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Abstract

A selection criteria is provided that assures a control valve will perform its control function without the attendant problems of erosion, vibration, noise and short life. The criteria involves limits on the fluid kinetic energy exiting through the valve throttling area. Use of this criteria has resolved existing valve problems as demonstrated by retrofitting of the internals of many valves and vibration measurements before and after the retrofit. The selection criteria is to limit the valve throttling exit fluid kinetic energy to 70 psi (480 KPa) or less.

NOMENCLATURE

- A_o Valve Throttling Area, in^{2} or m^{2}
- c Fluid Sonic Velocity, ft/s or m/s
- KE Fluid Kinetic Energy, psi or Kpa
- $M1$ Units Conversion Factor, Table 1
- $M2$ Units Conversion Factor, Table 1
- Vo Fluid Velocity at Trim Throttling Area, ft/s or m/s
- w Mass Flow Rate, lb/h or kg/s
- ro Fluid Density at Trim Exit, lb/ft3 or kg/m3

introduction

For many years the traditional method of sizing and selecting control valves has been to select a valve that contains the design pressure and temperature and meets the maximum capacity requirements. In addition to meeting capacity requirements and serving as a pressure boundary vessel, the valve should perform its intended control function, have long internals (trim) life, provide good shut-off and be relatively maintenance free. There is a need for guidelines to evaluate if a valve and its trim will provide this type of service.

This paper presents a criteria for selecting a valve design capable of eliminating problems. The guideline imposes limits on the kinetic energy of the fluid exiting from the valve trim. The criteria applies to all linear motion valve types. Each type of valve is capable of meeting the kinetic energy criteria for many of the flow conditions that have been dictated by tradition and experience.

Butterfly and Ball valves usually meet the proposed criteria for kinetic energy. The pressure drop across these valves is not large enough to accelerate the flow to a high velocity level. Thus, a much lower value of energy is realized.

Examples are given in which measurements have been made on problem valves and the same measurements made after the valve has been retrofitted with a different trim that limits the kinetic energy exiting from the valve trim. The measurements that are reported are vibration measurements that quantify the effect of the change in the valve trim. The vibration of the valve and the piping system is a strong indicator of valve integrity. It is a direct result of the energy levels in the fluid passing through the valve. As such, it is an indicator of the ability of the valve to provide good control with long life and low maintenance costs.

VALVE SELECTION PROCESS

There are numerous texts that cover the selection of control valves. Two of the most frequently used are ISA (1976) and Driskell (1983). The first step in selecting a control valve is to calculate the required flow capacity, Cv, based upon the requirements of flow rate, inlet and outlet pressure, and the fluid properties. Internationally accepted standards for calculating the required capacity are available in ANSI/ISA (1985) and IEC (1976, 1978, 1980) publications. The required Cv is then compared against tables of valve size and designs provided by the valve manufacturers. The valve hardware is selected to provide enough flow for the given conditions. Many different valve designs will satisfy the capacity requirements and so additional selection guidelines are used to make the final decision. Final selection of the valve and trim type is made through experience and/or by looking at one of the following parameters: pressure drop, pressure drop ratio (pressure drop divided by inlet pressure), fluid velocity or as presented here, the fluid kinetic energy.

Valve designs have ranges for the amount of pressure drop (energy) that they can effectively absorb. For example, low pressure drops are handled by butterfly valves. As the pressure drop level increases, a ball valve would be needed. Still larger pressure drops would require the linear motion globe/angle type valves. The globe/angle designs incorporate many different valve trims depending upon the level of pressure drop starting with a simple plug that opens an orifice. The next range of pressure drops would require a ported cage to help guide the plug and contain the energy dissipation. For the largest pressure drops, a tortuous path trim design is needed. For different valve and trim selections, the acceptable pressure drop ranges overlap. In general, the cost of the selected valve increases with the valve's ability to handle higher pressure drops. Manufacturers have developed designs to extend the pressure drop ranges in order to serve the market with the lowest first cost equipment. This extension of ranges usually is achieved by harder materials that may tolerate the resulting cavitation, erosion, vibration and noise levels.

