Development of a pressure and thermally controlled valve by using FEM - Simulation

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Abstract:

In solar heat installations the by outgassing from the solar fluid emitted gases has to be discharged from the system in continuous periods to guarantee whose secure and efficient function. In line with this article the development of a novel expansion actuator for valve applications shall be illustrated, which allows a regular and complete stand - alone de - airing of solar heat installations. The special feature of this innovation is that the expansion actuator does not need an external power supply and that there is no need for control electronic and sensor systems.

Keywords: FEM - simulation, smart valve, thermal control, solar heat

Presenting Author's biography

Uwe Risto is graduated with a diploma at the university of technology in ilmenau in the year 2006. Since 2006 he is a research assistant at the university of technology in ilmenau/germany at the depatment of mechanism technology. His main research field is the investigation of the snap - through behaviour of axisymmetric spherical shaped caps of a hyper - elastic material by using FEM - simulation. The investigations have the aim to create new and extraordinary compliant systems, especially for valve applications with smart mechanical features.

1. Introduction

Solar heat installations , figure 1, have a solar collector (1), which is mounted on the roof of a house. In the solar collector is a piping system (3), which is filled with solar fluid. The solar fluid will be heated by the absorbtion of the incident solar energy on the collectors. At the same time the solar fluid served as the medium to transport the gained thermal energy to a heat storage tank in the basement of the house (closed circulation). For the ventilation of the circulation system is a combination of float valve and a ball valve (2) used currently.

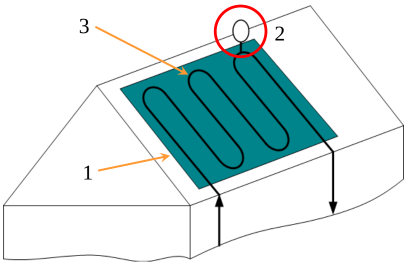

Fig. 1: *sheme of a solar heat installation*

2. Innovation

The innovation of the presented system is to make a supply of a fully autonomous and thermal controlled ventilation of the solar heat installation. This is realized as follow.
The heated solar fluid encloses an hollow expansion element of a hyper-elastic material, which is filled with a gas, figure 2. The function of the actuator is a result of a pressure changing inside the elastic element due to a temperature rising of the fluid.
For the time being, the element of expansion deforms continuously. If the pressure inside the element achieves a critical amount, a rapid deformation occurs at the face side of the expansion element in form of a mechanical snap-through effect. Based on these preferences of the system the inlet and outlet aperture will be closed, which implicates a hermetic closing of the solar heat installation, figure 2.

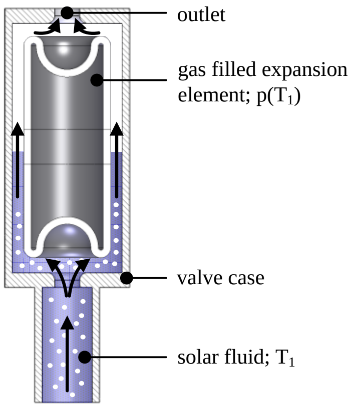

Fig. 2: *Thermal controlled expansion actuator at the opened state*

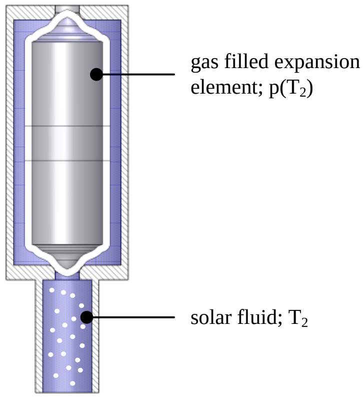

Fig. 3: *Thermal controlled expansion actuator at the closed state*

The ventilation of the system takes place in the opposite direction. If the solar fluid cools down a pressure decreasing occurs inside the expansion element and therefore a deformation of the elastic element up to the initial state. This process leads to the opening of the inlet and outlet aperture of the installation.

