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Integrity Evaluation of Ice Plugged Pipes Applied on Short Jacket

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Abstract

In special industrial fields such as nuclear power plants and chemical plants, it is often necessary to repair system components without plant shutdown or drainage of system having many piping structures which may have hazardous or expensive fluid. A temporary ice plugging method for blocking internal flow is considered as a useful method in that case. According to the pipe freezing guideline of the nuclear power plant, the length of a freezing jacket must be longer than twice of the pipe diameter. However, for applying the ice plugging to short pipes which do not have enough freezing length because of geometrical configuration, it is inevitable to use shorter jacket less than twice of the pipe diameter. In this study, the integrity evaluation for short pipes in the nuclear power plant is conducted by an experiment and the finite element analysis. From the results, the ice plugging process in short pipes can be safely carried out without any plastic deformation and fracture.

Key Words : ice plugging, freeze sealing, freezing jacket, thermal stratification

1. Introduction

In the course of performing certain nuclear power plant maintenance activities, piping system isolation is sometimes required. When this cannot be accomplished through the use of existing valves, draining of the system becomes necessary. This can be time-consuming and costly procedure. As an alternative, some operators have turned to the use of freeze sealing, or creation of ice plugging within the pipe by applying an external refrigerant to a local area, to resolve their temporary system isolation requirement[1]. In this procedure a heat exchanger is located around the water-filled pipe at the position where the blockage is to be made. Then the heat exchanger (jacket) is filled with liquid nitrogen(-196℃). The nitrogen vaporized within the jacket remove heat from the pipe and make an ice plug inside the pipe. These methods have been used in the nuclear power plants due to low cost and easiness of use since it was first applied in 1940 in U.S. navy[2~3]. But according to the pipe freezing guideline[4] of the nuclear power plant, the length of freezing jacket must be longer than twice of the pipe diameter. However, for applying the ice plugging to short pipes which do not have enough freezing length because of the geometric configuration of the piping systems, it is inevitable to use shorter jacket than twice of the pipe diameter.

In this study, a series of ice plugging experiments for shorter jackets are performed to identify plug formation and integrity of pipe material. And the integrity evaluation of pipe material which directly contacted with refrigerant is conducted by the finite element analysis. Because of the cryogenic liquid injection, pipes are subjected to severe thermal stress due to rapid cooling down, resulting in large tensile stresses, which may lead to propagation of pre-existent flaws. Thus, in addition to the thermal stress analysis, the fracture analysis has been performed to calculate the stress intensity factors for the postulated internal circumferential semi-elliptic cracks in the pipe. Fig.1 shows the flow chart of the research which includes a series of ice plugging experiments and their finite element analyses.

