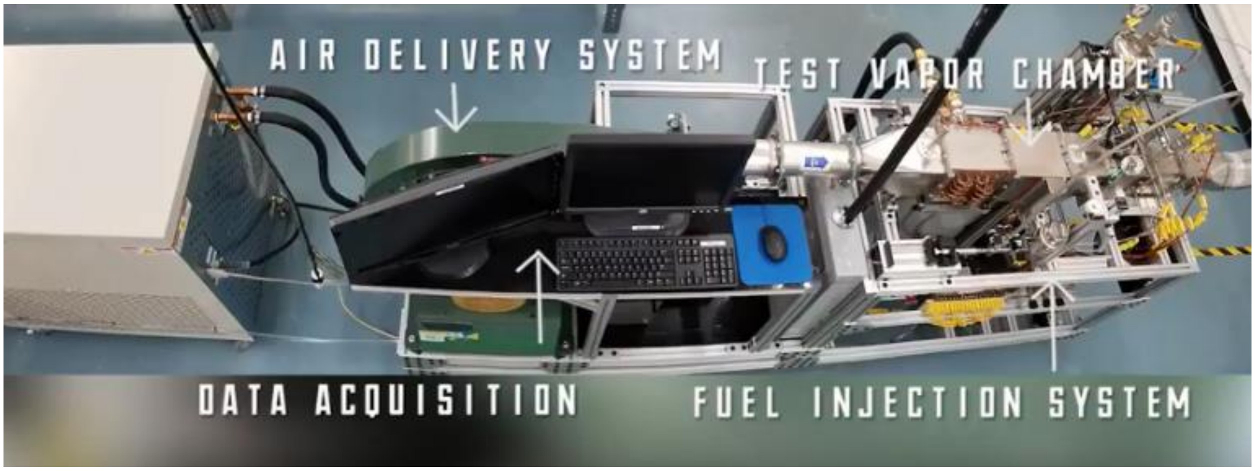
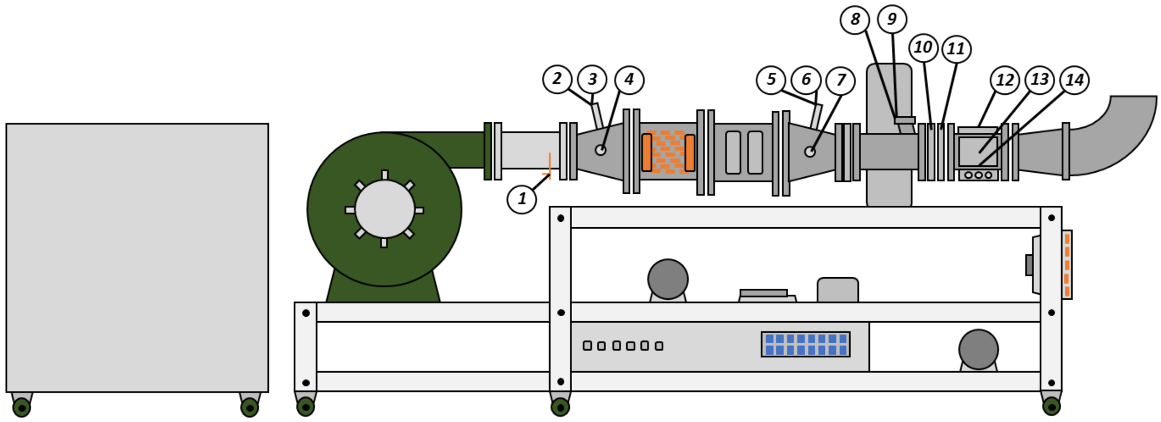


Figure 4. Hot surface ignition test apparatus developed at ACT.



1. **ΔP_1,** differential pressure measurement for sensing total flow rate of air through the duct.
2. **%RH_1,** relative humidity measurement to estimate gas state for interpretation of reading from instrument (1)
3. **T_1,** temperature measurement to estimate gas state for interpretation of reading from instrument (1)
4. **P_1,** absolute pressure measurement to estimate gas state for interpretation of reading from instrument (1)
5. **%RH_2,** relative humidity measurement to estimate gas state when entering the test section.
6. **T_2,** temperature measurement to estimate gas state when entering the test section.
7. **P_2,** absolute pressure measurement to estimate gas state when entering the test section.
8. **$V_{response}$,** voltage measurement of photodiode output voltage to detect ignition events.
9. **Video,** video capture of ignition testing for better understanding of how ignition occurs.
10. **$\Delta P_{2,array}$,** array of differential pressure measurements across the duct to characterize the velocity profile. Used during calibration only.
11. **$T_{3,array}$,** array of temperature measurements across the duct to characterize the thermal profile of air flow entering the test section.
12. **$T_{4,array}$,** array of temperature measurements across top wall of the ignition chamber (embedded close to surface) to characterize the inside surface temperature.
13. **$T_{5,array}$,** array of temperature measurements across both side walls of the ignition chamber (embedded close to the surface) to characterize the inside surface temperature.
14. **T_6,** temperature measurement on vapor chamber surface to characterize the test surface temperature.

