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Simulation of Thermoplastic Pipings Behaviour in Solar DHW Installations

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Abstract

Known for their low price, the use of thermoplastic pipes is in constant increase with the rising price of metallic materials as copper. These materials appear to be a good choice as for minimizing the building environmental impact, considering their reliability, their recyclable nature, their energy efficiency and their minimal laying time. Thus, it would be interesting to study their behavior in solar DHW installations. This is the main purpose of this article. In a first part, the energetic impact of using thermoplastic pipes in solar installation was examined using TRNSYS software. The studied solar installation is an active indirect solar water heating system with an external heat exchanger. It is located in a hotel in north-eastern Tunisia and part of the "PROSOL-TUNISIE" program. First, in order to identify TRNSYS model deficiencies, the installation was modelled as it is, and simulation results were compared with experimental measurements. Once this comparison completed, this model was used to simulate the storage tank water temperature and the power provided by the solar installation, for three various types of piping (PPR, PEX, CPVC). Encouraging results have been obtained with regard to the temperature reached at the storage tank and the collector outlet and the power supplied by the solar installation. Even if these results depend on season, they remain very advantageous compared to results obtained for metallic pipes such as copper. Moreover, even if thermoplastic pipings require likewise a thermal insulation in order to reach the necessary temperature of 60°C (to avoid legionella), this insulation remains thin compared to metallic materials. This fact added to their low price compared to metallic materials such as copper or steel would further minimize the cost of solar installations.In a second part, a study was carried out on the thermal expansion of three different types of thermoplastic piping (PEX, PPR, CPVC). It was found that the PEX has the highest thermal expansion reaching 72 cm, followed by the PPR and the CPVC reaching 54 cm and 25.2 cm respectively, for a temperature of 120°C. Since the primary circuit can reach high temperatures up to 120 °C during stagnation period, whatever the materials used it is necessary to implement expansion joints or to use other methods allowing to absorb pipes displacement as the expansion loop, the pipe offset and the pipes shift.

Keywords: thermoplastic pipings – solar installation – energetic impact – thermal expansion – experimental validation

