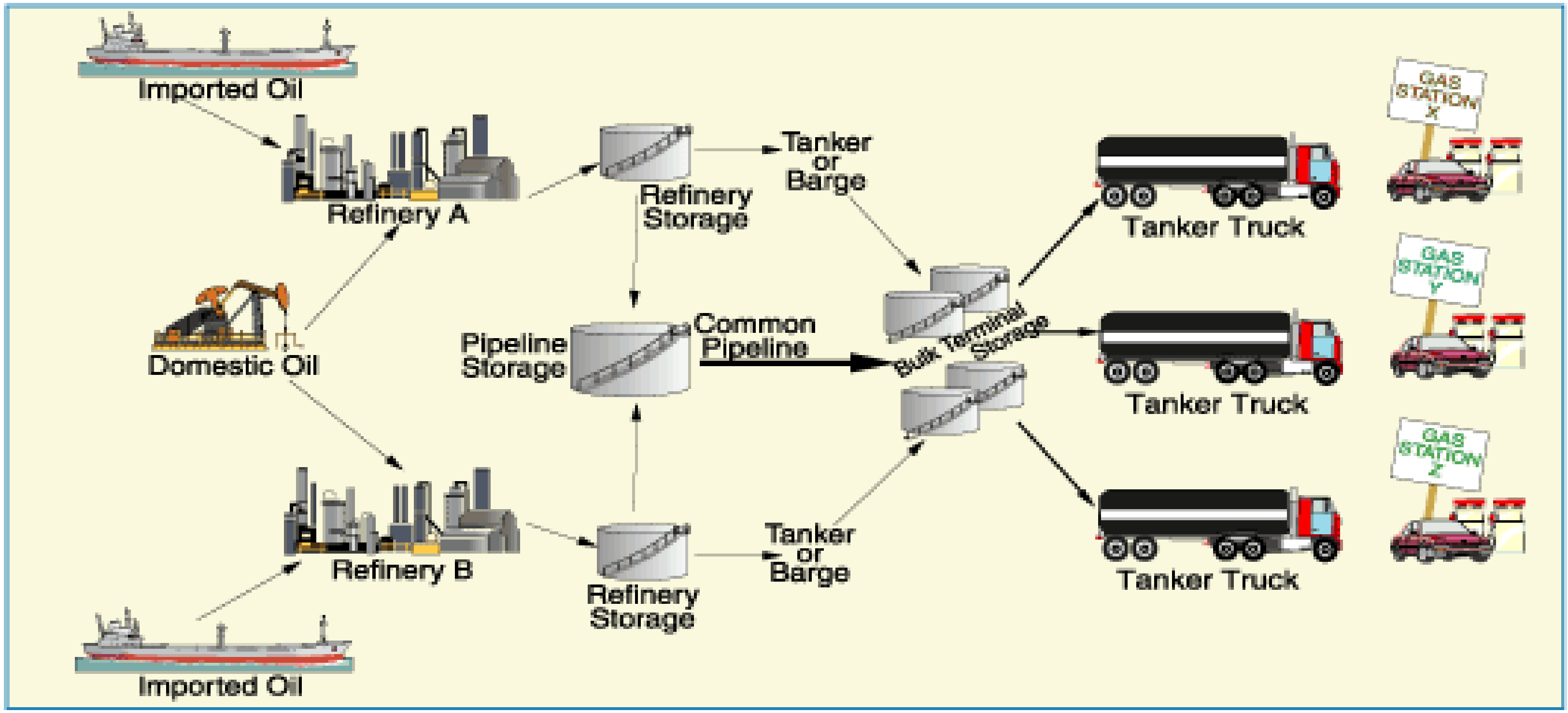
Flow and Volume Measurement Capabilities at CENAM and their link with the Energy Sector

Centro Nacional de Metrología
Dirección de Metrología Mecánica
SIM School 2024, Bogotá, Colombia

Content

- Motivation
- Realities
- Calibration & Measurement Capabilities
- Traceability chains
- International Comparability
- Aplications
- Regulation

motivation



Petroleum is metered > 11 times between the well head and the consumer!

motivation

energy consuption data, MX

By the end of 2023**, natural gas** consumption in Mexico would amount to around 227 million cubic meters per day (8 billion cubic feet per day).

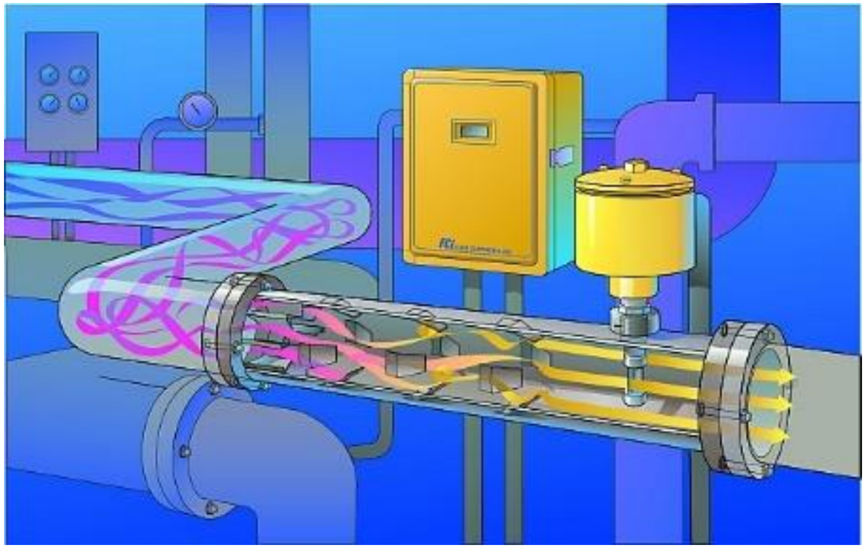
Daily consumption of **petroleum products** (gasoline + diesel + jet fuel + fuel oil) is of the order of 207 million liters, which means a daily per capita consumption of 1.6 liters.

realities

When measurements are made, it is not possible to obtain absolute certainty about the value of what is being measured; the random nature of the measuring instruments, the limited time available to perform the measurements, among other aspects, generate uncertainty in the measurement results...

Flow rate measurements are affected by:

- **Temperature**
- Pressure
- Density
- Viscosity
- moisture content
- fluid cleanliness
- installation conditions
- flow variations
- Pulsations
- Vibrations
- multiphase flows



realities

best measurement capabilities

quantity	uncertainty
time	10^{-12}
length	2.5×10^{-11}
mass	10^{-8}
temperature	7×10^{-8}
density	5×10^{-6}
pressure	2×10^{-5}
volume of liquids (test measures)	4×10^{-5}
liquid flowrate	3×10^{-4}
gas flowrate	1.5×10^{-3}

measurement capabilities

Volume and Flow Metrology

- Small volumes
- Large volumes
- **Liquid Flow**
  - Water
  - Oil
- Gas Flow
- Viscosity
- In situ services
  - master meters
  - proving tanks
  - pipe provers

