A Method for Reducing Jet Engine Thermal Signature

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Abstract

The protection of aircraft against shoulder fired heat seeking missiles is of growing concern in the aviation community. This paper presents a simple method for shielding the infrared signature of a jet engine from heat seeking missiles, by using water injection. The experimental results presented herein were obtained using a small (1 kN thrust) turbojet. Water was first injected at a mass flow rate of 13% of the mass flow rate of exhaust gases, reducing the temperature and producing some shielding. Water was then injected through a manifold at a mass flow rate of 118% of the mass flow rate of exhaust gases, producing a substantial reduction in temperature and complete shielding of the infrared signature. Results are presented in the form of thermocouple data and thermal images from the experiments.

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Nomenclature

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1 Introduction

The first guided missile prototypes were built in the decade following World War II. Initially, these missiles used radar technology, which proved to be expensive and problematic. Around 1947, Bill McLean, a Naval physicist devised a way to avoid the problems associated with radar guided missiles. He began to develop a new system that could track the heat given off by the enemies’ propulsion system. McLean’s new heat seeking missile had two main advantages over the radar guided missiles then currently under development. First, heat seeking missiles use a small photovoltaic infrared (IR) sensor rather than bulky radar equipment, making them smaller, lighter and less expensive per unit. Second, heat seeking missiles track a target using the IR energy emitted by the engine(s) rather than receiving radio waves reflected off the target. Consequently, heat seeking missiles are fire and forget, giving the pilot the ability to fire his missile and then get himself and his aircraft clear of the danger zone.

To defend aircraft against this emerging missile threat, engineers began to develop countermeasures (CM). The most popular CM are pyrotechnic infrared decoys (flares). Initial flares, composed mainly of $Mg/NaNO_3$, were relatively ineffective since the emissivity of $MgO$, its main combustion product, is low compared to blackbodies. Simply speaking, the flare does not radiate well and
therefore is not an attractive target for the seeker. Subsequent CM system development focused on generating large amounts of heat and extensive use of carbon black, since carbon black behaves much like a blackbody. The emissivity of carbon black is approximately 20 times greater than that of MgO, translating into radiant behavior much closer to the ideal blackbody and a more effective CM. Today, flares remain the most commonly used passive countermeasures due in part to inexpensive components, ease of handling and reliability.

As CM systems matured, missile designers developed ways to nullify the improved countermeasures. IR counter-countermeasures (IRCCM) allow missiles to detect the presence of flares and reject them as valid targets. IRCCM consist of two fundamental parts: the trigger, which detects the flare, and the counter, which takes a designated action to reject the flare. There are several types of triggers: rise time (temporal), two-color (spectral), kinematic, and spatial, as well as several types of counters: simple memory, seeker push-ahead, seeker push-pull, sector attenuation, electronic field-of-view gating, and time phase blanking (Deyerle, 1994).

Today’s IRCCM are more advanced than ever. Regardless of which trigger and counter employed, most CM are accurately detected and rejected. Thus, new methods for increased effectiveness of current inexpensive CM must be developed. If the heat produced by the target can be reduced, then IR seeker will be more inclined to track flares rather than aircraft. This can be accomplished simply by reducing the thermal signature of the aircraft hot spots.

The primary goal of the research presented herein was to determine the feasibility of reducing the thermal signature of a jet engine by injecting water into the exhaust stream; secondary goal is to determine how this injection would effect the acoustic signature. Ultimately, a foundation will be laid for future research in this area.

The next section introduces the fundamental types of IR seekers, laws of radiation, and discusses other relevant issues related to IR radiation. Section 3 presents the experiment design and explains
the two sets of experiments. Section 4 presents and compares the results from these experiments.

2 IR Seeker Technology

This section begins by briefly describing the fundamental types of IR seekers and how they work. Next, it explains the physics associated with the IR technology and discusses options for shielding the IR emission of a jet engine.

There are three main types of IR seekers: spin-scan, conical-scan, and imaging (Deyerle, 1994). The simplest of these is the spin-scan seeker with amplitude modulation tracking. It consists of four basic components: the optics, the reticle, the sensor element and assorted filters (Fig. 1). Energy emitted by the target (source) is focused by optics and passed through a spinning reticle, producing a modulated (pulsed) signal that impinges on the sensor element. Output from the sensor is fed through various filters, where the signal is conditioned by removing information regarding extended sources (e.g. clouds), the frequency of the spinning reticle, etc. The resulting output signal is the tracking error in the form of a sine wave. The amplitude and phase of this wave corresponds to the magnitude and direction of the tracking error, which is subsequently fed to the guidance subsystem.

