North Sea Flow Measurement Workshop

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Density Measurements: perspectives for traceable on-line sensors

P. Alberto Giuliano Albo, Simona Lago and Giuseppe Cavuoto

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Total net energy transferred

Transferred energy can be calculated with the following formula [1]:

$$E = G\,\rho V - E_{\text{Gas displaced}} \pm E_{\text{Gas to Engine Room}}$$

- E: Net energy transferred
- G: Gross calorific value
- ρ: Density
- V: Volume

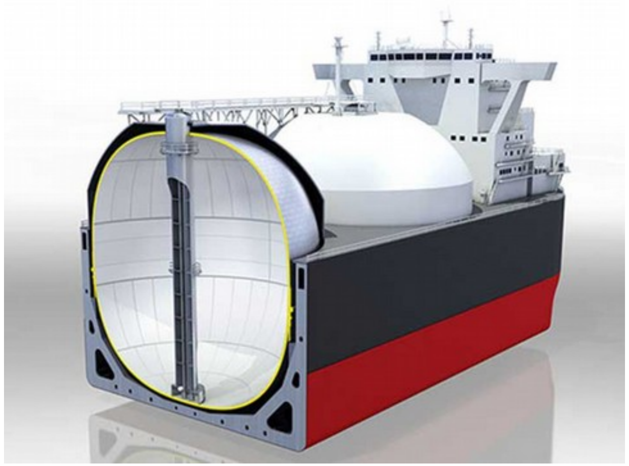
[1] GIIGNL–LNG Custody Transfer Handbook v. 5.00 (2017)

Mass determination

LNG **mass** can only be measured by direct weighing

it can be done with trucks and other **small-scale** carriers but **not for large amount** of fluid.

or by **Level/Volume** and **Composition** conversion [1]:



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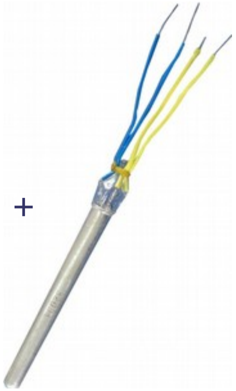

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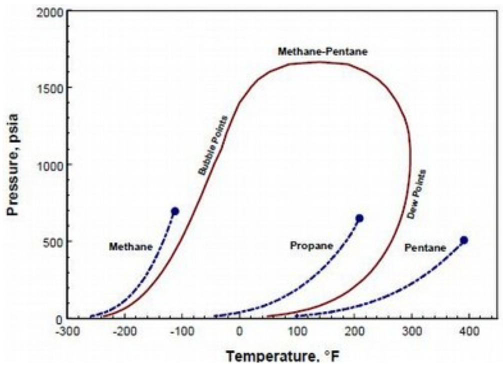


[1] GIIGNL–LNG Custody Transfer Handbook v. 5.00 (2017)

Requirements of density sensors

A **suitable density sensor** must satisfy at least two general **requirements**:

Technological

- Suitable to work in wide **range of temperature and pressure**;
- **Uncertainty in the order of 0.1%** or better over the whole measurement range;
- **High accuracy**;
- **Easiness** in design and operation;
- Measurement **time constant** in the order of **seconds**.

Commercial

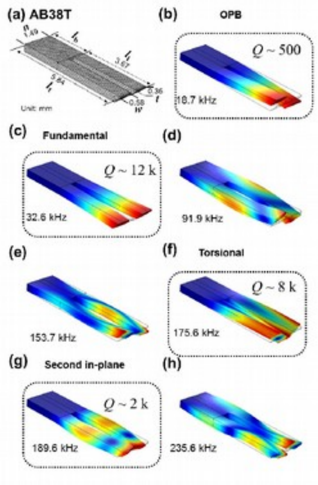
- Low cost;
- Traceable;
- Almost never failures;
- Simple / on-line calibration.

Static versus Dynamic Measurements

Static methods: density is measured **maintaining the fluid at its natural thermodynamic and mechanic equilibrium**

- **Time constants** are much **longer** than a second and may be in the order of hours or days;
- Since the fluid is in equilibrium, **high accuracy and low uncertainty** can be obtained;
- **Measurements** are usually **directly traceable** to the definition of the units of mass and volume.