1. Introduction

In order to minimize the energetic, environmental and economic impacts of the building, several states set up a building thermal regulation (RT 2012 in France [1], RTEBNT in Tunisia [2]) and/or a building environmental regulation (HQE [3], BREEAM [4], LEED…) [5]. The latter takes into account the energy consumption and the environmental impact of the building, during both the use and the construction. Therefore, in order to conform to this regulation, it is essential to select the best product of the various building components according to their materials, their costs and their effectiveness. In every heating, air conditioning, or domestic hot water production systems, pipings highly influence their effectiveness, their costs, and their lifetimes. These pipes were generally manufactured from steel or copper. But due to their rising price and corrosion and fouling problems, other materials, like thermoplastic polymers, were used. These materials are known for their low costs, their reliability and their recyclable nature. Several former studies were interested in thermoplastic pipings. Martin Denberg and AL. [6] studied the concentration profile and homogeneity of antioxydants and the breakdown products in a pipe of crosslinked polyethylene of type A (PEXa). They found that the composition of Irganox® 1076 is homogeneous in the radial direction and heterogeneous in the longitudinal direction. Concerning the composition of the breakdown products, the 2,6-di-tert-butyl-p-benzoquinone proved to be homogeneous in the radial direction and the longitudinal direction; and the 2.4-di-tert-butyl Phenol was homogeneous in the radial direction but heterogeneous in the longitudinal direction. Keven M. Kelley and Al. [7] studied the contaminants and the odor of drinking water caused by crosslinked polyethylene plumbings (PEX). Eleven regulated and not regulated contaminants were found in the systems of plumbing in PEX. For a period of thirty days, the levels of odor and TOC decreased. Nevertheless, the levels of odor caused by the PEX, even after these thirty days, remain above the level fixed by the US Environmental Protection Agency (USEPA). Moreover, the exposure to disinfectant could lead to higher odor levels. The researches conducted by Ingun Skjevrak and Al. [8] revealed that the migration of volatile components in drinking water and the odor of this latter are less important in the PVC pipes than in the high density polyethylene pipes and the crosslinked polyethylene pipes. Dick van der Kooij and Al. [9] studied the formation of biofilm and the multiplication of légionnelles in hot water system with crosslinked polyethylene, stainless steel and copper pipes. After approximately two years of operation, the légionnelles concentration on water in the copper pipes were on the same level as on the water in the stainless steel pipes and in crosslinked polyethylene pipes. D. Castagnetti and Al. [10] studied the effect of chlorinated water on the oxidation resistance and the mechanical resistance of the polyethylene tubes. The obtained results show that the chlorine dioxide is more aggressive than the sodium hypochlorite. Nevertheless, the pressure tests, at a constant temperature, do not show any failure of the pipes after 2000 hours of exposure to chlorinated water. F. Saghir and Al. [11] studied the temperature and frequency effects on the growth of the fatigue crack of chlorinated polyvinyl chloride (CPVC). It was noted that resistance to the growth of the fatigue cracks increases with the increase in the frequency, and decreases when the temperature increases. These results agree with those found by Nadia Temimi-Maaref [12], during his study on the thermomechanical behavior and the rupture of polypropylene. During the study of the effects of natural and artificial deterioration of the mechanical properties of chlorinated polyvinyl chloride pipes (CPVC), NR. Merah and Al. [13] showed that accelerated natural or artificial ageing has a limited effects on stress at break and modulus of elasticity of the material. However, the deterioration of stress at break is perceptible for one period of natural exposure of 15 days and an artificial period of exposure to the UV of 100 hours. J.J. Järvenkylä [14], studied buckling, the impact resistance and the minimal thickness of the wall of the thermoplastic pipes. Following this study, it presented the way in which the thermoplastic material conduits should be classified and how the choice of thermoplastic material is made. By using a concept of extrapolation, A. Franka and Al. [15] showed that the polyethylene pipes can reach a lifetime of about fifty years. Derick Scott [16] presents the various uses of thermohardening and thermoplastic materials in the transport and the storage of water. He describes in his work methods for design, for production and for the choice of the most adapted materials for each application. The researches undertaken by Mr. H. Zgoul and S. Mr. Habali [17] showed that the crosslinked polyethylene pipes and the polypropylene random copolymer pipes are more convenient for heating applications, more resistant to corrosion and more handy than traditional materials like steel and copper. Also, they have a satisfactory behavior when they are subjected to thermal stresses for long periods of time. Moreover, considering their low thermal and electric conductivity, they present a better energy conservation and a higher security than the forged pipes. According to research presented above, it is noticed that a good amount of researchers were interested in the sanitarian character of the thermoplastic pipes followed by the research on their thermomechanical behavior and their lifetime. Very little researches were interested in the energetic impact of using these pipes in energetic systems. It is within this framework, that we proposes in this article, to evaluate the energetic impact of using a thermoplastic pipes in a solar DHW installation while studying their thermal epansion. Three types of materials will be evaluated: crosslinked polyethylene (PEX), Crosslinked polypropylene (PPR), chlorinated polyvinyl chloride (CPVC). In a first part, the effect of each material on the storage tank outlet temperature to load, the collector outlet temperature and the power produced by the solar installation will be exposed. Then, in a second part, the thermal expansion of each material will be studied. The purpose of this study will be essential to emphasize the energetic and economic profit carried out by the use of the thermoplastic pipes, while taking into account their thermal expansion.

2. Description of the studied solar installation

The studied system is an active indirect solar water heating system with an external heat exchanger. It is located in a hotel in the north-east of Tunisia and is a part of the “PROSOL-TUNISIE” program.

Figure 1. The studied solar installation.

The solar installation (figure 1) is composed of:

- 450m ² of a flat-plate solar collector.
- A counter-flow plate heat exchanger with 3.85 m² of heat exchange surface and power equal to 315 kw.
- Three storage tank of 6000 liters unit volume.
- Two pumps.
- Temperature, solar radiation and water flow measuring equipments.

- **Measurement uncertainty**

- The used temperature sensors are class B PT100 sensors and have an uncertainty $\Delta T_i = \pm(0.3 + 0.005T\ [°C])$
- The pyranometer has an uncertainty of 2%.
- The flow meter has an uncertainty of 3%.

3. Energetic impact of using thermoplastic pipes in solar DHW installation

The studied solar installation was modelled using TRNSYS software. Several models are available in the library of this tool, both for the collector, the exchanger and the storage tank. The used models were selected according to their level of correspondence with the existing installation and their input parameters. Thus, the choice was fixed on the type1b for the collectors, the type 5b for the counter-flow heat exchanger, the type 4c for the storage tank and the type 31 for piping. The solar installation model simulated with TRNSYS is presented in figure 2. The meteorological data were introduced through the type 190-user component, the load profile was regulated through the type 14b component and the control strategy was carried out through the type 2b component.

