Cryogenic flow rate measurement with a Laser Doppler Velocimetry standard

Metrology for LNG

GIIGNL task force

12/09/2019

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In collaboration with Engie, Elengy in France and Natruguay, Reganosa in Spain for LNG terminal tests
Cryogenic flow rate meas. by LDV

Road map of the presentation

1. Who we are and what we do
2. Background regarding LNG
3. Description of the LDV technique and measuring system
4. How it works!
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8. LDV standard new design: Improvements, accreditation & complementary tests (air / LNG)
9. Conclusions and perspectives
Gas Flow metering Laboratory

In addition to holding and improving national gas flow references as an LNE Associated Laboratory (LNE-LADG), CESAME-EXADEBIT offers its clients expertise and experience of more than 35 years in the field of gas flow metering especially under high pressure.
Cryogenic flow rate meas. by LDV
Who we are and what we do (2/4)

Legal metrology

Gaz (Nat) Flowmeters
Verification (ISO 17020)
+ Repair => Initial verification (ISO 9001)

Industrial metrology

Gaz (Nat) Flowmeters
Calibration (ISO 17025)
. Safety valves tests

R&D tests

Aerodynamics
Aeroacoustics

TechnipFMC, TOTAL, CNES, ...

LNE mandate:
maintaining and enhancing the gas flowmeters standard
+ R&D; PhD student

Designated Institute

National Metrology Institute

Cesame-Exadebit s.a. / LNE-LADG

Scientific metrology

Origin = Association created by French National Metrology Office and GDF (Gaz De France, when public) in 1983

Private company (S.A) from 2002

Located inside ‘CEAT’, a research center for Aerodynamics of the University of POITIERS

Staff = 18 persons

~ 2000 calibrations / year

Manufacturers, CETIM members

services
Cryogenic flow rate meas. by LDV
Who we are and what we do (3/4)

CESAME EXADEBIT in metrology domain

French Designated Institute for high pressure gas flow metering

Cesame-Exadebit s.a. / LNE-LADG

BIPM
(Bureau international des poids et mesures)

Instituts Nationaux de Métrieologie et laboratoires désignés

Laboratoires d’étalonnage, souvent accrédités

Entreprises

Utilisateurs

Définition des unités

Étalons primaires nationaux, étrangers

Étalons de référence

Étalons industriels

Mesures

L’incertitude est accrue au pied de la chaîne de traçabilité

L'infrastructure métrologique nationale

métrologie française

LNE-LADG
Facilities for services

« M1 » bench
('secondary' ; standards = sonic nozzles)

« M3 » bench
('secondary' ; standards = sonic nozzles)

« M5 » bench
(safety valves tests)

Compressed AIR @ 200 bar from CEAT compressor and vessels (100 m3)

Mass flow rate: 0.003 to 20 kg/s
Volumic flow rate: 5 to 50000 Nm³/h
Diameter: DN25 à DN400
Pressure: 2 to 60 barA
Uec uncertainty: 0.2% to 0.25%

Volumic flow rate: 1 to 250 Nm³/h
Diameter: DN50 to DN100
Pressure: ~ ambient
Uec uncertainty: 0.2% to 0.3%

Mass flow rate: 10 kg/s @ 40 bar, 3 kg/s @ 180 bar
Diameter: DN25 to DN200
Pressure: 1 to 180 bar
Uec uncertainty: 1% to 2%
Cryogenic flow rate meas. by LDV

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Background regarding LNG (1/3)

GIIGNL(*) Annual report 2019 edition

Key figures 2018

- 313.8 Mt imported
- 42 importing countries
- 20 reporting countries
- +8.3% growth vs. 2017
- 99.3 Mt imported on a spot or short-term basis

76% of global LNG demand in Asia
44% of global LNG supplied from the Pacific Basin
32% of global LNG imported on a spot or short-term basis

868 MTPA total regasification capacity
406 MTPA total liquefaction capacity

Retail LNG in 2018

1540.10³ T (~0,8B€)

Where do we need accurate measurements?
Cryogenic flow rate meas. by LDV

Background regarding LNG (2/3)
Energy Transferred from the loading facilities to the LNG carrier or from the carrier to the unloading facilities

\[ E = V_{LNG} \times D_{LNG} \times GCV_{LNG} - E_{\text{gas displaced}} \]

