A hybrid thermal video and FTIR spectrometer system for rapidly locating and characterizing gas leaks

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ABSTRACT

Undiscovered gas leaks, known as fugitive emissions, in chemical plants and refinery operations can impact regional air quality and present a loss of product for industry. Surveying a facility for potential gas leaks can be a daunting task. Industrial leak detection and repair programs can be expensive to administer. An efficient, accurate and cost effective method for detecting and quantifying gas leaks would both save industries money by identifying production losses and improve regional air quality. Specialized thermal video systems have proven effective in rapidly locating gas leaks. These systems, however, do not have the spectral resolution for compound identification. Passive FTIR spectrometers can be used for gas compound identification, but using these systems for facility surveys is problematic due to their small field of view. A hybrid approach has been developed that utilizes the thermal video system to locate gas plumes using real time visualization of the leaks, coupled with the high spectral resolution FTIR spectrometer for compound identification and quantification. The prototype hybrid video/spectrometer system uses a sterling cooled thermal camera, operating in the MWIR (3-5 μm) with an additional notch filter set at around 3.4 μm, which allows for the visualization of gas compounds that absorb in this narrow spectral range, such as alkane hydrocarbons. This camera is positioned alongside of a portable, high speed passive FTIR spectrometer, which has a spectral range of 2 – 25 μm and operates at 4 cm^{-1} resolution. This system uses a 10 cm telescope foreoptic with an onboard blackbody for calibration. The two units are optically aligned using a turning mirror on the spectrometer's telescope with the video camera's output.

Keywords: gas detection, FTIR, thermography, infrared, spectroscopy,

1. INTRODUCTION

Toxic or hazardous air pollutants (HAPs) are an important environmental issue. Exposure to these classes of compounds has been linked to cancer and other serious health effects [1]. These compounds also react in the atmosphere to form ozone which also has adverse health effects to exposed populations [2]. Many industrial facilities emit compounds that are listed as HAPs or are implicated in regional air quality problems such as ozone and particulate matter formation.

Federal and state fugitive emission monitoring programs are currently based on EPA Method 21. This method involves the use of an organic vapor analyzer to monitor for a leak at the leak interface of fugitive emission components [3]. Monitoring is performed by comparing the hydrocarbon analyzer reading, or screening value, with the leak definition in the applicable regulation. Generally if a component is found to be leaking, an attempt to repair the component must be completed within a specified timeframe. The actual number of components to be tested in a refinery or chemical plant can be quite large, making Method 21 monitoring both time intensive and expensive. The use of remote sensing systems such as optical imagers offers an operator the ability to monitor components from a distance and identify, in some cases instantaneously, leaking components (of a sufficient mass) within the line of sight of the optical imager. The remote sensing and instantaneous detection capabilities of optical imaging technologies allow an operator to scan areas containing tens to hundreds of potential leaks, thus eliminating the need to visit and manually measure all potential leak sites.

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A 1997 API study of 11.5 million Leak Detection and Repair (LDAR) program monitoring values showed that less than 1 percent of potential leak sources at refineries contribute over 90 percent of fugitive emissions [4]. Finding these few leaks in a cost-effective way is a challenge. Current programs require operators to visit and measure each of the thousands of regulated components at industrial plants. While current LDAR programs have been successful in identifying and significantly reducing fugitive emissions from regulated components, monitoring procedures outlined by the current rule are time consuming, labor intensive and costly. A large U.S. refinery can spend $1M annually in monitoring, repair, and record keeping. Alternative remote sensing technologies are now available that are more cost-effective than using Method 21, but their performance needs to be verified [5].

While efficient gas leak detection is necessary and useful, the information required by the air quality community is an estimate of the mass flux of a leak, which is a quantification of the mass of compound per unit time. This project seeks to demonstrate a viable system that can retrieve gas leak quantification using commercially available technologies.

