Continuous Pump Performance Monitoring and Scheduling

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SYNOPSIS

Energy losses appear as heat. For a pump, the measurement of the differential temperature from suction to discharge, together with pump head and power input, allows the determination of both pump efficiency and flow-rate, without the requirement for separate flow meters. This is the thermodynamic method.

Continuous pump performance monitoring provides energy and environmental savings, improves plant and process reliability, and reduces maintenance costs. In multi-pump applications, such as those commonly found in Water Utilities, combining pump monitoring with scheduling software optimises energy savings.

In April 2005 a pump monitoring system with scheduling software was commissioned at Tai Po Tau No 4 pump station (Hong Kong), which has 7 pumps in the power range 1 to 3 MW. Since then, the system has performed stably without recalibration. Accuracy and repeatability of hydraulic efficiency and flow rate measurements are typically better than 1% and 0.2% respectively.

Field experience is summarised.

1 INTRODUCTION

Tai Po Tau No 4 Raw Water Pumping Station was commissioned in 1995 and has been designed to house fourteen pumps. However, to date only seven pumps have been installed, and these are shown in Table 1.

The pumpset is configured in angle arrangement to the culvert and transfers the raw water from the common suction culvert to the discharge aqueduct. The arrangement is shown in the following layouts and photograph. Due to the configuration of the pumping station, there was previously no possibility for continuous monitoring of individual pump flow rate and performance.

Pump No.	Duty	Delivery Destination
19, 20, 21	3.218 m3/s at 33m head, Motor power 1.5 MW	To Ngau Tam Mei (NTM) Aqueduct, Muk Wu and Lower Shing Mun (LSM) Supply Basin
29R	1.852 m3/s at 100m head, Motor power 2.5 MW	To Tai Po WTW
30N	1.736 m3/s at 106m head, Motor power 2.5 MW	To Tai Po WTW
22, 23	2.431 m3/s at 106m head, Motor power 3.45 MW	To Tai Po WTW

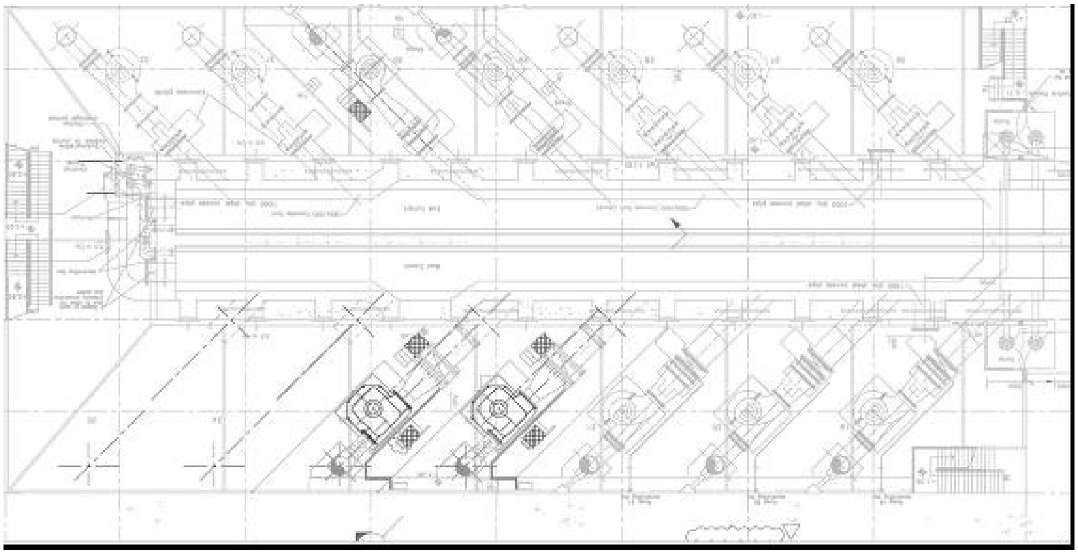
Table 1 Tai Po Tau No 4 pumps

Before the installation of the fixed pump monitoring system, the station utilized thermodynamic testing with portable units to measure and monitor the performance of the pump sets on a regular basis. This information gives the individual pump operational efficiency and determines the energy consumption within the station.

However, the optimization of the energy consumption in the station is not only dependent on the individual pump performance. It is also correlated to the combination of the various pump performances, and their operation in the combined situation.

