SIMULTANEOUS ON-LINE ULTRASONIC FLOWMETERY AND BINARY GAS MIXTURE ANALYSIS FOR THE ATLAS SILICON TRACKER COOLING CONTROL SYSTEM.

M. Doubek*, V. Vacek, M. Vitek, Czech Technical University, Technická 4, 166 07, Czech Republic
R. Bates, A. Bitadze, SUPA School of Physics and Astronomy, University of Glasgow, G627QB UK
M. Battistin, S. Berry, J. Berthoud, P. Bonneau, J. Botelho-Direito, G. Bozza, O. Crespo-Lopez, E. Da Riva, B. DiGirolamo, G. Favre, J. Godlewski, D. Lombard, L. Zwalinski, CERN, 1211 Geneva 23, Switzerland
N. Bousson, G. Hallewell, M. Mathieu, N. Langevin, A. Rozanov, Centre de Physique des Particules de Marseille, 163 Avenue de Luminy, 13288 Marseille Cedex 09, France
G. Boyd, Department of Physics & Astronomy, University of Oklahoma, Norman, OK 73019, USA
C. Degeorge, Indiana University, Department of Physics, Bloomington, IN 47405-7015, USA
C. Deterre, Deutsches Elektronen-Synchrotron , Notkestraße 85, D-22607 Hamburg, Germany
S. Katunin, B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI), 188300, Russia
S. McMahon, STFC Rutherford Appelton Laboratory – Harwell Oxford, Didcot OX11 OQX, UK
K. Nagai, Department of Physics, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria
D. Robinson, Department of Physics and Astronomy, University of Cambridge, Cambridge, UK
C. Rossi, Department of Mechanical Engineering - Thermal Energy and Air Conditioning Division, Università degli Studi di Genova Via All'Opera Pia 15a - 16145 Genova, Italy

Abstract

We describe a combined ultrasonic instrument for continuous gas flow measurement and simultaneous real-time binary gas mixture analysis. The analysis algorithm compares real time measurements with a stored data base of sound velocity vs. gas composition.

The instrument was developed for the ATLAS silicon tracker evaporative cooling system where C_3F_8 refrigerant may be replaced by a blend with 25 % C_2F_6, allowing a lower evaporation temperature as the LHC luminosity increases.

The instrument has been developed in two geometries. A version with an axial sound path has demonstrated 1 % of full scale precision for flows up to 230 l/min. A resolution of 0.3 % is seen in C_3F_8/C_2F_6 molar mixtures, and a sensitivity of better than 0.005 % to traces of C_3F_8 in nitrogen, during a >1½ year continuous study in a system with sequenced multi-stream sampling.

A high flow version has demonstrated a resolution of ± 1.9 % of full scale for flows up to 7500 $l.min^{-1}$.

The instrument can provide rapid feedback in control systems operating with refrigerants or binary gas mixtures in detector applications. Other uses include anaesthesia, analysis of hydrocarbons and vapour mixtures for semiconductor manufacture.

INTRODUCTION

Several versions of a novel on-line ultrasonic instrument have been developed [1-4] for use in the fluorocarbon evaporative cooling system of the ATLAS silicon tracker. These allow operation ranging from low-flow leak detection to intermediate and high volume flowmetry with simultaneous binary gas mixture analysis. In these instruments the difference in transit time of ultrasound pulses sent in opposite directions is proportional to gas flow rate while their average can be used with the sound path length to calculate the sound velocity. Mixture composition is then calculated by comparison with stored velocity-composition tables, since at known, measured temperature and pressure the sound velocity is a unique function of the relative concentrations of the two components.

Two axial sonar instruments, (Fig. 1: geometry “1”), with 490 mm sound paths analyze gas aspirated at constant low flow (~0.1 $l.min^{-1}$) from the nitrogen envelopes of the ATLAS silicon pixel and SCT detectors for trace concentrations of C_3F_8 coolant vapour. Temperature stability of ± 0.2 °C can be achieved in the 60 mm inner diameter (ID) sound tubes by liquid circulation in the double wall stainless steel tube.

Sound velocity is continuously monitored with gas temperature and pressure in a supervisory computer running PVSS-II [2, 5]. For the pixel detector an instrument has been in continuous operation for over 18 months [2]. The sound velocity measurement precision [1] of ± 0.05 ms^{-1} gives sensitivity to C_3F_8 of better than ± 0.005 %, and has allowed the identification of leaking cooling circuits. A third instrument for analysis of gas from the Transition Radiation Tracker (TRT) is foreseen.

