Forming an ice plug inside a high diameter pipeline in stationary water using a nitrogen vapour exhaust restriction

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Abstract. The ice plug isolation technology is used for repair or maintenance activities conducted on large diameter horizontal pipelines without shutting down the entire thermal-hydraulic installation or its water supply. The amount of information useful in dimensioning the ice plug devices as well as on the operating techniques themselves is extremely scarce. The nitrogen vapour exhaust nozzle diameter is arbitrarily chosen; reducing it by 24% has an important influence on the ice plugging process. Its influence is more or less dependent on the liquid nitrogen injection technique inside the device. The article contains a brief presentation of the experimental technological facilities used, followed by a series of two experiments performed on a 200 mm diameter testing section using stationary demineralized water under similar temperature and liquid nitrogen supply conditions. At the end of the article, there is a brief result analysis and a few conclusions. The paper is dedicated to specialists working in research and technological engineering.

1. Introduction

The ice plugging technique is used for isolating a large diameter pipe-line section from the rest of the circuit regarding maintenance or repair activities specific to thermal-hydraulic installations and does not require shutting down the whole plant or its water supply. It involves the usage of a specially built device and a series of preliminary tests specific to the diameter and the operating conditions required by the intervention. These tests are performed on experimental installations. The freezing device is shaped as a ring sleeve composed of two approximately identical subassemblies bolted together on the outside of the pipe. The assembly forms an inner circular compartment concentric to the pipe, which will contain the liquid nitrogen during the freezing process. The compartment is usually equipped with one or two exhaust nozzles (mounted on the upper clamp) for evacuating vaporized nitrogen. Injecting liquid nitrogen into the device starts a heat transfer process between the liquid inside the pipe and the freezing device’s liquid nitrogen compartment. The heat flow yielded by the working agent at the interface with the liquid nitrogen ring (pipe wall / sleeve compartment wall) intensifies the liquid nitrogen vaporization, thus raising the pressure inside the compartment and implicitly inside the liquid nitrogen supply circuit [1], [2]. In order to limit the pressure inside the device, the vaporized nitrogen is discharged through the specially provided exhaust nozzle(s).

A number of important factors are taken into consideration when choosing the appropriate constructive version of the freezing device: the pipeline geometry, the type of working agent used, the flow regime (laminar or stationary), the water and ambient temperatures, and the available volume of liquid nitrogen, [1]. Reducing the nitrogen vapour exhaust nozzle diameter (applied as a hydraulic...
resistance) may or may not be beneficial to the ice plug forming process results depending on the operating conditions and the application requirements, [3].

The article briefly describes the technological experimental facilities and two experiments. At the end of the article there is a brief result analysis and a few conclusions.

2. Technological facilities
The experimental test loop consists of a circulation pump (P), an assembly of pipes and fittings, and a filling / draining vessel (VU / G), Figure 1, and uses demineralized water as a working agent.

Figure 1 - Experimental testing loop – the simplified diagram

The great power of the circulation pump’s electric motor (20 kW) causes a continuous rise of the working agent temperature, although the flow rate on the test section (ST) is stationary. Closing the R3 valve stops the flow of water through the testing pipe, redirecting it on the bypass. The water temperature increase (downstream from the plug) reflects indirectly on the ice layer development. The experimental ice plug device is mounted on the horizontal test pipeline (200 mm in diameter), Figure 2. The nitrogen supply and discharge are made through separate nozzles on the upper side of the freezing device. The current device's constructive version has a single exhaust nozzle. For the presented experiments a 24 % diameter restriction was mounted between the exhaust nozzle and the exhaust pipe.

Figure 2 - The freezing device mounted on the testing pipe
The $\text{N}_2$ liquid nitrogen is transferred from the Dewar vessel to the supply nozzle through a pressure hose with special fittings. The pressure sockets are mounted on the lower half of the pipe on both sides of the testing section. They are connected with the differential pressure transducer through an impulse pipe.

Throughout the whole experiment temperatures on the outer pipe wall of the testing section (upstream and downstream from the freezing device, on both its upper and lower side) are measured and recorded. Knowing the temperature levels of variation allows us to estimate the thickness of the ice layers. We used a digital data acquisition system for measurements and recordings.

3. Experiment description

For this article we chose two experiments that were conducted on the 200 mm diameter testing pipe in similar conditions, but with different ambient temperature variations which were not monitored, [4].

The water temperature at the start of the first experiment had a value of $\sim 17.2 \, ^\circ\text{C}$ and reached $23.9 \, ^\circ\text{C}$ at the end; the water temperature at the start of the second experiment had a value of $17.3 \, ^\circ\text{C}$ and reached $23.7 \, ^\circ\text{C}$ at the end, Figure 3. For temperature measurements around the cryogenic device, we used Fe-Constantan thermocouples mounted on the outer pipe surface, upstream and downstream from the device in upper and lower position (four thermocouples), at the tip of the vapour exhaust vent, inside the liquid nitrogen compartment and inside the water tank.

![Deminalerized water temperature variation on the bypass](image1.png)

Figure 3 - Water temperature variations throughout the two experiments

The liquid nitrogen injection technique was completely different throughout the two experiments, Figure 4, [4].

![Vapor cushion pressure variation](image2.png)

Figure 4 - Vapour cushion injection pressure variation during the two experiments
For the first experiment conducted in the absence of a demineralized water flow inside the testing pipe (using the 24% restriction mounted on the nitrogen vapour outlet), the ice plug was formed primarily after 66 minutes. The test was carried out using a relative vapour cushion pressure fixed at a value of $p_1$ bar inside the Dewar vessel that was later dropped at $p_2$; ~2 minutes later it accidentally reached a threshold between $p_2$ and $p_3$ bar, returning quickly at $p_2$, and ~12 minutes later reached $p_3$ bar, which was constantly maintained throughout the rest of the experiment, Figure 4, [4].