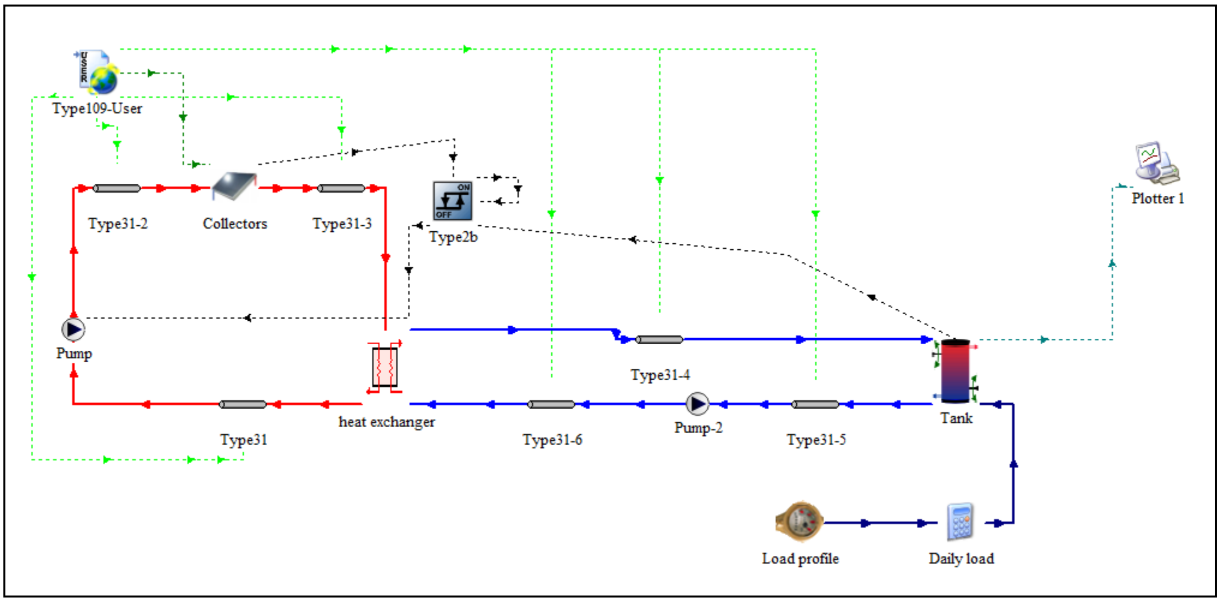

Figure 2. Simulation scheme under TRNSYS software.

Simulation was carried out for August 1st, 2015. The primary circuit pipes length are equal to 2m (type 31), 30m (type 31-2) and 30m (type 31-3). The secondary circuit pipes length are equal to 8m (type 31-4), 6m (type 31-5) and 2m (type 31-6). The characteristics of the various types of the studied pipes as well as the one existing in the solar installation (copper) are given in table 1. It should be noted that the existing pipes are copper pipes and are insulated by a closed-cell rubber foam sheath of nominal thickness of 32 mm and protected from ultra-violet rays by an aluminium shell of 6/10 mm of thickness. The studied variables were the collector outlet temperature, the storage tank outlet temperature to load and the power supplied by the solar system. The simulation results for four types of pipes (PEX, PPR, CPVC, copper) and experimental measurments for the existant solar installation (copper pipes) are presented in Figures 3, 4 and 5.

Tableau 1: Characteristics of the various types of pipings

Materials	PEX	PPR	CPVC	Copper
Internal diameter [mm]	54	51,4	48	50
External diameter [mm]	63	63	63	54
Thermal conductivity [W/m.K]	0,41	0,24	0,16	328
Linear expansion coefficient [mm/m.K^{-1}]	2.10^{-4}	$1,5.10^{-4}$	7.10^{-5}	$16,8.10^{-6}$

