Tests on shaped compensators used in heating systems made of chlorinated polyvinyl chloride – CPVC

Badania kompensatorów kształtowych w instalacjach grzewczych wykonywanych z chlorowanego polichlorku winylu – CPVC

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The use of plastic materials has become a standard in sanitary systems design. Due to numerous advantages of polymers, heating and hot water systems made of them have become an alternative to the ones made of traditional materials such as steel or copper.
The values of forces working on particular elements of compensators as well as their displacement result from linear thermal elongation of segments of the system mounted in fixed supports.
The article presents theoretical considerations on the subject of linear elongations and stress in shaped compensators that occur during exploitation of heating systems made of chlorinated polyvinyl chloride – CPVC. In order to verify the results of the theoretical considerations, both the analytical and the numerical ones, a series of fatigue and destruction experiments were performed in the next stage of the research.
Keywords: plastics, fatigue strength, heating system, shaped compensators;

Zastosowanie tworzyw sztucznych stało się standardem w projektowaniu instalacji sanitarnych. Systemy instalacji ogrzewczych oraz ciepłej wody użytkowej wykonane z polimerów ze względu na swoje liczne zalety już od dawna stały się alternatywą dla instalacji wykonywanych z tradycyjnych materiałów takich jak: stal i miedź. Wielkości sił działających na poszczególne elementy kompensatorów, jak i ich przemieszczenia wynikają z liniowej wydłużalności termicznej odcinków instalacji zamocowanych w podporach stałych.
W artykule przedstawiono rozważania teoretyczne nad wydłużeniami liniowymi i naprężeniami w kompensatorach kształtowych, występującymi podczas eksploatacji instalacji grzewczych, wykonanych z chlorowanego polichlorku winylu – CPVC. W celu zweryfikowania wyników otrzymanych z tych rozważań teoretycznych: analitycznych i numerycznych [20,24], w kolejnym etapie badań kompensatorów przeprowadzono serię badań doświadczalnych zmęczeniowych i niszczących.
Słowa kluczowe: tworzywa sztuczne, wytrzymałość zmęczeniowa, instalacja grzewcza, kompensator kształtowy;

Introduction

The use of plastic materials has become a standard in sanitary systems design. Due to numerous advantages of polymers, heating and hot water systems made of them have become an alternative to the ones made of traditional materials such as steel or copper. All these advantages of plastic systems do not exempt their designers and manufacturers from applying compensation for linear elongations in order to assure long-term and trouble-free service of heating systems. An elongation of a segment of a straight pipe is presented in Fig. 1. The increase of its length can be calculated with the formula:

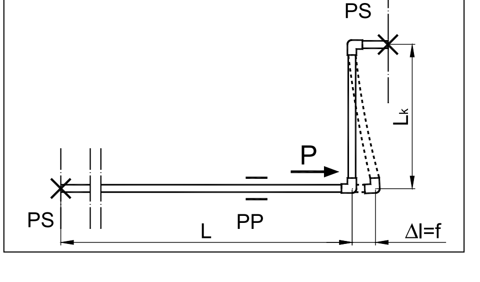
$$\Delta l = f = \alpha \cdot L \cdot \Delta t \qquad (1)$$

where:

- $\Delta l = f$, – deflection of the arm of compensator [mm],
- L – length of compensated pipeline segment [m],
- α – ratio of linear thermal elongation of the material [mm/m K],
- Δt – difference between temperatures of the system when just assembled and when in service [K].

