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THE TEST BENCH FOR STUDYING THE CHARACTERISTICS OF STRAW TUBES

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Стенд для исследования характеристик строу

Приводятся конструкция и технические параметры стенда, предназначенного для исследования характеристик тонкостенных трубок — строу. Описана методика и представлены результаты измерений характеристик строу диаметром 9,8 мм и с толщиной стенки 20 мкм. Определена область упругой деформации, которая простирается до натяжения $(1{,}85 \pm 0{,}02)$ кгс. Натяжение, превышающее эту величину, приводит к упругопластической деформации, при которой возрастает скорость релаксации натяжения и ползучесть материала строу. Измерен модуль упругости материала трубки, составляющий $(4{,}44 \pm 0{,}05) \cdot 10^9$ Н/м^2. Результаты исследований температурной зависимости модуля упругости позволяют выбрать оптимальный температурный режим строу детектора. Определен коэффициент Пуассона материала трубки, требуемый для оценки изменения ее натяжения в вакууме: $0{,}338 \pm 0{,}004$. Для процесса релаксации впервые рассматривается наличие квазипостоянного остаточного натяжения на временном масштабе типичного срока службы трекера, который зависит от выбора начального натяжения строу. Представленные результаты показывают высокую точность измерений.

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The Test Bench for Studying the Characteristics of Straw Tubes

The design and technical parameters of the stand developed for studying the characteristics of thin-walled tubes (straw) are given. The method of measuring straw characteristics with a diameter of 9.8 mm and a wall thickness of 20 μm is described, and the results are presented. The area of elastic deformation, which extends to a tension of (1.85 ± 0.02) kgf, was determined. A tension more than this value leads to elastoplastic deformation at which the tension relaxation and creep rate of the straw material increase. The elastic modulus of the tube material which is equal to $(4.44 \pm 0.05) \cdot 10^9$ N/m^2 was measured. The results of the elasticity modulus' temperature dependence studies allow selecting the optimal operating temperature for straw detector. Poisson's ratio of the tube material, which is required to estimate the change in its tension in vacuum, was determined. Its value was 0.338 ± 0.004. For a relaxation process, the presence of a semi-permanent residual tension on the time scale of a typical tracker lifetime, which depends on the choice of the initial straw tension, was considered for the first time. The presented results show high accuracy of the measurements.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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1. INTRODUCTION

In the technique of modern experiment on accelerators, coordinate gas-filled wire detectors based on thin-walled tubes, straw, made of polyethylene terephthalate film, are increasingly used [1, 2]. This type of detectors has numerous advantages. Small radiation thickness of the detector and cylindrical geometry for each channel of registration provide optimal temporary collection of ionization electrons drifting to the anodes. The assembled straw set is a cylindrical drift detector. The inner surface of a film is covered by a thin metal layer, which serves as the cathode. At the same time, the cathode is the screen reducing the mutual influence of the triggered straws. Signal wire, the anode, is attached to the contacts located in the straw end caps. In addition to the contacts, the end caps have holes for supplying the working gas mixture into the straw. Straw-based detectors have a simple design and high reliability [3, 4].

To ensure high coordinate accuracy of the straw detector, precision positioning of the wire inside the tube and the tubes themselves in the detector modules is required. The material from which the straw is made is also required to preserve its basic physical properties in time, as well as to be homogeneous throughout the length. The most important physical properties of the straw material are the area of elastic deformation, the value of the elastic modulus, which characterizes the straw strength, and the rate of stress relaxation. Knowledge of the Poisson ratio is required to select the straw initial tension, since its tension changes when operating in vacuum [5]. The purpose of this work was to create the stand for studying the straw properties and to estimate straws lifetime as the main part of the detectors.