In order to achieve the above expectation, a high accuracy measurement system was developed, based on the Direct Thermodynamic Method, which can fit into the limited space available within pumping station pipework. The system continuously monitors the performance of individual pumps and uses a logical algorithm to determine the optimum pump combinations.

The system was developed in two parts. The Pump Performance Monitors (PPM) were designed and supplied by Robertson Technology (Western Australia), and are operated from their own computer in the control room. Summary data is ported to a separate computer, running the Pump Scheduling Software (PSS), which was developed by Chevalier Envirotech (Hong Kong).



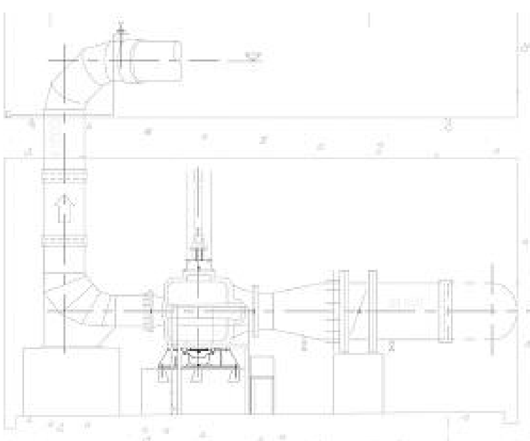


Figure 1   Tai Po Tau No 4 pump station, ground floor

2 THEORY

The Tai Po Tau installation and test equipment utilise the Direct Thermodynamic Method [1,2].

Using the principle of conservation of energy, pump parameters are summarised by the following equation:

$$\mathbf{n.M_E.P_W = q.\rho.g.H} \quad (1)$$

The left-hand side of equation (1) is the electrical power (energy per second) applied to the fluid, after losses in the motor drive and pump: -

- **n** is the hydraulic efficiency (expressed as a fraction)
- $\mathbf{M_E}$ is the motor and drive efficiency (expressed as a fraction)
- $\mathbf{P_W}$ is the electrical power to the motor (in watts)

The factor $\mathbf{n.M_E}$ is known as the 'Overall Efficiency'.

The right-hand side of equation (1) is the energy per second imparted to the fluid, and also has the units of watts (joule/s): -

- **q** is flow rate, in m^3/s
- **ρ** is the fluid density, in kg/ m^3, and is a function of temperature and pressure
- **g** is the acceleration due to gravity, in m/s^2
- **H** is pump total head, in m

The terms **ρ, g, H,** $\mathbf{P_W}$ **and** $\mathbf{M_E}$ are common to both 'conventional' and thermodynamic methods, with **ρ** and **g** being obtainable from reference tables.

The 'conventional' method of pump testing, commonly employed by pump manufacturers during acceptance tests, can be used when it is possible to measure the flow rate, **q,** to the requisite accuracy, using a flow meter. Then equation (1), rearranged, gives the method for obtaining pump efficiency:

$$\mathbf{n = q.\rho.g.H / (P_W.M_E)} \quad (2)$$

The accuracy of the conventional pump efficiency measurement is largely determined by the errors in the measurement of **q, H,** $\mathbf{P_W}$**, and** $\mathbf{M_e}$. The uncertainties add linearly. In practice, the accuracy of **q** is usually the limiting factor in the laboratory. On-site measurement by the conventional method requires a flow meter, but in many instances this is precluded by the layout of the pipe work. Where flow meters are fitted, accurate volumetric testing may be required for on-site calibration checks.

In the thermodynamic method, the pump efficiency, **n,** is determined from changes in enthalpy (energy per unit mass), using temperature and pressure probes. The calibration of these probes can be readily checked on-site. The uncertainty in **n** is primarily due to the uncertainty in differential temperature measurements.

The flow rate, **q,** is determined from equation (1), rearranged:

$$\mathbf{q = n.M_E.P_W / (\rho.g.H)} \quad (3)$$

Thus flow rate can be derived without the need for a separate flow meter.

The thermodynamic method determines pump efficiency to a high accuracy, since it is essentially measuring losses. For example, suppose a pump is 80% efficient, and that both the conventional and thermodynamic methods had an error of 5% of the measurement quantity.

Then the error in pump efficiency by the conventional technique would be 5%. However the error by the thermodynamic method would be 1%, since the losses of 20% (100-80) are measured to 5% accuracy and 5% of 20% is 1%.

