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COMPARING PREDICTED AND TESTED PERFORMANCE OF CRYOGENIC REACTION TURBINES UNDER LOCKED-ROTOR CONDITION

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ABSTRACT

Reaction turbines may experience a distinctive locked-rotor situation where the rotor is not rotating and the flow passages are unrestricted. Under these conditions a reaction turbine experiences a maximum torque on the rotor shaft and a minimum pressure drop across the turbine. While in this locked-rotor condition and operating at different flow rates the values for the pressure drop across the turbine generate a characteristic locked-rotor curve.

The overall performance of a reaction turbine under normal operation is directly related to its locked-rotor characteristic curve. In general, and particularly for large hydroelectric turbines, it is mechanically difficult to lock the rotor without restricting the flow passage in order to measure the locked rotor characteristic. However, in the case of cryogenic reaction turbines, which are typically driven by liquefied hydrocarbon gas, it is possible to create the locked-rotor condition. The condition is accomplished by using frozen humidity or by physically clamping the shaft to lock the rotor. This condition is therefore achieved without restricting the flow passage or changing the properties of the cryogenic fluid.

This paper presents predicted and tested data of a cryogenic reaction turbine driven by liquefied methane under the locked-rotor condition, and compares the overall performance of the reaction turbine with its locked-rotor characteristic.

INTRODUCTION

In 1996 Kimmel proposed to partially record turbine performance using the locked-rotor characteristic and in 2000 Habets proposed to partially monitor turbine performance using only the no-load characteristic. It is now proposed that it is possible to monitor and record overall turbine performance through de-energized generator testing, in which the no-load condition coupled with the locked-rotor condition is tested and used to predict turbine performance, including the best efficiency flow points. This is in contrast to typical performance testing in which the turbine is tested under no-load and under load at all rated flow and speed points. Turbine performance test data was used to analyze and support the de-energized generator performance testing theory. The machine used is an Ebara International Corporation (EIC) cryogenic reaction turbine model LX14-07. Performance data was recorded under the no-load and locked-rotor conditions, as well as, under load at two constant speeds of 2400 RPM and 3000 RPM.

NOMENCLATURE

H	Head [m]
Q	Flow [m3/hr]
N	Speed [RPM] and [RPS]
A, B	Constants relating head, flow and rotational speed
α, β	Constants specific to de-energized testing
a, b	Constants specific to typical testing
λ	Constant relating flow and speed under no-load
c	Constant relating head and flow under no-load
BEP	Best efficiency point

ε	Parabolic constant related to BEP
P_{out}	Output power
m	Constant related to P_{out}
NL	No-load
P_{in}	Input power
ρ	Density of fluid [m^3/kg]
g	Gravity
η, EFF	Efficiency

TURBINE PERFORMACE

The following sections present theory, calculations, and results using actual turbine performance data for both de-energized generator performance testing and typical performance testing.

Energy and Affinity Law Equation

Kimmel, in 1996 and 1997, presented an equation for the prediction of turbine performance. Kimmel's equation follows both the affinity laws and the conservation of energy principal,

$$H = A \cdot Q^2 + B \cdot N^2 \quad (1)$$

Equation (1) provides a three dimensional model that can be applied to tested data in several ways. To specifically denote the de-energized generator performance testing Eq. (1) is expressed with constants α and β,

$$H = \alpha \cdot Q^2 + \beta \cdot N^2 \quad (1a)$$

Similarly, Eq. (1) is expressed with constants a and b to indicate typical performance testing,

$$H = a \cdot Q^2 + b \cdot N^2 \quad (1b)$$

Under the no-load condition the inlet and outlet momentum of the fluid must be equal, yielding the following relationship between flow and rotational speed (Kimmel, 1997),

$$Q = \lambda N \quad (2)$$

A three dimensional curve fit specific to the no-load condition is then found by substituting Eq. (2) into Eq. (1),

$$H = cQ^2 \quad (3)$$

Using test data measured under the no-load condition and a least-square error fit the value of λ is found,

$$\lambda = 9.25855410\ 4 \quad (4)$$

Again, through a least-square error fit and no-load tested performance data, the value of *c* is found,

$$c = 0.00116448 \quad (5)$$

It is important to note that the value of both λ and *c* is only dependent upon tested data measured under the no-load condition and is therefore applicable to both typical performance testing and de-energized generator testing.

