Study of Causes of Plastic Pipe Failures

Lenar N. Shafigullin[1,a*], Natalya V. Romanova[2,b] and Alfred M. Suleymanov[3,c]

[1] Kazan Federal University, Naberezhnye Chelny, Russia

[2] Kazan Federal University, Naberezhnye Chelny, Russia

[3] Kazan State University of Architecture and Engineering, Kazan, Russia

[a]misharin_82@mail.ru, [b] romnatav@yandex.ru, [c] alfred-sulejmanov@yandex.ru

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Abstract. It has been observed that critical failures and loss of function occur in a shorter period than specified service life during operation of polypropylene pipes in hot water systems. The paper analyzes the failure causes of polypropylene pipes in closed loop hot water systems, and provides recommendations for increasing their service life. It has been established that the primary factors responsible for ageing and failure of polypropylene pipes during operation are medium temperature, stress due to internal pressure, water composition. It has been observed that a combined influence of the above mentioned factors provides a synergistic effect. We developed the recommendations for increasing a pipe service life, including close monitoring and recording of energy carrier temperature and pressure; changes in specifications for propylene pipes, including the recommendation for using random propylene pipe grades with high thermal oxidation stability in hot water systems.

Introduction

Energy consumption in buildings and facilities depends significantly on indicators for indoor climate, which influence health, productivity, and comfort of the people inside. Energy conservation measures with regard to them are measures for minimizing consumption of fuel and other energy sources in utility systems of buildings and facilities [1]. Energy saving technology is a part of resource saving technologies which, in addition to energy, include saving of materials, air, water, and other living resources. Generally, resource saving technologies also include the use of recycled resources, waste recovery, closed loop water system. Energy conservation measures should not come at the cost of public comfort and health [2].

A widespread use of energy saving technologies should produce an effect of conservation and recovery of resources, public health and environment, as well as give a significant economical incentive as energy saving can greatly reduce utility bills for today's housing and utilities complexes in many Russian large cities [3].

The effective measure for increasing energy efficiency is to switch to closed loop hot water systems where cold drinking water from a water supply system is heated with heating water in the additional heat exchanger and then supplied to a consumer.

Text

Since 2015, a closed loop hot water system has been functioning in the residential buildings in Naberezhnye Chelny, the Republic of Tatarstan, Russia. There is no water conditioning (deaeration). The chemical composition of hot water is not monitored for strong oxidizers (oxygen, chlorine). The quality indicators of drinking water for hot water systems after CHELNYVODOKANAL water treatment plant for a period of 6 months in 2019 showed the presence of oxygen and chlorine in cold water. It has been observed that critical failures and loss of function occur in a shorter period than specified service life during operation of polypropylene (PP) pipes in hot water systems.

According to the analysis of the relevant literature it has been established that the primary factors responsible for ageing and failure of PP pipes during operation are medium temperature, stress due to internal pressure, water composition [4-7].

Thermal motion plays a crucial role in polymer ageing. An increase in temperature by 10 °C in a certain interval is known to accelerate ageing twice. Thermal degradation is a process of macromolecular deterioration under the influence of elevated temperatures. At thermal degradation polypropylene degrades to form short chains with various structures. Thermal oxidative degradation is a process of macromolecular deterioration when polymers are subjected to both elevated temperatures and oxygen. The presence of oxygen significantly reduces PP heat resistance. Tertiary carbon makes PP more sensitive to oxygen, especially, at elevated temperatures. In this case, high temperature also acts as a factor which accelerates all the processes influenced by operational factors [8-10].

The ageing and fracture mechanism for PP pipe material in the stress-strain state should be analyzed with regard to kinetic thermofluctuation concept based on the notions of thermal motion in solid bodies. The kinetic approach is focused on atomic and molecular mechanism of fracture process which is viewed as an end result of gradual development and accumulation of micro-failures, or as a process of micro-crack propagation. A primary factor in this approach is thermal motion of kinetic units (atoms, molecule segments, etc.) which leads to interatomic or intermolecular migration, and promotes the influence of stress that changes the probability of these migrations. Strained bonds break when exposed to thermal energy fluctuations occurred in one bond or a group of bonds. Tensile stress increases the probability of bond rupture and reduces the probability of their reconnection. According to this concept, the long-term strength of a body under load is considered as a fundamental value [11-15].

