Australian Government
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National Measurement Institute

Establishment of an Ultra-High Accuracy 670 PVTt Gas Flow Primary Standard at NMIA

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In this Presentation:

- The Need of a New Standard
- PVT Design Methodology
- Uncertainty Analysis & Working Example
- Conclusions

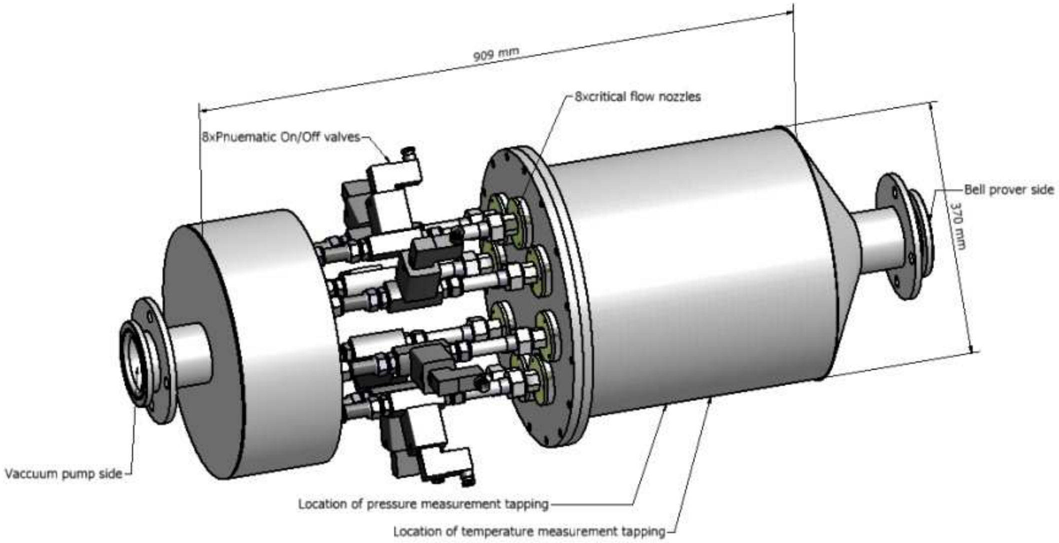
NMI Gas Flow Facility

Currently used at NMIA,

- 2 x primary standards:
  - 300L Bell Prover (±0.1%)
  - 5 x Mercury Sealed Piston Provers (±0.084-0.100%)
- 3 x Nozzle Arrays used as transfer standards for flowrates from 0.005 to 500 $m^3 h^{-1}$:
  - Rotor Sonic Nozzle Array, or RSNA (0.005 to 8 $m^3 h^{-1}$)
  - Satellite Sonic Nozzle Array, or SSNA (0.5 to 180 $m^3 h^{-1}$)
  - Rotor Sonic Nozzle Array, or RSNA (50 to 300 $m^3 h^{-1}$)

NMI Gas Flow Facility

300L Bell Prover at NMIA



Schematic Diagram of the Critical Flow Venturi Sonic Nozzle Array at NMIA

NMI Gas Flow Facility

Completed recently at NMIA,

- 670L **P**ressure, **V**olume, **T**emperature and **t**ime (PVTt) primary standard (Discussed today!)
- 7000 m^3 h^{-1} Critical Flow Venturi Nozzle Array (nick-named the Blue Spaghetti Monster Array or BSMA)

NMIA Gas Flow Facility

Disadvantages of using bell and mercury-sealed piston provers:

(1) safety concerns due to the use of mercury and oil as seals in these standards,

(2) the limitation on using these standards for measurement with pressures higher than atmospheric due to the oil and mercury liquid seals,

(3) difficulty in reducing the large spatial temperature non-uniformity in and around these standards while used in ambient air, which is currently assessed to be 150 mK, and

(4) difficulty in determining the volumes of these provers to better than 400 ppm (0.04%).

