A COMBINED ON-LINE ACOUSTIC FLOWMETER AND FLUOROCARBON COOLANT MIXTURE ANALYZER FOR THE ATLAS SILICON TRACKER*

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Abstract

An upgrade to the ATLAS silicon tracker cooling control system may require a change from C_3F_8 (octafluoro-propane) to a blend containing 10-30% of C_2F_6 (hexafluoro-ethane) to reduce the evaporation temperature and better protect the silicon from cumulative radiation damage with increasing LHC luminosity.

Central to this upgrade is a new acoustic instrument for the real-time measurement of the C_3F_8/C_2F_6 mixture ratio and flow. The instrument and its Supervisory, Control and Data Acquisition (SCADA) software are described in this paper.

The instrument has demonstrated a resolution of 3.10^{-3} for C_3F_8/C_2F_6 mixtures with $\sim20\% C_2F_6$, and flow resolution of 2% of full scale for mass flows up to $30 gs^{-1}$. In mixtures of widely-differing molecular weight (mw), higher mixture precision is possible: a sensitivity of $< 5.10^{-4}$ to leaks of C_3F_8 into the ATLAS pixel detector nitrogen envelope (mw difference 160) has been seen.

The instrument has many potential applications, including the analysis of mixtures of hydrocarbons, vapours for semi-conductor manufacture and anaesthesia.

INTRODUCTION

An upgrade to the ATLAS silicon tracker cooling control system may require a change from the present C_3F_8 evaporant (molecular weight = 188) coolant [1] to a blend with 10-30% of the more volatile C_2F_6 (mw = 138). Central to this upgrade a new acoustic instrument for real-time measurement of C_3F_8/C_2F_6 mixture ratio and flow has been developed, exploiting the phenomenon that the sound velocity in a binary gas mixture at known temperature and pressure depends solely on the molar concentrations of its components. This instrument builds upon the technology of ultrasonic gas analysis used in Cherenkov radiation detectors since the 1980s [2] and measures the molar concentrations of the two fluorocarbon components in the recirculating exhaust vapour following the evaporative cooling of the silicon tracker.

In the custom electronics sound bursts are sent via ultrasonic transceivers[◊] parallel and anti-parallel to the gas flow. A fast transit clock is started synchronously with burst transmission and stopped by over-threshold received sound pulses. Rolling average transit times in both directions, together with temperature and pressure, enter a FIFO memory and are passed to a supervisory computer via RS232 or CANbus.

Gas mixture is continuously analyzed using SCADA software implemented in PVSS-II [3], by comparing the average sound velocity in both directions with stored *velocity vs. concentration* look-up tables. These tables may be created from prior measurements in calibration mixtures or from theoretical thermodynamic calculations. Flow rates are calculated from the difference in transit time in the two directions. In future versions these calculations may be made in an on-board microcontroller.

Within the ATLAS experiment the instrument has been used for flowmetry and mixture analysis of C_3F_8/C_2F_6 blends and also as a sensitive detector of leaks of the present C_3F_8 evaporative coolant into the ATLAS pixel detector nitrogen envelope.

MECHANICS

The mechanical envelope and ultrasonic transducer mounting are illustrated in Fig. 1. The transducers are mounted around 660 mm apart in a flanged stainless steel tube of overall length 835mm. The temperature in the tube is monitored by six NTC thermistors – ($100 k\Omega$ at 25ºC) - giving an average temperature measurement uncertainty of better than ±0.3C. Pressure is monitored with a transducer having a precision better than ±15mbar.

