Ogura Industrial Corporation
Ballard Power Systems

In-situ Anode Recirculation Rate Measurement Method (Draft)

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1.0 Importance of Hydrogen Recirculation in PEM Fuel Cell Systems

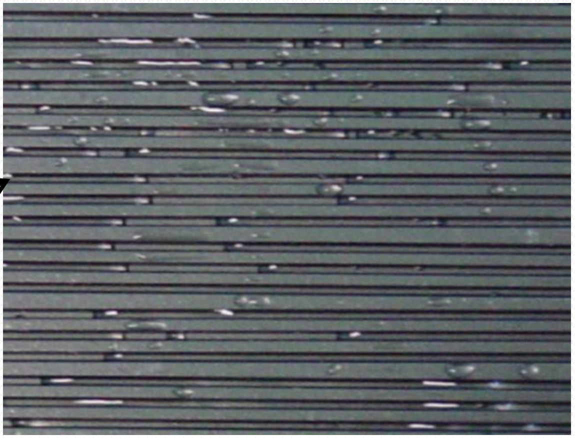
There are several key factors for proper anode gas mixture recirculation in Fuel Cell systems and they can be classified as follows:

- Ensure Minimum Anode dP across the stack (keep the channels clear from the liquid water droplets)
- Provide sufficient humidification of the gas mixture in the anode inlet
- Satisfy stack requirement with respect to the “H2 Stoichiometry”

Typically, some sort of Hydrogen Recirculation Device (HRD) is used and it has to be able to move the amount of gas that satisfies all of the requirements listed above, or in other words to provide adequate anode gas recirculation..

1.1 Minimum Anode dP

- Crucial for FC Stack durability: Clearing the channels of water droplets
- Typically the minimum Anode dP is around 30 mbard.
- This parameter can be measured directly



Water droplets in plate channels

1.2 Anode Inlet Humidification (RH%)

- Adequate humidification is crucial to stack performance
- This parameter can be measured directly

1.3 H2 Stoichiometry Definition

H2 Stoichiometry is a requirement provided by FC stack manufacturer.

$$H2Stoich = Vh\_1/Vh\_feed \quad (1)$$

Where
H2Stoch – Hydrogen Stoichiometry
Vh_1 – stream of dry hydrogen in the stack inlet
Vh_feed – stream of hydrogen consumed by the stack

Anode gas composition: H_2, Water Vapour, Nitrogen
Volume of ballast gases: 70%

<u>Challenge: determine which part of the recirculated gas mixture is hydrogen.</u>
(important for warranty disputes, trouble shooting, etc.)

1.4 Measurements of HRB Performance Parameters

- It is relatively easy to measure directly two of the three listed HRB performance parameters – these are:

  Anode dP

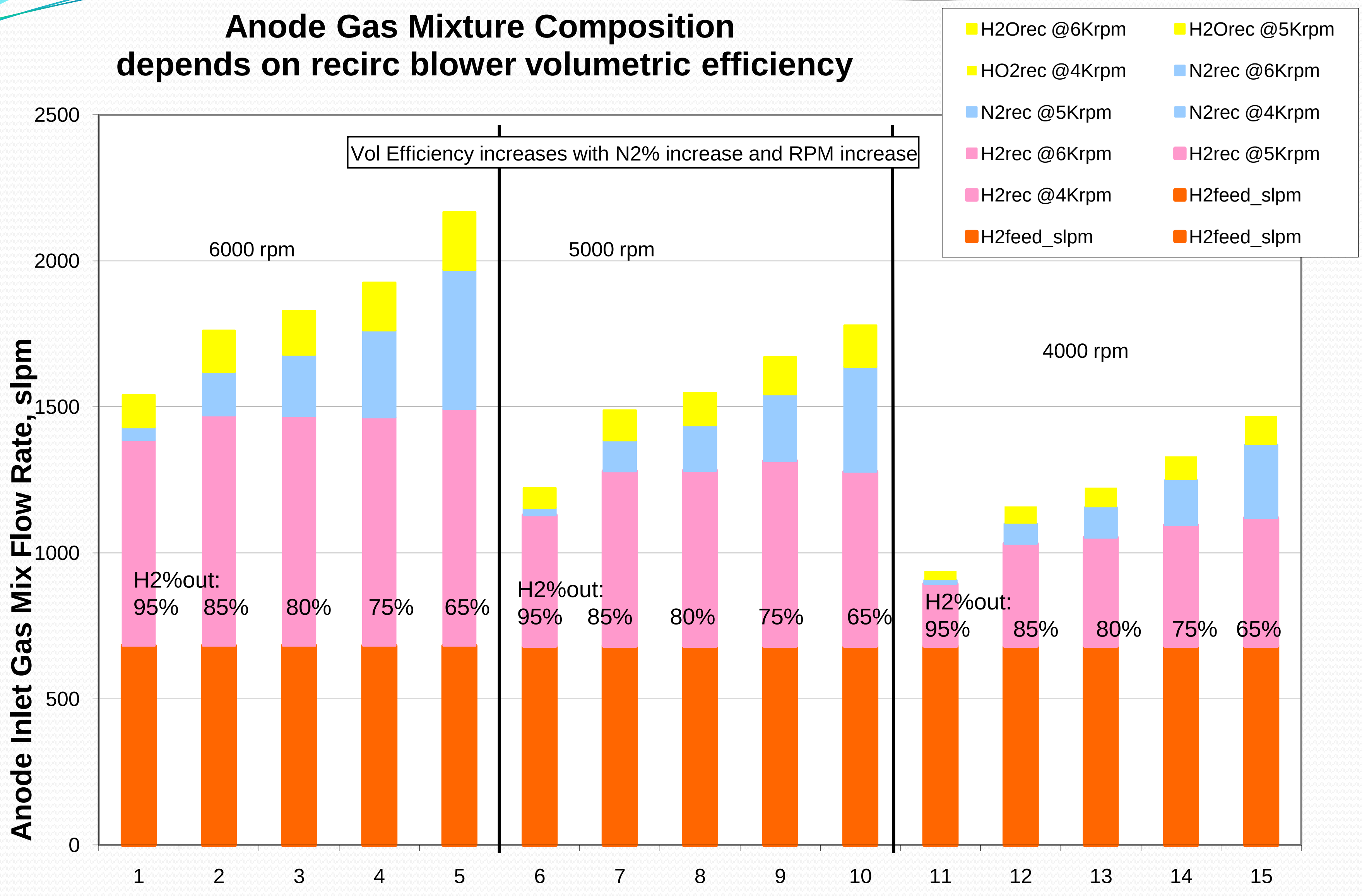
  Anode Inlet Humidification (RH%)