Dynamic methods: density is measured **setting the fluid out its natural thermodynamic and mechanic equilibrium** and monitoring some properties of the transitory.



- **Time constants** are in the order of seconds but can be much **smaller**;
- Out of the equilibrium, the fluid may show **properties influencing the measurements**;
- **Calibration** of the instrument is **needed** and the **traceability must be checked** time by time;
- Sensor **calibration** has to be **repeated frequently;**
- More **complex physics** that can **lead to higher uncertainty** when approximations are introduced;
- Dynamic **response of systems** can be used to **extract further information** of the state of system.

LNG pycnometers

The sample is expanded from one volume to a second volume. The ratio between these two volumes is equal to the ratio between the density ρ_0 before and after the expansion ρ_f.

Single Expansion Devices

Usual volume ratios from 50 to 1000, so that the final pressure is near to atmospheric.

$$\rho(T,p) = \frac{m - m_0}{m_{\mathrm{CH_4}} - m_0}\rho_{\mathrm{CH_4}}(T,p) + \rho_{\mathrm{a}}$$

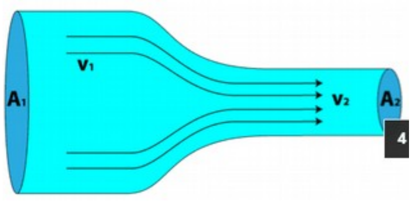
- Temperature range from (98 to 111) K;
- Pressure up to 0.6 MPa ;
- Declared uncertainty: 0.25 %;
- *m*-symbols refer to the pycnometer weights when filled with LNG, when evacuated and when filled by a reference fluid (i.e. methane), ρ_a is the density of air when pycometer is weighted in air.

INRiMs pycnometer for cryogenic density measurements

Density in flowing fluids

From conservation of 4-momentum (mass and momentum simultaneously):

$$\delta\Pi^\mu = \int \rho v^\mu v^\nu n_\nu |\partial S| = \int \nabla_\mu (\rho v^\mu v^\nu) |\mathrm{d}V|$$

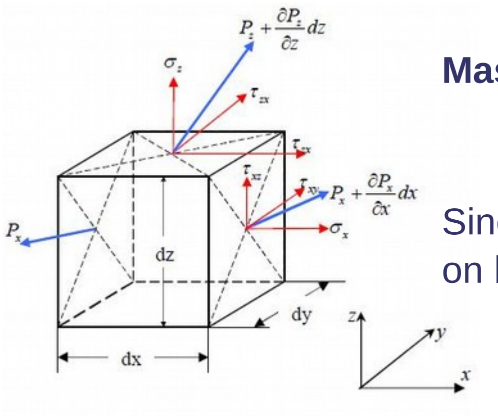


Mass conservation:

$$\delta m = \partial_t \rho + v^j \nabla_j \rho + \rho \nabla_j v^j$$

Momentum conservation:

$$\delta \pi^i = \rho(\partial_t v^i + v^i \nabla_j v^i) + v^i \delta m + \nabla^i p + f^i$$

