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CRYOGENIC PIPE FREEZING, A MODERN METHOD FOR THE MAINTENANCE OF NPP HYDRAULIC CIRCUITS

Doctoral thesis summary

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Keywords: pipe freezing, liquid nitrogen, horizontal pipe, finite volume method, ANSYS Fluent.

INTRODUCTION

1. *The topicality and opportunity of the thesis*

The potential for failure and the problems that arise from the occurrence of the aging phenomenon may increase as more and more installations approach the end of their projected lifespan. In the case of nuclear power plants, most of the problems related to the aging of SSC (Systems, Structures and Components) appear after 20 years.

Thus, the cryogenic pipe freezing technology is becoming a solution, due to a series of advantages:

- The actual duration of the intervention is reduced: the preparation for the intervention, the downtime period and the time necessary for re-commissioning;
- It eliminates the costs of transferring and storing liquid from the system or installation.

2. *Study objectives*

The aim of this paper was to develop a calculation model using the CFS program ANSYS Fluent 2019 R3 to simulate the pipe freezing process of horizontal in a stationary flow regime of water to meet the following requirements:

- Correlation of the results obtained from modelling with those obtained experimentally for the 200 mm nominal diameter pipeline;
- Using the experimentally validated model in the development of applications for larger nominal diameters pipes (from 300 to 800 mm).

3. *General content presentation*

In the first chapter of the thesis, several general aspects regarding the pipe freezing technology were presented along with the topicality and opportunity of the thesis. Also, the fields of applicability of this technology, the advantages of its use, the equipment and the intervention stages are described and detailed.

In the second chapter, several heat transfer aspects are analysed; a fist theoretical method for calculating the time and liquid nitrogen required to freeze a 200 mm nominal diameter horizontal pipe in a stationary flow regime. Also, a series of technical and practical concerns regarding the use of the pipe freezing technology in industrial installations are identified and calculated: the effects of cryogenic freezing on the pipe material, and the maximum allowed pressures and efforts for welded pipes. The problem of implementing the cryogenic freezing technology in the nuclear energy industry is being studied, with reference to the feeder area and the condenser cooling water circuit. Finally, some conclusions are drawn regarding the pipe freezing technology, and the study objectives of this paper are presented.

The third chapter describes the CFD modelling (using the ANSYS Fluent software) of the heat transfer during the progressive working agent solidification process inside the pipe until the ice plug's complete formation.

The fourth chapter presents a pipe freezing experiment performed on a 200 mm nominal diameter pipeline in stationary water; its purpose was to validate and verify the calculation model and the results obtained by the CFD simulation

In the fifth part's first subchapter several pipe freezing analyses by one ice plug were performed on pipes having 200 mm (at an initial water temperature of 20°C and 25°C), 300 mm and 400 mm nominal diameters (at an initial water temperature of 20°C). The input parameters and the results regarding the time required for the ice plugs formation, the natural convection currents inside the working fluid, the ice layers growth rate, the water temperature variation, and the pipe wall temperatures variation at the two ends of the freezing area are presented for each particular case. At the end of each case, the required liquid nitrogen quantity is calculated. Comparative results studies are performed at the end of the subchapter. Similarly, in the next subchapters, other horizontal pipe freezing analyses are performed using two ice plugs (on 200, 300, 400 and 500 mm nominal diameter pipes) and three ice plugs (on 600, 700 and 800 mm nominal diameter pipes); comparative result studies are performed at the end of the chapter.

The last two chapter of this thesis present the general conclusions, the original contributions of the author and detail the prospects for future research.

4. Prospects for future research

- Analyses for the effects of film and nuclear boiling on the heat transfer inside the freezing device;
- Cryogenic devices design for larger pipes;
- Streamlining the pipe freezing process by appropriately sizing the liquid nitrogen compartments according to each application requirements;
- Streamlining the pipe freezing process by more than one ice plugs by determining the optimal installation mounting distances for the freezing devices on the outer pipe wall;
- Liquid nitrogen injection control by varying the flow during the process;
- Structural analysis of the forces exerted on the pipe by the expanding ice plugs;
- Using the verified computation models for the research of freezing vertical pipes;
- Using the freezing technology on non-metallic pipes.

5. Observations

- All software programs and operating systems used during the research were licensed for use (Microsoft Windows, Microsoft Office and ANSYS Fluent 2019 R3);
- The experiments were organized and carried out in such a way as not to affect the health of the operational staff, always taking into account the protection of the environment.

Chapter 1. CRYOGENIC PIPE FREEZING

1.1. CRYOGENIC PIPE FREEZING ASPECTS

1.1.1. General considerations

In any industrial installation, the properties of the materials deteriorate during operation due to the stresses to which the components are subjected. The potential for failure and the problems that arise from the occurrence of the aging phenomenon can increase as more and more installations approach the end of their projected lifespan. In the case of nuclear power plants, methods of isolating the affected area are limited and usually involve decommissioning a large section of the plant or even the entire system.

1.1.2. Advantages of the pipe freezing technique

Cryogenic freezing is an economically efficient technique used to solidify the liquid inside a pipe to form a pressure-resistant plug, in order to isolate portions of a hydraulic installation that cannot be separated from the rest of the circuit by other methods. This makes it easier to carry out maintenance activities or network modifications without the need to drain or decommission the entire system. By reducing the duration of the intervention, the duration of the objective is reduced and implicitly the financial effort of the applicant.

1.1.3. Pipe freezing

1.1.3.1. The freezing device

The method involves applying a sleeve to the outside of the pipe in the chosen area (Fig. 1.1 [1]); the freezing device has a hollow interior into which will a liquid refrigerant (CO_2 or N_2) will be injected [2].

Fig. 1.1 - Rigid freezing device with liquid nitrogen circulation

The refrigerant draws heat from the device and pipe walls and from the liquid inside the pipe determining the local pipe wall temperature reduction and favouring the deposition of ice in successive layers, until the pipe section’s full closure.

1.1.3.2. The refrigerant

Typically, the refrigerant used for pipe freezing applications for pipes with a nominal diameter (Dn) of less than 50 mm is liquefied CO_2 and liquefied N_2 for pipes with a nominal diameter of up to 1220 mm.

1.1.3.3. Freezing the fluid in a portion of the pipe

The fluid freezing process in a specific portion of the pipe can occur as a result of a combined heat transfer process (conduction and convection) in which the predominant role belongs to the convection currents. The intensity of the convection heat transfer process largely depends on the mixing motion of the fluid. The intensification of the heat transfer process requires the acceleration of movement as a result of an external cause, a process called forced convection.

1.2. PIPE FREEZING HYSTORY

1.2.1. Between 1940 and 1980

Beginning in the 1940s, the method of cryogenic pipe freezing started being used in the United States in several types of installations (energy or defence industries). Later, the technology was adapted for hydraulic tests of strength and tightness of piping systems, especially leakage testing on buried lines [3].

1.2.2. After 1980

In the United Kingdom (at the University of Southampton) a program has been launched (still in operation today) for fundamental and applied research in cryogenics. The thermodynamic aspects of the vertical and horizontal pipes freezing process for different materials were studied.

1.2.3. Preoccupations in Romania

The technology was procedurally applied at Unit 1 in Cernavodă, at the fuel channel inlet/outlet feeders. Pipe freezing (using three ice plugs) was also used in the condenser water cooling circuit when an intervention was needed on a Dn 600 pipe. The intervention was not completed successfully; the stationary time of the installation was long and plastic deformation of the pipe wall in the freezing area was identified.

1.3. SAFETY PROCEDURES

1.3.1. Planning

Specific process elements and parameters must be taken into consideration since the planning procedures; visual inspections of the pipe, installation, supports location is also required for choosing the optimal position for the freezing device.

1.3.2. Personnel safety and labour protection measures

When forming and maintaining an ice plug, there are risks to both the operational staff and the installation equipment as a result of the action of the substances used in the process and the working conditions. It is therefore necessary to establish an action plan for the technicians involved in the process.

1.3.3. Other precautions

1.3.3.1. Personnel precautions

Appropriate protective clothing and equipment for cryogenic liquids are mandatory. The room must be properly ventilated, and the oxygen concentration in the air must be measured permanently.

1.3.3.2. Equipment precautions

Pipe freezing requires a series of checks throughout the whole process, both in the preparation phase and during the actual intervention.

1.3.4. The stages of the pipe freezing process

1.3.4.1. Identify the optimal area for mounting the freezing device

The ice plug should not be formed in fittings, valves or other operating components. It is also not recommended that the ice plug is formed in welded area; a non-invasive visual inspection of the pipe segment should be carried out before the start the freezing operations [4]. It is preferable to freeze a horizontal section of the pipe to avoid the complications that occur in vertical pipes due to the more pronounced convection currents, which can hinder the heat transfer process.

1.3.4.2. Determining the appropriate freezing agent and the required quantity

The determination should be done considering a series of factors: the pipe properties, the working agent properties and the environment properties.

1.3.4.3. Technological equipment preparation

The outside of the freezing device must be insulated accordingly. The temperature limits specified in the literature are: <43°C for the environment and <107°C for the working agent inside the pipe. If the working agent temperature is much higher than the ambient temperature, it must be reduced to a value as close as possible to the ambient temperature before the freezing process begins.

1.3.4.4. Forming the ice plug

In the case of water, the ice plug formation typically involves the circulation of liquid nitrogen in a jacket that wraps around the pipe in the area chosen to be frozen; the sleeve constitutes the freezing device (Fig. 1.2).

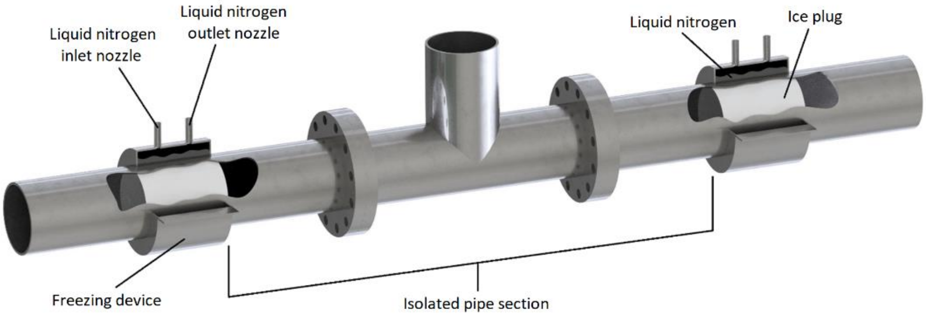

Fig. 1.2 - Installation section being isolated by two ice plugs

Before starting the operation, the air inside the pipe must be removed as it prevents the ice plug formation on the entire circumference of the pipe. The cryogenic liquid inside the freezing device (usually liquid nitrogen) extracts heat from the pipe wall and from the liquid phase inside the pipe. The heat thus absorbed vaporizes some of the nitrogen and is transported outside from the device by the vapours. At the exhaust nozzles, liquid nitrogen vapours have a maximum −193°C [2] [5]. During the ice plug formation, the liquid inside the pipe should be stationary. There are a critical flow and a critical pipe diameter above which it is impossible to achieve total pipe freezing [4]. In the case of multiple ice plugs formation (typically for pipes with Dn ≥ 350 mm), the distance between two plugs can be equal or greater than the pipe nominal diameter. For pipes with Dn ≤ 350 mm, the minimum distance between two ice plugs is 4·Dn.

1.3.4.5. Maintaining the ice plug

The outer pipe wall temperature must be constantly monitored during the pipe freezing process to confirm the structural integrity of the ice plug.

1.3.4.6. Melting the ice plug

After the completion of the repair operations performed on the pipeline, the liquid nitrogen is drained from the freezing device at the same time as the installation is refilled downstream from the ice plug and the upstream and downstream pressures are equalized. The freezing device is removed to allow the accelerated melting of the stopper to begin. The ice plug must be melted rapidly from one side of the pipe to allow the working agent to flow gradually. Do not use open flames to avoid damaging the pipe.

1.4. CONCLUSIONS

- Cryogenic freezing is an economically efficient technique used to solidify the liquid inside a pipe to form a pressure-resistant plug, in order to isolate portions of a hydraulic installation that cannot be separated from the rest of the circuit by other methods.
- The cryogenic pipe freezing method can be successfully used in nuclear installations, as they are usually provided with a small number of valves; therefore, the methods of isolating the affected area through taps / by-passes in order to carry out maintenance activities or modifications to the network are limited and usually involve draining or decommissioning a large section of the installation or even the entire system.

Chapter 2. STUDIES REGARDING THE PIPE FREEZING PROCES INSIDE A PIPE FROM A NPP HYDRAULIC CIRCUIT

2.1. THEORETICAL MODELING OF THE CRYOGENIC FREEZING OF A HORIZONTAL PIPE

An example of a calculation model was presented by H. Tinoco in the paper “Cryogenic pipe freezing − a theoretical model” in 1988 [6]. Freezing water inside a pipe is characterized by the problem of freezing the thermal boundary layer, located in a closed space and in a continuous evolution towards the axis of the pipe, for which there is no exact analytical solution [7] [8].