**Volume of LNG loaded or unloaded**

**Density of LNG loaded or unloaded**

**Gross calorific Value of LNG loaded or unloaded**

Combined Extended uncertainty on Energy Transfer

\[ U[E_{LNG};k=2] = 0.5\text{-}0.7\% \]

GIIGNL LNG Custody Transfer Handbook 2017

**TABLE 2: SOURCES OF UNCERTAINTY IN VOLUME**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge tables</td>
<td>Calibration Certificate</td>
</tr>
<tr>
<td>Level</td>
<td>Note 1</td>
</tr>
<tr>
<td>Liquid temperature</td>
<td>Calibration Certificate</td>
</tr>
<tr>
<td>Vapor temperature</td>
<td>Calibration Certificate</td>
</tr>
<tr>
<td>List (if applicable)</td>
<td>Calibration Certificate</td>
</tr>
<tr>
<td>Trim (if applicable)</td>
<td>Calibration Certificate</td>
</tr>
<tr>
<td>Tank thermal expansion factor (Spherical tanks)</td>
<td>Bibliography</td>
</tr>
<tr>
<td>WP No</td>
<td>Work Package Title</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------------------------------------</td>
</tr>
<tr>
<td>WP1</td>
<td>Reduced uncertainty for dynamic flow measurements</td>
</tr>
<tr>
<td>WP2</td>
<td>Traceable small scale liquefier and density measurements</td>
</tr>
<tr>
<td>WP3</td>
<td>Smart sensor development and testing</td>
</tr>
<tr>
<td>WP4</td>
<td>Smart sensor validation and engine tests</td>
</tr>
<tr>
<td>WP5</td>
<td>Creating impact</td>
</tr>
<tr>
<td>WP6</td>
<td>Management and coordination</td>
</tr>
</tbody>
</table>

Total months: 241.4
Cryogenic flow rate meas. by LDV

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Principle of the volume flow rate measurement with a LDV

LDV DANTEC

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

Laser wavelength $\lambda_0$
Principle of the volume flow rate measurement with a LDV

Optical path from the laser to the volume measurement

LDV DANTEC
- Measurement volume $dx = 0.07$ & $dz = 0.5$ mm
- Fringe spacing = $2.2 \, \mu m$
Principle of the volume flow rate measurement with a LDV

A typical Doppler burst that originates from a single particle passing through the measurement volume (so : LDV needs particles to reflect light of the laser)

The electronic signals are transformed into the frequency domain and band pass filtered in order to eliminate high frequency noise and the low frequency content from the signal.

A typical burst after filtering is shown in figure C. The Doppler frequency \( f_D \) is determined by doing a fast Fourier transform (FFT).
Principle of the volume flow rate measurement with a LDV

\[ U = \Delta i \cdot f_D \]

\[ \Delta i = \frac{\lambda_0}{2 \cdot \sin \left( \frac{\theta}{2} \right)} \]

Fringe spacing is calculated with laser wavelength – calibration (LENGTH)

Filtered and Fast FFT Calibration (TIME)

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

\[ Q_v = 2\pi \int_0^R U(r) r \, dr \]
Cryogenic flow rate meas. by LDV

Brief overview of the LDV package (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 on-site cryogenic flow meters
- or as an alternative to Coriolis and ultrasonic flow meter
Cryogenic flow rate meas. by LDV

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Velocity measurement by means of LDV technique

Two methods are examined to determine the volume flow rate from velocity measurements performed by the LDV:

1. **Integration of the velocity profile**

The method 1 is *a primary standard technique* since no previous calibration / correction have to be done.

