한국기계가공학회지, 제17권, 제6호, pp.144～150(2018.12) ISSN 1598-6721(Print)
Journal of the Korean Society of Manufacturing Process Engineers, Vol. 17, No. 6, pp.144~150(2018.12) ISSN 2288-0771(Online)

https://doi.org/10.14775/ksmpe.2018.17.6.144

Numerical Analysis on the Freezing Process of Internal Water Flow in a L-Shape Pipe

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L자형 배관내 물의 결빙에 관한 해석적 연구

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(Received 4 November 2018; received in revised form 9 November 2018; accepted 15 November 2018)

ABSTRACT

In this study, the freezing process of L-shaped pipe exposed to the outside was investigated numerically by considering the mushy zone of freezing water. From the numerical results, it was found that the flow was outwardly directed due to the influence of the L-shaped bending part in the outside exposed part of the pipe, and the ice was formed in the shape of longitudinal corrugation on the wall surface of the pipe after the bending part. It is confirmed that this phenomenon is caused by the venturi effect due to the freezing as seen in connection with the velocity distribution in the pipe. It is found that the remelting phenomenon at the end of the freezing section occur simultaneously during the process of forming the ice in the pipe section. In regard of the factors affecting freezing, it was found that the thickness of the freezing layer is increased as the exposed pipe surface temperature is decreased, and the pipe surface temperature had a significant effect on the change of the freezing layer thickness. At the same time, it was found that the freezing layer becomes relatively thin when the water inflow rate is increased. This phenomenon was caused by reducing the exposure time of freezing water due to the vigorous flow convection of the water fluid.

Key Words : Freezing(결빙), Bending Pipe(곡관), Ice Layer(결빙층), Water(물), Numerical Analysis(수치해석)

1. Introduction

A fluid flowing in a pipe exposed to the outside undergoes ice formation in a condition where the ambient temperature falls below the freezing temperature. In industrial sites with large piping facilities, such as power plants, refineries, and chemical plants, pipe freezing occurs frequently due to the cold in winter, often leading to industrial disasters. Pipe freezing accidents are increasing due to abnormal cold waves every year, and the resulting economic losses are also growing greatly. In South Korea, where there are four distinct seasons, many pipes are exposed to the outside in plants, such as water supply systems and waste heat recovery systems for sewage treatment, which results in freezing, as shown in Fig. 1.

The ice formations formed inside the frozen pipes

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are called “ice plugs.” Their shapes are affected by the type, temperature, flow rate, and pressure of the fluid in the pipe as well as the pipe wall temperature, diameter, and length.[1]

Suh et al.[2,3] examined the factors affecting freezing in straight pipes and analyzed the corrosion and heat transfer process inside straight pipes considering the effect of the flow in the pipes.[4,5] Furthermore, to prevent freezing accidents in winter due to ice formation inside pipes, Ohm[6] proposed the maximum pressure and threshold ice formation ratio to the diameter of each pipe in the event of water freezing inside carbon steel pipes, steel pipes, copper pipes, stainless steel plates for general piping, and hard vinyl chloride pipes for water supply.

To numerically examine the ice formation process inside L-shaped pipes and identify the factors affecting ice formation, this study investigates the effects of the changes in the wall temperature and flow rate of exposed copper pipes on ice formation inside the pipes. Furthermore, the changes in the thickness of ice along the length of the pipes in the freezing section, the ice formation process on the cross-section of the pipe, and the correlation between the ice layer and flow are examined.