The pressure drop increased at 1.2 bar in approximately 67 minutes, its evolution over time being considered linear up to about 0.8 bar, Figure 5. This pressure drop increase on the ice cap marked the pipe obstruction.

Figure 5 - Pressure drop variation, 1st experiment

After the 133 minutes of the experiment we started draining, disassembling and removing the pipeline section upstream from the testing section to visualize the finalized ice-plug, Figure 6, [4].

Figure 6 - Ice plug (1st experiment)

An imaginary section through the longitudinal testing pipe axis, according to the measurements relative to the testing rig upstream flange is reproduced in Figure 7, [4].
The maximum length of the ice deposit on the pipe inner wall was ~ 555 mm on the lower half of the testing section and 390 mm on the upper half. We estimated that the ice plug had an effective length of 280 mm, [4].

The second experiment was conducted without water flowing through the testing section and using the same 24 % restriction mounted on the nitrogen vapour outlet. The ice plug was formed primarily after 113 minutes.

The test was carried out using a relative vapour cushion pressure fixed at a value of $p_3$ bar inside the Dewar vessel that was dropped during the next 5-6 minutes at $p_4$; ~ 5-6 minutes later it returned at $p_3$, a value which was constantly maintained throughout the rest of the experiment, Figure 4, [4].

The pressure drop increased at 1.2 bar in approximatively 7 minutes, its evolution over time being considered linear until stabilization, Figure 5. This pressure drop increase on the ice cap marked the pipe obstruction, figure 8. The entire experiment lasted for about 130 minutes, [4].

After 130 minutes we started draining, disassembling and removing the pipeline section upstream from the testing section to visualize the finalized ice plug, Figure 9, [4].
An imaginary section through the longitudinal testing pipe axis, according to the measurements relative to the testing rig upstream flange is reproduced in Figure 10, [4].

![Figure 10 - Imaginary section through the longitudinal testing pipe axis, 2nd experiment](image)

The maximum length of ice plug on the inner wall of the test section was \( \sim 570 \) mm at the bottom of the pipe and \( 400 \) mm at the top. The length of the ice plug formed inside the pipe was estimated to approximately \( 270 \) mm [4].

### 4. Results

Both experiments were conducted using a 24% nitrogen vapour exhaust nozzle restriction. They were started using different liquid nitrogen injection pressures, but both of them reached a value of \( p_3 \) bar in about 15 minutes and was kept constant throughout the rest of the experiments. Although the injection techniques were different during the first 15 minutes, the estimated difference between the lengths of the ice plugs was only \( 10 \) mm. Although both pressure drops had a polynomial increase (Figure 11), the different liquid nitrogen supply techniques favoured a \( 40 \) mm difference between the upstream advancement of the ice plug during the first experiment compared to the final ice plug resulted from the second experiment.

![Figure 11 - Pressure drop evolutions during the two experiments](image)

The ice plug resulted from the first experiment was about \( 10 \) mm longer. On the second experiment, the primary ice plug formation took place 47 minutes later and was initially positioned further downstream; the ice deposit length was \( 25 \) mm longer downstream. Therefore, the positioning of the test section closure depends more on the liquid nitrogen injection technique and less on the ambient temperature considering that the water temperature evolution was similar during both experiments.

Both ice deposits’ lengths and thicknesses differ; they are influenced by the medium liquid nitrogen injection speed inside the freezing device. A higher medium speed favours a pipe closing further downstream from the freezing device (as seen in the second experiment).
The ice deposit thickness growth decreases the heat flow between the demineralized water and the liquid nitrogen inside the freezing device. As the heat exchange drops, temperatures on the outer pipe wall (upstream and downstream from the device) decrease accordingly.

The two ice plugs were completed in similar amounts of time even though the time required for their primarily formation was different.

If the ice layers’ thickness is reduced inside the area influenced by the freezing device, the thermal insulator effect of the ice will also be reduced, thus improving the heat exchange between the demineralized water and the liquid nitrogen (the case of the first experiment). The size of the restriction mounted at the nitrogen vapour exhaust nozzle certainly contributed to the result.

5. Conclusions

- Both experiments were conducted in similar geometrical and physical conditions in the absence of demineralized water flow on the test section. There were small differences regarding the water temperature; air temperature probably has a smaller influence over the results;
- Different liquid nitrogen injection techniques were used for the two experiments;
- The experiments were finalized with ice plugs of equivalent lengths, but differently positioned from the freezing device;
- The second ice plug primary completion time was 47 longer than the first experiment;
- The two experiments were completed in similar amounts of time; the first ice plug was an estimated 10 mm longer in length;
- Although both pressure drops on the ice plugs had a polynomial increase, the different liquid nitrogen supply techniques favored a 40 mm difference between the upstream advancement of the ice plug during the first experiment compared to the final ice plug resulted from the second experiment;
- The positioning of the test section closure in the influence zone of the device depends more on the technique of liquid nitrogen injection and probably less on the ambient temperature, given that the evolution of the water temperature was similar in both experiments;
- The higher liquid nitrogen average flow speed on the feeding circuit favors the closure of the pipe section further downstream from the area influenced by the freezing device and generates a different local deposition of ice layers over time;
- Temperatures measured on the outer pipe wall, both top and bottom, downstream and upstream from the freezing device, are noticeably different at during the closure of the test section and during the completion of the ice plugs.

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