A NEW ULTRASONIC INSTRUMENT FOR COMBINED REAL-TIME FLOWMETRY AND BINARY VAPOUR DETERMINATION IN A FLUOROCARBON EVAPORATIVE COOLING SYSTEM


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Overview

1. Introduction

2. The instrument
   1. Description
   2. CFD Simulations and experimental tests

3. Sonar implementation in the ATLAS thermosiphon

4. Conclusion
4 main experiments:
- ATLAS
- CMS
- ALICE
- LHCb
The ATLAS Experiment

General purpose experiment built to investigate a wide range of physics reactions produced by high-energy proton-proton collisions.

Main elements of ATLAS:
- Detectors
  - Inner Detector (Tracking),
  - Calorimeter,
  - Muon spectrometer
- Magnet System

Inner Detector:
- Pixel
- SCT (Semi-Conductor Tracker)
- TRT (Transition Radiation Tracker)
The ATLAS Inner Detector cooling system

The ATLAS Inner Detector is presently cooled using a compressor-driven fluorocarbon evaporative system operating with $C_3F_8$ (octafluoropropane: R 218).

The external part of the present plant will be replaced by gravity-driven thermosiphon system (better cooling of the detector and more reliable).

Thermosiphon operation will begin with pure $C_3F_8$. Future: $C_2F_6/C_3F_8$ blends → envisaged for lower temp. Pixel & SCT operation → higher level of protection against radiation damage as LHC luminosity increases.

Within the context of thermosiphon project different versions of ultrasonic instruments were developed ranging from real-time binary gas mixture analysis to quasi-static leak detection.
The *electronic transducer* or “sonar” uses the phenomenon whereby - for a given pressure and temperature - sound velocity is a binary gas mixture depends exclusively on component molar concentration. Sound bursts can also be transmitted in opposite directions to measure transit time in each direction for simultaneous flow measurement.

*Flanged stainless steel envelope housing a pair of 50 kHz capacitive ultrasonic transducers together with pressure and temperature sensors.*
1. A fast (40MHz) transit time clock is started in synchronism with the leading edge of the 1\textsuperscript{st} transmitted squared wave;
2. Signal received by 2\textsuperscript{nd} transducer biased to~300V DC and passed to amplifier and comparator;
3. If amplified signal crosses a user-defined comparator threshold → stop transit time counter;
4. The time between the first transmitted and received signal is measured.

Real time measurements:
- Transit time opposed directions + distance between transducers → gas flow rate
- Average transit time + distance between the transducers → sound velocity
- Sound velocity + temperature and pressure + database → binary gas composition

Gas composition vs. sound velocity table: created from prior measurements in calibration mixtures or theoretical thermodynamic calculations and stored in supervisory computer connected to sonar electronics
Numerous CFD simulations were performed with OpenFoam® package to investigate the behaviour of the instrument as a flowmeter.

**Aim** = determine the best transducer configuration and see the turbulence effects in the main tube and along the sound path

Series of CFD simulations:

- 3 crossing angles (α=15°, 30°, 45°)
- 2 different main tube diameter (D_{main})
- different placement of the transducers (T1, T2)

Simulations done for the thermosiphon working conditions (1.2kg/s, 20°C, 500mbar)

Some simulations were also done for an axial flowmeter intended for lower flow applications.

**Result** = both geometries proved to be linearly calibrable
CFD simulations were supported also by experimental tests with stainless steel axial flowmeter and PVC and stainless steel angled flowmeter.

**Axial flowmeter**

Sound velocity measurements for different molar blends in the range of interest of ATLAS cooling system (0-30% C$_2$F$_6$ in C$_3$F$_8$), compared with predictions of NIST REFPROP package.

Average difference ~ 0.05 m/s
Angled flowmeter

Flow velocity calibration tests done with an angled flowmeter.

*Preliminary test PVC, final test stainless steel*

Compressed air was injected and flow measurements calibrated against an anemometer.

\[ t_{up} = \frac{L}{(c - vc\cos\alpha)} + \frac{L'}{c} \]

\[ v = \frac{c(ct_{up} - \frac{D_{Main}}{\sin\alpha} - L')}{\cos\alpha(ct_{up} - L')} \]

Where:
- \( t_{up} \): transit time (the same values can be calculated for the transit time in the opposite direction \( t_{down} \))
- \( v \): flow velocity in the main tube evaluated from transit time measurements

\( L \): acoustic path length within the main flow tube
\( c \): speed of sound in the gas
\( \alpha \): angle between the main pipe and the sonar tube
\( L' \): remaining acoustic path length
\( D_{Main} \): internal diameter of the main tube

Calibration of the angled flowmeter vs Anemometer (Amprobe model TMA10A : 25 m/s Full Scale, intrinsic accuracy ±2%FS)
Angled flowmeter

Flow velocity calibration tests were done with a an angled flowmeter. 

*Preliminary test PVC, final test stainless steel*

Compressed air was injected and the flow measurements calibrated against an anemometer.