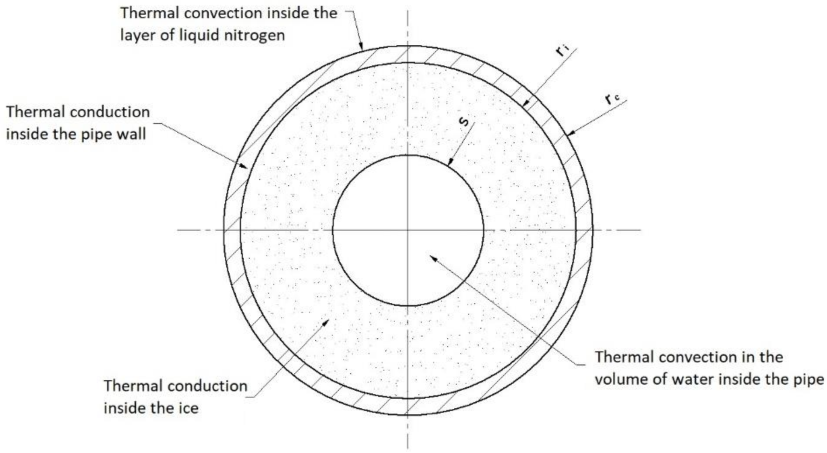

Fig. 2.1 - Heat transfer from the water inside the pipe towards the liquid nitrogen inside the freezer

The heat transfer from the water inside the pipe towards the surrounding liquid nitrogen (Fig. 2.1) is [7]

$$\dot{Q}' = 2\pi k\left(T_a - T_{lN_2}\right) = -2\pi\rho c_{LS} s\frac{ds}{dt}\ , \tag{2.1}$$

where:

- $\dot{Q}'$ − linear unit heat flux, [W/m];
- k − the overall heat transfer coefficient given by the relation(2.2), $[\mathrm{W/m\cdot K}]$;
- T_a – water temperature, [K];
- T_{lN_2}− liquid nitrogen temperature, [K];
- ρ – water density, $[\mathrm{kg/m^3}]$;
- c_{LS} – water latent heat of solidification, [J/kg];
- s − the inner radius of the region bounded by the position of the boundary layer at a given time, [m];
- t – time period, [s].

$$\frac{1}{k} = \frac{1}{r_e \propto_{lN_2}} + \frac{\ln\frac{r_e}{r_i}}{\lambda_c} + \frac{\ln\frac{r_i}{s}}{\lambda_g} + \frac{1}{s \propto_a}\ , \tag{2.2}$$

where:

- r_i – pipe inner radius, [m];
- r_e – pipe outer radius, [m];
- $\propto_{lN_2}$ – liquid nitrogen convection coefficient, $[\mathrm{W/m^2\cdot K}]$;

- λ_c – pipe steel convection coefficient, $[\mathrm{W/m \cdot K}]$;
- λ_g – ice thermal conductivity, $[\mathrm{W/m \cdot K}]$;
- $\propto_a$ – water convection coefficient, $[\mathrm{W/m^2 \cdot K}]$.

2.2. PROBLEMS OCCURRED DUREING PIPE FREEZING

Ice plug slippage

Ice plug slippage can only occur due to improper cryogenic liquid supply or due to the start of the pipe repairs before full plug completion and stabilization.

Pipe deformation and brittle rupture

Studies have shown that, although the mechanical properties of the material change with temperature, even the systematic repetition of several freeze-thaw cycles did not permanently affect the pipe steel, which regained its properties when returned to normal working temperatures [9]. The decrease of the wall temperature of the pipes made from ferritic alloys influences the material properties, as its breaking behaviour changes from ductile to brittle; crossing this threshold takes place in a narrow temperature range [10] [11]. The presence of welding defects, thickness variations or other manufacturing defects contribute to the propagation of cracks. Cracks may also be caused by shocks during the operation [12] [13] [14] [15].

2.3. THE EFFECTS OF CRYOGENIC FREEZING ON PIPES

2.3.1. Effects of cryogenic freezing on pipe material

The limits of elasticity and flow, the resistance to plastic deformation, in some cases also the hardness, the fatigue resistance and the modulus of elasticity of the metals, increase with the decrease of the temperature. At negative temperatures, however, among the mechanical characteristics, of particular importance are the toughness (ductility), significantly reduced, as well as the tendency of brittle fracture (notch sensitivity) of metals and alloys. They are decisively influenced by the content of alloying elements, the degree of deformation (hardening), the heat treatments applied to steels, cast irons and non-ferrous alloys for use in cryogenics [16].

2.3.2. Mechanical calculation of the efforts exerted on the pipe

The pressure exerted by the formation of the ice plug

Before starting the pipe freezing operation, it is necessary to determine both the values of the pressure formed by the evolution of the ice plug and the allowable pressures for the pipe undergoing the intervention. Table 2.1 shows examples of pressure values caused by the ice plug length increase inside a Dn 200 ($D_e = 219$ mm, $D_i = 203$ mm) 15-meter-long pipe.

Table 2.1

Pressure formed by the ice plug length increase inside a Dn 200 pipe, calculated for a 15 meters long pipe

Ice plug length increase [mm]	1	5	10	15	20	30	40	50	75	100
Pressure formed inside the volume of liquid [bar]	0.96	4.78	9.56	14.34	19.13	28.7	38.3	47.91	71.98	96.13

2.4. PIPE FREEZING TECHNOLOGY IMPLEMENTATION IN THE NUCLEAR ENERGY INDUSTRY

2.4.1. Feeder area

The freezing jacket assemblies were designed only as means of insulation for the maintenance of fuel channels, each feeder having a freezer assembly consisting of a jacket, tubbing for the liquid nitrogen supply and tubbing for thermocouple insertion. This method is used to seal feeder pipes with ice plugs in order to isolate the pressure tubes individually.

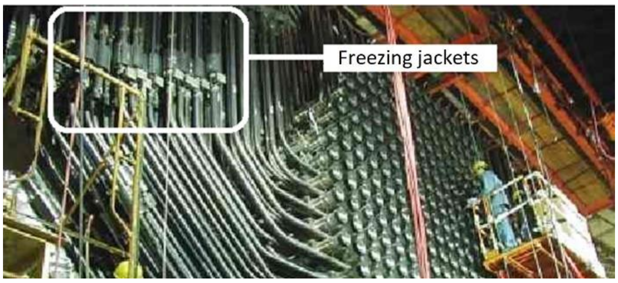

Fig. 2.2 - Freezing jackets mounted on feeder tubes

Freezing jackets are mounted on the feeder pipe, resting on the mounting weld between the lower and upper feeders (Fig. 2.2) [17].

2.4.2. Condenser water cooling circuit

In 2001, in an attempt to repair a horizontal water-cooling pipe (Dn 24”, 600 mm) at Unit 1 Cernavodă, two ice plugs were formed in order to reduce the flow so that by it will be totally stopped by the third ice plug. The actual intervention was not completed successfully; after the dismantling the freezing devices, the plastic deformation of the pipe wall in the area of the freezers was identified.

2.5. CONCLSIONS

- In the specialized industry, a series of technical concerns have been raised both regarding the theoretical modelling of the thermal transfer during pipe freezing and also regarding a series of problems specific to the process;
- The consequences of the implementation and improper use of the pipe freezing process were investigated, the effects of cryogenic temperatures on the pipe material were identified and analysed and a mechanical calculation model of the exerted efforts was presented.

Chapter 3. CALCULATION MODELS FOR FREEZING THE STATIONARY WATER INSIDE A DN 200 PIPE

3.1. THE NEED TO USE A CALCULATION MODEL

The pipe freezing technology is an attractive research topic both for the specialized institutions around the world and for companies. Generally, these researches are aiming at: determining the opportunity cost and/or cost efficiency, the efficiency of the technology, the development of the fields of applicability, the elimination of the risks and the dissemination of the advantages of using the technology.

The objective of the calculation models presented in this chapter is to determine the time and amount of liquid nitrogen required to perform pipe freezing of a Dn 200 pipe at an initial temperature of the stationary working agent (water) of 15°C, for a constant flow of cryogenic agent (liquid nitrogen) injected into the freezing device. Two calculation variants are considered:

- *The first variant* involves using the simplified Hernan Tinoco model [6] (presented in paragraph 2.1) to determine the time required for the ice plug primary formation. Considering the calculated time, the required quantity of liquid nitrogen can be determined;
- *The second variant* involves performing a non-stationary CFD analysis (using the ANSYS Fluent program) of the heat transfer during the freezing process of a horizontal pipe under the same conditions as in the first calculation variant.

3.2. NUMERICAL CALCULATION APPLICATION

3.2.1. Mathematical apparatus

At the beginning of the cryogenic freezing process, the radial heat flow from the water towards the outside of the pipe involves five distinct processes: conductive heat transfer in the pipe water, convective transfer in the pipe water and to the inner wall of the pipe, conductive transfer through the pipe wall, convective heat transfer from the outer pipe wall towards the liquid nitrogen and the phase change (boiling) of the liquid nitrogen (Fig. 3.1).

As the ice layers deposit on the inner pipe wall, a sixth process occurs, that of 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.

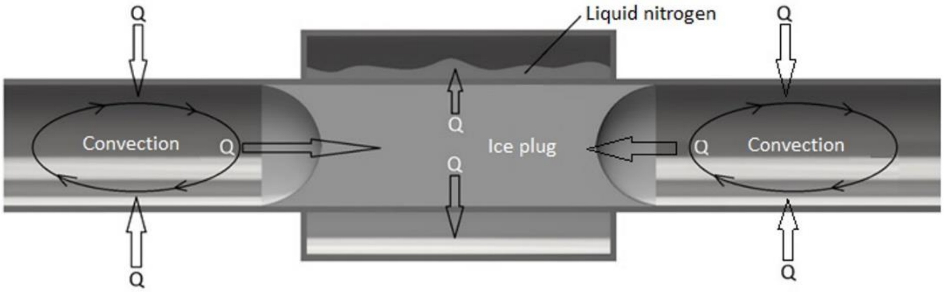

Fig. 3.1 - Heat transferred during the freezing of a horizontal pipe

The freezing of water inside a pipe is characterized by the problem of freezing the thermal boundary layer, located in a closed space and in a continuous evolution towards the axis of the pipe, for which there is no exact analytical solution. An approximate solution can be obtained following a stationary analysis which assumes that the heat transfer from water to ice, at the level of the moving thermal boundary layer, is constant.

The length of time $t[\mathrm{s}]$ in which the ice plug is primarily formed is given by the relation [6]:

$$t = \frac{\rho_a \cdot c_{LS} \cdot {r_i}^2 \cdot \mathrm{C}}{\lambda_g \cdot \left(T_a - T_{lN_2}\right)}\ , \tag{3.1}$$

where:

- ρ_a – water density, [kg/m^3];
- c_{LS} – water latent heat of solidification, [J/kg];
- r_i – pipe inner radius, [m];
- T_a – initial water temperature, [K];
- T_{lN_2} – liquid nitrogen temperature, [K];
- C – constant given by the relation [6]

$$\mathrm{C} = \frac{1}{4} + \frac{\lambda_g}{2}\left(\frac{\ln\frac{r_e}{r_i}}{\lambda_c} + \frac{1}{r_e \propto_{lN_2}} + \frac{2}{r_i \propto_a}\right), \tag{3.2}$$

where:

- ○ r_e – pipe outer wall, [m];
- ○ λ_c – pipe steel convection coefficient, [W/m · K];
- ○ $\propto_{lN_2}$ – liquid nitrogen convection coefficient, [W/m^2 · K],

$$\overline{\propto_{lN_2}} = 0{,}25 \cdot \sqrt[3]{\frac{\lambda''^2 \cdot c_p'' \cdot g(\rho' - \rho'')}{\nu''}}\ , \tag{3.3}$$

  where:

  - λ'' – nitrogen vapour film thermal conductivity;
  - c_p'' – nitrogen vapour film specific heat;
  - g – gravitational acceleration;
  - ρ' – liquid nitrogen density;
  - ρ'' – nitrogen vapour film medium density;
  - ν'' – nitrogen vapour medium kinematic viscosity.

- ○ $\propto_a$ – water convection coefficient, [W/m^2 · K],

$$\propto_\mathrm{a} = \overline{\propto_\mathrm{a}} = \frac{\overline{\lambda_{ech}}}{r_i}\ .$$

The total amount of heat transferred to the freezing device must be determined in order to calculate the liquid nitrogen requirement for the application. According to Fourier's equation for calculating the heat flux transferred through a solid wall and Newton’s equation for calculating thermal convection, the total heat absorbed by the freezing device during ice plug formation is equal to the sum of the amounts of heat transferred at each stage of the process in the area of influence from the freezing device plus the heat transferred to the pipe wall and then to the volume of working agent.

3.2.2. Time required to freeze Dn 200 horizontal pipe at an initial water temperature of 15°C

Considering that the water temperature decrease is linear in the area of influence from the freezing device (which will be confirmed experimentally on chapter 3), the mean heat transfer coefficient through convection for the water inside the pipe shall be calculated considering four stages that the water reaches before freezing: 15°C, 10°C, 5°C and 0,5°C

The results are shown in Table 3.1.

Table 3.1

Equivalent thermal conductivities for different water-cooling stages - numerical application

Water temperature [°C]	Pr	Gr	ε	λ_{ech} [W/m · K]
15	8,17	$26{,}8 \cdot 10^6$	18,62	10,93
10	9,45	$8{,}61 \cdot 10^6$	15,28	8,82
5	11,37	$1{,}3 \cdot 10^6$	10,86	6,17
0,5	13,55	$1{,}67 \cdot 10^5$	7,47	4,17

The average equivalent thermal conductivity is

$$\overline{\lambda_{ech}} = 7{,}52\ \mathrm{W/m \cdot K}. \tag{3.3}$$

The average water convection coefficient is calculated with the relation

$$\propto_a = \overline{\propto_a} = \frac{\overline{\lambda_{ech}}}{r_i} = 74{,}1\ \mathrm{W/m^2 \cdot K}. \tag{3.4}$$

Resulting

$$\mathrm{C} = 0{,}8074\,; \tag{3.5}$$

$$t_{max} = 3744{,}4\ \mathrm{s}\,. \tag{3.6}$$

3.2.3. The cryogenic liquid requirements

The total amount of heat absorbed by the freezing device throughout the ice plug development process (Q_t) is equal to the heat transferred during each stage of the process in the freeze area plus the heat loss through the pipe wall and the water inside the pipe:

$$Q_t = Q_1 + Q_2 + Q_3 + Q_4\,,$$

where:

- Q_t – total amount of heat absorbed by the freezing device, [J];
- Q_1 – necessary heat extracted from the water volume in order for it to reach 0°C, [J]:
- Q_2 – necessary heat extracted from the water volume at 0°C in order for it to freeze, [J];
- Q_3 – necessary heat extracted from the ice in order for it to reach the temperature required for the ice plug formation, [J];
- Q_4 – heat loss in the pipe wall and in the water around the ice plug, [J].

