UNUSUAL ASPECTS OF HYDRAULIC TRANSIENTS IN PUMPING PLANTS*

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SYNOPSIS

The computational procedures for the analysis of hydraulic transients in pump discharge lines with electric motor driven pumps has been known for many years. It started with the basic waterhammer contributions for valve operation by Joukousky and Allievi over 60 years ago. This was followed by many others in later years with the application of numerical, graphical, and high speed computer techniques. Although the mechanics of computation of the hydraulic transients in pump discharge lines has advanced rapidly in recent years, there are a number of unusual aspects which are still troublesome. It is the purpose of this paper to bring some of these to the reader's attention.

GENERAL CONSIDERATIONS

SCOPE OF PAPER: The aim of this paper is threefold. The first and major portion of the paper contains a discussion of some practical and unusual aspects of hydraulic transients in pumping plants which are sometimes overlooked. The second is to call attention to the available waterhammer solutions in the engineering literature which provide a ready solution of the hydraulic transients in pumping plants for a variety of waterhammer control devices. Finally, there is a discussion on the observed and computed transients in pumping installations with various types of pressure control devices.

BASIC ASSUMPTIONS: A number of assumptions were made in the derivation of the fundamental waterhammer equations and in the solution of the hydraulic transients in pumping systems. These assumptions involve the physical properties of the fluid and pipeline, the kinematics of the flow, and the transient response of the pump as follows:

(1) The fluid in the pipe system is elastic, of homogeneous density, and is always in the liquid state.

(2) The pipe wall material or conduit is homogeneous, isotropic, and elastic.

(3) The velocities and pressures in the pipeline, which is always flowing full, are uniformly distributed over any transverse cross section.

(4) The velocity head in the pipeline is negligible when compared to the pressure changes.

(5) At any time during the pump transient, when operating in the zones of pump operation, energy dissipation, and turbine operation, there is an instantaneous agreement at the pump, as defined by the steady state complete pump characteristics, of the pump speed and torque corresponding to the transient head and flow which exist at that moment at the pump.

(6) The length between the inlet and outlet of the pump is so short that waterhammer waves propogate between them instantly.

(7) Windage effects of the rotating elements of the pump and motor during the transients are negligible.

(8) Water levels at the intake and discharge reservoirs do not change during the transient period.

HIGH AND LOW HEAD PUMPING SYSTEMS: Waterhammer is of greater importance at low head pumping systems than at high head systems. The normal steady water velocities in both high head and low head pumping systems are usually of about the same order of magnitude. However, the pressure changes are proportional to the rate of change in the velocity of the water in the line. Then, for a given rate of change in the velocity, the pressure changes in the high and low head pumping systems are of about the same order of magnitude. Therefore, a head rise of a given amount would be a larger proportion of the pumping head at a low head pumping system than at a high head system.

DISCHARGE LINE PROFILE: The pump discharge line profile is usually based on economic, topographic and land right-of-way considerations. However, in selecting the alignment along which a pump discharge line is to be located, there are other considerations which often make one pipeline profile and alignment more favorable than another. For example, upon a power failure at the pump motors, the envelope of the maximum downsurge gradient along the length of the pipeline is a concave curve. Therefore, it may be possible to avoid the use of expensive pressure control devices at a pumping plant if the pipeline profile is also concave and is not located too far above the downsurge gradient curve. In some cases it may even be economical to lower the profile of the discharge line at the critical locations by deeper excavation. This was done at several large pumping plant installations and as a result some large expensive surge tanks were eliminated. If a surge tank at the pumping plant is definitely required, the most favorable pipeline profile is one with high ground near the pumping plant where the surge tank structure above the natural ground line would be much shorter in height.

RIGID WATER COLUMN THEORY: The question is often raised as to whether the rigid water column theory of waterhammer is sufficiently accurate for the computation of the hydraulic transients in pump discharge lines. In the rigid water column theory the water is assumed to be incompressible and the pipe walls rigid. In the author's experience, the accuracy of the rigid water column theory is often questionable for most of the waterhammer problems that occur in pump discharge lines. However, it can be used with sufficient accuracy in the analysis of the transients in pipelines with such devices as surge tanks and air chambers. With these devices the velocity changes in the pump discharge line are substantially reduced.