Shaped compensators made of plastic are mounted in heating systems according

Fig. 1.
Scheme of thermal elongation of a segment having the length *L*
***PS* – fixed supports, *PP* – sliding support, L_k – compensator arm length, *L* – length of pipeline between fixed supports, *P* – force acting on compensator's arm**



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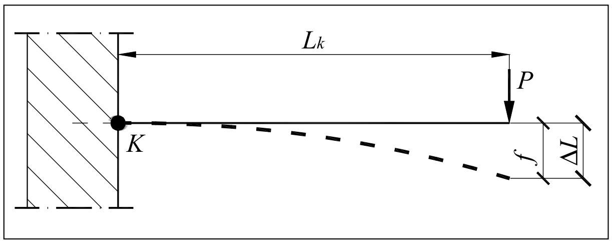
to the same rules that were applied to steel or copper pipelines [4,5,6,7]. These similar principles are applied when the use of pre-tension is required in the system. The values of forces working on particular elements of compensators as well as their displacement result from linear thermal elongation of segments of the system mounted in fixed supports. An assumption that pipelines made of plastic materials elongate in heating systems in the same way as steel or copper did turns out to be false. This fact has been proven through research [2,18,19,20,21,24,25,26,27,28,29,30] and throughout experiences in heating systems design or in exploitation of the systems that are already in operation. This observation has forced the authors to take a closer look at the phenomenon and gave rise to take up theoretical considerations and experiments.

The article presents theoretical considerations on the subject of linear elongations and stress in shaped compensators that occur during exploitation of heating systems made of chlorinated polyvinyl chloride – CPVC. In order to verify the results of the theoretical considerations, both the analytical and the numerical ones [20,24], a series of fatigue and destruction experiments were performed in the next stage of the research [19,21].

Theoretical considerations

Due to differences in temperatures of the system between the its new assembly and its work, the arm of compensator – L_k (Fig. 1) will be deflected with the force *P*. The force *P* is caused by the ΔL elongation of free tips of the system segment – *L*, under the influence of temperature [24,25,27,28]. When analysing the behaviour of an elongated segment of the pipeline between fixed supports, it can be concluded that the arm of compensator L_k, treated with the force *P* will deflect, as presented in Fig. 2, according to the dependence (1). The above represents a classical model of a bent beam that is one-sidedly fixed and loaded at its free end with a concentrated force – *P* (Fig. 2). The displacement of the free end of the beam – *f* (deflection of the beam) will be identical with ΔL extension of the pipeline if the installation has not been a subject to pre-tension. In this case the end of the compensator arm will move from point 0 to 1 (Fig. 3a) or from point 2 to 2` (Fig. 3b), if it was under tension during assembly (in point 2). During work of the system, the heating medium will flow with the working temperature higher than the assembly temperature. This situation

Fig. 2.
Bending of a beam fixed on one side, loaded on its free end by concentrated force *P*



will cause the pipeline to be elongated by the same value of ΔL as if the pipeline were not pre-stressed, but the stresses generated in the compensator arm will now be characterised by a bi-directional state of stress. This stress will be initially tensile – caused by pre-tension, and after passing through the point "0" in which it disappears (will equal zero), the elongating pipeline will cause compressive stress in the compensator.

In the arms of compensators, when the sections of the system are not subjected to pre-stress, stresses caused by the temperature of the flowing heating medium will always have a compressive character. The deflection – *f* of the compensator arms will always be the same in terms of value. In case of assembling a system without pre-stressing, the stresses in the compensator arms are one-sided during their operation. The values of the stresses is twice as high as in the case when the system was installed with a pre-stress. On the other hand, the initial stress of the system will cause a bi-directional state of stress in the arms of compensators, and the values of compressive stresses will be twice lower [19, 24].

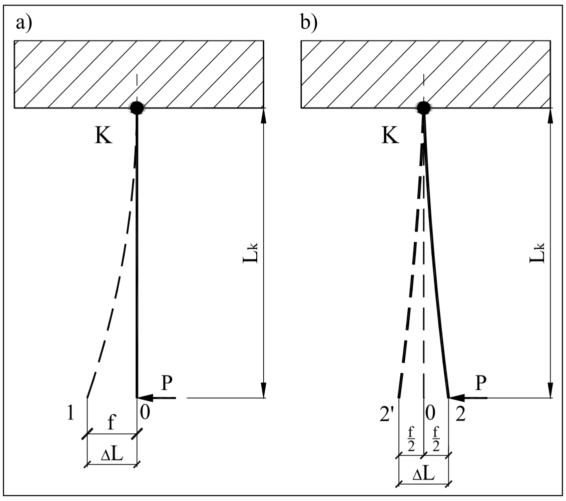
Possibility of compensating for the system elongations is twice as high when applying a compensator with pre-tension than when applying one without it. The maximum pre-tension of a compensator arm can have the value of the deflection *f*. In this case the compensator arm will move by a total value of *2f*, so it will be capable of compensating for twice as long an elongation as in the case of a compensator arm without pre-tension in the same working conditions of the system. Such a model of compensator work has been assumed for the experimental research.