Driskell (1983) in his chapter titled “Velocity, Vibration, and Noise” discusses the reasons why velocity should be controlled. Excessive velocity causes all of the destructive effects that result in a poor valve application. He notes that velocity induced vibration and noise are “...a blessing in disguise in that they are a warning of impending failure.” Driskell does not discuss where in the valve the velocity needs to be controlled. Unfortunately, when velocity guidelines have been translated to control valve selection they have been interpreted as the velocity exiting the valve body. By the time the fluid is ready to exit the valve body, the influence of “high energy” has already been imprinted into the fluid stream. For example, the fluid velocity exiting the trim may have created high velocity, erosive jets, areas of low pressure with resulting flashing and cavitation damage and noisy shock waves. Velocities should be controlled at the trim outlet, not the valve outlet.

The valve industry has in some cases defined velocity through the trim as a design guideline. These are presented in Ho (1995), Kowalski, et al. (1996), Laing, et al. (1995), Miller (1993, 1996), Stratton and Minoofar (1995) and are used as a basis for the presentation of the criteria discussed in this paper. Schafbush (1993) argues for emphasis on the driving force, pressure drop, instead of the results of the driving force (velocity and kinetic energy) as the selection criteria. Just looking at the pressure drop or fluid velocity at the trim exit ignores the density of the fluid, which is an important parameter in accessing potential problems. A guideline based on the kinetic energy exiting the valve trim involves the driving force, pressure drop, the resultant velocity and the fluid density. Many years of experience in applying this criteria have indicated it is a reliable indicator that is not overly conservative and is applicable to all valve designs.

TRIM OUTLET KINETIC ENERGY

For kinetic energy evaluation, the location in the valve of greatest concern is just downstream of where the fluid is throttled or controlled. At this location, the flow area is the smallest and the fluid velocity and kinetic energy are the highest. The parts of the valve responsible for controlling and seating are often located at this point and are therefore subjected to the highest energy fluid.

Figure 1 shows the throttle area for various kinds of valve trim. For a top guided globe valve, the trim outlet flow area is the annulus area between the plug and seat. In a cage guided valve, the trim outlet flow area is the exposed area of the windows in the cage. For a multi-path cage, the trim outlet flow area is the total area of all the exposed flow paths. For multi-stage trims, the flow area from stage to stage must not increase too rapidly or else the throttling will take place across the first stages and the later stages will be ineffective, see Figure 1(e).

In a valve, the disk or plug moves to increase or decrease the area through which flow can pass. For a given set of conditions, a fixed area of the trim is open to flow. Under any significant pressure drop conditions, this area will be considerably less than the inlet or outlet area of the valve. As a result, the fluid passing this point will have much higher velocities and kinetic energy levels than in other valve locations. The only way to increase this flow area without increasing the flow rate, is to increase the resistance of the throttling flow path. The flow conditions define how far the valve is open and the valve’s trim design (flow path resistance) defines how much flow area exists at the trim outlet. Once this area is defined, the continuity equation can be used to calculate the velocity of the fluid at the outlet of the trim.