3. Development by using FEM - Simulation

The systematic dimensioning of the expansion element is carried out by using the FEM - Software ANSYS 12.1. By the using of FEM - Simulation it is possible to take meaningful preliminary considerations, which reflects the target behaviour approximately.
The examination and dimensioning of the elastic expansion element is essential for the development of the expansion actuator, because this element takes the main function of the system.
The expansion element has a cylindrical shape with closed face sides and comprises of a hyper - elastic material, which allows large deformation by low stress. In the present case a butyl rubber IIR with a shore hardness of 58 A is used. This rubber is characterized by a very high airproof what is important for the long-term function of the actuator. The expansion element is filled with gas, which remains inside the element permanently.
The development of the expansion element is carried out under the consideration that a mechanical snap-through effect occurs on the face side by achieving the defined critical pressure inside the element.
This effect will achieved by a pressure on a face sided double curved compliant structure, figure 4.
The aimed critical pressure results from a practical specification, which indicates that the installation should be closed by the achieving a fluid temperature of 50°C.
Therefore is due to the assumption that the expansion element is filled with air by an atmospheric pressure under a temperature of 20°C, a temperature

increasing of 30 K, which in turn leads to an increase of pressure at of 100 mbar inside the expansion element.

$$\frac{p_0}{T_0} = \frac{p_1}{T_1} \rightarrow p_1 = T_1 \frac{p_0}{T_0} \quad (1)$$

Furthermore the selection of the face side geometry is based on the preliminary research of V. Böhm [1] und U. Risto [2, 3]. In the aforementioned works the basic principles of the mechanical snap - through behaviour of spherical shaped rotationally symmetric silicon caps are acquired and analysed.
In addition it must be pointed out that the snap - through effect and the whole deformation on the hyper - elastic hermetic closed element leads to a pressure changing inside the element.
This pressure changing has on the other hand a large influence on the switching behaviour of the whole system.
Thus, the snap - through occurs of the face sides, a rapid rising of the volume inside the expansion element will happen. This volume changing leads to a similar rapid decrease of pressure inside the element, which in turn leads to a dysfunction of the actuator. Due to this reason the Δ - volume is dimensioned in this way that the pressure inside is not less than the local minimum of the load - displacement - curve of a snap - through in the apex of the central cap of the element after the volume changing. Would the pressure be less than the local minimum after the snap - through; an immediate snap - back of the structure would occur or the structure would not take a rapid deformation and the snap - through effect would not happen.

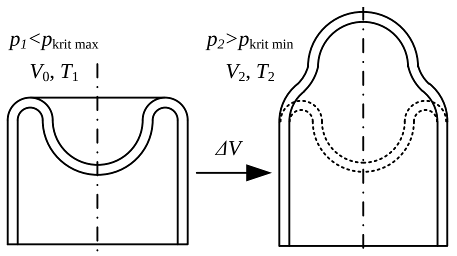

Fig. 4: *Sheme of the volume changing after the snap - through*

$$p_1 \bullet V_0 = p_2 \bullet V_2 \quad \rightarrow RB: \; p_2 > p_{krit\,\min} \quad (2)$$

A further essential criterion for the dimensioning of the expansion element is the whole volume inside the element.
The gas inside the element is heated by the solar fluid during the operation of the installation. The duration of the warming is depends strongly on the whole volume of the heated gas.
Therefore it is necessary to minimize the whole volume inside the expansion element. In summary the quantities in table 1 are classified as the essential parameters for the dimensioning of the expansion element.

Tab. 1: *Criterions of the dimensioning of the expansionelement*

Criterion	Aim
V_0 minimize	Minimize release time
ΔV adjusting in the way that a snap-through effect is possible	$p_2 > p_{krit\,\min}$
$p_{krit\,\max}$	releasing pressure inside the element depends on the temperature inside the element

Figure 5 a presents the initial geometry of the important element as it has already been analysed by V. Böhm [1]. The following figures will demonstrate the geometric changes, which are taken to achieve the aspired aim. In figure 5 b a dome will be applied on the cap to enforce the closeness of the expansion actuator. The dome will be applied in the apex of the central cap, because this is the point, which moves nearly straight in y - direction in the case of a snap - through deformation and thus takes a guidance of the dome.
Under this displacement, which is according to the amount the highest, the dome will move towards the inlet and outlet opening and hence support the sealing of the installation.
Figure 5 c will modulated the curvature of the outside contour and this is the next step of the optimization of the element. The FEM - calculations results in the existence of a ceritical angle between the central cap and the flange in geometry, so that a snap - through effect does not appear. Furthermore by the starting geometry the changing of the volume is large, what leads to a unrequested large whole dimension.