- A direct measurement of the third parameter,

  H2Stoich or Anode Outlet Gas Mixture flowrate (from which H2Stoich could be calculated)

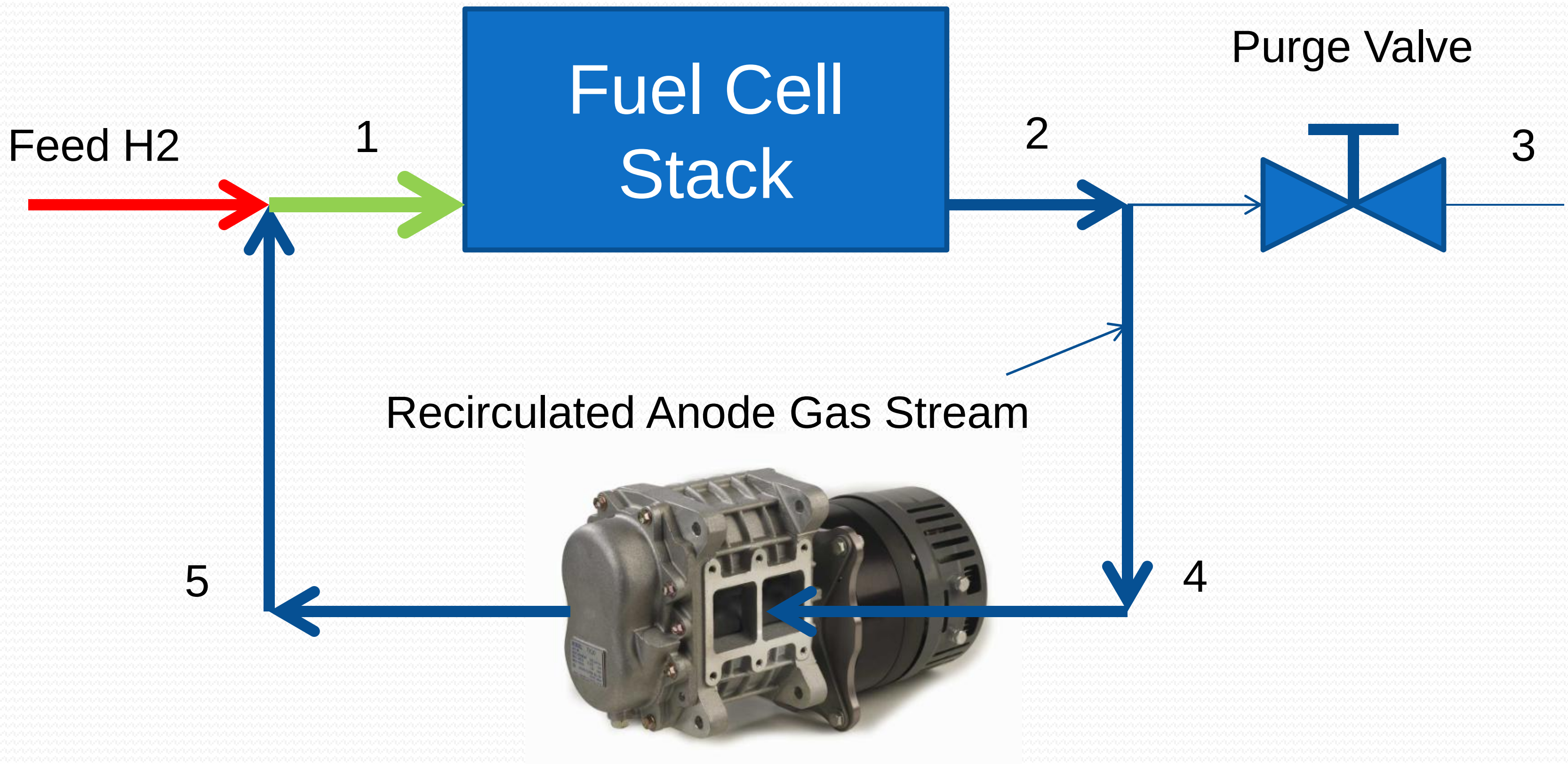
  using traditional gas flowrate measurement methods is not practical because the recirculated gas is a mixture of gases, and because of liquid water droplets presence in the gas stream, which considerably affects readings of the instruments.

