Cryogenic explosion-proof camera in LNG carrier tank– A Review

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***Abstract**-With an increase in the usage of LNG, there is a heightened interest about its safety aspects regarding the explosion of LNG carrier tank. The need for a cryogenic explosion-proof camera has increased. The camera has to work in cryogenic environment (below −160 °C) in LNG carrier. This study conducted design and heat transfer analysis of cryogenic camera to secure working time in limitation of heat source. The design with gap width of double pane windows was conducted based on simple vertical cavity model to insulate from cryogenic environment. The optimal gap width was 12.5 mm. For effective analysis considering convection within the camera, equivalent thermal conductivity method was adopted with ABAQUS. The working time of the camera predicted was over 10 h at warm-start condition. In cold-start condition, it required about 5 h of pre-warming time to work. The results of analysis were compared with the ones of the actual cryogenic test.*

I. INTRODUCTION

Liquefied Natural Gas (LNG) can be stored effectively by decreasing its volume till a six hundredth through the process of liquefying natural gas at cryogenic cooling conditions (−190 °C ~ −160 °C). Since a LNG is mostly extracted from the ocean and stored, and is carried for a long time and distance, lots of studies on pressed vessel and LNG transportation has been carried out (Chen[2] ; Lisowski ; Lee)[8].

Methane that covers about 96 percent of LNG poses a serious hazard to explosion. It requires careful control and the need for accident prevention is increasing such as detection of pre-leaked gas and internal inspection of LNG tank.

Inside of LNG storage tank, extreme cold conditions coexist in both liquid state (below −190 °C) and gaseous state (below −160 °C). In such situation, the electric circuit board of the camera must remain in a working temperature range to function properly. But there is limitation on electric power usage of the circuit board and the light system because of explosion hazard. In the electric power limitation, therefore, it is important to keep or secure working time based on a specific temperature range by heat transfer between the electric circuit boards inside the camera system and insulating from the cold outside.

Since the camera system consists of metallic housing, adiabatic double pane windows, electric circuit boards and lights as heat source and so on, conduction and convection phenomena appear between each component. A lot of research on heat transfer or structural analysis of a gas storage tank is being carried out, but there have been little studies on inspection equipment like this camera that has a complicated heat transfer phenomenon (Delaquis)[3].

In this paper, to begin with, we introduced non-explosion design and the analysis procedure. And optimal design of gap width of the double pane windows for insulation was carried out by using a simple vertical cavity model. Next, we explained heat transfer analysis method for camera system using ABAQUS (commercial finite element analysis software); the concept of equivalent thermal conductivity was applied to the heat transfer analysis considering convection of air cavity inside the camera housing without air flow. Finally, we carried out a cryogenic experiment and the test data was compared with the results of numerical analysis by ABAQUS.

II. DESIGN & ANALYSIS PROCEDURE NON EXPLOSION DESIGN

The cryogenic explosion-proof camera in a LNG carrier tank conforms to international administrative standard such as ATEX/IECEX and IEC. The equipment for gas applies explosion-proof class “EX i” according to ATEX/IECEX rules in Europe because the inside of the tank is zone 0 (Rockwell Automation, 2001). “EX i”, or intrinsic safety, limits the electric power usage in order to avoid spark energy and ignition temperature for explosion.

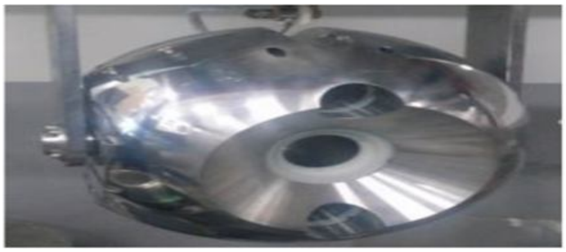
“EX i” limits power usage defining allowable current ampacity as voltage. Since allowable voltage of the cryogenic camera in this study is 12 V, current must be used below 3.33 A. The total allowable power is in the following equation (Korea Gas Safety Corporation, 2014).