WATERHAMMER WAVE VELOCITY: A number of articles have appeared in the technical literature during the past decade on the analysis of the wave velocities in steel pipes with various types of fixity. However, the differences in the numerical value of the wave velocities as computed by these various analyses and those given in Reference 1 are insignificant. It is also difficult to determine accurately the waterhammer wave velocity in rock tunnels because the elastic properties of the rock throughout the length of the tunnel are seldom known. As a practical matter a difference of 10 to 20 per cent in the magnitude of the waterhammer wave velocity usually has very little effect on the critical hydraulic transients in most pump discharge lines. The effect on the hydraulic transients of a possible error in the wave velocity can be verified by first computing the wave velocity as accurately as possible, and then recomputing the transients for the critical cases with a wave velocity which is about 20 percent different. At installations where alternative materials for the pipeline such as steel or concrete are being investigated, one waterhammer wave velocity and solution for the hydraulic transients for either alternative will usually suffice regardless of the pipe material finally selected.

PIPELINE SIZE: The diameter of the pipeline is usually determined from economic considerations based upon steady state pumping conditions. However, the waterhammer effects in a pump discharge line can be reduced by increasing the size of the discharge line since the velocity changes in the larger pipeline will be less. This is usually an expensive method for reducing waterhammer in pump discharge lines, but there are sometimes occasions, such as in small pipelines, where an increase in pipe size may be justified to avoid the use of more expensive waterhammer control devices.

NUMBER OF PUMPS: The number of pumps connected to each pump discharge line is usually determined from the operational requirements of the installation, availability of pumps, and other economic considerations. However, the number and size of pumps connected to each discharge line has some effect on the hydraulic transients. For pump start-up the more the number of pumps on each discharge line the smaller the pressure rise. Moreover, if there is a malfunction at one of the pumps or control valves, a multiple pump installation on each discharge line would be preferable to a single pump installation because the flow changes in the discharge line due to such a malfunction would be less. When a simultaneous power failure occurs at all of the pump motors, the fewer the number of pumps on a discharge line, the smaller are the hydraulic transients. For a given total flow in the discharge line, a large number of smaller pumps and motors will have considerably less total kinetic energy in the rotating parts than a fewer number of pumps. Consequently, for the same total flow, the waterhammer effects due to a power failure are a minimum when there is only one pump connected to each discharge line.

FLYWHEEL EFFECT (WR^2): Another method for reducing the waterhammer effects in pump discharge lines is to provide additional flywheel effect (WR^2) in the rotating element of the motor. As an average the motor usually provides about 90 per cent of the combined flywheel effect of the rotating elements of the pump and motor. Upon a power failure at the motor, the increased kinetic energy of the rotating parts of the motor and pump will reduce the rate of change in the flow of water in the discharge line. As a rule of thumb, an increase of 100 per cent in the WR^2 of large motors can usually be obtained at an increased cost of about 20 per cent of the original cost of the motor. Ordinarily, an increase in WR^2 is not an economical method for reducing waterhammer, but it might be possible in marginal cases to eliminate other more expensive pressure control devices.

SPECIFIC SPEED OF PUMPS: For a given pipeline and steady flow conditions, the maximum head rise which can occur in a discharge line subsequent to a power failure, where the reverse flow passes through the pump depends first on the magnitude of the maximum reverse flow which can pass through the pump during the energy dissipation and turbine operation zones, and then upon the reduced flow which can pass through the pump at runaway speed in reverse.

Upon a power failure the radial flow (low specific speed) pump will produce slightly more downsurge than the axial flow (high specific speed) pump (see Reference 5). The radial flow pump will also produce the highest head rise upon a power failure if the reverse flow is permitted to pass through the pump. There is practically no head rise at mixed flow and axial flow pumps when a power failure occurs. Hence, the results obtained for radial flow pumps for the hydraulic transients due to a power failure will give conservative results of the downsurge and upsurge for any type of pump. During a power failure with no valves, the highest reverse speed is reached by the axial flow pump and the lowest by the radial flow pump. Care must therefore be taken to prevent damage to the motors with the higher specific speed pumps because of these higher reverse speeds.