Conical-scan (con-scan) seekers function similarly to spin-scan seekers, but are somewhat more advanced. Con-scan seekers focus gathered energy through the outer edge of a stationary reticle to the IR sensor via a secondary spinning mirror. This mirror is tilted with respect to its rotational axis. The sensor outputs a frequency modulated sine wave which is first fed through a frequency discriminator before passing through various filters to produce the tracking error.

The third main type of seeker is the imaging seeker. This is the most advanced seeker, and uses an array of sensor elements called a focal plane array instead of a single reticle. From the detector array output, a spatial map of the scene is built and passed to processing software. Due to sophisticated software, imaging seekers can readily distinguish between aircraft, clouds, birds,
flares, etc. and are not easily fooled by CM.

The IR seekers are detecting the thermal radiation, that is, the electromagnetic radiation emitted by an object based solely on its temperature. The “thermal” region of the electromagnetic radiation spectrum is generally considered to extend from the short wave ultraviolet to the long range IR.

The sensor element in a typical IR seeker is generally sensitive only to select radiation bandwidths. For example, lead sulfide (PbS) detector elements are sensitive to the 2-3 μm range, designated α-band, and lead selenide (PbSe) detector elements are sensitive to the 3-5 μm range, designated β-band (Koch, 2001). Both the PbS and the PbSe detector elements are sensitive only to radiation in select IR bands.

Each band corresponds to a temperature range which can be quantified using Wien’s displacement law. Wien’s law states that the wavelength of peak energy emission of a blackbody is inversely proportional to its absolute temperature in K (Kreith, 1962, p. 12)

\[
\lambda_{\text{max}} = \frac{2897.756}{T}.
\]

As previously mentioned, the peak sensitivity of a typical uncooled PbS detector lies in the 2-3 μm range. According to Wien’s displacement law, the temperature range of the radiator with a
corresponding peak energy emission wavelength of 2-3 $\mu$m is 966-1449 K. This temperature range covers typical temperature values of jet engine turbines, justifying the suitability of PbS detectors for homing in on the hot tail pipes of jet aircraft.

![Figure 2: Variation of peak energy wavelength with absolute temperature.](image)

Figure 2 shows that as the temperature decreases, the peak of the emitted radiation shifts toward longer wavelengths. The implied result is that by reducing the operating temperature of the engine, it may be possible to shift the wavelength of IR radiation out of the detectable range of certain seekers. Realistically, an engine cannot be sufficiently cooled for this purpose in a short time interval.

One could certainly cool very fast the exhaust gases, for example by using liquid nitrogen (Guarnieri, 2004). A reduction of exhaust gases temperature from 1200 K to 800 K results in a 0.9 $\mu$m shift of the peak emission wave length. This shift of wave length could increase survivability by making pyrotechnic decoys appear more attractive to IR seekers. This reasoning is only true if the exhaust plume is a solid object radiating like a blackbody, which unfortunately is not the case with the
exhaust plume.

To reduce the IR signature of the jet engine one could modify the transmission of electromagnetic radiation from the source (the jet engine) to the IR seeker. Exitance, the source energy flux per unit area, is for thermal radiation given by the Stefan-Boltzmann Law (Kreith, 1962, p. 8)

\[ M = \epsilon \sigma T^4, \]

where \( \epsilon \) is a dimensionless property of the radiating surface called the emissivity, \( \sigma \) is the Stefan-Boltzmann constant \( (5.6696 \times 10^{-8} \text{ W/(m}^2\text{K}^4)) \), and \( T \) is the absolute temperature of the radiating surface in K.

Assuming the thermal radiation is effectively emanating from a single point that radiates with complete spherical symmetry, the energy flux per unit area at the detector is the incidence \( E \)

\[ E = \left( \frac{1}{4\pi R^2} \right) M. \tag{1} \]

The above transfer equation is idealized in the sense that it does not directly account for the energy lost to the atmosphere. IR energy is generally lost to the atmosphere in four ways: absorption, scattering, photochemical reactions, and photoionization (Wallace and Hobbs, 1977, p. 281-3). Scattering is simply the energy loss due to redirection away from the detector. Absorption is the energy loss due to vibration and rotation of molecules. Photochemical reactions generally involve only ultraviolet and visible radiation. Photoionization requires high energy photon and is usually only associated with wavelengths shorter than 0.1 \( \mu \text{m} \). Therefore, only absorption and scattering will be considered here. The overall energy loss, called attenuation, is primarily a function of the wavelength and range, but is also dependent on the properties of the atmosphere (e.g. humidity, composition, visibility).
An isolated gas molecule can store energy in various forms. Most of this energy is stored as kinetic energy and electrostatic potential energy of its electrons moving about the nuclei. Lesser amounts of this energy are associated with atoms vibration about their mean position and rotation of the molecule about its center of mass (Wallace and Hobbs, 1977, p. 282). According to quantum mechanics, only those molecules that have a dipole ($CO_2$, $H_2O$, $O_3$) are significantly excited by IR radiation. When a dipole absorbs IR radiation, a portion of the energy is converted to heat by the vibratory and/or rotational motion of the molecule. The remaining energy is then re-emitted, usually at longer wavelengths.