Fig. 1 Example of Anode Gas Mixture Compositions



2.0 Hydrogen Stoich Determination

Fig. 2 Fuel Cell Anode Loop



Hydrogen Recirculation Blower (Ogura TX technology)

2.0 Hydrogen Stoichiometry Determination

It is possible to measure the H2 concentration in a dry gas mixture of H2 and N2* in the stack inlet and outlet (H2%in and H2%out) with standard chromatograph.

The following equations can be written for the system presented in Figure 2:

$$H2\%in = (Vh\_feed + Vh\_2)/(Vh\_feed + Vh2 + Vn) \qquad (2)$$

$$H2\%out = Vh\_2/(Vh\_2 + Vn) \qquad (3)$$

where

H2%in, H2%out – Hydrogen concentrations in the stack inlet and outlet, respectively (measured parameters)

Vh_feed – stream of Hydrogen consumed by the stack

Vh_2 – stream of recirculated Hydrogen

Vn – stream of Nitrogen (assumed the same in the stack inlet and outlet)

*) N2 is almost always present in the anode gas mixture due to the diffusion through MEA. With proper setting of purge valve V1 the N2 concentration can be controlled and maintained at desired level.

2.0 Hydrogen Stoichiometry Determination

Note that Vh_1 from Equation1 can be expressed as:

$$Vh\_1 = Vh\_feed + Vh\_2 \quad (4)$$

Which allows to express the Equation 1 as:

$$H2Sto = 1 + Vh\_2/Vh\_feed \quad (1a)$$

After Equations (2) and (3) are re-written with respect to the parameter Vn and compared:

$$Vn = (Vh\_feed+Vh\_2 – H2\%in*(Vh\_feed+Vh\_2))/ H2\%in =$$
$$= (Vh\_2 – Vh\_2*H2\%out)/H2\%out \quad (5)$$

The following relationship is obtained:

$$(Vh\_feed+Vh\_2) = Vh\_2 * (1/H2\%out – 1)/(1/H2\%in – 1) \quad (6)$$

2.0 Hydrogen Stoichiometry Determination

After terms containing directly measured parameters (H2%in and H2%out) are separated from the other terms, the Equation 6 takes the following form:

Vh_feed/Vh_2 = (1/H%out – 1)/(1/H2%in – 1) – 1 (6a)

Left part of which contains elements of Equation 1a.
After Equation (6a) is combined with Equation (1a) the following expression for H2Sto is obtained:

H2Sto = H2%out * (1- H2%in) / (H2%in – H2%out) + 1 (7)

Where
H2Sto - Hydrogen stoichiometry
H2%out, H2%in – molar concentrations of H2 on dry basis in stack outlet and inlet, respectively, expressed as a fraction of 1 (not as %).

3.0 Method Accuracy Discussion

The method accuracy depends on the following factors:

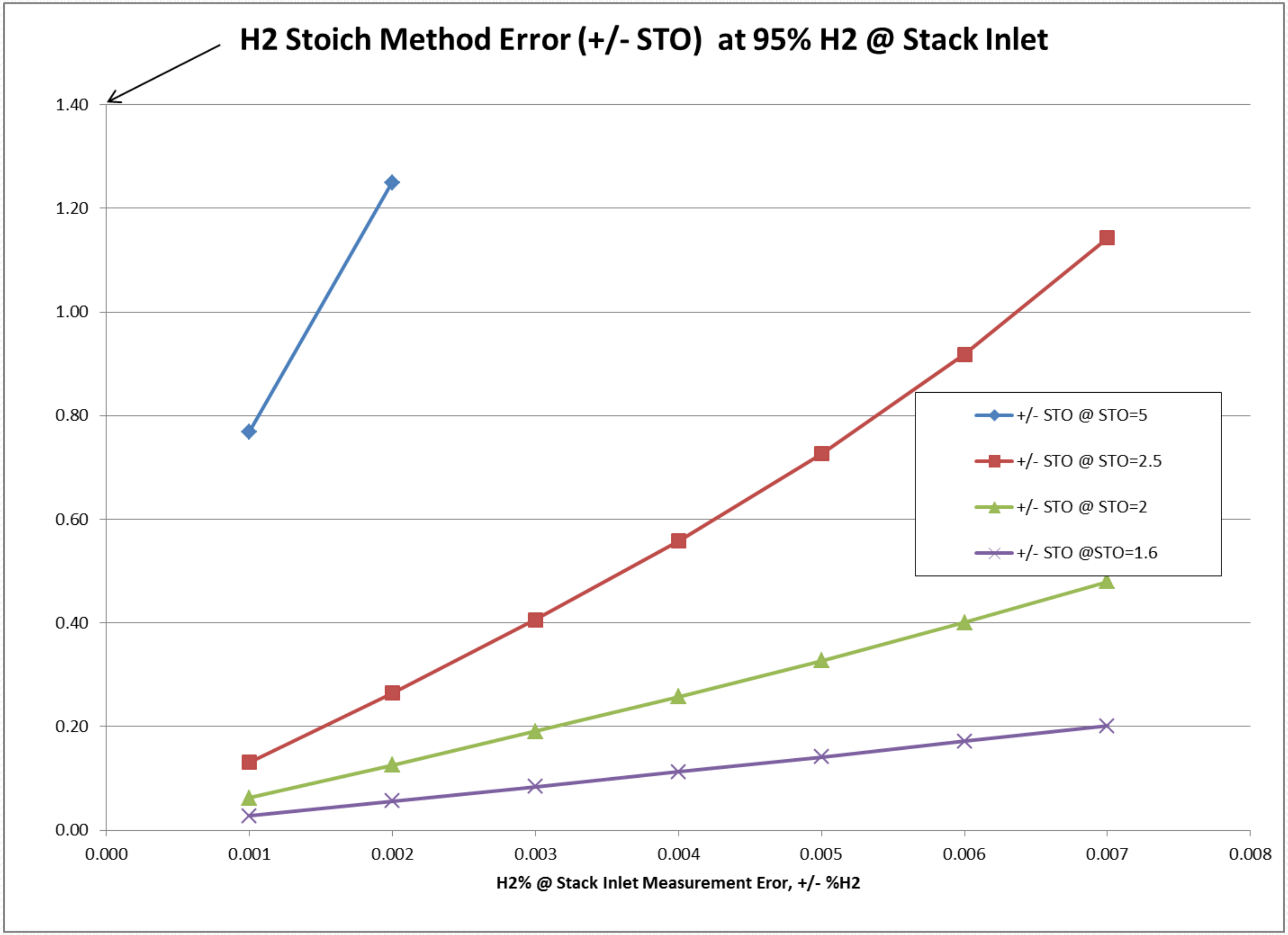
- H2% measurement accuracy
- Chosen H2 concentration level in the stack inlet which is controlled by the anode gas purge rate
- Actual recirculation rate (stoichiometry)
- Actual purge rate