Upon pump start-up against an initially closed check valve, the axial flow pump will produce the highest head rise in the discharge line since it also has the highest shut-off head. On pump start-up a radial flow pump will produce a nominal head rise but an axial flow pump can produce a head rise of several times the static head.

COMPLETE PUMP CHARACTERISTICS: In order to determine the transient conditions due to a power failure at the pump motors, the waterhammer wave phenomena in the pipeline, the rotating inertia of the pump and motor, and the complete pump characteristics, as shown in References 1 and 5, as well as other boundary conditions and head losses must be known. In the solution of waterhammer problems with computers, the complete pump characteristics are usually approximated by a polynomial expression in which the coefficients of the polynomial are obtained by fitting a representative curve through 3 adjacent points at specific locations on the pump characteristics diagram. Pump manufacturers sometimes provide limited information to determine these coefficients. However, a comparison between the polynomial values and the complete pump characteristics diagram indicates serious discrepancies in many cases especially in the zone of energy dissipation. Care must therefore be exercised in the use of an approximate polynomial expression as a substitute for the correct complete pump characteristics, to insure that a serious error does not result in the computation of the hydraulic transients.

COMPLEX PIPING SYSTEMS: As noted above in the basic assumptions, the waterhammer theory is strictly applicable for a pipeline of uniform characteristics. However, for waterhammer purposes a complex piping system can be reduced to a satisfactory equivalent uniform pipe system. The approximations are made by neglecting the wave transmission effects at the junctions and points of discontinuity and by utilizing the rigid water column theory. The pertinent waterhammer equations are then found to be analogous to those used in electrical circuits. In practice the waterhammer analysis with these approximations will usually be found to give more conservative results than those experimentally obtained for the actual pipe system. For a pipeline with a step-wise change in the diameter the equivalent length of uniform pipe is given in Reference 10.

AVAILABLE WATERHAMMER SOLUTIONS: The waterhammer solutions for various types of hydraulic transient problems in pumping plants are given in convenient chart form in Reference 1. These include the following:

(1) Hydraulic transients at the pump and midlength of the pump discharge lines for radial flow pumps with reverse flow passing through the pumps.

(2) Surge tanks.

(3) Air chambers.

In addition to the solutions noted above, References 2, 3, 4 and 5 also provide some additional waterhammer solutions in convenient chart form. These waterhammer solutions will be described in more detail below.

POWER FAILURE AT PUMP MOTORS

WITH NO VALVES AT THE PUMP: When the power supply to the pump motor is suddenly cut off, the only energy that is left to drive the pump in the forward direction is the kinetic energy of the rotating elements of the pump and motor. Since this energy is small when compared to that required to maintain the flow of water against the discharge head, the reduction in the pump speed is very rapid. As the pump speed reduces, the flow of water in the discharge line adjacent to the pump is also reduced. As a result of these rapid flow changes, waterhammer waves of increasing subnormal pressure are formed in the discharge line at the pump. These subnormal pressure waves move rapidly up the discharge line to the discharge outlet where complete wave reflections occur. Soon the speed of the pump is reduced to a point where no water can be delivered against the existing head. If there is no control valve at the pump, the flow through the pump reverses, although the pump may still be rotating in the forward direction. The speed of the pump now drops more rapidly and passes through zero speed. Soon the maximum reverse flow passes through the pump. A short time later the pump, acting as a turbine, reaches runaway speed in reverse. As the pump approaches runaway speed, the reverse flow through the pump is reduced. For radial flow pumps this rapid reduction in the reverse flow produces a pressure rise at the pump and along the length of the discharge line.

For a given set of radial flow (low specific speed) pump characteristics, the results of a large number of waterhammer solutions are given in chart form in Reference 1. These charts furnish a convenient method for obtaining the hydraulic transients at the pump and mid-length of the discharge line when no control valves are present at the pump. Although the charts are theoretically applicable to one particular set of radial flow pump characteristics, they are useful for estimating the waterhammer effects in any pump discharge line which is equipped with radial flow pumps. If the friction head in the discharge line during normal pumping operation is more than 20 per cent of the total pumping head, and provided that water column separation does not occur, the maximum head at the pump with reverse flow passing through the pumps will not exceed the initial pumping head. (See Reference 2.)