De-Energized Generator Performance Testing

Using only test data taken under the no-load and locked-rotor conditions from the tested performance data of EIC model LX14-07, the overall turbine performance is known though employment of Eqs. (1-5). To generate a surface fit using Eq. (1a) the values for α and β must be found.

Kimmel (1996) proposed to determine α by testing the de-energized generator locked-rotor performance. Under the locked-rotor condition the rotational speed is zero resulting in,

$$H = \alpha \cdot Q^2 \quad (6)$$

Using the least square error method the value of α is determined using data only measured under the locked-rotor condition as follows,

$$\alpha = 0.00028965\ 3 \quad (7)$$

Four relationships are known and given by Eqs. (1a), (2), (3) and (6). In addition, all constants, except for β, are known through Eqs. (4), (5) and (7). To find β, the known relationships from Eq. (2), (3), and (6) are substituted into Eq. (1a), solving for β,

$$\beta = \lambda^2 (c - \alpha) = 0.07499089 \quad (8)$$

Grouping and consolidating, there is a complete set of three relationships, with known constant values (α, β, c, λ), that were derived only from no-load and locked-rotor test data to accurately describe turbine performance,

$$H = 0.00028965\ 3 \cdot \mathrm{Q}^2 + 0.07499089\ \cdot \mathrm{N}^2 \quad (9)$$

$$H = 0.00116448\ \cdot Q^2 \quad (10)$$

$$Q = 9.25855410\ 4 \cdot N \quad (11)$$

De-Energized Generator Performance Testing and Q_{BEP}

Without knowing the efficiency characteristics of a turbine, the flow at the best efficiency point may still be calculated accurately using the following relationship,

$$Q_{BEP} = N_{Rated}\left(\lambda + \sqrt{\lambda^2 + \frac{\beta}{\alpha}}\right) \quad (12)$$

Equation (12) relates the best efficiency flow to the rated speed and constants from Eq. (1a) and Eq. (2) (Kimmel 1997). Using the above calculated values of α, β, and λ, Eq. (12) is solved for Q_{BEP} at the two rated speeds of 2400 RPM and 3000 RPM, they were found to be 1112.9 m^3/hr and 1391.1 m^3/hr respectively. These QBEP points lie on a parabolic curve (Kimmel 2000),

$$H = \varepsilon \cdot Q^2 \quad (13)$$

Using the above calculated values for Q_{BEP} the corresponding H_{BEP} is calculated using Eq. (9). These values are then substituted into Eq. (13) to find ε. The value of ε is found to be 0.000386529.

It has been shown that overall turbine performance can be known by carrying out a de-energized performance test. Figure 1 is a two-dimensional plot showing all performance results for de-energized generator testing plotted with the test data for no-load and locked-rotor.

Typical Performance Testing

Using the tested performance data of EIC model LX14-07 a simple surface fit using the least square error method for all data points was performed to find the constants in Eq. (1b). The values of *a* and *b* were found to be 0.000277886 and 0.074137245 respectively. This resulted in the following typical performance testing surface fit,

$$H = 0.00027788\,6 \cdot \mathrm{Q}^2 + 0.07413724\,5 \cdot \mathrm{N}^2 \quad (14)$$

Typical Performance Testing and Q_{BEP}

Efficiency is used in typical performance testing to find the best efficiency flow point (Q_{BEP}) for a rated rotational speed. Efficiency is defined as the electrical power out divided by the hydraulic power in.

The output power is measured during typical performance testing and is related to flow as follows (Kimmel 1997),

$$P_{out} = m\left(Q^2 - Q \cdot Q_{NL}\right) \quad (15)$$

In order to calculate the power out using Eq. (15) Q_{NL} and *m* for each rated speed must be found. Q_{NL} is the flow at the point where the rated speed curve and the no load curve intersect and is found by setting Eq. (1b) equal to Eq. (3).

$$Q_{NL} = N_{Rated}\sqrt{\frac{b}{c-a}} \quad (16)$$

At the rated speed of 2400 RPM Q_{NL} was found to be 365.78 m^3/hr, and at the rated speed of 3000 RPM Q_{NL} was found to be 457.22 m^3/hr. Using least-square error method *m* is found by using the test data taken at the two rated speeds. The values for *m* at 2400 RPM and 3000 RPM were found to be 0.000677636 and 0.000833744 respectively. Figure 2 is a plot of the flow verses power for both rated speeds showing actual data points as well as the curve fit generated by Eq. (15).

