CFD MODEL FOR THE HEAT TRANSFER DURING THE ICE PLUGGING PROCESS OF LARGE DIAMETER PIPES

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Abstract
This article proposes two computational models for the time and quantity of liquid nitrogen required for the operation of forming controlled ice plugs in pipeline installations in order to isolate a section from the rest of the circuit (a technique used for carrying out circuit maintenance or repair activities without shutting down the entire plant). The proposed ANSYS FLUENT CFD model will be used for a heat transfer analysis for the ice plugging process used on large diameter pipes.

Keywords: *Pipe freezing, Liquid nitrogen, Finite volume method, ANSYS Fluent*

Introduction

The technological pipe freezing process is continuously developed by specialized companies, considering the requirements of each individual application. The technique is used for maintenance in industrial installations, municipal pipelines, submarines etc..

Forming the ice plug inside a pipeline requires using specialized devices and specific techniques for its diameter and for the operating conditions for each individual application [1]. The collar shaped freezing device (fixed or removable) consists of two half-clamps bolted together around the pipe (see Fig. 1) [2].



Fig. 1. Rigid freezing jacket with liquid nitrogen circulation

The refrigerant draws heat from the device and pipe walls and from the liquid inside the pipe. The heat thus absorbed evaporates some of the liquid nitrogen and is transported outside the freezing device by the nitrogen gas. The heat and mass transfer determine the local pipe wall temperature reduction, favouring the deposition of ice in successive layers, until the pipe section is completely closed. From this point on, the ice formation continues along the pipe axis, towards the ends of the freezing jacket.

The freezing process is mainly influenced by the geometrical properties of the pipe (diameter, orientation), the geometrical properties of the freezing device and the water temperature. The variation of water temperature during the process characterizes the ice layers growth and implicitly the conductive and convective heat transfer coefficients at the two fluid/solid interfaces (between the water inside the pipe and the ice layer and between the pipe outer wall and the freezing agent). Maintenance operations cannot be conducted without an initial estimate for the required time and liquid nitrogen quantity.

This paper proposes a CFD computational model using ANSYS Fluent for the time required for the operation of forming controlled ice plugs inside different diameter pipelines (200, 300 and 400 mm) using stationary water at 20 °C and a calculus model for the required quantity of liquid nitrogen.

Geometrical models

The geometry for the chosen models was implemented using the Design Modeler environment proper to the ANSYS computational code. 3D pipes were modelled using the following characteristics:
- outer diameter (D_e) : 219 mm, 324 mm, 420 mm
- inner diameter (D_i) : 203 mm, 304 mm, 400 mm
- pipe length (L) : 6000 mm
- heat transfer length (l) : l_1, l_2, l_3.

The heat flux (resulted using Eq. (1)) shall be applied to the outer surface of the central pipe section (considered the freezing zone). The heat transfer between the other two pipe sections and surrounding environment was neglected.

Computational models

At the beginning of the cryogenic freezing process, the radial heat flow from the working agent towards the outside of the pipe involves three distinct processes: convective transfer between water and the inner pipe wall, conductive transfer through the pipe wall and convective nitrogen boiling at the outer pipe wall. As the ice layers deposit on the inner pipe wall, a fourth process occurs, namely the conductive transfer through the layers of ice. The ice layers act as an insulator, progressively slowing down the radial heat transfer towards the liquid nitrogen.

Heat transfer coefficients

Considering the high temperature difference between the pipe surface and the liquid nitrogen, the heat transfer at the pipe outer wall is achieved through turbulent film pool boiling. A correlation for the heat transfer coefficient in the case of steady turbulent film pool boiling is given by Miheev & Miheeva [3, 4]:

$$\overline{\alpha_{lN_2}} = 0.25 \cdot \sqrt[s]{\frac{\lambda''^2 \cdot c_p'' \cdot g(\rho' - \rho'')}{\nu''}} \quad (1)$$

where:

$\overline{\alpha_{lN_2}}$ = mean heat transfer coefficient for liquid nitrogen, [W/m^2·K]