PVTt System

What is a PVTt System?

- A well-determined volume with ultra-accurate pressure, temperature and chemical composition measurements used to calculate the density of gas inside this volume to determine the gas mass.
- Used mainly in calibrating nozzles by having a diverter valve with a start-stop timer.
- Usually housed inside a water tank for best temperature uniformity and stability (reducing a major source of uncertainty).

PVTt System

Reasons to have a PVTt System:

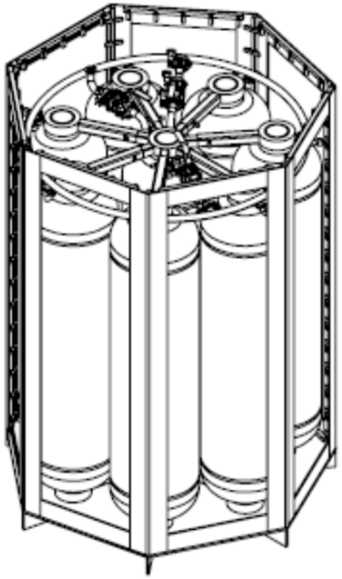
(1) replace the existing bell and mercury-sealed piston provers,

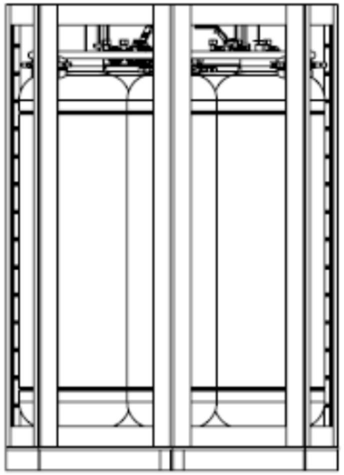
(2) increase the range of flowrate up to 120 kg h^{-1} as well as increasing CVFN calibration pressures to 7 bars, and

(3) improve the measurement uncertainties from ±0.1% to better than ±0.02%.

PVTt System

NMIA’s 670L PVTt System





PVTt System - Design Methodology

Design was based on existing standards but with several improvements made on:

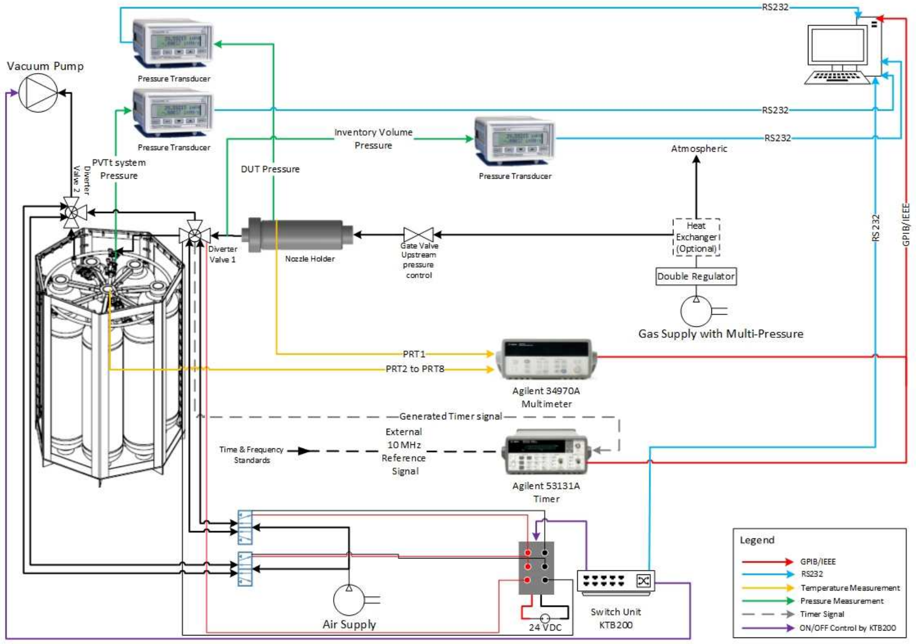
- Design and Mode of Operation.
- PVTt Tank Volume determination.
- Water Tank Temperature Control/Uniformity.