The stress occurring in cross-section of the beam in point K (Fig. 2) can be calculated out of the deflection condition [4,11,18]:

$$\sigma_{max} = \frac{3 \cdot f \cdot E \cdot D_z}{2 \cdot L_k^2} \qquad (2)$$

where:
- *E* – Young's module [MPa],
- D_z – outer diameter of the pipe [mm, m],
- L_k – length of the compensator arm [mm, m].

Fig. 3.
Scheme of loading of an arm in the shaped compensator having the length L with the load resulting from the transported heating medium with a temperature higher than during the system's assembly.
a) Scheme of compensator's work without pre-tension.
b) Compensator with pre-tension *f/2*.
where:
***f* – deflection of the arm of compensator during exploitation [mm],**
***P* – force [N],**
ΔL – compensative capability of one arm of the compensator [mm]



Literature for systems designers [5,6,7] offers a different form of the formula:

$$\sigma_{dop} = \frac{3 \cdot f \cdot E \cdot D_z}{L_k^2} \qquad (3)$$

The authors of the dependence formula (3) do not refer to the change made in the formula (2), although the stresses in this case are twice as high.

Formulas (2) and (3) are used for determining resultant stresses without taking into account the internal pressure from the heating medium transported within the system. Only the temperature difference resulting from the assembly and operation of this part of the pipeline is considered in the calculations. By introducing an appropriate calculation model, a calculation software based on the finite element method – Ansys [1] offers a possibility of taking into consideration all factors influencing stress in the pipe material used in the system. The software, in addition to determining the maximum reduced stresses (σ_{red}) also enables obtaining an image of stress distribution in the whole loaded element of the compensator (Fig. 4) and an image of deformations of this element. The highest values of stresses obtained during numerical analysis and reduced in places most exposed to damage are clearly visible in Fig. 4 [18, 20, 21, 24].

Table 1. Values of the calculated deflection – *f* in the function of a nominal diameter of the pipe

D_z [mm]	f [mm]
28,56	28,50
34,91	23,32
41,26	19,73

Comparison of tensions σ_{max} from the equation (2) and σ_{red} by Ansys 12.1 is presented in Fig. 5.

The values of reduced tensions σ_{red} calculated in Ansys are higher than the values of tensions σ_{max} calculated with the formula (2) because they take into account the influence of pressure and distribution of temperature in the pipe wall. It is obvious that tensions σ_{dop} calculated from the dependence (3) will be twice as high as σ_{max}, which, as earlier explained, has no justification in reality.

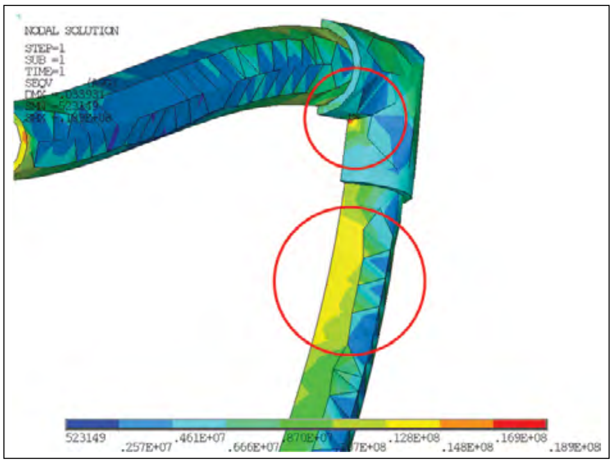


Fig. 4.
Reduced stresses in the "U" type compensator

An equation was performed for the purposes of comparison between the results of calculations of stresses determined with the use of different methods (analytical – formula (2) and numerical – Asnys 12.1). The following data [5,6,7] was used:

Temperature of transported heating factor – T = 70°C,

Young's module E – CPVC = 2026 MPa,

Poisson's number ν = 0.38,

Ratio of thermal conductivity of the pipeline material W λ = 0.16 W/mK,

Length of compensator arm L_k = 680 mm,

Pipelines with the following outer diameters were adopted for the purpose of considerations:

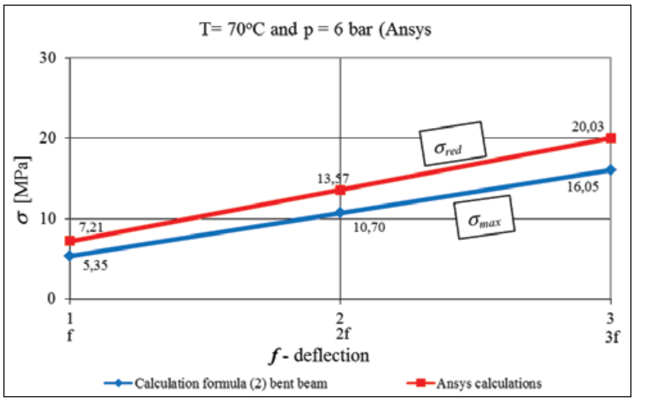
D_z = 28.56 mm, D_z = 34.91 mm, D_z = 41.26 mm

It was assumed that the acceptable stress for the temperature of 70°C was σ_{dop} = 5,35 MPa [5,6,7].

Maximum deflection f of a compensator arm for particular pipe diameters was calculated out of the dependence (2):

$$f = \frac{2 \cdot \sigma_{dop} \cdot L_k^2}{3 \cdot E \cdot D_z} \qquad (4)$$

Fig. 5.
Values of tensions in the arms of compensators in the deflection function for temperature of work 70°C and of assembly 20°C



In the next stage of the research, in order to verify the results obtained through theoretical considerations (analytical and numerical) [18,20,24], a series of fatigue and destruction experiments were performed on the arms of shaped compensators made of chlorinated polyvinyl chloride – CPVC [18,19]. The presented theoretical calculations enabled drawing a conclusion that previous recommendations for design and manufacturing in terms of the length of arms in shaped compensators were wrong (too long arms).

Tests were performed for elements of heating systems, and specifically for arms of compensators with the following outer diameter of pipes: D_z = 28.56 mm, D_z = 34.91 mm, D_z = 41.26 mm. The length of the compensator arms was assumed constant, and it equalled L_k = 680 mm [18, 19, 21, 24]. Arms were tested in sets of four elements connected in series and with water flowing through them. The water was heated in electric boiler. The automatics of the boiler enabled stabilising water temperature and pressure. The arms of compensators were mounted in a fixed support. The free end of the arm was bended on one side from the free position to the value of the fixed deflection f [18,24]. For the pipes with different diameters the values of deflection were each time set separately, so as to obtain the deflections having the value f, $2{\cdot}f$ and $3{\cdot}f$. The arms of compensator were double-sided bent from the location 0 to 2′ and from 0 to 2 (Fig.3b), simulating the work of a system assembled with the use of a pre-tension [18, 19, 21].

Each arm of the compensator was a subject to fatigue tests in 12 000 cycles. During the fatigue tests a heating medium (water) of 70°C was flowing through the tested system, and the constant pressure of 6 bar was maintained in the system during the fatigue tests. The accepted number of 12 000 cycles resulted from assuming 50 years to be the system exploitation time [12]. The deflection of the compensator arm was calculated with the formula (4). The values of the deflection for particular diameters of pipes are included in Table 1.

The deflection f was calculated under the condition of acceptable tensions in the pipe wall, and it was treated in the research as a model [3, 5, 6, 7, 11]. The experiments validating fatigue strength of compensators were carried out for a series of values assumed for deflection, starting from the deflection *f*, as the model, and then by using the doubled 2·*f* and tripled 3·*f*.