λ'' = vapour phase thermal conductivity, $\lambda'' = 15.89 \cdot 10^{-3}$ W/(m·K)

c_p'' = isobaric specific heat for the nitrogen vapour film $c_p'' = 1.044 \cdot 10^{-3}$ J/kg·K

g = gravitational acceleration, $g = 9.81$ m/s^2

ρ' = liquid phase density, $\rho' = 804$ kg/m^3

ρ'' = vapour phase density, $\rho'' = 1.975$ kg/m^3

ν'' = vapour phase kinematic viscosity, $\nu'' = 5.75 \cdot 10^{-6}$ m^2/s

which gives: $\overline{\alpha_{lN_2}} = 177.96$ W/m^2·K (2)

According to Newton's fundamental equation for thermal convection, the heat flux absorbed by the volume of liquid nitrogen inside the freezing device is

$$\dot{Q}'' = \alpha_{lN_2} \Delta T \quad (3)$$

where ΔT is the heat transfer potential (the temperature difference between the water inside the pipe and the liquid nitrogen at its boiling point), $\Delta T = 216$ K.

The heat flux through the surface cooled by liquid nitrogen (at an initial working temperature of 20 °C) is:

$$\dot{Q}'' = 38439.07 \text{ W/m}^2 \quad (4)$$

Phase change computational model

The heat transfer between the ice and the water in the interior of the pipe is carried out by turbulent free convection of the water. For the case of steady free convection in an enclosed space, Isacenko [5] gives the following correlations between the Raleigh number ($Ra = Gr \cdot Pr$) and the ratio of the equivalent thermal conductivity (including both conduction and convection) for the fluid thermal conductivity $\varepsilon = f(Ra)$ (see Table 1) :

$$\varepsilon = \frac{\overline{\lambda_{ech}}}{\lambda} \quad (5)$$

where:

$\overline{\lambda_{ech}}$ = water equivalent thermal conductivity, [W/m·K]

λ = water thermal conductivity, [W/m·K]

Pr = Prandtl number, $Pr = \frac{\nu \cdot \rho \cdot c_p}{\lambda}$ (6)

with:

ν = water kinematic viscosity for each temperature stage, [m^2/s]

ρ = water density for each temperature stage, [kg/m^3]

c_p = water specific heat for each temperature stage, [J/kg·K]

λ = water thermal conductivity for each temperature stage, [W/m·K]

Gr = Grashof number, $Gr = \frac{g \cdot \beta \cdot \Delta T \cdot l^3}{\nu^2}$ (7)

with:

β = water thermal expansion coefficient for each temperature stage, [1/K]

ΔT = temperature difference between water and the ice layer for each temperature stage, [K]

Table 1. Convection coefficient for steady free convection in an enclosed space – calculation relations

Heat transfer regime	Relation
$0 < Gr \cdot Pr < 10^3$	$\varepsilon = 1$
$10^3 < Gr \cdot Pr < 10^6$	$\varepsilon = 0.105 \cdot (Gr \cdot Pr)^{0.3}$
$10^6 < Gr \cdot Pr < 10^{10}$	$\varepsilon = 0.4 \cdot (Gr \cdot Pr)^{0.2}$

Considering that the water temperature decrease is linear in the area of influence from the freezing device (previously confirmed experimentally [6]), the average convection heat transfer coefficient for the water inside the pipe shall be calculated considering five stages reached by the water before freezing, namely: 20 °C, 15 °C, 10 °C, 5 °C and 0.5 °C, respectively.

In ANSYS Fluent Solver is not allowed the direct implementation of the dimensionless values (i.e. Grashof, Prandtl, Rayleigh numbers, etc.). For the heat transfer analysis with Rayleigh numbers greater than 108, the User's guide [7] recommends implementing a two-step solver [6] presented in the following:

- The first stage consists of a stationary analysis for calculating the reduced gravitational acceleration correspondent to the Rayleigh number, the fluid properties [8-10], the pipe geometrical characteristics and the heat transfer potential to be used in a secondary non-stationary analysis as an approximation for the simulation performed with the real gravitational acceleration values. The water heat transfer coefficients in an enclosed space will be calculated using a dimensionless coefficient for each stage of the water temperature decrease towards 0 °C (20 °C, 15 °C, 10 °C, 5 °C and 0.5 °C).

$$g = \frac{\overline{Ra} \cdot \overline{\nu} \cdot \overline{\alpha}}{\overline{\beta} \cdot \Delta T \cdot D_i^3} \quad (8)$$

where:

$\overline{Ra}$ = average value for the Rayleigh number for each stage of the water temperature decrease process towards 0 °C

ΔT = average temperature difference between water and pipe (determined experimentally) [6], ΔT = 51.1 K

Considering the new values for the gravitational acceleration g, the CFD simulation requires that the Grashof numbers and the thermal conductivities for each stage of the water freezing process should also be recalculated using the Eqs. (5-7). The results are shown in Tables 2, 3 and 4, respectively.