2. DESIGN OF THE TEST BENCH

The basic idea was to create a bench with the as simple as possible design that allows one to rebuild, add or remove parts and mechanisms for carrying out a wide range of straw characteristics measurements. The design of the developed test bench in a vertical section is presented in Fig. 1. The main parts of the stand are:

— metal base with a sealed Plexiglas body fixed on it;

— investigated straw with end caps and screw system for straw tensioning;

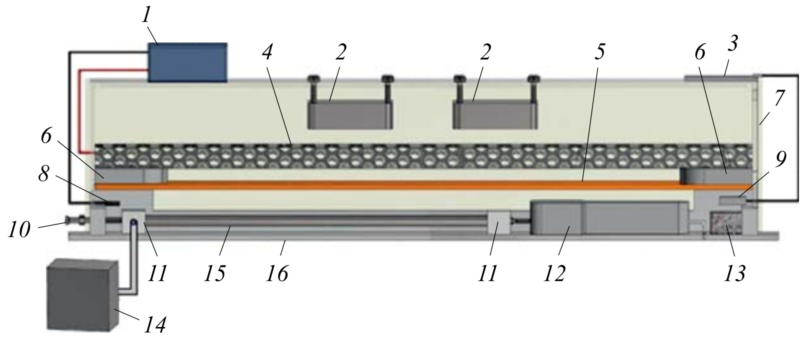

Fig. 1. The stand in a vertical section, where *1* — electronic temperature controller; *2* — fans for airflow and air circulation; *3* — Arduino controller; *4* — heating element and elements for cooling in frame; *5* — diffuser; *6* — centrifugal fan; *7* — Plexiglas body; *8* — sensor for temperature control; *9* — digital temperature and humidity sensor connected to Arduino controller; *10* — screw thread tube tension system; *11* — straw end caps; *12* — digital tension gauge; *13* — removable unit with moisture absorbing substance; *14* — gas supply system inside the tube, connected by a hose to the bushing in the end cap; *15* — investigated thin-walled tube; *16* — base

— digital tension gauge with USB interface connected to a personal computer;

— digital temperature and humidity sensor controlled by Arduino controller with the ability to connect to a personal computer for data transmission;

— heating and cooling elements;

— fans for airflow and air circulation;

— diffuser with holes for uniform and smooth movement of air inside the stand;

— removable unit with a moisture-absorbing substance;

— tube gas supply system.

To investigate the straw characteristics, end caps are glued to its ends. One straw end cap is connected to a tension gauge rigidly fixed on the base of the bench. The other one is connected to a straw tension system using a screw. The stand has a system of thermal and humidity stabilization maintaining these parameters in a given range. There are used fans and a diffuser with holes between the area of the tube location and the upper part of the stand for uniform and smooth movement of air masses inside the test bench. The above-mentioned stand's units are enclosed in a sealed volume formed by a metal base and a Plexiglas body. In addition, the bench includes a moisture stabilization system, which can be used as a removable element with a moisture-absorbing substance, such as silica gel. The working temperature inside the stand is selected based on the characteristics and nature of the particular measurement. For example, for

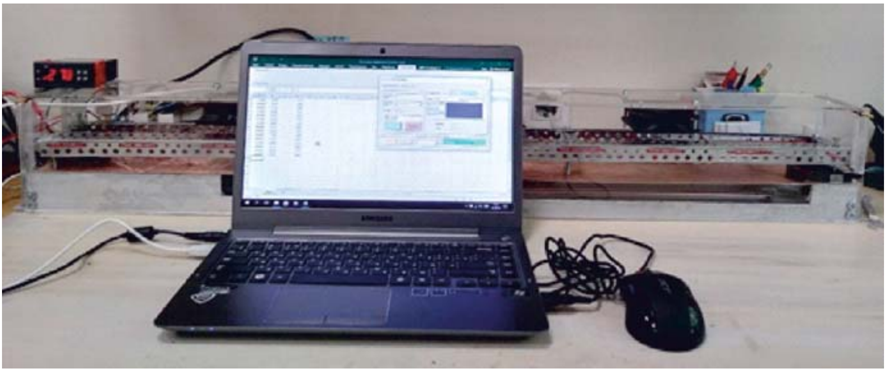

Fig. 2. General view of the bench

short-term measurements, the use of the above-described systems for stabilizing air parameters is not required. For long-term measurements, the stand may include only those systems that stabilize the most critical air parameters for the measurement.

