Nuclear plant operators have noticed a significant increase of the force needed to open cold wedge gate valves closed during a temperature transient. This phenomenon is known as "Thermal-Binding". At extreme ends, valves can't be opened. The consequences are an important risk for the safety of the unit and a decrease of its availability.

The goal of this study is to obtain an analytical, experimental and numerical analysis of this phenomenon. This allows to determine the requirements needed to avoid this situation.

The main part of this work is devoted to the calculation of the opening force after closure during a cooling transient. This can be divided in three phases: to begin with, an analytical model is set up. At the same time, the situation in a plant is reproduced on a loop. This gives some foundations to the model in several cases. Finally, the numerical simulation helps to investigate other scenarios and to have a deeper understanding of the phenomenon.

The main result is that there is a good agreement between experiment and numerical simulation either in the case where there is some binding or in the case where there isn't.

Study of the "Thermal-Binding" phenomenon: from experiment to numerical simulation

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For the safety valves of a nuclear plant, it is necessary to evaluate the force on the stem to be sure the valve will operate under all circumstances. Nuclear plant operators have noticed a significant increase of the force needed to open cold wedge gate valves closed during a temperature transient. This phenomenon is known as "Thermal-Binding".

It has been studied numerically, analytically and experimentally at EDF/R&D, in partnership with CEA and FRAMATOME. The main assumption is that, when a valve is closed during a cooling transient, thermal strains induce a severe binding of the disk. The consequence is an increase of the opening force.

This article explains how a simple and predictive model can be set up with the help of experimentation. This model is useful to analyze most of the cases. Numerical simulation is necessary to investigate further (other cooling situations, integrity checking, other temperature distributions...).

The first part of this article deals with the analytical model because it is the easier way to introduce the phenomenon.

The second part explains the interest of experimental simulation.

The last part explains how numerical simulation is able to reproduce the observed situation. This entitles to be confident in the reliability of the calculation.

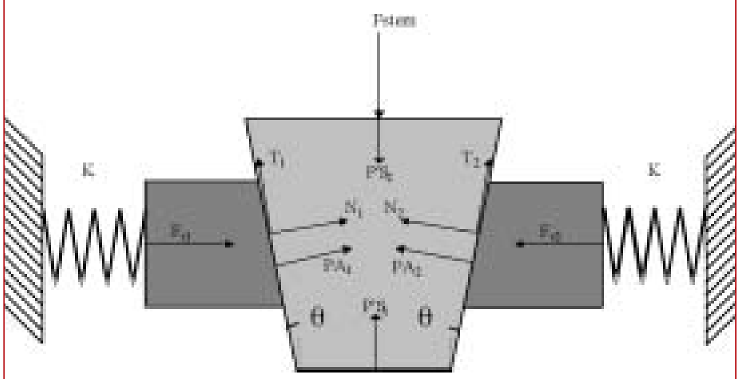

Figure 1: Modeled forces on the disk.

Analytical model

Without "Thermal-Binding"

A wedge gate valve can be seen as a rigid disk rubbing on two seats which are in series with springs of rigidity K [1] (Figure 1). In case of different upstream and downstream pressure, only one seat is involved in the contact. The changes in the calculations are obvious. Pressure in upstream and downstream pipe generates PA1 and PA_2 forces, pressure in the bonnet creates $P'S_1$ and $P'S_2$. The stem imposes the force F_{stem} on the disk. This force is maintained while the valve is closed. Indexes $_o$ and $_c$ are for "opening" and "closing".

When the valve is closed, equilibrium equation is:

$$F_{stem\_c} = (T_{1\_c}+T_{2\_c})\cos\theta + (N_{1\_c}+N_{2\_c})\sin\theta + P(A_1+A_2)\sin\theta + P'(S_1-S_2) \qquad (1.1)$$

$$F_{r1} + F_{r2} = (N_{1\_c} + N_{2\_c})\cos\theta - (T_{1\_c} + T_{2\_c})\sin\theta + P(A_1 + A_2)\cos\theta \qquad (1.2)$$

N_{1_c} and N_{2_c} are the normal components of the friction forces on the faces 1 and 2 of the disk. The disk is rubbing on the seat and the pairs (N_{1_c}, T_{1_c}) and (N_{2_c}, T_{2_c}) are located on the friction cone: $T_{1\_c} = \mu.\ N_{1\_c}$ and $T_{2\_c} = \mu.N_{2\_c}$. F_{r1} and F_{r2} are the forces due to the springs. P is the pressure in the pipes (upstream and downstream pressure are assumed to be equal in that example) and P' is the pressure in the bonnet. θ is the wedge angle.