Table 2. Equivalent thermal conductivities for different water stages used in the CFD simulation for the 200 mm pipe

Water temp. [°C]	***g*** **[m/s²]**	***Gr***	***ε***	**λ_{ech} [W/m·K]**
20	0.53	$3.46 \cdot 10^6$	12.00	7.16
15		$1.46 \cdot 10^6$	10.40	6.11
10		$4.68 \cdot 10^5$	8.54	4.92
5		$7.07 \cdot 10^4$	6.07	3.45
0.5		$9.11 \cdot 10^3$	4.17	2.33

Table 3. Equivalent thermal conductivities for different water stages used in the CFD simulation for the 300 mm pipe

Water temp. [°C]	***g*** **[m/s²]**	***Gr***	***ε***	**λ_{ech} [W/m·K]**
20	0.18	$1.39 \cdot 10^6$	10.01	5.97
15		$5.87 \cdot 10^5$	8.67	5.09
10		$1.89 \cdot 10^5$	7.12	4.11
5		$2.85 \cdot 10^4$	5.06	2.87
0.5		$3.67 \cdot 10^3$	3.48	1.94

Table 4. Equivalent thermal conductivities for different water stages used in the CFD simulation for the 400 mm pipe

Water temp. [°C]	***g*** **[m/s²]**	***Gr***	***ε***	**λ_{ech} [W/m·K]**
20	0.11	$1.17 \cdot 10^6$	9.67	5.77
15		$4.94 \cdot 10^5$	8.38	4.92
10		$1.59 \cdot 10^5$	6.88	3.97
5		$2.40 \cdot 10^4$	4.89	2.78
0.5		$3.09 \cdot 10^3$	3.36	1.88

▪ The second stage consists in an ANSYS Fluent CFD simulation for the ice plug formation using the water heat transfer coefficients resulted from the first stage using the ε coefficient.

Computational model for the required liquid nitrogen

According to Fourier's equations for calculating the heat flux transferred through a solid wall and Newton's equations for calculating thermal convection, the total amount of heat absorbed by the freezing device during ice plug formation is equal to the sum between the heat transferred at each stage of the water freezing process in the area under the influence from the device and the heat transferred to the pipe wall and then to the working agent inside the pipe.

$$Q_t = Q_1 + Q_2 + Q_3 + Q_4 \quad (9)$$

where:

Q_t = total heat absorbed by the freezing device, [J]

Q_1 = total heat removed from the water to cool it from 20 °C to 0 °C, [J]

$$Q_1 = m_a \cdot c_{p_a} \cdot (T_a - T_0) \quad (10)$$

with:

m_a = mass of water under the influence from the freezing device, [kg]

c_{p_a} = isobaric specific heat for water at T_a temperature, [J/kg · K]

T_0 = 273.15 K - water freezing temperature

Q_2 = heat removed to freeze the water at 0 °C, [J]

$$Q_2 = m_a \cdot C_{LS_a} \quad (11)$$

Q_3 = heat required to lower the ice temperature to the average value of the primary formation of the ice plug, [J]

$$Q_3 = m_a \cdot c_{p_g} \cdot (T_0 - T_{fp}) \quad (12)$$

with:

c_{p_g} = isobaric specific heat for water at T_{fp} temperature, [J/kg · K]

T_{fp} = temperature at which the primary ice plug formation occurs, [K]

Q_4 = heat loss in pipe wall and in the corresponding volume of water, [J]

$$Q_4 = Q_{pc} \cdot Q_{pa} \quad (13)$$

with:

Q_{pc}= heat loss in the pipe wall, [J]

$$Q_{pc} = 2 \cdot \frac{\lambda_c}{L_c} \cdot \Delta T_c \cdot \pi \cdot (r_e - r_i)^2 \cdot t \quad (14)$$

where:

L_c = pipe length corresponding to $T(L_c)$ temperature, [m]

$\Delta T_c = T(L_c) - T_{mc}$ = medium pipe temperature gradient between the end of the ice plug $T(L_c)$ temperature and the zone under influence from the freeze device T_{mc}, [K]

r_e = pipe exterior radius, [m]

r_i = pipe interior radius, [m]

t = time required for the ice plug primary formation, [s]

$$Q_{pa} = 2 \cdot \frac{\overline{\lambda_{ech}}}{L_c} \cdot \Delta T_c \cdot \pi \cdot r_i^2 \cdot t \qquad (15)$$

where:

$\overline{\lambda_{ech}}$ = water average equivalent thermal conductivity taking into account its thermal conductivity λ_a and the correction coefficient ε, [W/m · K]: $\overline{\lambda_{ech}} = \lambda_a \cdot \varepsilon$ (16)

The mass of liquid nitrogen required for the primary ice plug formation is given below:

$$m = N \cdot 2 \cdot m_{a_{N_2}} \qquad (17)$$

where:

N = number of required liquid nitrogen moles,[moles]

$$N = \frac{Q_t}{C_{LV_{N_2}}} \qquad (18)$$

with $C_{LV_{N_2}}$ = liquid nitrogen latent heat of vaporization, [J/mol]

$m_{a_{N_2}}$ = nitrogen atomic mass, [u].

Results and comparative analysis

To calculate the pipe wall temperature variation, the following 4 points were chosen:

- next to the upstream end of the freezing zone in the upper (Th3) and lower (Th4) sides of the pipe;
- next to the downstream end of the freezing zone in the upper (Th7) and lower (Th8) sides of the pipe.

The water temperature was calculated in a reference point on the pipe axis, at a distance of ~ 3 meters from the centre of the freezing zone.

200 mm nominal diameter pipe

The ice plug was primarily formed 85 min after the start of the 3D simulation (see Fig. 2).

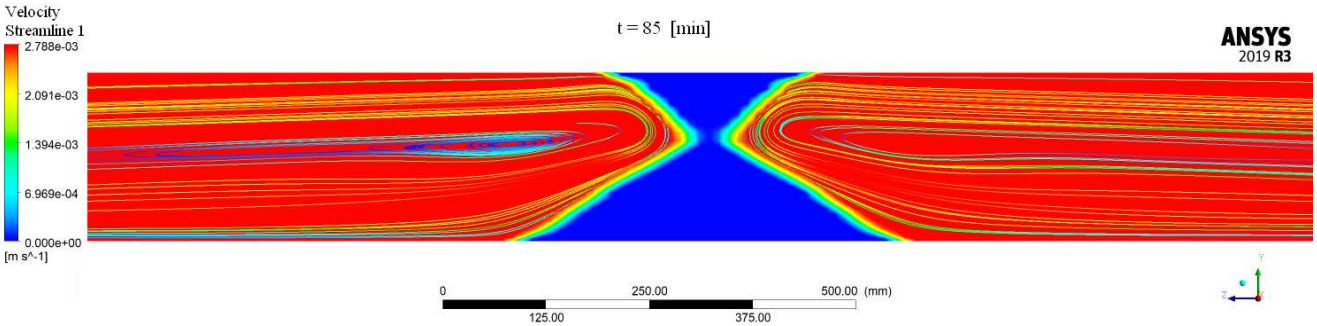


Fig. 2. Primary ice plug formation and water convection currents on the 200 mm pipe, t = 85 min

The water temperature decreased during the simulation by 10 °C (from 20 °C to 10 °C) with an average temperature gradient of 0,106 °C/min (see Fig. 3).