Maintaining a constant temperature inside the bench is carried out using the electronic temperature controller, which is connected to a temperature sensor located inside the stand in the straw area. If the temperature inside the stand deviates from the set point higher or lower than the threshold, one of the controller relays is turned on, and power supplies to the heating or cooling element, respectively. When the temperature reaches the set point again, the corresponding relay is turned off. The digital tension gauge is connected to a personal computer via a USB serial interface. The Microsoft Excel add-in program that is written in Visual Basic and modernized by the authors controls the working parameters of the tension gauge and receiving data. For additional control of temperature and humidity stability, a digital temperature and humidity sensor is placed in the inner area of the stand near the straw. The sensor is connected to the Arduino controller which in turn is connected to the personal computer. The control program for the Arduino controller is written by the authors in C programming language. Figure 2 shows the general view of the bench.

3. TECHNICAL PARAMETERS OF THE BENCH

The test bench includes the following measuring instruments:

• Controller RC-316M, manufactured by Xuzhou Ringder Electrical Equipment Co., LTD [6], used to control the heating element in the form of an insulated carbon conductor;

- Tension gauge FGP-2, manufactured by NIDEC-SHIMPO Instr. [7];
- Arduino Uno R3 controller [8], DHT22 digital temperature and humidity sensor connected to controller [9].

The main parameters of the stand are given in the table. The presence of the tension gauge, the system of thermostabilization and dehumidification, block of screw-thread straw tension, the gas supply system of the tube, — all this makes it possible to measure the characteristics of the tube on the stand with high accuracy. On the test bench it is possible to determine the area of elastic deformation and elastic modulus, for studying the temperature dependence of the elastic modulus, to determine Poisson's ratio, the relaxation time of the straw material tension. The study of the straw properties allows one to choose its tension, providing the required lifetime in the experiment especially when working in vacuum.

The main parameters of the stand

Parameter	Value
Operating temperature inside the bench, °C	12–30
Set temperature error, °C	±0.5
The length of the straw, cm	up to 63
Straw tension, kgf	up to 2
The time of sample interval	Arbitrary; programmable in the add-in
Communication with the computer	USB interface

4. MEASUREMENTS AND DISCUSSION OF RESULTS

The measurements were carried out on welded straws [10] of polyethylene terephthalate $(C_{10}H_8O_4)_n$ with a diameter of 9.8 mm, a wall thickness of 20 μm and one-sided coating of 70 nm thick aluminum. The straws have a cross section of 0.616 mm^2. The film for the straw was produced by Ltd SPE "POLYPLEN". The main characteristics of polyethylene terephthalate are presented in [11, 12].

4.1. Stress-Strain Dependence. Figure 3 shows the experimental dependence of the relative straw deformation ε, which is given by the straw tension force, on the stress σ. This and the following measurements were carried out at a temperature of 23°C, unless otherwise specified. The stress σ was determined after tension relaxation for two minutes. According to this dependence, the areas of elastic and plastic deformation and the elastic modulus of the straw material are determined. A tension gauge measures the tension force with an accuracy of ±1 gf [7]. The longitudinal straw deformation is determined by moving the straw end cap with the screw fixed in it. The movement of the end cap is carried out by rotating the nut with its constant position relative to the side bar, which is rigidly fixed on the base (Fig. 1). One turn of the nut along the M5 threaded