Figure 5. Process instrumentation for the HSI test apparatus.

Air Delivery System. A flow bench capable of delivering a precise flow rate of air into the ignition chamber, at a precise state, and with a precise composition was designed. It is capable of generating the air conditions illustrated in Table 1. Due to absolute humidity requirements, the incoming air to the test apparatus will always be cooled to 10 °C, removing excess moisture which may be present within the ambient laboratory air. Further, to obtain the desired ignition chamber inlet conditions the incoming air stream will always need to be heated to achieve the desired testing conditions. To provide the heating, commercially available single-phase duct heating coils were used. A centrifugal blower capable of 200 CFM flow rate and 7 inH_2O of pressure drop, was used.

Table 1. Ignition chamber inlet air conditions.

Parameter	Value – Units
Volumetric Flow Rate	50 to 200 CFM
Air Temperature	15 to 75 °C
Pressure	1.00 atm
Absolute Humidity	1.4 to 7.6 g-H_2O/kg-Air
Relative Humidity (RH) at 20°C	10 to 52 %
(Free Stream) Temperature Uniformity	±3 °C
Hot Surface Temperature	400 to 700 °C
Hot Section Wall Temperature	40 to 100 °C

Flow conditioning for the test section is required to redistribute non-uniform flow provided by the blower and upstream heat exchangers. Two elements are included within the flow bench for this purpose: a flow straightening element with flow meter, and a screen directly upstream of the test chamber.

Instrumentation, Sensors, and Visualization. Instrumentation is required in order to monitor and control the flow, temperatures in the system, fuel injection, and record information to determine the time to ignition. The inlet air velocity is monitored by an air flow meter at the outlet of the blower fan. The isothermal vapor chamber is outfitted with two thermocouples mounted to the surface in opposite corners to monitor the temperature and uniformity of the hot surface and provides feedback to a heater controller. At the inlet and outlet of the ignition chamber is an array of nine thermocouples to evaluate the uniformity of the air temperature. The inlet air should be uniform in temperature; however, the outlet may not be uniform as ignition and heat transfer from the hot surface may create a temperature gradient.

Additional safety mechanisms have been implemented into the instrumentation and controls scheme and other measurements outlined in Figure 5 are also included.

Fuel Injection. The HSI test apparatus uses the same syringe pump architecture developed for the HSI testing chamber that can deliver flammable liquids to the hot surface in a measured stream, spray, or droplet.

Hot Section Design. The hot section is comprised of a square duct where the bottom wall houses the vapor chamber, the two side walls contain fluid passages for heating and cooling, and the top wall has integral ports for fuel delivery and instrumentation, as well as passages for heating/cooling. The hot section is outlined in Figure 6. Hot surfaces of various geometries are made possible within the ignition chamber by using swappable vapor chambers of convex, concave, or flat surfaces.