Water absorbed by polymer can play a plasticizing role and promote creep. An increase in polymer creep under load is due to two factors: adsorbing one, which causes a decrease in a surface energy in the polymer-medium interface, and absorbing one, which increases a free volume of polymer-medium system and decreases a molecular interaction. Besides, products of polymer fracture are washed away when subjected to water in atmospheric conditions, resulting in the exposure of new ageing surfaces [8, 16-17].

It is evident that a combined influence of temperature, water, and stress provides a synergistic effect [6, 7].

In view of this, the purpose of the study was to analyze the causes of PP pipe failure and to create recommendations for increasing service life of PP pipes in closed-loop hot water systems.

The study objects were the following samples: sample 1 is a reinforced PP pipe, TEVO [18]; sample 2 is PP pellets, PP R007EX grade, TU 2211-083-70353562-2006, TNKhK [19]; sample 3 is a PP pipe, Truboplast, initial, no exposure [20]; sample 4 is a PP pipe, Truboplast, after 1 year at 68 °C and 8 atm.; sample 5 is a PP pipe, Truboplast, after oxygen exposure; sample 6 is a PP pipe, KONTUR, after being in use, 50 mm in diameter [21]; sample 6 is a PP pipe, KONTUR, after being in use, 76 mm in diameter. The life of the PP pipe samples did not exceed 3 years.

The failure causes of PP pipes were investigated with the following methods: thermal analysis of thermophysical properties and crystallization of the samples, study of macrostructure of the samples.

Thermal stability of the samples was studied with a Netzsch TG 209 F1 Iris thermogravimetric analyzer. A temperature of 550°C was being achieved at a rate of 10 K/min with continuous argon blowing. The thermograms were processed according to GOST R 29127-91 (ISO 7111-87) [22]. The oxidation inductive temperature and oxidation inductive time were recorded using a Netzsch DSC 204F1 Phoenix heat flow differential scanning calorimeter. The thermograms were taken according to GOST R 56724-2015 (ISO 11357-3:2011) [23, 24]. The oxidation inductive temperature was determined according to GOST R 56756-2015 [25]. In order to find oxidation inductive time, heating up to the test temperature was performed at a rate of 10 K/min with continuous argon blowing. Upon reaching the test temperature (230 °C), the supply of inert gas was stopped, the air supply was started with a rate of 50 ml/min, as well as the recording of DSC signal. In order to find oxidation inductive temperature, heating was performed at a rate of 10 K/min. Upon reaching a temperature of 150 °C, the supply of inert gas was stopped, the air blowing was started with a rate of 50 ml/min. The results of thermal analysis are shown in Table 1[26].

Table 1. Thermophysical properties of the samples

Sample	$T_{maxmelt2}$ PP, [°C]	ΔH_{melt2} PP, [J/g]	T_{maxcr1} PP, [°C]	Oxidation inductive temperature, [°C]	Oxidation inductive time at 240 °C, [min]	Tmax of decomposition, [°C]
1	146.2	57.2	106.1	274.9	30.4	404
2	146.5	69.9	100.7	262.7	-	403
3	149.7	59.9	98.7	262.5	11.5	403
4	150.7	61.7	102.9	(<213)	-	-
5	147.5	67.5	105.2	(<220)	-	-
6	156.0	72.7	108.6	213	-	-
7	154.5	79.2	106.6	244	-	-

The following conclusions can be made based on the analysis:

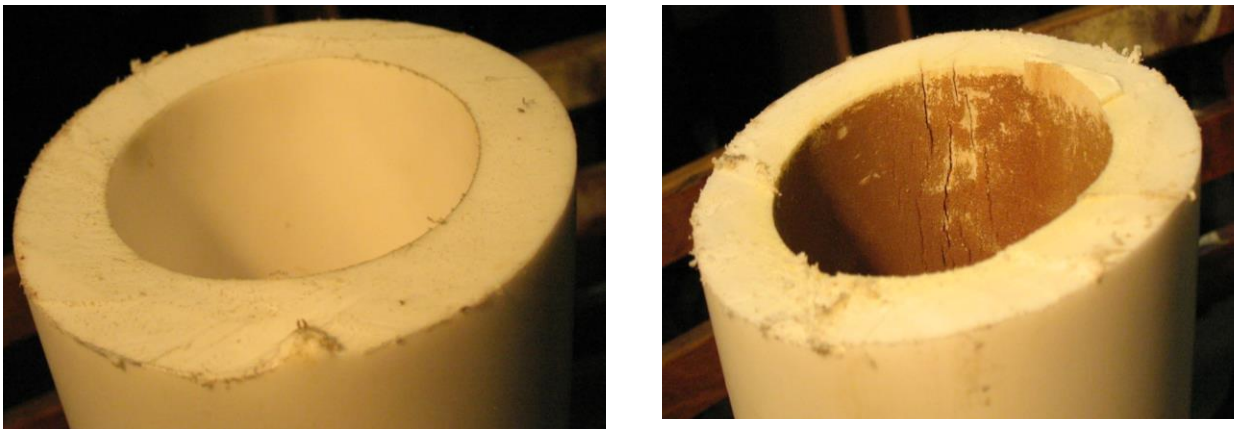
1. The results of the thermal analysis of thermophysical melting and crystallization properties showed that all the used samples were made of block copolymer of propylene and ethylene, and samples 4 and 5 differed the most in terms of melting and crystallization peaks.