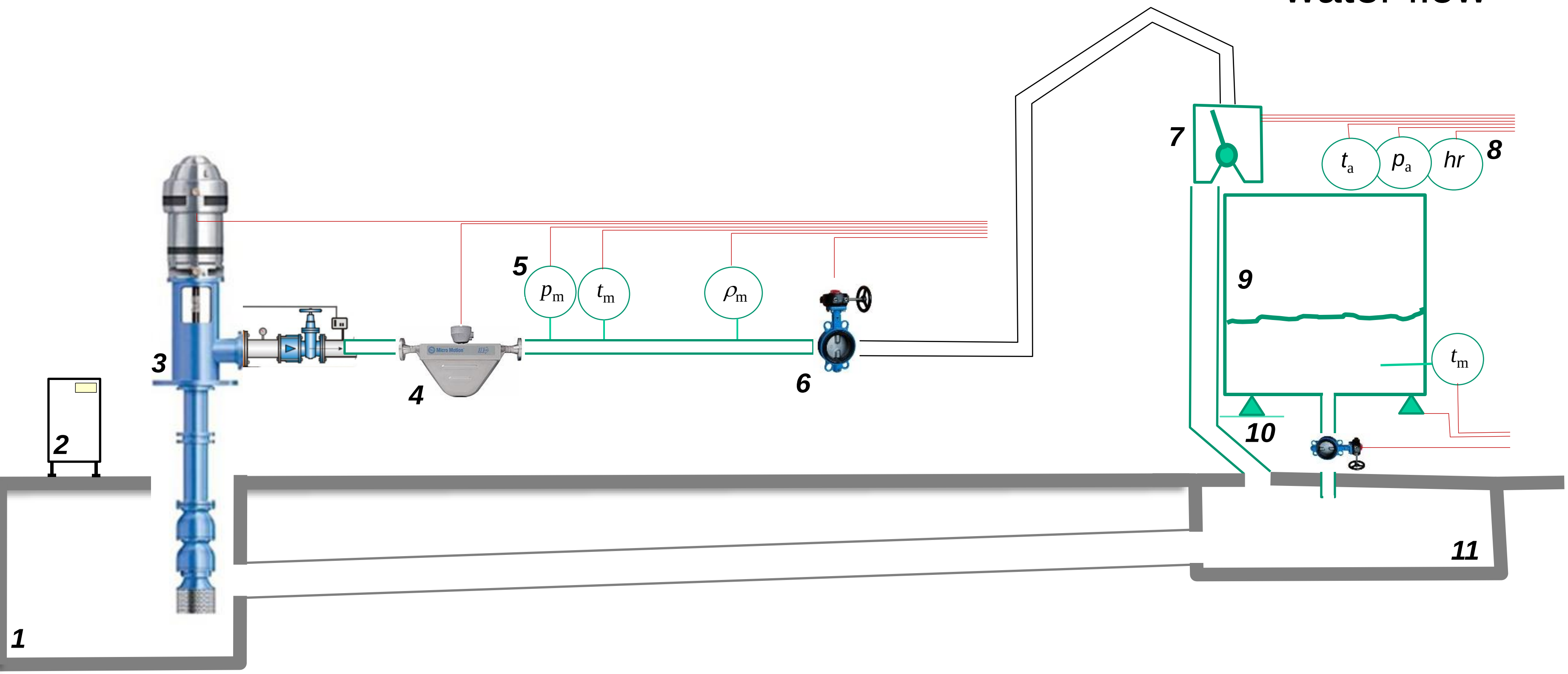
national measurement standards

Water flow

Type	Gravimetric
Flow range	(25 – 12 000) L/min
uncertainty	mass: 0.030 %, k = 2 volume: 0.038 %, k = 2
traceability	CENAM
Working fluid	clean water
weighing system	static
tanks	1500 kg, 10 000 kg
piping	(25 – 200) mm

PNFL

water flow



Pumping

V = (500....1950) rpm
P = 350 hp
V = 400 000 L

piping

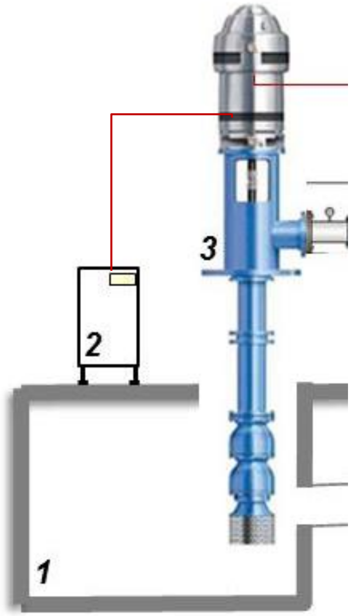
d = (25....200) mm
l ~ 36 m

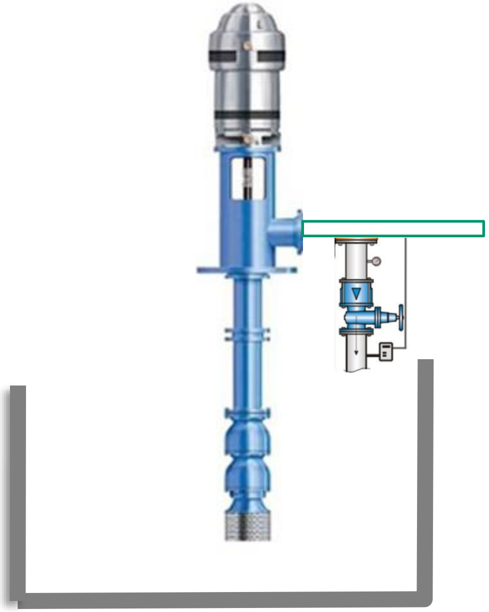
tanks

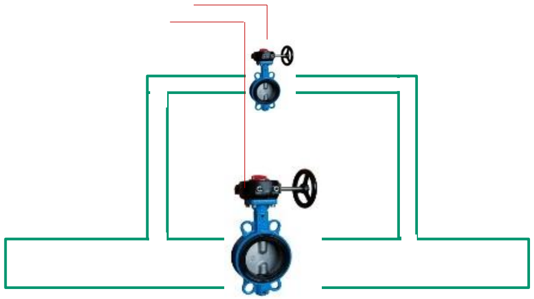
m_1 = 1 500 kg (5 g)
m_2 = 10 000 kg (10 g)

PNFL

flowrate control







Pump speed

- Saves energy consumption
- Avoids heating of the fluid

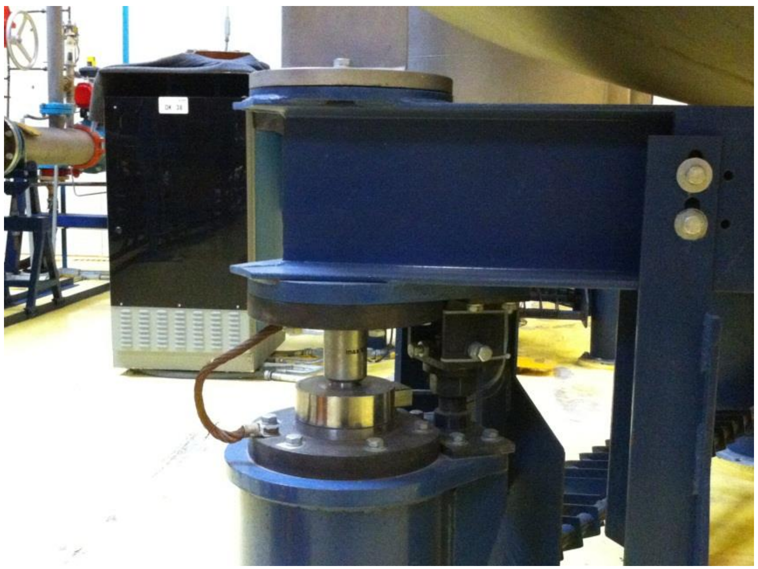
By-pass

- Avoids heating of the fluid
- Water hammer prevention

throttling

- fine control
- Cavitation prevention

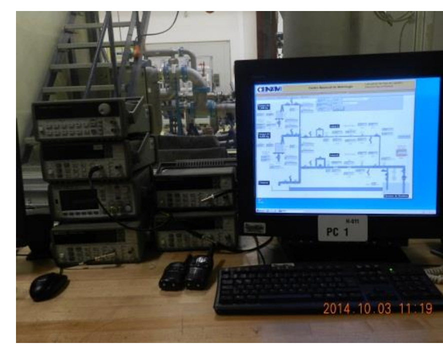
PNFL



load cells (3)
Schenk, torsion ring type.