$$V_o = \frac{w}{M_1 \rho_o A_o} \quad (1)$$

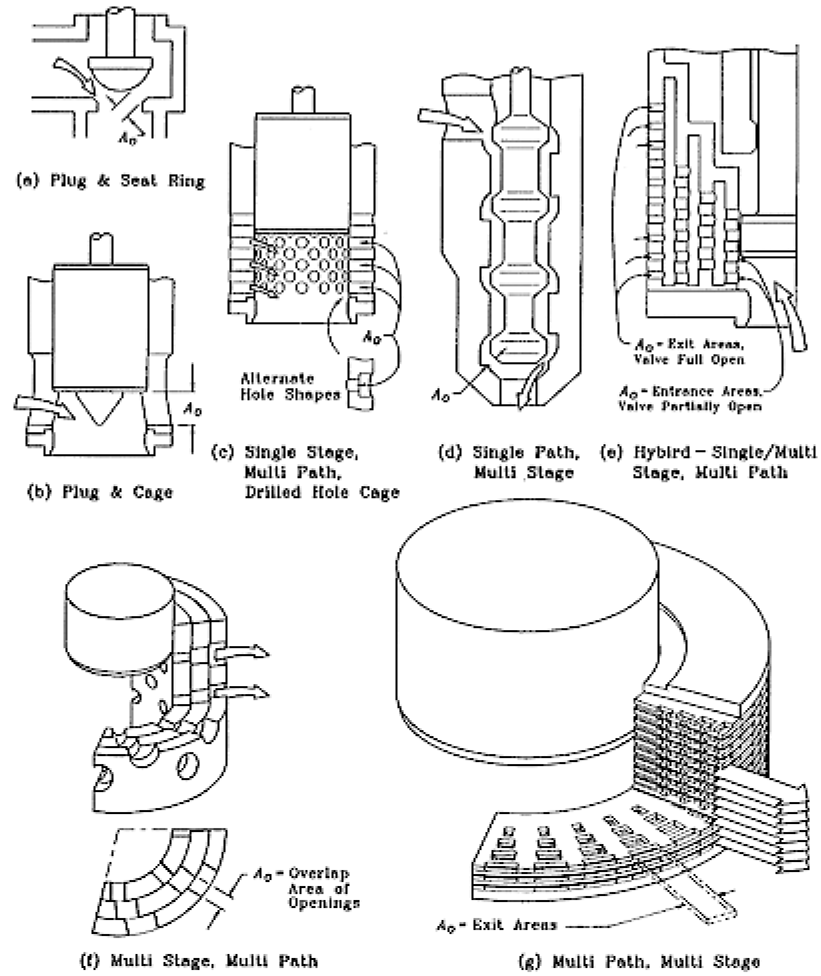

Figure 1. Throttling exit area (A_o) examples for typical valve trim designs

The fluid density and velocity are used to establish the fluid's kinetic energy.

$$KE = \frac{1}{2}\frac{\rho_o V_o^2}{M_2} \quad (2)$$

For gas or steam, the fluid velocity at the trim outlet may be sonic. If it is, the density of the fluid at the trim outlet must be higher than the outlet density, ρ_o, in order to pass the given mass flow rate, *w*. This higher density can be estimated using Equation 1 by substituting the fluid's sonic velocity, *c*, for the outlet velocity, *Vo*, and solving for density. Then, this density and sonic velocity are used in Equation 2 to find the kinetic energy.

Table 1. Numerical Constants for Velocity and Kinetic Energy Equations

Constant		**Units Used in Equations**				
M		***w***	r_o	***Ao***	***Vo***	***KE***
*M*1	25	lb/h	lb/ft^3	in2	ft/s	-
	1.0	kg/s	kg/m3	m2	m/s	-
*M*2	4636.8	-	lb/ft3	-	ft/s	psi

	1000	-	kg/m3	-	m/s	KPa

VALVE TRIM KINETIC ENERGY CRITERIA

The piping industry has long recognized the need to control the kinetic energy levels in the transport of fluids through a pipe. The industry has created design criteria that limits the fluid velocity in the pipe to acceptable limits. For example, a normal criteria for liquids in pipes is to limit the fluid velocity to a range of 5 to 50 ft/s (1.5 to 15 m/s). Assuming normal water densities, this is equivalent to a kinetic energy of 0.16 to 16 psi (1.1 to 110 KPa). The typical criteria for gases is to keep the fluid Mach number (actual velocity divided by the fluid's sonic velocity) below 0.15. Assuming saturated steam of 100 to 1000 psi (0.7 to 7 MPa) and a sonic velocity of 1630 ft/s (500 m/s), the kinetic energy is in the range of 1.5 to 15 psi (10 to 100 KPa).

Velocity criteria for liquids are much lower than for gases because liquid densities are much higher, resulting in higher energy levels. While the velocity limits are quite different, the kinetic energy limits are very close to the same.