In actual field, it is necessary to design a product with the smaller electric power due to the safety factor, and so the adiabatic design is very important to maintain the operating temperature inside the camera at this limit of heat source power and at about −190 °C outer temperature condition.

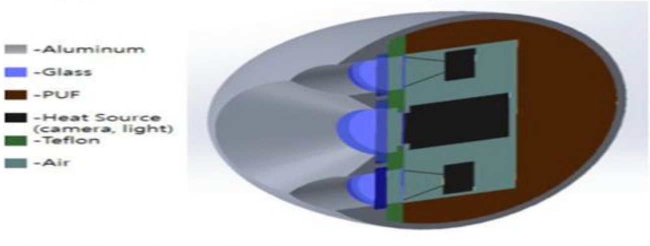
Actually, Fig. 1(b) shows a cross section of the cryogenic explosion-proof camera and it was designed to conform to the standard electric power of 40 W in using an 8 W camera circuit board at the middle and two 10 W lights (total 28 W of heat sources only in the real camera).

For developing a camera exposed to exterior cryogenic environment, this study was carried out in two parts. Firstly, the gap width of the Double Pane Windows (DPW) was decided through a simple vertical cavity model in order to protect any heat transfer change to the inside of the camera from cold outside circumstance. Secondly, to conduct an efficient heat transfer analysis considering convection, thermal analysis of cryogenic camera was carried out by using equivalent thermal conductivity.

Fig. 2 depicts the analysis procedure and geometry modeling for deciding the gap width of double pane windows. The disk shaped double pane windows are simplified to 60 mm height vertical cavity model in order to decide the gap width between the windows as shown in Fig. 2. For a simplified vertical cavity model, Ra (Rayleigh number) was calculated and the presence of natural convection phenomenon was checked. Next, Nu (Nusselt number) and h (heat transfer coefficient) that depended on the gap width of the windows were calculated by using empirical formula of a simple model (Incropera and DeWitt,)[4]. Finally, the total heat flux that is the sum of each by conduction and convection was calculated according to the gap width of double pane windows as adiabatic systems.



(a) Picture of the real product



(b) Sectional view of the 3D-model

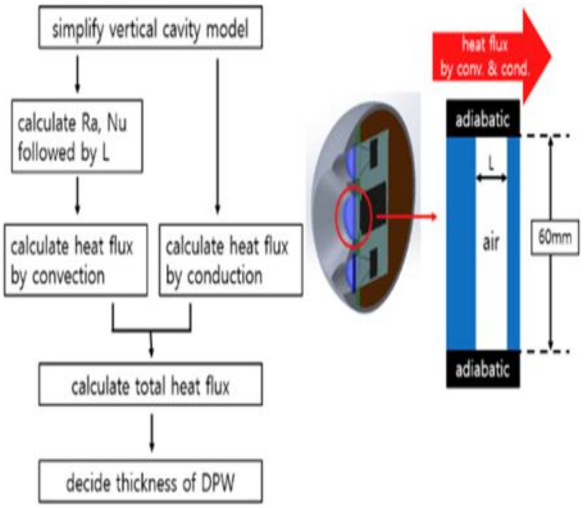
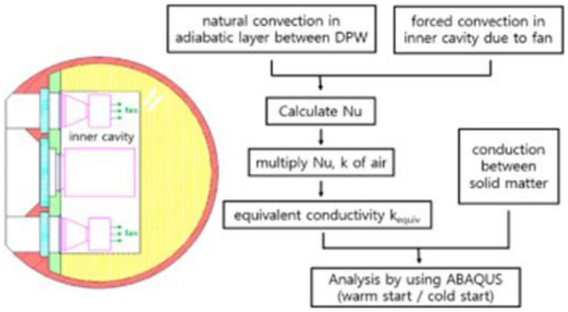


Figure 2. . Analysis procedure and geometry modeling for deciding the gap width of double pane windows.