2. Freezing Experiment

2.1. Conducting Experiment

In this study, the experiment is performed to

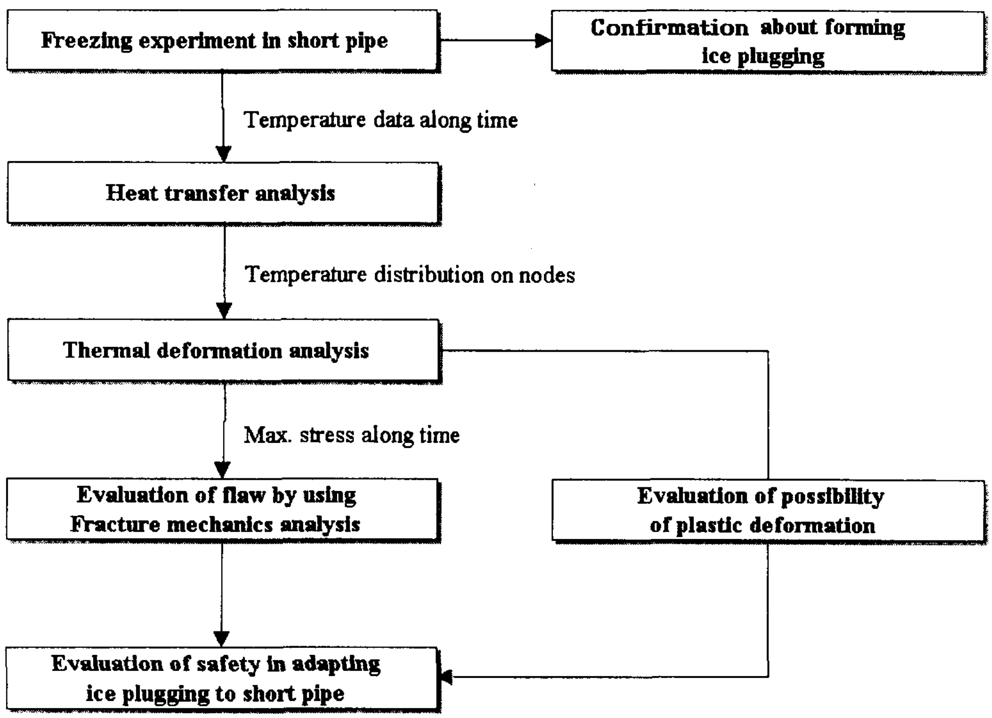
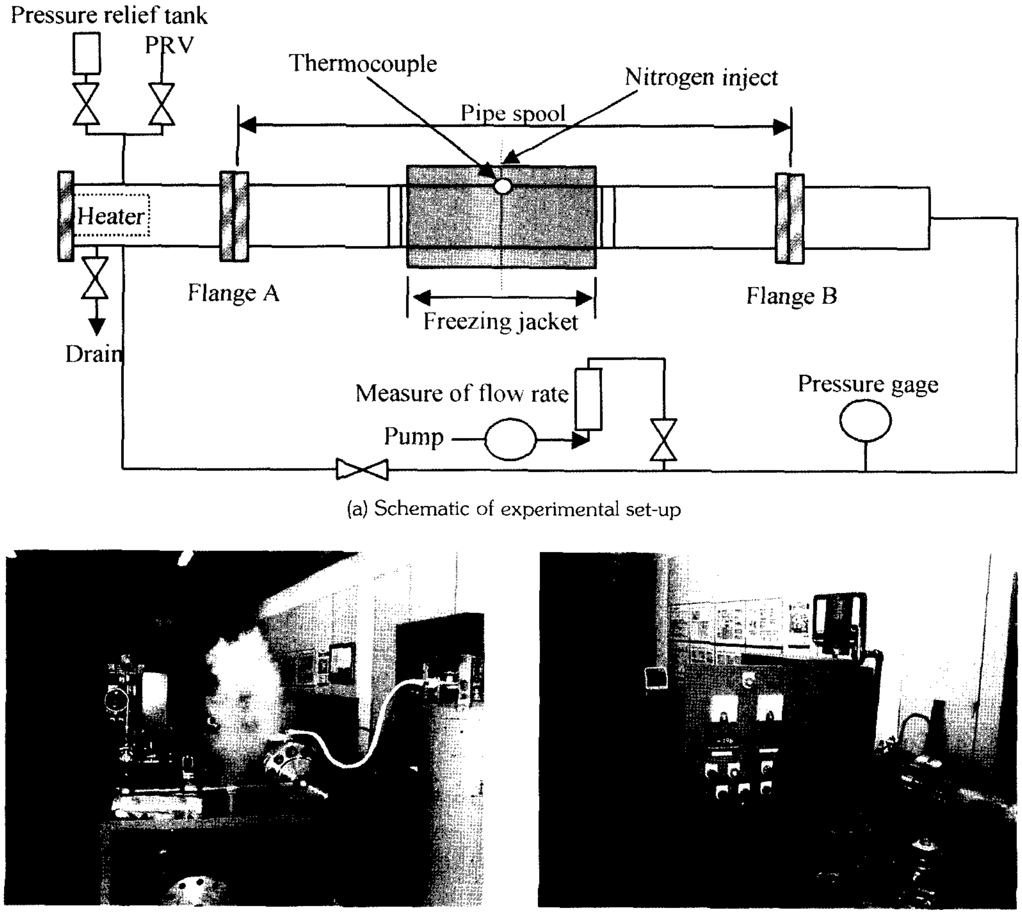


Fig. 1 Flow Chart of Research

demonstrate feasibility of the ice plugging formation using shorter jacket than twice of the pipe diameter. Only shorter jacket is suitable for the system piping configuration in the K nuclear power plant. The system has atmospheric pressure, because the plant has been stopped for refueling outage. The experiment is also implemented at the atmospheric pressure. The temperature data for the stress analysis needs to be obtained from the experiment. A hydrostatic test is utilized to confirm the ice plug formation and movement of the formed plug in the shorter jacket pipes. The schematic of experimental set-up is shown in Fig.2, consisting of pipe, freezing jacket, heater, thermocouple, pressure gages and so on. 16 thermocouples are attached to inside and outside surface of the pipe to measure temperature, as shown in Fig.3. Data acquisition system, NETDAQ 2640A/41A (FLUKE Co.) is used for data collection, and thermocouple is CO1-K(OMEGA Co.).