The effect of the first three factors is presented in the next 2 slides.

Typically, the hydrogen losses due to purging are at the 0.5% consumption level, therefore the effects of purge losses on the concentrations are negligible in most of the cases. If required, a correction factor in Equation 3 can be introduced to compensate the Vh_2 and Vn difference in the stack inlet and outlet.

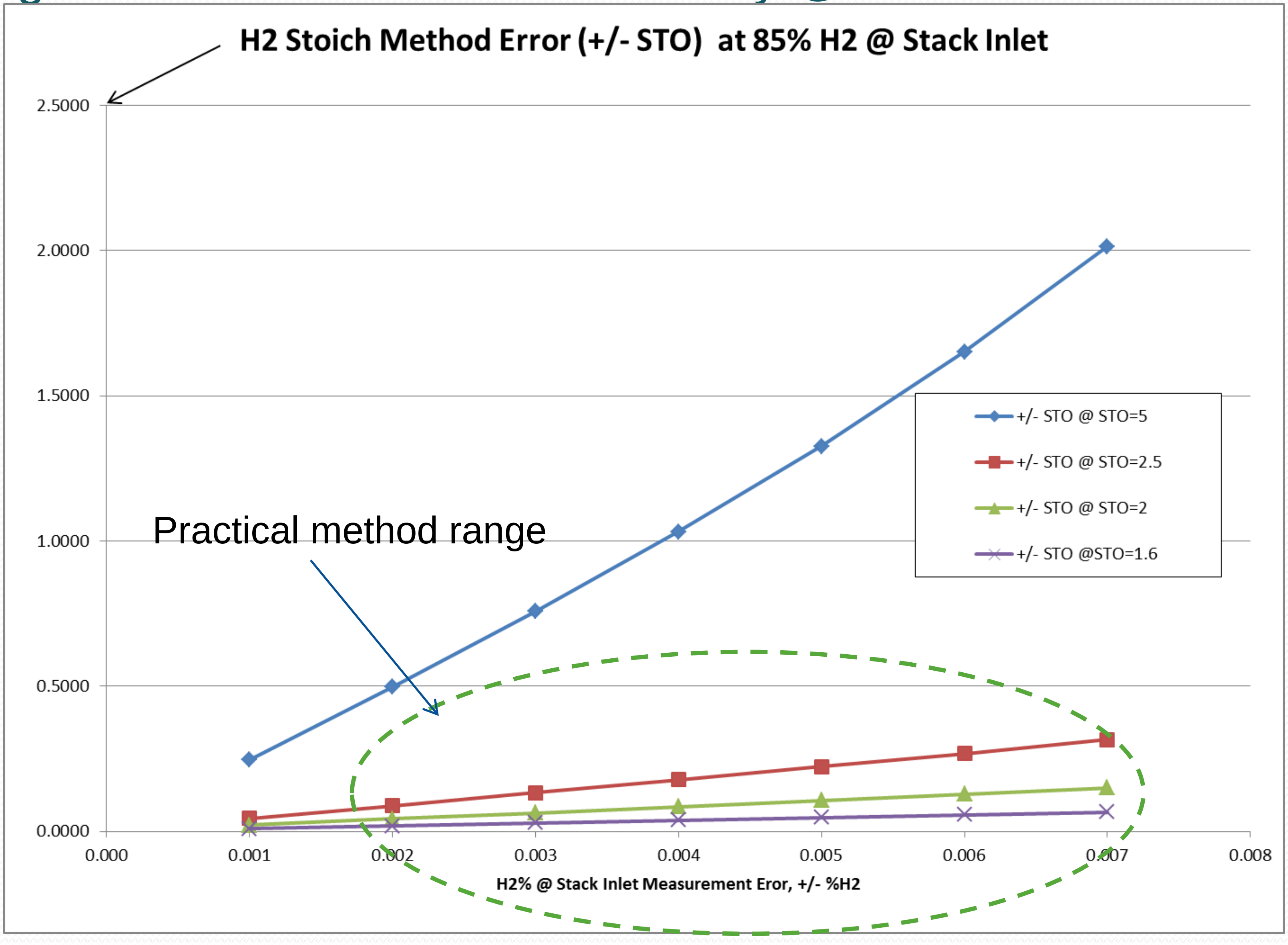
3.0 Method Accuracy Discussion

Fig. 3 Method Errors at 95% H2 dry @ Stack Inlet



2.0 Method Accuracy Discussion

Fig. 4 Method Errors at 85% H2 dry @ Stack Inlet



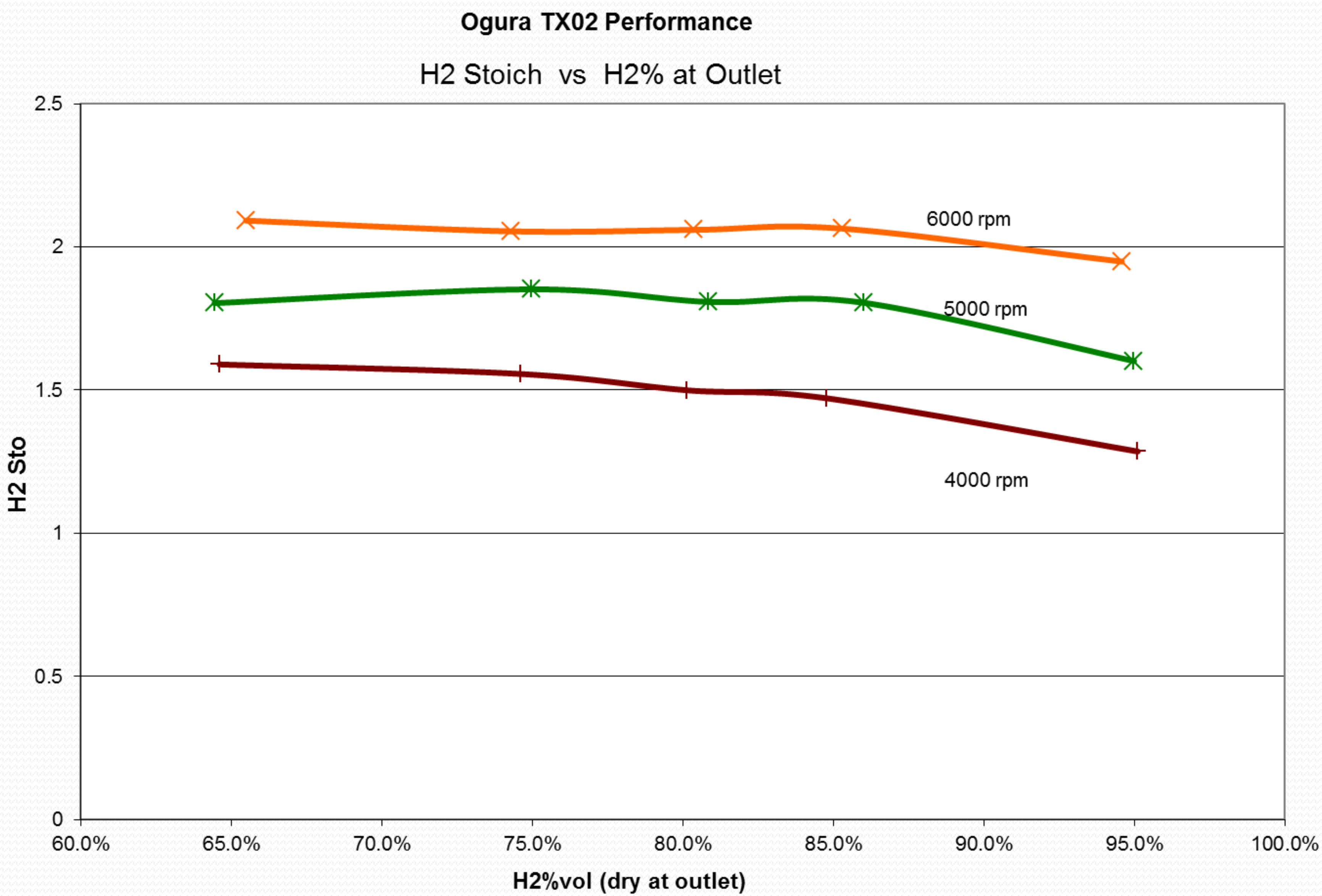
3.0 Method Accuracy Discussion

The presented method is relatively simple to use, however, the user should pay attention to the actual conditions at which the H2 Stoich is determined.

General method application "rules of thumb" are:

- Higher recirculation rates cause larger errors, however, at high recirculation rates the stack is usually "happy" and larger errors in determining the recirculation rate are tolerable.
- Higher H2 concentration levels result in higher errors – recommended H2%dry at stack inlet is 80 - 85% (controlled by purge rate)
- A small stream of N2 can be introduced into the anode recirculated mixture in order to increase the method accuracy. This stream has to be be compensated by purge to maintain mass balance in anode loop.