The wavelength(s) at which the atmosphere absorbs IR energy affects attenuation. Typical atmospheric constituents will absorb radiation at different wavelengths. Since $N_2$ and $O_2$ are diatomic molecules, they have no unbalanced charges and are relatively unaffected by IR radiation. $CO_2$, $O_3$ and $H_2O$, on the other hand, have unbalanced charge distributions and readily absorb IR radiation. So, although the atmosphere contains substantially less $CO_2$, $O_3$ and $H_2O$, than $N_2$ and $O_2$, they are the primary contributors to attenuation.

To better model attenuation influences in equation (1), let us include the exponential law, often called the Beer’s law or Bouguer’s law (Houghton, 1985, p. 34), that quantifies the fraction $\tau$ of the energy flux remaining after attenuation as a function of the range

$$\tau = e^{-BR},$$

where $B$ is the extinction coefficient and is a property of the specific detector. For the $\beta$ – band, $B$ is typically $6.7 \times 10^{-5} \text{ m}^{-1}$. The dimensionless transmission coefficient, $\tau$, goes to zero as the distance between the target and the detector increases. Using the transmission coefficient, the
transfer equation (1) becomes

\[ E = \left( \frac{T}{4\pi R^2} \right) M. \] (2)

In conclusion, cooling the exhaust gasses will not reduce the thermal signature of the jet engine because the IR radiation from the nozzle will penetrate the injected \( N_2 \) and still be visible to the seeker. To reduce the jet engine thermal signature we propose to reduce the transmission coefficient \( \tau \) by flooding the exhaust with \( H_2O \).

3 Experiment Design

This section presents the development of the facilities and equipment used in the experiment. This experiment used the Noel Penny Turbines 401 jet engine of the Propulsion Laboratory, shown in Figure 3. This is a 1kN turbojet which has a mass flow rate of 2 kg/s. Substantial modifications and additions to the Texas A&M Propulsion Lab Test Cell were made throughout this research. The most invasive of these was the new exhaust duct. Additionally, various instrumentation and associated hardware and software were added, including thermocouples, data acquisition components, dosimeter, a digital video camera, and related software.

3.1 Exhaust Duct

Previously, the test cell had no means for collecting thermal measurements in the jet exhaust. Any modifications to the original exhaust pipe would have been expensive and irreversible due to the extensive acoustic and heat insulation. Therefore, a new exhaust pipe was designed and fabricated to meet the requirements of the present research. Specifically, the new exhaust duct included strategically placed thermocouple taps, an IR sight glass viewport for thermal imaging.
Figure 3: Noel Penny Turbines 401 Turbojet Engine.

and windows for visual access.

Figure 4: Exhaust duct.

The exhaust duct was composed of seven flanged sections built from standard 22 inch schedule...
40 steel pipe. The five central sections measured 12 inches overall length, with three of the sections featuring two 8 inch by 12 inch flanged window openings. The section bolted directly to the turbojet enclosure measured 16 inches overall length due to the 4 inch protrusion into the enclosure. The last section measured 17 inches overall length and had a different flange on one end to connect the duct to the outside exhaust stack. When fully assembled the duct was approximately 8 ft long, 22 inches in diameter and weighed approximately 650 lb (Fig. 4).

3.2 Instrumentation

A single Pentium PC, running Windows 2000 and LabVIEW 7, recorded temperature data from the fourteen, twelve inch long, k-type Thermosensors thermocouples (TCs) and controlled the water flow via a solid state relay and a Parker Gold Ring solenoid valve. Three TCs were installed at 120° in each the solid exhaust duct sections and two TCs were installed at 180° in each of the windowed sections. Figure 4 shows seven of the fourteen TCs protruding from the exhaust duct. The TCs were wired in differential configuration to a pair of TBX-68 terminal blocks. The terminal blocks were linked to the multifunction DAQ board via a special 2 m shielded cable.

The LabVIEW program was a simultaneous dual loop control structure which ran continuously until user termination. The first loop recorded and displayed TC data while the other loop controlled the water injection sequence.