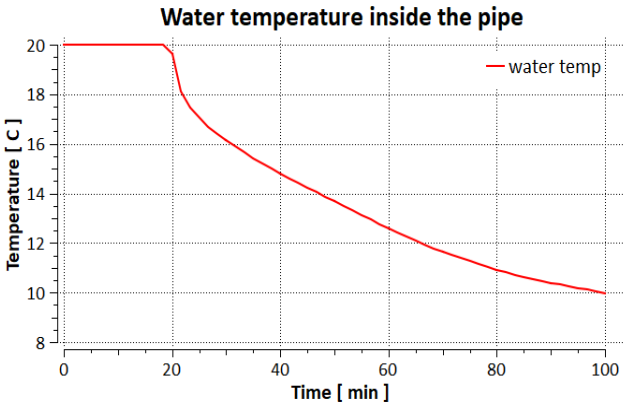


Fig. 3. Water temperature variation during the 200 mm pipe freezing

Due to the water natural circulation caused by the density variation, the upper pipe wall has a slower rate of decrease during the first 85 min (until the primary formation of the ice plug). The temperatures calculated at the two ends of the freezing zone coincide due to the symmetry of the analysed installation, both at the upper side of the pipe (Th3 – Th7) and in the lower side (Th4 – Th8).

The large difference between the temperatures calculated at the bottom of the pipe (Th4 and Th8) compared to those at the top (Th3 and Th7) is reflected in a difference between the ice layers lengths and thicknesses, and implicitly in the ice plug closing point, above the pipe axis (see Fig. 4).

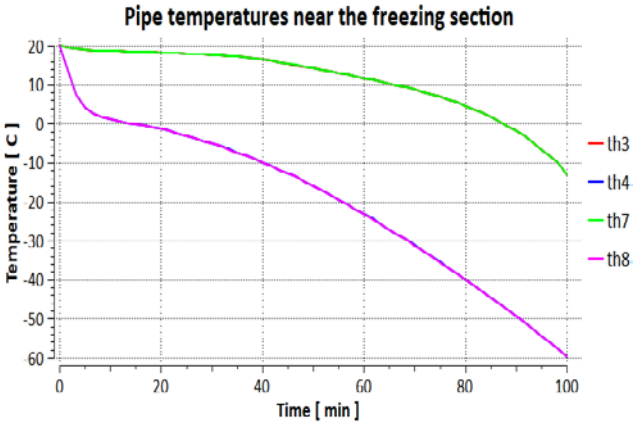


Fig. 4. 200 mm pipe wall temperatures variation at the ends of the freezing zone

The estimated liquid nitrogen requirement for forming an ice plug inside a 200 mm pipe with stationary water at an initial temperature of 20 °C is 79.7 kg.

300 mm nominal diameter pipe

The ice plug was primarily formed 156 min after the start of the 3D simulation (see Fig. 5).

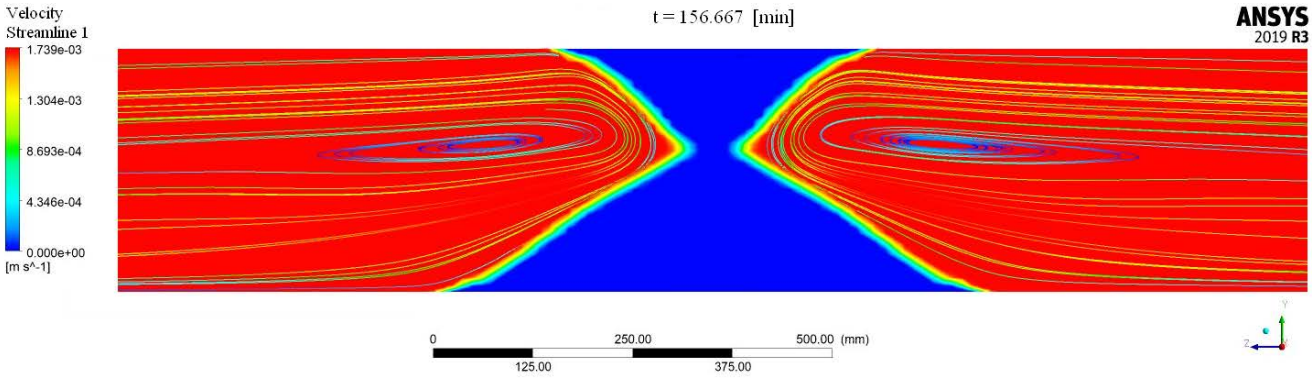


Fig. 5. Primary ice plug formation and water convection currents on the 300 mm pipe, t = 156 min

The water temperature decreased during the simulation by 12.4 °C (from 20 °C to 7.6 °C), with an average temperature gradient of 0.063 °C/min (see Fig. 6).