2. METHODOLOGY

This project utilizes two similar remote sensing technologies to create a single sensing package that leverages the strengths of each system. Specially modified thermal video camera systems are used to perform wide area surveys for gas release detection. These systems have proven effective in rapidly locating gas leaks from a wide variety of industrial activities [6]. These systems, however, operate as broadband single channel imagers and do not have the spectral resolution for compound identification. Passive FTIR spectrometers can be used for gas compound identification, but using these systems for facility surveys is problematic due to their small field of view. This hybrid approach optically boresights the thermal camera and the FTIR for gas leak quantification.

2.1 Thermal video camera

This prototype hybrid video/spectrometer system uses a sterling cooled thermal camera with an InSb focal plane, operating in the MWIR (3-5 μm) with an additional notch filter set at 3.4 μm. This filter allows for the visualization of gas compounds that absorb in this narrow spectral range, such as alkane hydrocarbons. The camera, the GasfindIR, is produced by FLIR Systems [7].

2.2 FTIR spectrometer

The FTIR subsystem uses a single pixel, passive, and portable system built by D&P Instruments. The core of this spectrometer is the proprietary D&P rotary interferometer. This contains infrared optics, beam splitter, and a rotating refractor assembly. Input light passes through the fore optics, an aperture, and a lens (which also seals the unit) into the interferometer. The rotating refractor is servo driven at a constant speed, producing the interference patterns. Because of the rotary nature of the scan, high spectral rates can be achieved, 25 scans per second for this system. The modulated output light passes through a focusing lens (which also seals the unit) onto an infrared detector in a liquid nitrogen (LN2) Dewar. The detector is dual element, consisting of the standard Mercury Cadmium Telluride (HgCdTe, or MCT) in combination with an Indium Antimonide (InSb). This dual detector has a spectral range of approximately 1.7 to 25 micrometers. The FTIR has an adjustable spectral range of 4, 6, and 16 cm^{-1}. At high spectral resolutions and short wavelength ranges, a temperature controlled laser diode (LD) is used to provide a reference for the sampling electronics, and thus the wavelength calibration for the spectrum. This unit uses a 4 inch fore-optic that has a 1.2 degree field of view. This fore-optic allows through-the-lens viewing of targets. Calibration is accomplished using on-board blackbodies. A 1 inch diameter blackbody element is located underneath the 4 inch fore-optic mount, with a motor-driven mirror for viewing. The benefit of this is that the FTIR subsystem can be calibrated easily in the field. The tradeoff for this arrangement is that the blackbody does not calibrate the final mirror.

2.3 Data Collection and Processing

The data processing and FTIR spectrometer control is accomplished by a rugged zed tablet style PC. This unit also powers the FTIR subsystem. The PC accepts the raw signal from the FTIR and the video feeds from both the thermal camera and from a miniaturized camera mounted on the FTIR spectrometer fore-optic. Both video feeds can be view simultaneously for optical alignment of both systems. The spectrometer signal and camera video can be recorded to the harddrive for subsequent data analysis. Both the thermal camera and the spectrometer are mounted on 3 degrees-of-freedom stages so that fine tuning of the alignment can occur since the range to the target can vary.

2.4 Data Analysis

Gas leak quantification is accomplished by determining 1) the presence of a leak; 2) the flow rate of the leak; 3) the identity of the compound(s) present, and 4) the concentration of the specie(s) present. Step 1 is determined by real time visualization of the image scene from the thermal camera. In most cases the scene background is warmer than the leaking gas so the operator is looking for absorbing effluents. These appear black in the scene. Recording of the camera video, together with knowledge of the range of the target gas leak to the camera (used to determine image pixel size for image measuration), is used to determine the flow rate of the leak using the time series of observations. The FTIR spectrometer is used to collect a high spectral resolution point measurement within the gas leak plume. This point measurement is compared to a library of laboratory of gas phase FTIR measurements for compound identification using stepwise regression [8]. Once the compound is determined and therefore the molecular weight is known, path integrated concentration can be calculated by knowing the volume of the plume [9, 10]. A simple assumption is made as to the volume of the leak by using a conical volume where the width of the plume is the same as the depth. After the appropriate conversion from standard to ambient temperature and pressure, the variables are multiplied together to arrive at an estimate of emission rate for the leak at the time it was observed and measured.