The TC loop constantly sampled the signal from each thermocouple in sequence at a predefined sampling rate. Once the set number of samples were read, they were averaged, the gauges were updated and the average temperature values were written to the designated output file. Since temperature fluctuations in the exhaust occurred over several seconds, averaging the samples over a comparably short interval (approximately 0.5 s) was a simple and effective means of reducing the number erroneous temperature readings without sacrificing measurement accuracy.
The water injection control loop constantly monitored the injection initiation switch located on the control panel. When activated, the loop waited a predetermined number of seconds, then sent the signal to open the water solenoid valve and started an elapsed time clock. Once the injection duration time was reached, the open signal was terminated and the water solenoid closed.

Temperatures were monitored from the Thermocouple Display and DAQ Control Screen (Guarnieri, 2004) via digital displays and gauges. In addition to monitoring temperature readings, from this screen the operator could adjust the sampling rate, number of samples to average, set the output file name and completely control the water injection sequence timing.

3.3 Injection Manifold

The second major component of the experiment was the injection manifold, shown in Fig. 5. The injection manifold face plate was a 12 inch square aluminum plate 0.5 inches thick. In the center of the plate was a 5.25 inch diameter through hole for unrestricted flow of the exhaust gasses. Injector ports were located on radii of 3.0 inches and 3.213 inches from the plate center. The ports were arranged in two concentric series of 128 equally spaced 0.0313 inch diameter holes. Water entered the manifold via a 0.5 inch diameter stainless steel hose through a single connection on the rear plate. The two plates were sealed with a 0.0625 inch thick Teflon™ gasket and twelve 1/4-20 Unified Coarse (UNC) socket head cap screws equally spaced on an 11 inch bolt circle.

3.4 IR Mirror

The last major component built specifically for this research was the IR mirror. This mirror facilitated the required aft view of the engine for thermal imaging. The second window on the starboard side of the exhaust duct was replaced with a 0.5 inch thick carbon steel plate. Mounted at the center of this plate, outside the pipe, was a 2 inch Hawk IR infrared sight glass. Centered
about the sight glass on the opposite side of the plate was the aft looking stainless steel mirror. An exploded view of the mirror solid model is shown in Figure 6.

The three main supports of the mirror assembly were machined from 0.625 inch thick aluminum plate and feature slots for mirror adjustment. The mirror was secured in a aluminum frame and bolted to the back support. The angle of the mirror could be fine tuned by inserting shims between the frame and the back plate. The entire IR mirror assembly was secured to the steel plate with eight 3/8-16 UNC socket head cap screws from outside the pipe.

A single hole probe was built to inject water into the exhaust stream. The hole probe was positioned at the center of the exhaust stream, 36 inches downstream from the exit nozzle. The hole diameter of the probe tip is 0.125 inch. Through the probe, water was injected against the exhaust stream at a mass flow rate of 0.266 kg/s. The plumbing was then rerouted to connect the injection manifold to the test cell water supply and water was injected through the manifold with
the exhaust stream at a mass flow rate of 2.36 kg/s.

4 Results

This section presents the results of the experimental investigations. The section begins by reporting results from the experiments on reducing the thermal signature of a steel plate by a water sheet. Then, results of water injection from the probe and from the manifold are discussed.

4.1 Water Blocking Test

Previous experimental investigations (Guarnieri, 2004) showed that liquid nitrogen injection decreases the temperature of the exhaust plume but does not reduce the IR signature, for the reasons mentioned in section 2. Consequently, prior to testing water injection in the jet engine exhaust nozzle, a simple experiment was designed to test the water IR blocking capability.

An elevated water reservoir with a rectangular slot cut into the bottom produced a water sheet approximately 0.0625 inch thick between a heated carbon steel plate (3.25x3.25x0.125 inches) and the FLIR Systems™P60 thermal imaging system. The steel plate was heated to approximately 500°C.

The FLIR camera thermal images shown in Figure 7 indicate that a relatively thin sheet of water completely blocked the IR signature of the heated steel plate. The left image shows the temperature profile of the carbon steel plate just before initiation of the water sheet. The right image is in the final stages of the test where the water sheet had a triangular shape. The IR energy radiated by the plate was clearly shielded wherever there was a coherent water sheet. This quick experiment verified that a thin water sheet could completely block the IR energy emitted by a hot steel plate.

Additional experiments were done with a steel plate partially electroplated with thin layers
of metals (Guarnieri, 2004). The purpose of these experiments was to evaluate the effect of the emissivity of different materials on the thermal signature. As expected, the thermal signature of gold plated steel was reduced by approximately 200°C, as shown in Figure 7. However, when water shielding was applied, the difference between the electroplated steel and non-electroplated steel was less than 1°C, because the water shielding blocked most of the IR (Figure 8).