The modern thermodynamic method evolved primarily from work carried out by the National Engineering Laboratory and the University of Glasgow, in the UK, in the 1960's [(3)], and in parallel by Austin Whillier, at the Mining Research Laboratory in South Africa.

The theoretical background to the thermodynamic method is primarily in the public domain. The performance of an instrument employing this method is largely determined by the design, accuracy and stability of the temperature and pressure probes.

The thermodynamic method for pump efficiency and flow rate relies primarily on the measurement of three parameters: (a) the differential temperature, **dT**, across the pump, (b) the differential pressure, **dp**, across the pump, and (c) the electrical input power, $\mathbf{P_W}$.

The hydraulic efficiency, **n**, is the ratio of two changes in energy per unit mass, each comprising of enthalpy, kinetic energy, and gravitational terms. $\mathbf{n = E_H/E_M}$ for pumps, and $\mathbf{E_M/E_H}$ for turbines, where $\mathbf{E_H}$ is the hydraulic energy per unit mass of fluid, and $\mathbf{E_M}$ is the mechanical energy per unit mass.

$\mathbf{E_H}$ is given by $\mathbf{E_H = dp/\rho + (U_2^2 - U_1^2)/2 + g(Z_2 - Z_1)}$

$\mathbf{E_M}$ is given by $\mathbf{E_M = a.dp + c_p.dT + (U_2^2 - U_1^2)/2 + g(Z_2 - Z_1)}$

For the enthalpy terms:

$\mathbf{c_p}$ is the specific heat capacity at constant pressure (change of enthalpy with temperature at constant pressure;

a is the isothermal coefficient (change of enthalpy with pressure at constant temperature;

$\boldsymbol{\rho}$ is the fluid density, which is a function of temperature and pressure

Data for the above three parameters are obtained from the tables in ISO 5198.

For the kinetic energy term:

$\mathbf{U_1}$ and $\mathbf{U_2}$ are the fluid velocities at the inlet and outlet measurement positions, respectively.

$\mathbf{U = q/A}$, where **A** = cross-sectional area

For the gravitational term:

$\mathbf{Z_1}$ and $\mathbf{Z_2}$ are the elevation of the inlet and outlet measurement positions, respectively, relative to a datum.

Having determined the efficiency, flow rate **q** (m^3/s) is obtained from the conventional pump performance equation

$$\mathbf{q = n.M_E.P_W / (\rho.g.H)} \qquad (3)$$

where **H** is pump total head, in m of water, given by

$$\mathbf{H = dp/\rho.g + (U_2^2 - U_1^2)/(2.g) + (Z_2 - Z_1)}$$

3 INSTRUMENTATION

The main technical requirement for the thermodynamic method is the stable and accurate measurement of dT, the differential temperature, which will vary with total head and pump efficiency. Low head pumps give lower differential temperatures. Pumps with lower efficiencies give higher differential temperatures.

Temperatures are typically measured in millikelvin (mK), i.e. thousandths of a degree. With portable units, measuring a snap-shot of pump performance over a few minutes or hours, it is possible to compromise the technical specification for dT, and compensate for short-term drift by swapping the probes and taking an average measurement. This is clearly not an option with fixed systems for continuous monitoring.

Table 1 shows dT as a function of hydraulic efficiency and head, at a water temperature of 10 °C. The signal increases slightly with water temperature.

Table 1. dT (mK) at 10 °C

Head, m of water	Hydraulic efficiency, %		
	70%	80%	90%
25 m	26 mK	16 mK	8 mK
50 m	53 mK	32 mK	16 mK
100 m	106 mK	64 mK	35 mK

Table 2. % change in hydraulic efficiency, for a 1mK variation in dT, at 10°C

Head, m of water	Hydraulic efficiency, %		
	70%	80%	90%
25 m	1.2	1.4	1.5
50 m	0.6	0.6	0.8
100 m	0.3	0.3	0.4

Table 2 shows the effect on the efficiency measurement of an uncertainty in dT of 1 mK.

For fixed systems, the specification for dT, to obtain an efficiency measurement to an accuracy of 1% for the low head pumps at Tai Po Tau, is that dT should be accurate to within 1 mK for a period of 1 year. It was reasonable to assume that calibration checks on dT could be carried out at yearly intervals.

