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REMOTE LEAK DETECTION: INDIRECT THERMAL TECHNIQUE

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ABSTRACT

Remote sensing technologies are being considered for efficient, low cost gas leak detection. Eleven specific techniques have been identified for further study and evaluation of several of these is underway. The Indirect Thermal Technique is one of the techniques that is being explored. For this technique, an infrared camera is used to detect the temperature change of a pipe or fitting at the site of a gas leak. This temperature change is caused by the change in temperature of the gas expanding from the leak site. During the 10-week NFFP program, the theory behind the technique was further developed, experiments were performed to determine the conditions for which the technique might be viable, and a proof-of-concept system was developed and tested in the laboratory.

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1. INTRODUCTION

As currently performed, locating a gas leak is a time consuming, labor-intensive process. The Remote Leak Detection Project grew out of the desire to vastly improve the efficiency of this process. The project's goal is to reduce the cost of detecting hydrogen and helium leaks into air by at least an order of magnitude. To achieve this goal, several remote sensing techniques are being considered by NASA for application to gas leak detection [1]. The Indirect Thermal Technique is one such technique being considered. With this technique, an infrared camera would be used to detect the temperature change in a pipe or fitting at the site of a leak caused by the change in temperature of the gas as it expands from the site. The specific goals for the 10-week 2002 NASA/ASEE Summer Faculty Fellowship Program were to increase the Technology Readiness Level (TRL) for the Indirect Thermal Technique and to develop a proof of concept that would be demonstrated in a laboratory setting. To increase the TRL, it was necessary to further develop the theory behind the technique as applied to remote leak detection, to test and refine the theory via experiments, and to determine the range of conditions for which the technique is viable. Progress has been made toward each of these goals, though further work is needed.

2. THEORY

With the Indirect Thermal Technique, an infrared camera is used to detect the temperature change of a container at the site of a gas leak caused by the change in temperature of the gas as it expands during the leak. Thus, the theory underlying the technique involves thermodynamics and gas dynamics of the leaking gas as well as heat transfer between the gas, container, and detector.

Thermodynamics

A gas leak can be considered a thermodynamic process involving a system (the leaking gas) and its environment (the container and the ambient air into which the gas leaks). The variables that describe the state of the system are called the state variables. These include the pressure (P), volume (V), density (ρ), absolute temperature (T), internal energy (E_{int}), enthalpy (H), and entropy (S). Equations of state such as the perfect gas law PV = nRT (discussed later) describe the relationship between the state variables. Other variables are involved in transitions between thermodynamic states, but are not state variables. Heat (Q) and work (W) are two such variables. The three laws of thermodynamics governing thermodynamic processes [ref.2, Ch.1] are given below.

0^{th} Law: If systems A and B are in thermal contact and $T_A = T_B$, then the two systems are in equilibrium.

1^{st} Law: $dE_{int} = dQ + dW = dQ - PdV$ (1)

In this equation, dE_{int} is the change in internal energy of the system, dQ is the heat transferred to the system from the environment, and dW is the work done on the system by the environment.

2nd Law: $\Delta S = S_B - S_A \geq \int_A^B \frac{dQ}{T}$ (2)

The entropy S is a measure of the disorder in a system, Q is the heat, and T is the absolute temperature.

The first law indicates that if heat is added or removed from a system and/or work is done on or by the system, the internal energy of the system will change. This simply means that energy is conserved when a system changes from one state to another during a thermodynamic process. The first law does not say anything about the direction of thermodynamic processes. However, the second law does, limiting natural or spontaneous processes to those for which entropy is conserved or increases. Entropy is a measure of the level of randomness in a system. In a gas leak, order is converted to disorder as organized gas flow is impeded by viscosity and turbulence resulting in an increase in the entropy of the system.

It is often appropriate to consider a gas to be a perfect or ideal gas. For such a gas, the size of the gas molecules is negligible, collisions between gas molecules and with container walls are perfectly elastic (that is, no energy goes into deforming the molecules), and the molecules do not interact with each other. For such a gas, the perfect gas law is a valid equation of state [3].

Perfect Gas Law: $PV = nRT$ (3)

Here, P is the pressure of the gas, V is its volume, n is the number of moles of gas, R is the Universal Gas Constant (8.314 J/mol·K), and T is the absolute temperature in Kelvin.