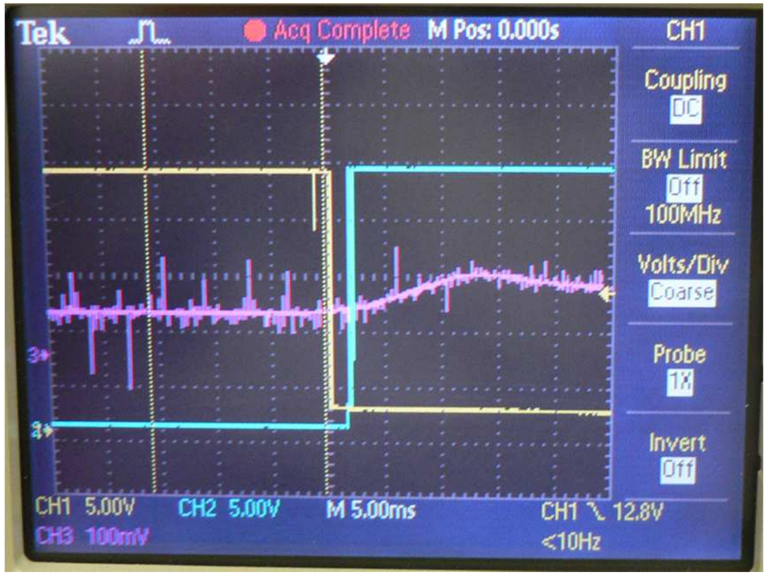
PVTt System – Design & Mode of Operation

Design and mode of operation

- Based on annular cylinders to allow heat transfer from the outside and inside walls.
- Placed vertically for better convective heat transfer.
- Fast 3-way valve to minimise uncertainty associated with Start/Stop of flow (<2ms).
- Full automation of calibration to minimise user errors and streamline data collection.
- Reduction of inventory volume as compared to that of total volume (<25 mL), hence leading to negligible effect on measurements.

