Centrifugal pumping

High-energy pumps: a major safety issue

Catastrophic failure is a possible outcome when inlet pipework is over-pressurized or when the rotor of a high-energy pump seizes. Both can result from the low-flow protection failing to act promptly. Dr Edward Grist shows that pipework layout, pump design and leak-off system design greatly influence the risk of failure.

Maintaining flow rate above the minimum necessary to protect a centrifugal pump from damage or loss of performance during normal service is easily achieved by providing an appropriate low-flow protection system. Low-flow protection in the early 20th century was by means of a small bypass flow through a 'leak-off' valve that was judged sufficient to prevent 'overheating'. When the valve in these systems failed to open the pump often seized.

In 1970, very few pumps could be classified as 'high-energy'*. At that time, the largest, most-powerful pumps were those used on power station feedwater duties or in deep mine drainage. These pumps were often directly driven by electric motors – typically with speeds less than 3,600 rpm and powers under 2 MW. At zero flow rate they had a large churned liquid mass within five or more impeller stages. This, in turn, gave ample time to respond to tardy operation of the low-flow protection but, again, failure to operate usually produced seizure.

The introduction of power station pumps running at speeds of up to 7,500 rpm with only two or three impeller stages and with driver powers up to 20 MW dramatically reduced the time to respond to low-flow protection failure. These pumps required low-flow protection to act within one second whereas their predecessors required a leisurely 15 seconds or more. On this shorter timescale there is no possibility of operator intervention or removal of the driver energy.

An important safety issue arises. Under fault conditions characterized by the low-flow protection operating too slowly or failing to operate at all, a risk of severe damage to pump internals exists. Operational records show that pumps that are unable to run vapour-locked can incur extremely costly repairs when components forming the internal hydraulic clearances between stator and rotor are damaged. Pumps having a vapour-lock running capability avoid such failures. However, all high-energy pumps, particularly those with a vapour-lock capability, have the potential to generate very high inlet pipe pressures. Certain combinations of pump set and pipework design significantly increase the possibility of this leading to a pressure-containment failure, an unacceptable catastrophic event.

At very low or zero flow rate, extensive vapour formation can be almost instantaneous. It is nearly always accompanied by violent cavitation surging, typically at 3 Hz. Clearly, the significant benefits associated with high-energy pump technology can only be reaped if the increased risks associated with low-flow protection failure are understood and dealt with.

The vapour-lock phenomenon

Vapour-lock running cannot be avoided with absolute certainty in high-energy pumps. The primary cause of vapour-lock running is the failure of the low-flow protection system to operate in a timely manner. Records show this to be a very infrequent event. However, it can and does happen.

When the flow rate through a pump is very low, the heat generated within the churned mass in and around the impeller(s) accumulates.

**High-energy pumps are defined as those that have a 'Pipichum' value of 100 kW/kg or more where:*

Pipichum value = pump power input/churned mass
= power when flow rate is zero (kW)/mass of liquid rotating within the pump (kg)

For safety assessments it is prudent to include pumps with a Pipichum value greater than ten.

Transient conditions arise in which cavitation develops and becomes ever more extensive. Eventually the impeller becomes vapour-locked. In multistage pumps the volume of vapour grows until the head generated by the inlet impeller collapses. This leads immediately to a cascading collapse in the head generated by any following stages and the pump becomes vapour-locked.

A pump designed for vapour-lock running can operate with its impeller(s) spinning in vapour. The noise emitted changes to what has been described[1] as 'a mild and not unpleasant siren-like note'. The power required to churn the lower density fluid is, of course, much reduced. Consequently, relatively benign conditions arise and, although the temperature within the pump increases steadily, it does so much more slowly. In theory, this could continue until the power loss within the pump is balanced by the heat losses to the pump external environment. In practice, long before this can happen the functional capability of the pump is challenged as the materials from which it is made expand and distort. This results in internal running clearances changing, shaft alignment going out of prescribed limits and, sometimes, to the deformation of the pump pressure-containment casing.

Designs are available that ensure a pump can easily withstand being vapour-locked for several minutes. This feature, provable by a works-type test, gives ample time to stop the pump undamaged. Timely action under these most extreme operating conditions means that the pump can always be stopped safely.