To analyze convective heat transfer of a structure with air cavity by using numerical analysis software, heat and flow analysis is required. But this study applied the concept of equivalent thermal conductivity to avoid conducting flow analysis and we were able to carry out the heat transfer analysis for cryogenic camera system with air cavities efficiently. Fig. 3 shows the analysis procedure by using equivalent thermal conductivity and ABAQUS for heat transfer analysis considering convection and conduct in Double Panel Windows (DPW) and camera housing inside.



Heat transfer analysis was performed for two conditions of warm-start and cold-start. warm-Start powers on electric power at room temperature (25 °C) and then the camera is inserted into the cold tank, but cold-start starts in the cryogenic environment of the tank without warming up (so the initial temperature is −160 °C). Gap width design of double pane windows Simplified vertical cavity model

The heat transfer phenomenon of double pane windows with air cavity is classified into conduction and convection. Especially, the effect of convection depends on the Rayleigh number, RaL. RaL is defined by buoyancy-to-resistance ratio of fluid and the empirical formula of vertical cavity model is defined by Eq. (2). There will be convective heat transfer if RaL is bigger than the critical value 103 (Jang et al., 1992; Lee et al., 1998).

$RaL=g\beta(Tin-Tout)L3\alpha\nu,(2<HL<10)$

As shown in Fig. 4, to design the gap width for the system, the disk-shaped double pane windows were simplified in the vertical rectangular cavity model. The value of RaL is over the critical value of 106 for convective heat transfer when at 5 mm width and 60 mm height, temperatures of internal air Tair = −70 °C, external window Tout = −150 °C and internal window Tin = −25 °C. The calculation of RaL shows the need for considering the convection effect.

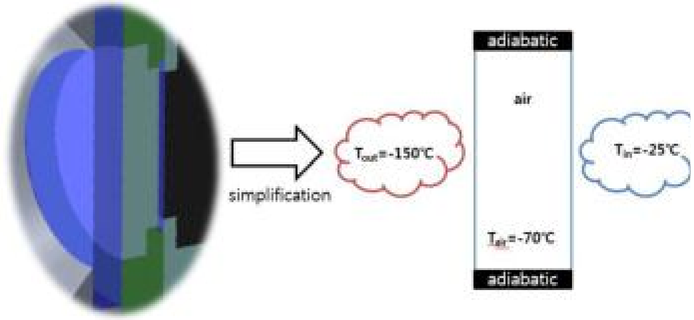


Fig. 4. Simplification of air layer in double pane windows system.

Heat transfer coefficient caused by convection is derived from the Nusselt number, and the empirical formula of average Nu for the simplified vertical cavity model is shown in the following Eq. (3a). Finally, the average heat transfer coefficient for simplified vertical cavity model can be calculated as shown in Eq.(3b).

$(3a)\overline{Nu}=0.22(Pr0.2+Pr\times RaL)0.28(HL)-14$

$(3b)\overline{h}=\overline{Nu}\times kL$

Decision of width between double pane windows From the above equations, heat transfer coefficients were calculated as the gap width between the windows. In the adiabatic air cavity of double pane windows, there are two kinds of heat transfer phase; conductive by thermal conductivity k of air, and convective by heat transfer coefficient h. The first heat flux by conduction can be calculated by using Fourier's law Eq. (4a), and the second heat flux by convection can be calculated by using Newton's cooling law Eq. (4b).

$(4a)q''=-kT2-T1L$

$(4b)q''=h(Ts-T\infty)$

Fig. 5 shows the results from the above calculations of each heat fluxes and total heat flux at air cavity. Heat transfer decreases by conduction and increases by convection as the gap width between the windows thicken. As the width became thick, total heat flux approach specific value and the appropriate gap of double pane windows was decided as 12.5 mm considering effectiveness of insulation and geometry of the product.