The volume flow rate is obtained by integrating the flow velocity across section S where R is the limit of integration:

\[ Q_V = 2\pi \int_{0}^{R} v(r)r\,dr \]
Cryogenic flow rate meas. by LDV
Feasibility with Air based experiments (3/5)

The fit is defined for positive velocities as:
\[ f(x) = \left[ d \left( 1 + (1 + c(\tanh(x)^2)) \tanh\left( b \left( \frac{0,5+a}{x} \right) - \left( \frac{x}{0,5+a} \right) \right) \right) \right] \]

and for negative velocities as:
\[ f(x) = ax^3 + bx^2 + cx + d \]

The mass flow is then calculated using:
\[ Q_v = 2\pi \int_0^{R_{\text{max}}} U_x r dr \]

Circulation zone in optical path

Fit of experimental data at 5 bar

\[ R_e = 2.6 \times 10^5 \]

issues:
- measurement is not $2\pi$ periodic
- need long time experiment

\[ Q_{v_{\text{mockup}}} (m^3/h) \quad 95.14 \]
\[ Q_{v_{\text{standard}}} (m^3/h) \quad 97.05 \]

Simpson’s integration
> ratio 1.02
Velocity measurement in pipe by means of LDV technique

Two methods are examined to determine the volume flow rate from velocity measurements performed by the LDV:

1. *Integration of the velocity profile*
2. *Calculation of the volume flow rate from a local velocity measured downstream of the throat.*

The method 2 (quicker) can be described as a **secondary standard** since a calibration function \( A(Re) \) has to be previously determine (experimentally in our case – possibility to be **primary standard if based on theoretical work**). Cesame Exadebit is currently working on an analytical model based on the boundary-layer theory (see Schlichting et al. for further explanations).

The volume flow rate calculation can be reduced to a single point measurement on the center line velocity measurement **directly at the throat**.

\[
\frac{V_{\text{axis}}}{\bar{V}} = A(Re_d) \quad Q_v = \pi R^2 \bar{V} = \pi R^2 \frac{V_{\text{axis}}}{A(Re_d)}
\]
Assessment of the boundary layers influence on mass flow

Cryogenic flow rate meas. by LDV
Feasibility with Air based experiments (5/5)

Reynolds number increasing

<table>
<thead>
<tr>
<th>Run</th>
<th>Re-nozzle</th>
<th>( \bar{V} )</th>
<th>( V_{\text{axis}} )</th>
<th>( V_{\text{axis}}/\bar{V} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>m/s</td>
<td>m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.14E+05</td>
<td>31.07</td>
<td>31.730</td>
<td>1.021</td>
</tr>
<tr>
<td>2</td>
<td>5.41E+05</td>
<td>41.28</td>
<td>42.040</td>
<td>1.018</td>
</tr>
<tr>
<td>3</td>
<td>7.61E+05</td>
<td>58.82</td>
<td>59.120</td>
<td>1.005</td>
</tr>
<tr>
<td>4</td>
<td>7.94E+05</td>
<td>30.60</td>
<td>31.120</td>
<td>1.017</td>
</tr>
<tr>
<td>5</td>
<td>1.06E+06</td>
<td>40.80</td>
<td>41.250</td>
<td>1.011</td>
</tr>
<tr>
<td>6</td>
<td>1.52E+06</td>
<td>58.53</td>
<td>59.210</td>
<td>1.012</td>
</tr>
</tbody>
</table>

\[ \frac{V_{\text{axis}}}{\bar{V}} = a + b \log(\text{Re}) + \varepsilon \]

Sonic nozzles
LDV

boundary layers influence determined with air experiments in Poitiers

\[ Q_v = \pi R^2 \bar{V} = \pi R^2 \frac{V_{\text{axis}}}{A(\text{Re}_d)} \]

LDV

\[ \frac{V_{\text{axis}}}{\bar{V}} = A(\text{Re}_d) \]
Cryogenic flow rate meas. by LDV

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9. Conclusions and perspectives
The LDV package test was run on the NIST cryogenic flow measurement facility. This facility has a combined uncertainty of 0.18% for the totalized volume flow (k=2).

Primary standard: gravimetric method
Comparison with the standard facility:

CESAME (as a first attempt) has applied the $A(Re)$ function determined during the air based campaign in Poitiers.

$$\frac{V_{\text{axis}}}{V} = A(Re_d)$$

CESAME has also taken into account the temperature constraints on the flow meter body. The paper of Thermeau presents the length modification ($\Delta l/l$) as a function of temperature in Kelvin. In our case, the $\Delta T$ is 213K resulting in a length modification around 0.27% on the throat diameter.
Comparison with the standard facility:

The comparison with the NIST LN2 primary standard was encouraging for CESAME!
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Safety: The standard has to be accredited for Explosive environment (ExIIIGT4).