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

$$m = N \cdot 2 \cdot m_{a_{N_2}}\,,$$

where:

- N – number of liquid nitrogen moles required for the ice plug formation,

$$N = \frac{Q_t}{C_{LV_{N_2}}} = 2621{,}97\ \mathrm{moli}\,,$$

  where $C_{LV_{N_2}} = 0{,}72\ \mathrm{kJ/mol}$ – liquid nitrogen latent heat of vaporization;
- $m_{a_{N_2}} = 14\ \mathrm{u}$ – nitrogen atomic mass.

Resulting

$$m = 73{,}4\ \mathrm{kg}. \tag{3.7}$$

3.3. CFD MODEL

In a CFD analysis, the dynamics of a fluid is examined according to its physical properties, such as speed, pressure, temperature, density, and viscosity. In order to generate the solution of a physical phenomenon in the field of fluid mechanics, without compromising on accuracy, these properties must be considered simultaneously.

3.3.1. The calculation program

The ANSYS software suite of calculation programs allow the interconnection of several types of calculation and analysis, thus being an indispensable tool for all industrial applications. CFD simulations (Fluent, CFX, etc.) are used successfully to streamline costs and working time in industries such as: energy, automotive, aerospace, petrochemical, electrical and electronics, medicine, construction, sports, etc.

3.3.2. Methods of implementing a CFD calculation

The process of numerical modelling of a CFD application involves five stages: CAD design, domain discretization with finite volumes, physical definition, solving and post-processing stage (analysis of results).

3.3.3. Geometric model implementation

3.3.3.1. Introduction

The main objective of this CFD modelling is to calculate the time required to plug horizontal pipes filled with stationary water with ice plugs, for a constant flow of liquid nitrogen injected into the freezing devices. The two phase-change processes (liquid nitrogen vaporization and water freezing) cannot be simulated at the same time by the calculation program, as they use different models to solve equations that describe the phenomena characteristic to the studied problem depending on the turbulence models and phases. processes. Thus, they will be treated separately in two stages, having the advantage of reducing the program load and thus the total calculation time:

- ➢ In the first stage, we calculate the thermal flow at the outer pipe wall corresponding to the boiling area of the refrigerant and the water equivalent thermal conductivity for each cooling stage until reaching the freezing temperature;
- ➢ In the second stage, with the energy transfer data calculated in the first stage, the solidification of the working agent inside the pipe is modelled using ANSYS Fluent.

3.3.3.2. Modelling the analysis domain geometry

The geometry of the chosen model was implemented using the Design Modeler environment specific to the ANSYS software. A 6-meter-long pipe divided into three sections was 3D modelled in (Fig. 3.2). The heat flux calculated on the basis of the average heat transfer coefficient of the liquid nitrogen inside the freezer using the relation (3.3) shall be applied to the outer surface of the central section. The heat transfer between the outer walls of the other two pipe sections and the environment is neglected.

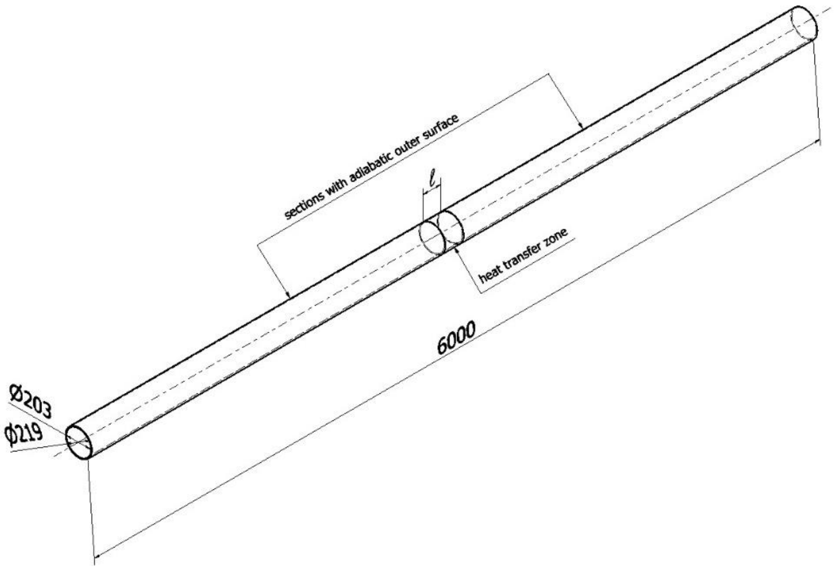

Fig. 3.2 - Analysis domain sizing Dn 200 pipe – 1 heat transfer zone

The outer pipe wall temperature variation was calculated in 8 points: immediately next to the freezing zone, upstream and downstream in the lower and upper positions (4 points) and 100 mm from the freezing zone, upstream and downstream in the lower and upper positions (4 points). The water temperature calculation was made at a reference point located on the pipe axis at the upstream end of the fluid volume.

The computing domain discretization using the finite volume method was performed with the Meshing program of the ANSYS suite. Following the implementation of the discretization algorithm resulted a calculation network consisting of 684226 elements and 710236 nodes.

3.3.4. Modelling the thermal transfer during the pipe freezing of a Dn 200 horizontal pipe at an initial water temperature of 15°C

The models implemented into the calculation program are: Multiphase − Volume of Fluid; Energy; Viscous-laminar; Solidification & Melting.

3.3.4.1. Material properties

To each field implemented in the calculation program (the pipe steel – steel with 0.1% carbon, water and ice), the corresponding properties according to the variations of the process temperature were assigned [18] [19] [20] [21].

3.3.4.2. Initial and boundary conditions

Initial conditions

- Initial water temperature: 15°C;
- Water pressure: 2 bar.

Boundary conditions

a. On the outer pipe wall, in the freezing area

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

$$\dot{Q}" = \overline{\propto_{lN_2}}\, \Delta T_{15} = 177{,}96 \cdot 211 = 37549{,}28\ \mathrm{W/m^2}\ , \qquad (3.8)$$

where ΔT_{15} − is the heat transfer potential (the temperature between the water inside the pipe and the liquid nitrogen boiling temperature), $\Delta T = T_a - T_{lN_2} = 211$ K.

b. On the other pipe wall surfaces, the heat flux will be neglected:
   - Between the pipe outer wall and the environment on the surfaces next to the freezing zone (upstream and downstream);
   - At the upstream and downstream ends of the pipe.

3.3.4.3. Modelling the phase change

The ANSYS Fluent Solver does not allow the direct implementation for the dimensionless values (Grashof, Prandtl, Rayleigh numbers, etc.). For the heat transfer analysis with Rayleigh numbers greater than 10^8 recommends implementing a two-step solver:

1. *The first stage* will consist of a stationary analysis for calculating the reduced gravitational acceleration correspondent to the Rayleigh number, the fluid properties, the pipe geometrical characteristics and the heat transfer potential:

$$g = \frac{\overline{\mathrm{Ra}} \cdot \bar{\nu} \cdot \bar{\alpha}}{\bar{\beta} \cdot \Delta T \cdot {d_i}^3} \cdot \tag{3.9}$$

$$\varepsilon = f(\mathrm{Ra}) = f(\mathrm{Gr} \cdot \mathrm{Pr})$$

$$Gr = \frac{g \cdot \beta(T) \cdot \Delta T \cdot l^3}{\nu(T)^2} \tag{3.10}$$

   The results obtained in the first stage for the calculation of the equivalent thermal conductivities for water for each cooling stage of cooling are presented Table 3.2.

Table 3.2

Equivalent thermal conductivities for different water-cooling stages - CFD simulation

Water temperature [°C]	Pr	Gr	ε	λ_{ech} [W/m · K]
15	8,17	$1{,}11 \cdot 10^6$	9,85	5,78
10	9,45	$3{,}56 \cdot 10^5$	8,08	4,66
5	11,37	$5{,}38 \cdot 10^4$	5,75	3,26
0,5	13,55	$6{,}93 \cdot 10^3$	3,95	2,2

2. *The second stage* will be an ANSYS Fluent CFD simulation for the ice plug formation using the water heat transfer coefficients resulted from the first stage, and the values for density, specific heat, thermal conductivity (for ice), dynamic and kinematic viscosities and the thermal expansion coefficient.

3.3.5. Results

One hour after the start of the 3D simulation, the temperatures calculated on the outer wall of the pipe dropped below 0°C; the moment also marked the primary ice plug formation. To stabilize the plug, the simulation was continued for a further 34 minutes. The evolutions of the lengths and thicknesses of the ice layers during the simulation are presented (Fig. 3.3, Fig. 3.4).

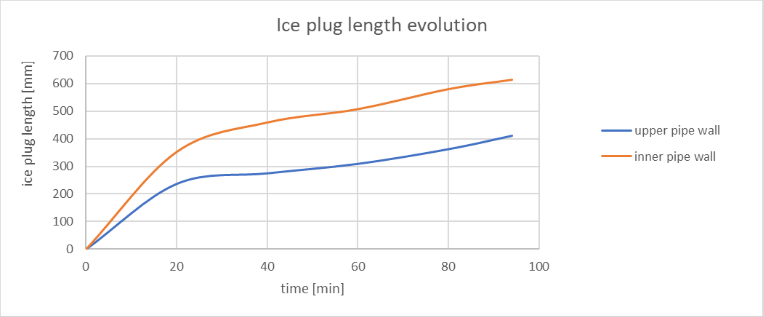

Fig. 3.3 - Ice plug length evolution on the inner pipe wall during the 3D simulation

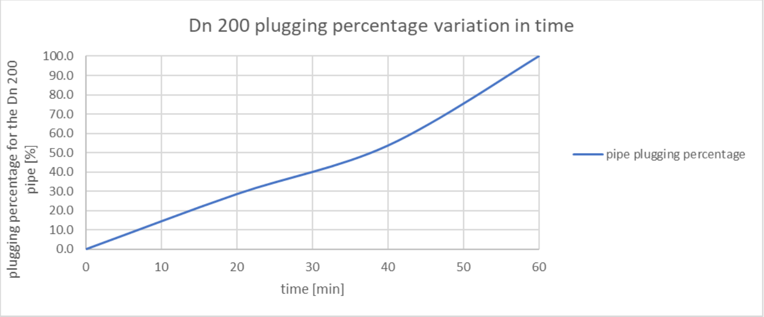

Fig. 3.4 - Pipe plugging evolution during the 3D simulation

The water temperature decrease during the simulation was 5,1°C (Fig. 3.5).

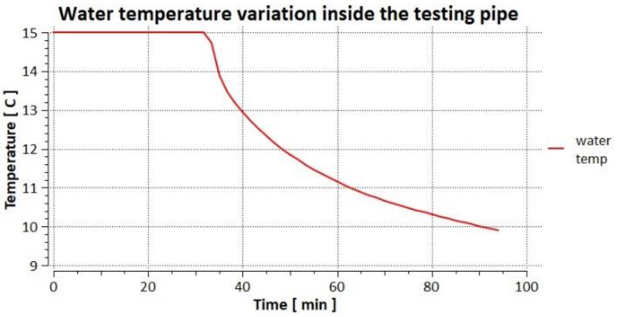

Fig. 3.5 - Water temperature variation at the reference point during the simulation

The temperatures calculated at the two ends of the freezing zone (upstream and downstream) coincide due to the symmetry of the analysed installation (Th3 - Th7 and Th4 - Th8) (Fig. 3.6). The cooling of the lower pipe wall (Th4 and Th8) occurs suddenly during the first 10 minutes and later has a linear evolution reaching −85,7°C after 94 minutes −85,7°C.

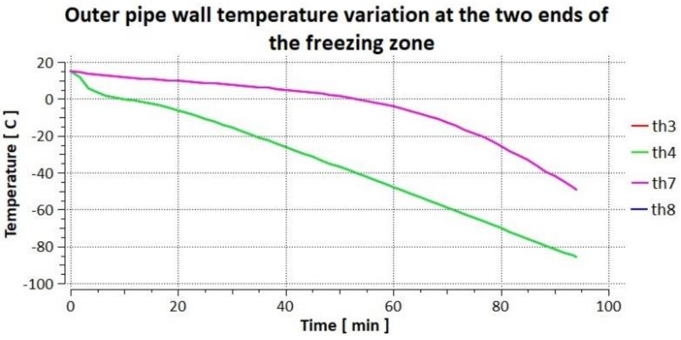

Fig. 3.6 - Pipe wall temperature variations at the ends of the freezing zone

For the calculation of the liquid nitrogen requirement, we used the average temperatures of the pipe wall and of the water collected during the simulation and the calculation method presented in paragraph 3.2.3. The calculated liquid nitrogen requirement for freezing a horizontal Dn 200 pipe containing stationary water at an initial temperature of 15°C is 74,8 kg.

3.4. CONCLUSIONS

- The geometric model for the ice plug formation installation was elaborated, the system with finite volumes was discretized and subsequently the ice plug formation inside the pipe was modelled using the data obtained in the first calculation stage.
- The primary ice plug formation was obtained 60 minutes after the start of the 3D simulation. The simulation continued for another 34 minutes, during which time the ice deposits evolved in both length and thickness.
- The calculated liquid nitrogen requirement for freezing a horizontal Dn 200 pipe containing stationary water at an initial temperature of 15°C is 74,8 kg.