Tap water is employed as the internal fluid, and liquid nitrogen(LN2) is used as the refrigerant. The jacket length around stainless steel AISI 304 pipe of 168mm outside diameter(schedule 80) is 140 mm and the room temperature is 23℃. And the pipe thickness is 11mm. The experiment is implemented according to the following



(a) Schematic of experimental set-up

(b) Side view

(c) Front view

Fig.2 Experlmental Set-up

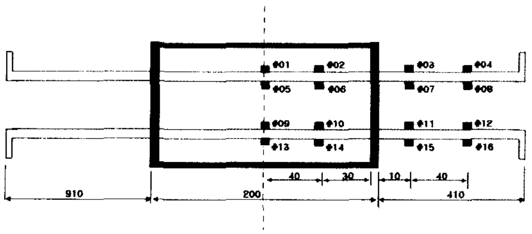


Fig. 3. Location of Thermocouples

procedure.

A sealing material is pasted around the jackets and two pieces of jackets are assembled around the pipe. The jacket is connected to a nitrogen container with an appropriate hose for low temperature to provide enough refrigerant during experiment. The manifold valve attached to the nitrogen container is slowly opened to prevent overflowing through the exhaust port of the jacket and to control flow rate to maintain the constant temperature inside the jacket, -196℃.

The formation of the ice plug in the shorter jacket pipe needs to be confirmed. The hydrostatic test can be used for this conformation. The differential pressure of 10 kgf/㎠ is applied at the ice plug for 10 minutes. Then the liquid nitrogen remained in the freezing jacket is vaporized by closing the valve from the nitrogen container, and the jackets are removed from pipes.

2.2. Results

After 50 minutes, the ice plug formation has been completed. From the hydrostatic test, it has been observed that the ice plug stands firmly against the pressure of 10 kg/㎠ without any collapse or movement. Therefore, it can be concluded that the ice plugging for the shorter jacket pipe will be successfully carried out. And the melting time is observed to check how long the ice plug will exist without refrigerant supply. This process is for the unexpected accident of