Long-term tests on similar temperature probes have shown no change in dT within experimental error (0.25 mK) over a four-year period. For additional assurance of long-term stability, there are two independent temperature sensors in each temperature probe. Any discrepancies between the two sensors are detected by the software and are indicative of drift of one of the sensors.

Each pump monitor has two temperature probes, two pressure probes, one power meter, and its' own software program. Multiple applications are run from the same computer. A fault in one pump monitor will not stop the programs for other pump monitors. The 7 sets of temperature and pressure probes, and 7 power meters, are individually cabled back to the control computer via 14 RS485 interfaces.

Pressure probes are provided with in-built temperature sensors, to provide 0.1% accuracy (relative to full-scale) over a wide fluid temperature range. These probes have a long-term stability of typically 0.1% of full scale per year. Electrical power to the pump motors is measured to an accuracy of 0.25%, plus errors in current and potential transformer ratios.

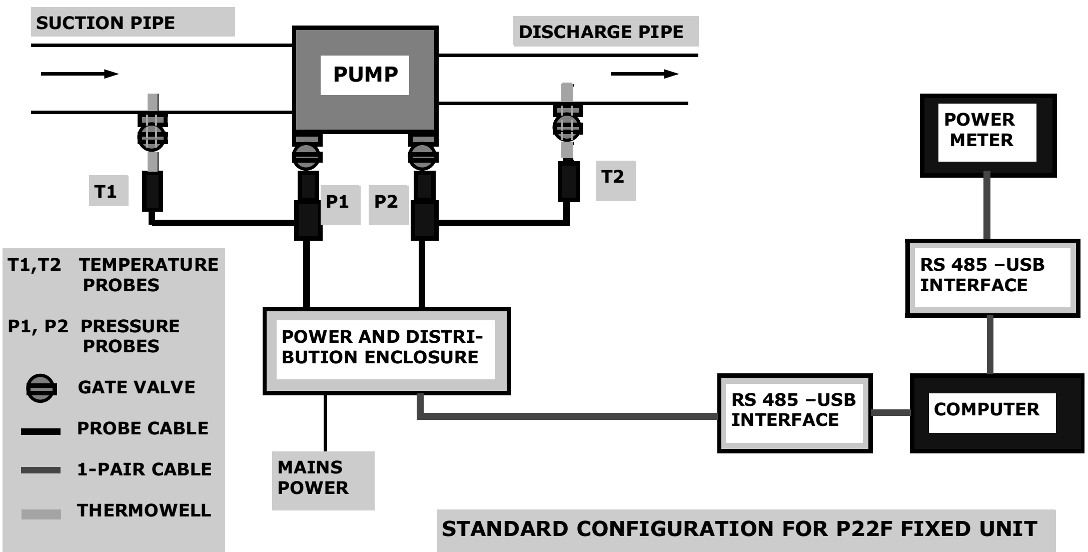


Figure 2. Schematic of single pump monitor

4 INSTALLATION AND COMMISSIONING

The required cabling between the pumps on the ground floor and the control room on the 6th floor, and power meters on the 4th floor, were installed by local technicians. Final installation and commissioning consisted of installation of the temperature and pressure probes, and testing. This took place over a period of five days. Each pressure probe was tested on-site with a portable pressure calibrator.

