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EXPERIMENTAL STUDIES ON THE DYNAMICS OF THE MOVEMENT OF CLEANING PIGS THROUGH TEE PIPE FITTINGS

STETSIUK Serhii[1], BONDARENKO Robert[1], DOROSHENKO Yaroslav[1*], HOLUBENKO Viacheslav[2]

[1] *Department of transportation and storage of energy carriers, Institute of Petroleum Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska 15, 76019 Ivano-Frankivsk, Ukraine, e – mail: yaroslav.doroshenko@nung.edu.ua*
[2] *Joint stock company «Ukrgasvydobuvannya», Kudriavska 26/28, 04053 Kyiv, Ukraine*

Abstract: Experimental setups using steel and transparent glass pipes, along with equally spaced steel stamped and transparent plastic tees, were designed for testing. The experimental results provided insights into the influence of flow directions, pig length, material properties, and air consumption on the dynamics and strength of the pigs within the tees. Furthermore, the study identified the causes of temporary halting, jamming, and the mechanisms of damage to cylindrical pigs made of hyperelastic materials within pipeline tees.

KEYWORDS: Gas pipeline, cleaning pig, hyperelastic material, tee, dynamics of movement, jamming.

1 Introduction

The current energy crisis in Ukraine demands attention to various aspects and issues concerning the maintenance of pipeline systems used for energy transportation. Technical solutions are needed to reduce energy consumption during transportation, minimize losses of energy carriers during transit, and increase recovered gas volumes.

One of the most significant factors influencing energy consumption, technical condition of pipeline systems, and energy transportation volumes is the accumulation of liquid and solid deposits within the internal cavities of pipelines with diverse purposes.

At present, most hydrocarbon fields in Ukraine are depleted and nearing the final stage of development. During this stage, a considerable amount of formation water and hydrocarbon condensate is produced alongside the gas flow [1-3], leading to the accumulation of liquid contaminants in low points of gas gathering and processing pipeline systems. These accumulations pose substantial hydraulic resistance, resulting in increased pressure losses, reduced pipeline capacity, and decreased the recovery of hydrocarbon volumes. [4]

Moreover, the accumulation of liquid contaminants within the internal cavities of gas pipelines can lead to erosive wear of fittings [5], internal corrosion processes, that prolonged operation reduces the parameters of resistance to fatigue and prolonged static loading in corrosive environments [6]. Corrosion processes are accompanied by significant losses of the transported product [7]. During the autumn-winter period, the presence of liquid in the gas causes the formation of hydrates. Hydrates can form not only in straight sections of gas pipelines but also in low points, bends, tees, valves, and other equipment. The formation of hydrates leads to a reduction in the pipeline's cross-sectional area and flow rate from wells, and in some cases, complete blockage of the pipeline, making it impossible to inject methanol for dissolution. [8, 9]

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In oil pipelines, paraffin deposits are formed on the inner wall, reducing the cross-sectional area of the pipe and increasing hydraulic resistance. As a result, the pipeline's capacity is decreased, and energy consumption for oil transportation is increased [10].

In gas pipelines serving residential areas and operating for many years, deposits of detached pipe scale, internal corrosion products, condensate, water, methanol, and others accumulate within the internal cavity. The primary contaminants found in the internal cavities of heat supply pipelines in residential areas include internal corrosion products, sludge deposits, mineral impurities, sand, soil, and more. The accumulation of contaminants in pipeline networks leads to increased hydraulic resistance of pipelines and, consequently, higher energy consumption for transportation. The hydraulic resistance of heat supply pipelines due to the buildup of contaminants can increase several times compared to its initial state, resulting in a substantial rise in electricity consumption for transportation.

2 Literature review

To reduce energy consumption during transportation and increase gas recovery, it is essential to enhance the hydraulic efficiency of pipelines by periodically cleaning their internal cavities from accumulated contaminants. Various methods are employed for this purpose, including devices for liquid drainage, surfactant application, creation of high-velocity gas flow, and the use of different types of cleaning pigs [11, 12]. Each method has its advantages and drawbacks, and the most favorable approaches are those that minimize energy losses and environmental pollution. Additionally, cost-effective pipeline cleaning must be ensured.

Effective cleaning of pipelines with minimal product losses and environmental contamination can be achieved using cleaning pigs. These pigs are not only efficiently applied during operation but also utilized during pipeline construction for debris and other construction waste removal [8], as well as sequential transfer of various oil grades [13].

The planning and application of cleaning pigs are often complicated due to the diverse configurations of gas gathering networks, gas fields, and heat supply systems. These pipeline systems are branched networks that contain numerous fittings such as bends, various tees (stamped and welded), reducers, and collectors with different internal geometries. Additionally, the flow direction changes within these fittings, leading to complex flow patterns [14, 15]. Such factors contribute to the unpredictability of pig application, increase the risk of pig jamming [16, 17], reduce their universality, and require an individualized approach to cleaning each pipeline. Pig jamming within a pipeline leads to significant costs associated with product transportation interruption, pipeline depressurization, pig retrieval, and may jeopardize transportation safety [18]. In some cases, pig jamming can also result in pipeline damage.

Research on the dynamics of pig movement through pipeline bends has been conducted, mainly through experimental studies, theoretical calculations, and numerical simulations. Studies have established the laws governing pig velocity and acceleration in bends [19, 20], determined the forces acting on pigs during this process [21, 22], and analyzed the stress state of pig seals during their passage through bends [23].

However, the physical processes governing pig movement within the internal cavities of pipeline tees have not been adequately studied and documented due to their dependence on numerous factors. These factors include the geometry of the tees, flow directions through the tees, gas dynamic processes resulting from flow direction changes, uneven compression of the pig against the walls, affecting the friction coefficient, and more. Moreover, pigs can be made of various materials and have different shapes and lengths [11], further influencing their behavior.

Tees can have various flow directions, such as:

- flow entering from both sides of the tee and exiting through its branch;
- flow entering through the branch and one side of the mainline tee and exiting from the other side of the mainline;
- flow entering through the mainline tee and completely passing through its branch;
- flow entering through the branch of the tee and completely passing through one side of the mainline.

For each of these flow directions through tees, little information is available regarding pig movement patterns. Excessive bending of pigs within tees can lead to their stoppage, jamming, and damage. The blockage of a hyperelastic pig within a tee can result in increased pressure behind it, leading to pig destruction or dislodgment, causing it to attain high velocities, posing additional risks [11].