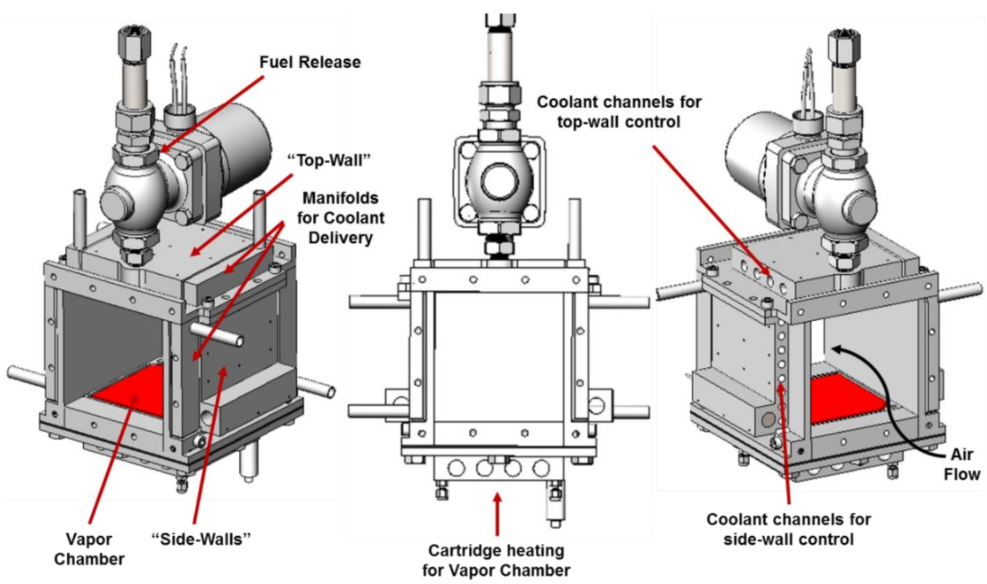


Figure 6. Final ignition chamber configuration.

Flat, Convex, Concave Vapor Chamber Design. The ignition of a fuel by a hot surface occurs when a fuel impinges on the hot surface, transfers heat from the hot surface, evaporates or boils, and mixes with the surrounding air. The shape of the hot surface can enhance or inhibit the evaporation/mixing of the flammable liquid with the surrounding air by spreading or pooling the flammable liquid, respectively, as shown in Figure 7.

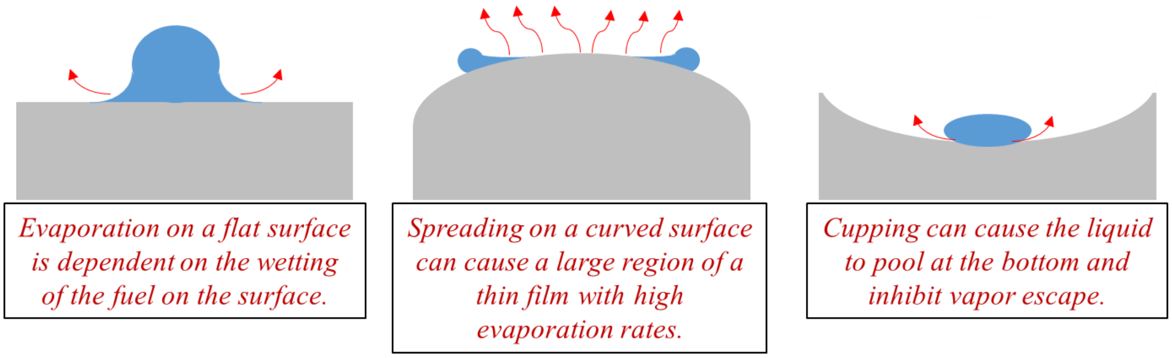


Figure 7. Evaporation of a fuel droplet on flat, curved, and cupped hot surface.

To evaluate the dependence of the hot surface geometry on the HSI process while maintaining isothermality to reduce errors, vapor chambers with flat, curved, and cupped geometries were designed and fabricated. As shown in the photographs of the fabricated vapor chambers in Figure 8, each vapor chamber utilizes a common flange to enable the vapor chambers to be interchanged.

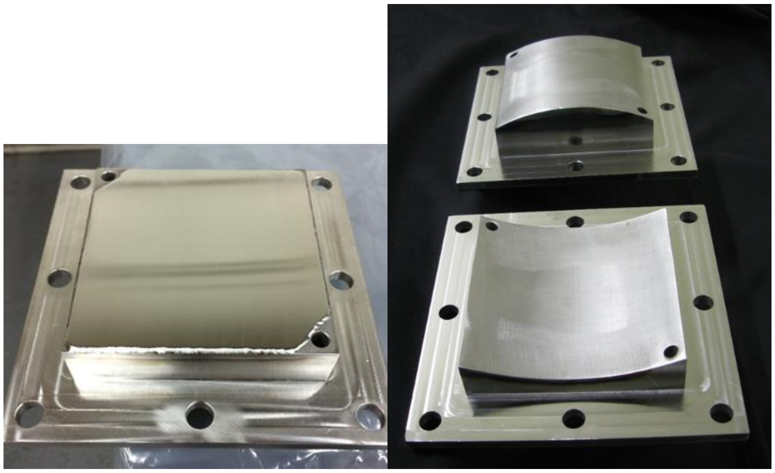


Figure 8. Flat, convex, and concave vapor chambers for HSI testing.

The vapor chambers' designs provide an isothermal hot surface for HSI testing at operating temperatures from 350°C to 750°C.