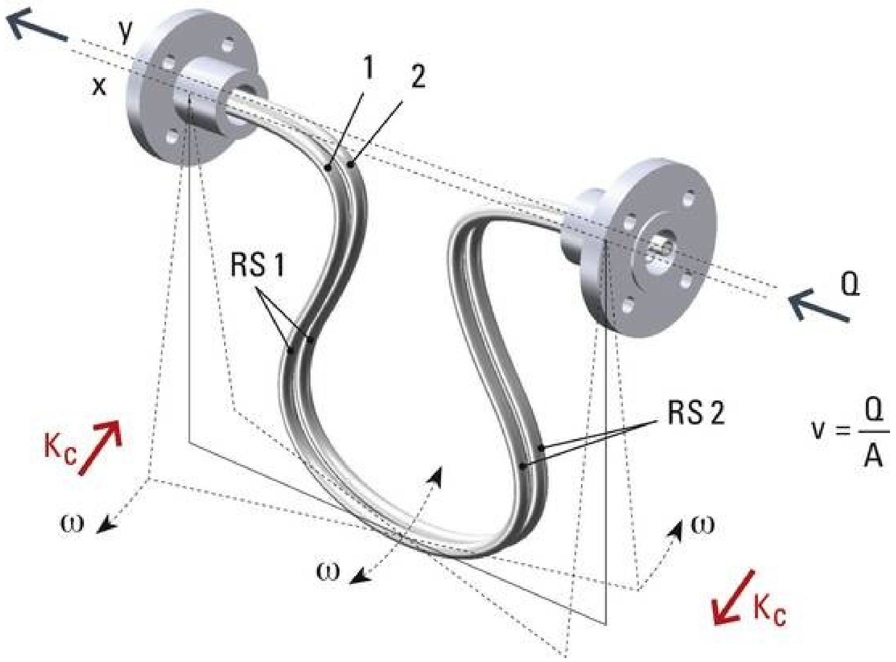


Mass and momentum conservation is the principle which **dynamic sensors are based on**.

Since **nabla** and volume depend on the geometry of the system, the density distribution depends on local **geometrical properties.**

Equations are **further complicated when viscosity and thermodynamic** terms are included.

Coriolis mass flowmeter



Picture taken from Bell Flow System web site

Mass flow rate: $\dot{m} \propto \Delta t$

Fluid density: $\rho \propto 1/f^2$

$$\rho = C(\nabla, \lambda, \mu, T, p)/f^2$$

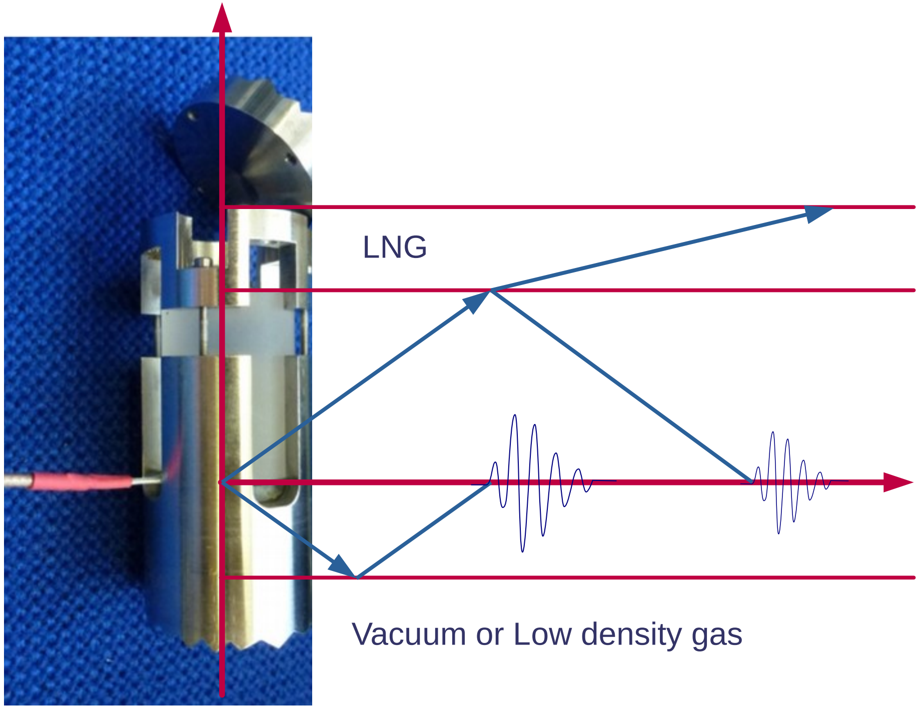
Tubes shapes

Elastic properties

Thermodynamic conditions

Calibration is the most suitable **procedure** to **eliminate or characterize** the *C*-function.
When characterization is needed, **physical models** play the most important **role**.

Acoustic densimeter



INRiM's pycnometer (prototype I) for cryogenic density measurements

Materials and dimensions are designed to **fit** the measurement range of **densities**

Acoustic densimeter measures the **density of the fluid directly**, without making use of Equation of States.

$$\rho_{\mathrm{f}} = \frac{1+R}{1-R}\frac{w_{\mathrm{s}}}{w_f}\rho_{\mathrm{s}}$$

Where s- and f- indexes refer to solid and fluid respectively while *w* is the speed of sound, *ρ* is density and *R* is the ratio of the signal amplitude.