4.2 Exit Nozzle Water Injection

The encouraging results from the water sheet tests lead to the exit nozzle water injection experiments. Water was injected into the exhaust of the turbojet in two ways. First, water was injected against the exhaust jet through a single hole probe. Second, water was injected with the exhaust jet through the manifold. In this case, water injection reduced the temperature of the exhaust gases as much as 150°C (Figure 9).

Temperatures reported by the FLIR camera were smaller than temperatures measured by thermocouple because the thermal imaging measurements were taken indirectly via the mirror. Measuring the engine temperature through the mirror introduces the emissivity of the mirror which cannot be compensated for by the FLIR camera. This results in the apparent temperature reported by the FLIR camera to be different from the actual temperature. For example, thermocouples in the turbine measure turbine outlet temperature at 861 K (588°C) compared to 552 K (279°C) reported by the FLIR camera. This phenomenon can be minimized by using a highly polished gold mirror instead of the current stainless steel mirror.

Although the temperature was reduced in both injection cases, the probe could not supply the quantity of water necessary to completely shield the IR signature of the engine. The mass flow rate of water through the probe was estimated to be 0.266 kg/s, or 13.3% of the mass flow of exhaust gasses. The FLIR camera images in Figure 10 show a temperature reduction of only 20°C for the
hot spot.

On the other hand, the manifold, with an estimated mass flow rate of 2.36 kg/s, or 118% of the mass flow of exhaust gasses, was able supply more than the necessary mass flow of water to completely shield the IR signature of the engine from the FLIR camera. The FLIR camera images in Figures 11 through 13 were recorded sequentially during a one minute water injection sequence. The left image in Figure 12 shows the apparent temperature of the engine before injection and serves as a reference. The right image was recorded seconds after the injection began. Almost immediately the water obscured the engine hot spot. The high temperatures indicated on the left edge of the image were due to the reflection of the exhaust pipe heat by the water cloud.

The temperatures reported by the FLIR camera steadily fell through Figures 12 and 13 reaching a minimum value of 331 K (58°C). During the one minute water injection, the temperature was reduced by 333 K (185°C). In both injection cases the engine’s acoustic signature apparently dropped pitch but the magnitude remained a steady 125 dB in the test cell.

5 Conclusions and Future Work

The primary goal of the investigation presented herein was to determine the feasibility of reducing the IR signature of a jet engine by injecting water into the exhaust stream. This goal was exceeded. The IR signature of the engine was not only reduced, but also completely shielded from detection.

This research, as conducted, illustrated how water can be used to shield the IR signature of hot objects. To the best of the authors knowledge, this is the first published work of its kind. This work lays the foundation for future investigations. Repeatable experiments confirmed that a thin coherent sheet of water was capable of completely blocking the IR radiation emitted by a metal plate regardless of the type of metal. Application of this phenomenon was extended to include shielding IR radiation with a water cloud. By injecting a mass flow of water roughly equivalent to
the exhaust gas mass flow, the IR signature of the turbojet can be completely shielded. This result has numerous potential applications including aircraft countermeasure systems.

With many issues left to address, a couple are of particular interest. First, it is necessary to determine the reduction of the apparent temperature (or the thermal imaging temperature) as a function of the mass flow rate of water. This should provide the minimum amount of water necessary to achieve a certain degree of shielding the engine.

Second, the experiments and the countermeasures are concerned with the apparent temperature rather than the actual temperature. Currently, however, the numerical simulations are not comparable to thermal images taken during the experiments. To address this issue, it is necessary to incorporate thermography into the numerical simulations.

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References


Figure 6: Mirror solid model exploded view.

Figure 7: Temperature profiles of carbon steel plate unshielded (left) and shielded (right).
Figure 8: Thermal images of phases one and two. Phase one: Heating the plate (left) and Phase two: Continuous water sheet (right).

Figure 9: Temperature versus time for $H_2O$ injection runs: probe injection (left) and manifold injection (right).

Figure 10: Aft view thermal image of turbojet before $H_2O$ injection (left) and during injection via probe (right).
Figure 11: Aft view thermal image of turbojet before $H_2O$ injection (left) and seconds after injection begins via manifold (right).

Figure 12: Aft view thermal image of turbojet during injection via manifold. As injection continues, temperatures reported by FLIR camera steadily fall.

Figure 13: Aft view thermal image of turbojet during injection via manifold. Temperatures reported by FLIR camera reach a minimum value of 331 K ($58^\circ$C) for a total reduction of 333 K ($185^\circ$C).