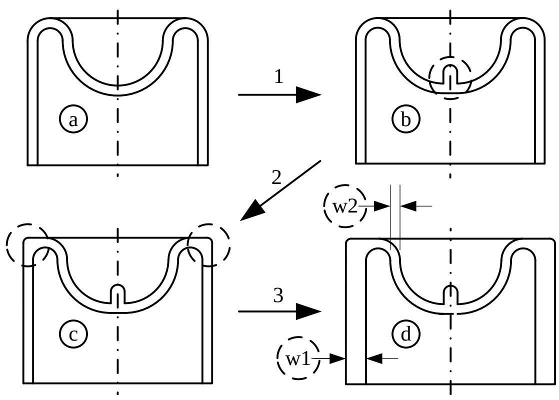

Fig. 5: *shematic evolution of the expansion element*

With the aid of the reduction of the curvature of the outside flange (circle marker in figure 5 c) it is possible to create a shallow structure, which leads to a decreasing of the Δ - volume while maintening the snap - through charakter.

Figure 5 d illustrates the final structure of the expansion element schematically. This structure has a variation of the wall thickness. In the spherical shape of the element a wall thickness exists, w2, which is less than the thickness w1 in the cylindrical casing whereas the changing from w2 to w1 is continuously and starts on the vertical section plane in the middle point of the curvature of the flange.

4. Results of a 2 - dimensional axisymmetric model

For the determination of the deformation and the load - displacement - characteristics of the model the arc - length - method is used. In the software package ANSYS the arc - length - method is used like M. A. Criesfield mentioned the usage. [4].

The following figures pictures the FEM - model of the final structure with the illustration of the applied boundary conditions and load. The load is applied in form of a consistent and steady pressure on the inside contour of the expansion element.

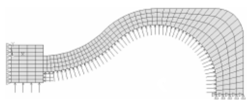

Fig. 6: *a - Simulation model at initial state*

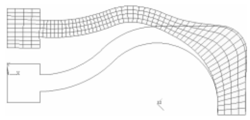

Fig. 7: *b- Simulation model before snap - through*

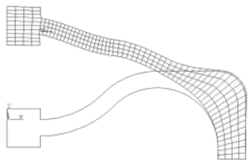

Fig. 8: *c - Simulation model after snap - through*

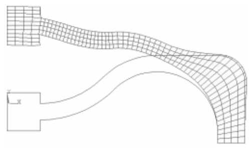

Fig. 9: *d - Simulation model before snap – through back*

Figure 7 displays the structure by achieving the critical point before the snap - through. The critical point constitutes a local maximum on the load - displacement - curve, fig. 10 b. In this point the structure moves from a stable state into a instable state and snaps through. This moment is the important point for the dimensioning of the triggering pressure for the closing of the installation.

Figure 8 demonstrates the structure after the snap - through and after the change - over from the instable to an anew stable behaviour. This deformation occurs at the same pressure as the shape before the snap - through but lays in the after critical zone of the load - displacement - curve.

Figure 9 on the other hand is the model that illustrates the second critical point, fig. 10 d. This critical point constitutes a local minimum on the load - displacement - curve. This leads to a deformation in form of a snap - through back into the initial shape in case of a cooling down of the installation. This point is used for the adjustment of the triggering pressure for the opening of the installation.

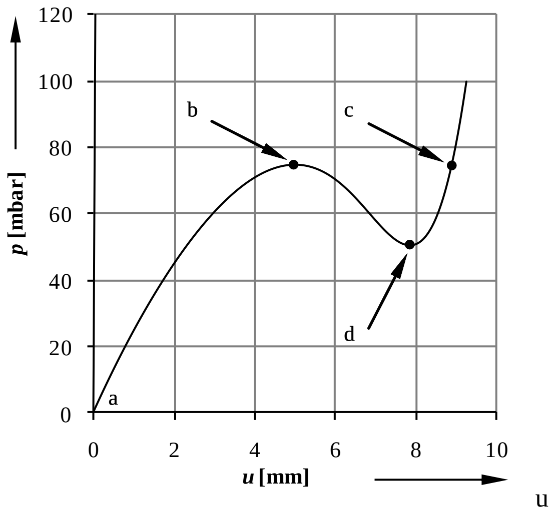

Fig. 10: *Load – displacement – curve of a 2 - dimensional FEM - simulation by using the arc - length - method*

The deformation figures 6 - 9 are dedicated to the unique interest points of the curve in figure 10. This figure is the load - displacement - curve of a point of the model, which is placed on the rotation axis respectively on the symmetry axis.