Conservative relative uncertainty estimation in **laboratory conditions**:

$u_r(w_s)$	~ 0.02 %	speed of sound in crystals
$u_r(w_f)$	~ 0.05 %	speed of sound in fluid
$u_r(R)$	~ 0.02 %	reflection coefficient
$u_r(\rho_s)$	~ 0.01 %	density of crystal
$\boldsymbol{U_r(\rho_f)}$	**<0.15 %**	**combined expanded uncertainty (*k*=2)**

Acoustic densimeter: implementation of on-line calibration

When **sensors** are **characterized and calibrated in laboratory conditions**, it is possible to use them on-line to **calibrate ultrasonic flowmeters by comparison**.

Comparison is a **well defined procedure** including shared measurement procedures and uncertainty analysis that is widely **used among Primary Metrological Institutes** to **disseminates** quantities.

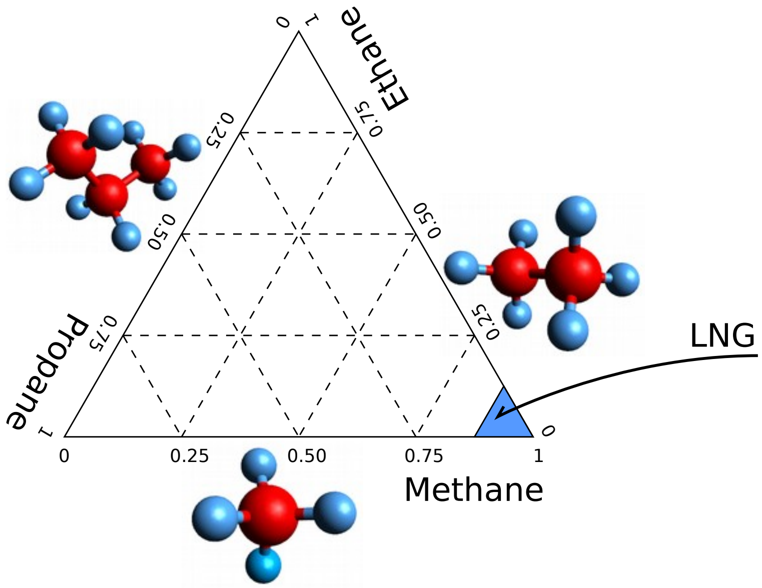
Speed of sound for **fluid at rest** when **fluid flows**:

$$w = \frac{L(t_{\mathrm{up}} + t_{\mathrm{dw}})}{2\; t_{\mathrm{up}} t_{\mathrm{dw}}}$$

Sensor **calibration**:

$$w_{\mathrm{ref}} = C\; w$$

Acoustic densimeter: composition monitoring



From simultaneous measurements of **speed of sound** w_0 and **density** ρ_0 it is possible to **monitor** the composition of **a ternary mixture** representing LNG, namely methane (85%), ethane (10%) and propane (5%).

Speed of sound and density can be expressed as a function of the composition x_i when the temperature T and the pressure p are known:

$$\begin{cases} w(x_\mathrm{m}, x_\mathrm{e}, x_\mathrm{p}) - w_0 = 0 \\ \rho(x_\mathrm{m}, x_\mathrm{e}, x_\mathrm{p}) - \rho_0 = 0 \\ 1 - x_\mathrm{m} - x_\mathrm{e} - x_\mathrm{p} = 0 \end{cases} .$$

Functions $w(x_\mathrm{m}, x_\mathrm{e}, x_\mathrm{p})$ and $\rho(x_\mathrm{m}, x_\mathrm{e}, x_\mathrm{p})$ are obtained from a dedicated equation of state describing the composition to be monitored.

When ultrasonic flowmeters are calibrated on-line by comparison with a reference speed of sound sensor, the **ultrasonic densimeter** can be used to **monitor relative variation of the composition** of the **flowing** LNG.

Conclusions

Dynamic measurements are **preferable for on-line** measurements and, thanks to their nature, can be exploited to insight **physical properties of the system.**

Metrology can help manufactures not only to **extract hidden information** but also to obtain the most **reliable measurements, traceable to units** definitions.

It is late but, for any further discussions feel free to contact us:

Simona Lago: s.lago@inrim.it
P. Alberto Giuliano Albo: a.albo@inrim.it

Thanks for your attention!