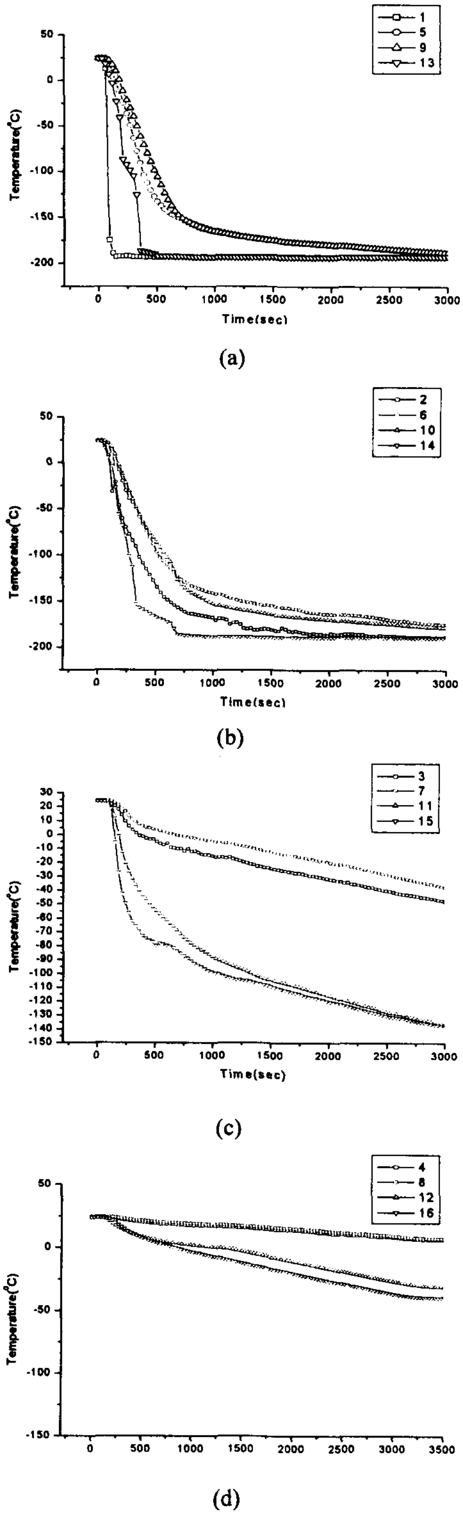


Fig. 4 Temperature History from Experiment

interrupting refrigerant supply during the actual maintenance activity. It took 13 hours and 15 minutes to melt the ice plug from interrupting the refrigerant supply. And the temperature history obtained from the experiment is shown in Fig.4. Fig. 4 (a) shows temperatures of the center of the jacket rapidly dropped at the beginning stage of the experiment. Temperature difference of the Point 1 and 5 at 60sec shows -195℃. Maximum temperature difference in Fig. 4 (b) indicates 105 ℃ from the Point 10 and 14 at 300sec. Maximum temperature difference of about 100℃ appears at the location of axially outside of the jacket as shown in Fig. 4 (c). Upper inside surface indicates the highest temperature while lower outside surface reveals the lowest temperature. Temperature difference is considered from natural convection of internal fluid. This temperature difference induces thermal stratification on the pipe which may cause large thermal stresses. Thermal stratification phenomenon has many times been issued in the nuclear industry since identified at pressurizer surge line in 1980s[18]. Temperatures of the points 50mm apart from the jacket show small amount of thermal stratification in Fig. 4 (d). All of the temperature data are used for finite element analysis to identify thermal stresses.

3. Thermal Analysis

3.1. Finite Element Model

The purpose of thermal stress analysis is to check whether the ice plugging in the shorter pipes can be safely performed without any plastic deformation of pipe system. The analysis is carried out for the actual pipe system in the nuclear power plant. The typical piping system configurations are shown in Fig. 5. These pipes can be classified into the three typical models. Eight-node isoparametric brick elements are used to build the finite element models. 3D FE modeling of the pipes is constructed by using a commercial package of FE analysis, ANSYS

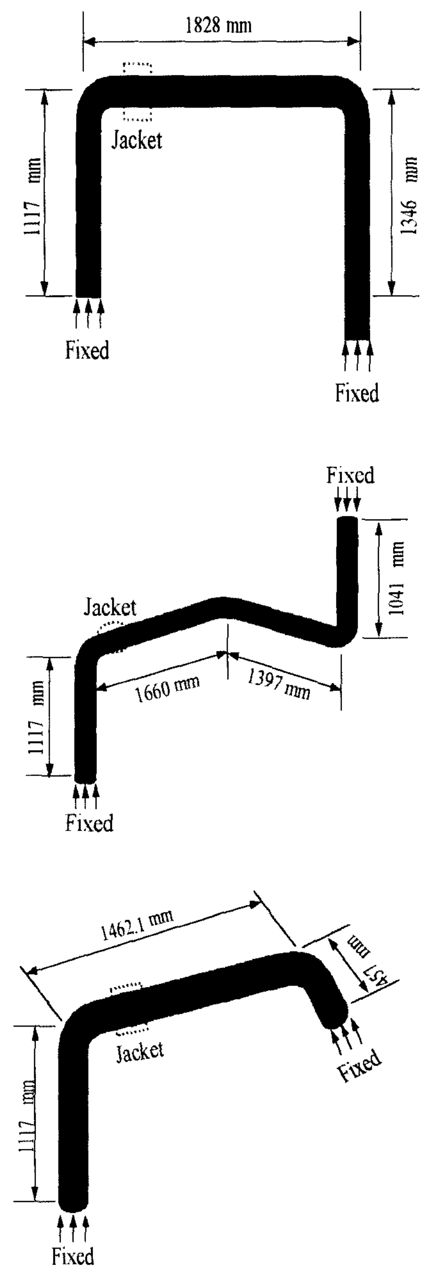


Fig.5 Typical Models for FE Analysis

5.5[5]. The material properties are listed in Table 1[6].

Temperatures acquired from the experiment are applied to the jacket area of the piping system as input data for analysis of the actual thermal stresses. Every node among the temperature acquisition points around and inside jacket is axially and circumferentially interpolated.

3.2. Initial and Boundary Conditions

• *Initial temperature conditions:*

In the thermal shock analysis, the initial temperature is 23℃ and the uniform temperature is applied to all nodes.