Amplifier
HBM DK38
GPIB

Windows CVI + DA
6602 NI



PNFL

$$K_m = \frac{N_m}{\frac{t_m}{t_{ref} + C_{div}}\left[\left(m_f + C_{cal,mf} - m_i - C_{cal,mi}\right)\cdot\frac{\rho_p - \rho_a}{\rho_p}\cdot\frac{\rho_{A,r} + C_{cal,\rho}}{\rho_{A,r} + C_{cal,\rho} - \rho_a} + \left(V_f\cdot\rho_{A,i,f} - V_i\cdot\rho_{A,i,i}\right)\right]} + C_{rep}$$

- N_m: *mut* response
- $\frac{t_m}{t_{ref} + C_{div}}$: time measurements
- $\left(m_f + C_{cal,mf} - m_i - C_{cal,mi}\right)$: mass measurements in tanks
- $\frac{\rho_p - \rho_a}{\rho_p}\cdot\frac{\rho_{A,r} + C_{cal,\rho}}{\rho_{A,r} + C_{cal,\rho} - \rho_a}$: air buoyancy corrections
- $\left(V_f\cdot\rho_{A,i,f} - V_i\cdot\rho_{A,i,i}\right)$: mass changes in inventory volume
- C_{rep}: repeatability of the calibration process

x_i	$u_i(K_m)$/(pulsos/kg)	%
C_{den}/(kg/m^3)	0.00	0.00
ϑ_{ref}/°C	0.000	0.00
ϑ_m/°C	0.00	0.00
p_m/MPa	0.00000	0.000
ϑ_a/°C	0.00264	0.08
p_b/hPa	-0.00077	0.01
hr/%	0.00015	0.00
d_{ref}/m	0.00001	0.000
l_{ref}/m	0.00015	0.00
e/m	0.00000	0.00
E/MPa	0.00000	0.00
α/°C^{-1}	-0.00001	0.00
p_{ii}/MPa	0.00026	0.001
ϑ_{ii}/°C	-0.00877	0.88
p_{if}/MPa	-0.00026	0.00
ϑ_{if}/°C	0.00880	0.89
m_i/kg	0.01219	1.70
m_f/kg	-0.07690	67.7
t_{ref}/s	0.03949	17.9
t_m/s	-0.00673	0.52
N/pulsos	0.00135	0.02
ρ_b/(kg/m^3)	-0.00025	0.00
C_{rep}/(pulsos/kg)	0.030	10.31
	$\sum$	100.0
$u(K_m)$/(pulsos/kg)		0.083
$U(K_m)$/(pulsos/kg)		0.166
$U(K_m)$/%		0.028

national measurement standards

gas flowrate

Type	Campana, DP
flow range	[30 – 2000] L/min
uncertainty	Volume: 0.15 %, k = 2
traceability	CENAM
working fluid	Dry air
Meters under test	DiaphragmRotary, turbine, vortex, variable area, ultrasonic, laminar flow

national measurement standards

gas flowrate

Type:	master meters
flow range:	up to 6000 m^3/h
Fluid:	ambient air
uncertainty:	0.25 %
Method:	direct comparison
pumping:	multistage blower, screw type compressor

traceability chain

gas flowrate

m — Length unit realization — 2.5×10^{-11}

s — Time unit realization — 10^{-12}

K — Temperature unit realization — 0.02 mK

universal counter — 10^{-7}

digital thermometer + Pt-100 — 0.01 ºC

Gas flow primary standard — 0.15 %

Reference system — 0.25 %

Meter under test — (0.3 – 0.4) %

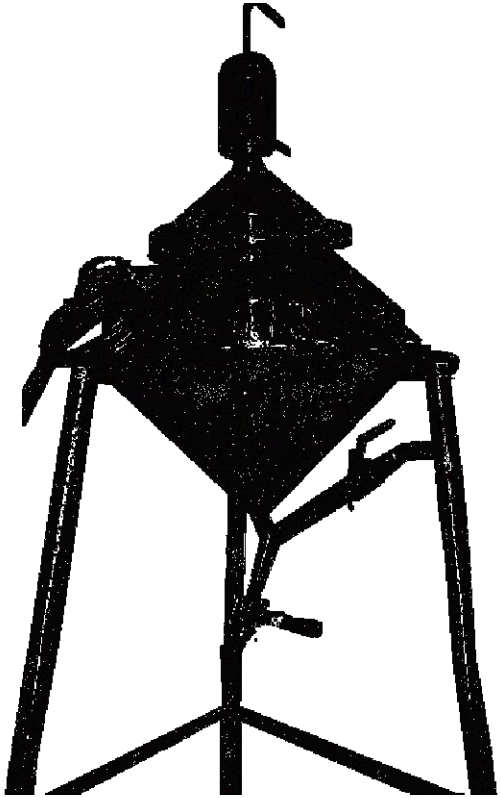
national measurement standards

Liquid hydrocarbon flow

Type:	unidirectional prover
Volume:	3000 L
Flow range:	up to 5000 L/min
Fluid:	Diesel
uncertainty:	0.037 %
Method:	flying start and stop