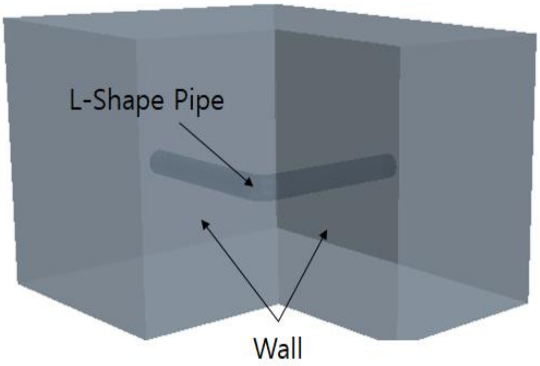

Fig. 1 Schematic diagram of the L-shape pipe installed into the wall of plant system

2. Numerical Analysis

2.1 Problem Setting

Pipes are generally exposed to the outside in certain sections through the outer wall in industrial facilities, as shown in Fig. 1. When the ambient temperature falls below the freezing point, ice formations are formed on the walls inside the pipes exposed to the outside. This study considers the case where an L-shaped pipe with a diameter D is exposed for a length of $2L_{outer}$ to the outside, as shown in Fig. 2. As the outside temperature falls below the freezing point, the wall temperature of the exposed pipe stays at wall temperature T_{outer} and ice is formed on the wall of the exposed pipe. It is assumed that regardless of the temperature, the density of the water flowing in the pipe and the flow rate at the pipe inlet are constant, and the pressure also stays the same at the atmospheric pressure.

2.2 Governing Equation and Conditions

In this study, a fixed grid system and the Eulerian multiphase model are used to analyze the phase change problem inside the pipe that appears during the process of pipe ice formation. In particular, there is a mushy region, which is an intermediate process between liquid and solid phases, in the ice formation process. To numerically analyze the fluid behavior in this region, the Darcy term proposed by Voller et al.[7] and Bennon and Incropera[8] was introduced. For the governing equations for analyzing the process of pipe ice formation, the continuity equation, momentum equation, and energy equation were used. The solid volume fraction in the fluid, α_s^*, is, as follows:

$$\alpha_s^* = \begin{cases} 1 & T^* < 0 \\ (1-T^*) & 0 < T^* < 1 \\ 0 & 1 < T^* \end{cases} \tag{1}$$

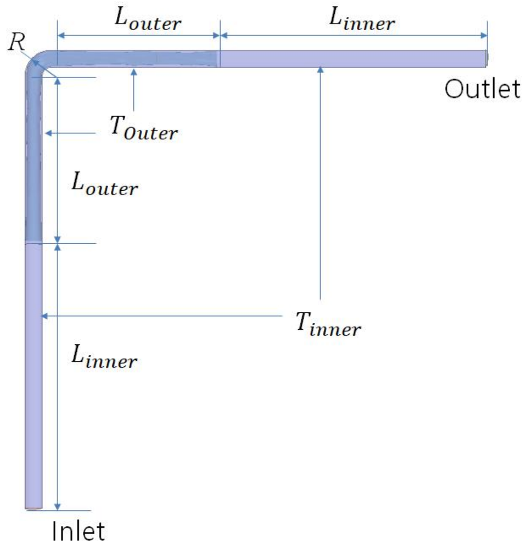

Fig. 2 Schematic diagram of the freezing phenomena of water in a L-shape pipe

where T^* is a dimensionless temperature, which is defined as follows:

$$T^* = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \tag{2}$$

The Carmen-Kozeny model[9] was applied to process the flow resistance with a porous concept of the mushy region caused by ice formation. When the Metzner model[10] is applied, viscosity in the solid–liquid mushy region becomes as follows:

$$\mu^* = \mu_l \left[1 - \frac{\alpha_s^* \cdot F_\mu}{A} \right]^{-2} \tag{3}$$

where, A is a crystal constant. The solid–liquid conversion function F_μ is as follows:

Table 1 Configuration conditions for simulating water freezing within a L-shape pipe

Specification	Physical Values
Pipe Diameter (D)	20mm
Inner Pipe Length (L_{inner})	300mm
Outer Pipe Length (L_{outer})	200mm
Rounding Radius of Pipe (R)	10mm
Inlet Velocity (V_{in})	0.05m/s
Outer Wall Temperature (T_{outer})	-20℃
Inner Wall Temperature (T_{inner})	2℃

$$F_\mu = \begin{cases} 0 & \alpha_s^* < \alpha^{*cr} \\ 1 & \alpha^{*s} > \alpha^{*cr} \end{cases} \tag{4}$$

It was assumed that the inlet and outlet of the pipe were at atmospheric pressure and the water flowed in at a constant rate at the temperature of 2°C. The basic conditions for the pipe size, pipe wall temperature, and flow rate are listed in Table 1.