The lack of information on pig movement patterns through tees complicates planning, analysis, and route determination, creating numerous uncertainties and hindering reliable assessments of a pipeline's suitability for pig application. Consequently, comprehensive research on the dynamics of pig movement through tees is necessary to enable more confident pig usage, route planning, and practical implementation.

3 Manufacturing of cleaning pigs

Due to the directional flow changes in many tees of diverse pipeline systems, the pigs experience excessive bending and pressing against the walls. The physical and mechanical characteristics of the material used to manufacture the pigs significantly influence their dynamics within the tee. Different materials employed for making cleaning pigs exhibit varying density, elastic, and strength properties. If the pig is made from an inadequately chosen material, it may get stuck, block the pipeline, incur damage, or even break apart. Therefore, selecting the appropriate material for manufacturing cleaning pigs is of utmost importance. The pig's material should be capable of undergoing significant deformation under load without altering its volume and promptly returning to its original shape after removing the loads. Additionally, the pig's material must be sufficiently strong to withstand all applied forces.

For experimental investigations, the pigs were manufactured as solid cylinders using silicone sealant with a density of 1020 kg/m³ (Fig. 1, a), silicone compound with a density of 1450 kg/m³ (Fig. 1, b), self-destructive elastic polymer composition with a density of 1180 kg/m³ (Fig. 1, c), and polyurethane foam with a density of 150-160 kg/m³ coated with

a) b) c) d)

Fig. 1 Cleaning pigs for pipeline: a) – pig made from silicone sealant; b) – pig made from silicone compound; c) – pigs made from self-destructive elastic polymer composition; d) – pig made from polyurethane foam coated with urethane

urethane (Fig. 1, d).

The experimental values of bending and tensile modulus of elasticity for each pig's material used in the study are provided in Tab. 1.

Tab. 1 Modulus of elasticity for bending and tensile of materials used for pigs manufacturing

Material	Modulus of elasticity for bending, Pa	Tensile modulus of elasticity, Pa
Polyurethane foam	$4.0 \cdot 10^6$	$1.2 \cdot 10^6$
Elastic polymer composition	$5.0 \cdot 10^3$	$1.3 \cdot 10^3$
Silicone sealant	$1.0 \cdot 10^3$	$0.2 \cdot 10^3$
Silicone compound	$0.6 \cdot 10^6$	$0.3 \cdot 10^6$

4 Manufacturing of cleaning pigs

The dynamics of pig motion within pipeline tees is complex and depends on various factors. The best way to determine the patterns of pig movement within pipeline tees and investigate their dynamics is through laboratory experiments. For this purpose, one steel stamped equal tee (Fig. 2, a) with an internal diameter of 47 mm and two plastic equal tees (Fig. 2, b) with internal diameters of 39 mm and 47 mm were selected. The plastic tees are designed similarly to the steel welded tees found in various pipeline systems. The advantage of using transparent plastic tees is the possibility of visually observing the pig motion dynamics.

a) b)

Fig. 2 Tees: a) – steel; b) – plastic

For experimental investigations, experimental setups were developed and assembled using both steel and glass pipes. The stamped equal tee was mounted on the steel pipeline (Fig. 3, a), while the plastic tee was mounted on both the steel (Fig. 3, b) and glass pipelines (Fig. 3, c). To quickly assemble and disassemble the tees to the pipes, they were connected with strong adhesive tape, and for enhanced strength of the connections, reinforced adhesive tape was used.

The research was conducted for various flow directions through the tees. To achieve this, the locations of air intake and release were changed, and additional pipes were attached to the tees for blocking purposes. During the motion of the pigs within the tees, the process was recorded using video recording.

Fig. 3 Mounted tees: a) – stamped on a steel pipeline; b) – plastic on a steel pipeline; c) – plastic on a glass pipeline

The experimental setup for investigating the dynamics of pig motion within tees, where the flow enters the main part of the tee from both sides and exits through its branch (Fig. 4), consists of a tee 9 to which three steel pipes 6, 7, 8 with an inner diameter of 47 mm are connected. A launching chamber 4 for the pigs 5 is attached to pipe 6. Air from the compressors 1 is supplied to pipes 6 and 7 and exits through pipe 8.