Restricted inlet pipe backflow

The severity of potential consequences is strongly influenced by the pipework layout preceding the pump inlet. In systems where there is a restriction to flow returning back through the inlet, such as a non-return valve, the fluid in the pump and the pipework local to it can become trapped (Figure 1). Typically this happens when the discharge line is closed (e.g. during pump start-up or shut-down) and the low-flow protection fails to operate. Heating of the trapped fluid results in a very rapid pressure rise, particularly in layouts where the trapped volume is small. Only a tiny amount of alleviation can be given by leakage paths through shaft seals etc. during such an event. Most pumped liquids, and certainly deaerated water[2], are in

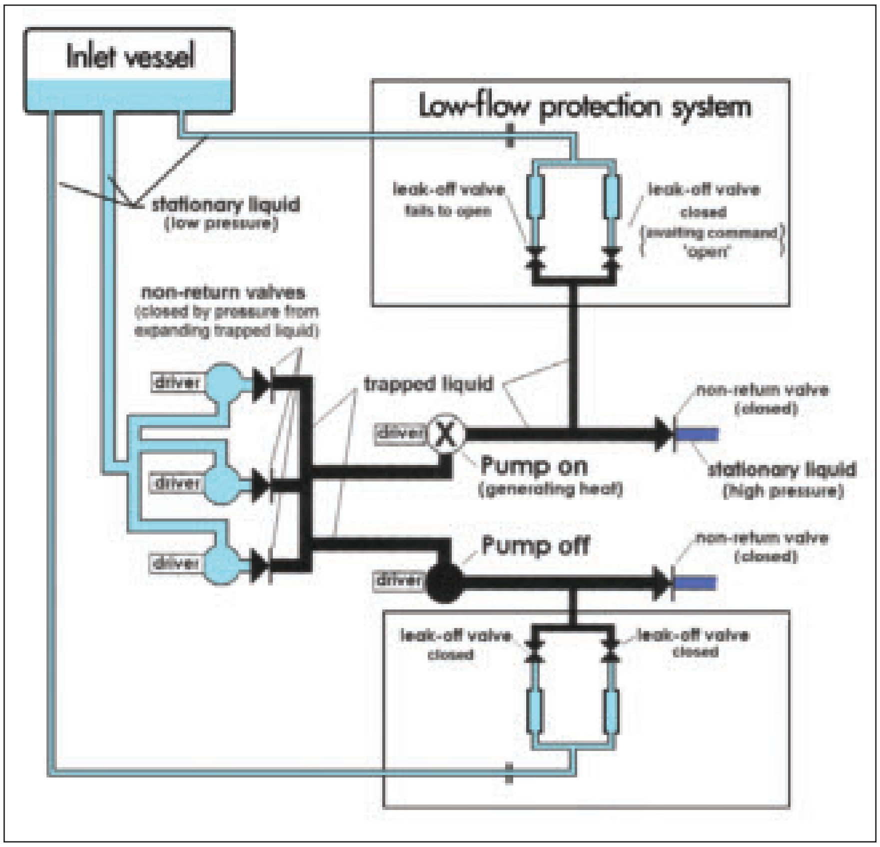

Figure 1. Low-flow protection – inlet pipe with restricted backflow.