Chapter 4. PIPE FREEZING EXPERIMENTAL RESEARCHES FOR A Dn 200 HORIZONTAL PIPE IN STATIONARY WATER

4.1. RESEARCH OBJECTIVES

The experiment aims to perform the freezing of a Dn 200 pipe containing stationary water at an initial temperature of 15°C, using a constant flow of cryogenic agent (liquid nitrogen) injected into the freezing device. During the test the following measurements and observations will be performed:

- The temperature variation for water, for the outer pipe wall (at several reference points), for the liquid nitrogen inside the freezing device and for the nitrogen vapours at the exhaust nozzle;
- The evolution of the ice layers inside the pipe;
- The times for the primary ice plug formation and its stabilisation;
- The total mass of liquid nitrogen consumed throughout the experiment.

4.2. EXPERIMENTAL FACILITIES AND EQUIPMENT

4.2.1. The experimental installation

The experiment was performed in the Fuel Elements Testing Stand of RATEN ICN Pitești on the test installation used for the pipe freezing technique development. The experimental loop is designed to work in an open circuit and contains a recirculation pump, a set of pipes and fittings, a filling-emptying water tank, a series of valves and measuring devices (manometers and pressure transducers). The measurement of pressures and temperatures and their recording is done with a digital data acquisition system.

4.2.2. The freezing device

The freezing device is composed of two subassemblies bolted together forming a collar with an annular compartment around the outside of the pipe [22] representing the liquid nitrogen compartment. The device is thermally insulated on the outside by vacuum compartments.

4.2.3. The video surveillance device

The geometric characteristics of the ice plugs resulting from the experiments performed on the Dn 200 testing pipe vary depending on the test conditions (initial water temperature and the flow of liquid nitrogen injected into the circuit) and the manoeuvres performed during the test. Studying the evolution of the ice deposits in the area influenced by the freezing device facilitates data collection which is useful for the process development and for the thermal calculation and design of freezing devices in order to further develop the technique for applications that include larger diameter horizontal pipes (up to Dn 800) [23].

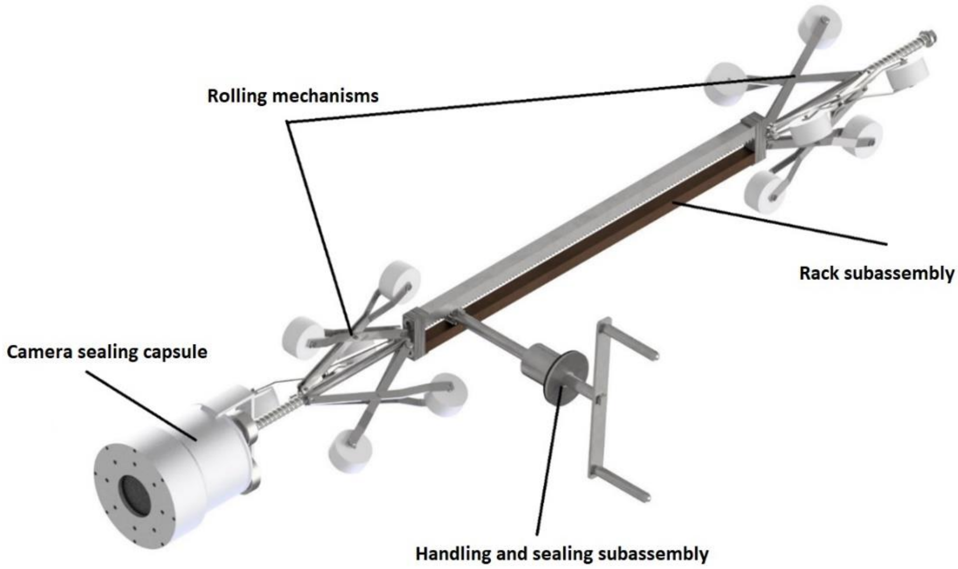

Fig. 4.1 - Video surveillance system for the ice plug formation (isometric representation)

For this purpose, the design and execution of a support device for a video camera was performed (Fig. 4.1). The device is mounted inside the horizontal testing pipe and allows real-time visualization of the formation of ice layers as a result of the experimental conditions and manoeuvres performed on the liquid nitrogen injection flow, in order to develop a comparative analysis with the theoretical results for different ice plug formation stages.

4.2.4. Measuring equipment

4.2.4.1. The temperature sensors

During the experiment, for measuring the temperature variation at the level of the pipe wall, Fe-Constantan thermocouples were placed (having the temperature measuring range of −200÷780°C and the sensitivity of 0.025÷0.063 mV/°C):

- Next to the freezing zone both upstream (in the upper – Th3 and lower – Th4 sides of the pipe) and downstream (in the upper – Th7 and lower – Th8 sides of the pipe);
- 100 mm from the freezing zone both upstream (in the upper – Th1 and lower – Th2 sides of the pipe) and downstream (in the upper – Th9 and lower – Th10 sides of the pipe);
- Inside the freezing device (Th5) at the tip of the nitrogen vapour exhaust nozzle (Th6).

The water temperature was measured at a reference point on the pipe axis at the upstream end of the fluid volume.

4.2.4.2. The pressure transducers

The pressure of the working agent in the experimental loop during the application is measured by a pressure transducer mounted downstream from the test section. Additionally, to signal the moment of primary ice plug formation, the pressure drop on the ice plug is measured by a differential pressure transducer having the sockets at both ends (upstream and downstream) of the test section.

4.3. THE EXPERIMENTAL APPLICATION

The water temperature in the test section was 14,9°C at the beginning of the test. The liquid nitrogen injection pressure was set at a constant value p throughout the application through a valve mounted at the transfer hose inlet. 79 minutes after the start of the test the ice plug was primarily formed (Fig. 4.2). The outer pipe wall temperatures measured −44,8°C and −47,3°C on the upper section of the pipe upstream and downstream (Th3 and Th7) and −64,4°C and −67,8 on the lower half of the pipe upstream and downstream (Th4 and Th8). The water temperature measured 13,1°C.

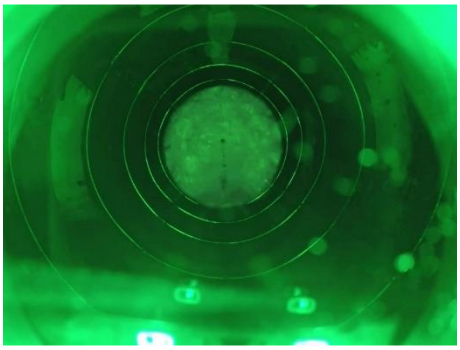

Fig. 4.2 - Primarily formed ice plug

After 17 minutes the pressure-drop on the ice plug reached 0,2 bar. Subsequently, the pipe sections upstream and downstream of the test section were dismantled in parallel with the emptying of the installation and their removal. To measure the amount of liquid nitrogen consumed during the freezing process, the Dewar vessel was weighed before the start of the test and at the end; the amount of liquid nitrogen consumed for the application was 116 kg.

4.4. EXPERIMENTAL RESULTS INTERPRETATION

The lengths and thicknesses evolutions of the ice layers are presented by reference to the equidistant rings of the indicator device (Fig. 4.3, Fig. 4.4).

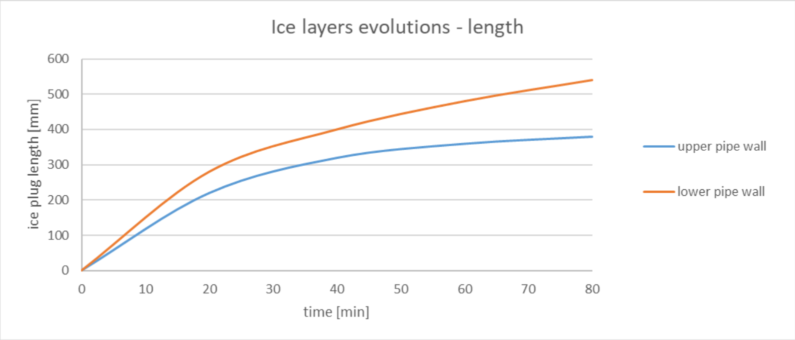

Fig. 4.3 - Ice layers evolutions inside the Dn 200 testing pipe, up to the moment of primary plug formation

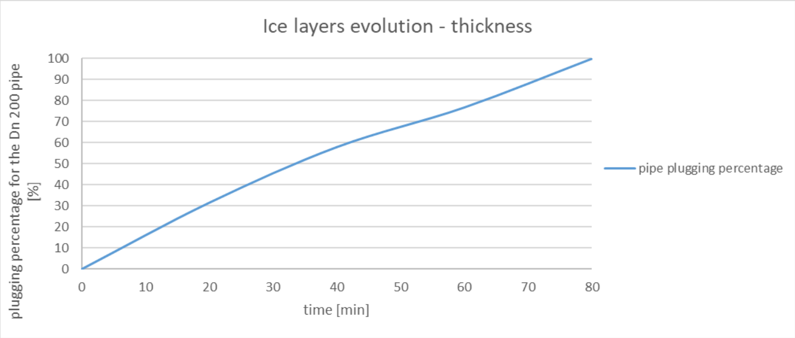

Fig. 4.4 - Pipe plugging evolution - experimental results

The water temperature reduction throughout the experiment was small, only 2,2°C (from 14,9°C at the beginning of the test to 12,7°C at the end) (Fig. 4.5). The outer pipe wall temperature variations at the upstream and downstream ends of the freezing zone are presented (Fig. 4.6).

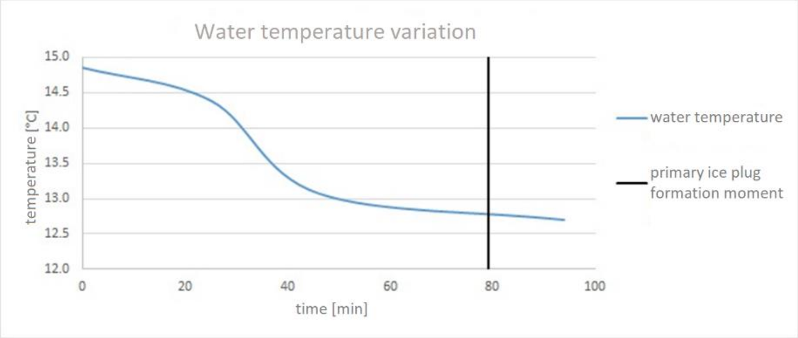

Fig. 4.5 - Water temperature variation on the reference point during the experiment

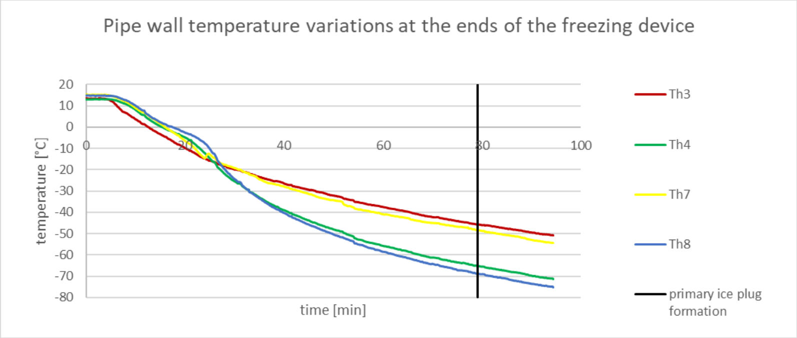

Fig. 4.6 - Pipe wall temperature variation at the ends of the freezing device

4.5. THEORETICAL MODELS VALIDATION

The temperatures measured during the experimental application in the upper half of the pipe at the two ends of the freezing zone (Th3 and Th7) have a different variation from those obtained from the Ansys Fluent simulation (Fig. 4.7). This is due to the cryogenic agent injection into the freezer sleeve circuit through the nozzle mounted at the top; liquid nitrogen first flows on the upper pipe wall, so that temperatures drop abruptly after the first 3 minutes and later have an almost linear decrease.

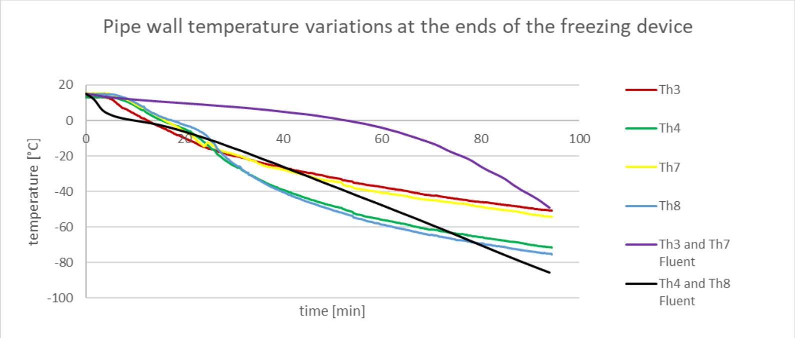

Fig. 4.7 - Pipe wall temperature variations comparison (experiment and ANSYS Fluent simulation) at the ends of the freezing device

Temperatures measured at 100 mm from the ends of the freezing zone at the top of the pipe (Th1 and Th9) have a linear decrease during the two experiments (Fig. 4.8).