For opening, the force F_{stem_o} is in the opposite direction of F_{stem_c}. The disk is rubbing on the seats, but relations between normal and tangential forces have changed: $T_{1\_o} = \mu N_{1\_o}$ and$T_{2_o} = -\mu.N_{2_o}$. When the tangential force passes from one side to the other of the friction cone, the force ($F_{r1} + F_{r2}$) due to spring doesn't change. It is then possible to write [3]:

$$F_{stem\_o} = -(T_{1\_o}+T_{2\_o})\cos\theta + (N_{1\_o}+N_{2\_o})\sin\theta + P(A_1+A_2)\sin\theta + P'(S_1-S_2) \qquad (1.3)$$

$$F_{r1} + F_{r2} = (N_{1\_o} + N_{2\_o})\cos\theta + (T_{1\_o} + T_{2\_o})\sin\theta + P(A_1 + A_2)\cos\theta \qquad (1.4)$$

and thus:

$$\frac{F_{stem\_0} - P(A_1+A_2)\sin\theta - P'(S_1-S_2)}{F_{stem\_c} - P(A_1+A_2)\sin\theta - P'(S_1-S_2)} = \left(\frac{\sin\theta - \mu\cos\theta}{\sin\theta+\mu\cos\theta}\right)\cdot\left(\frac{\cos\theta - \mu\sin\theta}{\cos\theta+\mu\sin\theta}\right) \qquad (2)$$

With "Thermal-Binding"

When the valve is closed during a cooling transient, the temperature field is decreasing heterogeneously. There are two main consequences:

- A change of the force imposed by the stem to the disk, which can be seen as a variation ΔF_c of F_{stem_c}. This is due to the fact that the stem and the bonnet are not in the same material and have different dilatation coefficients.
- An increase of F_{r1} and F_{r2} to take into account the fact that the body shrinks around the disk and creates a variation ΔF_o of F_{stem_o}.

It is then possible to rewrite equation 2 in the following way:

$$\frac{F_{stem\_0} + \Delta F_0 - P_0(A_1+A_2)\sin\theta - P'_0\,(S_1-S_2)}{F_{stem\_c} + \Delta F_0 - P_0(A_1+A_2)\sin\theta - P'_c\,(S_1-S_2)} = \left(\frac{\sin\theta - \mu\cos\theta}{\sin\theta+\mu\cos\theta}\right)\cdot\left(\frac{\cos\theta - \mu\sin\theta}{\cos\theta+\mu\sin\theta}\right) \qquad (3)$$

The experimental study allows to correlate ΔF_c and ΔF_o with the variation of temperature in the valve.

Experimental study

Some tests have been performed in the Civaux plant: a valve is cooled from downstream and closed during the thermal transient [2]. Since the instrumentation is light, other tests have been performed on an experimental loop in representative conditions [3-4].

These experiments provided foundations for the analytical model.

- ΔF_c is easily correlated with ΔT_{bonnet} the difference of temperature in the bonnet between closing and opening

$$\Delta F_c = \left[\frac{1}{K_{disk}} + \frac{L_{stem}}{S_{stem}.E}\right]^{-1}\cdot(L_{bonnet}\cdot\alpha_{body} - L_{stem\text{-}low}\cdot\alpha_{stem})\cdot\Delta T_{bonnet} \qquad (4)$$

where K_{disk} is the disk vertical rigidity,

L_{stem} is the stem length,

S_{stem} is the stem section,

E is the stem Young modulus,

α is a dilatation coefficient,

L_{stem_low} is the length of the part of the stem penetrating in the bonnet,

L_{bonnet} is the bonnet height (in general $L_{stem\_low} = L_{bonnet}$),

- ΔF_o is more difficult to evaluate accurately. It seems to depend deeply on the way the valve is cooled (from upstream or downstream). In the former case, we are entitled to use a model described in detail in [1]:

$$\Delta F_o = \left[\frac{\mu - tg\theta}{1+\mu.tg\theta}\right].K\gamma\Delta T_{b/d} \qquad (5)$$

where K is the body rigidity (analog to the spring rigidity in the analytical model), γ a coefficient (equal to α_{body} if the disk is infinitely rigid), $\Delta T_{b/d}$ the maximum difference of temperature between body and disk after closing.

Analytical evaluation of $K\gamma$ is complex because of the valve shape. This is the reason why ΔF_o evaluation requires tests or numerical simulations to determine this empirical parameter. For instance, MMC department tests give a value of $K\gamma$ for a 6'' flexible wedge gate valve: $K\gamma = 2300$ N/K [3].