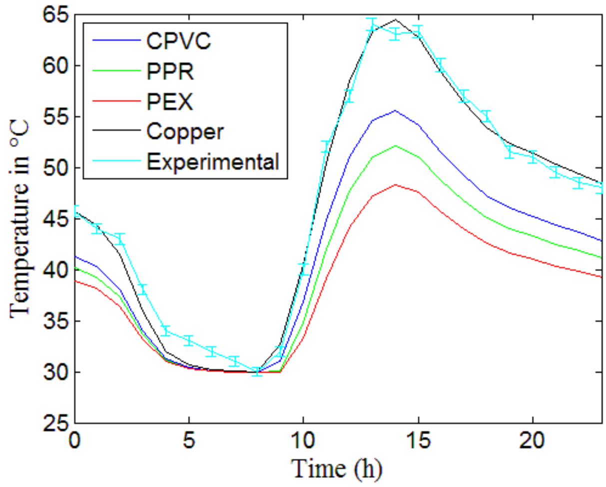

Figure 3. Storage tank outlet temperature to load.

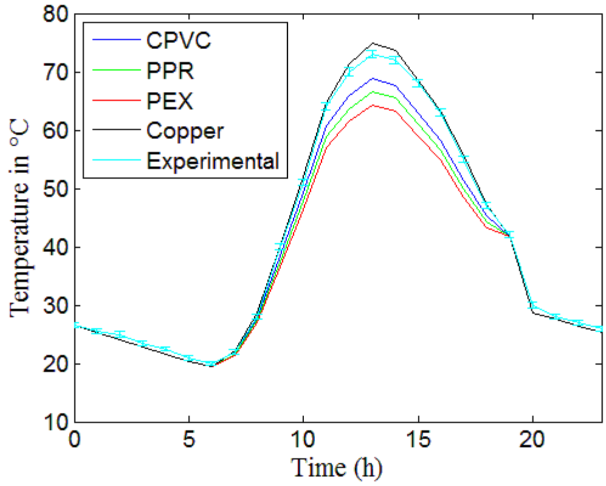

Figure 4. Collector outlet temperature.

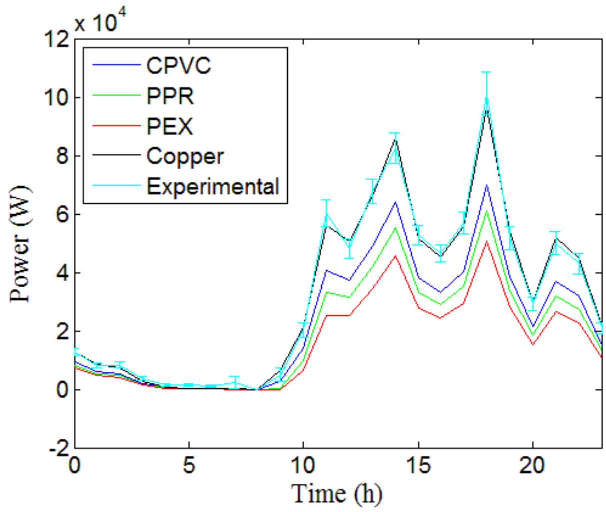

Figure 5. Power provided by the solar installation.

First, in order to identify the TRNSYS model deficiencies, the simulation results were compared with experimental measurements (for copper pipes case).

According to figure 3, showing the evolution of the storage tank outlet temperature to load, the results given by the TRNSYS tool are consistent with the experimental results. However, a maximum deviation of 1.98°C and an average deviation of 0.36°C were observed. It should be noted that an undervaluation at the beginning of the day and an overvaluation at the end of the day of the storage tank outlet temperature to load were noticed.

Concerning the collector outlet temperature (figure 4), obtained results are also consistent with eperimental results. Yet, a maximum deviation of 1.87°C and average deviation of 0.68°C were observed. It was also found that TRNSYS tends to overstate the collector outlet temperature during the solar production hours and to underestimate it at the beginning and the end of the day.

The power provided by the solar installation (fig. 5), being closely related to the storage tank outlet temperature to load, the same remarks stated for this latter apply. As for the gap between theoretical and experimental results, its maximum value is 6% and its average value is 4%.

Then, once the experimental comparison is completed, this model was used to simulate the evolution of the storage tank outlet temperature to load and the power provided by the solar installation, for three various types of pipings (PPR, PEX, CPVC). It should be noted that these latters were simulated without thermal insulation. Indeed, being known for their low thermal conductivity, it is of interest to evaluate the storage tank outlet temperature to load that could be reached and the power that could be provided using these types of pipes without thermal insulation. This evaluation will show if their use without thermal insulation would satisfy the energy need and would reach the setpoint temperature, which will reduce the installation cost considerably.