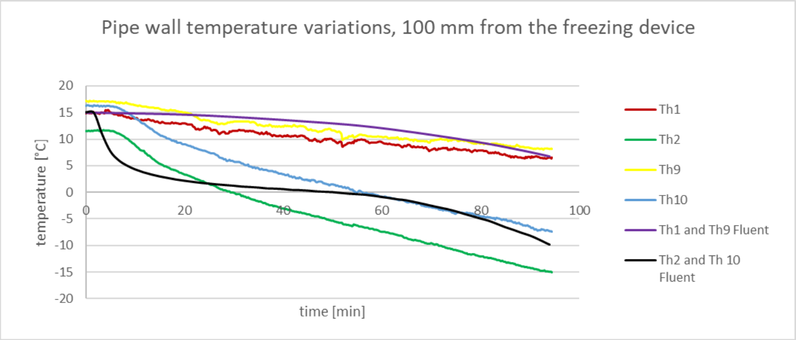

Fig. 4.8 - Pipe wall temperature variations comparison (experiment and ANSYS Fluent simulation) 100 mm from the ends of the freezing device

Data corelation

For each regression line obtained, the square of the correlation coefficient R^2 was determined. A correlation coefficient (R^2) can have values in the range $[0,1]$; the closer its value is to 1, the stronger the correlation, and vice versa, the closer it is to 0, the weaker the correlation. If $R^2 \geq 0{,}8$, the correlation obtained is considered to be good, and if $R^2 \geq 0{,}9$, then the corelation is considered to be very good.

The corelation coefficients obtained are presented in Table 4.1.

Table 4.1

Correlation coefficients between the temperature values obtained by the two methods (experimental and CFD simulation)

Temperature measuring point	Th1	Th2	Th3	Th4	Th7	Th8	Th9	Th10	Water temp.
R^2	0,848	0,8571	0,6764	0,9143	0,6629	0,9174	0,8731	0,8428	0,9601

The primary ice plug formation duration of during the experiment is about 31% longer than in the case of the calculation model (79 min compared to 60 min). On the Ansys Fluent model, 74.8 kg of liquid nitrogen were calculated to be necessary for the primary ice plug formation, while during the experiment 98.7 kg were consumed (approximately 32% higher). The main causes for these differences are given by the implementation of the CFD model which considers that the heat transfer on the outer surface of the pipe is uniform and constant. In reality, however, the higher concentration of biphasic liquid nitrogen - nitrogen vapor mixture at the top of the freezing device greatly reduces the heat flow, so that the decrease in temperatures measured by the thermocouples Th1 and Th9 is slower than that of temperatures measured by thermocouples Th4 and Th8.

4.6. CONCLUSIONS

- The experiment aimed at forming an ice plug inside a horizontal Dn 200 pipe containing a stationary working agent (demineralized water).
- The initial water temperature inside the test section was 14,9°C during. The liquid nitrogen injecting pressure into the freezing device was set at a constant value p throughout the application.
- The primary formation of the ice plug was obtained 79 minutes after the start of the test. To stabilize the plug, the experiment was continued for a further 34 minutes, during which time the ice layers evolved both in length and thickness.

- The primary ice plug formation duration of during the experiment is about 31% longer than in the case of the calculation model (79 min compared to 60 min). On the Ansys Fluent model, 74.8 kg of liquid nitrogen were calculated to be necessary for the primary ice plug formation, while during the experiment 98.7 kg were consumed (approximately 32% higher).
- The main causes for these differences are given by the implementation of the CFD model which considers that the heat transfer on the outer surface of the pipe is uniform and constant. In reality, however, the higher concentration of biphasic liquid nitrogen-nitrogen vapor mixture at the top of the freezing device greatly reduces the heat flow in this area.

Chapter 5. MODELLING THE ICE PLUG FORMATION IN LARGE DIAMETER HORIZONTAL PIPES IN DIFFERENT FREEZING DEVICES CONFIGURATIONS

5.1. SINGLE ICE PLUG PIPE FREEZING

5.1.1. Forming an ice plug inside a Dn 200 pipe at an initial water temperature of 20°C

5.1.1.1. Freezing model

For modelling the ice plug formation inside a Dn 200 pipe at an initial water temperature of 20°C, we used the same 3D domain geometry previously developed and presented in paragraph 3.3.3.2 as well as the discretisation model with finite volumes.

Also, the equivalent thermal conductivities λ'_{ech} were recalculated according to the ε coefficient (Table 5.1) [24].

Table 5.1

Parameters for modelling the ice plug formation inside a Dn 200 pipe at an initial water temperature of 20°C

Water temperature	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$1{,}53 \cdot 10^8$				
g_{20} [m/s^2]	0,53				
Gr	$3{,}46 \cdot 10^6$	$1{,}46 \cdot 10^6$	$4{,}68 \cdot 10^5$	$7{,}07 \cdot 10^4$	$9{,}11 \cdot 10^3$
ε	12	10,4	8,54	6,07	4,17
λ'_{ech} [W/m · K]	7,16	6,11	4,92	3,45	2,33

On the pipe wall (in the freezing zone), the heat flux absorbed by the volume of liquid nitrogen inside the freezing device is

$$\dot{Q}"_{20} = 38439{,}07\ \mathrm{W/m^2}\ .$$

5.1.1.2. Results

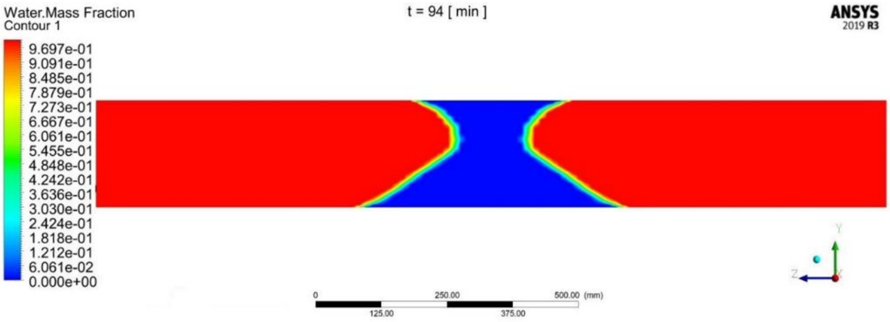

Fig. 5.1 - Ice deposits on the inner wall of the Dn 200 pipe (at an initial water temperature of 20°C) at the end of the simulation, t = 94 min

The ice plug was primarily formed after 85 minutes; the ANSYS Fluent simulation continued for another 9 minutes, during which time the ice layers continue to increase in length

(Fig. 5.1). The calculated liquid nitrogen requirement for freezing a horizontal Dn 200 pipe containing stationary water at an initial temperature of 20°C is 79,7 kg.

5.1.2. Forming an ice plug inside a Dn 200 pipe at an initial water temperature of 25°C

5.1.2.1. Freezing model

For modelling the ice plug formation inside a Dn 200 pipe at an initial water temperature of 20°C, we used the same 3D domain geometry previously developed and presented in paragraph 3.3.3.2 as well as the discretisation model with finite volumes. Also, the equivalent thermal conductivities λ'_{ech} were recalculated according to the ε coefficient (Table 5.2).

Table 5.2

Parameters for modelling the ice plug formation inside a Dn 200 pipe at an initial water temperature of 25°C

Water temperature	25°C	20°C	15°C	10°C	5°C	0,5°C
$\dot{Q}"_{25}$ [W/m^2]	39328,86					
$\overline{\mathrm{Ra}}$	$2{,}54 \cdot 10^8$					
g_{25} [m/s^2]	0,64					
Gr	$8{,}17 \cdot 10^6$	$4{,}16 \cdot 10^6$	$1{,}75 \cdot 10^6$	$5{,}63 \cdot 10^5$	$8{,}5 \cdot 10^4$	$1{,}1 \cdot 10^4$
ε	13,84	12,45	10,79	8,86	6,3	4,33
λ'_{ech} [W/m · K]	8,39	7,43	6,33	5,11	3,58	2,42

On the pipe wall (in the freezing zone), the heat flux absorbed by the volume of liquid nitrogen inside the freezing device is

$$\dot{Q}"_{25} = 39328{,}86\ \mathrm{W/m^2}\ .$$

5.1.2.2. Results

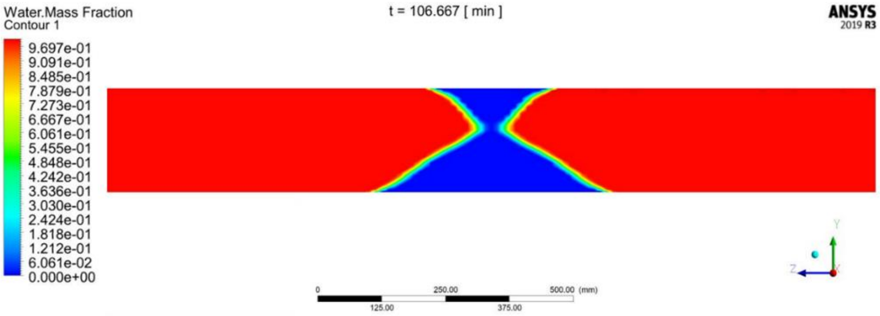

Fig. 5.2 – The moment of primary ice plug formation inside a Dn 200 pipe, at an initial water temperature of 25°C, after 106 minutes

The ice plug was primarily formed after 106 minutes (Fig. 5.2); the ANSYS Fluent simulation continued for another 10 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 200 pipe containing stationary water at an initial temperature of 25°C is 83,6 kg.

5.1.3. Forming an ice plug inside a Dn 300 pipe

5.1.3.1. Freezing model

For modelling the ice plug formation inside a Dn 300 horizontal pipe at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 304$ mm; outer pipe diameter: $D_e = 324$ mm; pipe length: $L = 6$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{300} = 1{,}05 \cdot l$ [mm] (where l – the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 946270 elements and 919836 nodes. Also, the parameters for ANSYS Fluent modelling were recalculated; the values obtained are presented in Table 5.3 [24].

Table 5.3

Parameters for modelling the ice plug formation inside a Dn 300 pipe at an initial water temperature of 20°C

Water temperature	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$1{,}78 \cdot 10^8$				
g_{20} [m/s^2]	0,18				
Gr	$1{,}39 \cdot 10^6$	$5{,}87 \cdot 10^5$	$1{,}89 \cdot 10^5$	$2{,}85 \cdot 10^4$	$3{,}67 \cdot 10^3$
ε	10,01	8,67	7,12	5,06	3,48
λ'_{ech}[W/m $\cdot$ K]	5,97	5,09	4,11	2,87	1,94

On the pipe wall (in the freezing zone), the heat flux absorbed by the volume of liquid nitrogen inside the freezing device is

$$\dot{Q}"_{25} = 38439{,}07 \text{ W/m}^2 .$$

5.1.3.2. Results

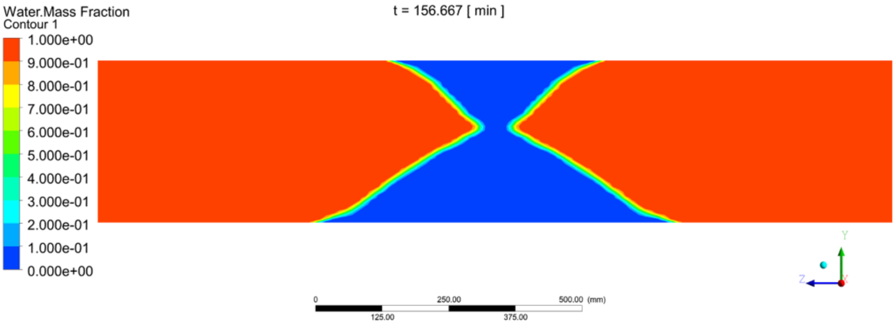

Fig. 5.3 - The moment of primary ice plug formation inside a Dn 300 pipe, at an initial water temperature of 20°C, after 156 minutes

The ice plug was primarily formed after 156 minutes (Fig. 5.3); the ANSYS Fluent simulation continued for another 41 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 200 pipe containing stationary water at an initial temperature of 20°C is 188,6 kg.

5.1.4. Forming an ice plug inside a Dn 400 pipe

5.1.4.1. Freezing model

For modelling the ice plug formation inside a Dn 400 horizontal pipe at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 400$ mm; outer pipe diameter: $D_e = 420$ mm; pipe length: $L = 6$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{400} = 1{,}17 \cdot l$ [mm] (where l − the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 1291500 elements and 1264466 nodes. Also, the parameters for ANSYS Fluent modelling were recalculated; the values obtained are presented in Table 5.4 [24].

Table 5.4

Parameters for modelling the ice plug formation inside a Dn 400 pipe at an initial water temperature of 20°C

Water temperature	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$2{,}46 \cdot 10^8$				
g_{20} [m/s^2]	0,11				
Gr	$1{,}17 \cdot 10^6$				
ε	9,67	$4{,}94 \cdot 10^5$	$1{,}59 \cdot 10^5$	$2{,}4 \cdot 10^4$	$3{,}09 \cdot 10^3$
λ'_{ech} [W/m · K]	5,77	8,38	6,88	4,89	3,36

On the pipe wall (in the freezing zone), the heat flux absorbed by the volume of liquid nitrogen inside the freezing device is

$$\dot{Q}'' = 38439{,}07\ \mathrm{W/m^2}\,.$$

5.1.4.2. Results

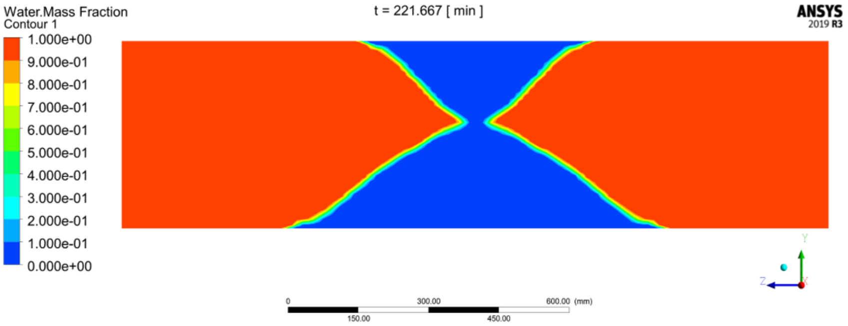

Fig. 5.4 - The moment of primary ice plug formation inside a Dn 400 pipe, at an initial water temperature of 20°C, after 221 minutes

The ice plug was primarily formed after 221 minutes (Fig. 5.4); the ANSYS Fluent simulation continued for another 29 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 400 pipe containing stationary water at an initial temperature of 20°C is 356,9 kg.