Cesame designed a safety procedure to use all their equipment in such environment and received the needed certification.
Outcomes:

- On-site* measurements on an industrial process during trucks filling (July 2017).
- The safety (explosive environment) has been handled and the standard have the required accreditations.
- The tests were transparent for the operators.
- Natural micron-sized tracers have been found to insure the quality of the measurements.

* LNG terminal in Montoir de Bretagne (France, dept 44) : ELENGY Cie

Really promising on-site experiments!
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According to the GUM (Guide to expression of uncertainties in measurements), the combined standard uncertainty \( u_c(y) \) of the estimate \( y \) of \( Y \) obtained from the input estimates \( x_i \) of input quantities \( X_i \) is given by the square root of the combined variance \( u_c(y)^2 \), itself given by:

\[
    u_c^2(y) = \sum_{i=1}^{N} c_i^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_i c_j u(x_i) u(x_j) r(x_i, x_j)
\]

where

- \( c_i = \frac{\partial f}{\partial x_i} \) is the sensitivity coefficient associated with estimate \( x_i \) of input quantity \( X_i \)
- \( u(x_i) \) is the standard uncertainty of estimate \( x_i \)
- \( r(x_i, x_j) \) is the cross-correlation coefficient between the uncertainty in \( x_i \) and \( x_j \)

The quantity \( u_c(y) \) is the **combined standard uncertainty** of the measurement result \( y \) and the quantity \( U_e(y) = k \times u_c(y) \) is the **expended uncertainty**.
Cryogenic flow rate meas. by LDV

Uncertainty budget assessment in cryogenic conditions (2/3)

Volume flow rate

\[
Q_v = \frac{\bar{v}\pi d^2}{4}
\]

Calibration function

\[
\frac{v_{axis}}{\bar{v}} = a + b \ln(Re_d) + \epsilon
\]

Reynolds number estimation

\[
Re_d = \frac{\rho v_{axis} d}{\mu}
\]

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

<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>
Uncertainty budget assessment in cryogenic conditions

\[ Q_v = \frac{v_{axis}\pi d^2}{4A} \quad A = \frac{v_{axis}}{\bar{v}} \quad \frac{v_{axis}}{\bar{v}} = a + b \ln(Re_d) + \epsilon \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_d )</td>
<td>( \frac{\partial Q_v}{\partial d} = \frac{\pi d v_{axis}}{2A} )</td>
<td>Sensitivity with throat diameter</td>
</tr>
<tr>
<td>( c_{v_{axis}} )</td>
<td>( \frac{\partial Q_v}{\partial v_{axis}} = \frac{\pi d^2}{4A} )</td>
<td>Sensitivity with axial velocity measurement</td>
</tr>
<tr>
<td>( c_A )</td>
<td>( \frac{\partial Q_v}{\partial A} = -\frac{\pi d^2 v_{axis}}{4A^2} )</td>
<td>Sensitivity with model function coefficient</td>
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</tbody>
</table>


<table>
<thead>
<tr>
<th>measurand</th>
<th>( X_i )</th>
<th>unit</th>
<th>( U(X_i) )</th>
<th>unit</th>
<th>Contrib</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d )</td>
<td>0,03985</td>
<td>m</td>
<td>0,038</td>
<td>%</td>
<td>3%</td>
</tr>
<tr>
<td>( A )</td>
<td>1,015</td>
<td>-</td>
<td>0,360</td>
<td>%</td>
<td>78%</td>
</tr>
<tr>
<td>( v_{axis} )</td>
<td>2,04</td>
<td>m/s</td>
<td>0,18</td>
<td>%</td>
<td>19%</td>
</tr>
<tr>
<td>( y = Q_v )</td>
<td>0,0025</td>
<td>m³/h</td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>( u(y)/y )</td>
<td></td>
<td></td>
<td>0,31</td>
<td>%</td>
<td>(k=1)</td>
</tr>
</tbody>
</table>

A is defined as the ratio of the axial velocity to the cross section average velocity

This value has been assessed by Monte Carlo simulations with Air / LN2 experiments

The diameter is measured and certificate gives a value with related uncertainties

Cryogenic conditions have been handled (thermal dilatation coefficient)

The velocity \( v \) of a fluid particle in the flow measured in LDV is determined from: the fringe spacing calibration, the Doppler frequency calibration, the assessment of misalignment