4.0 Examples of HRD Characteristics:



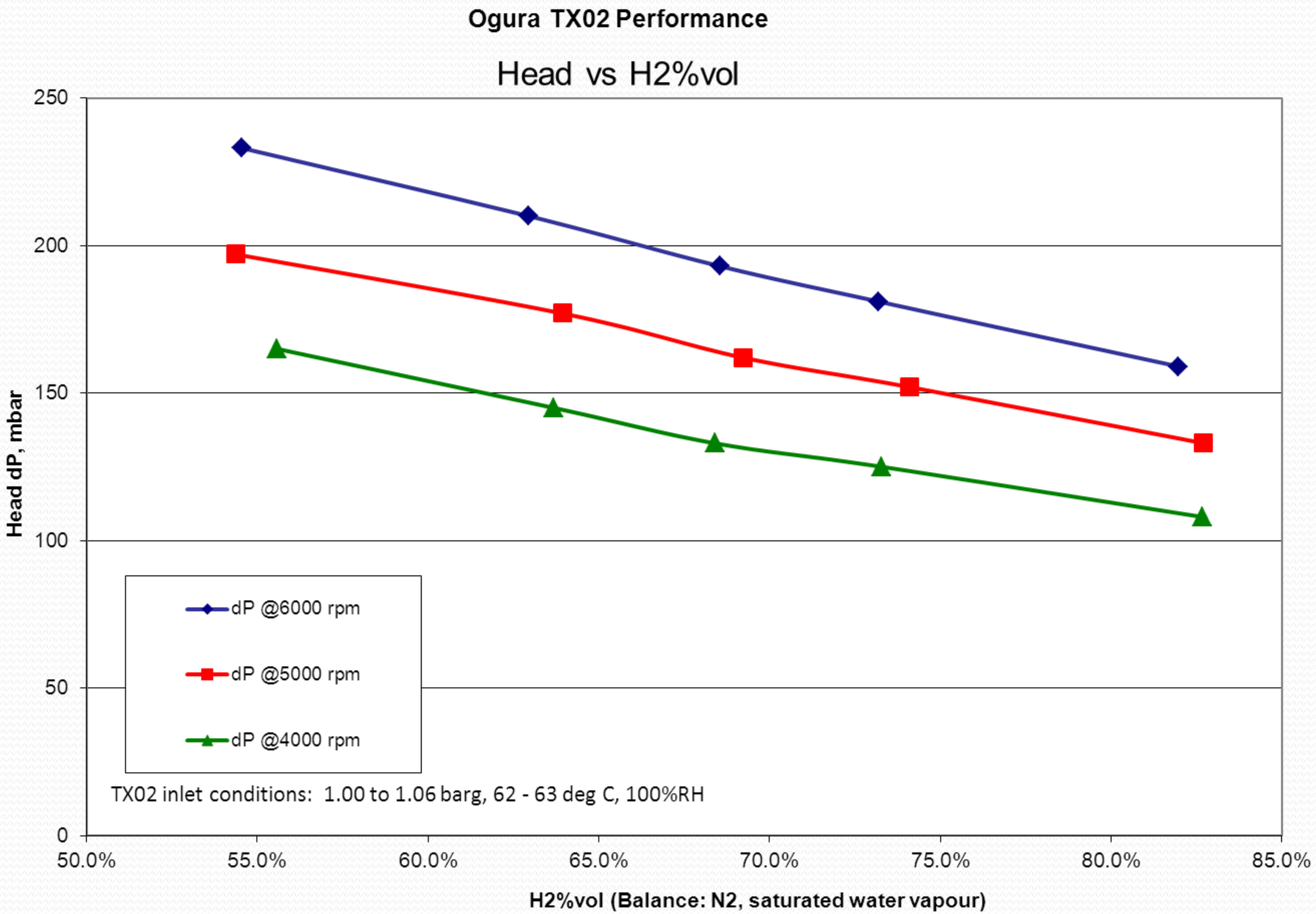
4.0 Example of HRD Characteristics:

After the H2 Stoich is determined from Equation 7, it is possible to determine the HRD volumetric efficiency and actual performance (recirculated anode gas volumetric flow rate):

- The Vh_feed can be calculated from the Current Sensor reading (it also includes a purge flow rate)
- The recirculated dry H2 stream (Vh_2) is calculated from Equation 1a.
- The nitrogen content in recirculated gas is calculated from Equation 5.
- The water vapour content is calculated from the RH% direct measurement.

The resulting HRB characteristics are presented in the next few slides.