We have developed a combined flowmeter/analyser (Fig. 1: geometry “2”), with a sound path aligned with the gas flow. Calibration with two reference flowmeters demonstrated its linearity, with an *rms* precision of ± 1 % of full scale for flows up to 230 l/min [1]. The gas flow is streamlined around the transducers by cones machined

*Communicating author

ISBN 978-3-95450-139-7

from PEEK. The stainless steel envelope is welded from sections of 65 mm ID tube - in which the transducers are centred with a linear separation of 660 mm, reduction cones and a central 50 cm tube of 44 mm ID. The envelope uses UHV flanges and is rated for operation between vacuum and 20 bar. Six internal NTC thermistors are fitted, together with ports for evacuation and the injection of calibration gas.

The sound velocity measurement precision of ± 0.05 ms^{-1} allowed mixture determination to a precision of ± 0.3 % [1] in C_3F_8/C_2F_6 blends containing up to 25 % C_2F_6. Such blends are of interest since they allow lower evaporation temperatures than with the presently-used C_3F_8; this would help protect the silicon substrates of the ATLAS inner tracker from leakage current - induced thermal runaway as the future luminosity of the LHC increases.

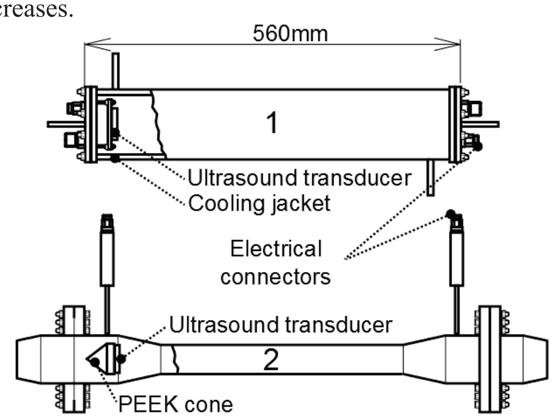

Figure 1: Axial binary gas analyzers/flowmeter.

We have developed a flowmeter/analyser with a sound path crossing the gas flow at 45° [1,2] for operation in fluorocarbon vapour flows up to 20000 l.min^{-1} (Fig. 2) through a tube of 133.7 mm ID. The positioning of the ultrasonic transducers to minimize pressure drop and turbulence in the sound path was the subject of an extensive CFD simulation [1]. The final instrument, constructed in stainless steel with a total sound path around 800 mm, has been recently calibrated in air in flows up to 10 ms^{-1}, demonstrating linearity with *rms* precision of ± 2.3 % of full scale.

This instrument will be used as a high-flow flowmeter in the new ATLAS thermosiphon fluorocarbon recirculator [6] (section III). The transducers can be isolated from the main flow with ¼ turn ball valves, allowing replacement with no disruption to the cooling plant. The volumes outboard of the valves would then be evacuated through dedicated ports in the UHV flanges carrying the transducers, to protect the system from air pollution. The ball valve orifices have the same inner diameter as the sound tubes to avoid reflections. The envelope is rated between vacuum and 20 bar.

Since the condenser of the new thermosiphon system will operate below atmospheric pressure, air ingress will be monitored using ultrasonic binary gas mixture analysis in an instrument above the condenser. This instrument will trigger the evacuation of excess air (section III).

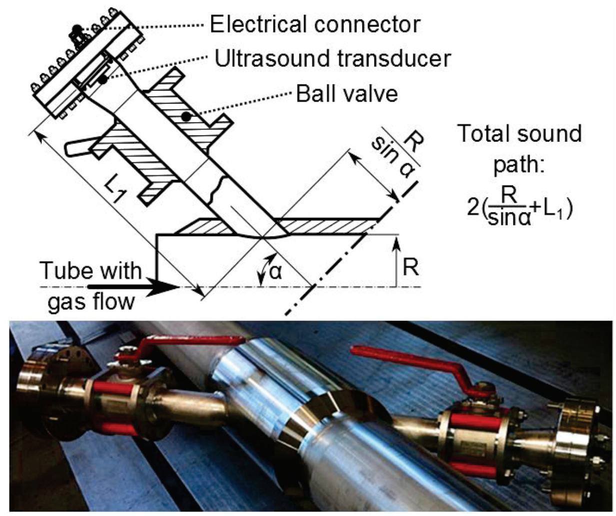

Figure 2: The high volume 45° angled flowmeter.