However, at high pressures and low temperatures or at low pressures and high temperatures, gases deviate from the perfect gas law. In the low pressure, high temperature regime, molecules are subject to dissociation. In the high pressure, low temperature regime, intermolecular forces become important [ref.2, p.34]. The van der Waal equation [3] is an approximation often used for gases in the low temperature, high pressure regime.

van der Waal equation of state: $\left(P + a\left(\frac{n}{V}\right)^2\right)(V - nb) = nRT$ (4)

In this equation, *a* is related to the intermolecular attractive force between molecules and *b* is related to the size of each molecule. The intermolecular attractive force reduces the gas pressure for a given volume and temperature. The finite size of the molecules effectively reduces the volume in which the molecules move.

Of relevance to the problem of a leaking gas is the process followed as the gas goes from one state to another. The polytropic equation of state can be used to describe the thermodynamic process that a system follows in going from state A to state B [ref.4, pp.77-79].

Polytropic equation of state: $PV^n = const$ (5)

Here, n is the polytropic exponent. Many types of processes are possible. A constant temperature (isothermal) process, for example, has n = 1. A constant entropy (isentropic) process has n = γ with γ being the adiabatic index. Combining the perfect gas law (3) and the polytropic equation of state (5), relationships between pairs of state variables can be formed. Of interest for this project is the relationship between the temperature and the pressure.

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\left(\frac{n-1}{n}\right)} \qquad (6)$$

The polytropic exponent in these equations depends on the type of process as well as on whether the process is reversible or irreversible. A reversible process is one in which equilibrium exists throughout the process. Equilibrium exists if there are no currents of heat, mass, or momentum. In such processes, entropy is conserved. Spontaneous processes are irreversible and in such processes entropy increases due to the currents of heat, mass, or momentum in the process [ref.2, pp.6-7].

A gas leak can be considered an adiabatic process. An adiabatic process is one for which no heat is transferred between the system and environment (Q = 0). An adiabatic process can occur when the system is insulated from its environment or when the process occurs too quickly for heat transfer to occur. With a gas leak, the process occurs too quickly for heat to be transferred. If the process were reversible, the polytropic equation $PV^{\gamma} = constant$ would apply with the adiabatic index γ depending on the gas. For diatomic gases such as nitrogen and hydrogen, $\gamma \cong 1.4$. For a monatomic gas such as helium, $\gamma \cong 1.67$ [ref.4, p.724]. Note that a reversible adiabatic process is an isentropic process (n = γ). When a perfect gas undergoes a reversible adiabatic expansion, its temperature will always decrease. For example, consider the expansion of nitrogen gas at T_1 = 300K from P_1 = 54.7psi to P_2 = 14.7psi. The temperature of the gas from equation (6) after expansion is T_2 = 206K for a change in temperature of ΔT = -94K = -94°C!

A gas leak, however, is a spontaneous, and thus irreversible, expansion process. For an irreversible adiabatic expansion, the polytropic index lies between 1 and γ. The more irreversible the process (i.e. the more entropy is generated), the closer the index is to 1, and the more closely the process resembles an isothermal (constant temperature) process.

Gas leaking through an orifice can be considered a throttling process in which the gas flow is impeded by a resistance. Because this process involves fluid flow, it is more appropriate to consider the enthalpy of the gas instead of the internal energy. The enthalpy of the gas is given by the following equation [ref.2, Ch.2].

Enthalpy: $H = Q + PV$ (7)

Like internal energy, enthalpy has units of energy.

Gas Dynamics

Because the gas flows through an orifice or crack when it leaks from its container, the state variables will vary throughout the flow and thus gas dynamics are important. The general equations that govern steady fluid flow are given below [ref.2, Ch.2]. Here, steady flow means that the masses of fluid passing any two cross-sections in the flow are equal.

Continuity Equation: $\rho uA = const$ (8)

Energy Equation: $q = h_2 - h_1 + \frac{1}{2}u_2^2 - \frac{1}{2}u_1^2$ (9)

Momentum Equation: $\rho_2 u_2^2 A_2 - \rho_1 u_1^2 A_1 = (p_1 A_1 - p_2 A_2) + p_m (A_2 - A_1)$ (10)

In the above equations, A is the cross-sectional area of the flow, u is the fluid speed, and p_m is the mean pressure.