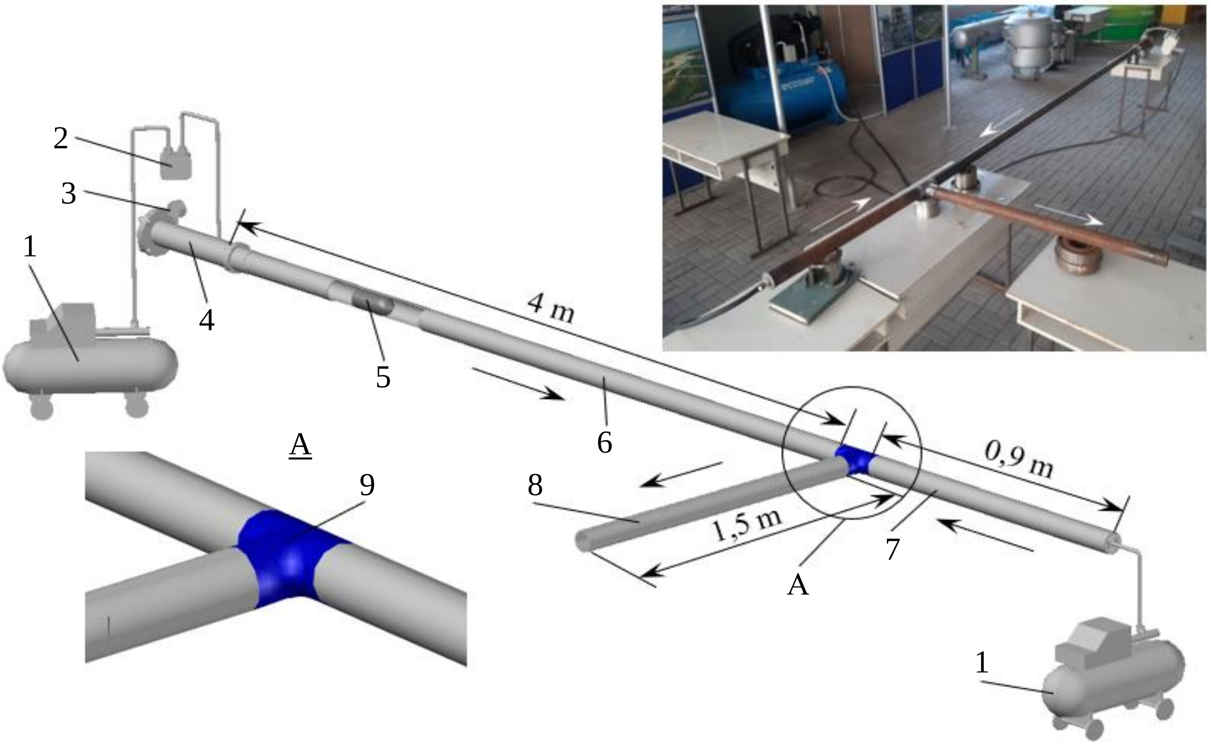

Fig. 4 Experimental setup for studying the dynamics of the movement of pigs through a tee (the flow from two sides enters the main tee and exits from its branch): 1 – compressor; 2 – counter; 3 – manometer; 4 – chamber for launching pigs; 5 – pig; 6, 7, 8 – pipe; 9 – tee

Additionally, an experimental setup has been developed and assembled to investigate the dynamics of pig motion within tees, where the flow enters the branch of the tee and one side of its main part and exits from the other side of the main part (Fig. 5). Air from the compressors is supplied to pipes 7 and 8 and exits through pipe 6.

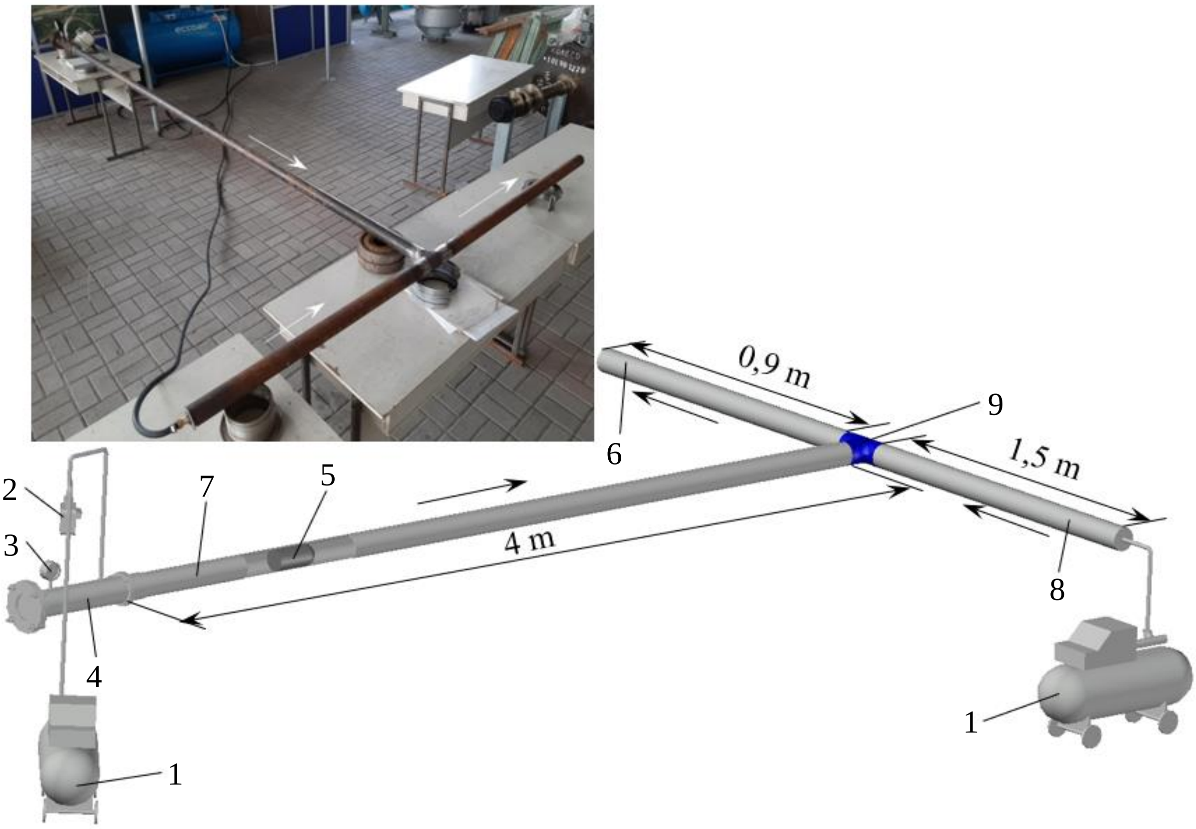

Fig. 5 Experimental setup for studying the dynamics of pig movement (the flow enters the branch of the tee and one side of its main line and exits from the other side of the main line): 1 – compressor; 2 – counter; 3 – manometer; 4 – chamber for launching pigs; 5 – pig; 6, 7, 8 – pipe; 9 – tee

In order to allow the flow to pass only from the branch of the tee to one side of its main part or vice versa, one of the pipes connected to the tee is sealed off using a plug. For instance, in the experimental setup where the flow enters the branch of the tee and entirely passes to one side of its main part (Fig. 6), pipe 8, which is connected to the other side of the tee's main part, is sealed off with plug 10. Air from the compressor 1 is supplied to pipe 6 and exits through pipe 7.

In the experimental setup, where the flow enters one side of the main pipeline's tee and fully flows into its branch (Fig. 7), pipe 7, which is connected to the second side of the main pipeline's tee 9, is sealed off with plug 10. Air from compressor 1 is supplied to pipe 6 and exits from pipe 8.

Similar experimental setups were also assembled using glass pipes with a transparent plastic tee. One of these setups, featuring glass pipes and a transparent plastic tee, where the flow enters the branch and one side of the main pipeline and exits from the second side of the main pipeline, is shown in Fig. 8.

