Analysis and Modification of Vibration Issue of Condensate Regulating Valve in a Nuclear Power Plant

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Abstract. Regulating valves are widely used in nuclear power plants. The critical application of regulating valves determines whether the unit and system can operate safely, stably and economically. Taking the analysis and modification of the vibration issue of the conventional island condensate regulating valve in a pressurized water nuclear power plant as an example, this paper expounds the essence of the vibration issue of the regulating valve and provides reference for other power plants to deal with the same issue.

1. Introduction
Regulating valve is generally used for regulating medium flow. In the key position of nuclear power plant unit, the valve has a wide range of applications, such as condensate regulating, main feed water regulating, pressurizer spray regulating and so on. The stable operation of the valve plays an important role in the safety and economy of the unit.

However, during the actual operation of the power plant, the valve often has defects due to frequent open, close and throttling, such as abnormal valve regulation, oscillation, vibration, packing leakage and so on, among which the vibration problem is the most difficult to deal with, because there is no effective maintenance means to handle it. Based on the analysis and modification of the vibration issue of the conventional island condensate regulating valve in a nuclear power plant, this paper expounds the essence and treatment measures of the vibration issue of the regulating valve, so as to provide reference for other power plants.

2. Introduction of vibration issue of the valve
The condensate of a nuclear power plant is regulated by two parallel regulating valves to maintain the level of the downstream deaerator, as shown in Figure 1. The regulating valve unit adopts the configuration of "one main and one sub". During the start-up and low-power-stage of the unit, the sub valve (small valve V1009) controls the condensate flow. With the increase of load, the main valve (large valve V1005) is put into operation. Condensate regulating valve is pneumatic control valve, the actuator of which is double-acting piston cylinder type, balanced plug, and large open window type cage. It will be closed when the valve fails. V1005’s diameter is DN400, V1009’s is DN200.
Since the start of the unit, the opening of the main condensate regulating valve increases continuously with the increase of the unit power. When the position of the valve reaches more than 50%, the vibration of the valve increases significantly as well. And due to that the upstream and downstream pipelines are supported on the ground, the vibration is transferred to the floor, which lead to obvious floor vibration. At the same time, the valve stem moves up and down at a high frequency within the range of ±1%-3% of the set value, causing frequent packing leakage during operation. More seriously, the stem’s moving up and down leads to serious wear of the piston sealing ring inside the actuator, which results in the failure of the piston seal and out control of the valve, endangering the stable operation of the unit.

3. Cause analysis

According to the fact that V1005 vibrates at a small opening and valve stem’s flapping is not obvious during the unit startup, temporary measures are adopted to partially open the bypass motor operated valve V1007 to share the flow of V1005, thus decrease the V1005’s position from nearly 80% to about 65% and reducing valve vibration and stem flapping. However, as a motor operated gate valve, long-term throttling of V1007 will lead to sealing surface’s erosion, valve internals’ looseness and other defects, after which the metal bracket at the bottom of V1007’s double gate falls off. As the valve opening is small and the bracket is stuck on the sealing surface, the bracket will be rushed into the downstream as foreign material if the valve opening increases, causing more damage.

Therefore, the V1005 vibration and stem flapping problem must be resolved. Valve vibration and stem flapping problem were investigated on site and it turns out that they were not caused by abnormal instrumentation or control system. Due to the fact that the vibration is reduced
when the valve position is small, it can be judged that the vibration is caused by the valve internals, and the vibration source is not the connected pipe or the ground.

The theory that valve vibration is caused by the valve internals mainly considers the impact of turbulence caused by flow through the internal parts, even the choking flow and cavitation. When choking flow occurs, bubbles generates at the valve cage, resulting in that the flow will not increase with the increase of differential pressure between inlet and outlet. Massive bubble generation or rupture will have a strong force on the valve internals, causing vibration, noise and other problems.