The hydraulic input power is calculated as follows,

$$P_{in} = H \cdot Q \cdot \rho \cdot g \quad (17)$$

Where, H is given by Eq. (1b). Equation (15) divided by (17) results in the following efficiency equation,

$$\eta = \frac{m\left(Q^2 - Q \cdot Q_{NL}\right)}{1000 \cdot \left(aQ^2 + bN^2\right) \cdot Q \cdot \rho \cdot g} \quad (18)$$

The BEP flow point for each speed is found by taking the first derivative of Eq. (18) with respect to *Q*, setting it equal to zero and then solving for *Q*. This provides the flow at the highest efficiency,

$$Q_{BEP} = Q_{NL} + \sqrt{\frac{b}{a} N_{Rated}^2 + Q_{NL}^2} \quad (19)$$

The Q_{BEP} calculated at the rated speeds of 2400 RPM and 3000 RPM are 1113.9 m^3/hr and 1392.3 m^3/hr respectively. These QBEP points lie on a parabolic curve,

$$H = \varepsilon \cdot Q^2 \quad (20)$$

Using the above calculated values for Q_{BEP} the corresponding H_{BEP} is calculated using Eq. (14), these values are then substituted into Eq. (20) to find ε. The value of ε is found to be 0.000373488.

Figure 3 is a two-dimensional graph showing all performance results for typical performance testing plotted with test data.

VERIFICATION OF NEW TESTING METHOD

A numerical comparison was utilized to compare and verify results from de-energized generator performance testing with typical performance testing. Table 1 is a comparison of the calculated values by percent difference from both the de-energized generator performance testing and the typical performance testing. The comparisons indicate that the de-energized generator performance testing results are within reasonable percentages for all values demonstrating that the de-energized performance testing is a viable method for recording and monitoring overall turbine performance including the determination of best efficiency operating points.

Table 1: Comparison of calculated values from de-energized generator and typical performance testing

Compared Value	De-Energized	Typical	% Difference
A	α = 0.000290	a = 0.000278	4.15%
B	β = 0.074991	b = 0.074137	1.14%
ε	0.000386529	0.000373488	3.43%
Q_{BEP} 2400 RPM	1112.9	1113.9	**0.09%**
H_{BEP} 2400 RPM	478.7	463.4	**3.25%**
Q_{BEP} 3000 rPM	1391.1	1392.3	**0.08%**
H_{BEP} 3000 RPM	748.0	724.0	**3.26%**

American National Standards Institute and American Petroleum Institute Standard 610 allows for an error window of +/-5% in both head and flow (ANSI/API 2004). The BEP head and flow percent differences shown in Table 1 are all less than the allowed +/-5%, especially for Q_{BEP} where the percent differences are less than 0.1% for both speeds. Figure 4 is a plot of the BEP parabolic curves calculated in the above sections for both testing methods. This figure shows that both of the BEP points calculated using the de-energized testing method are within the API error range signified by the boxes. Therefore, the de-energized generator performance testing method is verified for overall turbine performance prediction.

It is possible to reduce performance deviations by including test points at the flow range close to the BEP. However, during rotational operation in typical performance testing axial rotor oscillations occur. These oscillations will have an influence on the small deviations between the de-energized generator and typical performance testing (Finley 2002).

CONCLUSIONS

De-energized generator performance testing was proposed as a viable testing method to predict the overall performance of a hydraulic reaction turbine. Actual performance test data was used in conjunction with theory to predict turbine performance using both typical and de-energized generator performance testing. Results from both testing methods were compared to verify the applicability of de-energized generator performance testing. Results of the analysis show that the de-energized generator performance testing method presented produces all the necessary data to predict the energized turbine performance within acceptable error limits.