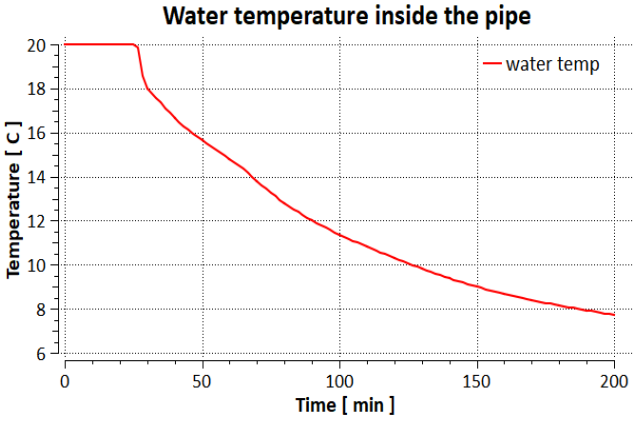


Fig. 6. Water temperature variation during the 300 mm pipe freezing

The temperatures calculated at the two ends of the freezing zone coincide due to the symmetry of the analysed installation, both at the upper side of the pipe (Th3 – Th7) and in the lower side (Th4 – Th8), as presented in Fig. 7.

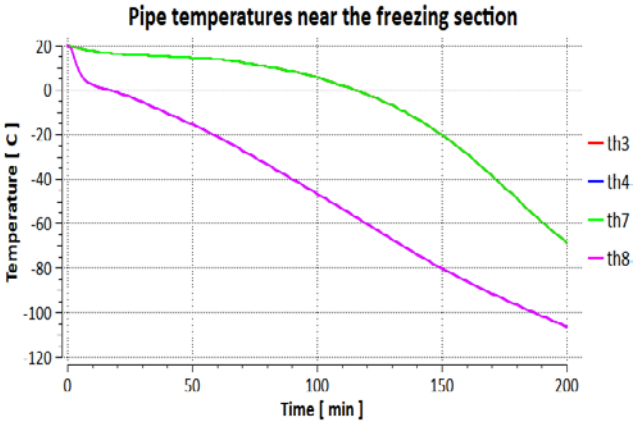


Fig. 7. 300 mm pipe wall temperatures variation at the ends of the freezing zone

The estimated liquid nitrogen requirement for forming an ice plug inside a 300 mm pipe with stationary water at an initial temperature of 20 °C is 188.6 kg.

400 mm nominal diameter pipe

The ice plug was primarily formed 221 min after the start of the 3D simulation (see Fig. 8).

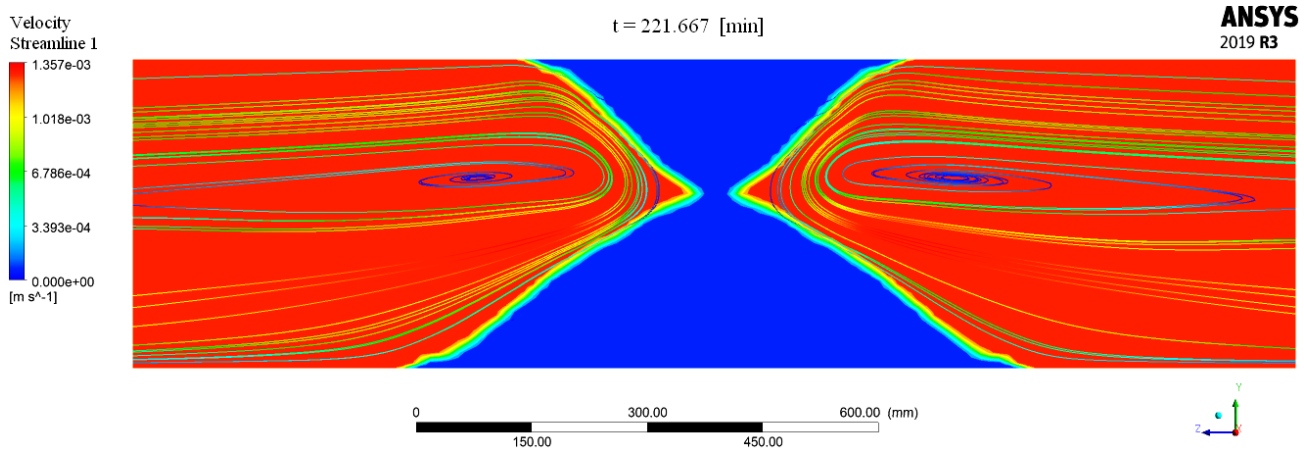


Fig. 8. Primary ice plug formation and water convection currents on the 400 mm pipe, t = 221 min