5.1.5. Results interpretation

The speed of convection currents during ice plug sealing applications decreases as the nominal pipe diameter increases (considering the shorter heat transfer zones relative to pipe diameters) (Fig. 5.2, Fig. 5.8, Fig. 5.14, Fig. 5.20). A lower intensity of the convection currents causes that at the moment of primary ice formation, the ratio between the pipe diameter and the length of the ice deposits on the inner wall decreases with the fluid volume increase in thickness (relative to the pipe diameter, the obturation is performed progressively smaller plugs).

5.2. DOUBLE ICE PLUG PIPE FREEZING

For the double ice plug pipe freezing analysis, we will use pipes with Dn 200, Dn 300, Dn 400 and Dn 500 containing water at an initial temperature of 20°C and at an initial working agent pressure of 2 bar.

In the implementation of the geometric models of the analysis domains (Fig. 5.5) two cooling zones with different unit heat flux were used: $\dot{Q}"_1 = 38439{,}07$ $[\mathrm{W/m^2}]$ and $\dot{Q}"_2 = 0{,}9 \cdot \dot{Q}"_1 = 34595{,}16$ $[\mathrm{W/m^2}]$, to avoid closing the two plugs at the same time (to avoid the production of an overpressure in the section between them, which in the case of a practical application could affect the integrity of the pipe wall).

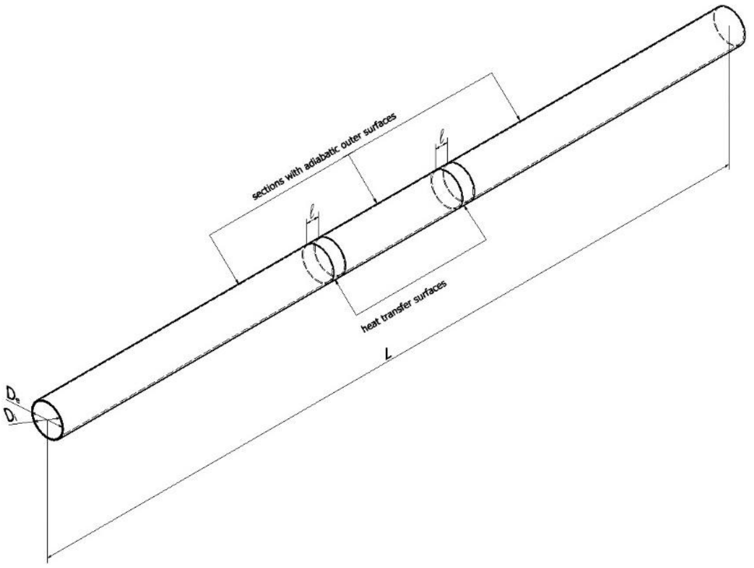

Fig. 5.5 - Analysis domain configuration for a double ice plug pipe freezing

The heat transfer between the testing pipe and the outer environment is neglected on the areas next to the freezing zones and at the upstream and downstream ends of the volume of fluid. The distance chosen between the two freezing zones was 4·Dn.

5.2.1. Double ice plug on a Dn 200 pipe

5.2.1.1. Freezing model

For modelling double the ice plug formation inside a Dn 200 pipe at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 203$ mm; outer pipe diameter: $D_e = 219$ mm; pipe length: $L = 7$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): l mm.

After implementing the discretization algorithm, the resulted calculation network consisted of 625365 elements and 595680 nodes. The values used for ANSYS Fluent modelling are those presented above (Table 5.1).

5.2.1.2. Results

The first ice plug was primarily formed after 68 minutes, and the second after 73 minutes (Fig. 5.6).

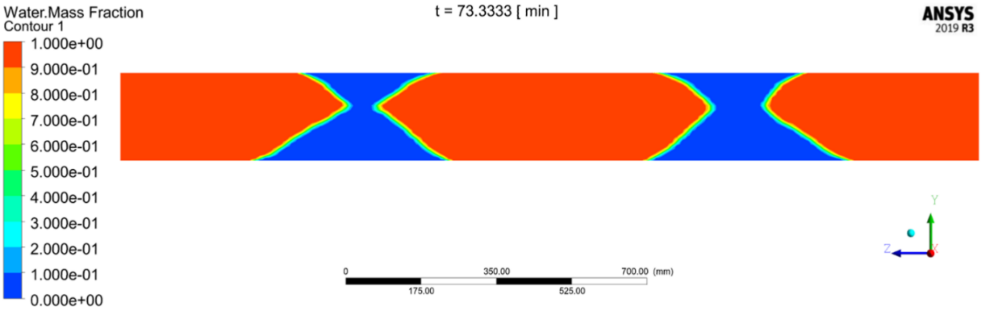

Fig. 5.6 - The moment of primary formation for the second ice plug inside a Dn 200 pipe, at an initial water temperature of 20°C, after 73 minutes

The ANSYS Fluent simulation continued for another 10 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 200 pipe containing stationary water at an initial temperature of 20°C with a double ice plug is 151,5 kg.

5.2.2. Double ice plug on a Dn 300 pipe

5.2.2.1. Freezing model

For modelling double the ice plug formation inside a Dn 300 pipe at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 304$ mm; outer pipe diameter: $D_e = 324$ mm; pipe length: $L = 7$ m; distance between the two heat transfer zones: $D = 1{,}2$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{300} = 1{,}05 \cdot l$ [mm] (where $l -$ the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 1095104 elements and 1065393 nodes. The values used for ANSYS Fluent modelling are those presented above (Table 5.3).

5.2.2.2. Results

The first ice plug was primarily formed after 130 minutes, and the second after 138 minutes (Fig. 5.7). The ANSYS Fluent simulation continued for another 28 minutes, during which time the ice layers continue to increase in length.

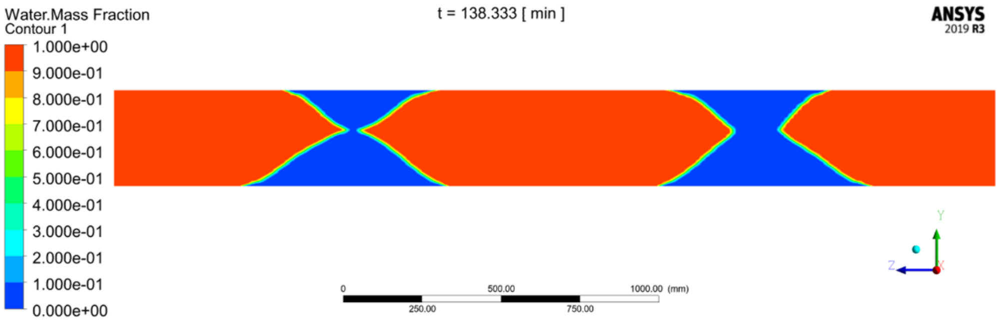

Fig. 5.7 - The moment of primary formation for the second ice plug inside a Dn 300 pipe, at an initial water temperature of 20°C, after 138 minutes

The calculated liquid nitrogen requirement for freezing a horizontal Dn 300 pipe containing stationary water at an initial temperature of 20°C with a double ice plug is 358,3 kg.

5.2.3. Double ice plug on a Dn 400 pipe

5.2.3.1. Freezing model

For modelling double the ice plug formation inside a Dn 400 pipe at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 400$ mm; outer pipe diameter: $D_e = 420$ mm; pipe length: $L = 8$ m; distance between the two heat transfer zones: $D = 1{,}6$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{400} = 1{,}17 \cdot l$ [mm] (where $l -$ the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 1754118 and 1718764 nodes. The values used for ANSYS Fluent modelling are those presented above (Table 5.2).

5.2.3.2. Results

The first ice plug was primarily formed after 195 minutes, and the second after 208 minutes (Fig. 5.8).

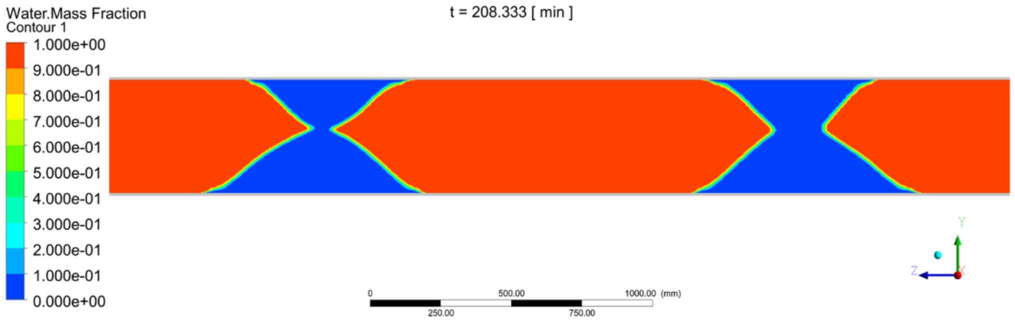

Fig. 5.8 - The moment of primary formation for the second ice plug inside a Dn 400 pipe, at an initial water temperature of 20°C, after 208 minutes

The ANSYS Fluent simulation continued for another 8 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 400 pipe containing stationary water at an initial temperature of 20°C with a double ice plug is 678,07 kg.

5.2.4. Double ice plug on a Dn 500 pipe

5.2.4.1. Freezing model

For modelling double the ice plug formation inside a Dn 500 at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 488$ mm; outer pipe diameter: $D_e = 508$ mm; pipe length: $L = 8$ m; distance between the two heat transfer zones: $D = 1{,}6$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{500} = 1{,}38 \cdot l$ [mm] (where l − the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 2194905 elements and 2159508 nodes. Also, the parameters for ANSYS Fluent modelling were recalculated; the values obtained are presented in Table 5.5.

Table 5.5

Parameters for modelling the ice plug formation inside a Dn 500 pipe at an initial water temperature of 20°C

Water temp.	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$4{,}08 \cdot 10^8$				
g_{20} [m/s²]	0,1				
Gr	$1{,}78 \cdot 10^6$	$7{,}49 \cdot 10^5$	$2{,}41 \cdot 10^5$	$3{,}64 \cdot 10^4$	$4{,}69 \cdot 10^3$
ε	10,51	9,11	7,47	5,31	3,65
λ'_{ech}[W/m · K]	6,27	5,35	4,31	3,02	2,04

5.2.4.2. Results

The first ice plug was primarily formed after 240 minutes and the second after 251 minutes (Fig. 5.9). The ANSYS Fluent simulation continued for another 14 minutes, during which time the ice layers continue to increase in length.

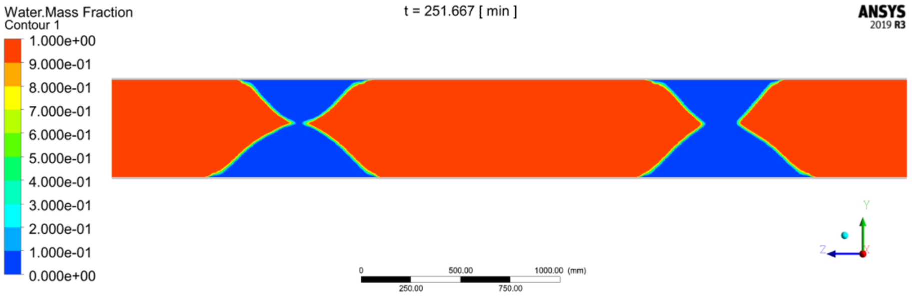

Fig. 5.9 - The moment of primary formation for the second ice plug inside a Dn 500 pipe, at an initial water temperature of 20°C, after 251 minutes

The calculated liquid nitrogen requirement for freezing a horizontal Dn 500 pipe containing stationary water at an initial temperature of 20°C with a double ice plug is 1175,5 kg.

5.2.5. Results interpretation

The double ice plug pipe freezing technique has a number of advantages over the single ice plug method:

- The duration of the intervention and implicitly the overall installation downtime are reduced;

- The resulted ice adhesion on the inner pipe wall is much stronger (about 4 times stronger) than on the single ice plug freezing;
- Although in the present cases the consumption of cryogenic agent is approximately twice as high as in the case of single ice plug freezing, by optimizing the injection of liquid nitrogen in the two freezing devices it is possible to obtain a considerable reduction of the total consumption during the intervention.

5.3. TRIPLE ICE PLUG PIPE FREEZING

For the triple ice plug pipe freezing analysis, we will use pipes with Dn 600, 700 and 800 containing water at an initial temperature of 20°C and at an initial working agent pressure of 2 bar. In the implementation of the geometric models of the analysis domains (Fig. 5.10) three cooling zones with different unit heat flux were used: ($\dot{Q}"_1 = 38439{,}07\ [\mathrm{W/m^2}], \dot{Q}"_2 = 0{,}9 \cdot \dot{Q}"_1 = 34595{,}16\ [\mathrm{W/m^2}]$ and $\dot{Q}"_3 = 0{,}8 \cdot \dot{Q}"_1 = 30751{,}26\ [\mathrm{W/m^2}]$, pentru a se evita închiderea în același timp a celor două dopuri (to avoid closing the two plugs at the same time (to avoid the production of an overpressure in the section between them, which in the case of a practical application could affect the integrity of the pipe wall).