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t_{up} = \frac{L}{(c - vcos\alpha)} + \frac{L'}{c}
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\[
v = \frac{c(ct_{up} - \frac{D_{Main}}{sina} - L')}{cos\alpha(ct_{up} - L')}
\]

*rms accuracy ±1.9% of the max flow velocity (11m/s)*

Encouraging test results allowed installation of the stainless steel angled ultrasonic flow meter into vapour return tube of ATLAS thermosiphon (\(D_{Main}=133.7\text{mm}, \ \alpha=45^\circ\)), even if experimental calibration with expensive fluorocarbons was not possible.
The precision of the instrument for mixture determination depends on uncertainty in measured sound velocity, $\delta c$; which itself depends on other measurement errors:
- Transducer spacing ± 0.1 mm
- Temperature ± 0.2 C
- Pressure ± 4 mbar
- Transit time ± 100 ns

$\rightarrow$ Overall sound velocity error ± 0.05 m/s

The precision on the concentration of the two components, $\delta(mix)$, is given by

$$\delta(mix) = \frac{\partial c}{m'}$$

Where $m'$ is the local slope of the sound velocity vs. molar concentration curve at the measured temperature and pressure

At 20% $C_2F_6$ concentration in $C_3F_8$ $m' = 0.18 \text{ ms}^{-1} [% C_2F_6]^{-1}$

$\Rightarrow \delta(mix) = \pm 0.3 \%$
Similar axial sonar devices have been used to check for $C_3F_8$ leaks from ATLAS inner detector cooling system into surrounding $N_2$ envelope. Sound velocity measurement uncertainty of 0.05m/s will give sensitivity of $4.10^{-5}$ to $C_3F_8$ leaks.

Results from continuous 18 month study of $C_3F_8$ leaks from ATLAS pixel detector
ATLAS thermosiphon evaporative cooling system will be equipped with 2 sonar instruments:

- A “degassing” sonar placed on the top of the condenser
- An angled FM placed on the vapour return line
The angled flowmeter will operate in a flow of around 18000 l/min in pure C$_3$F$_8$ or around 20000 l/min in blends containing up to 30% C$_2$F$_6$ in C$_3$F$_8$, as a flowmeter. The instrument can be easily adapted through the addition of temperature and pressure sensors to allow simultaneous measurement of the C$_2$F$_6$/C$_3$F$_8$ blends, if the blends will be used in the thermosiphon.

The degassing sonar is aimed to the detection and elimination of air ingress into the thermosiphon condenser.
Sonar implementation in the ATLAS thermosiphon

Condenser = element at lower temperature and pressure (-60°C, 300 mbar$_{\text{abs}}$) in the circuit point where air from leak ingress will accumulate increasing condensation temperature/pressure and reducing thermosiphon performance.

1. Air will concentrate in a tank above condenser where the thermally-stabilised sonar will measure sound transit time in air/$\text{C}_3\text{F}_8$ mixture;

2. Electronics will report measurements to the supervisory computer and the thermosiphon PLC control system;

3. When transit time drops below a pre-defined threshold tank and sonar will be isolated from the condenser and their contents evacuated to a vacuum network.

Sound velocity measurement uncertainty of 0.05 m/s will give sensitivity of $\approx 10^{-3}$ to air leaks. This system will allow degassing thermosiphon system during run conditions, without interfering with normal operation of the plant.
The instrument exploits the principle whereby the sound velocity in a binary gas mixture at known T & p depends uniquely on the component molar concentration.

Real time measurements:
- Transit time in opposed direction + distance between transducers → gas flow rate
- Average transit time + distance between the transducers → sound velocity
- Sound velocity + temperature and pressure + database → binary gas composition

CFD simulations and experimental tests validated the instrument and showed an interesting flow measurement precision (±0.3%) and mixture resolution (2% of full scale for flows up to 11 m/s)

The instrument has many applications where continuous binary gas composition measurement is required: leak detection, hydrocarbon and anaesthetic gas mixtures, ...
Thank you!

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Back up slides
Sonar – more sensitive to low concentration of heavy additive into light carrier
(slope of sound velocity/composition curve is steeper)
→ sound velocity uncertainty (0.05m/s) divided by a larger gradient to get mixture resolution

$\text{C}_3\text{F}_8$ leaks into $\text{N}_2$:
0 – 1% $\text{C}_3\text{F}_8$ in $\text{N}_2$ → heavy additive ($\text{C}_3\text{F}_8$ : MW = 188) in light carrier ($\text{N}_2$ : MW = 28)
→ steep slope: $-12.27$ m/s/%$\text{C}_3\text{F}_8$ → Mixture resolution = $0.05/12.27 = 4 \times 10^{-3}$ % = $4 \times 10^{-5}$

**TS Condenser:**
Air leaks into $\text{C}_3\text{F}_8$ → light contaminant (Air : MW = 29) into heavy carrier ($\text{C}_3\text{F}_8$ : MW = 188)
→ shallow slope: $+0.53$ m/s/%air → Mixture resolution = $0.05/0.53 = 0.09$ % = $9 \times 10^{-4} \approx 10^{-3}$