• *Boundary conditions for heat transfer:*

Due to heat transfer from refrigerant through the pipe material to internal fluid, selecting the heat transfer coefficient to apply at the pipe is very difficult. So the measurement of surface temperature from the experiment is the only useful method to consider the change of the fluid heat flux along with temperature and the latent heat effect by phase change. Temperature histories measured from the experiment are applied to the pipe of the jacket part. The convection heat transfer coefficient of the atmosphere at room temperature is employed on the pipe area except

Table 1. Material Properties of AISI 304 and AISI 1030

			AISI 304	AISI 1030
Material Properties	Yield Strength(MPa)	-196℃	433	≥1000
		-18℃	295	
		20℃	250	430
	Ultimate Strength(MPa)	-196℃	1,627	
		-18℃	862	
		20℃	590	620
	Young' s Modulus(GPa)		190	210
	Poisson' s Ratio		0.3	0.27
	Mass Density (kg/m^3)		7,920	7,870
	Heat Conductivity (W/m℃)	-173 ℃	9.2	53
		-73 ℃	12.6	52.5
		27 ℃	14.6	51.9
		127 ℃	16.6	50.7
	Thermal Expansion Coeff.	15℃~ -184℃	0.00167 /℃	0.00111 /℃
	Specific Heat (J/kg℃)	-173 ℃	272	470
		-73 ℃	402	474
		27 ℃	477	477
		127 ℃	515	486

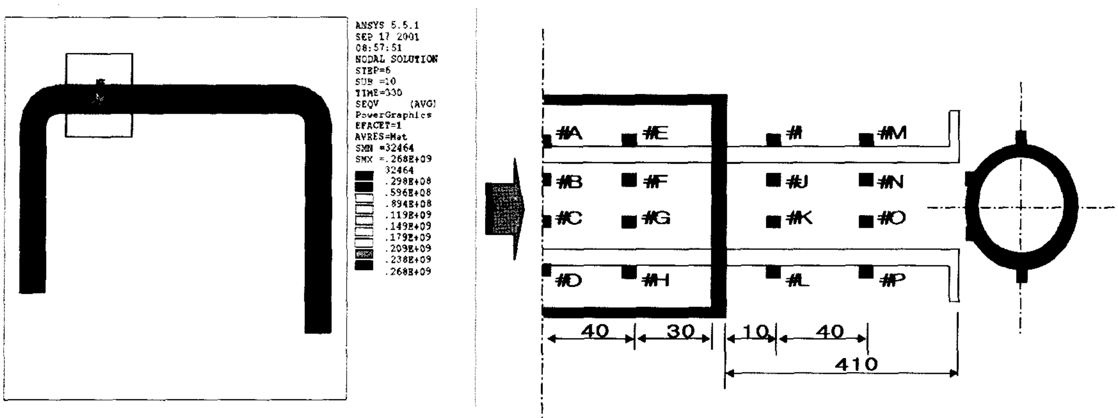


Fig. 6 Equivalent Stress Distribution for Model 'A'

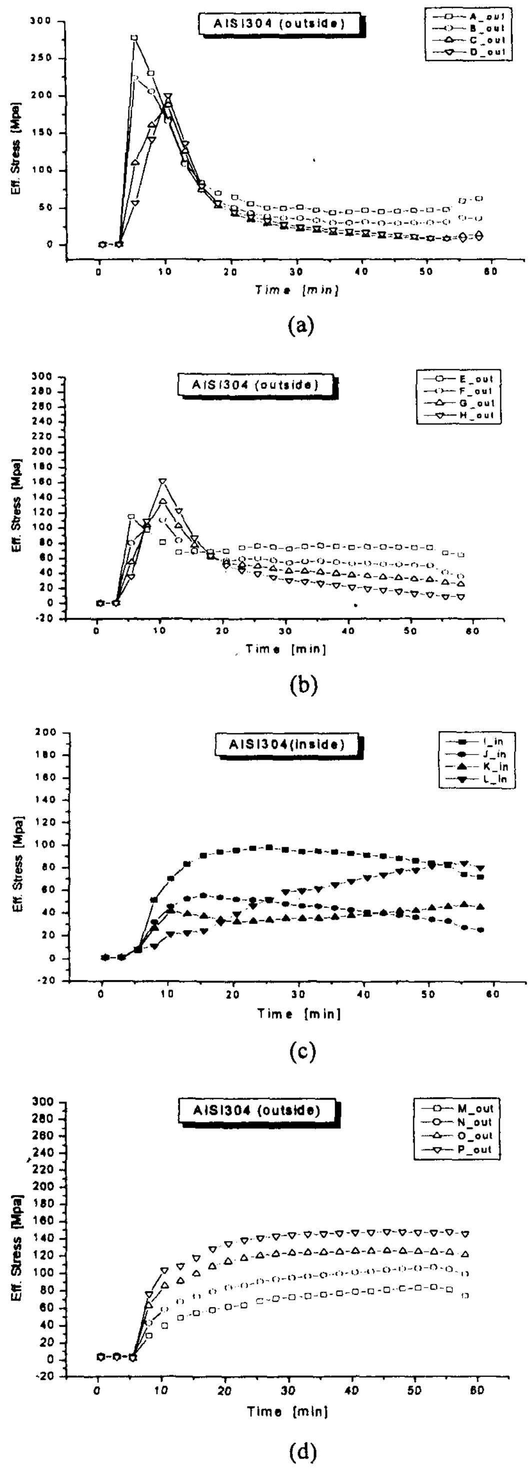


Fig. 7 Stress History of FE Analysis

jacket part as $15W/m^2 \cdot ℃$.[7]