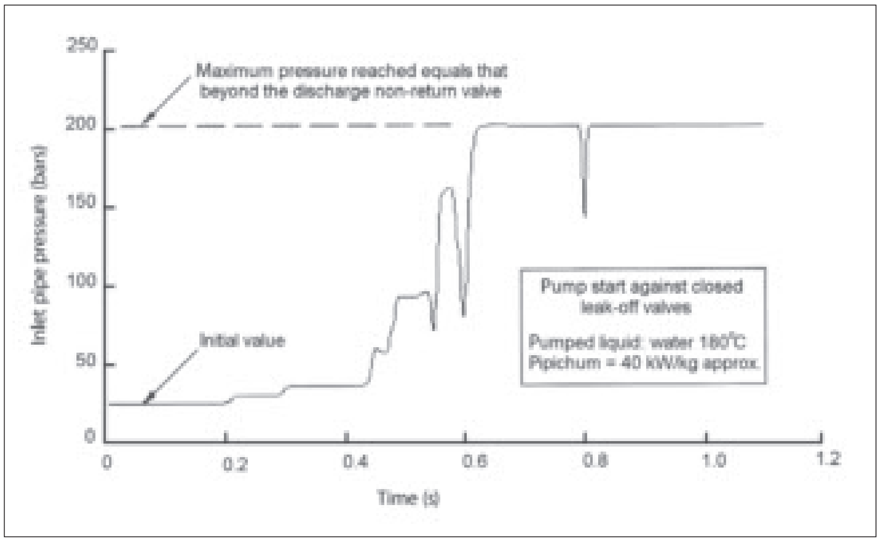

Figure 2. Inlet pipe pressure test for a pump – zero inlet pipe backflow.

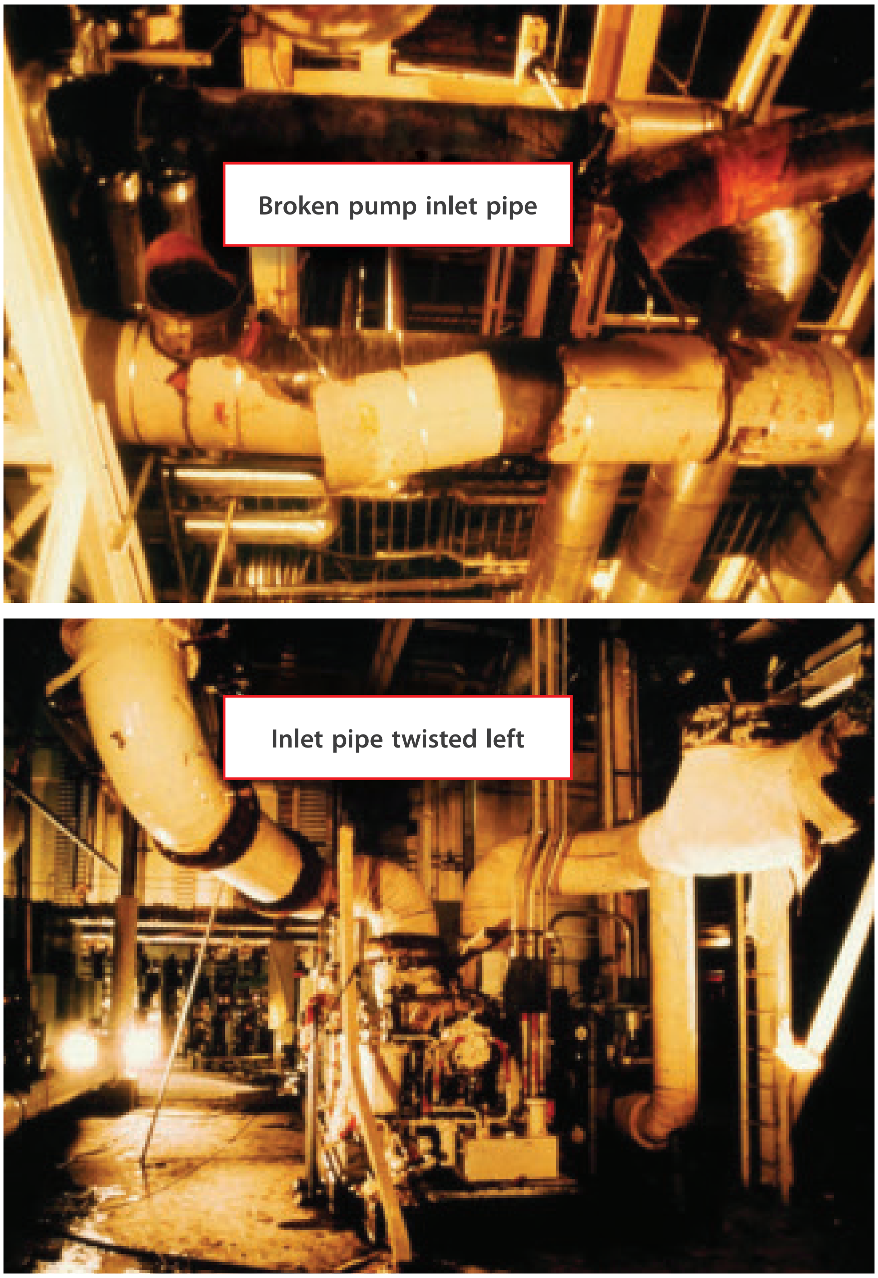

Figure 3. Catastrophic failure of a feedwater pump inlet pipe.