Results of fatigue tests of compensators arms

After the fatigue tests each sample was thoroughly inspected [13, 14, 15, 16], and on this basis the following conclusions were formulated:

a) None of the samples was a subject to destruction,
b) No water leakage or dewing on the surfaces of the tested sets or glued connections were observed,
c) Surfaces of pipes and fittings of the tested arms of compensators did not manifest any changes in structure of their surfaces,

Tensile tests were performed in order to determine how the fatigue tests of compensators arms influenced durability of polymer– chlorinated polyvinyl chloride – CPVC. The trials were carried out with the use of tensile machine Instron 3384 produced in the USA.

Results of tensile tests

The results of tensile tests were registered and saved by computer and simultaneously printed in the form of a graph [17]. The axis of the graph reflected the absolute elongation [mm], and the ordinate was a reference to the increasing tensile force [N]. On each of the graphs the maximum tensile force was marked, For this force the programme calculated maximum tensile stresses and the accordant relative elongations of the samples. The end of each registered curve representing a tensile trial stood for tearing of the sample or for stopping the test due to the sample having entered the phase of its material fluidity. Exemplary courses of tensile tests are presented in Fig. 6.

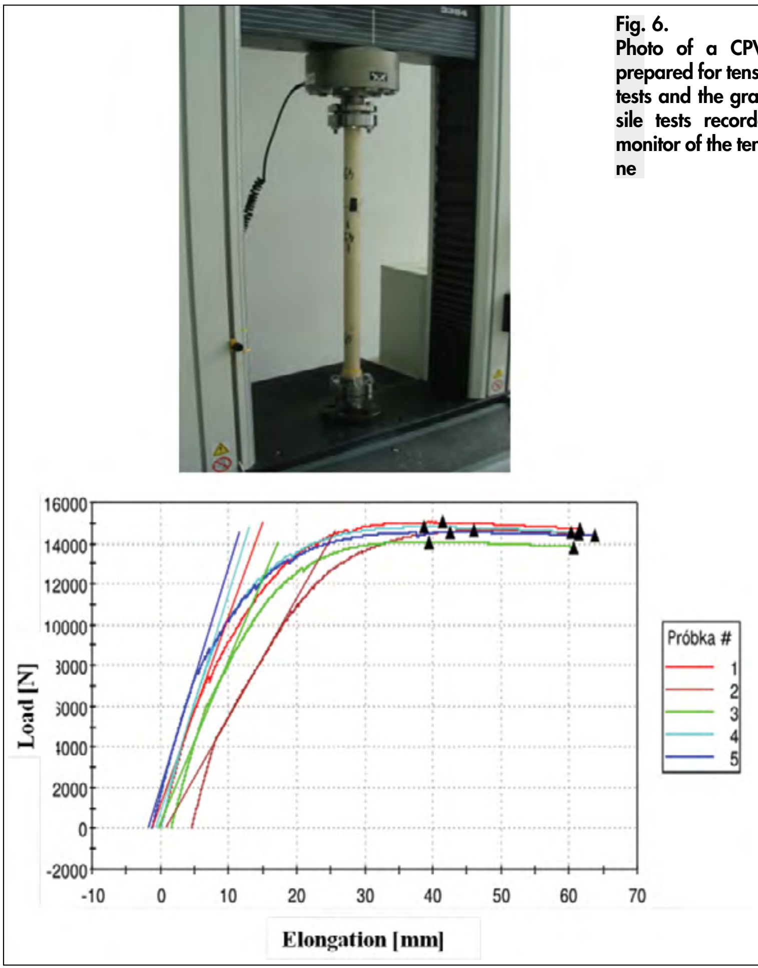


Fig. 6.
Photo of a CPVC sample prepared for tensile strength tests and the graphs of tensile tests recorded on the monitor of the tensile machine