5. Results of a 3 - dimensional axisymmetric model

The previous simulations are limited to the 2 - dimensional sector and give a first insight into the deformation and the snap - through behaviour of the examined expansion element. However, since the structure optained of a hyper - elastic material it is nessecary to consider the 3 - dimensional behaviour, because it is known that a pressure loaded axisymmetric spherical shaped cap optained of a material with linear character and under specific geometric conditions deforms asymmetrically, [5, 6].

The simulations take place, as opposed to the 2 - dimensional, with the standard newton - raphson - method. The program ANSYS 12.1 has a function, called “stabilize”, which allows to overcome a critical point and determinate the deformation behaviour in the after critical area.

Under the use of these function it is not possible to get loadcurves with a negative increase, videlicet it is not possible to get full informations about the behaviour in the after critical area, like in case of using the arc - length - method. However the method provides evidence about the deformation at the critical point and about the behaviour of the structure when the after critical area posseses a stable character.

The boundary contitions are oriented on them of the 2 - dimensional simulations. The structure is quartered simulated because of symmetric reasons. The structure gets a frictionless mounting in the xy - plane and zy - plane with one degree of freedom in y - direction. Futhermore is a load applied in form of a consistent and steady pressure on the inside contour of the expansion element.

The demonstration in figure 11 shows the 3 - dimensional initial model. Figure 12 displays the structure by achieving the critical point before the snap - through. These deformations occur at the point b at the load - displacement - curve in figure 15. With overcoming of the critical point the structure goes over in the instable state and snaps through. However the curve in figure 15 shows not the whole course of the real load - displacement - behaviour as already explained, videlicet the area of the cours with a negative increase of the load is not determinated.

On the instable area, which is marked through the curve with a zero - increase, follows a new stable deforming behaviour, figure 13, point c in figure 15.

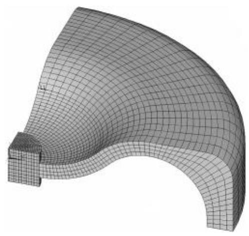

Fig. 11: *a - 3D - Simulation model at initial state*

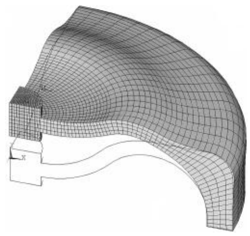

Fig. 12: *b - 3D - Simulation model before snap - through*

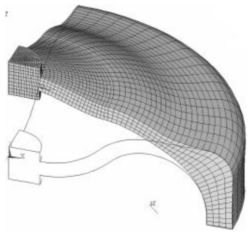

Fig. 13: *c - 3D - Simulation model after snap - through*

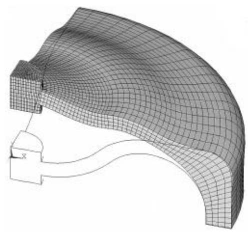

Fig. 14: *d - 3D - Simulation model before snap – through back*

The unloading follows with achieving of the maximum load. The structure behaves stable till a under critical point. On this point the deformation is like in figure 14, point d in figure 15. Overcomes the structure this point she goes over in a instable state again and snaps through, videlicet the structure deforms back to the initial form.

The curve in figure 15 demonstrates a load - displacement – behaviour, which is similar to the curve in figure 10 except she does not show the course with a negative decrease. The critical loads differ just a little. Furthermore occurs the deformation rotational symmetric as far as possible.