PUMPS EQUIPPED WITH CHECK VALVES: There are a number of problems asociated with the use of check valves in pump discharge lines. Under steady flow conditions the pump discharge keeps the check valve open. However, when the flow through the pump reverses subsequent to a power failure, the check valve closes very rapidly under the action of the reverse flow and the resulting dynamic forces on the check valve disc. Under these conditions the head rise in the discharge line at the check valve is about equal to the head drop which existed at the moment of flow reversal. However, as shown in Reference 1, in the event that the check valve closure upon flow reversal is momentarily delayed due to hinge friction, malfunction, or inertial characteristics of the check valve, the maximum head rise in the discharge line at the check valve is considerably higher. On the other hand, if the check valve closure can be accomplished slightly in advance of the time of flow reversal, the head rise in the pump discharge line at the check valve is lower than that obtained with the check valve which closes at the moment of flow reversal. This feature is utilized by a number of check valve manufacturers by providing spring loaded or lever arm weighted devices on the check valve hinge pins to assist in closing the valve discs before the flow reverses. With these devices the hydraulic forces on the valve disc under normal flow conditions must be sufficient to overcome the sping or lever arm weight forces in order to keep the check valve disc wide open so that the head losses at the valve will be a minimum.

CHECK VALVE SLAM: In addition to the waterhammer phenomena noted above, there is another difficulty which often occurs with check valves in pumping plant installations. This involves the objectionable slamming of the check valve discs against their seats upon closing. Upon a power failure, for the same pumping head conditions, short discharge lines will produce a much more severe check valve disc slam than long discharge lines for the same check valve. For long discharge lines the water in the pipeline takes a longer time to slow down and to reverse its direction. This permits the check valve disc more time to adjust its closing movement to the flow changes before an appreciable reverse flow has been established at the valve. In short pump discharge lines the water column reverses in much less time, and unless the valve disc can close very quickly, the water in the discharge line will attain a high reverse velocity. This will accelerate the closing movement of the disc and cause it to seat with a considerable slam. For check valve slam purposes, pump discharge lines which are equipped with surge tanks or air chambers at the pumping plant perform as very short discharge lines. Upon a power failure, with such pressure control devices, there is only a slight reduction in the head at the discharge side of the pump and consequently the flow reversal at the check valve occurs very rapidly.

Check valves in pump discharge lines may be grouped into two general classes, namely, rapid-closing check valves or slow-closing check valves. From the considerations noted above, the primary requirement for a check valve upon a power failure is that it should close quickly before a substantial reverse flow has been established. When this primary requirement for a fast closing check valve cannot be met due to the flow characteristics of the system as noted above and the design of the check valve, another alternative is to provide a device such as a dash-pot which will slow down or cushion the last portion of the check valve closure. This feature has been utilized by a number of check valve manufacturers.

CONTROLLED VALVE CLOSURE: A method of analysis is given in Reference 1 for determining the hydraulic transients in a pump discharge line subsequent to a power failure at the pump motors, when there is a controlled closing of a valve on the discharge side of the pump. In this method of analysis it is assumed that either the pump or the controlled closing valve controls the flow, whichever permits the least flow to pass through the system. Experimental evidence at several large pumping plants indicates that this method of analysis is reasonably accurate (see References 6 and 7).

Another method of analysis which is sometimes used is to include the effect of the closing valve as a variable concentrated head loss at the discharge side of the pump. The use of such a head loss concept is somewhat tedious. However, it does provide a method for computing the changes in the pump speed throughout the entire transient, as well as the head and flow changes in the discharge line. For practical purposes the pressure changes obtained by both methods are comparable.