this context practically incompressible. Figure 1 shows a typical pipework arrangement that restricts backflow. The very high pressure that can be reached in less than one second is shown in Figure 2. An outline analytical method for assessing the consequences of the pulsations observed during a pressure build-up is presented in Ref. 3.

The conditions arising during heating of the trapped fluid are complex. The balance between the extent to which cavitation can occur as temperature rises and the self-pressurization resulting from the geometry constraining the trapped fluid is further complicated by the reduction in the power driving vapour production once the impeller becomes vapour-locked.

Cavitation surging has been observed in high-energy pumps. In power station feedwater pumps operating at low flow rates, the violence of this surging is very dramatic. Platform-mounted pumps and machinery weighing about 50 tonnes shake at 3 Hz.

Cavitation surging is characterized by large momentum changes in the inlet impeller. This causes a corresponding dynamic response in the magnitude of the axial thrust. A pump with an external thrust bearing offers the possibility of measuring changes in axial load thereby providing a means of detecting the presence of the surge phenomenon and remotely taking remedial action.

As cavities grow in the inlet of a pump impeller, there is the possibility that before vapour-lock conditions are reached the pressure in the trapped volume reaches a value that lifts a discharge non-return valve, as shown in Figure 2 (i.e. it is greater than the pressure downstream of this valve). In the past, the inlet pipework has rarely been designed with this possibility in mind. Clearly, if the pressure that is reached exceeds the pressure-retaining capability of the pump or the pipework system, a catastrophic failure is the outcome.

A search of the literature has not found any record of an inlet pipework failure attributable to low-flow protection system malfunction in high-energy pumps. However, the author has been present shortly after a feedwater pump inlet pipework failure that was positively identified as being due to another cause[4]. The result of this inlet pipe failure is shown in Figure 3. The massive forces released as high-temperature water escaped readily twisted and distorted the steel inlet pipework. Once seen never forgotten.

Where the pumped liquid is hot feed-water, a pipe failure is accompanied by a massive explosion as the escaping steam/water mixture expands. The consequences are fatal for personnel unfortunate to be in the vicinity of such a break.

To calculate the maximum pressure reached requires knowledge of:

(i) the power input at the outset when pumping liquid;

(ii) the volume of vapour that signals the change to pumping vapour;

(iii) the power input when pumping vapour; and

(iv) the time that the power source is withdrawn.

Even with all this data there is no general way of calculating the extent of inlet pipe pressurization. A large variation in outcome arises because of the strong conflicting influences of pumped liquid properties, inlet pipework configuration and, most importantly, a lack of an ability to quantify for a particular impeller the cavity volume reached when rapid growth is significantly reduced immediately following vapour lock.

Unrestricted inlet pipe backflow

A typical pipework arrangement that imposes no restriction to backflow is shown in Figure 4.

Pumps not designed to run vapour-locked usually experience rotor/stator contact followed by severe damage to internal hydraulic clearances. Seizure is probable after a short time if the pump is not stopped. If at the outset the flow rate through the pump is zero (e.g. when the low-flow protection fails to open) a vapour lock occurs typically in less than one second.

There is no reliable way of addressing all the possible causes of vapour-locking for pumps not designed to withstand this condition. A pragmatic strategy is to accept the risk of failure and consider what secondary measures to mitigate its effect are feasible. Such measures include immediately stopping the pump following detection of unacceptable rotor/stator contact and minimizing the number of times it occurs by adopting 'best practice' in low-flow protection measures appropriate to the particular pump installation.