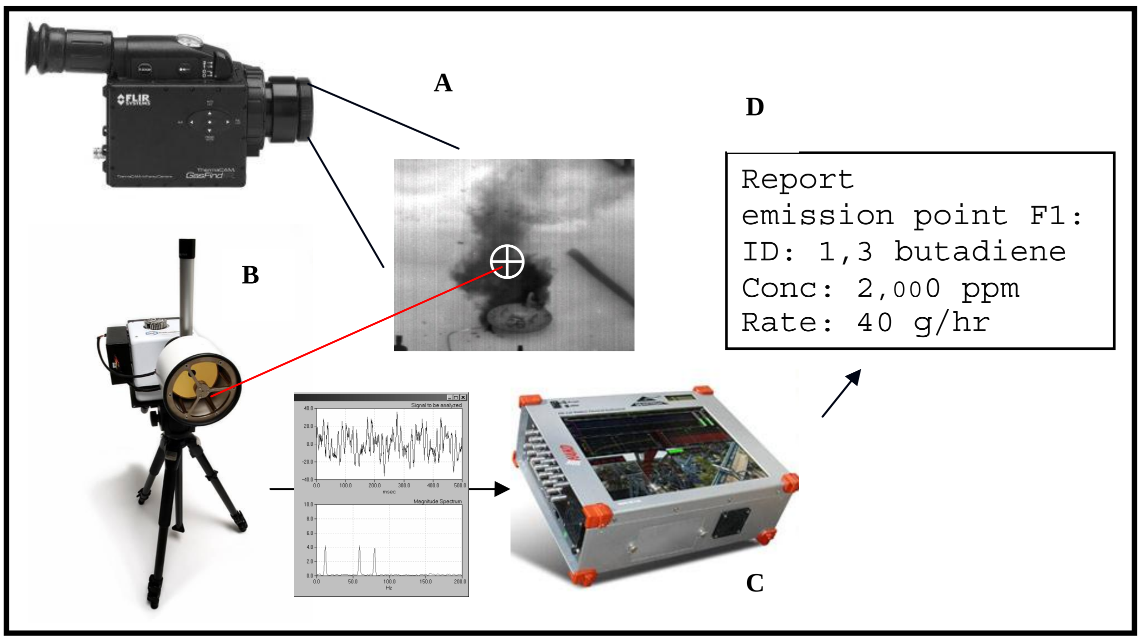

Figure 1: Concept of operations for prototype unit. A) facility is surveyed using thermal video camera and leak is detected (in this case a faulty sample cover on a floating roof tank containing gasoline). The camera records the leak and the field of view is centered such that the dense part of plume is in the middle of the frame. B) FTIR spectrometer measures spectra of background, then spectra of gas plume. C) The interferograms are sent to computer and processed. A ratio (sample/background) is calculated and used to identify the compound against the library. Leak velocity and volume is calculated from the video, concentration is estimated and D) an emission report is generated and data is saved to database.

The final configuration for the prototype system will have the thermal camera mounted alongside the FTIR spectrometer, using a flip mirror to align the spectrometer field of view with the center of the thermal camera's field of view. While the final build has not been accomplished in time for this paper, the notional concept of operations is presented (figure 1).

3. DISCUSSION

EPA's Environmental Technology Verification (ETV) program has a new element, the Environmental and Sustainable Technology Evaluations program. This program seeks to develop testing protocols and verifies performance on innovative and commercial-ready technologies with potential to address high-risk environmental problems. In 2006, an ESTE project, "Verification of Portable Optical and Thermal Imaging Devices for Leak Detection at Petroleum Refineries and Chemical Plants" was undertaken to verify the performance of remote sensing leak detection technologies to support the new LDAR alternative work practice described previously [11]. The hybrid system will be used in conjunction with this testing to help validate the technologies as well as further the research into portable remote sensing technologies for atmospheric measurements. Programs related to air quality monitoring, surveillance, and homeland security can all benefit from this research.

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