At most pumping plants the use of a single speed valve closure upon a power failure will limit the head rise in the discharge line to an acceptable value. However, it will usually be found that with the optimum single speed closure some reverse rotation below the maximum runaway speed of the unit in reverse will occur. If it is desired from other considerations to prevent or to limit the reverse speed of the unit, a two speed valve closure can be used. In such cases the discharge valve should close the major portion of its stroke very rapidly up to about the moment that the flow reverses. It should then complete the remainder of its stroke at a slower rate in order to limit the pressure rise in the discharge line to an acceptable value. At pumping plants where there are more than one pump on the same discharge line, a compromise must be obtained on the optimum single speed and two speed closure rates for the various combination of pumps which might be in operation at the time of a power failure.

SURGE SUPPRESSORS: Surge suppressors are sometimes used in pumping plants to control the pressure rise that occurs in pump discharge lines subsequent to power interruptions. A typical surge suppressor consists of a pilot-operated valve which opens quickly after a power interruption through the loss of power to a solenoid, of by a sudden pressure reduction at the surge suppressor. This valve provides an opening for releasing the reverse flow of water. The valve is later closed at a slower rate by the action of a dash-pot to control the pressure rise as the reverse flow of water is shut off. A properly sized and field adjusted surge suppressor can reduce the pressure rise in the discharge line to any desired value including no pressure rise. The charts given in Reference 3 can be used to determine the required flow capacity of the surge suppressor.

The proper field adjustment of a surge suppressor is very important. If the surge suppressor opens too rapidly subsequent to a power failure, the downsurge at the pump and along the discharge line profile would be more than if no surge suppressor was present. As a result a water column separation condition may actually be produced in the discharge line by a faulty opening action of the surge suppressor. If the surge suppressor closes too rapidly after the maximum reverse flow has been established, a large pressure rise will occur.

WATER COLUMN SEPARATION: Water column separation in a pump discharge line subsequent to a power failure at the pump motors occurs whenever the momentary hydraulic gradient reduces the pressure in the discharge line to the vapor pressure of water. Whenever this condition occurs, the normal waterhammer solution is no longer valid. If this subatmospheric pressure condition inside the pipe persists for a sufficient period, the liquid water in the discharge line parts and is separated by a section of water and vapor. Whenever possible, water column separation should be avoided because of the potentially high pressure rise which often results when the two liquid water columns rejoin.

An accurate solution of the hydraulic transients in pump discharge lines where water column separation occurs, which includes all of the pertinent factors, is quite tedious. As an example, a detailed graphical waterhammer solution utilizing the elastic water column theory, and including the inertial of the pump and motor, is given in Reference 8. A subsequent paper (see Reference 9) provides a simplified approximate waterhammer solution for the water column separation phenomena in pump discharge lines. In this paper the following assuptions are made:

(1) The rigid water column theory is utilized until the instant that the separated water columns rejoin.

(2) The effect of the pump and motor rotating inertia on the deceleration of the water columns upstream or downstream of the separation are neglected.

(3) The cushioning effect of the small amount of air, if any, which enters the pipeline at the point of separation is neglected.

The referenced paper gives the necessary equations for computing the total interface separation of the water columns, the velocity of the columns at the moment the columns rejoin, and the maximum head rise due to the rejoining of the water columns. The results obtained by this latter method are conservative when compared to field observations and the more detailed method of analysis noted above.

QUICK-OPENING SLOW-CLOSING VALVES: A quick-opening slow-closing valve can be used to limit the pressure rise at the high points in the discharge line where water column separation occurs. When the pressure in the pipeline at the point of water column separation drops below a predetermined value for which the valve is set, the valve opens quickly and a small amount of air is admitted into the pipeline. After the upper water column in the pipeline stops, reverses, and returns to the point of separation near the valve, the valve is now wide open. At first the air and water mixture, and then clear water discharges through the valve. The open valve provides a nearby point of relief and reduces the pressure rise due to the rejoining of the water columns. The valve is later closed slowly under the action of a dash-pot so that the head rise in the discharge line at the valve location due to shutting off the reverse flow is not objectionable. Whenever these valves are used, precautions should be taken to insure that they are properly sized, field adjusted to the proper opening and closing times, and adequately protected against freezing.