- *Boundary conditions for thermal deformation:*

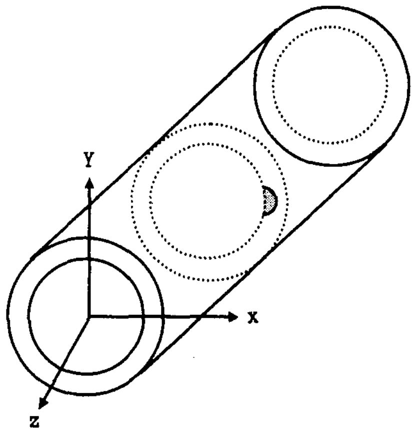
The end sides of each pipe model are constrained by pipe supports as shown in Fig. 5.

3.3. Results and Discussion

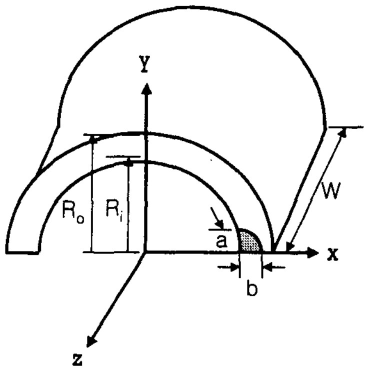
The equivalent stress distribution for model A is shown in Fig. 6. Nodes on the location of the temperature sensors are selected. Nodes(A to H) directly contacting with the liquid nitrogen and the rest(I to P) located in the outside of the jacket are selected. The stress history of each node is shown in Fig. 7. The maximum stress appears at the beginning stage on the upper center node 'A', and then the stress converges to the steady state value shown in Fig 7 (a). The maximum stress, 268 MPa, is below the yield strength of the pipe. It is approximately 62% of the yield strength of the pipe material at -196℃. This relatively high stress is considered as resulting from the temperature difference of the inside and outside surface of the pipe. The stresses at the locations slightly inside jacket border are lower than the stresses of center area as shown in Fig. 7 (b). Fig. 7 (c) shows the stresses on the inside surface of pipe resulted from thermal stratification at the outside of the jacket on the pipe. These stresses do not affect significantly to the integrity of the pipe structures.

Fig. 7 (d) indicates stresses at the outside location of 50mm axially apart from jacket border.

For model B and C, they show almost the same stress histories and the stress distributions. The stress analysis shows that the equivalent stress increases rapidly to a maximum value due to large temperature difference at the beginning of the freezing process. The maximum stress occurs at the center of the freezing part directly contacting with the cryogenic nitrogen, and any plastic deformation or failure is not predicted, which

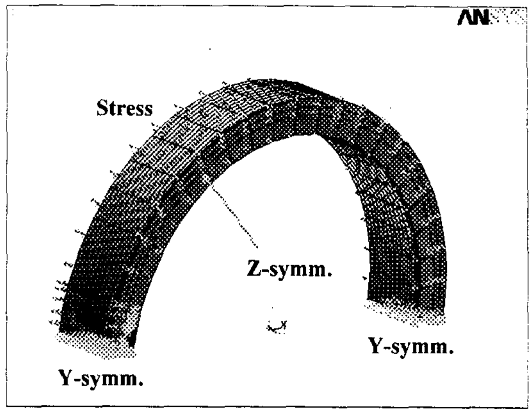


(a) Sub-model for fracture analysis

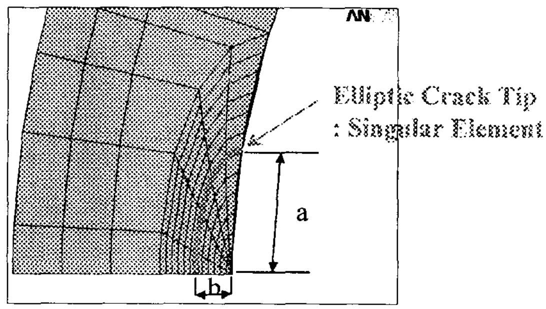


(b) Control volume for FE Analysis

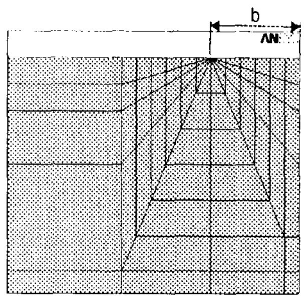
Fig. 8. Finite Element Model for Fracture Analysis