◊ Model 600 50kHz instrument grade ultrasonic transducer: SensComp, Inc. 36704 Commerce Rd. Livonia, MI 48150, USA
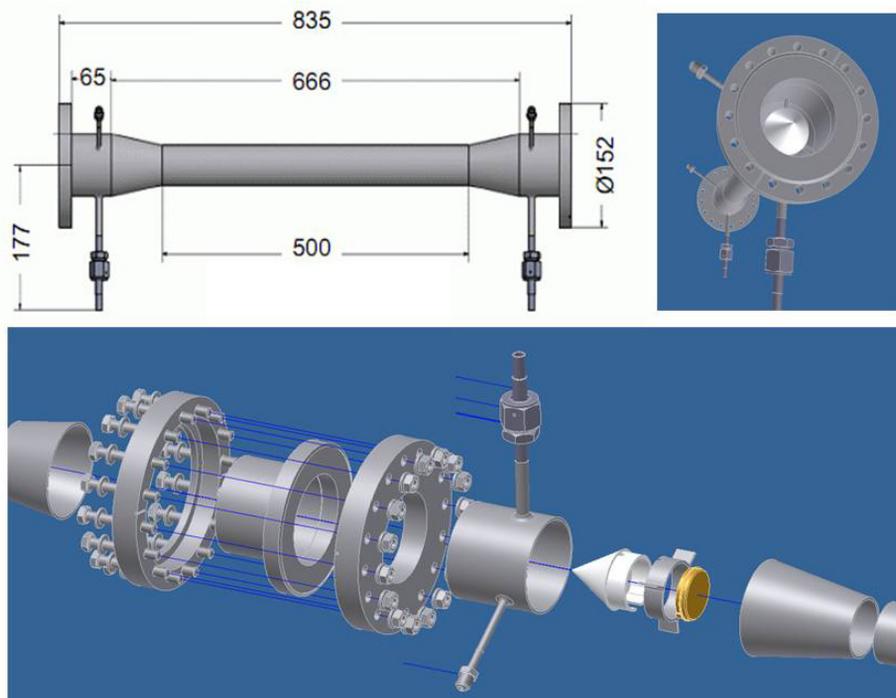
Figure 1: Views of the instrument mechanical envelope, showing an ultrasonic transducer, its mounting and axial flow-deflecting cone, together with tubes for pressure sensing and the evacuation and the injection of calibration gas.

ELECTRONICS

The custom electronics is based on a Microchip ® dsPIC 16 bit microcontroller. This generates the 50kHz sound burst signals emitted by the transducers and includes a 40 MHz transit clock that is stopped when an amplified sound signal from a receiving transducer crosses a user-definable comparator threshold.

The HV bias for the vibrating foils of the capacitive transducers, settable in the HV range 180-360V, is generated by a DC-DC converter. When transmitting, a transducer is excited with a train of (1-8) HV square wave pulses, built using the 50kHz LV pulses from the microcontroller and the DC-DC converter output. When receiving, a transducer is biased with a flat HVDC bias and its signal passed to an AD620N amplifier followed by a comparator.

Sound transit times are computed from the number of 40MHz pulses counted between the rising edge of the first transmitted 50KHz sound pulse, and the time the first received, amplified sound pulse crosses the comparator threshold. Transit times, computed alternately in the two transmission directions are continuously entered into an internal FIFO memory. When a measuring cycle is requested by the supervisory computer a time-stamped running average from the 300 most recent transit times in each direction in the FIFO memory is output, together with the average temperature and pressure, at a rate of up to 20 averaged samples per second.

In addition to the I/O connectivity for communications,

the ultrasonic transducers, pressure and temperature sensors, two (4-20 mA) analog outputs provide feedback for adjustment of the C_3F_8/C_2F_6 mixing ratio by the external gas mixture control system.

CALIBRATION AND MEASUREMENTS IN PURE C_2F_6 AND C_3F_8

For high precision mixture and flow analysis the uncertainty in the sound flight distance should be minimized. It is necessary to perform a one-time transducer foil inter-distance calibration. The most convenient method is to calculate this distance from an average of measured sound transit times with the tube filled with a pure gas (or gases) having well-known sound velocity dependence on temperature and pressure. We initially made calibrations using xenon, whose sound velocity and mw (175.5 ms^{-1} at 20ºC, 137 units) are closest [4], [5] to those of the fluorocarbon mixtures in the ATLAS application [1], and whose thermo-physical behaviour is that of an ideal gas. Later calibrations demonstrated sufficient precision with nitrogen and argon, which are considerably cheaper and more widely available. The average uncertainty in transducer inter-distance measured in this way is ± 0.1mm.