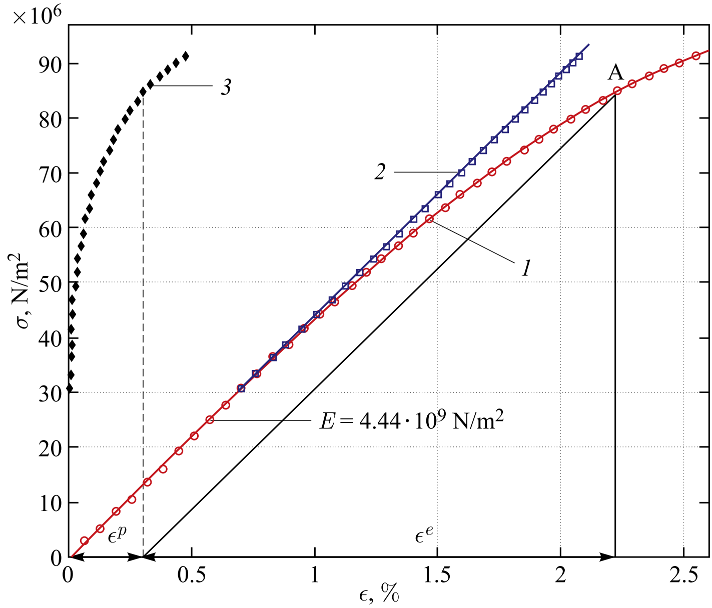

Fig. 3. Areas of elastic and plastic deformation of straw

screw causes the tube elongation by 0.8 mm. Since the nut has six faces, the straw longitudinal deformation can be measured with the nut rotation accuracy of 0.5 face, which corresponds to an elongation error of ± 33 μm, and the relative longitudinal strain error will be less than 0.01%. For most straws used in the detectors, their tension exceeds 1 kgf, so the error introduced by the change in tension does not exceed 0.1%. In Fig. 3 the measurement results are represented by line *1*.

Up to the stress of $30 \cdot 10^6$ N/m^2 the dependence is linear, deformation is elastic and submits to Hooke's law [13–15]. The specified stress value corresponds to a tension of (1850 ± 1) gf and serves as a boundary of the elastic stress region. Exceeding this tension value causes the appearance of a plastic component of deformation, which increases the rate of tension relaxation and straw creep, and dependence becomes nonlinear. An example of determining the value of plastic deformation at point A is shown in Fig. 3, where ε^p and ε^e are respectively relative components of plastic and elastic deformation. Dependence of plastic deformation on stress in Fig. 3 is represented by curve *3*.

For comparison, the line *2* corresponds to elastic deformation only. The modulus of elasticity E is determined in accordance with GOST 9550-81 based on the results of the data obtained in the linear deformation region. It is equal to the slope ratio of the dependence and in this case is $E = (4.44 \pm 0.05) \cdot 10^9$ N/m^2. The accuracy of the elastic modulus measurement of the straw material exceeds the tabular data and, most importantly, its value corresponds to the typical value for the straw material. It is worth considering that the properties of the material can change in the process of straws welding.

4.2. Temperature Dependence of Elasticity Modulus. The results of the study of elasticity modulus in relation to temperature are presented in Fig. 4. The elasticity modulus was defined for the set temperature in linear deformation range in the same way as described above for Fig. 3. In this measurement, the tension value was obtained immediately after straw deformation without taking into account relaxation process.

From the obtained dependence it follows that the modulus value in the temperature range 12–22°C is larger, which causes lower straw deformation and creep. With an increase in temperature, the elasticity modulus decreases linearly with slope $0.025 \cdot 10^9$ N/m$^2 \cdot$ °C. The decrease is caused by thermal phonons in the structure of the material [16, 17]. There is a sharp decrease in the value of the elasticity modulus due to the thermal motion of the conduction electrons in the temperature range 23–28°C. The dependence obtained for this material is similar to that presented in [16]. Taking into account the above dependence, in the experiment straw detector should operate in the specified temperature range of 12–22°C. The behavior of the straw temperature dependence for different materi-

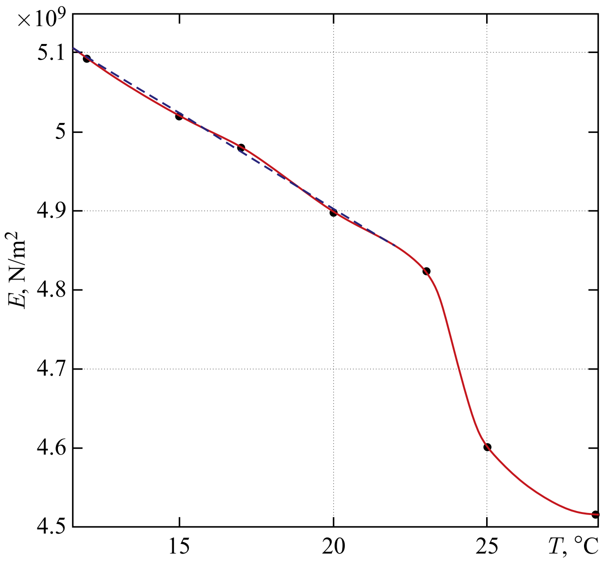

Fig. 4. The temperature dependence of the elastic modulus

als will be similar, but the temperature range and elastic modulus' rate of change will vary. Therefore, this dependence has to be checked in order to select the optimal operating mode.