4.0 Examples of HRD Characteristics:



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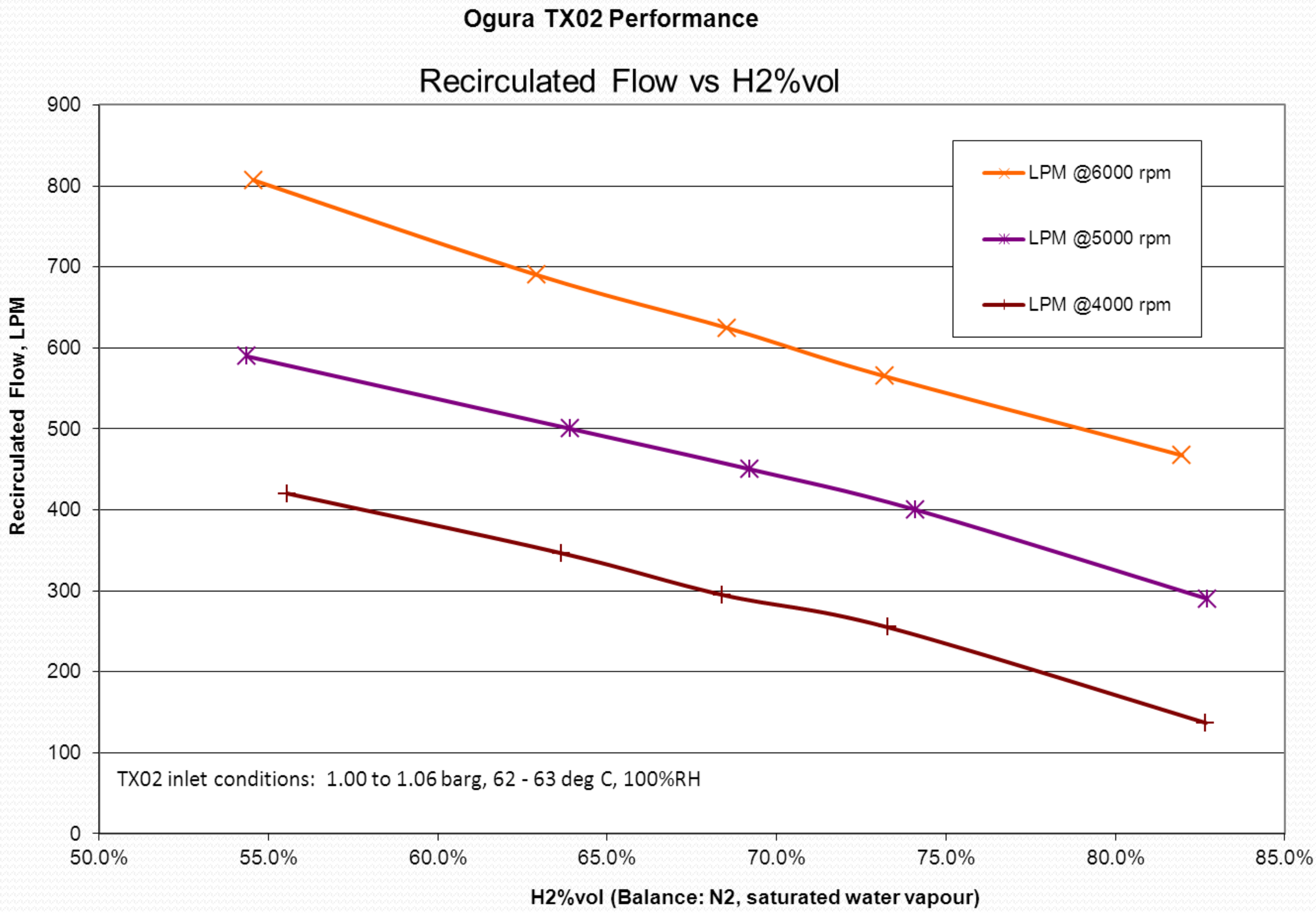

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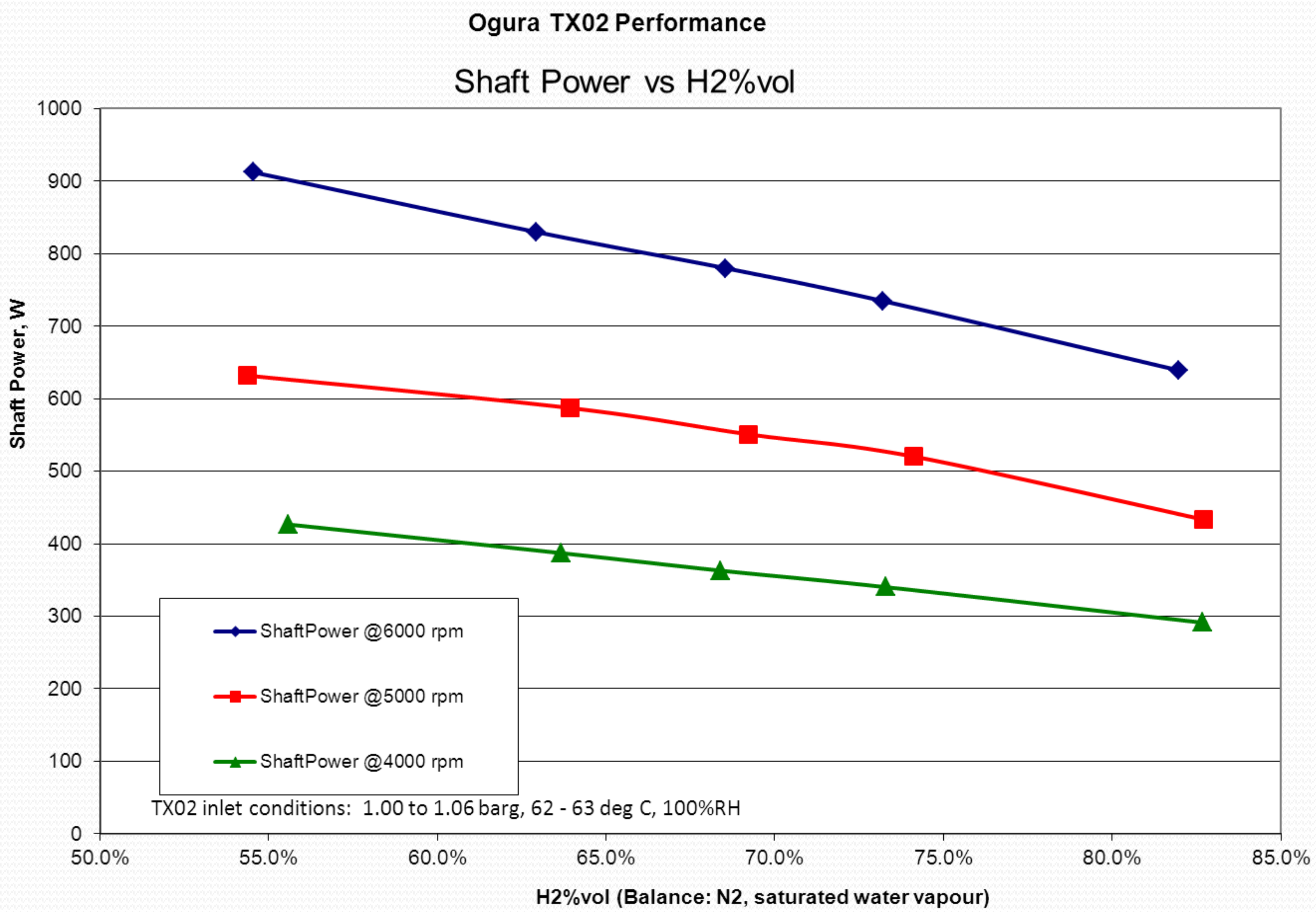