Multiple measurements were made in pure C_3F_8 and C_2F_6 at around 19.5°C, with pressure in the range 0.4 - 2.7bar$_{abs}$[6]; conditions expected in an acoustic vapour analyzer installed in the (superheated) vapour return path some tens of metres from the evaporative zone within the ATLAS silicon tracker. The average difference between measured sound velocities and the predictions from a PC-

SAFT[□] equation of state (EOS) [6], [7], [8]) was less than 0.04% in both fluids.

SCADA & ANALYSIS SOFTWARE

The specialized software for the gas analyzer operation is coded as a standalone component in the PVSS II, v3.8 SCADA environment [3], [6]; a standard at CERN. Its main tasks include:

- vapour flow rate determination;
- sound velocity and molar vapour mixture concentration determination;
- RS232 or CANOpen communication, to start and stop the measuring cycle, and to request time-stamped bidirectional sound transit times, temperature and pressure data from the instrument FIFO memory;
- calculation and transmission of the set-points for the analog (4-20mA) output signals for C_3F_8/C_2F_6 ratio adjustment in the external cooling plant;
- visualization via a Graphical User Interface (GUI);
- archiving of sound transit times, velocities, flow, mixture composition, temperature and pressure into a local and/or remote data base.

The vapour flow rate is calculated from the sound transit times measured parallel, t_{down}, and anti-parallel, t_{up}, to the flow direction, according to the following algorithm:

$$t_{down} = L / (c + v) , \quad t_{up} = L / (c - v) \quad (1)$$

where v is the linear flow velocity (ms^{-1}), c the speed of sound in the gas and L the distance between transducers.

The gas volume flow V (m^{3}s^{-1}) can therefore be inferred from the two transit times by:

$$V = L/2 * A * ((t_{up} - t_{down})/ t_{up*} t_{down}) \quad (2)$$

where A is the internal cross sectional area of the axial flow tube between the two ultrasonic transducers (m^2).

The sound velocity c can also be inferred from the two transit times via:

$$c = L/2 * ((t_{up} + t_{down})/ t_{up*} t_{down}) \quad (3)$$

It can be seen from Eqs. (1) – (3) that knowledge of the temperature of the gas is not necessary for flowmetry.

Figure 2 shows the linearity of the ultrasonic flowmeter element of the instrument in C_3F_8 vapour at 20°C through comparison with a Schlumberger Delta G16 gas meter, at flows up to 230 lmin^{-1} (~30 gms^{-1}); the maximum mass flow in the presently-available C_3F_8/C_2F_6 blend circulation system. The average precision is 2% of full scale.

The calculation of gas mixture molar ratio requires the use of ("c, t, p") look-up tables of gas mixture composition in the binary mixture to be analyzed, corresponding to sound velocities, c, at known temperatures, t, and pressures, p).

Look-up table data may be gathered from prior measurements in calibration mixtures or from theoretical data. Fig. 3 compares measured sound velocities in calibrated mixtures of C_3F_8 and C_2F_6 with sound velocity predictions at 19.2°C from a PC-SAFT EOS [7], [8] and the refrigerant-oriented extended Benedict-Webb-Rubin