III. Results

III.A. Vapor Chamber based Hot Surface

First, we compare the hot surface of a vapor chamber with conventional HSI testing options. This involved comparing the high temperature vapor chamber designed for the test apparatus, against a metal block with embedded cartridge heaters. A thermograph of the vapor chamber surface and the baseline metal surface at 500°C is presented in Figure 9.

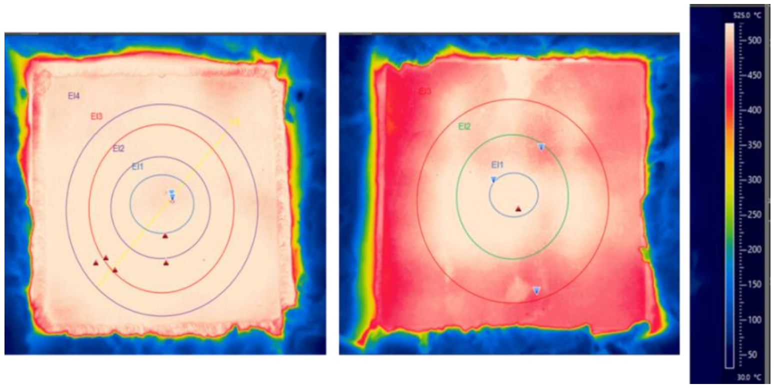
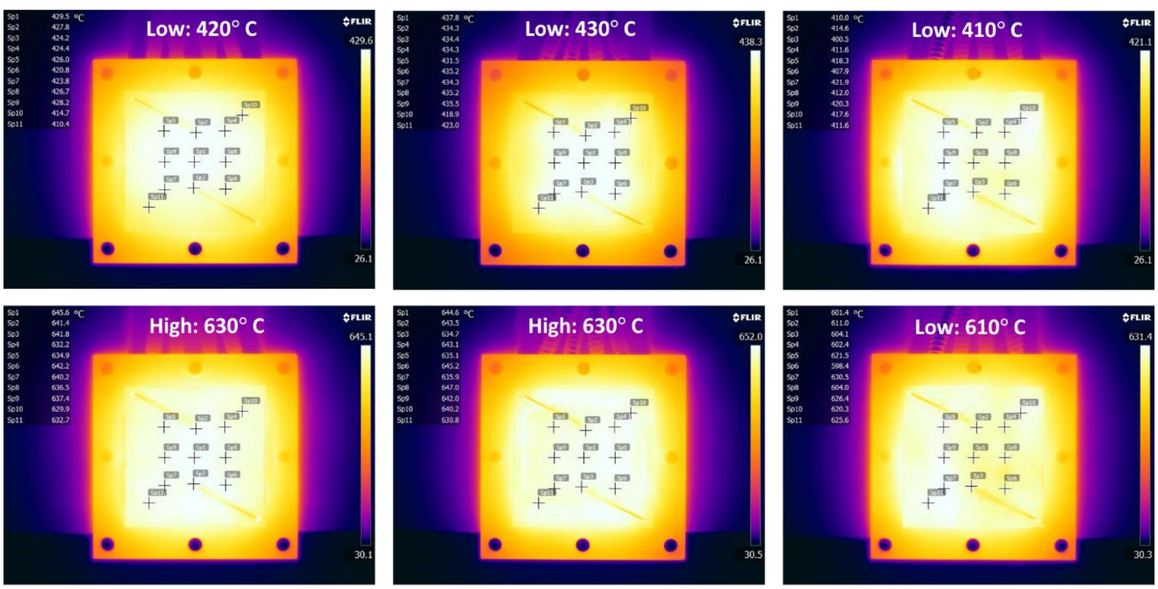


Figure 9. *(Left)* IR image of the vapor chamber surface at 500 °C and *(Right)* IR image of an Inconel 600 block with embedded heaters at 500 °C.

As shown in Figure 9, the vapor chamber produced a hot surface with a uniform surface temperature while the Inconel 600 block with embedded heaters produced a hot surface with a non-uniform temperature distribution. The standard deviation of the temperature on the vapor chamber surface was 3.9 °C, while the standard deviation of the temperature on the heated Inconel 600 block was 11.7 °C within the largest ring drawn on Figure 9 which represents the flammable liquid impingement region. Additionally, the maximum temperature that region is greater than 500°C for the metal block with embedded heaters. Thus, the vapor chamber demonstrated an isothermal surface that reduces error due to spatial dependence of the droplet on the hot surface. Figure 10 shows thermographs of all three hot surface geometry vapor chambers, demonstrating isothermal operation from near 400 to 600 °C.