4.3. Dependence of the Elasticity Modulus on the Straw Wall Thickness. It is worth to note the dependence of the elastic modulus on the straw wall thickness, which is shown in Fig. 5.

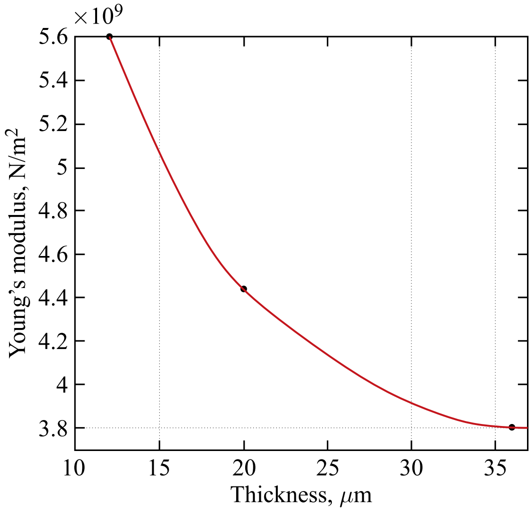

Fig. 5. Dependence of the elastic modulus on the straw wall thickness

The elasticity modulus decreases with increase in the straw thickness. This effect is associated with the film production technology for a straw by the authors. The thin film production technology involves rolling a thicker film between the rollers with smaller gap between them than the initial film thickness. In this case, there is the restructuring of the material fibers in the longitudinal direction and hardening of the material itself under the action of rollers' pressure force, directed perpendicular to the film. These processes will cause a decrease in the straw longitudinal deformation during its tensioning which characterizes a higher value of the elastic modulus. A three times increase in film thickness resulted in a 32% decrease in modulus.

4.4. Overpressure Effect on Straw Wall. Another factor that affects the straw tension during the work in a vacuum is difference of internal and external pressure. The overpressure causes a tangential straw stress that, according to [18], gives a longitudinal component. The value of the longitudinal component depends on the value of Poisson's ratio of the straw material. Its value is determined by the dependence of the changes in the tension gauge readings on the pressure

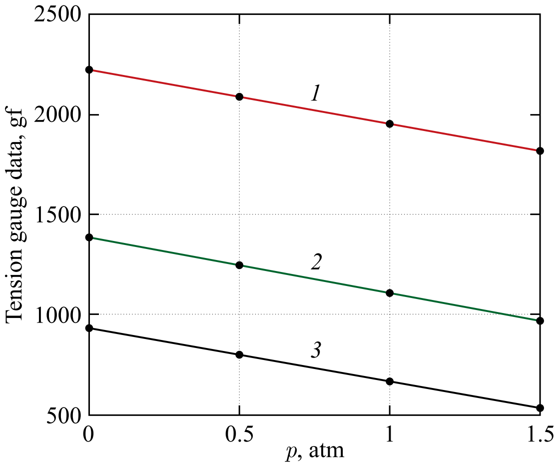

Fig. 6. Dependence of straw tension on overpressure where lines *1*, *2* and *3* correspond to different initial straw tension

value shown in Fig. 6 for different values of the initial straw tension. For the given dependence, it should be taken into account that the tension gauge registers the value of the resultant force, which includes the straw tension force and the pressure force acting on the end surface of the end cap and on the inner straw surface. The pressure force on the end cap reduces the tension gauge readings, and the pressure on the straw leads to an increase in tension and the tension gauge readings. Since the force of pressure on the end surface of the end cap is greater than the force of the tangential stress and lateral force acting on the straw wall, the tension gauge reading decreases with the increase in pressure drop. The result of the overpressure is a (482 ± 1) gf/atm increase in the straw tension [5].

The method of Poisson's ratio calculation is described in [5]. Its value was 0.338 ± 0.004. The error in the calculation is associated with the error in determining the tension gauge and pressure sensor readings.