Figure 3 shows that, when using thermoplastic pipes, the storage tank outlet temperature to load could reach an encouraging values. Indeed, reached values are of 55,52°C for the CPVC, 52°C for the PPR and 48,2°C for the PEX. These values compared with the one obtained when using copper pipes (about 64°C), which profits from a thermal insulation of nominal thickness of 32 mm, appear advantageous.

Figure 4 shows that the reached temperature at the collector outlet remain below the boiling temperature which will avoid a premature attrition of the solar installation. Moreovers, the difference between the reached temperature at the collector outlet for the four type of pipes are lower than the difference between the reached temperature at the storage tank (see fig.3 and fig.4).

Figure 5 presents the power provided by the solar installation. It shows that the maximum powers reached by the three various types of pipes are of about 69.840 kW for the CPVC, 60.879 kW for the PPR and 50.734 kW for the PEX. Here again, when using these three thermoplastic pipes, attempted power compared with the one reached when using copper pipes (about 96.641 kW) appear encouraging.

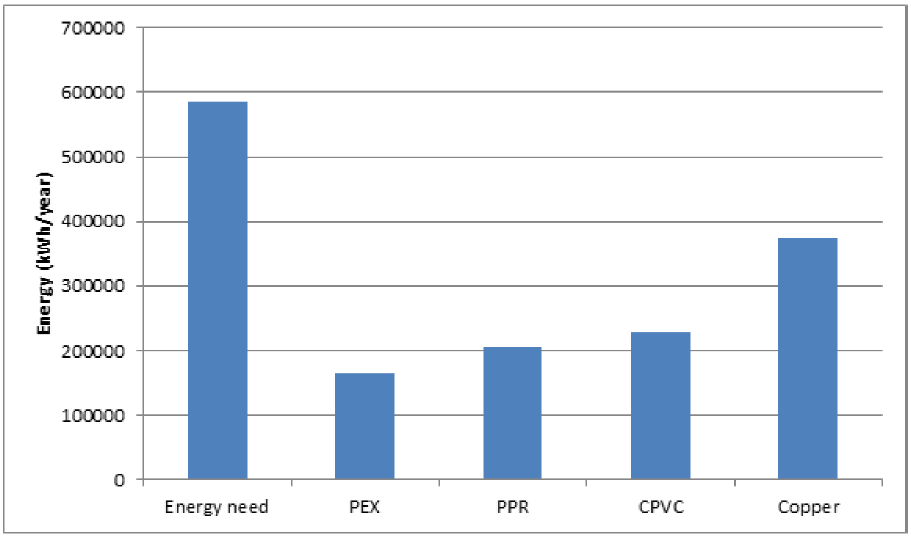

Figure 6. Figure 1. Energy provided by the solar installation for different piping material.

In order to verify if the energetic performances reached previously for a period of one day remain valid for all season, the energy production of the solar installation was calculated for a period of one year. Figure 6 shows that for an annual energy need of 585,389 kWh/year (calculated for a fixed daily consumption), the annual solar coverage ratio for each type of pipes is of 64% for copper, 39% for the CPVC, 35% for PPR and 28% for the PEX. Thus, since the reached values for a period of one year are lower than the reached values for a period of one day, it is clear that the attempted levels of performance depend on the season. However, these results are very encouraging and show the energetic importance of using thermoplastic materials in solar thermal installations. Moreovers, considering their weak price compared to metallic materials as copper or steel, the use of thermoplastic materials will allow to minimize solar installations costs. Even if thermoplastic pipings still require a thermal insulation in order to reach the setpoint temperature of 60°C (to avoid legionella), this insulation remains of low thickness compared with metallic materials.

4. Thermoplastic pipes expansion

In any structure or system, thermal expansion can cause unacceptable mechanical stresses that can lead to breakage. It can also lead to leaks at fittings and valves. Therefore, it is essential to study the effects of thermal expansion in order to guarantee the durability of solar hot water systems.

Thus, a study on thermal expantion of three various types of thermoplastic pipings (PEX, PPR, CPVC) was carried out. This study was performed on the part of piping having the highest length and the most subjected to temperature variations. This piping section is located in the primary circuit between the the solar collectors outlets and the heat exchanger.