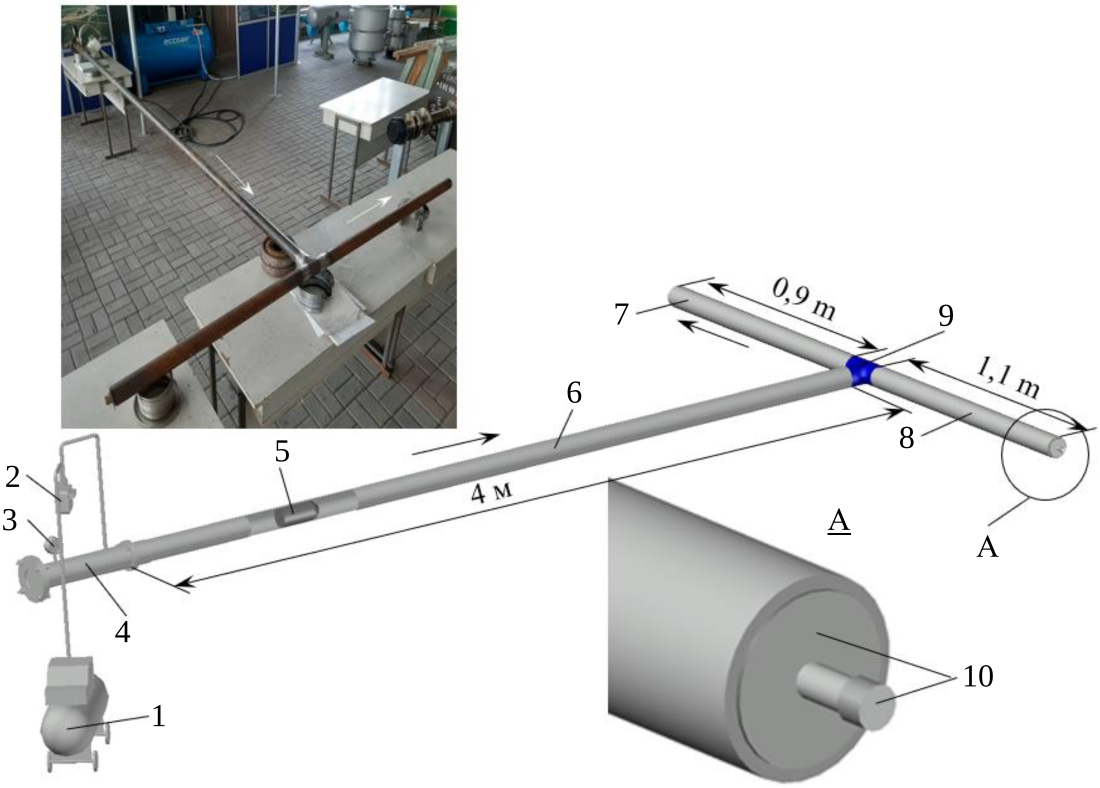

Fig. 6 Experimental setup for researching the dynamics of the movement of pigs through a tee (the flow enters the branch of the tee and completely flows into one of the sides of its trunk): 1 – compressor; 2 – counter; 3 – manometer; 4 – chamber for launching pigs; 5 – pig; 6, 7, 8 – pipe; 9 – tee; 10 – plug

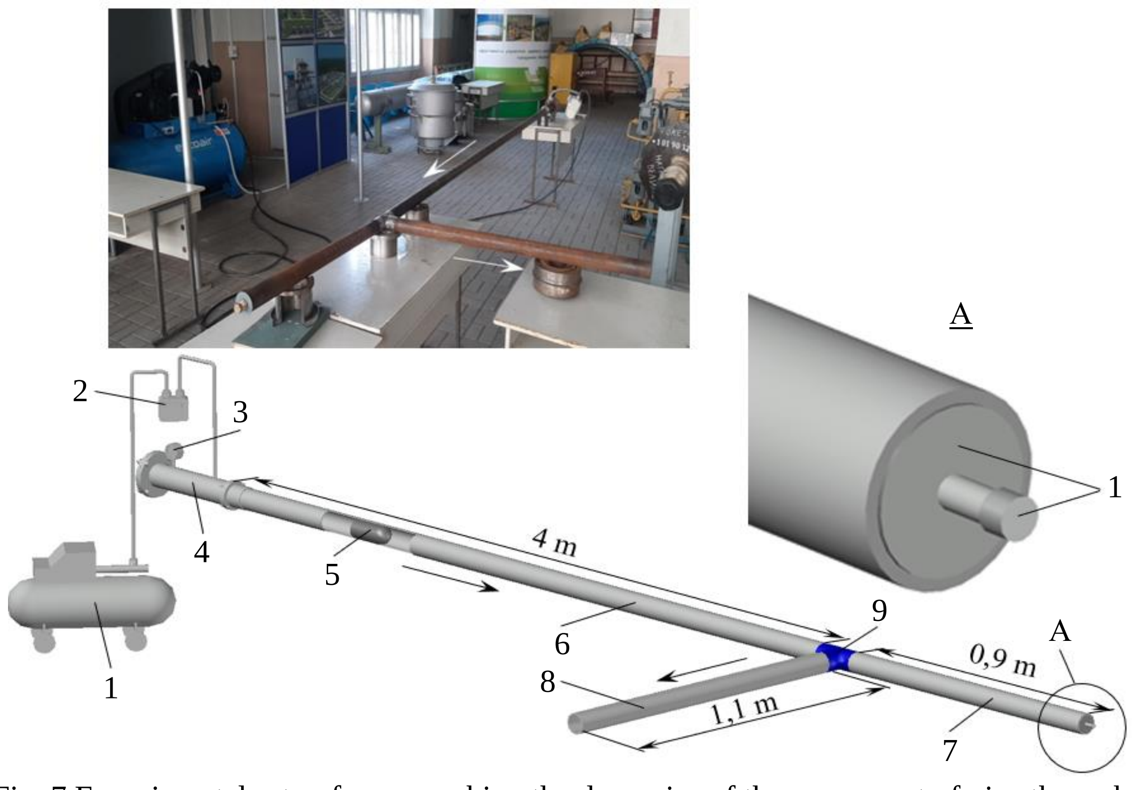

Fig. 7 Experimental setup for researching the dynamics of the movement of pigs through a tee (the flow enters one of the sides of the main tee and flows completely into its branch): 1 – compressor; 2 – counter; 3 – manometer; 4 – chamber for launching pigs; 5 – pig; 6, 7, 8 –pipe; 9 – tee; 10 – plug