For an adiabatic flow process, the energy equation (9) becomes $h + \frac{1}{2}u^2 = constant$. For a perfect gas, the equation relating the temperature in the upstream reservoir to the temperature in the orifice (throat) is $c_pT_2 + \frac{1}{2}u^2 = c_pT_1$. Using the sound speed of N_2 (353m/s at 300K) as the gas speed in the orifice, the temperature of the gas flowing through the nozzle is computed to be 240K for a temperature drop of 60K = 60°C from the upstream reservoir temperature of 300K! Again however, real gases are not ideal and the fluid flowing in the leak is not at equilibrium due to viscosity and turbulence.

The throttling process or Joule-Thomson process is an adiabatic process in which enthalpy is conserved as gas flows from one reservoir (where $u = 0$) into another [ref.2, pp43-44]. For a perfect gas, the enthalpy is a function of temperature only and $h = c_pT$. Thus, when a perfect gas undergoes a throttling process, enthalpy conservation ($h_1 = h_2$) implies temperature conservation ($T_1 = T_2$). However, real gases change temperature as a result of the throttling process. The Joule-Thomson coefficient μ can be used to relate the change in temperature to the change in pressure [ref.5, p.1-33].

Joule-Thomson coefficient: $$\mu = -\frac{1}{c_p}\left(\frac{\partial H}{\partial P}\right)_T = \left(\frac{\partial T}{\partial P}\right)_H$$ (11)

Note that if $\mu > 0$, the gas will cool upon expansion and if $\mu < 0$, the gas will become warmer upon expansion. Each gas has a characteristic temperature, the inversion temperature, below which the gas will cool upon expansion and below which the gas warms upon expansion.

Using thermophysical data published by the National Bureau of Standards (now the National Institute of Standards and Technology), the relationship between the change in gas temperature as a function of the pressure change experienced by a gas as it passes through an orifice (a throttle) was determined. Specifically, tabulated data for the enthalpy as a function of pressure at T = 300K were used to compute the Joule-Thomson coefficient (equation 11) for several gases [5, 6, 7, 8]. From this, the change in gas temperature ΔT as a function of pressure change ΔP experienced by the gas was computed. Empirically determined relationships were computed for nitrogen, oxygen, helium, and hydrogen. Nitrogen and oxygen are predicted to cool as they expand (N_2: ~-0.0143°C/psi,
O_2: ~-0.0185°C/psi), while helium and hydrogen are expected to become warmer (He: ~+0.0043°C/psi, H_2: ~+0.0005°C/psi). At 300K, nitrogen and oxygen are below their Joule-Thomas inversion temperatures, whereas helium and hydrogen are above their inversion temperatures.

Note that the Joule-Thomson process relates gas properties in two reservoirs, yet reservoir conditions (flow speed equal zero) will not be met close to the site of the leak. In addition, a real gas leak will not be a truly adiabatic process since heat will be transferred between the gas and the walls of the orifice or crack. Since the gas properties will vary as the gas flows through the orifice or crack, gas dynamics should be considered in more detail.

Heat Transfer

For the temperature of the container at the site of the leak to change, energy transfer must take place. The transferred energy is called heat. There are three forms of heat transfer – conduction, radiation, and convection. Conduction is the transfer of heat from molecule to molecule as kinetic energy is transferred via collisions. Radiation is heat transfer in the form of electromagnetic waves. Convection is the transfer of heat via motion of a group of molecules [ref.9, pp.1.1-1.6]. In a natural process, heat is always transferred from a region of high temperature to a region of low temperature.

Conduction

The general equation describing heat transfer via conduction and that describing the temperature as a function of position and time are given below [ref.10, pp.7 and 11].

General heat conduction: $dQ = -kdA\frac{\partial T}{\partial n}$ (12)

Here, dQ is the heat transferred to the surface element dA, T is the temperature, k is the thermal conductivity of the material, and n is the vector normal to dA. Good thermal conductors, such as metals, have high values for thermal conductivity. Poor conductors, such as gases and insulating materials, have low thermal conductivities.