Table 2 shows criteria for a valve trim's outlet kinetic energy. The valve trim should be selected to keep the kinetic energy below these levels. The examples that follow support the values shown in the table.

Table 2. Trim Outlet Kinetic Energy Criteria

Service Conditions	**Kinetic Energy Criteria**		**Equivalent Water Velocity**	
	psi	**KPa**	**ft/sec**	**m/s**
Continuous Service, Single Phase Fluids	70	480	100	30
Cavitating and Multi-phase Fluid Outlet	40	275	75	23
Vibration Sensitive System	11	75	40	12

For most conditions, an acceptance criteria of 70 psi (480 KPa) for the trim outlet kinetic energy will lead to a trouble free valve. In some applications, where the service is intermittent (the valve is closed more than 95% of the time) and the fluid is clean (no cavitation, flashing or entrained solids), the acceptance criteria can be increased, but should never be higher than 150 psi (1030 KPa).

In flashing service, liquid droplets are carried by their vapor at much higher velocities. To eliminate the risk of erosion, the acceptance criteria for flashing or potentially cavitating service should be lowered to 40 psi (275 KPa). The same criteria exists for liquids carrying entrained solids.

Special applications may require even more stringent kinetic energy criteria. For example, pressure letdown valves used in pump test loops must be vibration free so that proper evaluation of the pump can be made. These valves are designed with trims that reduce the kinetic energy to less than 11 psi (75 KPa). Gas or steam valves with very low noise requirements may also result in extra low trim outlet kinetic energy requirements.

RETROFIT EXAMPLES

Table 3 shows a summary of the service conditions, before and after trim style, and the corresponding kinetic energy levels for four valve designs retrofitted with multi-stage trim. Each of these valves was retrofitted because the original valve trim was not allowing good control or there were limitations in the valve's use due to excessive vibration. In some cases, the valves would cause the system to trip. After repeated attempts to fix the problems and the plant's need for working valves, the valves were retrofitted with trim designed to reduce the kinetic energy at the trim outlet. The only change made to the valves was to change the internal valve trim and hence, the trim outlet kinetic energy. No changes were made to the valve bodies. Since the bodies were not changed, the fluid velocities exiting the valve bodies were the same before and after the retrofit. In all cases, significant improvements in valve performance were achieved by retrofitting the trim to meet the suggested kinetic energy design criteria.

Table 3. Attributes of Four Valves, Before and After Retrofit

		Example Number			
	Units	**1**	**2**	**3**	**4**
Application		Residual Heat Removal	Feedwater Regulator	Core Spray	Steam Dump
Quantity		4	2	4	1
Fluid		Water	Water	Water	Steam
Flow Rate	MM lb/hr kg/s	4.5 560	4.4 550	2.2 280	1.8 230
Inlet Pressure	psia KPaa	155 1070	1546 10660	295 2030	740 5100
Inlet Temperature	F C	100 38	440 227	110 43	511 266
Outlet Pressure	psia KPaa	35 240	972 6700	15 100	334 2300
Capacity, $C_{vreq'd}/C_{vtotal}$		820 / 830	400 / 780	290 / 300	1400 / 1432
Valve Size		14" x 14"	12" x 12"	8" x 8"	18" x 18"
Valve Inlet/Outlet Kinetic Energy	psi KPa	3 / 3 20 / 20	5 / 5 34 / 34	5.5 / 5.5 38 / 38	6.4 / 14 44 / 97
Plug Size		12"	9.5"	5.5"	14"
Original Trim Type		Top Guided Plug	Drilled Hole Cage	Top Guided Plug	3 Concentric Drilled Hole Cages
Original Trim Outlet Kinetic Energy	psi KPa	148 1020	380 2630	290 2020	83 570
New Trim/Cage		4 and 2 Stages	10, 6 and 4 Stgs	4 and 2 Stages	8 Stages
New Trim Outlet Kinetic Energy	psi KPa	13 - 24 88 - 168	17 - 61 118 - 420	30 - 57 204 - 390	25 172

For examples 1 and 3, the water outlet pressures were close enough to the water's vapor pressure to suggest cavitation and two phase flow conditions may exist. Therefore, the acceptance criteria for the trim outlet kinetic energy was the more stringent 40 psi (275 KPa) value for the pressure conditions that could result in vaporization.