2.3 Numerical Analysis Method

To numerically analyze the ice formation process inside an L-shaped pipe, the governing equations were discretized and then arranged into algebraic equations using the finite volume technique. Then, the final solution was determined using the commercial CFD solver Star-CCM+. In particular, the density changes of water and ice according to temperature were ignored, and a segregated model was applied to the convection term. Furthermore, the $k-\epsilon$ standard model was applied to the turbulence to calculate the speed field and temperature field. For the calculation, a polyhedral grid was used by default, and a prism grid was applied considering the viscosity on the wall and the calculation of the ice layer. Approximately one million grids were used.

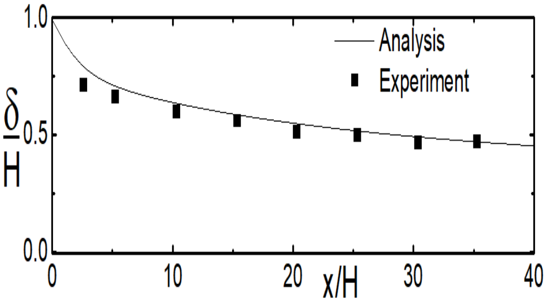

Fig. 3 The ice layer shape for freezing of liquid in steady-state laminar flow between two parallel plates in T_w=-1.2°C, T_∞=2°C, $u_{mi}H/\nu$=175, Experimental results from Ref. (11) (rectangular) and numerical results from this study (solid lines)

3. Analysis Results and Discussion

For numerical verification, the experimental results of Kikuchi et al.[11] for ice formation in a laminar flow inside parallel plates in 2H intervals with conditions similar to those in this condition were compared with the analysis results using the method adopted in this study. They were found to match each other relatively well.

3.1 Characteristics of Ice Formation in L-shaped Pipe

To grasp the ice formation inside a pipe exposed to freezing ambient air, the result at 60 secs after the beginning of ice formation was examined in a pipe exposed to the outside for the conditions in Table 1, which correspond to the most representative case.

Fig. 4 shows the shape of an ice formation on the wall along the length of the pipe in the freezing section of an L-shaped pipe exposed to the outside. The dark color in this figure indicates the ice layer, and the center of the pipe indicates the water flow. As shown in this figure, the ice is formed in growing thicknesses along the length of the pipe. Then, as the water passes through a bent pipe, the water flow is pushed toward the outside (top) of the bent pipe, and the ice layer in the inner side of the bent pipe becomes relatively thick. Furthermore, after the bent pipe, the ice layer is formed in a wave shape.

Fig. 5 shows the flow rate distribution that changes along the pipe in order to examine the flow characteristics inside the pipe, which have a considerable effect on the formation of the ice layer. As the ice layer becomes thicker along the pipe, the channel becomes narrower toward the center of the pipe, and the flow rate increases at the center. It can be seen that as the flow passes through the bent section of the pipe, it is pushed toward the outside of the pipe, and the ice layer becomes thinner. As a result, the flow rate becomes slower. Immediately after the bent pipe, the thin ice layer becomes gradually thicker again, and the flow rate increases again. In the latter part of the bent pipe, the Venturi effect appears due to the increasing water speed, and the ice layer becomes thinner again. This phenomenon appears repeatedly. Consequently, it can be seen that the ice layer inside the pipe is formed in a wave shape along the pipe length due to this phenomenon.