TRANSDUCERS AND ELECTRONICS

SensComp model 600 capacitive transducers operating at 50 kHz are used as receiving and transmitting elements. These are based on low inertia gold-coated Mylar membranes with fast (< 5 µs) 10-90 % signal rise-time in response to pressure changes caused by arriving ultrasound pulses.

Each transducer has a DAC-adjustable DC bias voltage in the range 180-360V generated in the local electronics using a custom DC/DC convertor, and it is AC-coupled to an AD620N operational amplifier.

When transmitting, a transducer is driven with square wave transitions (Fig. 3) to ground from the bias voltage. We have found that single pulse excitation is sufficient to allow detection of the subsequent pressure pulse at the receiving transducer, over a 500-800 mm sound path in fluorocarbon blends and mixtures with air and nitrogen at pressures in the range 0.3-3bar$_{abs}$.

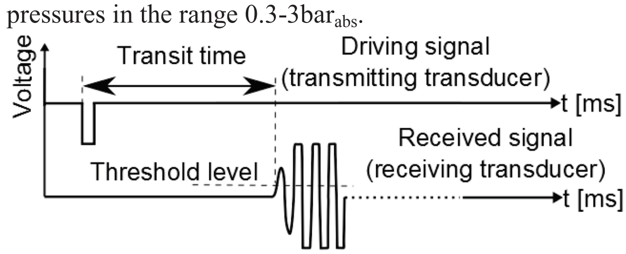

Figure 3: Signal detection and transit time measurement.

Bi-directional transit times are measured with a 40 MHz counter implemented in a Microchip ® dsPIC 16 bit microcontroller. Amplified transducer signals stop the counter when a DAC-generated threshold is crossed.

Since both bidirectional transducer channels are equipped with amplifiers the counter is started when an attenuated image of the driving pulse crosses the threshold after passing the amplifier and comparator. This technique adds the same delay to the counter start as counter stop on the receiving side, eliminating the amplifier - comparator time delay.

Bidirectional transit times are measured approximately 20 times/second and the running averages of 300 samples

ISBN 978-3-95450-139-7

from a FIFO memory are calculated and sent to the supervisory computer.

The distance between the transducer foils required for sound velocity and flow calculations can be measured to a precision of ± 0.1 mm from sound transit times in calibration gases having a well known velocity dependence with temperature and pressure. Suitable gases include Nitrogen, Argon and Xenon [1].

The local electronics can read temperature and pressure sensors and has RS232 or Ethernet connectivity to the supervisory computer. The electronics can also provide 4-20 mA current outputs proportional to sound velocity and flow. While the gas mixture analysis is performed using dedicated sound velocity/mixture composition look up tables stored in the supervisory computer, the 4-20mA outputs may be used in a hard-wired industrial programmable logic control (PLC) system such as that of the new ATLAS thermosiphon.

FLOWMETERY AND CONDENSER VAPOUR ANALYSIS IN THE ATLAS THERMOSIPHON

A new evaporative coolant recirculator, working on a thermosiphon principle ([6], Fig. 4) is being built for ATLAS silicon tracker. This will begin operation with C_3F_8 in 2013 - with possible future operation with C_3F_8/C_2F_6 blends - and will replace the present compressor-driven cooling system where maintenance has proved costly and problematic. In the new system the required liquid delivery pressure is provided by the hydrostatic column in a 92 metre liquid pipe descending from a condenser operating at -60 °C to the ATLAS underground cavern.

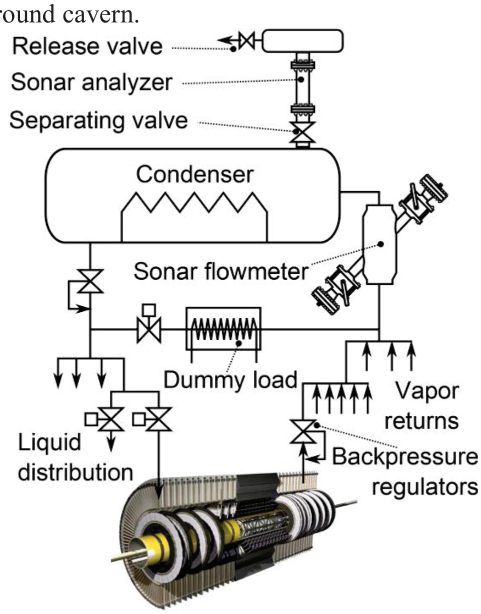

Figure 4: The thermosiphon recirculator with sonar installations in the vapour return to the condenser and its degassing system.