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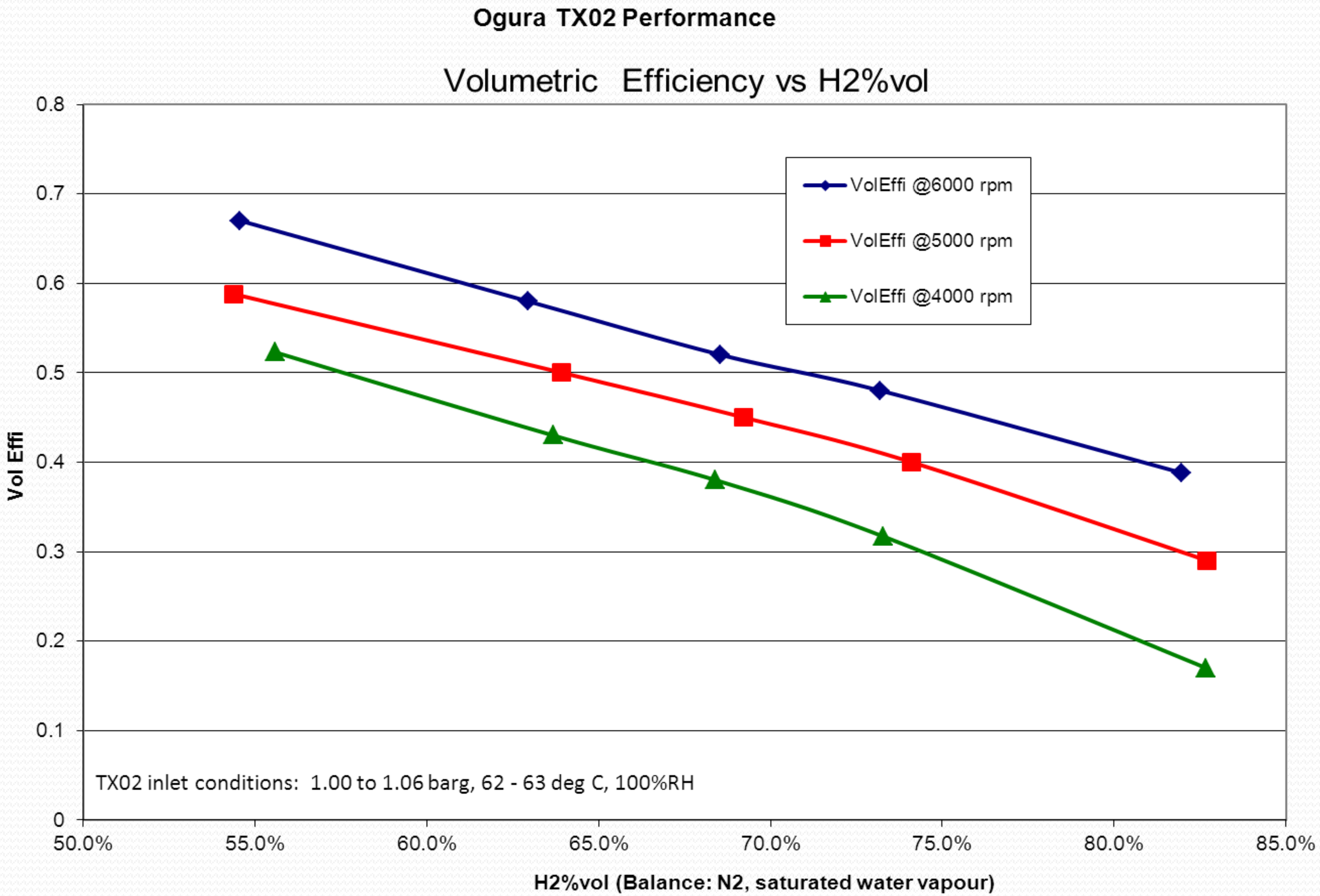

5.0 Acknowledgments

The presented work has been accomplished during Ogura-Ballard joint program towards Hydrogen Recirculation Blower development, as a result of which Ogura long-life, high efficiency TX04U-M roots type blower has been developed and used in Ballard FCvelocity®-HD6 bus module.

Thank You For your Time…

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Questions?

For further information please contact:

Hydrogen Stoich Measurement Methodology

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