ONE-WAY SURGE TANKS: The one-way surge tank which was introduced by the writer about 10 years ago (see Refernce 8) is an effective and economical pressure control device for use at locations where water column separation occurs. Numerous pipelines are now in service with one or more one-way surge tanks in the discharge line system. A one-way surge tank is a small tank filled with water to a level far below the hydraulic gradient. It is connected to the main pipeline with check valves which are held closed by the discharge line pressure. Upon a power failure, when the head in the discharge line at the one-way surge tank drops below the head corresponding to the water level in the tank, the check valve opens quickly and the tank starts to drain, thus filling the void formed by the separation of the water columns. When the flow in the upper column starts to reverse, the check valves at the one-way tank close before any appreciable reverse flow is established in the discharge line. Thus, the pressure rise due to the rejoining of the water columns is avoided. The connecting pipes to the one-way surge tanks which have been built and field tested to date have been equipped with more than one non-slam type check valves. The initial level of water in the one-way surge tank is usually maintained automatically with float control valves. It should be noted that the one-way surge tank does not act during the starting up cycle of the pump discharge line, and that it must also be protected against freezing.

AIR CHAMBERS: An effective device for controlling the pressure surges in a long pump discharge line is a hydro-pneumatic tank or air chamber. The air chamber is usually located at the pumping plant. The air chamber can be of any desired configuration and may be placed in a vertical, horizontal or sloping position. The lower portion of the chamber contains water, while the upper portion contains compressed air. The desired air-water levels are maintained with float level controls and an air compressor. When a power failure occurs at the pump motor, the head and flow developed by the pump decreases rapidly. The compressed air in the air chamber then expands and forces water out of the bottom of the chamber into the discharge line, thus minimizing the velocity changes and waterhammer effects in the discharge line. When the pump speed is reduced to the point where it cannot deliver water against the existing head, which is usually a fraction of a second after power failure, the check valve at the discharge side of the pump closes rapidly, and the pump then slows down to a stop. A short time later the water in the discharge line slows down to a stop, reverses, and flows back into the air chamber. As the reverse flow enters the chamber, usually through a throttling orifice, the air volume in the chamber decreases and a head rise above the pumping head occurs in the discharge line. The magnitude of this head rise depends on the volume of air which has been provided in the tank. For estimating purposes the total volume of the air chamber can usually be taken as about 5 per cent of the total volume of the discharge line.

The results of a large number of graphical waterhammer air chamber solutions using the elastic water column theory is given in convenient chart form in Reference 1. These charts are based on the following assumptions:

(1) The air chamber is located near the pump.

(2) The check valve at the pump closes immediately upon power failure.

(3) The rotational inertia effects of the pump and motor are neglected.

(4) The pressure volume relation for the compressed air in the air chamber is taken as $PV^{1.2}$ = constant.

(5) The differential throttle at the entrance to the air chamber is proportioned so that the ratio of the total head loss for the same flow into and out of the air chamber is about 2.5 to 1.

(6) The hydraulic losses in the pump discharge line are small when

compared to the head loss at the orifice for the same flow passing into the air chamber.

Another study of the action of air chambers at pumping plants subsequent to a power failure, using the rigid water column theory and the isothermal pressure volume relation $PV = \text{constant}$ for the compressed air in the air chamber, is given in Reference 4. Although the isothermal relation for the pressure volume changes in not attained in actual practice, the results of this study are useful for estimating purposes because they include separately the orifice head losses and the hydraulic losses in the pipeline.

A characteristic of air chambers at pumping plants which is often overlooked is that when a power failure occurs at the pump motors, there is also a sudden temperature drop associated with the rapid expansion of the air in the chamber. At a recent installation the computed minimum air temperature in the air chamber associated with the initial pressure drop and an assumed pressure volume relation $PV^{1.2} = \text{constant}$ was about $-20°F$. The inside of the air chamber was therefore provided with suitable protective coatings to minimize the effect of the sudden temperature drop on the air chamber shell.