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[□]Purturbed-Chain Statistical Associating Fluid Theory
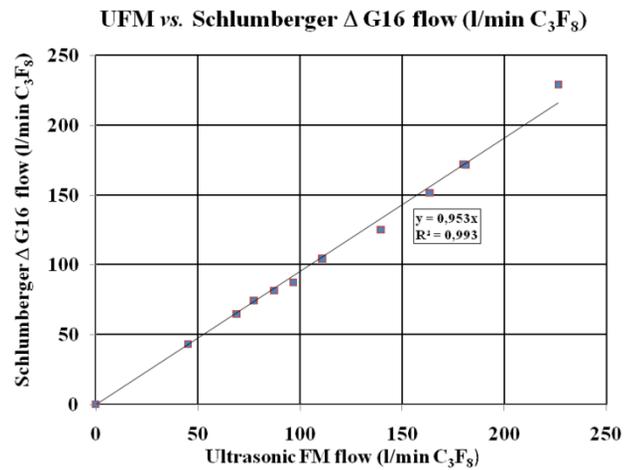
Figure 2: Ultrasonic flowmeter linearity comparison with a Schlumberger Delta G16 gas meter: C_3F_8 vapour.

(BWR) EOS used in the NIST REFPROP thermo-dynamic software package [9]. The (0→35%) C_2F_6 concentration range spans the region of thermodynamic interest to the ATLAS silicon tracker cooling application.
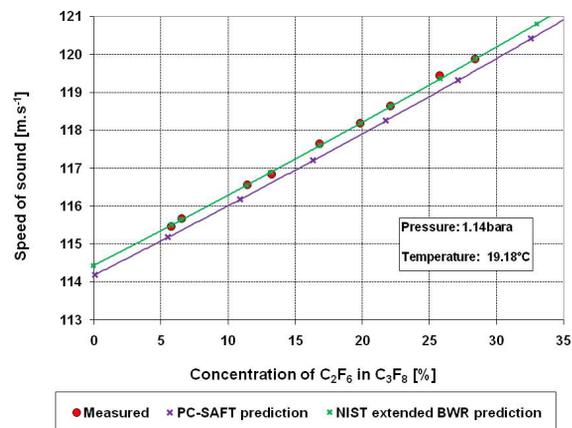
Figure 3: Comparison between measured sound velocity data and theoretical predictions in C_3F_8 / C_2F_6 mixtures.

The mixtures of C_3F_8 and C_2F_6 shown in Fig. 3 were set up by partial pressure ratio in the previously-evacuated tube, creating a molar ratio binary gas mixture. The transducer foil inter-distance had been previously established using the above-described gas calibration procedure, to a precision of ± 0.1mm.

The average difference between measured and the PC-SAFT and NIST-REFPROP predicted sound velocities in mixtures with (0→35%) C_2F_6 in C_3F_8 were respectively 0.5% and 0.05% at pressures around 1 bar$_{abs}$ and temperatures in the range 15-25°C. It is recognised that the present version of the NIST-REFPROP [5] database is the more precise in predicting the thermophysical properties of mixtures of saturated fluorocarbons (having molecular structures of the form $C_nF_{(2n+2)}$).

The precision of mixture determination, $\delta(mix)$, at any concentration of the two components is given by;

$$\delta(mix) = \delta c/m \quad (4)$$

where m is the local slope of the sound velocity/ concentration curve and δc is the uncertainty in the sound velocity measurement - dependent on transit time resolution, transducer spacing and uncertainties in the measured temperature and pressure ($\pm 0.2°C$, ± 5mbar in this instrument) or variations between these parameters and the (t, p) values of the nearest (c, t, p) curve in the calibration database. For example, at a sound velocity of ~ 118 ms^{-1}- corresponding to a blend of 20% C_2F_6 in C_3F_8 (Fig. 3) - the combined measurement uncertainties result in a sound velocity uncertainty of 0.06 ms^{-1}, yielding a concentration uncertainty $\sim 0.3\%$ at 20%C_2F_6, where the slope of the velocity/ concentration curve is ~ 0.18ms^{-1}%$^{-1}$.