4.5. The Stress Relaxation of the Straw. The tension of straw with fixed length is influenced by relaxation. Stress relaxation (tension relaxation) is a process of decreasing the stress inside the material and its tension under constant length, i.e., constant total strain. Therefore, it is important to ensure the initial tension at which the cylindrical shape and the required accuracy of event registration remain for a long time. This is a long-term study with continuous data acquisition. Only the heating system was included in the system for stabilizing air parameters, the cooling system as well as the unit with moisture absorbing substance were not implemented. The temperature inside the test bench was $+27°$C, to ensure that it exceeds the room temperature by 2–5°C throughout the entire year. Tension data acquisition occurs automatically and with an adjustable time interval in the control add-in. Also, the humidity value is received from the Arduino controller synchronously to monitor this parameter.

Figure 7 shows straw tension relaxation at an early stage, the time interval is 15 min. During this period, humidity and temperature remain almost constant and the relaxation process is under the same conditions. In the first two minutes, there is a sharp drop in tension by 1.6%, then the relaxation rate decreases.

Figure 8 presents data on stress relaxation for 150 days.

There are two main processes of the relaxation: physical and chemical relaxation. At the stage of physical relaxation, the rearrangement of the molecular and supramolecular structure of the material occurs, and the stage of chemical relaxation involves the rearrangement of chemical bonds within the material. The first process represents the fast component of relaxation, and the second one