General temperature relation: $\frac{\partial T}{\partial t} = \alpha \nabla^2 T$ (13)

In this equation, $\alpha = k/\rho c_p$ is the thermal diffusivity of the material, k is the thermal conductivity (assumed independent of temperature for this equation to be valid), ρ is the density, and c_p is the specific heat at constant pressure. This equation assumes no heat is generated within the material. Some special cases of interest are described below [ref.9, Ch.3].

Slab:

A slab of thickness l with walls at T_1 and T_2 approximates a container wall (or the insulation covering a container) having different inside and outside wall temperatures.

Half-Space:

A material of semi-infinite extent with an infinite planar surface is at an initial temperature T_{amb} considered to be the ambient room temperature. At time $t = 0$, the temperature of the planar surface is set to the constant value T_f. This case is an approximation to a leak from an approximately planar crack. When the leak begins, the temperature of the crack's wall is considered to suddenly change to the temperature of the gas flowing through the crack. Of course, more realistically, the wall temperature would vary with time.

Cylindrical hole:

Another relevant case is the cylindrical hole through a material of infinite extent. Again the initial temperature of the material is considered to be the ambient room temperature T_{amb}. At time $t = 0$, the temperature of the cylinder walls is set to T_f. This is an approximation for a leak through a circular orifice.

Equations for these special cases [ref.9, Ch.3] for the fractional temperature change with time and distance from the leak site were solved. It was found that the temperature changes much more quickly with time for a half-space (linear crack) than for a cylindrical hole. Also, a temperature gradient with distance exists near the leak site. The temperature gradient is steeper for the cylindrical hole than for the half-space.

Radiation

A blackbody is an ideal object that absorbs all radiation incident upon it and reradiates in all over a range of wavelengths according to Planck's equation [ref.9, pp.7.1-7.12].

Planck's equation: $$W_\lambda = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)} \times 10^{-6} [Watt / m^2 \mu m] \qquad (14)$$

In this equation, W_λ is the radiant emittance at wavelength λ (in meters), c is the speed of light (3×10^8 m/s), h is the Planck constant ($h = 6.6 \times 10^{-34}$ $J{\cdot}s$), k is Boltzmann's constant ($k = 1.4 \times 10^{-23}$ J/K), and T is the absolute temperature in Kelvin. Integrating Panck's equation over all wavelengths yields the total emittance.

Total emittance: $$W = \sigma T^4 \qquad (15)$$

Here, σ is the Stefan-Boltzmann constant ($\sigma = 5.7 \times 10^{-8}$ $Watt/m^2$). The wavelength at which the maximum emission occurs decreases as the temperature increases according to Wien's Law ($\lambda_{max} = 2898/T$ *microns*). (The shorter wavelength blue part of a flame is hotter than the longer wavelength yellow part of the flame.) Objects that are at room temperature emit most of their radiation at infrared wavelengths. Also, the hotter the object, the more radiation is emitted at all wavelengths. These factors indicate that small changes in temperature will result in large changes in the emittance over a specific wavelength regime.

Real objects are not perfect blackbodies. Instead they can be considered graybodies that are described by the equation below.

Total Emittance: $$W = \varepsilon \sigma T^4 \qquad (16)$$

The emissivity ε varies with material ($0 \le \varepsilon \le 1$). Metals have very low emissivities and very high reflectivities ρ. For opaque objects like metals, $\varepsilon + \rho = 1$.

Convection

Natural convection occurs when a collection of molecules with relatively higher kinetic energy (and thus higher temperature) are buoyed to regions of relatively lower kinetic energy (and thus lower temperatures), transferring their energy in the process. Forced convection is the transfer of energy that occurs when there is forced fluid flow. Such would be the case within the orifice or crack for a gas leak unless the gas leak is extremely slow. The equation describing the convection of heat involving high-speed flows is given below [ref.9, pp1.4-1.6].