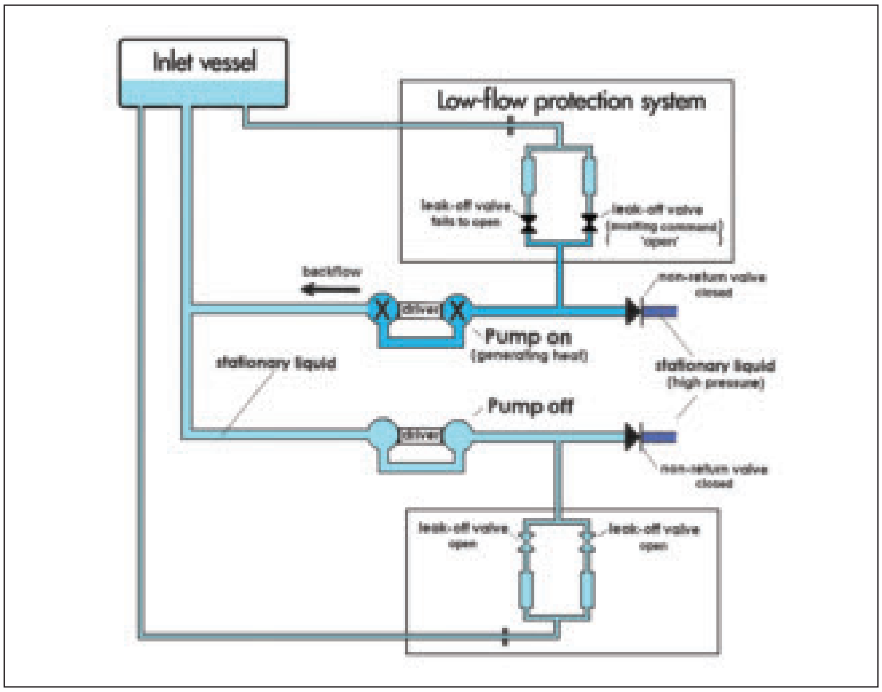

Figure 4. Low-flow protection – inlet pipe with unrestricted backflow.