Overall uncertainty on LDV measurement

The uncertainty budget will be reduced by a better assessment of the correlation function soon
Cryogenic flow rate meas. by LDV

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LDV standard new design: Improvements (1/3)

All electrical equipment can be remotely controlled from a safe location.
CH4 detectors (infrared & catalytic bead) + Gas Detection Controllers
New 3D displacement system
New Laser Doppler system
New IP webcam
New vortex cooler system
New Electro-pneumatic valve
Axial expansion joint
Self regulated hotwire
Pressure and temperature sensors
Nozzle design (0.3mm nozzle lip to avoid wake effect)
New windows: avoid vortex area
Cryogenic flow rate meas. by LDV
LDV standard new design: Improvements (2/3)

What about seeding?
Cryogenic flow rate meas. by LDV
LDV standard new design: Improvements (3/3)

New design

Magnetic particles

Cavitation technique

N2 injection
Ineris tests:

- Oxygen presence test during the nitrogen purge cycle
- Oxygen removal time
- Pressure resistance test of the enclosures

- Depressurization test
- Methane detection
- Shutdown of electrical power if an increase on the vacuum level is detected

Preliminary tests in AIR with the new design
Cryogenic flow rate meas. by LDV
LDV standard new design: tests in AIR (1/6)

Air tests at 5 and 10 bar
Cryogenic flow rate meas. by LDV
LDV standard new design: tests in AIR (2/6)

Air tests:

- Radial velocity profile at the throat
- Axial velocity profile (on the centreline)

Jet profile is flat
Canonical
Step velocity gradient
No negative velocities

**Ideal condition with nice seeding**: data rate up to 4000 Hz
Air tests:

- New assessment of the calibration function

\[ y = -0.011 \ln(x) + 1.3188 \]
\[ R^2 = 0.7743 \]
Air tests: Flow disturbances

- Half plain flange
- Double bent
Air tests: Flow disturbances

Half plain flange

Without perturbation

With perturbation
Air tests: Flow disturbances

Double bent

After this tests, the LDV standard has been sent to MURGADOS Reganosa LNG terminal
Cryogenic flow rate meas. by LDV
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:

- $U_{\text{mean}} = 16.95 \text{ m/s}$
- $U_{\text{rms}} = 0.3 \text{ m/s}$
- $Q_{\text{CFM}} = 74.4 \text{ m}^3/\text{h}$
- $Q_{\text{LDV}} = 75.9 \text{ m}^3/\text{h}$
- ~2% deviation (first raw estimation)

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 MURGADOS

Operator interface:

Natural seeding: data rate up to 50 Hz (best case scenario) – 25000 measurements

Can we increase the data rate?
Go to MONTOIR
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
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:**

- $U_{mean} = 18.3 \text{ m/s}$
- $U_{rms} = 0.7 \text{ m/s}$
- $Q_{CFM} = 78.9 \text{ m}^3/\text{h}$
- $Q_{LDV} = 81.9 \text{ m}^3/\text{h}$

~2.9% deviation

*Natural seeding: data rate up to 500 Hz – 213000 measurements*
Cryogenic flow rate meas. by LDV

Road map of the presentation

1. Who we are and what we do
2. Background regarding LNG
3. Description of the LDV technique and measuring system
4. How it works!
5. Let’s go to cryogenic conditions: NIST experiments
6. On-site calibration of cryogenic flow meters
7. Uncertainty budget assessment in cryogenic conditions
8. LDV standard new design: Improvements, accreditation & complementary tests (air / LNG)
9. Conclusions and perspectives
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Conclusions and perspectives

• CESAME wants to perform an accuracy evaluation of the cryogenic flowmeters with and without standard perturbations (previously characterized) (Montoir de Bretagne (Fr), Reganosa (Sp)) and compare with numerical simulation

Flowmeter on-site (bend – no straight pipe before flow meters)

NIST facility - No bend – long straight pipe

• CESAME wants to determine the modification in the extended uncertainty budget due to the standard perturbations (previously characterized)

• Looking for opportunities to create a cryogenic loop in a LNG terminal to calibrate cryogenic flow meters with the LDV standard
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Thank you!

Thank you for your attention
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