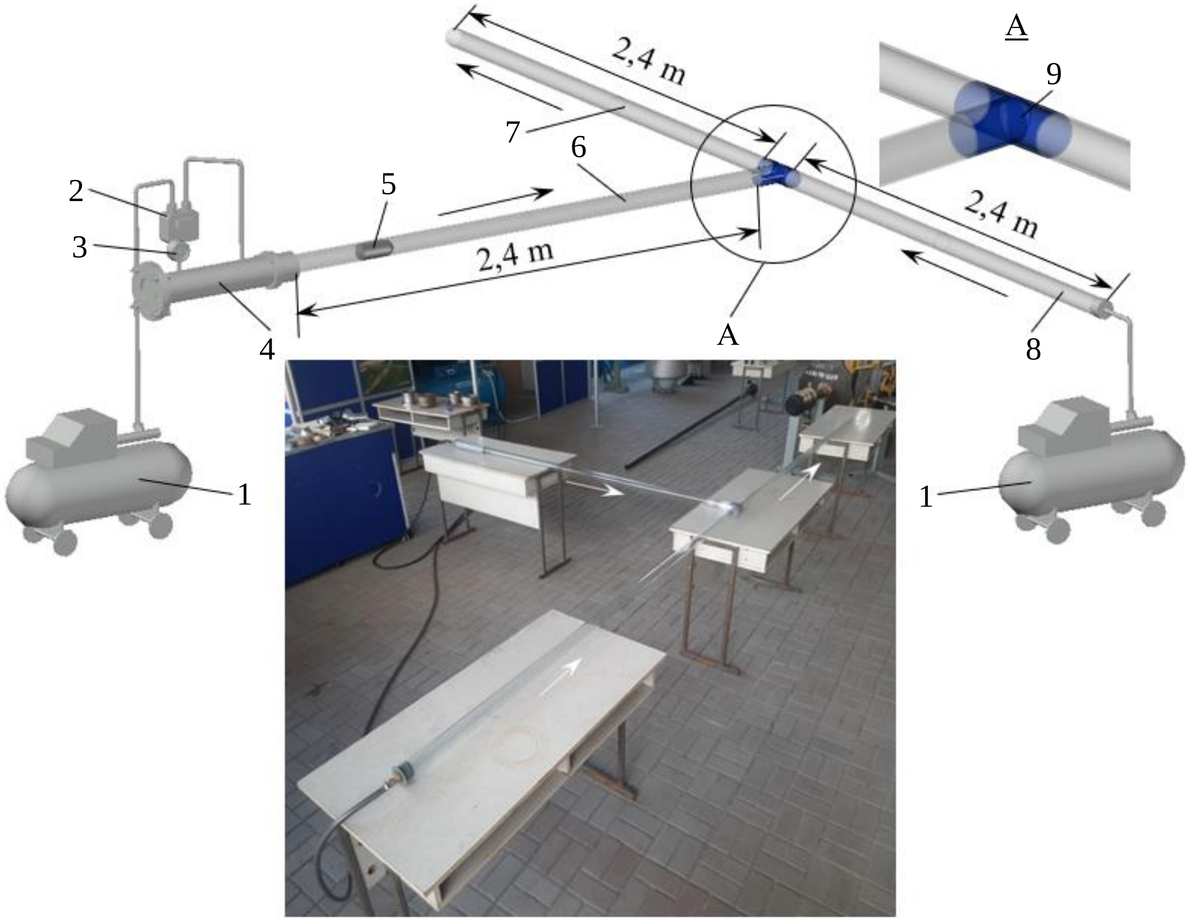

Fig. 8 Experimental setup for studying the dynamics of pig movement through a transparent plastic tee (the flow enters the branch of the tee and one side of its main line and exits from the other side of the main line): 1 – compressor; 2 – counter; 3 – manometer; 4 – chamber for launching pigs; 5 – pig; 6, 7, 8 – pipe; 9 – transparent plastic tee

5 Results

During the experimental investigations, in all examined flow directions using stamped steel and plastic tees, the pigs moved along with the flow.

No failures or damages were observed in the pigs made from the silicone compound, which possesses the highest flexural modulus (Tab. 1), while passing through the tees. However, pigs made from the elastic-polymer composition, silicone sealant, and low-density polyurethane foam, which have the lowest flexural modulus (Tab. 1), developed transverse cracks when passing through tees where the flow crossed between the main pipeline and the branch (Fig. 9). Specifically, in pigs made from the elastic-polymer composition, transverse cracks appeared after two to three passes through the tee, whereas pigs made from the silicone sealant exhibited such cracks after more than ten passes.

As for the dynamics of pigs made from hyperelastic materials passing through pipeline tees, numerous physical phenomena occur within the tees, which can be described by corresponding theories. To provide an accurate description, a significant number of laboratory experimental investigations have been conducted.

When the flow enters the tee's branch and one side of its main pipeline while exiting from the second side of the main pipeline (Fig. 5), the pig entering the tee's branch undergoes deformation within the tee, following the direction of the flow exiting from it (Fig. 10), as illustrated in the scheme presented in Fig. 11.

a) b)

Fig. 9 Transverse cracks in the pigs after they pass through the tees: a) – a pig made of an elastic polymer composition; b) – a pig made of silicone sealant

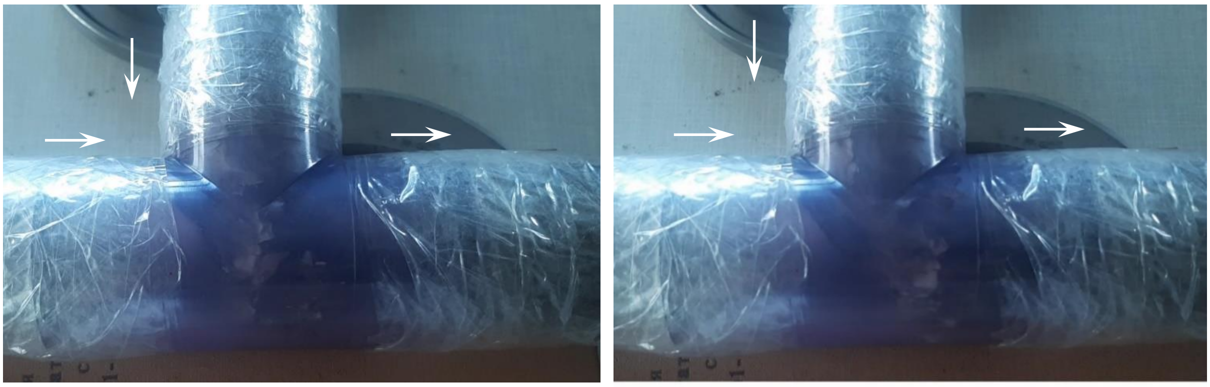

Fig. 10 The movement of the pig through a tee, in which the flow enters the branch and one side of the main line and leaves the other side of the main line, and the pig enters the branch