SURGE TANKS: A surge tank is one of the most dependable devices that can be used at a pumping plant to control the pressure changes resulting from rapid changes of flow in the discharge line subsequent to a power failure at the pump motor. Following a power failure the water in the surge tank provides a nearby source of potential energy which will effectively reduce the rate of change of flow and waterhammer in the discharge line. The analysis of the surges in surge tanks has been worked out by many investigators. One presentation and a set of charts are given in Reference 1 from which the surges due to the sudden starting or stopping of a pump can be readily obtined.

One of the disadvantages of a conventional surge tank is that since the top of the tank must extend above the normal hydraulic gradient to avoid spilling, the tank could be quite tall and expensive at high head pumping installations. At booster pumping plant installations a lower level surge tank on the suction side of the booster plant is an effective and economical method for controlling the pressure surges in the combined discharge line system. In order to obtain the most economical surge tank design, care should be given to the proper sizing of the throttling device at the base of the tank.

NON-REVERSE RATCHETS: Another device for reducing the pressure rise in a pump discharge line upon power failure which is occasionally used is a non-reverse ratchet on the pump and motor shaft which prevents the reverse rotation of the pump. This device is effective for controlling the pressure rise upon a power failure because of the large reverse flow which can pass through the stationary impeller. The author's experience to date with the non-reverse ratchet mechanisms has been very disappointing. At a number of small pump installations where these devices were used, the shock to the pump and motor shaft system due to the sudden shaft stoppage created other serious mechanical difficulties.

AUTOMATIC RESTART OF MOTORS: At small unattended pumping plants it is often desirable after a power failure ot automatically return the pumps to service as soon as the power is restored. However, at one project it was found that occasionally, subsequent to a very short power outage, a number of the induction motors at various pumping units could restart and come quickly up to speed while a large reverse flow was still passing through the pump. Under these conditions the pressure rise in the discharge line was very objectionable. If a pump motor has the capability of restarting under such transient conditions, a time delay or similar device should be installed at the motor controls so that the pump motor can be restarted only when it is safe to do so.

LONG SUCTION LINES: The detailed analysis of the hydraulic transients upon power failure for a pumping plant with a long suction line is given in Reference 1. The selection of the most appropriate waterhammer control device for a particular installation with a long suction line is a matter of judgment and economics. Surge tanks and air chambers on the suction side of the pumps often provide an effective method for controlling the pressure surges in long suction lines. At a recently built installation, the control of the pressure rise in a 7 mile long suction line consisted of a number of bypass valves on the suction side of the pumps. When a power failure occurs, these bypass valves open quickly and discharge water from the suction line into the atmosphere thus relieving the pressure rise due to the rapid deceleration of the flow in the suction line. The bypass valves are later closed at a slow rate to minimize any further waterhammer effect in the suction line.

SIPHON OUTLETS: A siphon structure is sometimes used at the outlet end of a pump discharge line to prevent backflow from the receiving reservoir or canal during a pump outage. During normal pumping operation the siphon flows full and a negative pressure is created at the siphon either naturally from the flow of water or with the aid of a vacuum pump. When a power failure occurs at the pump motor, the siphon breaker valve opens quickly and admits air into the siphon, thus disrupting the flow and preventing backflow from the canal or reservoir into the discharge line. This operation generates a positive pressure wave at the siphon outlet which moves opposite to the direction of the flow toward the pump. This positive pressure wave assists in reducing the amount of the downsurge in the discharge line and in some cases may actually prevent a water column separation which might otherwise occur. The magnitude of the generated positive pressure wave is equal to the difference between atmospheric pressure and the negative pressure that existed at the siphon during steady state flow conditions.

NORMAL PUMP START UP

WITH CONTROLLED VALVE OPENING: At some pumping plants the pump is brought up to speed against a closed valve on the discharge side of the pump. The valve is then opened slowly and there is very little waterhammer in the discharge line. However, it will be found that nearly all of the pump flow in the discharge line is established with only a relatively small valve opening since the head loss across the valve decreases very rapidly during the opening stroke. For long discharge lines the head loss and flow characteristics of the valve during the opening stroke must be considered in determining the optimum rate of opening.

WITH CHECK VALVES: At pumping plants where the pipeline is held full with pump check valves, the pressure rise in the discharge line due to a pump start up can be objectionable in some cases. If the motor comes up to speed very rapidly, the pump will develop a pressure rise in the discharge line as the sudden increase in flow moves into the line. As noted above this pressure rise is lower for radial flow (low specific speed) pumps than for axial flow (high specific speed) pumps.