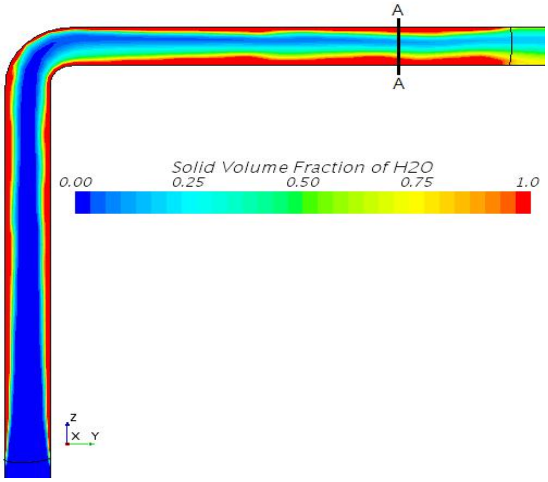

Fig. 4 Variation of solid volume fraction of water along the L-shape pipe

To check the circumferential formation of the ice layer inside the pipe, the shape of the ice layer (left) and temperature distribution (right) for the pipe cross-section area are shown in Fig. 6. This is the pipe cross-section area 5 cm upstream from the outlet of the ice formation section exposed to the outside. The bottom and top parts in this figure show the inner and outer sides of the pipe, respectively. From this figure, it can be seen that the ice formation inside the pipe is thicker than that outside the pipe. As can be seen in Fig. 5, this is because as the flow passes through the bent pipe section, it is generally pushed toward the outside. It can be seen from the cross-section of the pipe that the temperature gradient on the outer wall is larger than that on the inner wall in correspondence with the thickness of the ice layer. The circumferential thickness change of the ice layer in the pipe appears in a wave shape, because a similar flow change is generated on the cross-section as well due to the change of the ice layer thickness in a wave shape along the pipe.

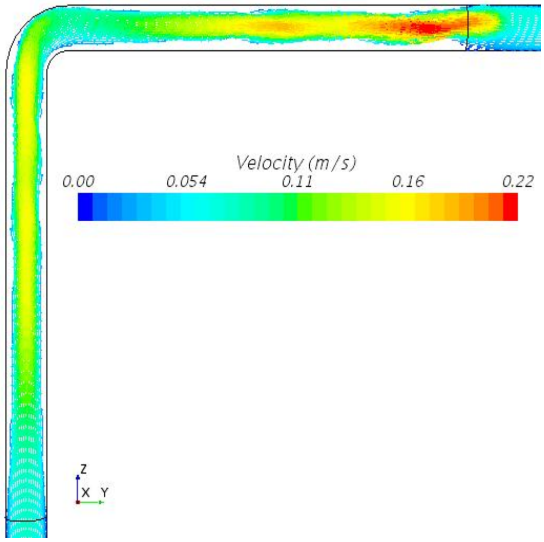

Fig. 5 Velocity distribution of water flow during ice forming along a L-shape pipe

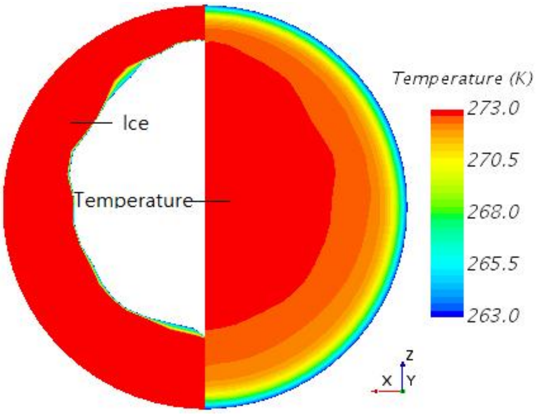

Fig. 6 Sectional distribution of the ice(left) and temperature distribution(right) of water within a pipe (A-A section in Fig. 4)