national measurement standards

Volume of liquid

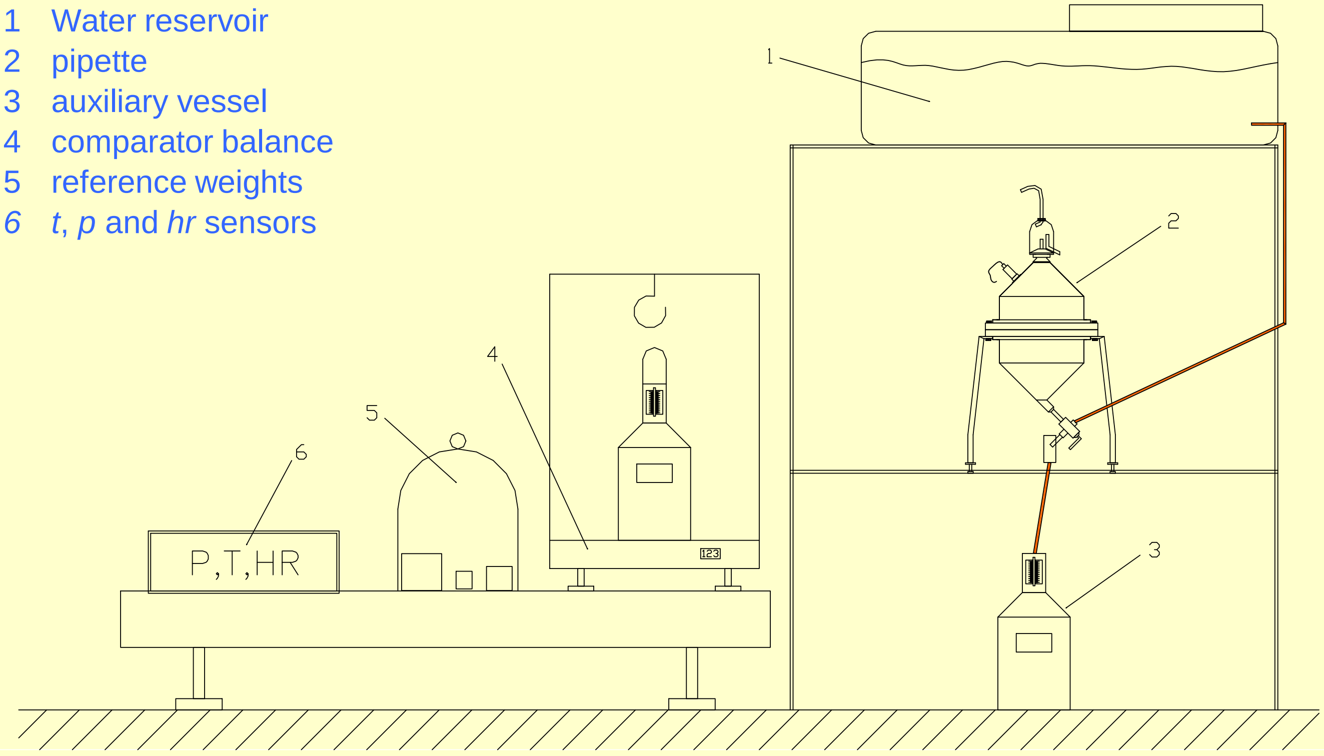


Type:	pipette
Volume:	20 L, 50 L
Fluid:	pure water
uncertainty:	0.003 0 %, k = 2
Method:	gravimetric
Material:	304 ss
resolution:	overflow

Volume of liquid

calibration method: doble substitution

1 Water reservoir
2 pipette
3 auxiliary vessel
4 comparator balance
5 reference weights
6 t, *p* and *hr* sensors



Volume of liquid

calibration method: doble substitution

$$V_{20°C} = \frac{\left(\sum_{i=1}^{n} m_f - \sum_{i=1}^{n} m_i\right) \cdot \left(1 - \frac{\rho_a}{\rho_m}\right) + A_f - A_i}{\rho_{ag} - \rho_a} \cdot \left[1 - \beta \cdot \left(t_{ag} - 20\right)\right]$$

$$A_f = \frac{L_{f2} + L_{f3} - L_{f1} - L_{f4}}{2} \cdot \frac{m_s \left(1 - \frac{\rho_a}{\rho_{ms}}\right)}{L_{f3} - L_{f2}}$$

$$A_i = \frac{L_{i2} + L_{i3} - L_{i1} - L_{i4}}{2} \cdot \frac{m_s \left(1 - \frac{\rho_a}{\rho_{ms}}\right)}{L_{i3} - L_{i2}}$$

- m_f: mass of the final reference weights
- m_i mass of the initial reference weights
- ρ_a: air density
- ρ_m: density of reference weights
- A_f: Final mass differential
- A_i: initial mass differential
- L: mass readings
- ρ_{ms}: density of sensitivity weights
- β: coefficient of thermal expansion of steel
- t_{ag}: water temperature

Volume of liquid

calibration method: doble substitution

1 Record the values of ta, p_a, *HR* and t_{ag}.

2 Load the reference weight m_i, and record the reading as L_{i1}.

3 Remove the m_i weight and place the empty auxiliary vessel, and record as L_{i2}

4 Add the sensitivity weight m_s, and record the reading as L_{i3}

5 Remove the vessel and reload the m_i weight, together with the m_s weight, and record as L_{i4}.

6 Fill the volumetric standard with pure water.

7 Empty the standard into the auxiliary vessel, allowing 30 s draining time.

8 Record the values of t_a, p_a, RH and t_{ag}.

9 Load the weight mf, record this reading as L_{f1}.

10 Remove the mf weight and place the container filled with water, record this reading as L_{f2}.

11 Add the m_s weight, and record the balance reading as L_{f3}

12 Remove the container and place the weight mf, record this reading as L_{f4}.

Volume of liquid

Ec. Tanaka, et. al.

$$\rho_A = a_5\left[1 - \frac{(a_1 + \vartheta)^2 \cdot (a_2 + \vartheta)}{a_3 \cdot (a_4 + \vartheta)}\right]$$

$a_1/°C = -3.983\,035 \pm 0.000\,67$

$a_2/°C = 301.797$

$a_3/°C^2 = 522\,528.9$

$a_4/°C = 69.348\,81$

$a_5/(kg\ m^{-3}) = 999.974\,950 \pm 0.000\,84$

air density

Richard Davis, at. al.

2. The CIPM-2007 equation and its uncertainty

2.1. The CIPM-2007 equation

Formally, the derivation of the CIPM-2007 equation is the same as that of its predecessors [1, 2].

The density of moist air is evaluated using an equation of state

$$\rho_a = \frac{pM_a}{ZRT}\left[1 - x_v\left(1 - \frac{M_v}{M_a}\right)\right], \qquad (1)$$

where the quantities and units are p/Pa: pressure, $t/^\circ\mathrm{C}$: air temperature, T/K: thermodynamic temperature $= 273.15 + t/^\circ\mathrm{C}$, x_v: mole fraction of water vapour, $M_a/(\mathrm{g\,mol^{-1}})$: molar mass of dry air, $M_v/(\mathrm{g\,mol^{-1}})$: molar mass of water, Z: compressibility factor, $R/(\mathrm{J\,mol^{-1}\,K^{-1}})$: molar gas constant.

The recommended ranges of temperature and pressure over which the CIPM-2007 equation may be used are unchanged from the original CIPM-81 version [1] and are repeated here for completeness:

$$600\,\mathrm{hPa} \leqslant p \leqslant 1100\,\mathrm{hPa},$$

$$15\,^\circ\mathrm{C} \leqslant t \leqslant 27\,^\circ\mathrm{C}.$$

air density

OIML R111

E.3 Approximation formula for air density

The most accurate formula of air density is the CIPM formula (1981/91) [39].

An approximate formula may also be used:

$$\rho_a = \frac{0.34848\ p - 0.009\ (hr) \times \exp(0.061\ t)}{273.15 + t} \qquad (E.3\text{-}1)$$

Where: the density of air, ρ_a, is obtained in kg m^{-3};

the pressure, p, is given in mbar or hPa;

the relative humidity, hr, expressed as a percentage; and

the temperature, t, in °C.

Equation *(E.3-1)* has a relative uncertainty of 2×10^{-4} in the range 900 hPa < p < 1100 hPa, 10 °C < t < 30 °C and hr < 80 %.

air density

OIML R111

Ciudad	h/m	p_b/hPa
México D.F.	2200	780
La Paz	3700	653
Bogotá	2600	744
Quito	2900	718
Atacama	2400	762

air density

OIML R111 modificada

Simposio de Metrología 2012 8 - 12 de Octubre, 2012

AMPLIACIÓN DEL ALCANCE DE APLICACIÓN DE LA ECUACIÓN SIMPLE SUGERIDA EN OIML R111-1 PARA EL CÁLCULO DE LA DENSIDAD DEL AIRE

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Resumen: En diversos documentos técnicos se incluyen versiones simplificadas para describir el estado termodinámico del aire atmosférico, como una función de la temperatura, presión y humedad relativa ambientales. Específicamente, en la recomendación internacional OIML R111-1 se incluye un modelo simplificado para calcular la densidad del aire, con el inconveniente de que el alcance de aplicación se limita al intervalo de $900 < p/\text{hPa} < 1100$. En este trabajo se propone un modelo matemático para ampliar el alcance de aplicación para los siguientes intervalos: $15 < t/°\text{C} < 27$, $700 < p/\text{hPa} < 1013$, $0 < hr/\% < 80$. Se incluye un ejercicio de estimación de incertidumbres para las condiciones típicas de laboratorios de calibración.