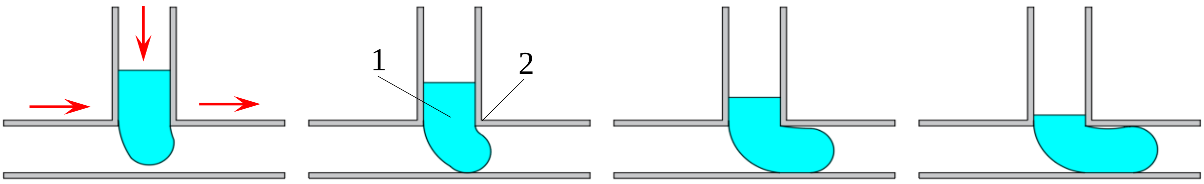

Fig. 11 Scheme of the movement of the pig through the tee, in which the flow enters the branch and one side of the main line and leaves the other side of the main line, and the pig enters the branch: 1 – pig; 2 – a tee

If both the flow and pig enter the tee's branch, with the flow completely passing through one side of the main pipeline (Fig. 6), the dynamics of the pig depend on the flexural modulus of the material from which it is made. If the flexural modulus is high (silicone compound, polyurethane foam (Tab. 1)), the pig within the tee undergoes deformation towards the direction of the flow exiting from it, following the scheme illustrated in Fig. 12. Notably, unlike the previous case (Fig. 11), the deformation of the pig occurs only after its front part exits the branch into the main pipeline of the tee and, while moving linearly, impacts the inner wall of the main pipeline opposite the branch (Fig. 12).

If the flexural modulus of the material from which the pig is made is low (silicone sealant, elastic-polymer composition (Tab. 1)), the pig within the tee undergoes deformation towards the direction of the flow exiting from it (Fig. 13), following the scheme illustrated in Fig. 14. After the front part of the pig exits the branch into the main pipeline of the tee and impacts the inner wall of the main pipeline opposite the branch, the pig undergoes deformation in its middle section. As the pig continues moving along the main pipeline of the tee, its front part starts to deform, gradually assuming a more cylindrical shape.

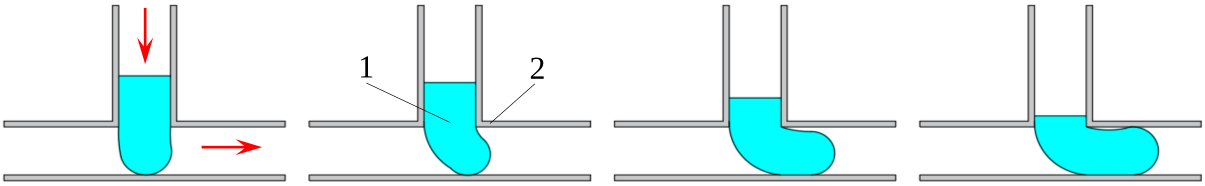

Fig. 12 Scheme of the movement of the pig through the tee, in which the flow and the pig enter the branch of the tee, and exit to one of the sides of its trunk (the modulus of elasticity for bending of the material from which the pig is made is large): 1 – pig; 2 – a tee

Fig. 13 The movement of the pig through the tee, in which the flow and the pig enter the branch of the tee, and exit to one of the sides of its trunk (the modulus of elasticity for bending of the material from which the pig is made is small)

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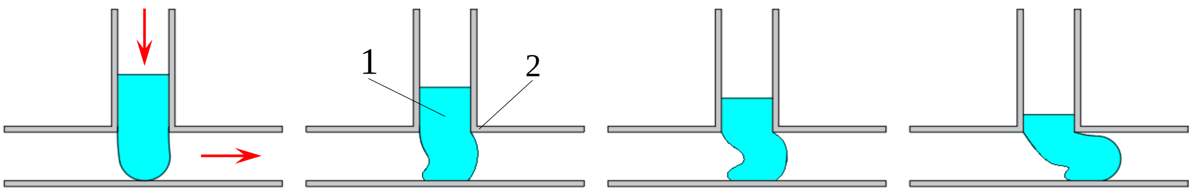

Fig. 14 Scheme of the movement of the pig through the tee, in which the flow and the pig enter the branch of the tee, and exit to one of the sides of its trunk (modulus of elasticity for bending of the material from which the pig is made is small): 1 – pig; 2 – a tee

If the flow enters the tee line from two sides and exits from its branch (Fig. 4), and the pig enters the tee from one side of the line, the pattern of pig movement depends on the amount of air flow that enters the tee line from the side opposite to the direction of pig movement. If this flow rate is large (more than 1.5 times the flow rate in which the pig moves), then the pig bends in the tee in the direction of branching (Fig. 15) according to the scheme shown in Fig. 16.

If the flow of air entering the tee line from the side opposite to the direction of the pig movement is small, then the dynamics of the pig movement depends on the length of the pig. If the length of the pig is up to 2·DN (DN is the conventional diameter of the pipeline), then it moves in the tee according to the diagram shown in Fig. 17. The pig in this case does not bend into a branch (as shown in the diagram shown in Fig. 16) but continues to move by inertia the trunk of the tee until its rear part is opposite the branch. Then it stops and the rear part of the pig bends into a branch. After such a distortion, the pig begins to move and go out into the branch of the tee. In this case, after the pig leaves the tee, its rear part becomes the front part, and vice versa, the front part becomes the rear part (Fig. 18).