The present software [6] uses a pre-loaded look-up table of NIST-REFPROP BWR-generated sound velocity with 0.25% granularity in C_3F_8/C_2F_6 molar mixture and covering the expected range temperature and pressures (16.2$\rightarrow$26.1°C, 800$\rightarrow$1600mbar$_{abs}$ with 0.3°C & 50mbar granularity). The algorithm calculates mixture composition by minimizing a quadratic norm, n_i, for each (c_i, T_i, P_i) table entry:

$$n_i = k_1(p_{i,\,table} - p_{running\,average})^2 + k_2(t_{i,\,table} - t_{running\,average})^2$$
$$+ k_3(c_{i,\,table} - c_{running\,average}) \qquad (5)$$

where $k_{1,2,3}$ are sensitivity parameters [6] and p, t & $c_{running\,average}$ are real-time outputs of the instrument FIFO memory.

A new software version [6] will implement a database covering a much larger c, T, P range and will allow "zooming" to smaller sub-tables (O$\sim$10,000 c, T, P data points), corresponding to a narrower process range - as in the present application.

In a second application related to the ATLAS evaporative cooling system, we use ultrasonic binary gas analysis to detect low level C_3F_8 vapour leaks into the N_2 environmental gas surrounding the ATLAS silicon tracker. Figure 4 compares measured sound velocities in mixtures containing up to 10% C_3F_8 in N_2 with sound velocity predictions from the PC-SAFT EOS°. A reduction in sound velocity of 0.6 m/s from the base velocity of $\sim$351 ms^{-1} was seen during a long term ($>$ 1 year study). From the $\sim$-12.27ms^{-1}%$^{-1}$ average gradient of the sound velocity-concentration curve at trace C_3F_8 concentrations in the range 0$\rightarrow$0.5% (Fig. 4) this sound velocity indicated, using Eq.(4), a C_3F_8 leak ingress of 0.049%, later traced to one of 204 evaporative cooling circuits into the ATLAS silicon tracker nitrogen envelope.

CONCLUSION

We have developed a combined, real-time ultrasonic flowmeter and binary gas analyzer, whose accuracy was determined following calibration in pure reference gases - by a set of measurements in C_3F_8/C_2F_6 blends. Sound velocity measurements were within 0.05% of the predictions of the NIST-REFPROP package, allowing mixture resolution of 0.3% in the (0-35% C_2F_6) concentration range of interest for the ATLAS silicon tracker.
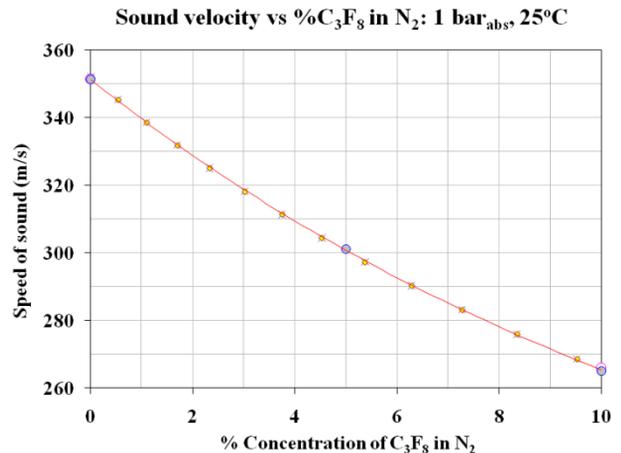
Figure 4: Comparison of sound velocity measurements (°) and PC-SAFT predictions (◊) in C_3F_8/N_2 mixtures.

The instrument presently analyzes vapour mixtures of C_2F_6/C_3F_8 and N_2/C_3F_8, respectively having a molecular weight difference of 50 and 160 units, the mixture resolution being seen to increase with the mw difference of the components. The instrument has applications in the analysis of hydrocarbon-air mixtures, refrigerant-air mixtures (leak detection), vapour mixtures for MOCVD semiconductor manufacture and anaesthetic gas mixtures.

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