air density

OIML R111, modified

OIML R111-1

$$\rho_a = \frac{a_0 p - a_1 hr \times e^{(a_2 t)}}{273.15 + t}$$

$$\rho_a = \frac{a_0 p - a_1 hr \times e^{(a_2 t + a_3 p)}}{273.15 + t}$$

ρ/(kg/m^3)	air density
p/hPa:	barometric pressure
hr/%:	relative humidity
t/°C:	air temperature
a_0, a_1, a_2, a_3:	constants to be determined

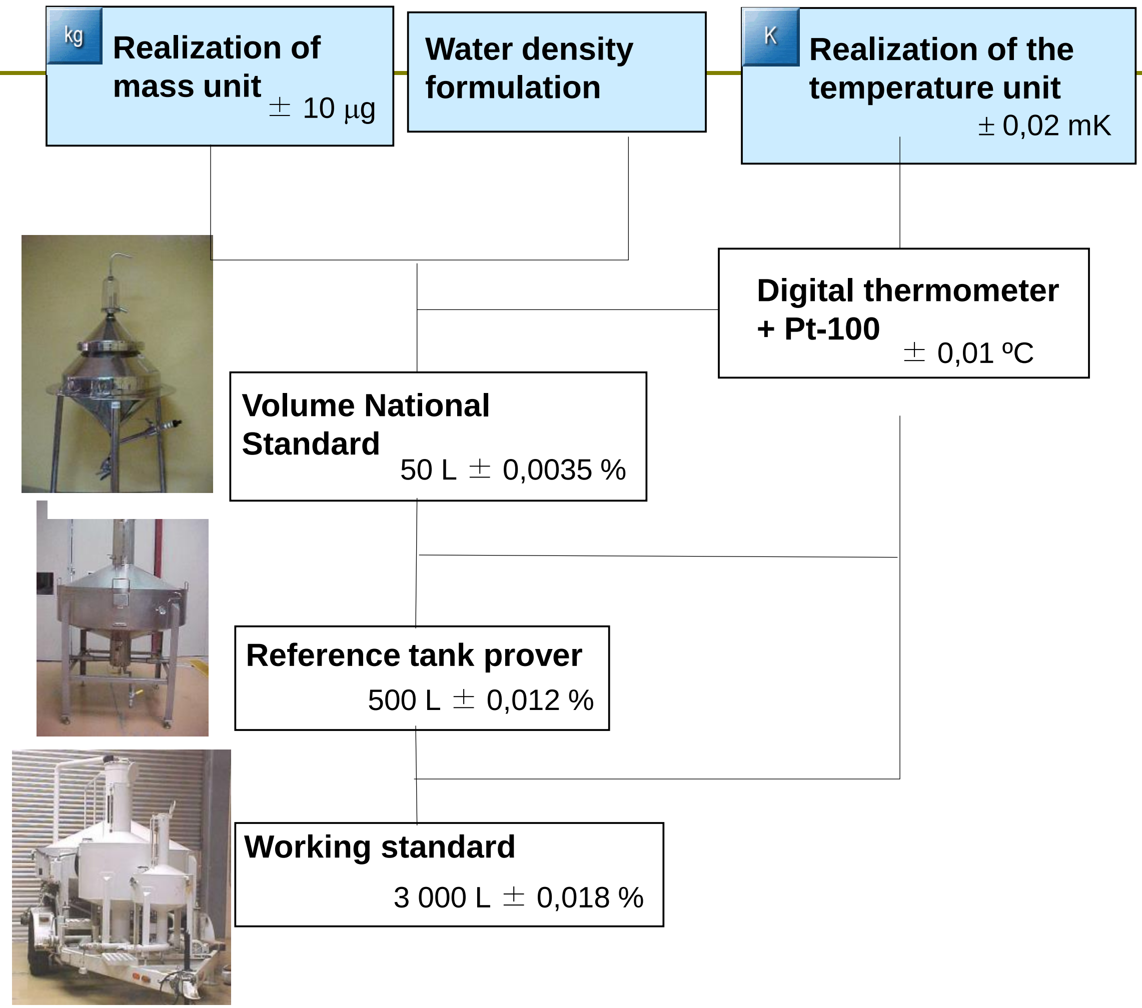
air density

```
p<- runif(100 000, 700, 1013.25)
t<-runif (100 000, 15, 27)
hr<-runif(100 000, 0, 80]
sol<-nls(ρa~(a0·p-a1·hr·exp(a2·t+a3·p))/(273.15+t)), start=list(a0=0.3, a1=0.01,a2=0.5,a3=0)
```

a_0/(kg K kJ^{-1}) = (3.484 785 8 ± 0.000 002 1)×10^{-1}
a_1/(kg K m^{-3}) = (9.174 8 ± 0.006 4)×10^{-3}
a_2/ºC^{-1} = (6.249 2 ± 0.001 9)×10^{-2}
a_3/kPa^{-1} = (– 5.230 ± 0.066) ×10^{-5}

measuring ranges:

15 < t/ºC < 27
700 < p/hPa < 1013
0 < hr/%< 80;



Traceability chart for volume of liquids measurements by using tank provers.