Two ultrasonic instruments are implemented in the thermosiphon. The first operates as a flowmeter in the vapour return to the condenser (Fig. 2 and Fig. 4) - with a possible future combined flowmeter/analyser function - while the second forms part of the condenser "degassing" system. Since the condenser operates 700 mbar below atmospheric pressure contamination from the ingress of incondensable air is possible. Since air is lighter than C_3F_8 it will concentrate in a tank above the condenser where an ultrasonic instrument will measure sound transit time in the air/C_3F_8 mix

When the air concentration (expressed as a 4-20 mA signal proportional to transit time) crosses a pre-defined threshold, the analyser and tank will be isolated from the condenser by the thermosiphon PLC control system and their contents will be evacuated via a release valve.

The venting frequency will depend on the air ingress rate. The analysis precision will be relatively undemanding: air concentration of a few per cent will probably trigger venting. Too low a level would waste expensive fluorocarbon, while too high a level might allow the condenser pressure to rise to a level that would unacceptably reduce fluorocarbon vapour return flow. The trigger point will be determined during thermosiphon commissioning.

The supervisory computer will continuously compare measured sound velocity to a velocity/composition look-up table for air/C_3F_8 mixtures in a similar way to that used in N_2/C_3F_8 analysis [2]. The look-up table has been prepared using the C_p/C_v ratio in the mixture, γ_m, computed for a variety of mixture compositions:

$$\gamma_m = \frac{\sum_i x_i C_{pi}}{\sum_i x_i C_{vi}} \qquad (1)$$

where $x_{i=1,2}$ are the molar concentrations of air and C_3F_8 while $C_{P\,i=1,2}$ and $C_{V\,i=1,2}$ are their respective specific heats at constant pressure and temperature [$J.mol^{-1}K^{-1}$].

The sound velocity, c, in the lookup table is given by:

$$c = \sqrt{\frac{\gamma_m RT}{\sum_i x_i M_i}} \qquad (2)$$

where R is the universal gas constant [$J.mol^{-1}K^{-1}$], T is the absolute temperature [K] and $M_{i=1,2}$ are the molar masses [kg] of air and C_3F_8.

Figure 5 graphically illustrates sound velocity/molar composition tables for mixtures of air and C_3F_8 at temperatures that might be expected in the instrument. The tube will be electrically heated to keep the gas mixture at a stable temperature around 20 °C and counteract cold ingress from the condenser.

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

$$\partial(mix) = \frac{\partial c}{m} \qquad (3)$$

where m is the local slope of the sound velocity/concentration curve and ∂c is the uncertainty in the sound velocity measurement. For example, for 0-10 % air contamination in C_3F_8 where the average slope of the velocity/concentration curve is ~0.56 $ms^{-1}\,\%^{-1}$, a sound velocity measurement precision of ± 0.05 ms^{-1} would yield an uncertainty in air concentration of ± 0.09 %.

ISBN 978-3-95450-139-7

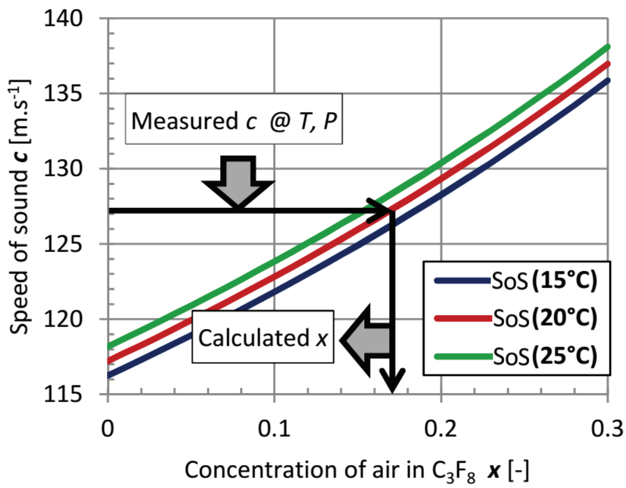

Figure 5: Sound velocity vs air/C_3F_8 composition at 3 temperatures and a pressure of 300 $mbar_{abs}$.

OVERALL SYSTEM ARCHITECTURE

The on-line ultrasonic instruments for coolant leak detection, thermosiphon condenser degassing and flowmetry will be implemented in the ATLAS detector control system (DCS) as illustrated in Fig. 6.