(a) Boundary condition for finite element model



(b) Front view



(c) Bottom view

Fig. 9. Finite Element Modeling Around Crack Plane

indicates that the ice plugging can be safely performed for the pipes applied shorter jacket ice plugging.

The yield strength of the pipe material is increasing along with the temperature decrease as shown in the Table 1. The stresses from the FE analysis are less than the yield stress and therefore there is some margin of safety.

4. Fracture Analysis

The existence of defects in the pipe material can not be excluded in structural components. During manufacturing and industrial applications of metallic pipes such as welding, there may exist some surface cracks which can not be detected or be examined by nondestructive testing and inservice inspection[8~9]. Noting that the fracture toughness of materials decreases at cryogenic temperature[16], fracture analysis during ice plugging is necessary. In this study, the possibility of crack propagation is evaluated using the finite element method. Since carbon steel pipe material is more susceptible to fracture than stainless steel at cryogenic temperature, this study deals carbon steel pipe as well as stainless steel for fracture analysis.

Generally carbon steels undergo a ductile-brittle transition as a function of temperature. Below the transition temperature, the impact toughness can markedly decrease, increasing the likelihood of brittle fracture. The transition temperature for carbon steel is typically less than -40℃, while stainless steel is below -240℃[17]. Material properties of the carbon steel pipe(AISI 1030) are also shown in Table 1. And the pipe dimensions are the same as the pipe used in the thermal analysis. From thermal stress analysis, the maximum stress of 268 MPa is applied to the z-direction of the pipe.

4.1. Finite Element Model

Due to the symmetry, only one-forth of the pipe with a circumferential crack at the center of the cylindrical portion is considered in the modeling as shown in Fig 8. The three-dimensional finite element models are prepared using the mixture of eight-node and twenty-node brick elements. The twenty-node elements are used near the crack to capture the steep stress gradient, while the eight-node elements are used at locations away from the crack zone. Sufficiently fine meshes are used near the crack tip. For elastic analysis, the singular elements are used to model around the crack front by shifting the mid-side nodes to the quarter position, which produce square root singularity along the crack. In most practical engineering accidents involving the metallic cylinders, the cracks are often found approximately to be semi-elliptical in shape[10~11]. The semi-elliptical crack and its coordinate system are shown in Fig. 8 and the specification of the geometry assumed 1/4t depth and 1.5t length is listed in Table 2. Fig. 9 shows the detailed finite element modeling of the crack plane. The finite element analysis was carried out using the ANSYS program package.

4.2. Stress Intensity Factor

In small scale yielding conditions, the plastic stress intensity factor is related to the elastic stress intensity factor. The stress intensity factor (K) of mode I is calculated from the J-integral value and given as

$$K=\sqrt{\frac{JE}{1-\nu^2}} \tag{1}$$

where ν and E denote Poisson' s ratio and Young' s modulus. The stress-strain state of the cylinder with a part-through defect has its peculiarities. The plane strain condition has been assumed for the crack front area close to the deepest point, whereas near the internal free surface of the cylinder it is generally believed that plane stress might prevail there. The J-integral is calculated in elliptic crack plane at the deepest point using the formulation by Shivakumar and Raju[12~13]. The J-integral is a path-independent line integral that measures the strength of the singular stress and stain near a crack tip. The calculated J-integral will