To verify the assumption, we calculated the flow distribution of the regulating valve unit. Using the valve flow calculation formula:

\[ QL = \frac{Cv\sqrt{\Delta P}}{\sqrt{SL}} \]

1) Cv: valve flow coefficient;
2) SL: the ratio of liquid relative to the proportion of water in the standard temperature 60 °F (water ratio = 1.0 @ 60 °F), for environmental temperature condensate, SL approximately takes 1;
3) ΔP: differential pressure between valve inlet and outlet;
4) QL: Liquid flow, GAL/min (GPM)
5) Before and after V1007 opening, the data of the system parameters were analyzed:
6) The upstream condensate pump outlet pressure keeps constant, 2.871 MPa
7) The downstream outlet pressure of feed water heater basically remains unchanged, 1.020 MPa
8) V1005’s position decreases from 77.5% to 65%
9) V1009’s position remains unchanged at 50%
10) V1007’s position is about 4% - 5%
11) The overall flow of valve unit basically remains unchanged, 3940 t/h

Since the inlet and outlet pressures remain unchanged before and after V1007’s opening, and the position of V1009 keeps constant, it can be seen from the formula that the flow rate through V1009 keeps constant.

V1005 flow calculation:
Operating conditions of V1005 are as follows:

| Table 1. Operating conditions of V1005. |
|----------------------------------------|
| Flow T/h | Inlet pressure MPa | Outlet pressure MPa | Temperature °C |
| Transient condition | 4190 | 2.795 | 1.6 | 10-45 |
| Rated load condition | 3177 | 2.83 | 1.566 | 10-45 |

During Rated power operation, the difference between inlet and outlet pressure of V1005 is 1.26mpa (183.3psi), and the V1005’s position is 65% after V1007 opens. The flow coefficient can be obtained from Cv curve, which is about 900.

![Figure 3. Flow characteristic curve of V1005.](image)
According to the flow formula \[ Q_L = \frac{C_v \sqrt{AP}}{\sqrt{SL}} \], after V1007 opens, the flow calculation of V1005 is about \( Q_L = 900 \times 13.54 \text{gpm} = 12186 \text{GPM} = 2770 \text{m}^3/\text{h} \).

V1009 flow calculation:
The Cv of V1009 at 50% opening is 133.
The operating condition of V1009 is as follows:

| Table 2. Operating conditions of V1009. |
|-----------------|-----------------|-----------------|-----------------|
| Flow T/h        | Inlet pressure MPa | Outlet pressure MPa | Temperature ℃   |
| Transient condition | 1544           | 3.18            | 0.62            | 10-45           |
| Rated load condition | 794            | 2.83            | 1.572           | 10-45           |

During rated power operation, the differential pressure between inlet and outlet of V1009 is 1.258MPa (182.4psi). (182.4psi);

According to the flow formula \[ Q_L = \frac{C_v \sqrt{AP}}{\sqrt{SL}} \], after V1007 opens, the flow calculation of V1005 is about \( Q_L = 133 \times 13.5 \text{ GPM} = 1795 \text{ GPM} = 408 \text{ m}^3/\text{h} \).

Thus, the flow after V1007 opening can be calculated \( 3940 - 2770 - 408 = 762 \text{ m}^3/\text{h} \);

Analysis of flow distribution relationship:

| Table 3. Analysis of flow distribution relationship. |
|-----------------|-----------------|-----------------|
| Calculated value of designed differential pressure flow m3/h | Flow before V1007 opening | Flow after V1007 opening |
| V1009           | 408             | 408             |
| V1005           | 3532            | 2770            |
| V1007           | 0               | 762             |

If the flow rate of V1005 before V1007’s opening is calculated directly using the formula \[ Q_L = \frac{C_v \sqrt{AP}}{\sqrt{SL}} \], the Cv at 77.5% position is 1500, and the differential pressure between inlet and outlet keeps unchanged=1.264MPa (183.3psi), then \( Q_L=1500 \times 13.5 \text{ GPM}=20250 \text{ GPM}=4602 \text{ m}^3/\text{h} \).

The flow rate is much higher than the above calculation of 3532 m³/h, thus it can be judged that there is choking flow when V1005 is 77.5% open.

![Figure 4. Pressure/velocity variation of the flow through one stage restrictor](image)

As shown in the figure above, when the water flows through the restrictor, the flow velocity at the restrictor increases. According to Bernoulli equation, the pressure decreases as the flow velocity
increases, and the greater the differential pressure between before and after, the greater the flow velocity. When the pressure at the restrictor drops below the saturation vapor pressure at that temperature, vaporization occurs, forming bubbles, due to the existence of which, with the continuous increase of pressure difference, the flow will not increase significantly, which is the choking flow [1].