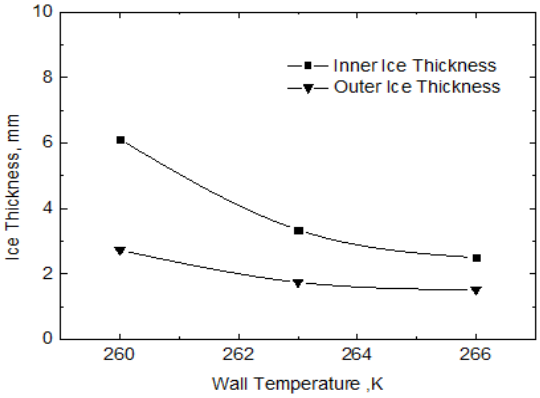

Fig. 7 Variation of ice thickness formed on the wall of pipe with the outside wall temperature at 10cm ahead of the exit port of pipe

3.2 Effects of External Wall Temperature

Fig. 7 shows the thickness changes of the ice layer in the pipe according to the wall temperature change of the pipe exposed to the outside 10 cm before the pipe outlet. In this figure, the rectangular symbol indicates the thickness of the ice layer in the innermost part of the bent pipe, and the inverted triangle symbol indicates the ice layer thickness in the outermost part of the bent pipe. It can be seen that as the wall temperature rises, the ice layer thickness decreases, and the ice layer inside the bent pipe becomes thicker. The thickness reduction of the ice layer is the fastest inside the bent pipe. This means that the ice layer formed on the inner wall of the pipe is more sensitive to wall temperature changes.

3.3 Effects of Flow Rate

Fig. 8 shows the thickness changes of the ice layer in the pipe exposed to the outside according to the flow rate change of the water flowing in at the pipe inlet 10 cm before the pipe outlet. In this figure, the rectangular symbol indicates the thickness of the ice layer in the innermost part of the bent pipe, and the inverted triangle symbol indicates the ice layer thickness in the outermost part of the bent pipe. As the water flow rate increases, the ice layer inside the bent pipe becomes thinner, and on the outside of the bent pipe, the ice layer tends to become thicker and the thicknesses of the ice layers at the inner and outer sides of the bent pipe become similar. This appears to be due to the tendency of the liquid water to be pushed to the center of the pipe as the flow rate becomes faster.

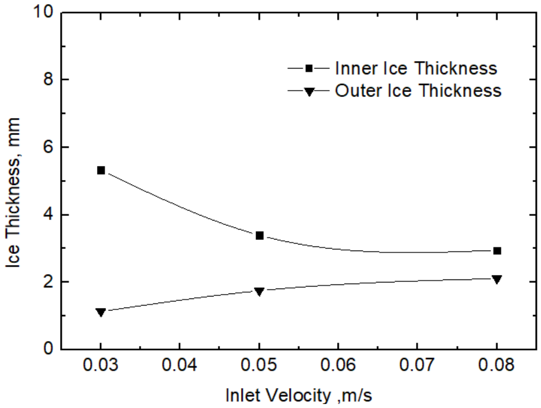

Fig. 8 Variation of ice thickness formed on the wall of pipe with the inlet velocity of water at 10cm ahead of the exit port of pipe

4. Conclusions

This study numerically analyzed the ice formation process in an L-shaped pipe exposed to the outside. The numerical analysis results showed that in the ice formation section exposed to the outside, due to the effect of the L-shaped bent section, the flow tends to be pushed toward the outside. As a result, the ice layer on the pipe wall after the bent section appears in a wave shape. An examination of this phenomenon in connection with the flow rate distribution in the pipe confirmed that it was due to the Venturi effect resulting from ice formation. As the flow rate inside the pipe increased, the thicknesses of the inner and outer parts of the bent pipe became similar.

This study was conducted to identify the factors affecting ice formation in pipes, and the results showed that as the wall temperature of the exposed pipe decreased, the ice layer thickness generally increased, which had a significant effect on the changing thickness of the ice layer. Furthermore, when the water inflow rate was increased, the ice layer became thinner. This was found to be due to the reduced ice exposure time resulting from the active flow convection of the fluid at temperatures above the freezing point.

Acknowledgment

This study was partially funded by the BK21 Project.

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