The water temperature decreased during the simulation by 13 °C (from 20 °C to 7 °C) with an average temperature gradient of 0.052 °C/min (Fig. 9). Temperatures calculated at the two ends of the freezing zone are shown in Fig 10.

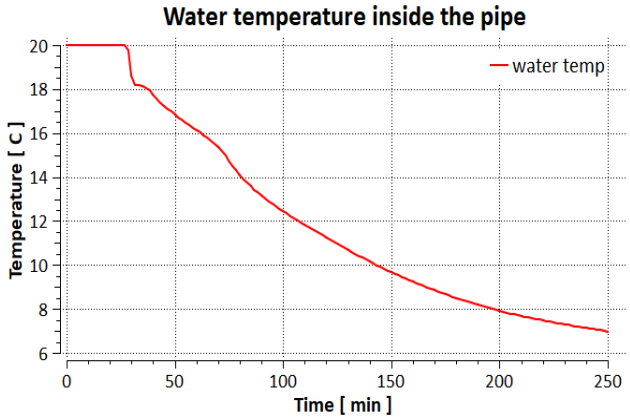


Fig. 9. Water temperature variation during the 400 mm pipe freezing

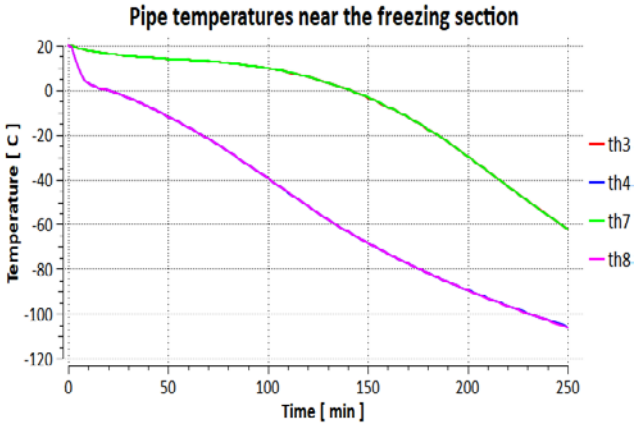


Fig. 10. 400 mm pipe wall temperatures variation at the ends of the freezing zone

The estimated liquid nitrogen requirement for forming an ice plug inside a 400 mm pipe with stationary water at an initial temperature of 20 °C is 356.9 kg. The evolutions of the lengths of the ice layers during the 200 mm pipe freezing are presented in Fig. 11.

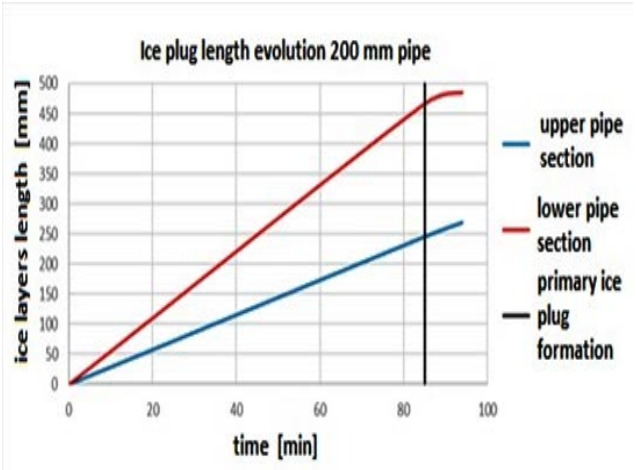


Fig. 11. Ice layers evolutions during the 200 mm pipe freezing

During the 300 mm pipe freezing test, the temperatures measured on the outer pipe wall dropped to much lower values compared to the similar test conducted on a 200 mm pipe, reaching ~ –71 °C at the top and ~ –107 °C at the bottom of the pipe. This decrease also reflects in a higher water temperature variation (~ 12.4 °C).