EXAMPLE 1, RESIDUAL HEAT REMOVAL, arnold, et al. (1996)

The valves were originally top guided, Figure 1(a) control valves without a cage. The valves were retrofit with a tortuous path trim such as shown in Figure 1(g). The kinetic energy on the top guided version is calculated in the annulus area created between the plug and the seat ring. The kinetic energy for the retrofitted trim is at the outlets of each of the disks forming the cage.

A typical reduction of the vibration velocity is shown on Figure 2. The accelerometer that resulted in this maximum output was located on the actuator and measured a direction that was rotational around the centerline of the pipeline. Vibration velocity for the five accelerometers located on each of four valves showed reductions in value that ranged from 49 to 91 percent with even larger reductions occurring on piping components in the system.

The retrofitted valves were able to pass full design flow rates without the accompanying cavitation. All concerns regarding the potential of piping fatigue as a result of the vibration were eliminated.

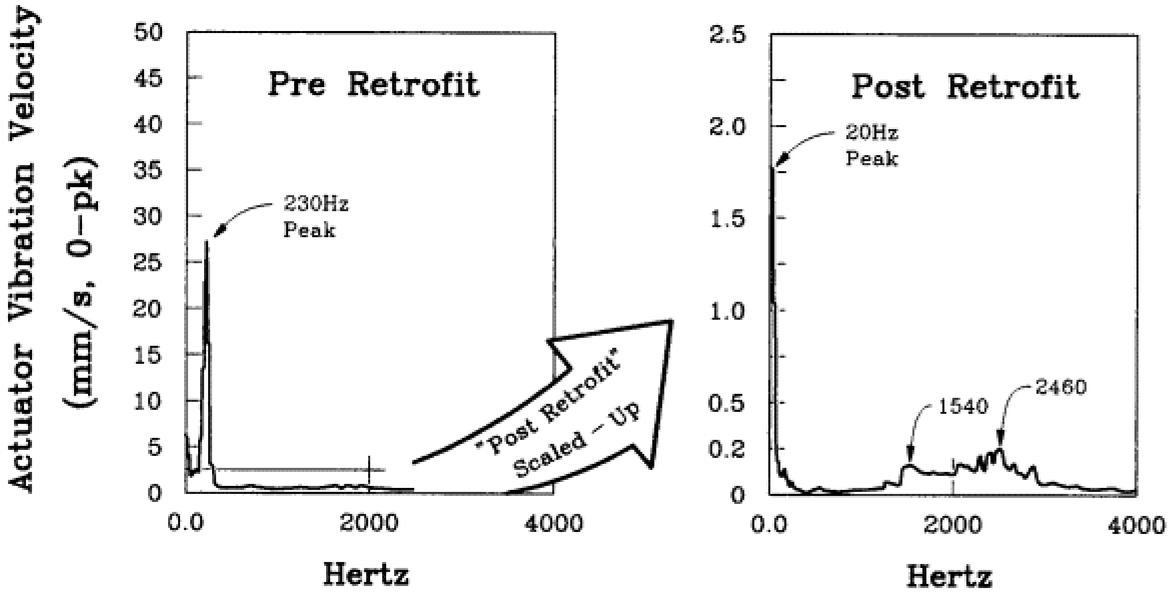

Figure 2: Residual heat removal

EXAMPLE 2, FEEDWATER REGULATOR, parker, et al. (1994)

The original trim started out as a cage guided trim and was later changed to a drilled hole cage in one of many attempts to salvage the valve design. The retrofit used a tortuous path trim, Figure 1(g), that absorbs the fluid energy inside the trim and has an acceptable exit kinetic energy. The throttling points in the original trim are the cage orifices, Figure 1(b), and the small holes in the drilled hole cage, Figure 1(c), tried later.