Table 2. Dimensions of Semi-elliptic Crack

Ro	84.14 mm
Ri	65.90 mm
W	30 mm
a (major)	8.25 mm
b (minor)	2.75 mm

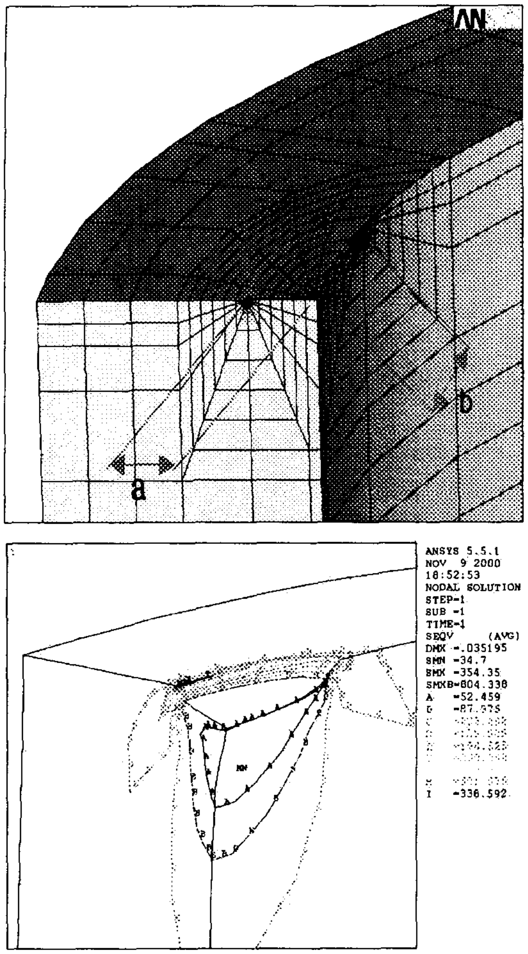


Fig. 10. Stress Distribution Around Crack Tip

represent the average J over 4 node near the deepest crack front. Therefore the effect of mesh sensitivity on the calculated J-integral values is significantly reduced at the crack front[14~15].

4.3. Results and Discussion

In this study, the semi-elliptical internal surface flaw in carbon steel pipe under tension loading is considered. The resulting stress distributions along the crack front are shown in Fig.10.

It shows that the stress increases as approaching to the deepest point. Then the stress at the deepest point is only considered because it is proportional to the stress intensity factor. The transient stress intensity factor distribution along with temperature is computed as shown in Fig. 11. It shows the comparison between the stress intensity factor(K_I) obtained from simulation and the fracture toughness(K_{IC}) for the material. And the stress intensity factor for stainless steel assumed as linear elastic material is also indicated at Fig. 11, to compare with carbon steel pipe as a reference. It can be concluded that both the stress intensity factors are below the fracture toughness.

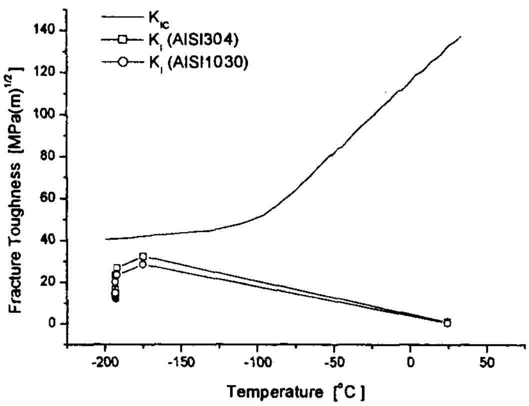


Fig. 11. Comparison Between Stress Intensity Factors and Fracture Toughness

5. Concluding Remarks

From this study, the feasibility of corrective maintenance by ice-plugging using a shorter jacket has been verified for various application of ice plugging method to maintenance activities. The experiment has been performed to confirm the possibility of ice plug formation in a shorter jacket pipe. And three-dimensional finite element analyses for thermal stress analysis and fracture analysis have been carried out. There are many facts that affect the ice plugging job such as pipe material, length, size, thickness and temperature, pressure, flow rate of internal fluid. From which of them, the length of a pipe applying freezing jacket is considered. From the results, the following conclusions were obtained.

(1) For the ice plugging process of the 140mm jacket length which is even shorter than the 168mm diameter of a stainless steel pipe, the ice plug is formed normally. And the well formed ice plug stands against 10 kg/㎠ of the hydrotest pressure without any failure or movement.

(2) It takes 50 minutes and is consumed 52 l of refrigerant for the plug formation. It is consumed 33 l /hr of LN2 refrigerant to maintain the formed plug. And the melting time of the formed plug is 13 hours from interrupting the refrigerant.

(3) Thermal stratification phenomenon is observed at the location of axially outside the jacket from convection of the internal fluid.

(4) The maximum thermal stress obtained from the finite element analysis indicates 62% of the yield strength. Therefore there is no possibility of plastic deformation.

(5) The fracture analysis revealed that the stress intensity factor(K_I) of the pipe material(carbon steel) applied LN2 refrigerant is approximately 73.6% of the maximum of the fracture toughness(K_{IC}) at the deepest crack front.

Acknowledgement

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