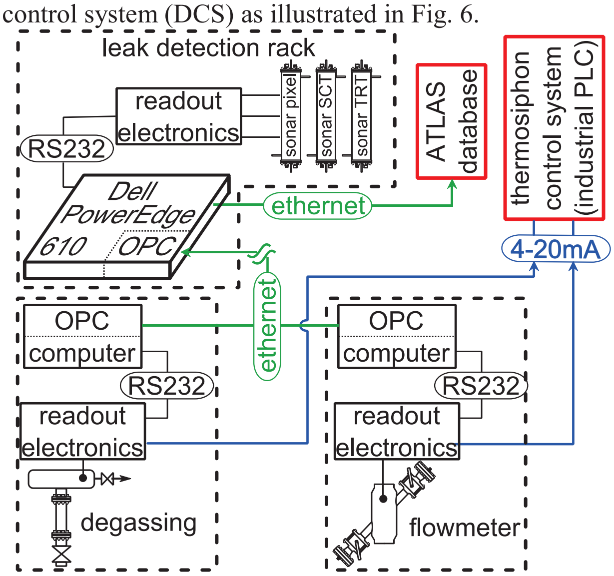

Figure 6: Interconnection of sonar instruments in ATLAS.

The μ-controller based local electronics of each instrument will pass sound transit time, temperature and pressure to a PowerEdge 610 supervisory computer running PVSS-II [5] under Linux, where more complex tasks such as the composition analysis or flow calculations will be performed. The computer is located in an underground technical cavern in a rack with the local electronics of the leak detection system. The custom PVSS II project gathers data from all the instruments. Its tasks include:

- communication with the remote (thermosiphon condenser and flowmeter) instruments via Ethernet using an OPC client, and with the local (leak detection) instruments via short serial links;
- the graphical user interface for all the instruments;
- calculating flow and mixture composition using on-line transit time, temperature and pressure data;
- archiving data, including calculated flow and mixture compositions to the ATLAS DCS database;
- abstracting critical data parameters to be sent to the ATLAS alarm handling FSM (finite state machine) and control room personnel.

All the electronics of Fig. 6 will operate on UPS. The electronics of the two remote (thermosiphon) instruments includes a local computer operating an OPC server which communicates over a shared Ethernet network with the supervisory machine. TCP/IP and HTTP are possible candidates for the communication protocol.

The 4-20 mA current signals proportional to flow and air contamination, are considered critical for thermosiphon operation: it has been decided that they should be hard-wired directly to the thermosiphon PLC without an intervening computer.

CONCLUSIONS

We have developed an ultrasonic instrument for continuous gas flow measurement and simultaneous real-time binary gas mixture analysis. The analysis algorithm compares real time measurements with a stored data base of sound velocity vs. gas composition. The instrument is being integrated into the ATLAS DCS and the hardwired control system of the new thermosiphon fluorocarbon evaporative coolant recirculator.

The combined architecture provides a high level graphical user interface and data archiving for an ensemble of distributed instruments with the abstraction of critical parameters and rapid hardwired feedback to industrial control systems. Other potential applications requiring binary gas analysis include anaesthesia, analysis of hydrocarbons and vapour mixtures for semiconductor manufacture.

ACKNOWLEDGMENT

Co-authors from the CTU Prague are grateful for the support provided by the Grant No.: SGS/FIS 161-831-320

REFERENCES

[1] R. Bates et al, JINST 8 (2013) P02006.
[2] R. Bates et al, "A custom on-line ultrasonic gas mixture analyser with simultaneous flowmetry, developed for the upgraded evaporative cooling system of the ATLAS Silicon Tracker." Proc. 3rd international conference on Advancements in Nuclear Instrumentation, Measurement Methods and Applications, Marseille, June 23-27 2013; to be published in IEEE Transactions on Nuclear Science.
[3] R Bates et al, JINST 8 (2013) C01002.
[4] R. Bates et al, IEEE Trans. Nucl. Sci. 59(2012) 2367.
[5] PVSS II Process visualization and control system, Version 3.8 (2009) : http://www.etm.atETM professional control, A-7000, Eisenstadt, Austria.
[6] J. Botehlo-Direito et al, "General description of the full scale thermosiphon cooling system for ATLAS SCT and Pixel detectors", CERN EN-CV Document 1083852 (19/11/2010) https://edms.cern.ch/document/1083852/1.

ISBN 978-3-95450-139-7