It is important to notice that, during the transient, ΔT_{stem} and $\Delta T_{b/d}$ are decreasing with time. The values of ΔF_c and ΔF_o then depend on the closing moment. The delay between the beginning of the cooling and the closure thus becomes the industrial parameter useful for plant operators.

The analytical model has been used to reproduce some tests on a loop. There is an average accuracy of 15% [3].

Finite element simulations

Main steps

Numerical simulation allows studying valves internal organs behavior during cooling. The agreement between simulation and experimental tests entitled us to be confident in future simulations with other valves or other cooling scenarios. The purpose of this part is to show how numerical simulation is able to reproduce two situations observed in the Civaux plant: one where "Thermal-Binding" is important and one where it is negligible. The interest is to be able to predict the phenomenon with the fluid temperature as an input data.

The structure mesh is made of 10 000 nodes and 50 000 elements (figure 2). Two meshes have been done: one for the opened situation and one for the closed one.

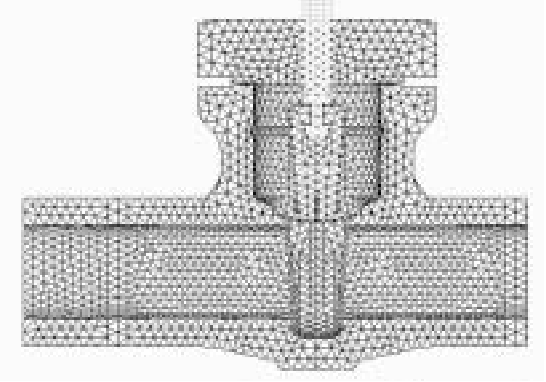

Figure 2: Mesh of the opened valve.

The first step of the simulation is to calculate the temperature field evolution in the solid between the beginning of the cooling and the closing time. We use the "opened" mesh. Due to the difficulty of on-site instrumentation, temperatures can only be measured on the external face of the body. With a very simple analytical model including only conduction, we adjust temperatures of the fluid to obtain the measurements (exchange coefficients are taken from the literature). These fields are introduced in finite elements calculations as an input. Though the whole evaluation of the "Thermal-Binding" phenomenon is correct, as we will argue in the following, a coupling with a fluid mechanics code would be a good improvement because it would give the opportunity to predict the "Thermal-Binding" phenomenon from theoretical studies.

The temperature field is then projected on the mesh in "closed" position. In the following, there is a contact and friction condition at the contact between disk and seats.

A force is then applied on the stem to simulate the actuator operation. The force passes from a null value to the nominal value in a few seconds and then is maintained at a constant level. At this step, the disk is sliding on the seats. Contact forces are evaluated at each step of the simulation. We can see in figure 3 that normal and tangential forces are on the friction cone. Each calculation is performed under the assumption of linear elasticity and small deformations. We let the structure evolve toward cold thermal equilibrium while the force is maintained on the stem.

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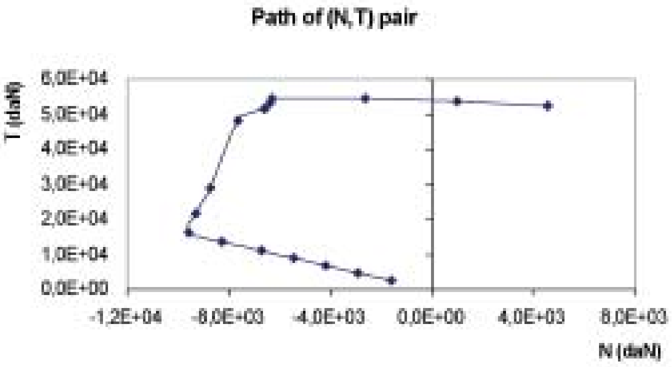


Figure 3: Evolution of (N, T) point for the case where "Thermal-Binding" is important.

Then the force is gradually relaxed and an opening force is applied. The normal and tangential components of the contact forces pass from one side to the other of the friction cone. There is no relative displacement between body and disk during this phase.

The last step is to determine the opening force. We follow the evolution of the normal (N) and tangential (T) forces at the contact between disk and body. When the temperature evolves after closing, the representative point (N, T) is inside the friction cone. When an opening force is applied, the point tends to pass from one side to the other of this cone. Unfortunately, due to convergence problem, it is not possible to obtain numerically the moment when sliding occurs. We then derive a relation between N_0 and T_0 the normal and tangential forces when the stem force is zero and $F_{opening}$, the force needed to open the valve after cooling. where θ is the wedge angle

$$F_{opening} = \frac{T - \mu N}{\mu \sin \theta - \cos \theta} \qquad (6)$$

As numerical simulation gives access to stresses and strains, it is possible to calculate ΔF_c and ΔF_0. This part of the work has not been performed yet.