The vibration velocity results are shown in Figure 3. The reductions in the vibration are quite dramatic because the vibration levels are not very high to begin with. The comparison of results is made with the drilled hole cage trim as results did not exist with the original cage trim. The reductions resulted in at least a 40 percent reduction in the velocity at the piping frequency of 10 Hertz and essentially an elimination of the vibration at the higher frequencies. Displacement measurements showed reductions of 53 percent and acceleration measurements showed an 86 percent reduction.

All of the problems of vibration, plant trips, and broken stems were resolved by the lower kinetic energy levels at the trim exit. The plant was started up and power escalated to full load for the first time on automatic control as was intended from the inception of the plant design.

EXAMPLE 3, CORE SPRAY, arnold (1995)

The valves were designed with a top guided plug, Figure 1(a). The trim was retrofitted with the tortuous path trim using the logic of Figure 1(g). The throttling area of the original valve was the annulus area between the plug and the seat ring. The retrofit throttling point was the exit from the disk outlets.

Another change in the system was made in this application. When the retrofitted trim was installed, downstream restricting orifices were removed. Thus, the valve pressure drop was increased to a value equivalent to the original trim and the orifice. This represents a more severe set of conditions for the retrofit trim in controlling any destructive affects due to the higher potential energy that would be converted to kinetic energy across the trim.

The downstream piping system vibration measurements were the most significant changes recorded between the pre and post retrofitted valves. These measurements showed that the pipe displacement dropped from 64 to 92 percent. Pre-retrofit values of displacement were 0.090 inches (2.3 mm) or greater and the largest displacement after the retrofit was 0.020 inches (0.51 mm).

The root cause of the system vibration was cavitation. The post retrofit vibration levels were minor and eliminated any concern regarding the piping system stresses and potential for damage due to fatigue.