2. The studies of oxidation inductive temperature during heating from 200 °C at a rate of 10 °C/min with continuous air blowing showed that the oxidation inductive temperature of sample 1 was 274.9 °C, which was higher than oxidation inductive temperature of samples 2 and 3 by 12.2 °C and 12.4 °C respectively, i.e. sample 1 has better resistance to thermal oxidation in comparison with these samples under the conditions of the experiment.

3. Oxidation inductive time at 240 °C with continuous air blowing was 30.4 minutes for sample 1, which was longer than oxidation inductive time for sample 3 by 18.9 minutes. It indicates that sample 1 has better resistance to thermal oxidation in comparison with sample 3.

4. The studies of oxidation inductive temperature of samples 4 and 5 during heating from 200 °C in air showed a continuous DSC signal change, so it is difficult to make accurate calculations of oxidation inductive temperature for these samples. It indicates the samples were not resistant to thermal oxidation in these test conditions.

A macrostructure of the samples was studied using Canon PowerShot A640 digital camera with the stationary tripod in natural and artificial light. The results of macrostructure analysis are shown in the figure 1.



a) b)

c) d)

e) f)

Fig. 1. External view of the samples: a) Sample 3; b) Sample 4; c) Sample 5; d) Sample 6; e) Sample 7; f) Sample 1

When exposed to the operational factors (temperature, pressure, oxygen and chlorine dissolved in water), the inner surface of PP pipes (see Fig.1.) changes visually to a significant degree, and cracks form on it.

Conclusions

1. Time to pipe failure has an inverse relation to temperature and pressure according to GOST 32415-2013. Pressure thermoplastic pipes and their fittings for water supply and heating systems. General specifications [27] and rupture strength nomograms. The reference operating parameters of polypropylene pipes in hot water systems are as follows: a pressure of 5-6 atm and temperature of 60 °C. It has been established that the reference values of hot water system parameters were broken, which was one of the reasons for thermal oxidative degradation and failure of polypropylene pipes prior to expiration of standard service life. In that regard, close monitoring and recording of these parameters are required. The lower temperature and pressure in a system, the higher durability.
2. At this moment, TNKhK website [19] has no offers for propylene copolymer with grade 23007. TEVO PP pipes are made of random propylene copolymer. The comparative thermal studies showed that the analyzed “random” PP grade had a higher thermal oxidation stability. In this regard, it is recommended to include random grades of polypropylene with high thermal oxidation stability in the specifications, a customer’s approval is required if used propylene grade is different from grades specified in the specification TU 2248-032-00284581-98. Pressure polypropylene copolymer pipes and their fittings for cold and hot water supply and heating systems [28].
3. When subjected to the operational factors (temperature, pressure, oxygen and chlorine dissolved in water), the inner surface of PP pipes changes visually to a significant degree. The following defects are observed: longitudinal cracks which penetrate the base material to a depth of

up to 6 mm; presence of a distinctive defective layer with a thickness of up to 4 mm. The changes in the appearance look like defects which result from thermal oxidative degradation.

4. Thus, the failure cause of polypropylene pipes is thermal oxidative degradation. So, for example, a residential building has a closed loop hot water system and there is no water conditioning (deaeration). The chemical composition of hot water is not monitored for strong oxidizers (oxygen, chlorine). Heat exchangers are flushed regularly with chemical agents and neutralizers, and no public sources have any information about their safety for PP pipes. Temperature control systems in hot water systems theoretically allow for overtemperature in case of a failure of a temperature sensor. Pressure control systems in hot water systems theoretically allow for overpressure in case of a failure of a pressure sensor. A system can experience water hammers during operation. These factors act simultaneously thus reinforcing their impact. A synergistic effect occurs.

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