Cryogenic flow rate measurement with a Laser Doppler Velocimetry standard

Metrology for LNG

LNG metrology workshop

28/05/2020

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In collaboration with Engie, Elengy in France and Natrugy, Reganosa in Spain for LNG terminal tests
1. Description of the LDV technique and measuring system

2. Uncertainty budget assessment in cryogenic conditions

3. LDV standard: LNG tests

4. Conclusions and perspectives
Cryogenic flow rate meas. by LDV
Description of the LDV technique (1/1)

**Principle of the volume flow rate measurement with a LDV**

LDV needs particles to reflect light of the laser

The volume flow rate could be calculated by velocity profile integration over a diameter & it is directly traced back to SI units of **Length and Time**

**LDV DANTEC**

- Laser power = up to 300 mW
- \( \lambda = 532 \text{ nm} \) (green light)
- Back scattering mode
- Focal length : \( F = 200 \text{ mm} \)
- \( D_{\text{Laser}} = 1.8 \text{ mm} \)
- \( D_{\text{Beams}} = 60 \text{ mm} \)

\[ U = \Delta i \cdot f \cdot D \]
Cryogenic flow rate meas. by LDV
Brief overview of the LDV standard (1/1)

- **Measurement System**
  - Seeding unit
  - Conditioning the flow with a convergent
  - Local velocity measurement or full velocity profiles with LDV
  - Vacuum insulation to avoid icing of the optical windows
  - Optical access for laser beams & flow visualization

- **Traceable to SI units**

- **Two way to use it**: as a reference for cryogenic flow meters calibration or as an alternative to Coriolis and ultrasonic flow meter

- **New design #3 (2018)**

- DN 80
- Beta Ratio = 0.5
- Total length 12 D
- Quartz or sapphire windows
Cryogenic flow rate meas. by LDV
LDV standard new design (1/2)
Cryogenic flow rate meas. by LDV

Road map of the presentation

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### Cryogenic flow rate meas. by LDV

**Uncertainty budget assessment in cryogenic conditions (1/2)**

**Axial velocity**

\[ v_{axis} = \frac{I(f_D - f_S)}{\cos(\gamma)} \]

**Volume flow rate**

\[ Q_v = \frac{v_{axis} \pi d^2}{4} \frac{1}{A(Re)} \]

**Volume flow rate (with correction function)**

\[ Q_v = \frac{v_{axis} \pi d^2}{4} \frac{1}{a + b \ln(\rho v_{axis} d / \mu) + \epsilon} \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_v)</td>
<td>Volumetric flowrate obtained from the LDV system</td>
<td></td>
</tr>
<tr>
<td>(v_{axis})</td>
<td>Measured axial velocity using the LDV system</td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>Internal diameter of the LDV convergent throat</td>
<td></td>
</tr>
<tr>
<td>(a)</td>
<td>Intercept of the model function</td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>Slope of the model function</td>
<td></td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density of LNG at local conditions of pressure and temperature</td>
<td></td>
</tr>
<tr>
<td>(\mu)</td>
<td>Viscosity of LNG at local conditions of pressure and temperature</td>
<td></td>
</tr>
<tr>
<td>(\epsilon)</td>
<td>Model function error</td>
<td></td>
</tr>
</tbody>
</table>
Cryogenic flow rate meas. by LDV

Uncertainty budget assessment in cryogenic conditions (2/2)

Volume flow rate
(with correction function)

\[ Q_v = \frac{v_{axis}\pi d^2}{4} \left( \frac{1}{a + b \ln(\rho v_{axis}d/\mu)} + \epsilon \right) \]

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard uncertainty</th>
<th>Unit</th>
<th>Variance contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>88,75</td>
<td>0,20</td>
<td>m³/h</td>
<td>101 %</td>
</tr>
<tr>
<td>Fluid density</td>
<td>437,2</td>
<td>1,8</td>
<td>kg/m³</td>
<td>0,0 %</td>
</tr>
<tr>
<td>Fluid viscosity</td>
<td>0,00011</td>
<td>0,00001</td>
<td>Pa.s</td>
<td>5,2 %</td>
</tr>
<tr>
<td>Model error</td>
<td>0,00000</td>
<td>0,00115</td>
<td>-</td>
<td>25,1 %</td>
</tr>
<tr>
<td>Throat diameter</td>
<td>39,892</td>
<td>0,005</td>
<td>mm</td>
<td>1,2 %</td>
</tr>
<tr>
<td>Corrected (v_{axis})</td>
<td>19,999</td>
<td>0,033</td>
<td>m/s</td>
<td>55,2 %</td>
</tr>
<tr>
<td>Model coefficients</td>
<td>collective</td>
<td>-</td>
<td>-</td>
<td>13,7 %</td>
</tr>
</tbody>
</table>