Figure 3. Temperature probe in thermowell

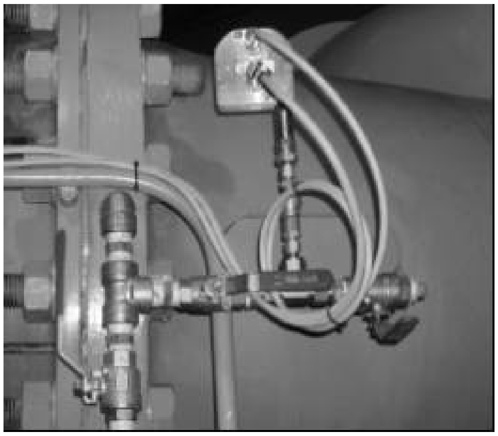


Figure 4. Pressure probe connected to existing tapping point on pump flange

Figure 5. Power meters

Figure 6. Local display and power distribution

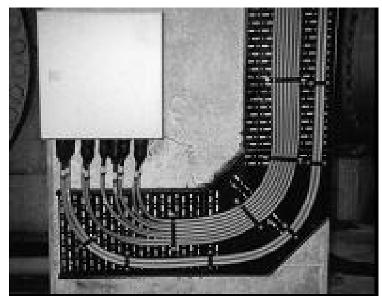
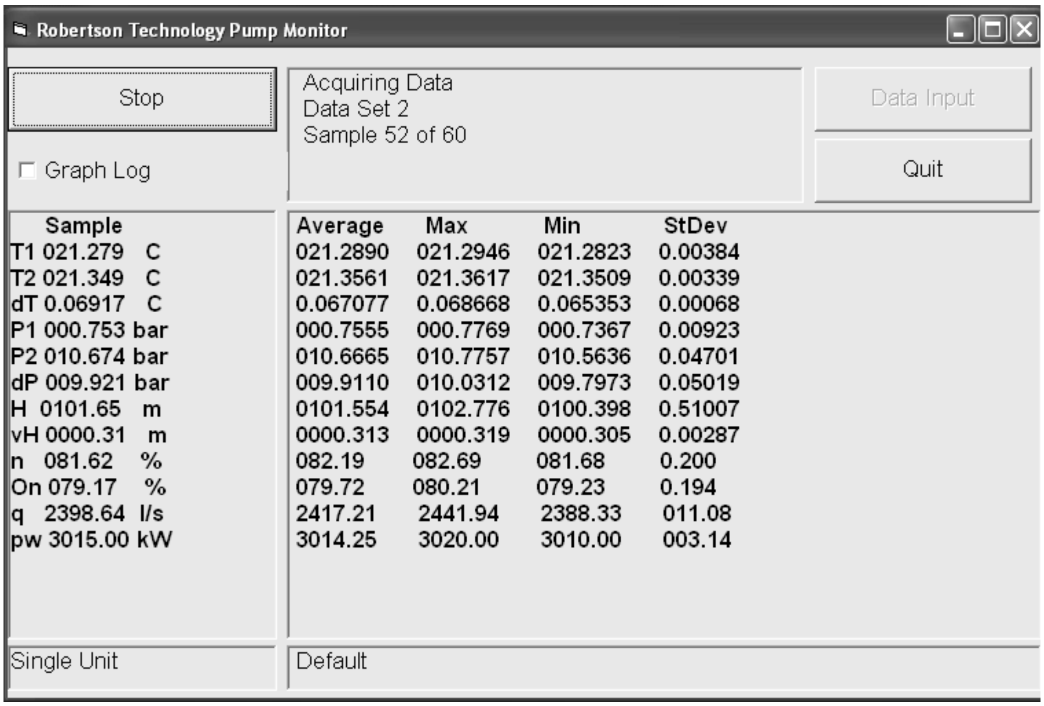


Figure 7   RS485 cabling

Figure 8. Control room (6th floor), with temporary control and analysis display used during test and commissioning (foreground), and separate Pump Scheduling Software computer to its right.

Use was made of existing tapping points on suction and discharge, each more than one pipe diameter from the corresponding pump flanges. The thermowells were designed with due consideration for vortex shedding frequency and total stress. The temperature probes were secured to the thermowells to avoid heating effects due to vibration, but can be easily removed for maintenance.

Summary data from each pump monitor is transferred to the separate Pump Scheduling Software (PSS). Two displays are available to the operator. In normal use, the PSS is displayed. However, in the event of any fault message, the operator or maintenance technician can switch to a different screen, showing real time information from each of the pump monitors. An example is given below.



The left-hand column shows sample 52 of the Data Set 2. In this instance, 60 samples are being counted, at the rate of 1 per second. Thus a complete data set takes about 1 minute to acquire.

This data, and other parameters, are passed to log files. At the conclusion of the data set, averages, maximum and minimum readings, and standard deviations are calculated and displayed. Above, the data in the four right-hand columns is that for Data Set 1.

T1 is the inlet probe temperature (°C), T2 is the outlet probe temperature (°C) and dT is the differential temperature (°C).
P1 is the inlet pressure (bar gauge), P2 is the outlet pressure (bar gauge), and dP is the differential pressure (bar).
H is the pump total head in m of water, vH is the velocity head in m, n is the pump efficiency (in %), On is the Overall Efficiency (in %), q is the volume flow rate in l/s, and pw is the electrical input power to the motor, in kilowatts.

Note the low standard deviation (StDev) for dT, the differential temperature, 0.00068 °C. This parameter is the main indicator for stable and accurate measurement. Typically it is less than 0.001 °C.