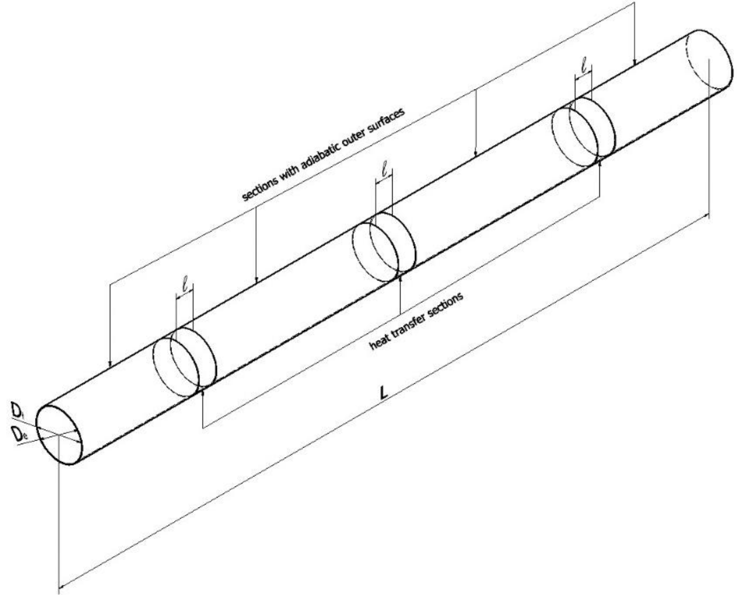

Fig. 5.10 - Analysis domain configuration for a triple ice plug pipe freezing

The distance chosen between the two freezing zones was, as in the double ice plug pipe freezing simulations, 4·Dn. To reproduce as accurately as possible the conditions of an intervention over an industrial installation, the pipe length was increased to $L = 10$ m. The heat transfer between the testing pipe and the outer environment is neglected on the areas next to the freezing zones and at the upstream and downstream ends of the volume of fluid.

5.3.1. Triple ice plug on a Dn 600 pipe

5.3.1.1. Freezing model

For modelling triple the ice plug formation inside a Dn 600 at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 594$ mm; outer pipe diameter: $D_e = 610$ mm; distance between the two heat transfer zones: $D = 2{,}4$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{600} = 1{,}73 \cdot l$ [mm] (where $l -$ the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 3268944 elements and 3224473 nodes. Also, the parameters for ANSYS Fluent modelling were recalculated; the values obtained are presented in Table 5.6.

Table 5.6

Parameters for modelling the ice plug formation inside a Dn 600 pipe at an initial water temperature of 20°C

Water temp.	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$7{,}98 \cdot 10^8$				
g_{20} $[\mathrm{m/s^2}]$	0,11				
Gr	$3{,}76 \cdot 10^6$	$1{,}58 \cdot 10^6$	$5{,}1 \cdot 10^5$	$7{,}69 \cdot 10^4$	$9{,}91 \cdot 10^3$
ε	12,21	10,58	8,68	6,17	4,24
$\lambda'_{ech}[\mathrm{W/m \cdot K}]$	7,29	6,21	5,01	3,51	2,37

5.3.1.2. Results

The first ice plug was primarily formed after 270 minutes, the second ice plug after 273 minutes, and the third after 298 minutes (Fig. 5.11).

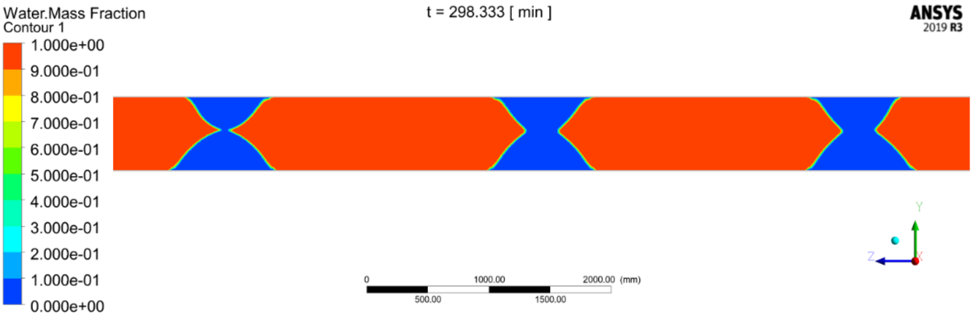

Fig. 5.11 - The moment of primary formation for the third ice plug inside a Dn 600 pipe, at an initial water temperature of 20°C, after 298 minutes

The ANSYS Fluent simulation continued for another 35 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 600 pipe containing stationary water at an initial temperature of 20°C with a triple ice plug is 3073,1 kg.

5.3.2. Triple ice plug on a Dn 700 pipe

5.3.2.1. Freezing model

For modelling double the ice plug formation inside a Dn 700 at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 695$ mm; outer pipe diameter: $D_e = 711$ mm; distance between the two heat transfer zones: $D = 2{,}8$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{700} = 2{,}3 \cdot l$ [mm] (where l − the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 4292768 elements and 4247274 nodes. Also, the parameters for ANSYS Fluent modelling were recalculated; the values obtained are presented in Table 5.7.

Table 5.7

Parameters for modelling the ice plug formation inside a Dn 700 pipe at an initial water temperature of 20°C

Water temp.	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$1{,}87 \cdot 10^9$				
g_{20} $[\mathrm{m/s^2}]$	0,16				
Gr	$1{,}28 \cdot 10^7$	$5{,}41 \cdot 10^6$	$1{,}74 \cdot 10^6$	$2{,}63 \cdot 10^5$	$3{,}39 \cdot 10^4$
ε	15,61	13,52	11,1	7,89	5,42
$\lambda'_{ech} [\mathrm{W/m \cdot K}]$	9,32	7,94	6,4	4,48	3,03

5.3.2.2. Results

The first ice plug was primarily formed after 270 minutes, the second ice plug after 280 minutes, and the third after 295 (Fig. 5.12).

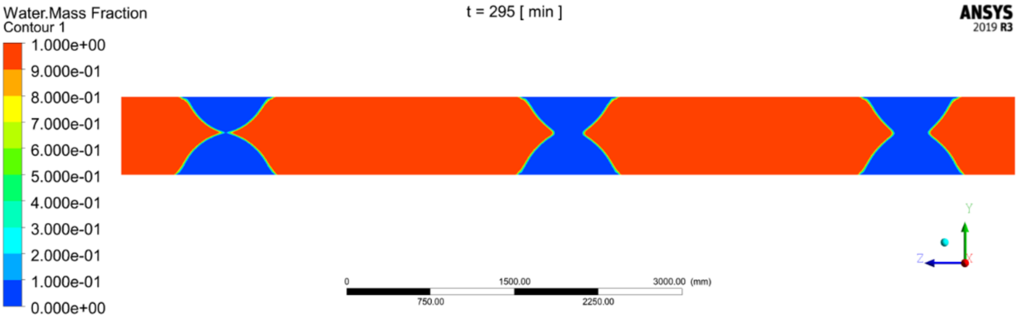

Fig. 5.12 - The moment of primary formation for the third ice plug inside a Dn 700 pipe, at an initial water temperature of 20°C, after 295 minutes

The ANSYS Fluent simulation continued for another 95 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 700 pipe containing stationary water at an initial temperature of 20°C with a triple ice plug is 5562,6 kg.

5.3.3. Triple ice plug on a Dn 800 pipe

5.3.3.1. Freezing model

For modelling double the ice plug formation inside a Dn 800 at an initial water temperature of 20°C, the testing installation was 3D modelled with the following characteristics: inner pipe diameter: $D_i = 797$ mm; outer pipe diameter: $D_e = 813$ mm; distance between the two heat transfer zones: $D = 3{,}2$ m; length of the heat transfer zone (equivalent to the section of pipe in contact with the liquid nitrogen inside the device): $l_{800} = 3{,}2 \cdot l$ [mm] (where $l -$ the length of the heat transfer area on the Dn 200 pipe simulations). After implementing the discretization algorithm, the resulted calculation network consisted of 2551104 elements and 2507681 nodes. Also, the parameters for ANSYS Fluent modelling were recalculated; the values obtained are presented in Table 5.8.

Table 5.8

Parameters for modelling the ice plug formation inside a Dn 800 pipe at an initial water temperature of 20°C

Water temp.	20°C	15°C	10°C	5°C	0,5°C
$\overline{\mathrm{Ra}}$	$5{,}2\cdot10^9$				
g_{20} [m/s^2]	0,3				
Gr	$6{,}61\cdot10^7$	$2{,}78\cdot10^7$	$8{,}95\cdot10^6$	$1{,}35\cdot10^6$	$1{,}74\cdot10^5$
ε	21,65	18,77	15,4	10,95	7,53
λ'_{ech}[W/m · K]	12,93	11,02	8,89	6,22	4,2

5.3.3.2. Results

The first ice plug was primarily formed after 250 minutes, the second ice plug after 260 minutes, and the third after 275 minutes (Fig. 5.13).

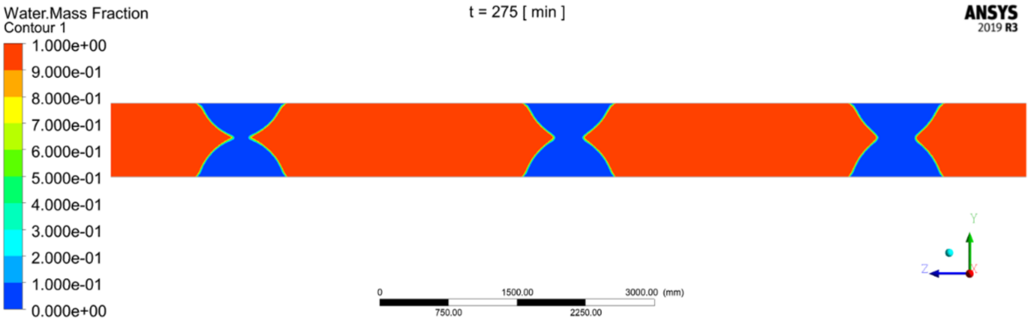

Fig. 5.13 - The moment of primary formation for the third ice plug inside a Dn 800 pipe, at an initial water temperature of 20°C, after 275 minutes

The ANSYS Fluent simulation continued for another 45 minutes, during which time the ice layers continue to increase in length. The calculated liquid nitrogen requirement for freezing a horizontal Dn 800 pipe containing stationary water at an initial temperature of 20°C with a triple ice plug is 10175,5 kg.

5.3.4. Results interpretation

Using the triple ice plug pipe freezing technique has the advantage of rapidly cooling the working agent inside the pipe, thus favouring a rapid evolution of the ice plugs. Although its advantages are obvious, the technique needs to be further studied in terms of:

- Structural analysis of the forces exerted by the development of ice plugs on the pipes;
- Streamlining the process triple ice plugging by determining the optimal transfer surfaces (of contact between the cryogenic agent and the pipe) and the mounting distances between the freezing devices on the outer pipe wall.

5.4. CONCLUSIONS

- The values of the parameters for modelling the pipe freezing were determined by calculation, for each presented example;
- CFD modelling for the heat transfer was performed in case of single, double and triple ice plug pipe freezing of large diameter horizontal pipes (Dn 200 ÷ Dn 800) at initial temperatures of the working agent (stationary water) of 20 and 25°C;

- For each example, the time required for the primary and complete the ice plug formation was determined, and the required quantity liquid nitrogen was calculated.

CONCLUSIONS

1. GENERAL CONCLUSIONS

- Optimizing the functioning of a system or a technological process involves (most of the time) the analysis of several physical phenomena as well as the interactions between them.
- The aim of this paper was to develop a calculation model using the CFS program ANSYS Fluent 2019 R3 to simulate the pipe freezing process of horizontal in a stationary flow regime of water to meet the following requirements:
  - Correlation of the results obtained from modelling with those obtained experimentally for the 200 mm nominal diameter pipeline;
  - Using the experimentally validated model in the development of applications for larger nominal diameters pipes (from 300 to 800 mm).
- The experimental results confirmed the theoretical data obtained using CFD software ANSYS Fluent. Therefore, it was concluded that the method can be implemented in the development of technologies for larger diameter horizontal pipes with stationary water as a working agent;
- Using the experimentally confirmed calculation method, CFD modelling for the heat transfer was performed in case of single, double and triple ice plug pipe freezing of large diameter horizontal pipes (Dn 200 ÷ Dn 800) at initial temperatures of the working agent (stationary water) of 20 and 25°C; for each case, the estimated liquid nitrogen requirement was calculated based on an experimentally confirmed model.

2. ORIGINAL CONTRIBUTIONS

Theoretical contributions

- Studies regarding the current research state for the cryogenic freezing technology of water-filled pipes in industrial installations (and especially of hydraulic circuits in NPP) and determining the potential use of the method;
- Identification and presentation in a coherent scientific manner of the problems related to the analysis of the main parameters involved in the heat transfer study for the pipe freezing process of large diameter horizontal pipes (Dn 200...Dn 800);
- Studying the existing scientific literature and determining the problems encountered during the cryogenic freezing of pipes. Identifying and analysing the effects of cryogenic freezing on the pipe material; constructing a mechanical calculation model for the exerted efforts;
- Detailed research regarding the consequences for the improper use of pipe freezing during a technological intervention;
- Establishing the planning procedures and safe conduct for the pipe freezing process and its specific stages;
- Designing a video surveillance system for real-time visualisation of the evolution of the ice deposits in the area influenced by the freezing device facilitates data collection, useful for the process development and for the thermal calculation and design of freezing device;

Numerical contributions

- Development of a model for calculating the liquid nitrogen requirement for the primary ice plug formation;
- Researches regarding the opportunity of using a software dedicated for studying the main thermal transfer parameters in the controlled freezing process of high diameter (Dn 200... Dn 800) horizontal pipes;

- Using the software to develop a viable CFD calculation model for determining the time and required quantity of liquid nitrogen for the controlled pipe freezing of large diameter pipes (Dn 200 ÷ Dn 800) at different working agent temperatures.
- Numerical simulations using ANSYS Fluent for determining the influence that the heat transfer surfaces (of contact between the cryogenic agent and the outer pipe wall) and the distances between several heat transfer zones have on the heat transfer parameters of the controlled pipe freezing process using single or multiple ice-plugs;
- Development and solution analyses regarding the single, double and triple controlled pipe freezing of large diameter pipes in stationary water.