Breakdown of corrected axial velocity uncertainty

<table>
<thead>
<tr>
<th>Corrected (v_{axis})</th>
<th>19,999</th>
<th>0,033</th>
<th>m/s</th>
<th>100,00 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>20,000</td>
<td>0,001</td>
<td>m/s</td>
<td>0,12 %</td>
</tr>
<tr>
<td>Fringe spacing</td>
<td>0,000</td>
<td>0,003</td>
<td>µm</td>
<td>99,77 %</td>
</tr>
<tr>
<td>Resolution</td>
<td>9,06E-08</td>
<td>2,89E-04</td>
<td>m/s</td>
<td>0,01 %</td>
</tr>
<tr>
<td>Misalignment</td>
<td>-4,75E-04</td>
<td>5,00E-01</td>
<td>Deg</td>
<td>0,10 %</td>
</tr>
<tr>
<td>Doppler correction</td>
<td>-3,02E-09</td>
<td>1,00E-05</td>
<td>MHz</td>
<td>0,00 %</td>
</tr>
<tr>
<td>Shift correction</td>
<td>-1,50E-08</td>
<td>1,00E-05</td>
<td>MHz</td>
<td>0,00 %</td>
</tr>
</tbody>
</table>

The standard in-use model uncertainty, disregarding uncertainty in the observation points (the x-axis). The field trial data had Reynolds numbers up to around 2.5·106. The plot gives an indication of the increased uncertainty in extrapolation.

Standard uncertainty for measurements ranging from 1 m/s to 20 m/s with inputs outlined in input data section. The graph shows three different values for the model error, to indicate the influence of changes to this input. The expanded uncertainty is not shown, but the coverage factor is very close to 2.
Cryogenic flow rate meas. by LDV

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LDV standard new design: tests in **MURGADOS**

Cross comparison between: Flow meter, LDV standard and weighing technique
Cryogenic flow rate meas. by LDV
LDV standard new design : tests in MURGADOS

Operator interface :

Comparison between the cryogenic standard and the weighing bridge during truck loading

Uec bridge = 0,164%
Uec LDV (vol) = 0,22%
Uec (density) = 0,2%
Uec LDV (mass) = 0,59%

Q VFM vs Q LDV
2,05% deviation

Can we increase the data rate ?

Natural seeding : data rate up to 50 Hz (best case scenario) – 25000 measurements
Cryogenic flow rate meas. by LDV
LDV standard new design: tests in MONTOIR
Cryogenic flow rate meas. by LDV
LDV standard new design: tests in MONTOIR

Cesame-Exadebit s.a. / LNE-LADG
Cryogenic flow rate meas. by LDV
LDV standard new design: tests in MONTOIR

Data rate
Up to 10 Hz

Data rate
Up to 400 Hz
Cryogenic flow rate meas. by LDV
LDV standard new design: tests in MONTOIR

Operator interface:

\[ Q_{CFM} = 79.50 \text{ m}^3/\text{h} \]
\[ Q_{LDV} = 81.71 \text{ m}^3/\text{h} \]
\[ \sim 2.6\% \text{ deviation} \]

Natural seeding: data rate up to 500 Hz – 213000 measurements
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Conclusions and perspectives

• CESAME has built a primary standard for cryogenic flow meter calibration

• CESAME and JV have built a Matlab toolbox to determine the modification in the extended uncertainty budget for in use application

• CESAME has created an injection system to increase significantly the seeding in cryogenic condition

• Looking for opportunities to create a cryogenic loop in a LNG terminal to calibrate cryogenic flow meters with the LDV standard
Cryogenic flow rate meas. by LDV

Thank you!

Thanks you for your attention
Need more information:
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