Convection: $$Q = hA(T_w - T_{aw}) \qquad (17)$$

Here h is the convective heat transfer coefficient, T_w is the temperature of the surface (the wall of the orifice or crack), T_{aw} ($= T_f + ru^2/2c_p$) is the adiabatic wall or recovery temperature of the flowing gas, T_f is the gas (fluid) temperature, u is the speed of the gas, c_p is its specific heat, and r is the recovery factor (a number between 0.8 and 1 for most gases). Note that this equation is from the gas dynamic energy equation relating the temperature of a perfect gas in a reservoir to that in a flowing fluid. The value of h depends on the geometry, the temperatures of the gas and wall, as well as the temperature gradient within the gas.

In real processes, all three forms of heat transfer will occur. The temperature at each point within the material will no longer change once equilibrium is reached. Once equilibrium is reached, the net flow of heat across a surface equals zero. That is, $Q_{conduction} + Q_{radiation} + Q_{convection} = 0$. This equation will govern the final equilibrium temperature of the leak site. If convection can be neglected, much more heat is transferred initially via conduction than via radiation. When equilibrium is reached, conduction and radiation will balance.

3. EXPERIMENTS AND RESULTS

Camera Specifications

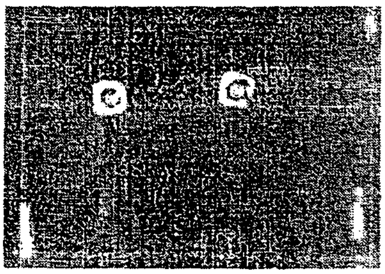
A FLIR Systems ThermaVision IRVM™ 320M infrared camera that is planned for deployment at the Shuttle Launch Complex was used. The camera is sensitive over wavelengths between 7.5μm and 13μm. The image is formed on a 320 × 240 pixel detector and has a field of view of 24° × 18°. To determine if a leak will be detectable with this camera, the minimum temperature change detectable is needed along with the camera's resolution. The manufacturer indicates that temperature differences of 0.1°C are resolved by the camera. Experiments were carried out that suggest that smaller temperature differences can sometimes, though not always, be detected using a technique described later.

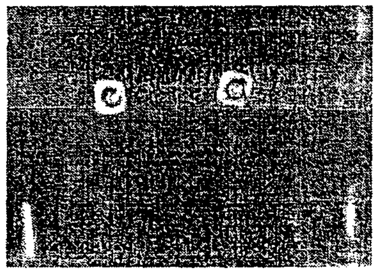
The relationship, $d = 1.851 \times 10^{-3} x$ gives the minimum diameter d of the feature as viewed from a distance x. The constant ($\theta = 3.7 \times 10^{-3}$ *radians*) is the angular size of an object that subtends a 2 × 2 square pixel section of the detector. A 2 × 2 square pixel region was chosen as the minimum area covered by an object that can be reliably detected. A single bright or dark pixel in an image may be due to a bad pixel, not an actual feature. (Of course, if the feature seen in only one pixel moves across the image as the camera is scanned, it can be considered a real feature and not a bad pixel.) From a distance of 0.5m (the camera's closest range), the camera would be able to detect features as small as ~2mm. From 100m, the camera would be able to detect features ~40cm across.

Proof-of-Concept System

In order to detect very small temperature differences, a procedure borrowed from astronomical image analysis was employed. Notice that the two images in Figures 1 and 2 appear practically identical. Both images show two fittings. One is connected via a hose and regulator to a K-bottle of gas. The other is sitting isolated on a plastic stand. Other metal posts are seen as well. Note that the metal appears very bright despite its low emissivity because it has such a high reflectivity and thus reflects nearby thermal sources (including the researcher). One image was made prior to a gas leak and the other during the gas leak. It is not possible to determine which fitting has the leak from a comparison of these two raw images. By producing difference images, very small temperature changes can be detected. Two images are subtracted pixel by pixel to produce a difference image. If all objects in the image maintain a constant temperature between the two images, the difference image will appear featureless. All objects will vanish.

If instead an object cools between the two images, the object will appear darker in the difference image than objects that have not changed temperature. If the object warms between images, it will appear brighter in the difference image than objects that have not changed temperature. Figure 3 shows the difference image made by subtracting a pre-leak image from an image made during the leak. Inspection of the difference image shows that only the fitting on the right experienced a change of temperature, cooling during the leak. All other objects remained at their pre-leak values and thus they do not show up in the difference image.