PVTt System - Design & Mode of Operation



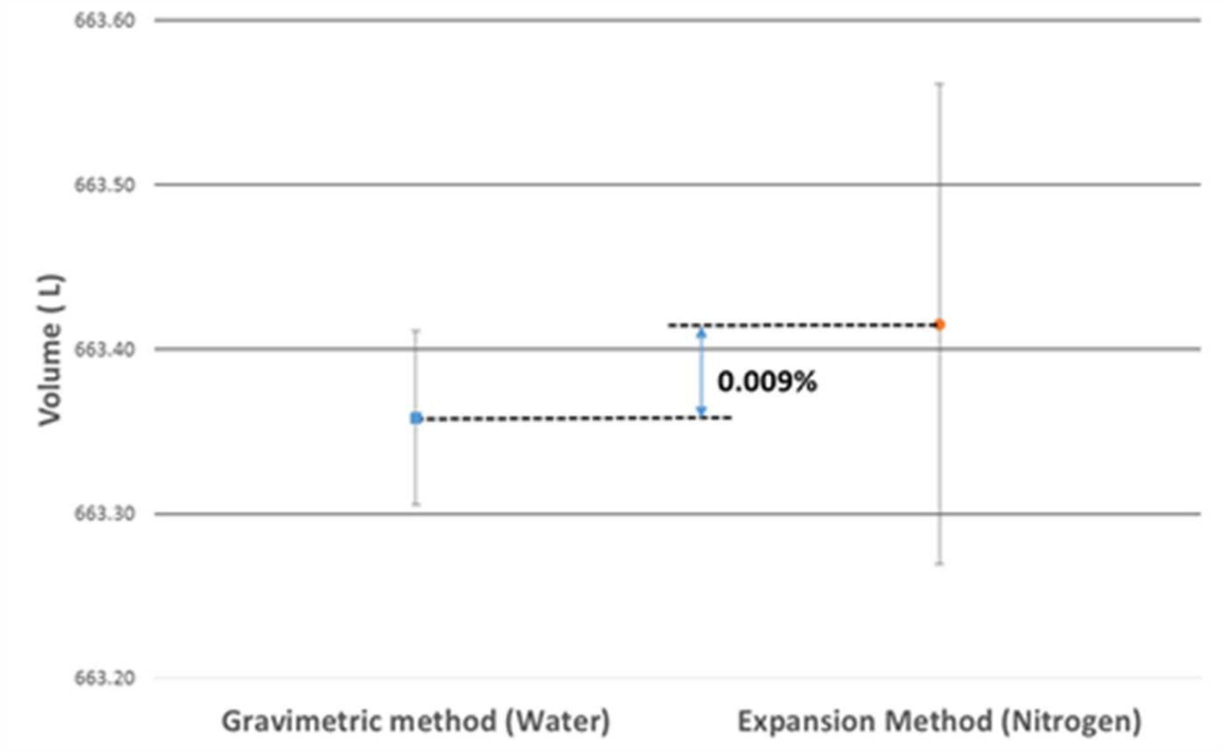


PVTt System – Volume Determination

Two measurement methods were employed:

- ☐ Gravimetric method using water – conducted by NMIA MRQ team with an uncertainty of ±80 ppm.
- ☐ Gravimetric method using nitrogen (aka expansion method) – conducted by Gas Flow and Chemical Metrology Groups with assistance from Dr Li Chunhui (NIM) with an uncertainty of ±221 ppm.