The motors for the 3 high head pumps are water-cooled, and the heat transferred to the cooling water adds to the heat dissipated by the pump. An appropriate correction is made in software.

The following information is passed to the PSS

- All the parameters in the data acquisition screen
- Additional power meter parameters
- Warning and error messages

The uncertainty in efficiency and flow-rate measurements is a function of systematic and random errors. Since large data sets are acquired, random errors due to electronic noise in temperature and pressure probes are negligible. Similarly, random variations in differential temperature (dT) measurement due to water mixing will be negligible. Systematic errors in dT are estimated at less than 0.5 mK.

It is a characteristic of the thermodynamic method that a % error in differential pressure measurement will result in about a third of that % error in the hydraulic efficiency measurement.

The estimate for the uncertainty (at the 95% confidence level) in efficiency measurement is <0.5% for the high head pumps, and <1% for the low head pumps. The uncertainty in the flow rate measurement will be somewhat higher, due to errors in power measurement and motor efficiency, adding in quadrature. Repeatability is governed by random errors and will be better than 0.2 %.

5 SUBSEQUENT FIELD EXPERIENCE

Being a fixed installation, it is essential to minimize the maintenance need, and provide long-term reliability. During the past two years of operation, there have been only a few site incidents, proving the integrity of the system arrangement.

The temperature probes have dual sensors, with indication of a fault in one sensor. However, a temperature probe with a faulty sensor can still provide the reading from the second sensor until a replacement is ready. In field use, only one sensor in one probe has failed, due to overstressing of a resistor. Temperature calibration has not altered.

Originally, 2-bar suction pressure sensors were fitted. However, there were some failures due to pressure surges, and several have been replaced with 5-bar sensors, after which there have been no further failures.

As mentioned, the system is based on two separate computers, one for the PPM and one for the PSS. Some data has been lost over the data link, however, operations data is stored in both computers, which simplifies the data restore arrangement.

The system can provide the individual flow rate and motor information, which assists the operator to cross-check the performance of the individual pump and motor.

The pump scheduling program is used to select the optimum pump combination. Due to the operation requirement within this period, pump selection combinations were limited, thus the actual cost saving cannot be determined. On the other hand, the system can identify the difference in pump efficiency at the same duty, which is of benefit for the future pump selection and long-term cost saving. An example calculation for two of the high head pumps is given below.

	Present Overall Efficiency	Motor Input Power
Pump 1	81.8%	2386 kW
Pump 2	84.2%	2076 kW

The flow rate of the pumps varies as per the demand of the flow control device, so it is difficult to directly compare the efficiency against each other. The comparison is based on the 160 Ml/d record of delivery of the water to the uphill plant within the same month.

The cost saving for operation of the most efficient pump is as follows:

	Energy Saving	Yearly Energy saving #	Cost saving *
Pump 2 vs Pump 1	310 kW	2,715,600 kWh	HK$ 2,995,306 (US$ 384,013)

If operating 24 hours and 365 days * Hong Kong Electric tariff HK$ 1.103 per kWh

6 CONCLUSIONS

The first requirement for any thermodynamic based scheduling system is that reliable, accurate and consistent pump performance measures are obtained from the operating plant. The Robertson Thermodynamic monitoring system, installed at Tai Po Tau, has clearly demonstrated this capability for over 2 years making continual monitoring and dynamic pump scheduling a reality.

The system described is the first fixed pump monitoring unit using the Direct Thermodynamic Method in Hong Kong. The system is very compact and overcomes the space limitation in the pumping station. As the system just requires one tapping point at each of the suction and discharge sides, it is simple and appropriate for both new and existing pumping station.

The failure record is very low, and demonstrates the stability and reliability of the system. There is some room for improvement in the data link, presentation and data analysis. The hardware is reliable and fit for the pump monitoring purpose, and long-term cost-saving data collection.

7 REFERENCES

1) Code of Practice for Pump Efficiency Testing by the Direct Thermodynamic Method, Pump Centre Report 695/27, June 1995 (UK)

2) BS EN ISO 5198:1999 Centrifugal, mixed flow and axial pumps – Code for hydraulic performance tests – Precision class.

3) The thermodynamic method of pump efficiency determination, UK Dept of the Environment, Future Practice R&D Report 17, July 1997

8 ACKNOWLEDGEMENTS

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