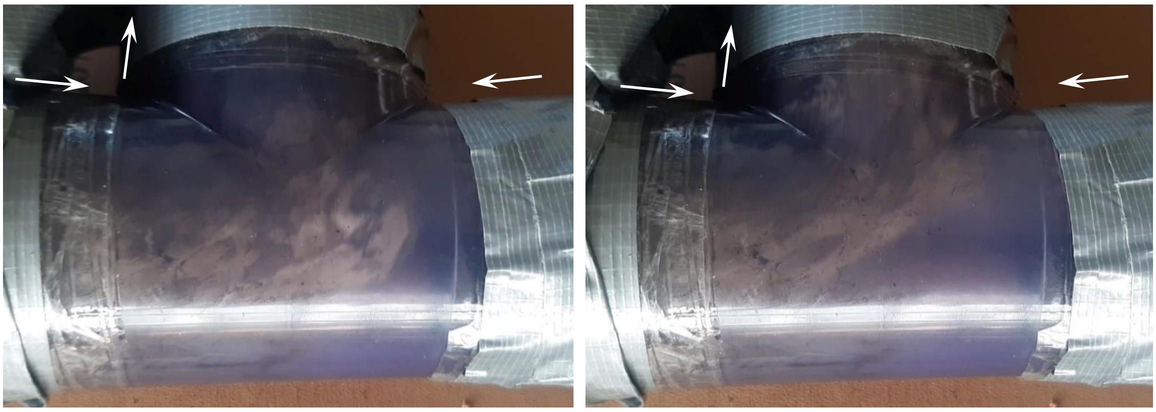

Fig. 15 The movement of the pig through the tee, in which the flow from two sides enters the tee main and leaves its branch (the pig enters the tee from one side of the main, and the flow of air entering the tee main from the opposite side is large)

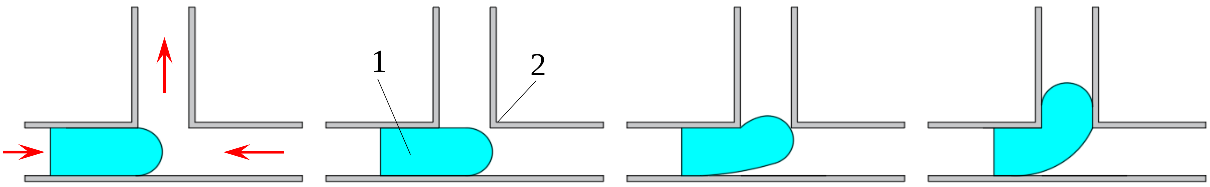

Fig. 16 Scheme of the movement of the pig through the tee, in which the flow from two sides enters the main tee and exits from its branch (the pig enters the tee from one side of the main, and the flow of air entering the main of the tee from the opposite side is large): 1 – pig; 2 – a tee

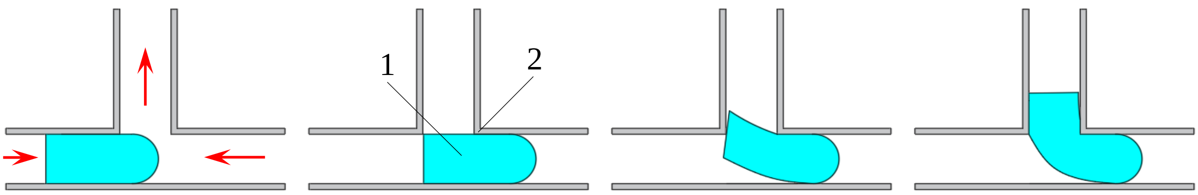

Fig. 17 Scheme of the movement of the pig through the tee, in which the flow from two sides enters the tee main and leaves its branch (the pig enters the tee from one side of the main, and the flow of air entering the tee main from the side opposite to the direction of the movement of the pig and pig length is small): 1 – pig; 2 – a tee

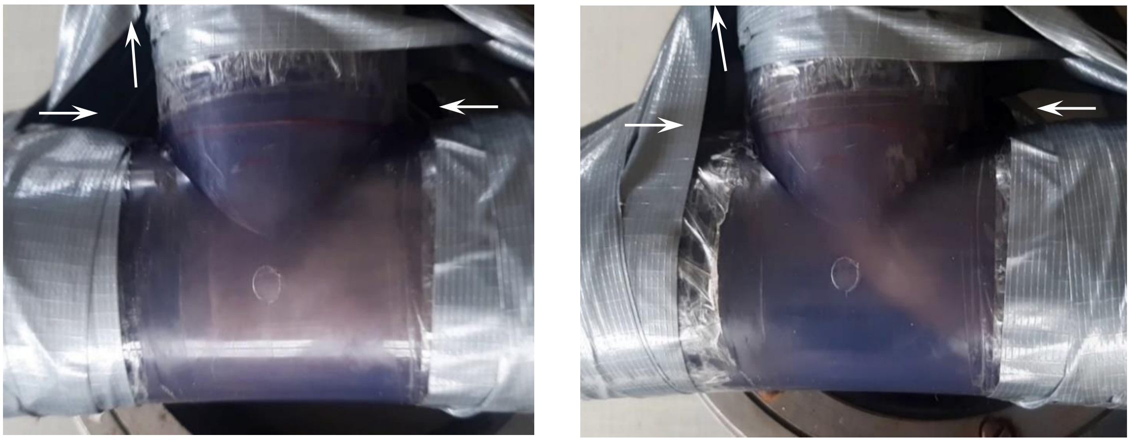

Fig. 18 The movement of the pig through the tee, in which the flow from two sides enters the tee main and leaves its branch (the pig enters the tee from one side of the main, and the flow of air entering the tee main from the side opposite to the direction of pig movement and the length small pig)

If the length of the pig exceeds 2·DN (where DN represents the diameter of the tee), it moves according to the scheme depicted in Fig. 19. In this case, the pig comes to a stop within the main pipeline of the tee, with its middle section positioned opposite the branch. Subsequently, the flow begins to force the middle section of the pig into the branch (Fig. 20). As a result, either the rear or front part of the pig extrudes into the branch, initiating its movement into the branch. If the rear part of the pig is extruded into the branch, during its further movement, it becomes the front part, and vice versa.