PVTt System – Volume Determination

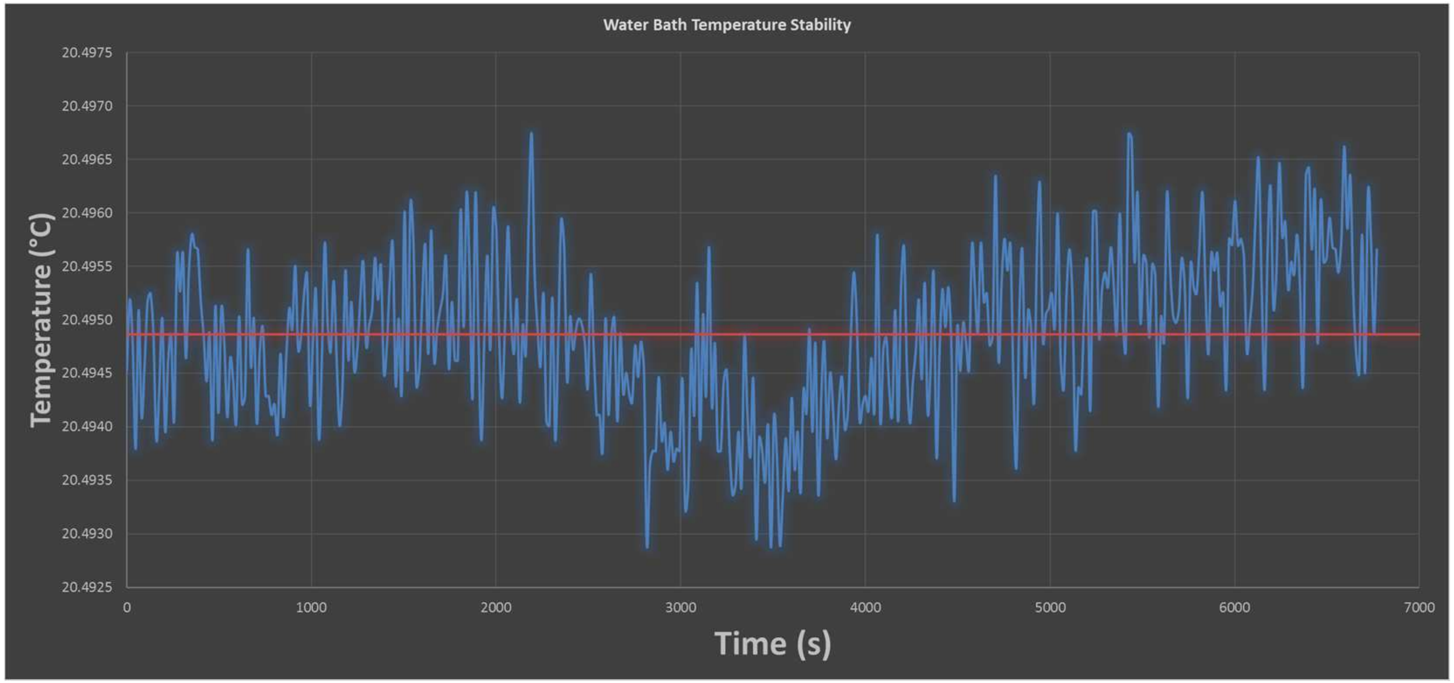


PVTt System – Tank Temperature

Water Tank Temperature Control/Uniformity

- ❑ Water bubbling at centre of cylinders to mix water and provide cooling effect.
- ❑ PID controller connected to heater elements and an SPRT for accurate temperature control.
- ❑ Seven PRTs used at various locations inside the tank to assess uniformity at all times – better than 2 mK observed.

PVTt System – Tank Temperature



Graph of temperature measurement of NMIA water bath versus time.
Standard deviation was calculated to be 0.9mK

PVTt System - Uncertainty Analysis

Mathematical model used (conservation of mass):

$$Q_m = \frac{(m^e_{PVTt} - m^s_{PVTt}) + (m^e_{Inv} - m^s_{Inv})}{t} \quad \text{, or}$$

$$Q_m = \frac{V_{Inv}(\rho^e_{Inv} - \rho^s_{Inv}) + V_{Inv}\ (\rho^e_{Inv} - \rho^s_{Inv})}{t}$$

For a mathematical model with correlated uncertainty components, the following equation can be used:

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

For fully correlated components, $r(x_i, x_j) = 1$.

For non-correlated components, $r(x_i, x_j) = 0$.

PVTt System - Uncertainty Analysis

The uncertainty components V_{PVTt}, V_{Inv} and t are obtained by various measurement methods and therefore considered to have non-correlated uncertainties, hence their $r\left(x_i, x_j\right) = 0$.

On the other hand, the two sets of densities, $(\rho^e_{PVTt}, \rho^s_{PVTt})$ and $(\rho^e_{Inv}, \rho^s_{Inv})$, are calculated from measurements of pressure and temperature in conjunction with a published equation of state and therefore considered to be correlated.

It follows from the above:

$$u_{Q_m} = \sqrt{\begin{gathered}\left(c_{V_{PVTt}} u_{V_{PVTt}}\right)^2 + \left(c_{\rho^e_{PVTt}} u_{\rho^e_{PVTt}}\right)^2 + \left(c_{\rho^s_{PVTt}} u_{\rho^s_{PVTt}}\right)^2 + \left(c_{V_{Inv}} u_{V_{Inv}}\right)^2 + \\ 2c_{\rho^e_{PVTt}} c_{\rho^s_{PVTt}} u_{\rho^e_{PVTt}} u_{\rho^s_{PVTt}} r(\rho^e_{PVTt}, \rho^s_{PVTt}) + 2c_{\rho^e_{Inv}} c_{\rho^s_{Inv}} u_{\rho^e_{Inv}} u_{\rho^s_{Inv}} r(\rho^e_{Inv}, \rho^s_{Inv})\end{gathered}}$$

PVTt System – Working Example

A CFVN with a nominal diameter of 2 mm was connected in series with the PVTt standard. The starting pressure in the PVTt tank was set to ~100 Pa. Dry nitrogen, with a purity better than 99.999% produced by the boil-off of liquid nitrogen at NMIA cryogenic facility, was allowed to flow into the PVTt tank through the CFVN for a period of 420 s giving an end pressure of ~39 kPa. The temperature of the tank's water was set to 20.450°C and this set point was maintained within ±0.9 mK. Measurements of the PVTt tank pressures and water temperatures were recorded. These measurements were repeated seven times.