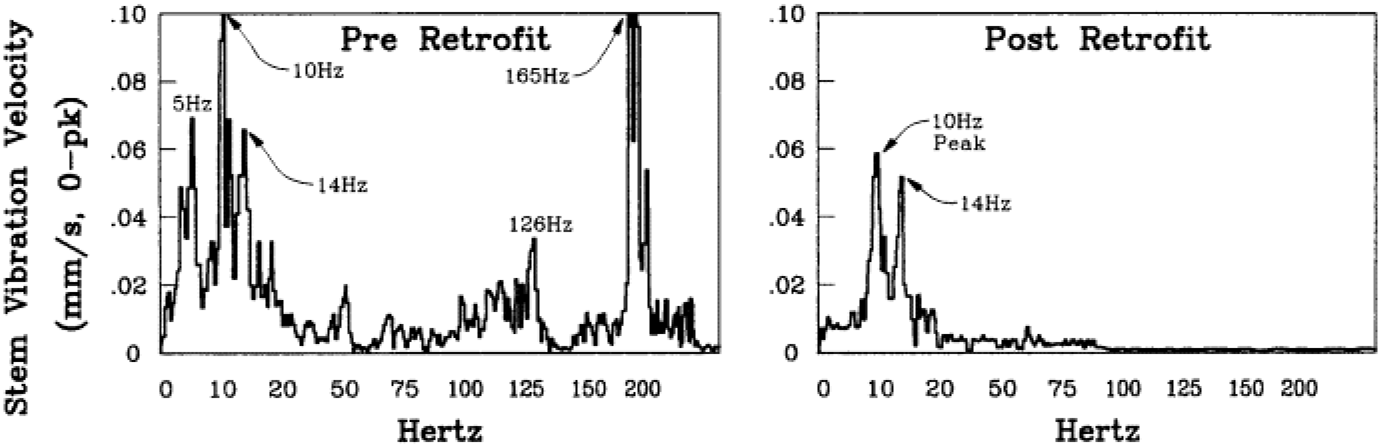

Figure 3. Feedwater regulator

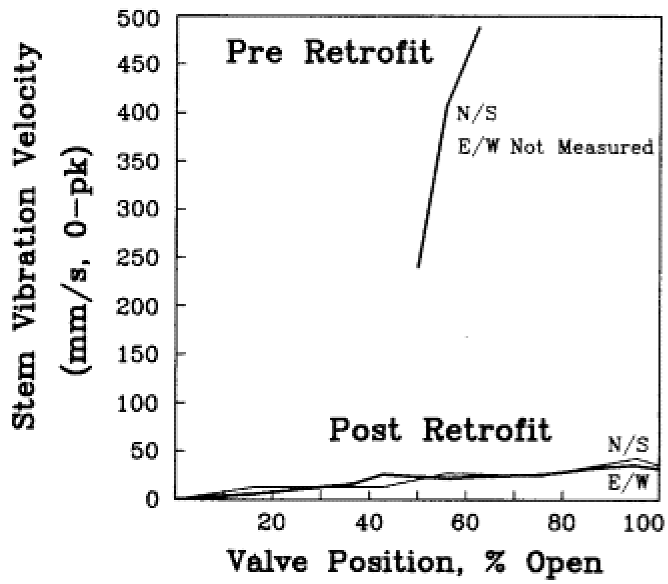

Figure 4: Steam dump

EXAMPLE 4, STEAM DUMP, persad (1995)

The valve instrumented was a steam valve with a flow to open trim consisting of three concentric cages with drilled holes in each cage. The cages were tightly touching so that there was no axial flow between the cages. Each cage was

slightly offset to create a tortuous path for the pressure letdown. This type of trim is shown in Figure 1(f). The throttling area is the flow area caused by the restriction of the last two cages. The outlet area of the last cage is not the throttling area because there is little pressure letdown associated with the expansion from the overlap orifice. The expansion is too large to have much influence and the jet from the overlap area is the dominate kinetic energy source exiting the trim.

The values reported in this case were a sum of the vibration velocity peaks in the 0 to 500 Hertz range. The results are shown in Figure 4 where the vibration velocity magnitude is plotted as a function of the valve stroke. Values are not available beyond 65 percent of stroke for the original trim as the valve was not operated in this region because of the severity of the vibration.

The reduced trim exit kinetic energy solved the severe vibration problems associated with this steam system.

OTHER EXAMPLES

All of the examples presented above happen to be installed in nuclear plants. However, these are typical control valve applications and are representative of the many applications in different industries that have been experienced. In the past 20 years, over 150 valves ranging in size from 2" to 24" x 36" have been retrofitted to achieve the kinetic energy criteria identified above.

Table 4. Partial List of Retrofit Applications

Applications	
Condensate Recirculation	Atmospheric Steam Dump
Aux Pump Recirculation	Turbine Bypass
Recirculation	Reactor Water Cleanup
DA Level Control	Wellhead Choke
Aux Feedwater Regulator	Compressor Recycle
Feedwater Regulator	Compressor Anti-Surge
Reheat Spray	Water Injection
Steam Letdown	Injection Control
Auxiliary Steam	Moisture Separator Reheater
Condenser Steam Dump	Gas to Flare

Table 4 is a partial list of applications involved. All of these retrofits arose as a result of a problem with the original installation. In all of the cases, the retrofits were successful in resolving the root cause of the valve problem and the only significant change was the limiting of the fluid kinetic energy exiting the valve trim.

CONCLUSIONS

A criteria for the selection of a control valve has been provided which goes beyond the many rules and exceptions being used in the industry. The criteria is a limit on the kinetic energy exiting from the valve trim, defined as the throttling point of the trim. It addresses the energy that contributes to the problems associated with valves. The combination of fluid velocity and density cause:

- unstable forces inside the valve,
- low local pressures that result in cavitation,
- erosion of critical parts,
- shock waves that create unwanted noise, and
- turbulence that results in vibration.

Using the kinetic energy criteria, which has many years of application experience, will eliminate valve problems. It will provide the user with a means to evaluate the different types of valve designs that look as though they will meet the system needs.

The first step is to select the valves that can meet the capacity requirements. Then the valve types are sorted to select the correct valve by using the kinetic energy levels. This will assure the engineer that the lowest cost system is installed.

ACKNOWLEDGEMENTS

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