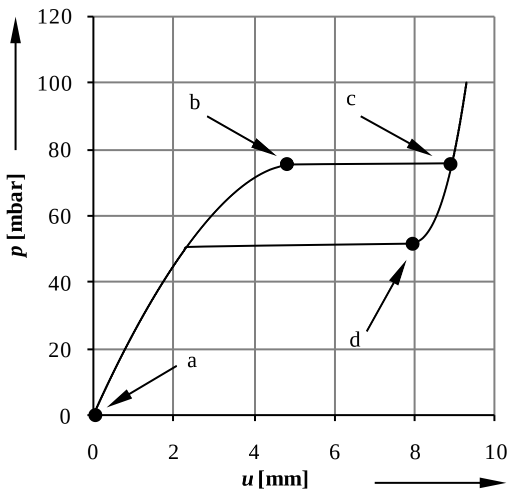

Fig. 15: *Load – displacement – curve of a 3 - dimensional FEM - simulation by using the newton - raphson - method and the "stabilize" function*

6. Results of a practical experiment

The simulation results are tested within a practical experiment in order to get information on the practicability of the theoretical results.

Therefore a cap of butyl rubber manufactured with the calculated geometric dimension will be produced in a pressure – heating – process. This cap is assembled with a pressure testing device and the whole assembly is hermetic closed, fig 11.

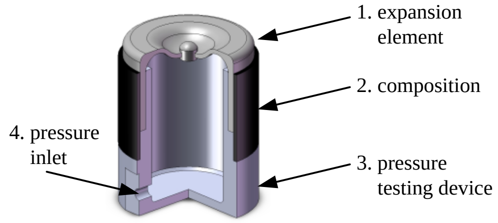

Fig. 16: *Pressure testing assembly*

The pressure testing device (3) is filled with a uniformly distributed pressure inside the device over a inlet (4) by a PC - controlled pressure regulator. This pressure will be effected by the expansion element (1) like it has been fixed at the beginning of the simulations.

In order to measure the displacement in the apex of the dome during the operation a point laser triangulation system is used, which is placed vertically to the measuring point. The pressure control and the laser system have an analog signal output and they are connected over a data aquisiton system with a PC. The examination of the measuring results offers a pressure - displacement - context in the apex of the dome, which it is shown in fig. 12.

The displayed curve illustrates the course during the pressure rising and decreasing. In case of the pressure increasing at approximately 130 mbar and an approx. 4,8 mm a local maximum exists with a following little pressure decreasing and a local minimum at approx. 6,6 mm. This demonstrates that a rapid displacement with a simultaneous pressure changing appears inside the testing device, which is on the other hand available in case of a snap – through effect. Therefore it is not possible to measure a greater fall of the pressure in the given example by controlling the pressure regulator, which aspire

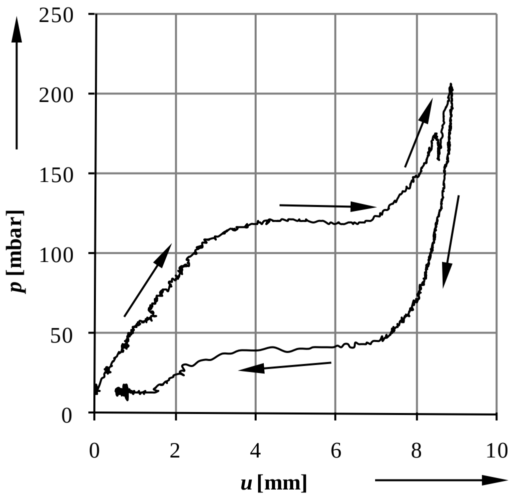

Fig. 17: *Load – displacement – curve of a meassuring at the pressure testing assembly*

the adjusted maximum magnitude of the pressure inside the device, However it has shown that the volume changing does not effect the triggering behaviour negatively, respectively the changing is less enough to realize a snap - through.
Moreover at approximately. 200 mbar the unloading phase occurs. That demonstrates that by approx. 7 mm and 40 mbar a strong decrease happens, which has the amount of the negative ascent of the curve.
This decrease occurs during the snap - through of the element in reverse direction. In this area are a maximum or minimum unknowable. Due to that the great volume inside the testing device and the volume reducing because of the snap - through back does not generate a measurable pressure increasing.

7. Conclussion

The presented examinations and testings devoted that it is possible to dimensioning under the use of FEM – simulations an expansion element for valve applications.
It has shown that the practical results of the triggering pressure differ strongly from the theoretical results. These deviations are caused by possible manufacturing differences of the expansion element and of the theoretical material parameters.
Consequently, it is necessary to upgrade and optimize the manufacturing and to determine better material parameters.

8. References

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