REFERENCES

ANSI/API (American National Standards Institute/ American Petroleum Institute) Standard 610, 10th Ed. “Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries, Annex C, Hydraulic Power Recovery Turbines.” Washington DC, October 2004.

Finley, Christopher D. “Observation of jump phenomena in non-linear axial rotor oscillations.” 9th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery. ISROMAC-9, February 10-14, 2002, Honolulu, HI, USA.

Habets, Gilbert L.G.M. “Monitoring cryogenic turbines using no-load characteristics.” 8th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery. ISROMAC-8, March 26-30, 2000, Honolulu, HI, USA.

Kimmel, Hans E. “Cryogenic Francis Turbines.” 8th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery. ISROMAC-8, March 26-30, 2000, Honolulu, HI, USA.

Kimmel, Hans E. “Speed controlled turbines for power recovery in cryogenic and chemical processing.” World Pumps, June 1997.

Kimmel, Hans E. “Variable speed turbine generators in LNG liquefaction plants.” GASTECH 96, Vienna, Austria, 3-6 December 1996.

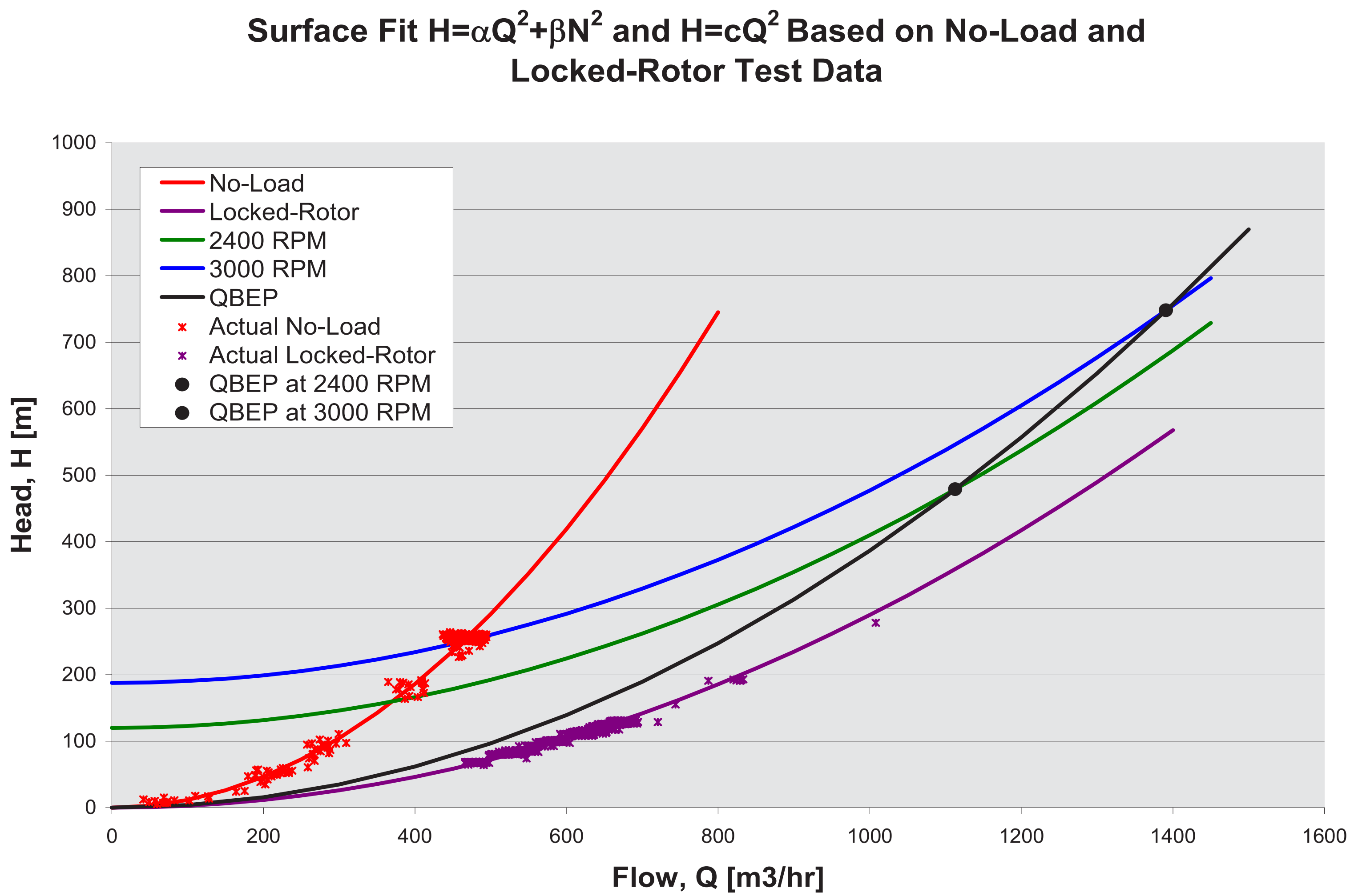

Fig. 1: De-energized generator performance testing

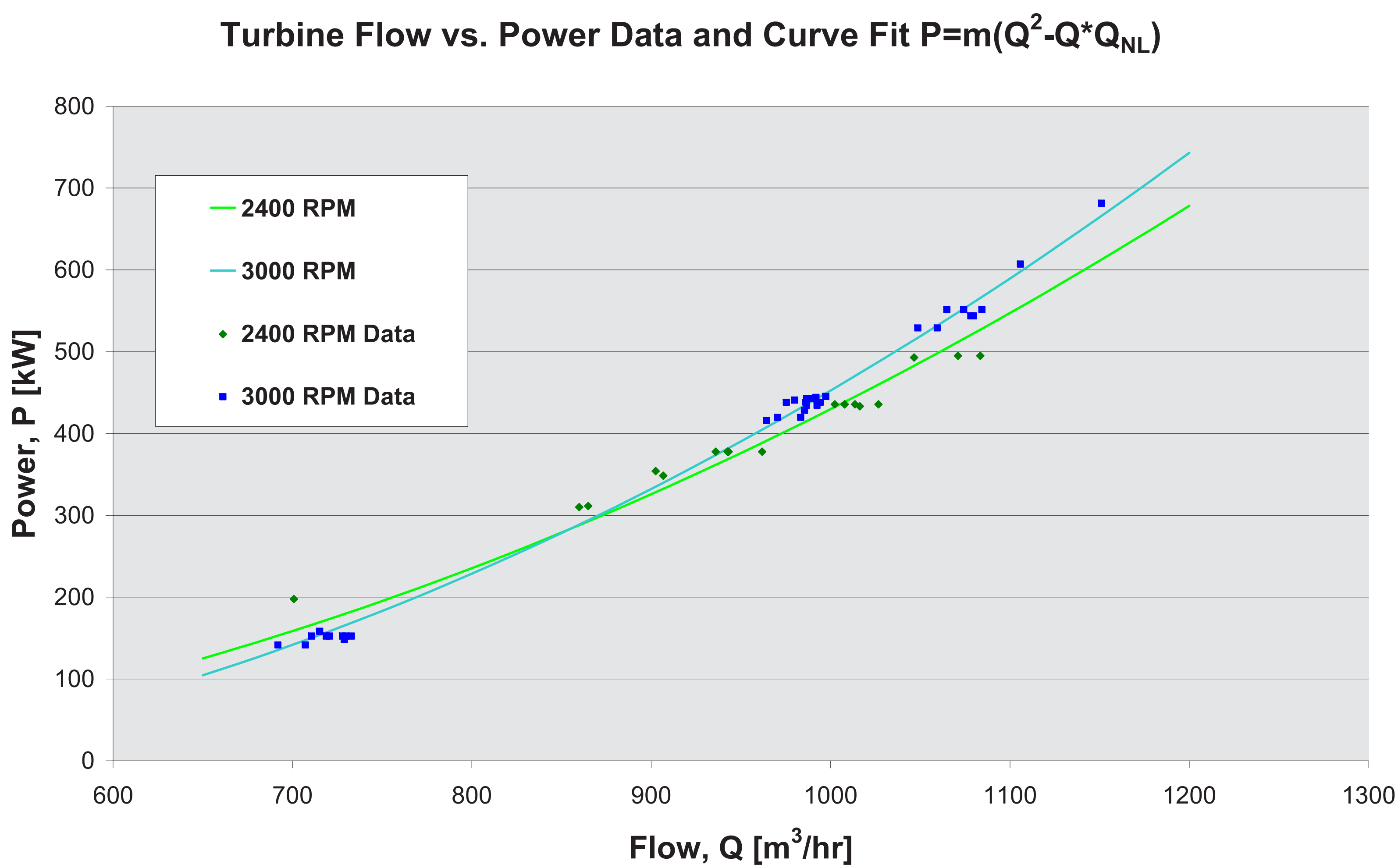

Fig 2: Flow vs. power curve fit for typical performance testing

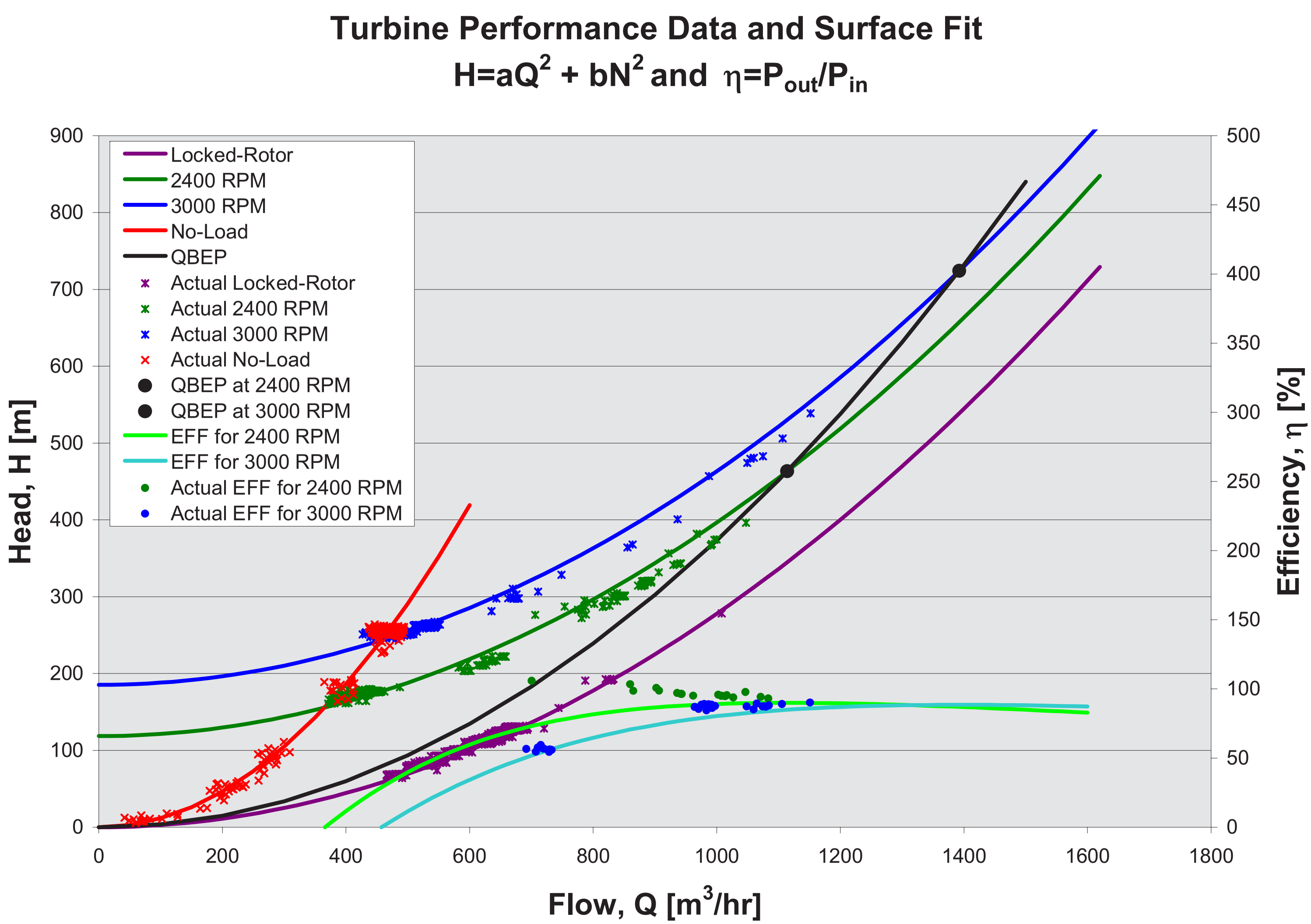

Fig. 3: Typical performance testing

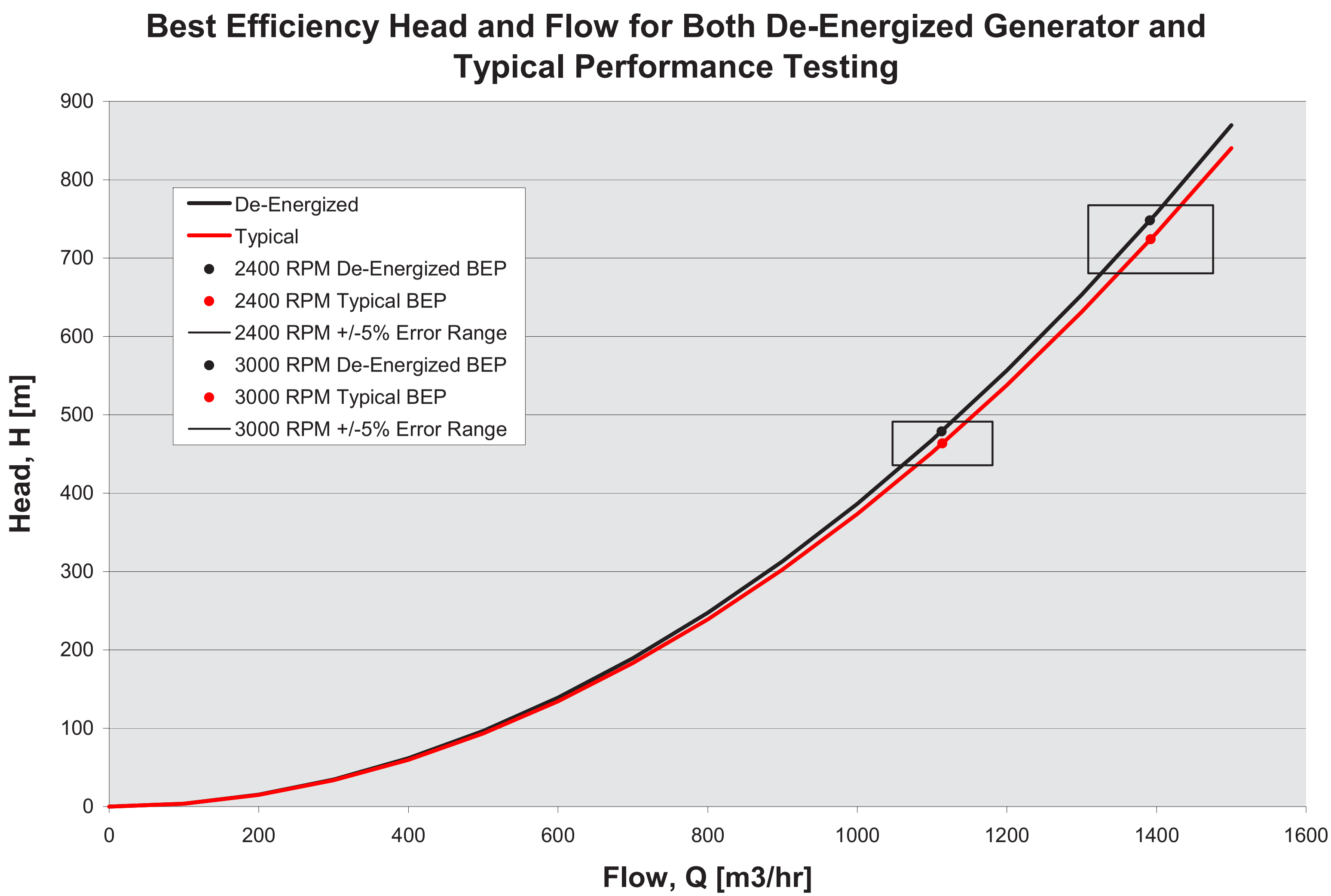

Fig. 4: BEP Verification and Error