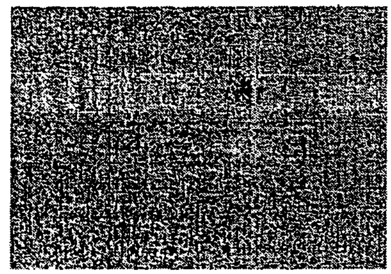


Figure 1 – Raw pre-leak image. Figure 2 – Raw image during leak. Figure 3 – Difference image.
(Leaking – Pre-leak)

Numerous steps were involved in producing the difference images. The camera was connected to a monitor that, in turn, was connected to a DVD recorder. DVD recordings of experiments were made. Images were grabbed off of the DVD recorder and saved as bitmap files using a National Instruments® LabVIEW program written by Dr. Christopher Immer of Dynacs. Off-site, these bitmap files were converted to FITS file format and analyzed using the Axiom Research® Mira AP_{TM} image analysis software. In the field, the system would need to be much less labor intensive and should work in real time. For this reason, Dr. Christopher Immer was asked to write a LabVIEW program that would produce difference images in real-time by subtracting images being acquired from the camera (or DVD) from a stored reference image of the scene made in the absence of leaks. The reference image is displayed along with continuously updated raw acquired images and difference images. This LabVIEW program would need some minor adjustments to perfect it for use in the field. It was, however, used and shown to be effective on recorded images acquired from the DVD.

Experiments
A number of experiments were carried out using K-bottles of pressurized gas. Two different fittings were used in these experiments. One fitting had a small (0.010in diameter) hole drilled in the center of a metal plate at its end. This *end-hole fitting* was attached to the end of the hose from the regulator and impeded the flow of gas through the hose. Another fitting had a somewhat larger hole (0.025in diameter) drilled into its side. This *side-hole fitting* connected a small section of pipe to the hose, extending the length of the hose.

Nitrogen
In one experiment, nitrogen gas was allowed to flow under pressure through the end-hole fitting. Experiments were run for various pressure differences. The change in temperature as a function of time near the site of a leak was measured using a thermoelectric temperature probe. The temperature decreased with time as expected for heat conduction associated with a cylindrical hole.

In addition, the temperature change of the metal near the leak site varied as a function of pressure change, decreasing by less than a degree even with $\Delta P = 50$psi. The observed results for the metal are in fairly good agreement with the predicted results for the gas obtained using the Joule-Thomson coefficient and assuming a throttling process. Certainly, the observed results are in much better agreement with the throttling process predictions than they are with the predictions made assuming static, reversible, adiabatic expansion ($\Delta T \sim -100$°C) or with predictions made by equating reservoir enthalpy with enthalpy plus kinetic energy of the flow within the orifice ($\Delta T \sim -60$°C).

Because a real gas leak will likely have gas in the pipe flowing perpendicular to the gas flowing from the leak site, the side-hole fitting was used. The gas flowed from the hose through the fitting into the pipe. The gas was allowed to flow freely within the pipe and some leaked out of the hole. The temperature of the metal near the orifice (~1-2mm away) was measured. The change in temperature that was measured was comparable to that observed using the end-hole fitting.

The end-hole fitting was used to direct a leak toward the back (unseen) side of External Tank Insulation. A temperature change was noted where the gas flowed around the edges of the insulation. When a hole was pierced through the insulation and the gas directed into the hole, the results were unexpected. A hot spot would appear in raw images when the leak first started. Occasionally the hot spot was absent entirely. Usually, it appeared, sometimes persisting and sometimes quickly dissipating. A 4.2°C temperature rise was observed at one point (as measured by the infrared camera). This hot spot is likely caused by a shock front where the high speed gas from the orifice is drastically slowed and compressed within the hole in the insulation. After the hot spot dissipated, the insulation cooled off at the site of the leak as discovered examining difference images.

Because insulation has a much lower thermal conductivity than metal, the temperature gradients from the leak site are steeper for insulation than for metal. Thus hot or cold features appear much more compact on insulation than on metal.