(a) Flat surface (b) Concave surface (c) Convex surface

Figure 10. Thermal imaging of the hot surface vapor chambers, demonstrating isothermal operation.

III.B. HSI Test Apparatus – Demonstration

The 704 TG/OL-AC provided ACT with Jet-A fuel for testing, since this is the new standard for the USAF, replacing JP-8. The test apparatus was used to evaluate the sensitivity of the time to ignition of Jet-A under various operating conditions of air velocity, inlet air temperature, and degree of enclosedness (i.e., side wall temperature).

ACT and 704 TG/OL-AC reviewed the test matrix for the Phase II effort to provide a set of data that can be used to produce a statistical model. The original test matrix outlined a test set that had small and frequent increases in level changes for specific parameters. However, to review the causal effects of the various parameters, the test matrix was revised to have a coarser change in all parameters. Initial testing, however, showed that the test matrix developed, which covered the full range of parameters outlined in Table 1 did not include any parameter sets where any meaningful data could be obtained. Ignition of Jet-A could not be detected for any of the conditions in the original matrix. Some testing outside the original design capabilities of the test apparatus was then performed. By turning off the blower and physically blocking the exhaust, flow rates lower than 50 CFM could be obtained. Ignition was detected for a case with ~20 CFM flow rate and a 700 °C hot surface. Table 2 documents the results from these tests with the flat surface geometry. Additional testing with the other two surface geometries was not able to be completed within the scope of this project. A visual overview of the HSI apparatus developed by ACT is available online [5].

Table 2. Hot surface ignition testing configurations and results.

Geometry	Surface Temperature (°C)	Air Flow Rate (CFM)	Wall Temperature (°C)	Inlet Air Temperature (°C)	Ignition
Flat	600	10	65	50	no
Flat	685	10	30	13	yes
Flat	690	10	65	13	yes
Flat	700	10	65	20	yes
Flat	700	10	65	50	yes
Flat	685	10	30	50	yes
Flat	700	15	65	13	yes
Flat	700	15	65	50	yes
Flat	685	15	30	13	yes
Flat	700	20	65	13	yes
Flat	685	20	30	13	yes
Flat	700	25	65	13	no
Flat	685	15	30	50	yes
Flat	700	20	65	50	no
Flat	685	20	30	50	yes
Flat	685	25	30	50	no

IV. Conclusions

Currently, hot surface ignition is not considered to be a hazard unless the hot surface temperature is ~182°C above the AIT of the flammable liquid. However, literature has shown that this rule of thumb is not always correct and the conditions that lead to deviations from this rule of thumb are not well known[6]. Additional testing will be required to fully characterize this rule of thumb, but the testing indicates, that for Jet-A the hazard of HSI is fairly low in the presence of air flow. The AIT of Jet-A is 210 °C and in the presence of flows down to 20 CFM, the fuel did not ignite until reaching over 700 °C, nearly 500 °C greater than the AIT. This is a positive result that indicates a lower risk of a damaging HSI event occurring.

The primary factor affecting the results was the air flow rate. In the static testing performed with the HSI testing chamber, a time to ignition could be measured and was found to be between 1 to 3 seconds for JP-8. Observations through the viewports into the HSI test apparatus' test chamber indicate that while the fuel drops do indeed impact the hot surface, the airflow pushes the droplet off of the hot surface in less than a second for airflow of 50 CFM or greater. With lower flow rates, drops sometimes recirculate for some time on the surface and ignition occurs, though, this is not consistent, since it depends on the eddy currents that swirl the fuel droplet around on the surface to give it time for the vapor to build up and ignite.

More detailed studies of each of the parameters such as wall temperature, air temperature, and surface geometry are needed to fully characterize HSI in the presence of air flow. The testing apparatus is capable of performing these experiments, and while the tests were not able to be performed at ACT, the 704 TG/OL-AC will now have the capability of performing these more detailed studies using the Testing Apparatus delivered in this program.

This program focused primarily on delivering a functioning test apparatus that provides many options for control of a wide variety of parameters. Because extra time and resources were spent on the automated control scheme and fabrication of additional features, an exhaustive study of the actual HSI process was not able to be completed. Therefore, the primary recommendation is for the 704 TG/OL-AC to utilize the test apparatus as a tool for further study of the HSI process.

V. Acknowledgments

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VI. References

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