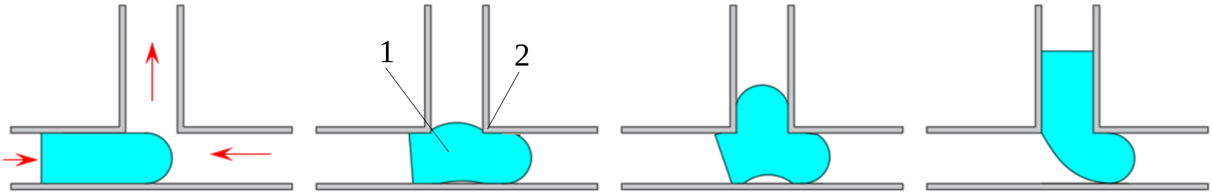

Fig. 19 Scheme of the movement of the pig through the tee, in which the flow from two sides enters the tee main and leaves its branch, and the pig enters the tee from one side of the main (the air consumption that enters the tee main from the side opposite to the direction of pig movement is small, and the length of the pig is long): 1 – pig; 2 – a tee

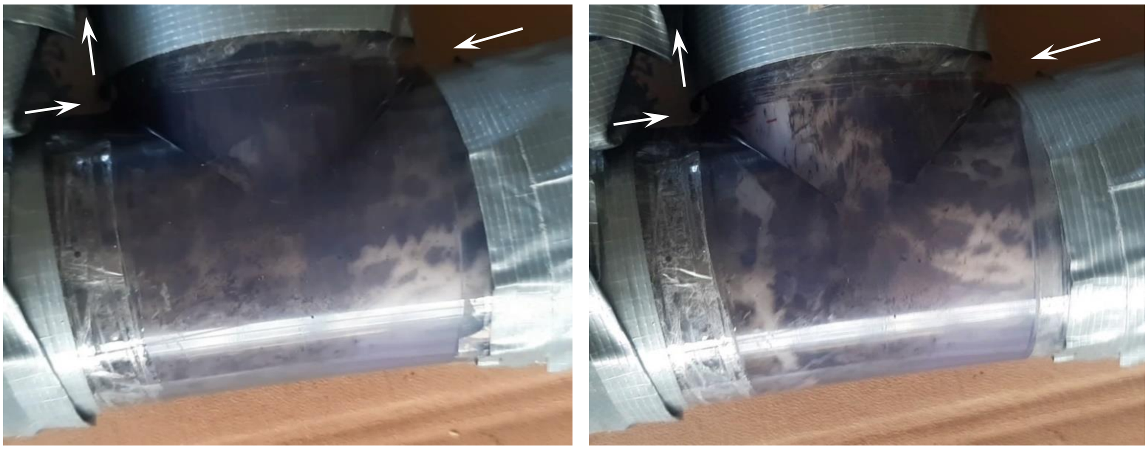

Fig. 20 The movement of the pig through the tee, in which the flow from two sides enters the tee main and leaves its branch, and the pig enters the tee from one side of the main (the air consumption that enters the tee main from the side opposite to the direction of pig movement is small, and the length of the pig is long)

If the flow, along with the pig, enters the main pipeline of the tee from one side, with the flow completely passing into the branch (Fig. 7), the pig does not undergo deformation and moves along with the flow into the branch of the tee. However, due to inertia, it continues to move along the main pipeline of the tee until its rear part aligns with the branch (Fig. 21). At this point, the pig comes to a stop, and its rear part undergoes deformation as it enters the branch. Following this deformation, the pig resumes movement and exits into the branch of the tee. In this scenario, after the pig exits the tee, its rear part becomes the front part, and vice versa, due to the change in direction.

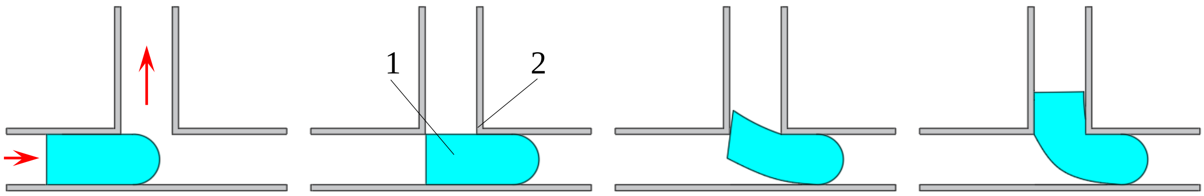

Fig. 21 Scheme of the movement of the pig through the tee, in which the flow and the pig enter the main tee from one side and leave the branch: 1 – pig; 2 – a tee

During the experimental investigations, the movement of pigs made from hyperelastic materials in the tees was slowed down and, in some cases, completely halted due to significant frictional forces resulting from the deformation (bending) of the pig and the emergence of substantial contact forces. The tees with the highest density hyperelastic pigs exhibited the best performance. However, there were isolated instances of jamming and temporary stoppage of pigs made from elastic-polymer composition, silicone sealant, and silicone compound in the tees. Additionally, pigs made from polyurethane foam, having the lowest density and consequently experiencing less inertia, temporarily halted and resumed movement under certain conditions and sometimes became stuck in the tees. As the movement speed decreased, the magnitude of air passing through the pig, and the length of the pig increased, the ability of pigs made from polyurethane foam to pass through the tees diminished.

CONCLUSION

The conducted experiments have revealed that cylindrical pigs made of hyperelastic materials move in the direction of the flow in stamped and welded tees of pipeline systems. However, no damages or disruptions were observed in pigs made of silicone compound, which has the highest flexural modulus. On the other hand, pigs made of low-density elastic-polymer composition, silicone sealant, and low-density polyurethane, which have the lowest flexural modulus, developed transverse cracks during their passage through tees where the flow from the mainline was directed into the branch, or vice versa. In elastic-polymer composition pigs, transverse cracks appeared after two to three passages through the tee, while in silicone sealant pigs, it took more than ten passages for such cracks to occur.

The dynamics of pigs made of hyperelastic materials in tee configurations are influenced by numerous factors, including the flow direction in the tee, the density and flexural modulus of the pig material, the length of the pig, and the transported product flow rate.

An interesting observation is that in tees where the flow enters the tee from both sides and exits through the branch, and the pig enters the tee from one side of its mainline, after exiting the tee, its rear becomes the front, and vice versa. The same pattern is observed when the flow and the pig enter the tee from one side of the mainline and exit through the branch (the second side of the tee is sealed).

The results of the experimental studies are valuable for planning the routes of cylindrical pigs made of hyperelastic materials in pipeline systems containing tees. They allow for assessing the suitability of pipelines for using pigs made of different hyperelastic materials and prevent pig damage during pipeline cleaning processes.

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