Pump efficiency monitoring in the water industry

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Introduction

In the UK the percentage of pumping plant operating unattended is steadily increasing as more telemetry and local automatic control systems are installed. This growing trend towards automatic operation whilst improving operational flexibility will have the undesirable effect of increasing the number of incipient faults which remain undetected, resulting in:
(1) The increased likelihood of unexpected failure or breakdown.
(2) Increased incidence of inefficient pump operation.

This article is concerned with the latter point and in particular the measurement of pump efficiency on site.

To give some perspective to the value of being able to measure the efficiency of a pump in its operating environment it is helpful to look at pumping energy costs. It is generally accepted that the UK water industry spends between £100 million and £110 million per annum on electrical energy for pumping in our water supply systems (this excludes energy used to pump sewage and power water treatment processes). Recent measurements in the water industry at pumping stations have indicated that by restoring pumps to their original performance and also by ensuring that they operate at or near their best efficiency point an average improvement in pumping efficiency of about 8% would result. If say an average of 5% could be achieved nationally then energy cost reductions in the industry of the order of £5 million per annum are possible. Significant reductions in operating costs can also be obtained by optimising the operation of water supply networks. Accurate information on pumping performance is an essential input to the optimisation process.

To illustrate this, Fig 1 gives a very simple example of how pump refurbishment and modification can improve efficiency. However it is important to understand that only after reliable *in-situ* pump performance data has been obtained is it possible to identify and evaluate the most cost effective way of improving pump performance.

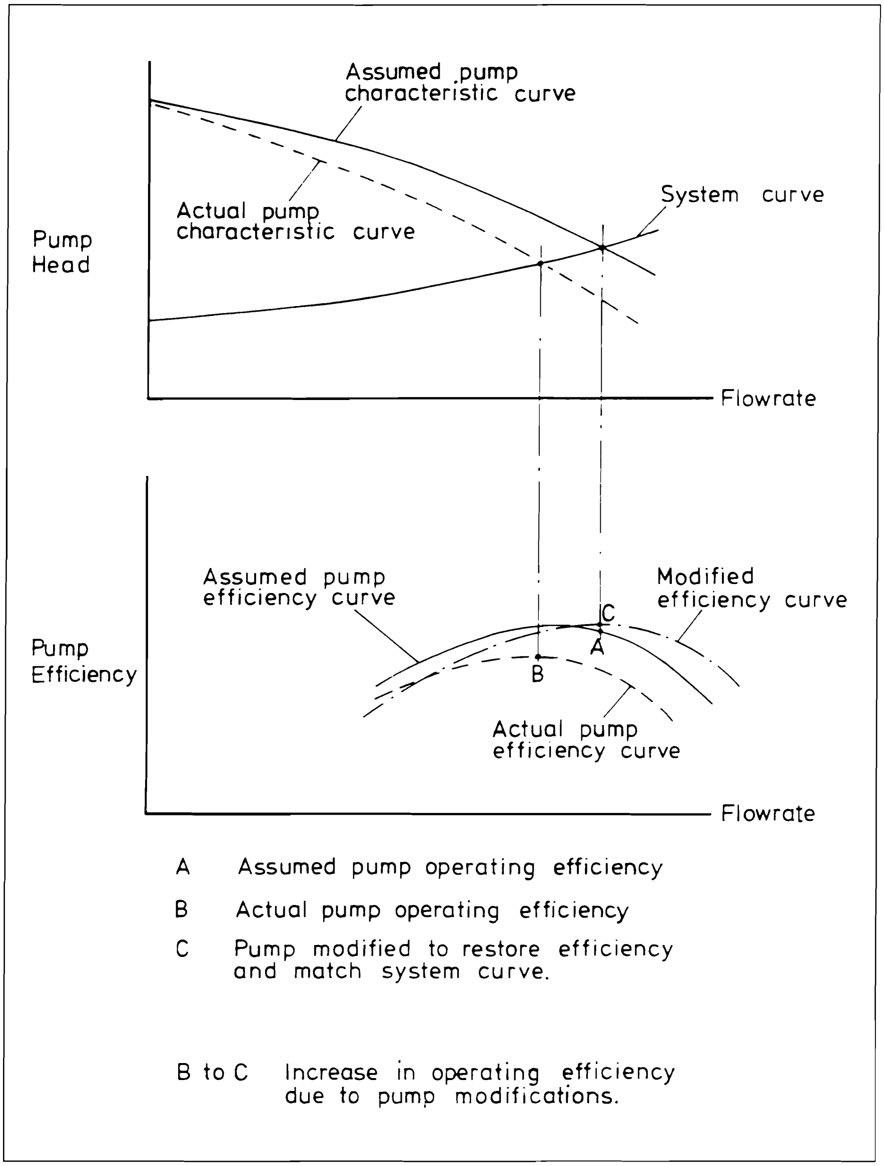

Fig 1 Example of how pump modification can improve operating efficiency

Measurement of pump efficiency

The normal parameters required for the evaluation of efficiency are net pump head, flowrate and power consumption; head and power are readily measured on site, flowrate is often very difficult to measure accurately. The main difficulties are:

- If a flowmeter is fitted *in-situ*, calibration is difficult and the meter may be sized for the combined flow of several pumps not for the flow from an individual pump.
- If a flowmeter is not fitted then pipework has to be moved and replaced during installation. Such disruption may not always be acceptable.

In addition there may not be adequate lengths of straight pipe up and down-stream of the meter.

- In some cases it is possible to measure flowrate accurately if a calibrated tank or reservoir is available. Radioactive tracer dilution techniques have been used but they are cumbersome and although safe their extensive use in potable water systems might not be acceptable to the consumer.

It is the difficulties associated with flowrate measurement which have up to now prevented the widespread availability of *in-situ* pump performance data. An alternative technique known as the 'thermometric' or 'thermodynamic' method avoids the need to measure flowrate directly by relying on the fact that almost all of the losses in a pump are converted into heat which is dissipated in the pumped fluid. These losses result in a small increase in water temperature between pump inlet and outlet. (Only a very small amount of the losses, about 1%, are transferred directly to the surroundings through glands and bearings). Pump efficiency can be calculated knowing the temperature increase and fluid head or pressure increase across the pump. Pump flow rate can be determined when the power input to the pump is known. A simplified derivation of the expressions used to calculate the pump characteristics is given below.

(Pump efficiency) $\eta_p =$

$$\frac{\text{Work out of pump}}{\text{Work into pump}} \quad \text{and}$$

$$\begin{matrix}\text{Work out}\\ \text{of pump}\end{matrix} = \begin{matrix}\text{Work into}\\ \text{pump}\end{matrix} - \text{losses}$$

therefore,

$$\eta_p = \frac{1}{1 + \dfrac{\text{losses}}{\text{Work out of pump}}}$$

If the dissipated heat (i.e. the losses) is defined as:

$$Cp.m.\triangle T$$

where: Cp = specific heat of the fluid (Joules/kg°C)
m = mass flowrate (kg/sec)
$\triangle T$ = the temperature rise (°C)

and,
the work out = $m.g.\triangle H$

where,

g = acceleration due to gravity (m/sec²)

$\triangle H$ = net pump head (m)

$$\text{then } \eta_p = \frac{1}{1 + \dfrac{Cp.m.\triangle T}{m.g.\triangle H}}$$

$$= \frac{1}{1 + \dfrac{Cp.\triangle T}{g.\triangle H}}$$

For water
$C_p = 4186$ J/kg°C and $g = 9.81 \text{m/sec}^2$

the equation now becomes:

$$\eta_p = \frac{1}{1 + \dfrac{426.7 \triangle T}{\triangle H}} \qquad (1)$$

The derivation of the full equation is given[1], but for most purposes the above expression is adequate. Corrections to the value of $\triangle H$ need to be made if either the pump inlet and discharge velocities, or the heights of the inlet and outlet pressure measurement points differ.

It can be seen from equation (1) that η_p is now dependent only on temperature rise and pump head, the mass flowrate cancelling out. Measurement of head is usually straightforward. Temperature rise has to be measured to an accuracy of a few milli-degrees Celsius but it is now possible to do this with care and the appropriate instrumentation.

Flowrate can be calculated by substituting the values found for pump efficiency and head into the standard equation for pump hydraulic efficiency:

$$\eta_p = \frac{m.g.\triangle H}{P.\eta_m}$$

where: P = motor power absorbed (W)
η_m = motor efficiency and
m = $p.Q$
p = density of water (kg/m³)
Q = volume flowrate (m³/sec)

State of the Art

The idea of using the temperature rise between the inlet and outlet of a water turbine to measure its efficiency is not new and was first conceived by Poirson in 1914 and subsequently developed in France (Willm, and Campmas 1954)[2]. The method has since been applied to efficiency measurements on water pumps (Foord et al 1964, El Agib 1964)[3,4,1] and to hydrostatic oil pumps (Nordgard 1972)[5]. Application of the technique in relation to fluid power is discussed by Witt (1977)[6], in a compendium of articles which also contains tabulated information on the thermodynamic properties of hydrocarbon-based fluids. A survey of other work in this field is presented by Kjolle (1978)[7].