Additional experiments were carried out using the boil-off from liquid nitrogen as a source of very cold gas. When a hole was pierced into a piece of insulation with cold gas behind it, the hole would appear darker as the cold gas flowed into the hole, cooling the insulation at that spot. Another experiment was performed to see if a cold gas impinging on the back of a slab of insulation would be detectable from the other side of the insulation. A weak flow of cold nitrogen gas boil-off was directed toward the back of a piece of ET insulation and observed with the IR camera from the other side. The leak was detectable through 3cm thick ET insulation even without using the difference imaging technique. The leak was not detectable through 3inch thick ET insulation despite using the difference imaging technique. However, leaks of colder gases may be detectable even through thicker insulation.

Helium

The experiments using the end-hole fitting were performed using helium as the leaking gas. The temperature was measured to decrease. This observation conflicts with predictions of a temperature increase based on the conservation of enthalpy in an adiabatic throttling process. When the leak was from the side-hole fitting, the temperature near the fitting (~1 – 2 mm) was observed to increase ($\Delta T < 1$°C). The observed temperature change as a function of pressure change is in fair agreement with the predicted values using the Joule-Thomson coefficent and assuming a throttling process. However, different images of these experiments show a cold spot at the site of the leak, not a hot spot as was measured by the temperature probe. The temperature of the pipe was measured to increase and is seen to become brighter during the leak process. Perhaps this heating is due to the friction between the gas and the pipe walls. Or, perhaps it is due to heating caused by expansion of the gas from the high pressure side of the regulator to the low pressure side ($\Delta P \sim 1500$psi).

The temperature probe was placed in the path of the flow near the end-hole fitting. When the flow is impeded by the temperature probe, the stagnation temperature is measured. That is, the temperature inside the reservoir where the flow rate is zero is measured because the gas is compressed to its reservoir conditions. The temperature increased very slightly for the gas leaking from the end-hole fitting (~0.2°C). In contrast, the measured temperature decreased dramatically (~6 - 8°C within a few seconds) when the temperature probe was placed in the flow escaping from the side-hole fitting. These results suggest that the stagnation temperature for the freely flowing gas is lower than for the gas impeded by the end-hole fitting. The gas dynamic energy equation (9) indicates that enthalpy is reduced from its reservoir conditions when gas is flowing. Perhaps the reduced enthalpy corresponds to a decrease in temperature below reservoir conditions for the flowing gas. Indeed this would be the case for a perfect gas.

More theoretical work is needed to better understand the temperature behavior of a gas expanding from a leak site. Specifically, the thermodynamics and gas dynamics of the flow through the orifice or crack need to be more thoroughly investigated.

4. CONCLUSIONS

Theoretical progress was made toward describing the temperature of the leaking gas via the laws of thermodynamics and gas dynamics. A gas leak is considered a throttling process with the non-ideal gas flowing through a resistance from one reservoir into another. Depending on the gas, the temperature of the gas can increase or decrease with expansion. Experiments are in fairly good agreement with theory, though there are still some perplexing issues to be addressed. To make further progress toward understanding the temperature within the flow through the leak site, gas dynamics need to be considered more carefully. The theory describing the heat transfer between the gas and the container wall was considered. Neglecting convection, conduction is a far more important heat transfer mechanism than radiation when the leak first begins, though over time equilibrium will be approached for which there will be balance between conduction and radiation. The convection will be forced convection of the fluid flow and should be considered in more detail. It was not considered in detail here because of the uncertainly of the value for the convective heat transfer coefficient. This coefficient is experimentally determined for specific situations.

The image analysis technique of difference imaging was applied to images from the infrared camera, allowing detection of temperature changes that would otherwise be lost in the background noise. A prototype system was developed that uses LabVIEW to generate these difference images in real time. Such a system should allow for on-the-spot detection of small temperature changes caused by a leaking gas. (This LabVIEW application was written by Dr. Chris Immer of Dynacs.)

Experiments suggest that the Infrared Thermal technique would be viable when large leaks are present through an uninsulated metal pipe or fitting. These leaks however would likely make their presence known in other, more obvious ways. Leaks of cryogenic material may be detectable when the leak site is covered with insulation. If the leaking gas flows through a hole or crack in the insulation, the hole or crack will appear much cooler at the leak site. Even without a hole or crack in the insulation, the insulation near the leak site may cool by a detectable amount. The thinner the insulation, the more likely it will be to detect the leak. Also, leaks of cooler cryogens are more likely to be detected through thicker insulation.

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