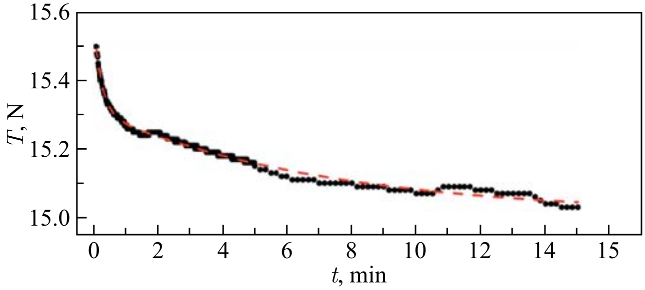

Fig. 7. Tension relaxation at the initial stage

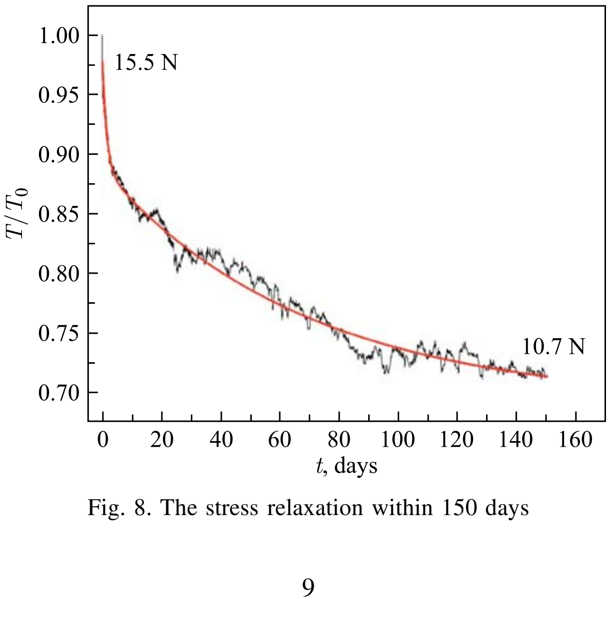

Fig. 8. The stress relaxation within 150 days

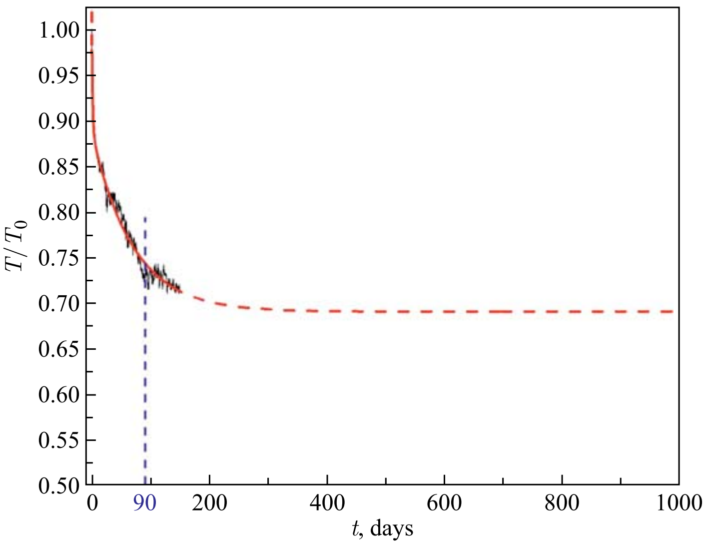

Fig. 9. Long-term stress relaxation

represents the slow one. In this regard, the double exponential function with a free term was selected from a number of approximating functions (Fig. 8). The use of this function gives the most accurate approximation of the experimental data and takes into account the fact of a sharp decreasing in the relaxation rate, starting from the 90th day (Fig. 9). Exponential terms describe the fast and slow relaxation process with time constants $\tau_1 = 1.45$ days and $\tau_2 = 68.9$ days. The long-term data extrapolation up to 1000 days is shown in Fig. 9. An important fact that the authors considered for the first time for welded straws is the presence of semi-permanent residual tension on the time scale of a typical tracker lifetime. In the long time interval, the straw tension does not fall to zero, but continues to relax with an extremely large time constant, which allows disregarding the residual relaxation.

The value of residual tension during long-term relaxation $T_{\rm res}$ is described by the expression

$$T_{\rm res} = (T_0 + T_v \cdot P) K_{\rm relax},$$

where T_0 is the initial tension in gram-forces, T_v is the increase in straw tension in vacuum, equal to 482 gf/atm, P is the pressure inside the straw in atm, $K_{\rm relax}$ is the relaxation coefficient. The study of tension relaxation at atmospheric pressure allows one to determine the relaxation coefficient $K_{\rm relax} = T_{\rm res}/T_0 \cong 0.69$. Within 150 days the tension decreased from 15.5 to 10.7 N. The presence of the semi-permanent residual tension term allows one to choose the optimal initial straw tension for operation in a vacuum by the formula

$$T_0^{\rm opt} = T_{\rm res}^{\rm req}/K_{\rm relax} - T_v \cdot P,$$

where $T_0^{\rm opt}$ is the optimal initial straw tension, $T_{\rm res}^{\rm req}$ is the residual straw tension, providing the required coordinate resolution. For example, the tension of the straw with a force $T_0 = 1.23$ kgf will ensure its long-term operation in a vacuum with almost constant tension. The tension relaxation during the detector assembly will be compensated by the increase of tension in vacuum, which in 7–8 months will be stabilized at the level of 1.2 kgf. The stage of fast relaxation component ends in 90–110 days (Fig. 9).

5. SUMMARY

• The test bench for studying the characteristics of thin-walled tubes has been developed. The stand has been tested in the study of polyethylene terephthalate straw properties with a diameter of 9.8 mm and a wall thickness of 20 μm.

• The area of elastic deformation, which is limited by the upper tension value of $30 \cdot 10^6$ N/m^2, has been determined. In the range of elastic deformation, relaxation and creep of the straw material are minimal. The value of the elasticity modulus of the straw material of $(4.44 \pm 0.05) \cdot 10^9$ N/m^2 has been determined too.

• The dependence of the elasticity modulus on temperature has been studied and the temperature regime of 12–22°C is recommended for straw operation in the experiments. In this range, the value of the elasticity modulus is maximum. With increasing temperature, the magnitude of the elastic modulus decreases proportionately to $0.025 \cdot 10^9$ N/m$^2 \cdot$°C.

• The value of Poisson's ratio of 0.338 ± 0.004 has been determined. This value is required to take into account the straw tension increase by (482 ± 1) gf/atm due to overpressure when operating in vacuum.

• The dependence of stress relaxation on time has been investigated. The presence of a semi-permanent component of tension during its relaxation on the time scale of a typical tracker lifetime for strained welded straws is shown for the first time. The obtained value of the stress relaxation coefficient is 0.69. The tension relaxation function which contains two exponentials terms with constants $\tau_1 = 1.45$ days and $\tau_2 = 68.9$ days has been defined. When the tension is relaxed for more than 8 months, straw tension decreases with such a low speed that the residual relaxation can be disregarded.

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