PVTt System – Working Example – Uncertainty

Gas used: dry nitrogen, N_2
Starting Pressure = 100 Pa, End Pressure = 39×10³ Pa
Temperature = 20.450°C,
V_{PVTt} = 0.663 358 m³, V_{Inv} = 18×10⁻⁶ m³, t = 420 s

Components	$\boldsymbol{u}$(@1SD or k=1)		**Source**
		ppm	
$\boldsymbol{V_{PVTt}}$	27 mL	40	Cal report
$\boldsymbol{\rho^e_{PVTt}}$			
Pressure	5 Pa	132	[6]
Temperature	6 mK	21	[6]
Equation	2.2×10^{-5} kg m^{-3}	50	[5]
$\boldsymbol{\rho^s_{PVTt}}$			
Pressure	5 Pa	131	[6]
Temperature	6 mK	0.06	[6]
Equation	6.2×10^{-8} kg m^{-3}	0.2	[5]
$\boldsymbol{V_{Inv}}$	0.18 mL	0.1	[6]
$\boldsymbol{\rho^e_{Inv}}$			
Pressure	5 Pa	0.004	[6]
Temperature	6 mK	<0.001	[6]
Equation	2.3×10^{-5} kg m^{-3}	0.002	[5]
$\boldsymbol{\rho^s_{Inv}}$			
Pressure	5 Pa	0.004	[6]
Temperature	6 mK	<0.001	[6]
Equation	2.3×10^{-5} kg m^{-3}	0.001	[5]
$\boldsymbol{t}$	5×10^{-3} s	12	[6]
if all uncertainties are non-correlated $\boldsymbol{u_{Q_m}}(k=1,\ r=0)$ = 182 ppm			
Let r = 0.95 *(highly correlated uncertainties)*			
$\boldsymbol{u_{Q_m}}(k=1,\ r=0.95)$ = 57.8 ppm			
$\boldsymbol{U_{Q_m}}\ (k=2,\ r=0.95)$ = 116 ppm			

Components	$\boldsymbol{u}$(@1SD or k=1)		**Source**
		ppm	
$\boldsymbol{Q_{m,STD}}$	3.9×10^{-8} kg s^{-1}	58	Table 1
$\boldsymbol{\rho_N}$			
Pressure	7.9 Pa	39	Combined
Temperature	4 mK	7	Combined
Equation	5.9×10^{-5} kg m^{-3}	25	[5]
$\boldsymbol{p_N}$	7.9 Pa	39	Combined
Repeatability (7 trials)	1.4×10^{-10} m²	15	Measured
$\boldsymbol{u_N}(k=1,\ r=0)$ = 85.5 ppm			
$\boldsymbol{U_N}(k=2,\ r=0)$ = 171 ppm			

Conclusions

- NMIA's gas flow measurement uncertainty has been improved from ±0.1% to ± 0.012% credited primarily to better volume determination of ±0.008% and stringent water temperature control and uniformity of 2 mK.
- Further improvements on the uncertainty can be achieved (1) by using more accurate transducers, and (2) increasing the correlation among various components from highly correlated , $r = 0.95$, to fully correlated, $r = 1$.
- Improvements on the measurement uncertainty of calibrating a CFVN can be made by (1) using better pressure transducers, and (2) placing the CFVN in a more uniform and better controlled temperature environment (water tank!).
- Preliminary comparison with NMIA standards has shown good agreement however a formal comparison that involves other national institutes around the world is needed.

Thank you

Questions?