A standard method of thermometric efficiency measurement for high head turbomachines (> 100 m), is specified in BS 5860[8], although satisfactory results have been obtained by Colon (1969)[9], on a low head pump producing only 7.6 m head of water. The small temperature increment produced at low heads generally causes a higher margin of uncertainty in the calculated efficiency than would be found with other, more conventional methods of efficiency determination, unless highly sophisticated and precise instrumentation is available.

Thermometric technique for determining the efficiency of hydraulic machinery exhibit several advantages over the more conventional methods. They are relatively simple, causing little interruption to the working of the machine, and require only the provision of thermometer pockets or probe tappings. The method has facilitated *in-situ* measurements on boiler feed and water supply pumps, where accurate determination of flowrate (as required by conventional methods) is hindered by the prevailing temperatures and pressures in the former application and the impracticality of accurately calibrating flow-meters in the latter. The technique is equally expedient for pumps handling noxious or corrosive fluids if their thermodynamic properties are known.

An important point concerning the method is that the calculated value of efficiency is fairly insensitive to inaccuracies in the temperature measurements themselves. A water supply pump in good working order might typically have a head $\triangle H$, of 60 m and an efficiency η_p of 75%.

By rearranging equation (1)

$$\triangle T = (1 - \eta_p) \frac{\triangle H}{426.7 \, \eta_p}$$

$$= 0.047°C$$

For a 10% uncertainty in $\triangle T$:

$$\triangle T = .047 \pm .0047°C$$

we have a change in efficiency of:

$$\triangle\eta_p = \frac{1}{1 + \dfrac{426.7}{60}(.046 - .0047)} - \frac{1}{1 + \dfrac{426.7}{60}(.047 - .0047)}$$

$$= 76.87 - 73.12$$

$$= 3.75 \text{ percentage points or}$$

$$\triangle\eta_p = 75 \pm 1.875 \text{ percentage points}$$

i.e. a 2.5% uncertainty in the value of efficiency, which means that at these heads and efficiencies the accuracy of the calculated efficiency is about four times better than the temperature measurement.

Although BHRA use instrumentation which can measure temperature differences to an accuracy of about ±.001°C, site conditions introduce several sources of error and so accuracies of about ±.005°C are probably more realistic. This means that in the

Fig 2 'Using thermometric equipment on site'

example efficiency measurements will have an uncertainty due to temperature measurement error of about ±2 percentage points in 75, which is perfectly adequate for most applications.

In practice the main causes of error are:

1) Radial temperature gradients in the measuring section.

2) Probe vibration.

It is advisable to check that significant radial temperature gradients across the pipe do not exist. Current experience indicates that in the majority of installations mixing is sufficient to give fairly flat temperature profiles.

Vibration caused by buffeting and vortex shedding can shift the calibration of the temperature probes. Vibration is minimised by probe stiffening and rigid probe mounting. Checks on calibration should be carried out on site as a matter of course before and after each test.

Some pumps have water cooled bearings which can effect the measurement of efficiency if the coolant flow either re-enters the pipe upstream of the suction temperature probe or drains to waste. In such cases the coolant flow rate and temperature should be measured and added to the 'losses' term in the efficiency equation.

Heat transfer along the probe is not generally a problem in water pumping installations unless there is a significant difference between water and air temperature and if, for some reason, water temperature near the pipe wall is being measured. Normally water temperature is measured on the pipe centre line.

Future development

BHRA has developed a very sensitive temperature measurement system based largely on commercially available components, which is currently used for pump efficiency measurements throughout the water industry. As has already been described, a knowledge of pump efficiency can have a significant impact on the operating costs of individual stations.

Most stations are however part of extensive water distribution networks and it is to optimising the operation of these networks that many water authorities are now looking to achieve further reductions in operating costs. Such aspects as making use of efficient pumping stations, low cost water resources and efficient scheduling of pump operation to maximise the use of low cost electrical energy are being considered. This level of analysis, which involves the use of powerful networking programmes is only possible if accurate network and pump efficiency data are available. It is envisaged that such large scale analyses will comprise a major proportion of BHRA's future work on water supply system operating cost reduction.

Thermometric measurements are currently made periodically using portable equipment. Continuous efficiency monitoring can be justified on larger plant particularly when combined with other condition monitoring functions such as vibration measurement. BHRA is currently assessing the technical problem this poses with a view to developing permanently installed efficiency monitoring systems.

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