The primary ice plug formation took place after 156 min; at this moment the ice layers measured ~ 376 mm on the upper pipe wall and ~ 662 mm on the lower pipe wall (131 and 195 mm, respectively, longer compared to the test conducted on the 200 mm pipe). After this moment, the ice plug thickness continued to grow (at a much slower rate at the bottom of the pipe) as presented in Fig. 12.

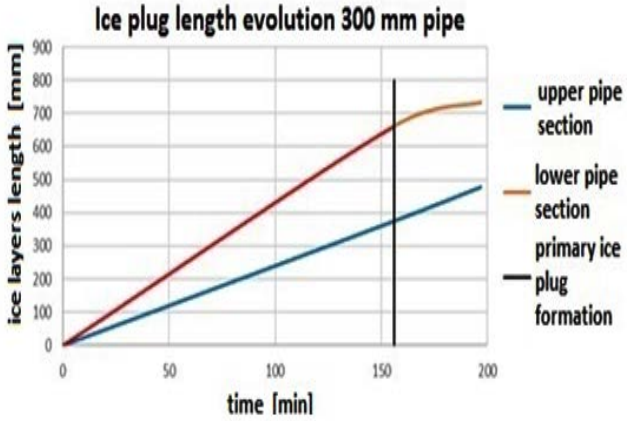


Fig. 12. Ice layers evolutions during the 300 mm pipe freezing

At the end of the 400 mm pipe freezing test, temperatures reached ~ –60 °C at the top of the pipe and ~ –107 °C at the bottom, similar results to the 300 mm pipe freezing test. The ice plug was primarily formed after 221 min; at this moment the ice layers measured ~ 469 mm on the upper pipe wall and ~ 780 mm on the lower pipe wall (93 mm and 118 mm, respectively, longer compared to the test conducted on the 300 mm pipe) as shown in Fig. 13.

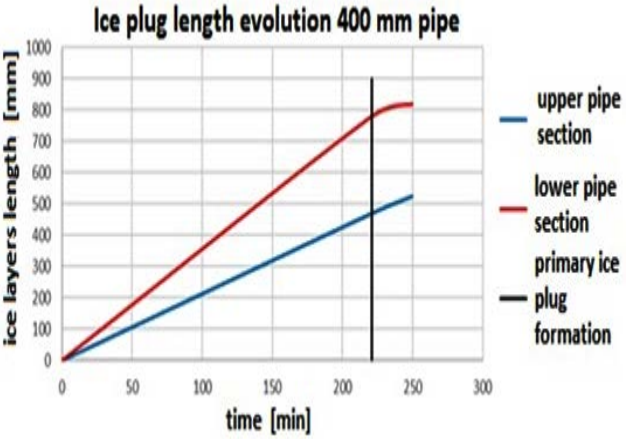


Fig. 13. Ice layers evolutions during the 400 mm pipe freezing

Conclusions

Technological pipe freezing represents a fast, clean and efficient method for carrying out repairs and piping alterations without having to isolate or drain an entire piping system.

Over the past 30 years, pipe freezing for temporary pipe isolation has become one of the safest, reliable and cost-effective methods for allowing valve replacement and general pipe work modifications.

The paper goal was to perform a heat transfer analysis for the ice plugging process used on large diameter pipes.

A CFD computational model using ANSYS Fluent was developed to predict the time needed for the controlled ice plugs forming inside pipelines with various diameters, containing stationary water at 20 °C initial temperature.
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Meantime, a calculus model was proposed to characterize liquid nitrogen quantity required for the ice plug formation inside the pipes.

As much as the speed of the convection currents decreases, the nominal diameter of the pipes increases, as can be seen in the previous section (see Fig. 2, Fig. 5 and Fig. 8, respectively). Increasing of the pipe diameter lead to a reduction in the length of the ice plugs (relative to the pipe diameter).

The estimated quantities of liquid nitrogen required for the ice plugs formation inside the considered large diameter pipes increased from 80 kg for a 220 mm exterior diameter pipe, to about 190 kg for a 320 mm exterior diameter pipe, and reaches about 360 kg for a 420 mm exterior diameter pipe.

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