Traceability chain

liquid hydrocarbons

Reference standard

3 000 L ± 0.020 %

Water draw method

Bi-directional prover

$V_{20\ ºC,\ 0\ Pa}$ ± 0.03 %

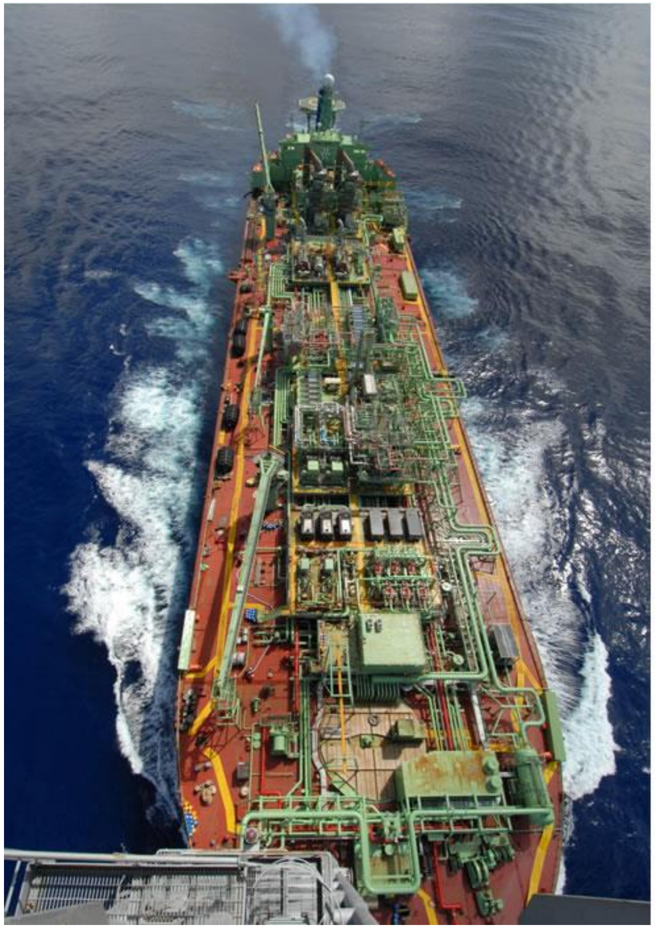
Direct comparison method

On line meters

$V_{T,P}$ ± 0.1 %

relevant projects

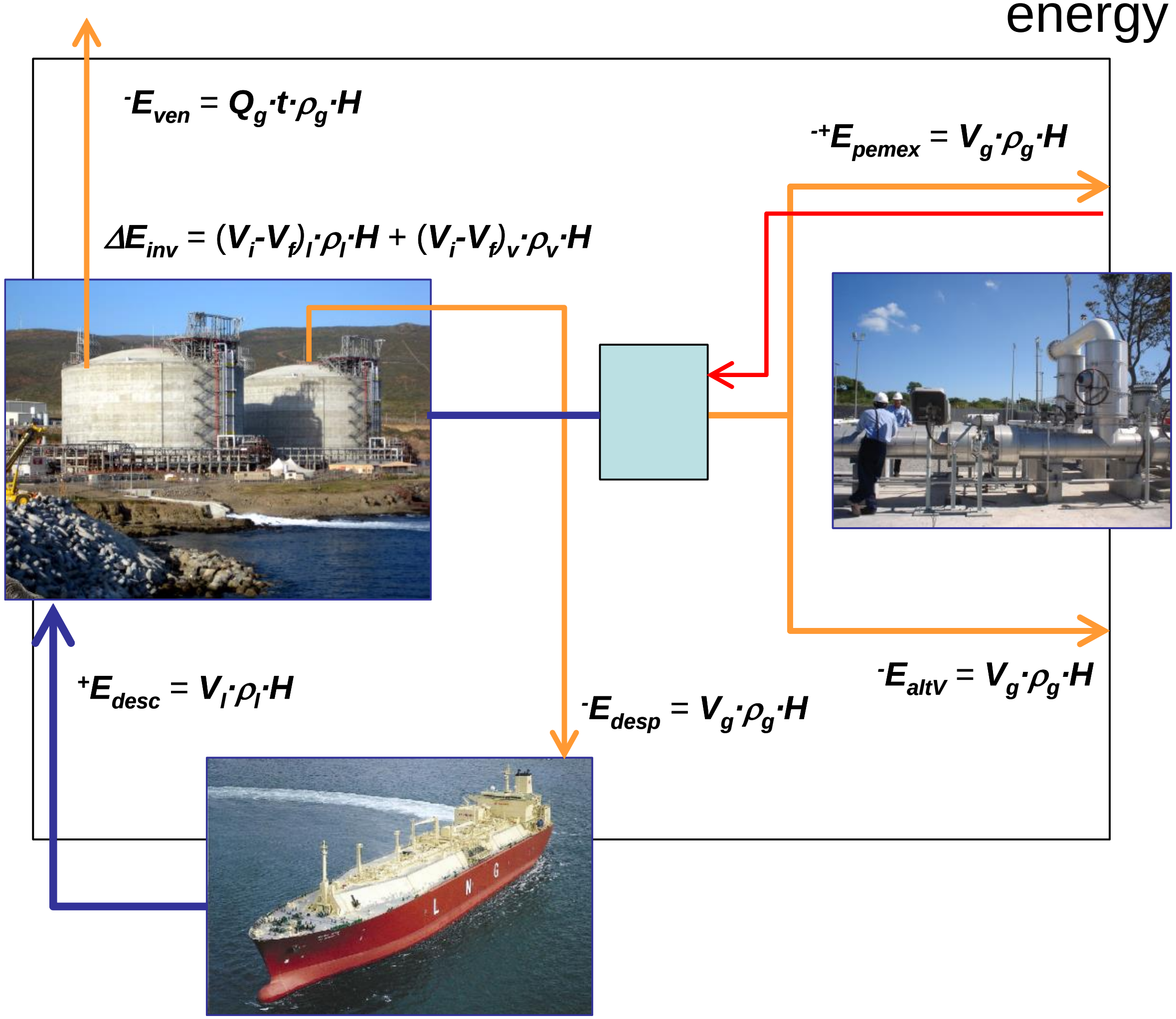
PEMEX – Bergesen Worlwide



- Measurement system design review
- Performance testing of the measurement system
  - FAT (Houston, TX)
  - Assembling site tests (Singapur)
- Performance tests using crude oil
  - En SPSE (Fos sur Mer, Francia)
- Performance testing at Kuu Maloob Zaab field
- Measurement system uncertainty estimation

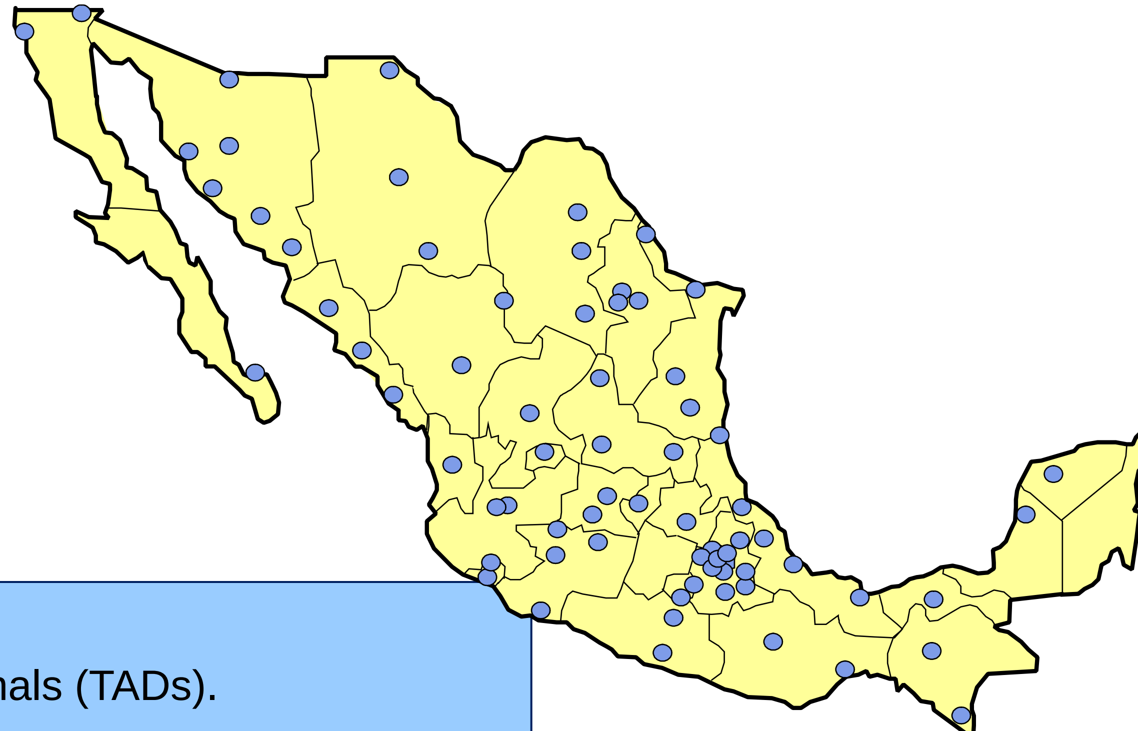
relevant projects

energy balance, TLA



relevant projects

PEMEX LOGÍSTICA



77 Storage and Distribution Terminals (TADs).

- Calibration of master meters
- Calibration of proving tanks
- Determination of the MPD