Experimental contributions

- Designing and carrying out a significant number of experiments regarding the controlled pipe freezing process of large diameter horizontal pipes for different water flows and for different conditions;
- Designing and conducting experiments for the controlled freezing of a Dn 200 horizontal pipe in stationary water. Data collection on:
    - The evolution of pipe wall temperatures;
    - the evolution of the geometric characteristics of the ice deposits on the inner wall of the pipe;
    - the evolution of the water temperature in the testing section;
    - the time required for the primary and for the total ice plug formation;
    - the evolution of the pressure-drop on the ice plug;
    - the quantity of liquid nitrogen required for the pipe freezing processes.
- Numerical determination and graphical representation of the experimental results regarding the controlled horizontal Dn 200 pipe freezing process in stationary water;
- Theoretical models validation by correlating the numerically determined values with experimental data.

The author suggests some directions for further research and development, for example: ways to optimize the process, the development of cryogenic devices for larger pipes and the application of experimentally confirmed calculation methods for research on the freezing of vertical pipes.

3. RESEARCH PERSPECTIVES

The main direction of continuing the work is the development of ANSYS models that aim to solve a series of problems that have arisen over time in the implementation of the technology of pipe freezing in industrial installations:

- Structural analysis of the forces exerted by the development of ice plugs on the pipe;
- Structural analysis of the adhesion between the ice plug and the inner pipe wall at high working pressures;
- Development of cryogenic devices for larger pipes;
- Streamlining the process pipe freezing by sizing the liquid nitrogen compartments inside the freezing devices according to the requirements of each specific application;
- Streamlining the pipe freezing process by several ice plugs by determining the optimal mounting distances between cryogenic devices on the pipe;
- Analysing the effects of film and nuclear boiling on the heat transfer inside the freezing device;
- Controlling the formation of ice plugs by varying the flow of liquid nitrogen injected into the freezing devices;
- Application of experimentally validated calculation methods in the research of the freezing of vertical pipes.

The results can be useful for the development of future research directions aimed at freezing pipes procedures in various industry branches. Currently, there are several companies operating in the world specialized pipe freezing. However, there are very few situations in which these companies have the necessary training to apply the technology on non-metallic pipes because the plastics (polymers) from which they are made of are more susceptible to cracking due to stress caused by thermal shocks, shrinkage or by the internal pressure exerted by the ice plugs formation.

4. DISSEMINATION OF RESULTS

The dissemination of the obtained results was achieved by publishing a number of 19 articles:

Corbescu B., Puiu D., Matei E., Panaitescu V. N. *CFD model for the heat transfer during the ice plugging process of large diameter pipes*," Journal of Nuclear Research and Development, ISSN 2247-191X, nr. 20-21, pp. 49-55, Mai 2021.

Corbescu B., Ionescu D., Gyöngyöşi T., Chihaia R. A., Panaitescu V. N. *Ice plug obturation of a horizontal pipe. Computational model and experimental validation,* Buletinul Științific al Universității Politehnica din București, seria D, Vol. 83(1)/2021, ISSN 1454-2358, pp. 281-292.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N. *Forming an ice plug inside a horizontal 200 mm nominal diameter pipeline using a 55 % nitrogen vapours exhaust nozzle restriction,* The 12th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2019. Nuclear Technology and Materials. Pitești, 3-4 June, 2019.

Gyöngyöşi T., **Corbescu B.**, Puiu D., Valeca Ș., Panaitescu V. N. *The influences of reducing with up to 25 % the nitrogen vapour exhaust from the ice plugging device mounted on a 200 mm nominal diameter pipe containing stationary water*, The 12th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2019. Nuclear Technology and Materials. Pitești, 3-4 June, 2019.

Glonț A., Valeca Ș., C. Roth, **Corbescu B.**, Gyöngyöşi T., *Establishing the theoretical limit of the liquid nitrogen requirement for the freeze isolation of a horizontal pipeline,* The 12th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2019. Nuclear Technology and Materials. Pitești, 3-4 June, 2019.

Corbescu B., Puiu D., Gyöngyöşi T., Panaitescu V. N. *Forming an ice plug inside a high diameter pipeline in stationary water using a nitrogen vapour exhaust restriction,* Resort − International Conference on Sustainable Future and Technology Development, 15 October 2018, Bucharest, Romania, vol. 1122, Journal of Physics: Conference Series.

Corbescu B., Gyöngyöşi T., Puiu D., Chihaia R., Panaitescu V. N. *Vizualizare secvențială a procesului de formare a dopului de gheață în secțiunea de testare a unei conducte de diametru mare. Partea I.* A XVII-a Conferința internațională multidisciplinară „*Profesorul Dorin Pavel − fondatorul hidroenergeticii românești*". Cluj Napoca 1-2 iunie 2018. *Știință and inginerie*. Vol. 34/2018, ISSN 2067-7138, Editura AGIR, București, 2018, pp. 365-374.

Corbescu B., Gyöngyöşi T., Puiu D., Chihaia R., Panaitescu V. N. *Vizualizare secvențială a procesului de formare a dopului de gheață în secțiunea de testare a unei conducte de diametru mare. Partea a II-a.* A XVII-a Conferința internațională multidisciplinară „*Profesorul Dorin Pavel − fondatorul hidroenergeticii românești*". Cluj Napoca 1-2 iunie 2018. *Știință and inginerie*. Vol. 34/2018, ISSN 2067-7138, Editura AGIR, București, 2018, pp. 375-380.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N. *Forming an ice plug inside a horizontal high diameter pipeline (200 mm nominal diameter) using a 15 % nitrogen vapours exhaust nozzle restriction*, The 11th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2018. Nuclear Technology and Materials. Pitești, 23-25 May, 2018.

Gyöngyöşi T., **Corbescu B.**, Puiu D., Valeca Ș., Panaitescu V. N. *Pipe ice plugging tests using a ~ 15 % exhaust liquid nitrogen vapor restriction for the freezing device mounted on a 200 mm horizontal pipe, in a stationary flow regime*, The 11th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2018. Nuclear Technology and Materials. Pitești, 23-25 May, 2018.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N. *Calculus estimation of the time and liquid nitrogen quantity required to isolate a horizontal high diameter pipe-line*. International Symposium for Nuclear Energy SIEN 2017. București, October 1-4, 2017

Corbescu B., Puiu D., Gyöngyöşi T., Panaitescu V. N. *Elemente de calcul al necesarului de azot pentru izolarea cu dop de gheață a unei conducte orizontale de diametru mare. A XVII-a* Conferința internațională multidisciplinară „*Profesorul Dorin Pavel − fondatorul hidroenergeticii românești*”. Sebeș − Alba, 2-3 iunie 2017. *Știință and inginerie*. Vol. 30/2017, ISSN 2067-7138, Editura AGIR, București, 2017, pp. 167-174.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N. *Comparative analysis between two processes of isolating high diameter pipelines (≤ 300 mm nominal diameter) by ice plugs in stationary water*. The 10th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2017. Nuclear Technology and Materials. Pitești, May 24-26, 2017, Proceedings of Nuclear 2017, part 1/3, pag. 282-289

Gyöngyöşi T., **Corbescu B.**, Puiu D., Valeca Ș., Panaitescu V. N. *The influence of the flow regime over the ice plug isolation of a horizontal 200 mm nominal diameter pipeline*. The 10th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2017. Nuclear Technology and Materials. Pitești, May 24-26, 2017, Proceedings of Nuclear 2017, part 1/3, pag. 291-298.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N**.** *O încercare de obturare cu dop de gheață a unui tronson de conductă orizontală (DN 300 mm) străbătut de apă demineralizată*, A XVI-a Conferința internațională multidisciplinară „*Profesorul Dorin Pavel − fondatorul hidroenergeticii românești*”. Sebeș − Alba, 10-11 iunie 2016. *Știință and inginerie*. Vol. 29/2016, ISSN 2067-7138, Editura AGIR, București, 2016, pp. 483-492.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N. *Attempts to isolate a horizontal high diameter (300 mm nominal diameter) pipeline with an ice plug at minimum water flow and without water flow*, The 9th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2016. Nuclear Technology and Materials. Pitești, May 18-20, 2016.

Gyöngyöşi T., Valeca Ș., **Corbescu B.**, Puiu D., Panaitescu V. N. *Forming an ice plug inside a horizontal high diameter pipeline (300 mm nominal diameter) using stationary demineralized water*, The 9th Annual International Conference on Sustainable Development through Nuclear Research and Education, Nuclear 2016. Nuclear Technology and Materials. Pitești, May 18-20, 2016.

Gyöngyöşi T., Valeca Ș., **Corbescu B.**, Puiu D., Panaitescu V. N. *Demineralized Water Flow Cancelling Tests with Ice Plug into High Diameter Horizontal Tube (300 Nominal*

Diameter). The International Symposium on Nuclear Energy SIEN 2015, 19-21 October 2015, Bucharest, Romania.

Corbescu B., Gyöngyöşi T., Puiu D., Panaitescu V. N. *The convenience of visualizing the controlled formation of ice plugs in horizontal pipe/line section.* A XV-a Conferință internațională multidisciplinară „*Profesorul Dorin Pavel − fondatorul hidroenergeticii românești*”. Sebeș − Alba, 5-6 iunie 2015. *Știință and inginerie*. Vol. 28/2015, ISSN 2067-7138, Editura AGIR, București, 2015, pp. 363-368.

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BIBLIOGRAPHY

[1] „Huntingdon Fusion Techniques,” [Interactiv]. Available: http://www.huntingdonfusion.com. [Accesat 11 2019].

[2] T. Gyöngyöși, Ș. Valeca și L. Constantin, „Dispozitiv de înghețare pentru conducta Dn 200 mm. Proiect de execuție model experimental,” ICN Pitești, R.I. 7138/2005.

[3] G. J. Howard, *Oil and gas journal,* pp. 108-110, Aprilie 1982.

[4] C. Doca, L. Doca and N. Anghel, “Aspecte teoretice privind formarea dopului de gheață într-o conductă,” ICN Pitești, R.I. 9283/2011.

[5] C. Doca, „Asupra timpului de obturare, prin înghețare criogenică, a unei conducte umplute cu apă,” în *A XVII-a Conferință Națională cu Participare Internațională "Progrese în criogenie și separarea izotopilor"*, Călimănești-Căciulata, Vâlcea, 26-28 octombrie 2011.

[6] H. Tinoco, “Cryogenic pipe freezing – a theoretical model,” Swedish State Power Board, Aelvkarleby, Vasteras, 1988.

[7] H. S. Carslaw and J. C. Jaeger, Conduction of heat in solids, Oxford: Oxford University Press, 1959.

[8] J. Crank, Free and moving boundary problems, Oxford: Oxford University Press, 1984.

[9] M. T. Flaman and N. N. Shah, “Structural Integrity Investigation of Feed Pipe Ice Plugging Procedures,” Ontario Hydro Research Division, Ontario, 1984.

[10] N. Ichiyanagi, „The Freezing Method for the Oil Stop in POF Cable Repair,” *IEEE Transactions on Power Apparatus and Systems,* vol. 98, nr. 6, pp. 2037-2046, 1979.

[11] J. F. Kiefner, Development of guidelines for use of ice plugs in pipeline maintenance and hydrostatic testing, Battelle Columbus Laboratories, 1982.

[12] R. J. Twigg, “Ice plugging of pipes using liquid nitrogen,” Atomic Energy Control Board, Ottawa, 1987.

[13] D. H. Tantum and D. A. Wigley, in *Proceedings of the Eighth International Cryogenic Engineering Conference*, Genova, 3-6 Iunie, 1980.

[14] R. W. Vance and W. M. Duke, Applied Cryogenic Engineering, New York: John Wiley and Sons, 1962.

[15] A. P. Rao, in *Proceedings of the 1st National Symposium on Cryogenics - Indian Institute of Technology*, Khargapur, 24-25 Mai, 1975.

[16] A. Domșa, Materiale metalice în construcția de mașini și instalații, Cluj Napoca: Editura Dacia, 1981.

[17] “CanTech,” [Online]. Available: canteach.candu.org. [Accessed 02 2020].

[18] K. Raznjevic, Tabele și diagrame termodinamice, București: Editura Tehnică, 1978.

[19] “Engineering Toolbox,” [Online]. Available: www.engineeringtoolbox.com. [Accessed 03 2020].

[20] “Microelectronics Heat Transfer Laboratory, University of Waterloo,” [Online]. Available: www.mhtl.uwaterloo.ca/old/onlinetools. [Accessed 04 2020].

[21] “Dortmund Data Bank,” [Online]. Available: http://www.ddbst.com. [Accessed 04 2020].

[22] B. Corbescu, T. Gyöngyöși, D. Puiu, R. A. Chihaia and V. N. Panaitescu, “Vizualizare secvențială a procesului de formare a dopului de gheață în secțiunea de testare a unei conducte de diametru mare,” *Știință și inginerie,* vol. 34, no. ISSN 2067-7138, pp. 365-374, 2018.

[23] B. Corbescu, T. Gyöngyöși, D. Puiu and V. N. Panaitescu, “Oportunitatea vizualizării formării controlate a dopului de gheață pe un tronson de conductă orizontală,” *Știință și inginerie,* vol. 28, no. ISSN 2067-7138, pp. 363-368, 2015.

[24] B. Corbescu, D. Puiu, E. Matei and V. N. Panaitescu, “CFD model for the heat transfer during the ice plugging process of large diameter pipes,” *Journal of Nuclear Research and Development, ISSN 2247-191X,* no. 20-21, pp. 49-55, Mai 2021.

[25] Y. Takefuj and T. Okubo, “Double-ice-plug freezing using liquid nitrogen for water pipe repairs,” *Urban Water Journal,* vol. 15, no. 1, pp. 1-3, 2017.