If the downstream pressure is consistently below the saturation vapor pressure at the temperature, the resulting bubble persists, a phenomenon known as flashing. Nevertheless if the downstream pressure is higher than the saturation vapor level, the bubbles will rupture again. The rapid rupture of massive bubbles will have a strong impact on the restrictor, causing serious vibration and honeycomb erosion on the surface of the parts, which is called cavitation.

Figure 5. Valve spool valve cage cavitation damage

Choking flow (flashing, cavitation) is the basic reason of many valves vibration problems. In addition, the upper stream pipe of valve unit is DN800 and the diameter of V1005 is DN400, and the valve is installed by two transition pipes to system pipe. Obvious diameter change is generated here, which aggravates the instability of the flow.

To sum up, the vibration problem of V1005 is caused by the choking flow under the large opening, and the obvious diameter change further aggravates the turbulent state of the flow. The V1005 stem flapping is also closely related to the generation of choking flow, that is the dramatic changes in flow velocity and pressure have uneven forces on valve internals, and actuator size is not enough to resist the impact of flow on valve internals, leading to the stem moving up and down frequently.

4. Handling Measures
The choking flow of the valve causes the valve vibration and stem flapping, so the problem can be solved fundamentally by eliminating the choking flow of the valve.

Figure 6. Pressure/velocity variation of the flow through two-stage restrictor
From the process of choking flow’s generation, it can be seen that the key to eliminate choking flow is to reduce the flow velocity at the stricctor, so as to improve the pressure reduction at the restrictor, avoiding the pressure falling below the saturation vapor pressure at that temperature, and preventing the vaporization of the flow from bubbles forming [4]. Multistage restrictor can reduce the differential pressure between the inlet and outlet of each stage, increasing the pressure at the restrictor, realizing the stable reduction of pressure and eliminating the choking flow [2].

4.1. Modification of the internal parts
Due to the critical position, the valve directly affects the stable operation of the unit. To be conservative, the design of the large window of the valve cage is changed into a two-stage pressure-reducing valve cage, so as to step down the pressure and eliminate choking flow [3].

![Figure 7. V1005 cage upgraded to two-stage decompression](image)

Increased pressure control capacity means increased flow resistance, hence we need to increase valve size to meet flow capacity (Cv) requirements [5]. According to the requirement of maximum Cv demand (working condition 1), $C_v = \frac{Q\sqrt{SL}}{\sqrt{\Delta P}} = 1401$, and the designed characteristics of the manufacturer's valve cage and margin-reserving requirements, the final size of the inner parts of the valve is DN500 and the maximum Cv of valve is 1745.

| Table 4. Transient condition |
|-----------------------------|
| Flow T/h | Inlet pressure MPa | Outlet pressure MPa | Temperature ºC |
| Transient condition | 4190 | 2.795 | 1.6 | 10-45 |

4.2. Modification of pipeline interface
According to the selection results of valve internals of V1005 and the intention to minimize the influence of transition pipe, the final size of V1005 inlet and outlet interface was determined as DN600. V1005:DN800-DN600-DN500-DN600-DN800. Multistage transition between valve inlet and outlet is finally achieved.

4.3. Other Modifications
In order to eliminate the influence of vibration on the valve instrumentations, except the valve position feedback accessory, all others are installed separately from the actuator.

The valve airline is made of stainless steel to enhance the strength of it.

4.4. Effectiveness Verification
According to the above treatment measures, new valve was purchased on the basis of the new technical requirements and was replaced during the unit fueling outage. After the verification during the unit start-up and full power operation, the problems of valve vibration and stem flapping have been effectively solved.
5. Summary

The project starting from the on-site troubleshooting, cause analysis of the problem, to measures’ formulation and effectiveness verification, accurately found the primary cause of the valve vibration and stem falpping, and carried out measures to replace multi-stage cage valve for the choking problem, successfully resolving major defects of the operation-stability problems of the unit since the operation of the nuclear power plant. More importantly, the project provides a detailed analysis and calculation of the essence of valve vibration, which provides an important reference for other nuclear power plants to deal with similar problems.

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