internacional comparability

water flow

CCM.FF-K1

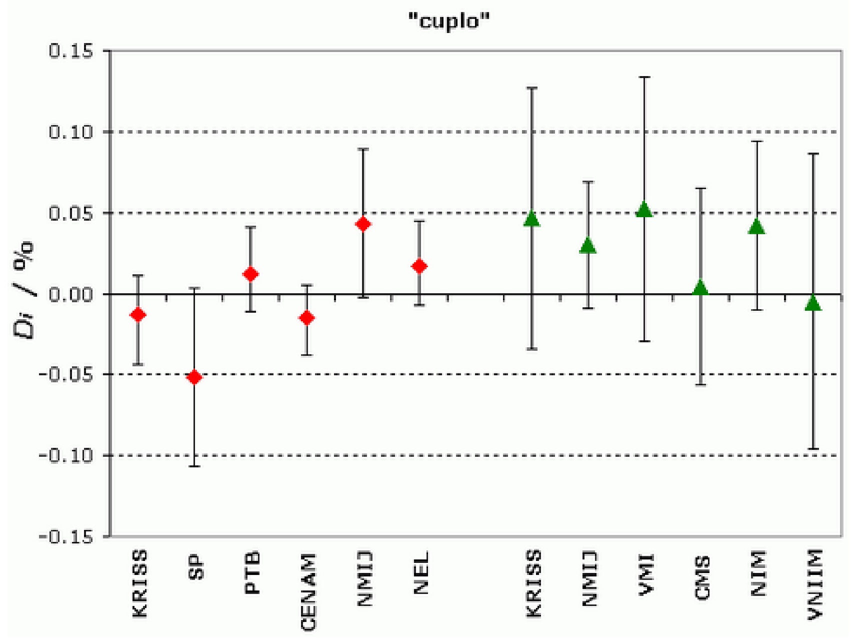
Results

Laboratory individual measurements | Equivalence statements | Degrees of equivalence | Graph(s) of equivalence

CCM.FF-K1 and APMP.M.FF-K1

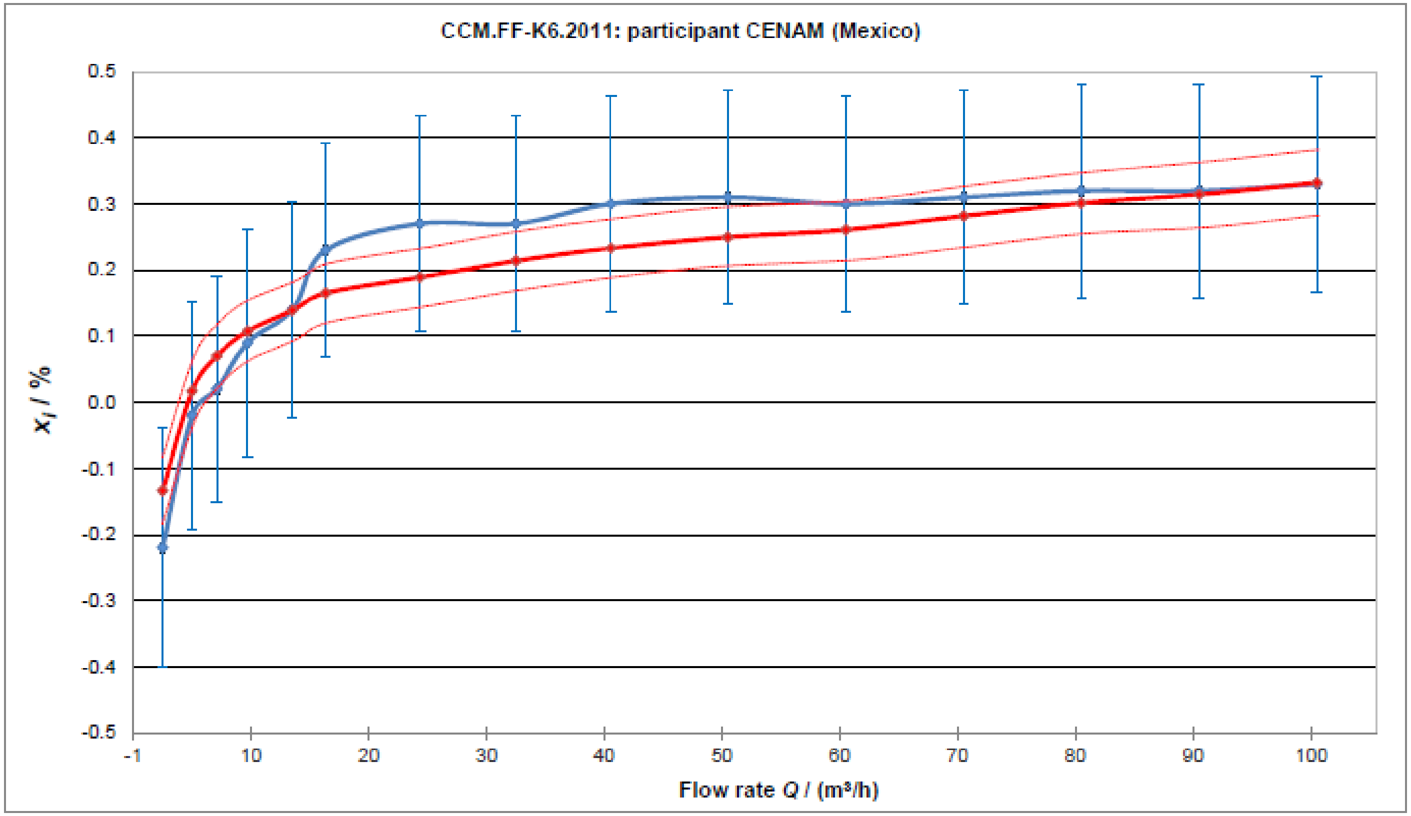
Water flow
TRANSFER STANDARD : Coriolis flowmeter
MEASURAND : Mass K factor
CONFIGURATION: Upstream
HIGH WATER FLOW: 70 m^3/h

Degrees of equivalence: offset D_i and expanded uncertainty at a 95 % level of confidence



internacional comparability

gas flow



The solid blue curve represents the participant's results, x_i, with expanded uncertainty bars (k = 2), U_{i8}

The solid red curve represents the key comparison reference value

The two red dash curves correspond to ($x_R + U_R$) and ($x_R - U_R$), where U_R is the expanded uncertainty (k = 2) of x_R

internacional comparability

Liquid volume

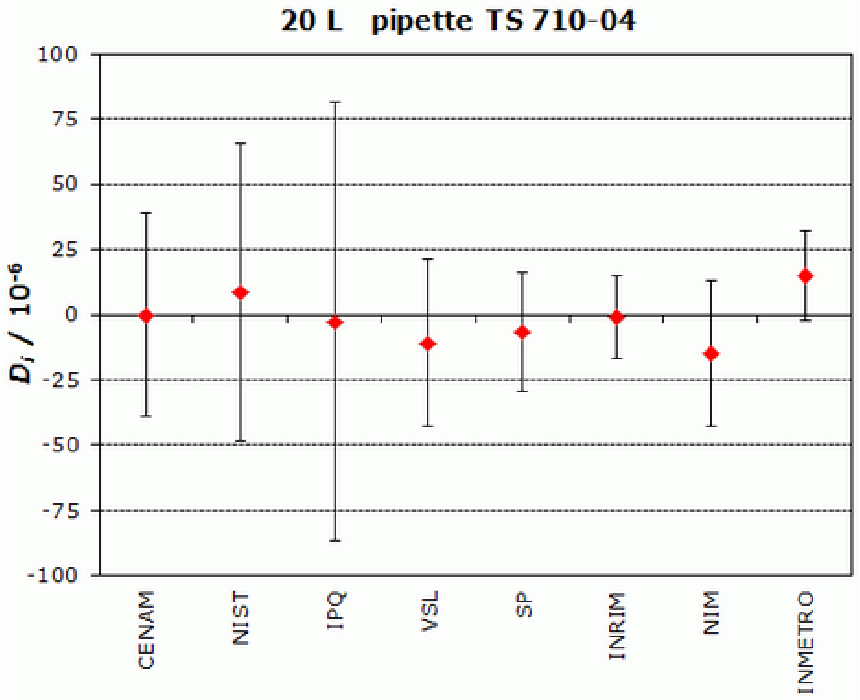
CCM.FF-K4.1.2011

Results

Laboratory individual measurements	Equivalence statements	Degrees of equivalence	Graph(s) of equivalence