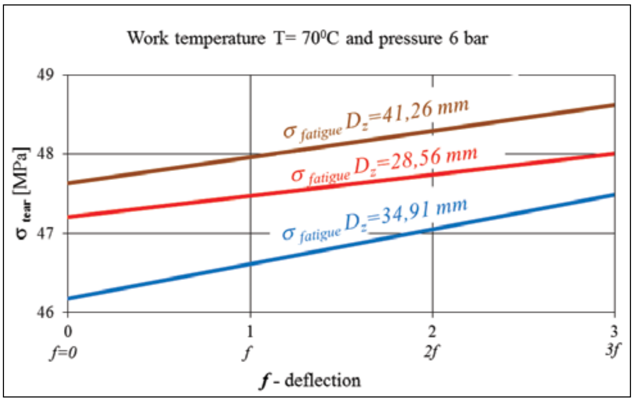


Fig. 7.
Influence of the size of the sample deflection on the change in tensile strength of CPVC polymer

The influence of the value of fatigue load of a sample on the change in tensile strength of the compensator arms for three tested diameters of pipes are presented in Fig. 7. The values σ_{tear} for the deflection *f* = 0 marked in the graph apply to the samples loaded in the process of fatigue test only by pressure and temperature of the heating medium – they were not bent.

Conclusions

As a result of fatigue experiments [18,19,21] and theoretical considerations [18,20,24] conducted for shaped compensators the following conclusions were formulated:

- Under the influence of multiple bending and temperature [18, 19], PVC-C polymer cures, which causes increase in its tensile strength. However, the above does not mean the increase of durability in time (Fig.7);
- The larger the deflection during system testing, the greater the material strengthening. This increase basically does not depend on the diameter of the pipeline but only on the value of stresses introduced in the bending process. A repetitive nature of the course of function is more important (Fig. 7);
- The acceptable deflection of the compensator arms recommended in the literature on subject [5,6,7] are too 'safe', which results in designing shaped compensators that are too long. It should be remembered that the deflection f_{proj}, calculated on the basis of formula (3) is equal to half of the deflection *f* assumed in the tests (formula 2). During the tests the loaded compensation arms were equal to three deflection *f*, which corresponds to as much as $6 \cdot \sigma_{dop}$, and none of the samples tested, in the forecasted durability period (12000 cycles), was damaged;
- Looking at the results of the research obtained from theoretical considerations and experimental studies, it is

clear that the lengths of the compensator arms are oversized. On this basis, it can be concluded that the length of these arms could be 2, or even 2.5 times shorter. This is due to the dependence (3) from which the length of compensator arms can be estimated according to the guides for installation designers:

$$L_k = \sqrt{\frac{3 \cdot E \cdot D_z \cdot f}{\sigma_{dop}}}\ [m] \qquad (5)$$

Assuming that stress in the arm can be even 6 time higher than the acceptable one, which was confirmed in fatigue tests using formula 2 for the calculation of deflection, then:

$$L_k = \sqrt{\frac{3 \cdot E \cdot D_z \cdot f}{6 \cdot \sigma_{dop}}}\ [m] \qquad (6)$$

or

$$L_k = 0,4 \cdot \sqrt{\frac{3 \cdot E \cdot D_z \cdot f}{\sigma_{dop}}}\ [m] \qquad (7)$$

As resulting from the formula (7), the modulus 0,4 reduces the length of compensators arms in heating systems made of chlorinated polyvinyl chloride to 40% of their original length calculated according to recommendations for designers;

- It is known from practice that there occur breakages of moulders used in shaped compensators made of chlorinated polyvinyl chloride. Still, the reasons of these breakages have not been clearly and undoubtedly recognised. From bibliographical data [8,9,10] and research work [21] one can conclude that the lowest durability of material occurs in places where streams of plastic get connected during injection moulding of fittings. Mechanical properties of PVC-C within the lines (planes) along which the streams join together can reduce the strength from 10% to 50%, and in case of impact resistance even up to 85%, depending on the type of polymer and operating temperature of a system. The information obtained from the producer of PVC-C pipes and fittings – NIBCO, from the system installers and from the authors' own research [21] confirms these assumptions.

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