The length variation of this piping section has been calculated by the following formula :

$$\Delta L = \alpha . L_0 (T - T_{amb}) \tag{1}$$

ΔL: elongation in mm.
L_0: pipe initial length in m.
α: materials linear expansion coefficient in mm/m.K^{-1}.
T: pipe final temperature in K^{-1}.
T_{amb}: ambient temperature in K^{-1}.

The obtained results are shown in figure 5.

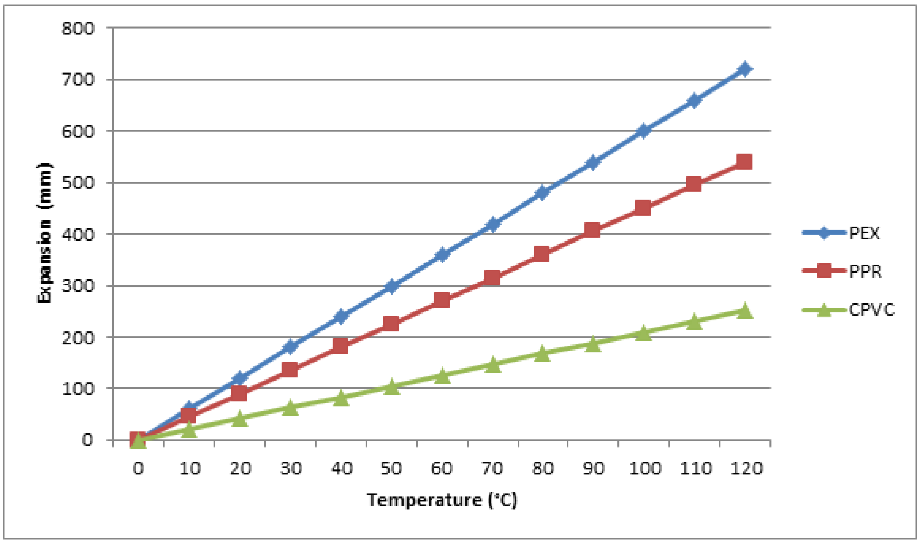

Figure 7. Thermal expansion of different types of piping as a function of temperature.

It is clear that the PEX presents the highest thermal expansion. This latter can reach 72 cm for a temperature of 120°C. the PEX is followed by the PPR and the CPVC which reaches respectively 54 cm and 25.2 cm for a temperature of 120°C. Knowing that the primary circuit can reach high temperatures to arround 120°C during stagnation period, whatever the materials used, it is necessary to implement expansion joints or to use other methods allowing to absorb pipes displacement as the expansion loop, the pipe offset and the pipes shift.

5. Conclusion

The behavior of thermoplastic pipes in an existing solar installation located in a hotel in the north-east of Tunisia and part of the "PROSOL-TUNISIE" program, was studied. In a first part, the energetic impact of using thermoplastic pipes in solar DHW installation was examined. First, in order to identify the TRNSYS model deficiencies, the simulation results were compared with experimental measurements (for copper pipes case). Then, once the experimental comparison is completed, this model was used to simulate the evolution of the storage tank outlet temperature to load, the collector outlet temperature and the power provided by the solar installation, for three various types of pipings (PPR, PEX, CPVC). Encouraging results have been obtained regarding the storage tank outlet temperature to load, the collector outlet temperature and the power provided by the solar installation. Even if these results depend on season, they remain very advantageous in comparison to results obtained for metalic pipes such as copper. Moreovers, even if thermoplastic pipings still require a thermal insulation in order to reach the setpoint temperature of 60°C (to avoid legionella), this insulation remains of low thickness compared with metallic materials. This fact, added to their weak price compared to metallic materials like copper or steel could allow to further minimize the cost of solar installations. Then, in a second part, a study on thermal expantion of three various types of thermoplastic pipings (PEX, PPR, CPVC) was carried out. It was found that the PEX presents the highest thermal expansion reaching 72 cm, followed by the PPR and the CPVC reaching respectively 54 cm and 25.2 cm, for a temperature of 120°C. Knowing that the primary circuit can reach high temperatures to arround 120°C during stagnation period, whatever the materials used, it is necessary to implement expansion joints or to use other methods allowing to absorb pipes displacement as the expansion loop, the pipe offset and the pipes shift.

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