MEASURAND: Water volume
NOMINAL VALUE: 20 L
TRANFERT INSTRUMENTS: Two pipettes, serial numbers TS 710-04 and TS 710-05

Graphs of equivalence obtained for each pipette:
offset D_i and expanded uncertainty U_i (k = 2) expressed in 10^{-6}



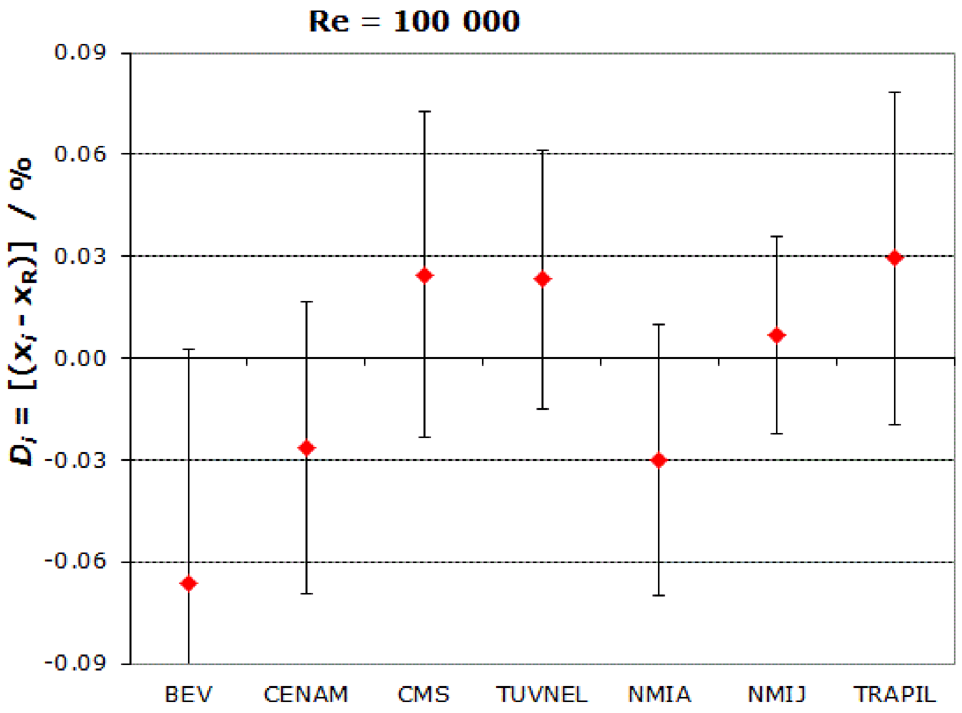
internacional comparability

hydrocarbon flow

CCM.FF-K2.2015 Hydrocarbon liquid flow

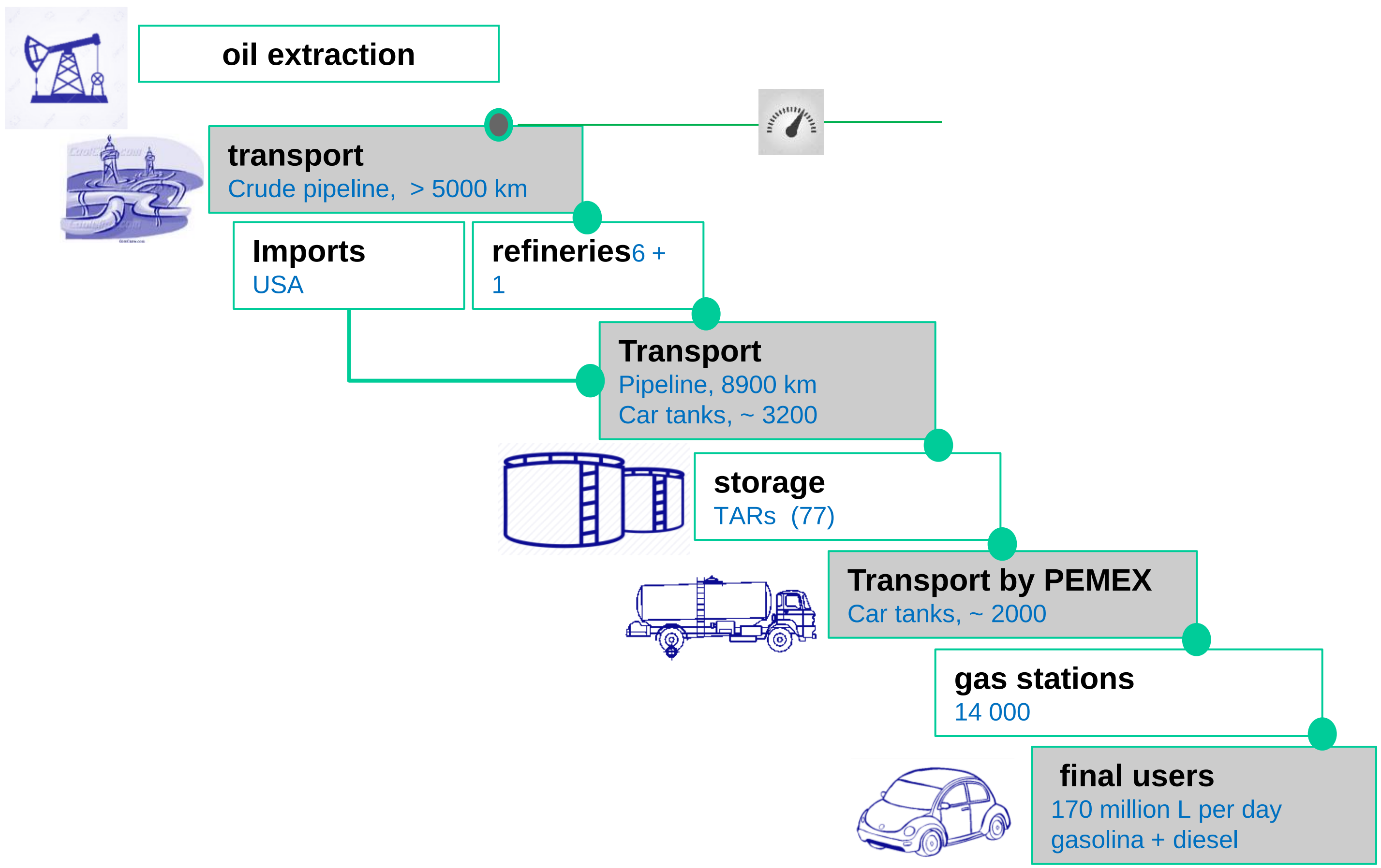
Measurand: relative *K* factor at a specific Reynolds number

Transfer instrument: screw type positive displacement flow meter



production chain

fuels



regulations