Results

We simulate two tests in plant, with a closing force of 22 150 daN.

The cooling always begins at t_0=5 500s. In the first test (figure 3), the closing happens at t_1 = 8 750 s and, in the second one, t_1 = 10 000 s. The opening always happens at t_3 = 30 000 s when the valve is in thermal equilibrium. Figure 3 shows the evolution of the point (N, T) in the first case:

- After closing, the cooling of the closed valve induces an important increase of the force along the pipe axis. Because of the wedge-angle this is seen as an important increase of the normal force and a light increase of the tangential one.
- When the tangential force is positive, convergence of calculations is longer and longer.

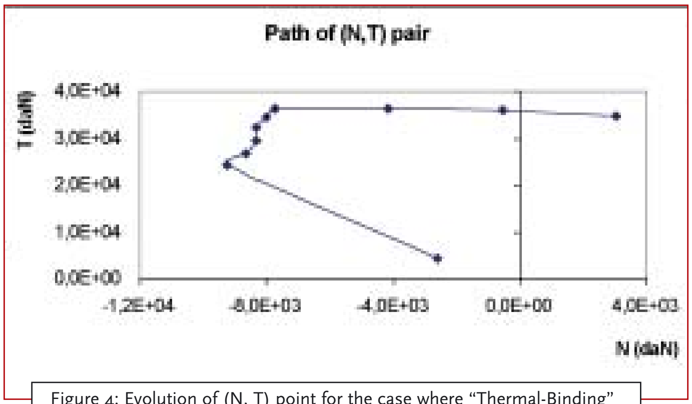
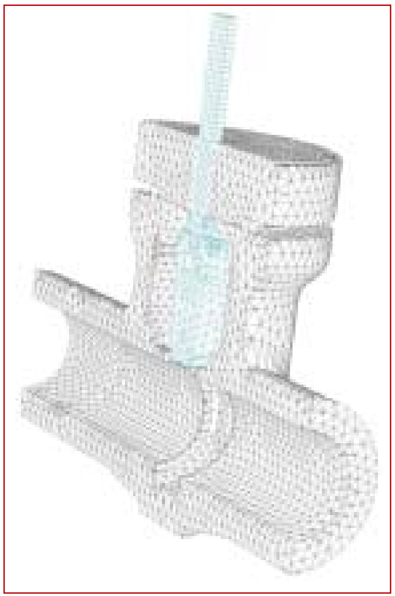


Figure 4: Evolution of (N, T) point for the case where "Thermal-Binding" is negligible (the friction cone has not been evaluated).

When the stem force is zero, the normal contact force is 52 460 daN and the tangential one is 4 580 daN. The opening force, evaluated with the formula (6) is 28 500 daN. This is very close to the experimental value (28 000 daN). For the second simulation, when the stem force is zero, the normal contact force is 34 870 daN and the tangential one is 3 050 daN. The opening force evaluated with the above formula is 18 900 daN. The experimental value is 16 000 daN. The numerical simulation gives a slightly higher value than experiment. Nevertheless, the agreement between both values is correct for industrial purposes.

Those results show that it is possible to be confident in the numerical simulation of the "Thermal-Binding" phenomenon.



Conclusion

The "Thermal-Binding" phenomenon is an increase of the force needed to open a wedge gate valve closed during a thermal transient. It is important to characterize it, since it can conduct to opening failure and eventually to integrate it in dimensioning when it cannot be avoided. Knowledge of stresses and strains in the valves can help to solve the problem with a good choice of materials and operating procedures.

Tests in plants allow characterizing the phenomenon whereas tests on a loop entitle to understand the influence of several parameters. We identified that the main contributions where the stem dilatation and the body contraction around the disk. A simple analytical model has been set up, but there still remain empirical parameters and the conclusions are not very accurate. A numerical simulation has then been considered. For every considered situation, results are in a very good agreement with experiments though there lack a coupling with a fluid mechanics code.

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About the author

David Hersant, who gained the title of Mechanical Engineer from the CESTI (FRANCE) and a PhD in Metallurgy from the Faculté d'Orsay (PARIS), has been a research engineer at EDF since 1991.

From 1991 to 2000 he investigated the wear of control rod clusters and SG tubes. Since 2000 his focus has been the experimental, analytical and numerical modelisation of valve behaviour. One of the goals of the R&D "Technology, Sealing, Valve and Fittings Group" is to provide EDF with models to study valves behaviour in standard and accidental conditions.

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