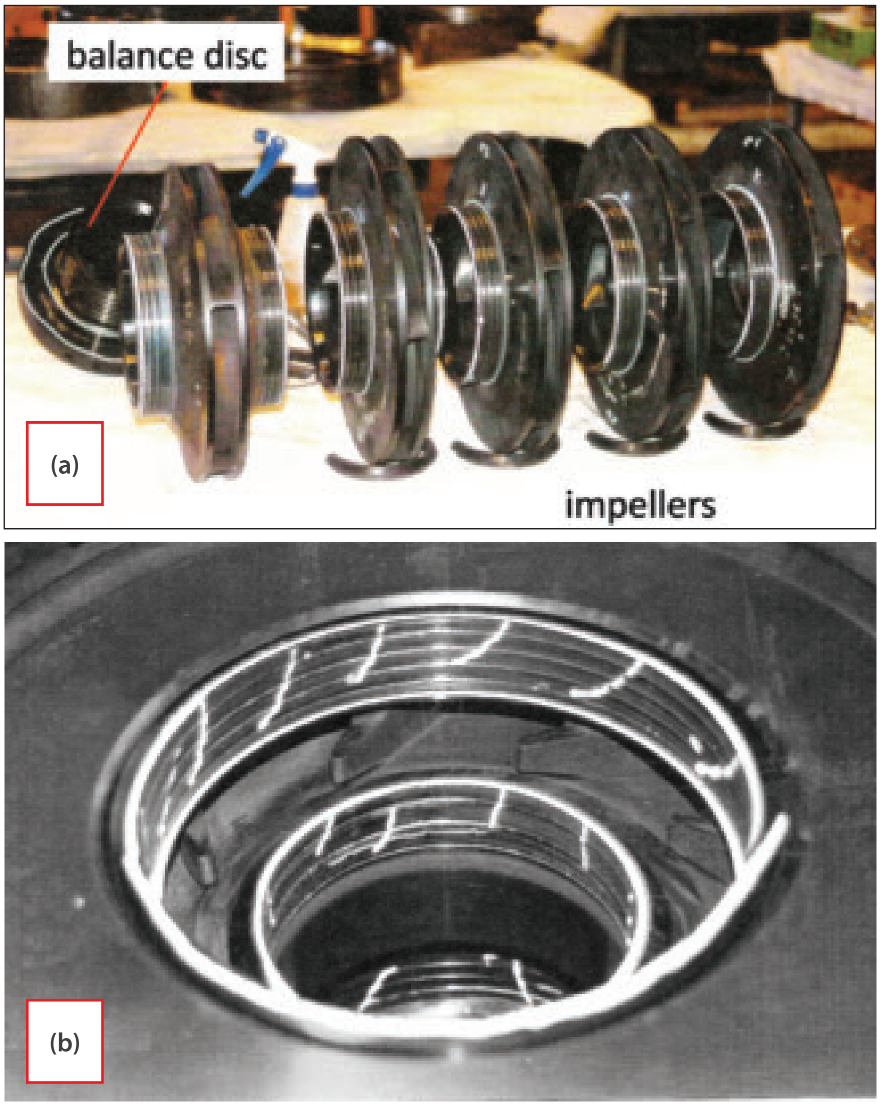

Figure 5. Damage to pump internals from failure of low-flow protection to act promptly. Damage to (a) the impeller necks and on the balance disk, and (b) the interstage running clearances (shown by white chalk).

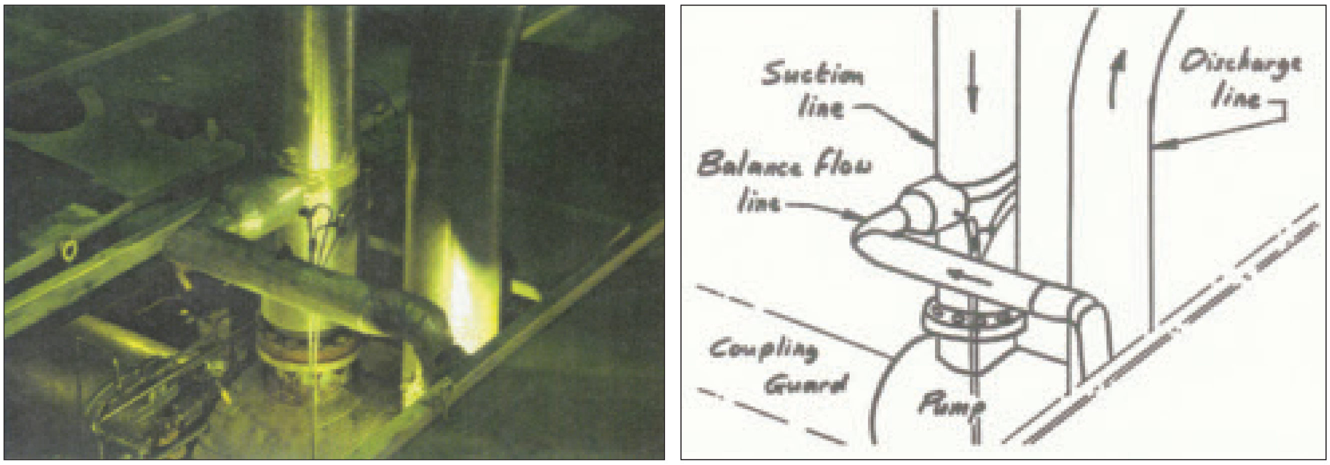

Figure 6. Balance flow line is too close to the feedwater pump inlet to allow adequate mixing of the returning heated liquid.

Damage to the impeller and interstage clearances of a pump not designed to run vapour-locked is shown in Figure 5.

Low-flow protection systems

The low-flow protection system must ensure that for all normal continuous operating conditions the flow rate never falls below the leak-off rated flow rate. For all other conditions (start-up, shut-down and during a fault) the low-flow protection system must operate in a way that best protects the plant from vapour lock.

In normal service, leak-off valves are required to:

(i) Stand closed for long periods with a large pressure difference across the valve seat.

(ii) Open very quickly.

(iii) Withstand frequent severe thermal shocks in applications where the pumped liquid is at a temperature very different from that of the liquid standing behind the valve.

(iv) Move to the open position on loss of power to the actuator.