WITH CASING UNWATERED: At pumping plants which are equipped with large pumps or pump-turbine units, normal starting as a pump is often performed with the pump casing unwatered. This is accomplished by depressing the water level below the impeller by means of compressed air, which is admitted into the pump casing with the pump discharge valve closed and the discharge line full. After the motor is synchronized on the line, the compressed air in the pump casing is bled off allowing water to re-enter the pump from the suction elbow, after which the discharge valve is slowly opened.

This type of operation has been satisfactory with most large pumping units and there are normally no significant waterhammer effects in the discharge line. However, there have been some difficulties with this type of operation at large pump-turbine units. In the latter case, when the rising water level in the suction elbow first reaches the pump impeller, a very fast pumping action occurs within a few seconds resulting in a sudden large power demand on the electrical system. If the discharge valve is still closed or nearly closed when this fast pumping action occurs, there is usually very little if any waterhammer effect in the discharge line.

WITH SURGE TANKS OF AIR CHAMBERS: With a surge tank or air chamber at the pumping plant, it makes very little difference whether the increased pump flow is sudden or gradual, inasmuch as the major portion of the sudden increased flow will enter the surge tank or air chamber. With these devices the steep front of the pressure rise in the discharge line is transformed into a much smaller pressure rise and a subsequent slow oscillating movement in the surge tank or air chamber.

EMPTY DISCHARGE LINE: A large pressure rise may occur in a pump discharge line during the rapid filling of an empty pipe. At one installation a very large pressure surge and a pipe failure occurred when the fire fighting pumps at the power plant were started up to fill a long empty pipeline. When the water in the discharge line reached the air release valves and spray nozzles at the upper end in the switchyard, the air release valves closed abruptly and a very large pressure rise occurred. To avoid this condition empty pipes must be filled slowly and furthermore the air from the high points in the pipeline must also be released slowly.

NORMAL PUMP SHUT DOWN

The pumping installation which produces the least waterhammer effect in a pump discharge line during a normal pump shut down is one in which the control valve on the discharge side of the pump is first closed, and then the power to the pump motor is shut off. If check valves only are in operation on the discharge side of the pumps, and the power to one of several pump motors which are connected to the same discharge line is cut off, the flow at the pump which has been shut down will reverse very rapidly, and the check valve will also close very rapidly. At several nuclear installations very severe check valve slam and damage occurred due to such sudden flow reversals. Consequently special anti-slam features were incorporated in the replacement check valves.

COMPARISON BETWEEN COMPUTED AND OBSERVED TRANSIENTS

In the author's experience in the field testing of pumping plants, the agreement between the computed and observed hydraulic transients has been acceptable but not as good as that obtainable with valve operation only. In most cases the observed transients were less severe than those which were computed.

At one pump-turbine installation large periodic instantaneous type pressure shocks were observed on the oscillograph pressure traces during the pumping power failure tests. There is a possibility that these pressure shocks were due to wicket gate vibration or to the interchanges in the control of the flow between the closing wicket gates and the pump as the pumping unit was increasing its reverse speed.

On water column separation tests it has been found that axial symmetry of the water columns at the point of separation does not always exist. Instead it is found that occasionally at the point of separation there is a long void or cavity at the upper portion of the pipe cross section and liquid at the bottom portion. The observed maximum pressure rise due to the rejoining of the water columns has not been in excess of the computed values based on the assumption of axial symmetry of the separated water columns.

The convential surge tank and one-way surge tank solutions agree very well with observations. In tests with air chambers there is good agreement if the air expansion exponent K in the equation PV = constant is taken between 1.2 to 1.3.

CONCLUSIONS

A variety of waterhammer control devices for pumping plants are available to the designer. In most cases the experienced designer can narrow the choice of the most suitable device to a few practical alternatives. A prior knowledge of the available waterhammer solutions for these devices will reduce the amount of detailed computational work which must be made to determine the critical hydraulic transient effects.

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