(v) Be available to provide immediate protection and not have any time-wasting activities in the control and actuation logic.

For high-energy pumps, a vapour lock is probable sometime during its operational life. The risk of it occurring cannot be eliminated. In hot-liquid applications, valves can stick at critical times when subjected to rapid temperature changes. Causes such as these can, however, be significantly reduced by making prudent choices with regard to hardware design and method of operation.

Leak-off valves

Knowledge of the minimum flow rate required to sweep heated fluid through the pump impeller(s) to prevent a vapour lock developing and of the minimum opening time a leak-off valve has to achieve this flow rate to prevent a plant failure is an ideal requirement. In an industrial context, these values are always determined by commercial limitations. The pragmatic view is to define the boundary for high-energy pump protection when utilizing the performance capabilities of commercially acceptable valves and actuators.

The leak-off valve *duty* flow rate is defined as that necessary to provide protection against cavitation surging and cavitation erosion damage under all *normal* pump operating conditions. Quantifying the *minimum* flow rate to prevent vapour-locking poses a problem.

In the absence of a more compelling argument, past experience dictates that the minimum flow rate is taken to be 5% of the best efficiency flow rate. Choosing to achieve this flow rate within two seconds establishes commercially attainable design boundaries that enable risk assessments to be made. Pumps that are unable to run vapour-locked may well be shown to be unacceptable. The sensitivity of a particular design to lowering these thresholds where more certainty of pump and/or leak-off valve performance is available can be explored. This practical approach results in a test being formulated that demonstrates that, on receiving a command to open, each leak-off valve reaches this flow rate promptly. This test should be carried out when the pump is commissioned and repeated throughout its operational service life.

There are commercially acceptable valve designs that can, with certainty, provide protection against a vapour lock that occurs in less than two seconds. Parallel slide valves with pneumatic actuators have been observed to achieve this easily.

Design options

Pump design: balance flow return

Many high-energy pumps have internal hydraulic axial thrust balancing arrangements – usually either a balance disc or a balance drum. Such internal devices allow a small amount of the pumped liquid that has passed through to the pump discharge to return to the pipework preceding the pump inlet. All liquid passing through a pump is heated by the inefficiencies of the pumping process so that at the discharge it is typically more than 2°C hotter. Consequently, returning this liquid to the inlet raises the possibility of triggering vapour production if it is not mixed thoroughly with the incoming liquid.

This problem goes away of course if the returned liquid is introduced well upstream of the pump (but within any isolating valve), preferably beyond but in the plane of a bend, so that thorough mixing takes place. An example of a balance flow return very close to a pump inlet is shown in Figure 6.

Duplicate leak-off valve operation

Duplicate leak-off valves that operate *sequentially* provide a means of progressively changing leak-off flow rate as a pump leaves or enters service. In the event of one valve failing there is an element of built-in redundancy. In the past I have recommended sequential operation[5]. This is no longer the case. It conflicts with fault condition requirements. The need to provide rapid-response back-up protection under fault conditions takes precedence. Where duplicate valves are used they should always operate *simultaneously*.

Leak-off valve actuation

A loss of power supply that prevents electrically operated valve actuation is a possibility. Leak-off valves must always fail to the open position – the inherently safe position. Pneumatically operated actuators that allow a valve to quickly move to 'open' should be considered. This form of actuation when used in conjunction with parallel slide valves has proved to be a fast and effective way of meeting this onerous requirement.

Leak-off valve modulation

Modulation, as applied to low-flow protection systems, means adjusting the rate of opening of the leak-off valve(s) so that when it is called on to operate the sum total of flows through it and the pump discharge branch are 'balanced' in some way. This presumes a knowledge of the rate at which the flow rate is falling and the time to open the valve (including clearing its seat). Experience reveals that modulation does not always do this. It has been observed to give rise to hunting. Closing at the wrong time is a possibility. Pumps do not need modulation. This added complexity should be avoided. ■

References

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Contact

Dr Edward Grist
Congleton, UK
Email: pumps@gristgen.co.uk
[Dr Grist was formerly Head of Pumps & Water Turbines, Central Electricity Generating Board, Gloucester, UK]