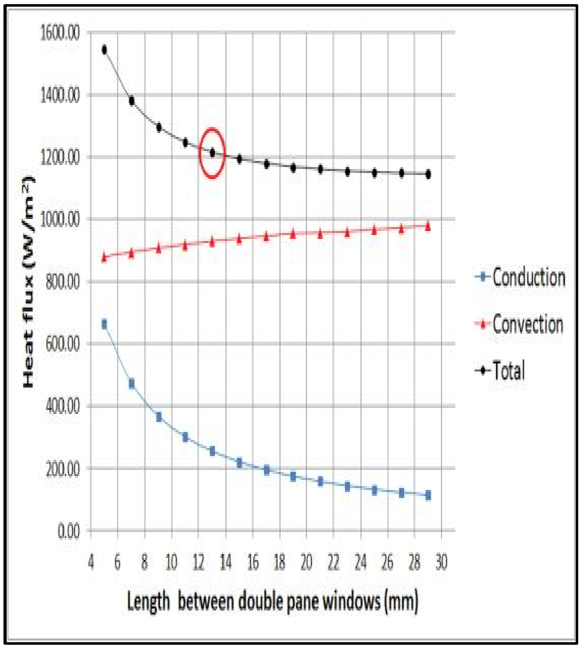


Fig. 5. Heat flux dependent on the gap width of the double pane windows system.

Heat transfer analysis of the whole camera system Equivalent thermal conductivity methodThermal conductivity depends on the property of the material but the heat transfer coefficient for convection is an experimental constant affected by behavior and properties of fluid, distribution of temperature, etc. For this reason, convection analysis requires some effort, such as performing fluid analysis, unlike conduction analysis. This study used the analysis technique without fluid analysis by using the concept of equivalent thermal conductivity when thermal analysis including convection was carried out. Simple methods like this are efficient in application to actual complex-shaped products considering variable boundary conditions. If Length (L) and Nusselt number (Nu) are already known, heat flux will be derived from Eq. (5) in rectangular enclosure such as cavity of double pane windows and inner air cavity around camera and lights as shown Fig. 3.

$q''=h(T1-T2)=kNuT1-T2L(h=kNuL)$

Eq. looks like Fourier's law of conduction when thermal conductivity assumes to k·Nu. It means convective heat transfer in the cavity is equal to the conductive effect in case the fluid layer thermal conductivity is k·Nu. Therefore, equivalent conductivity of a cavity can be defined as k·Nu as in Eq. (6).

$(6)keff=k\cdot Nu$

It is possible to get the results effectively through just conductive heat transfer analysis without fluid analysis for convection by using equivalent conductivity derived from Nu, and it is found from already known data of experiments or empirical formula of well-known geometry (Cengel and Ghajar,)[1],

Numerical model

In this study, we used 10-node quadratic heat transfer tetrahedron mesh (DC3D10 in ABAQUS 6.14) and the number of elements is 224,527 to effective analysis. Also transient analysis was conducted until 36,000 s (10 h) and time step size was 100 s. The mesh sensitivity test was performed in advance to the numerical analysis. We used two kinds of mesh size of the numerical model; the numbers of meshes are 224,527 and 942,915. It made difference of the temperature results in preliminary analysis from a minimum of 0.26 °C to a maximum of 2.7 °C. Figs. 6 and 7.

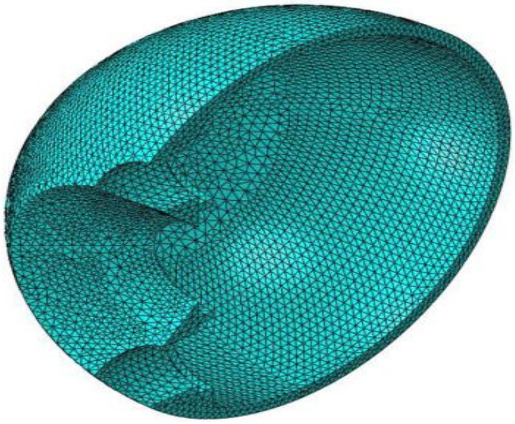


Fig. 6. Mesh model of cryogenic camera.

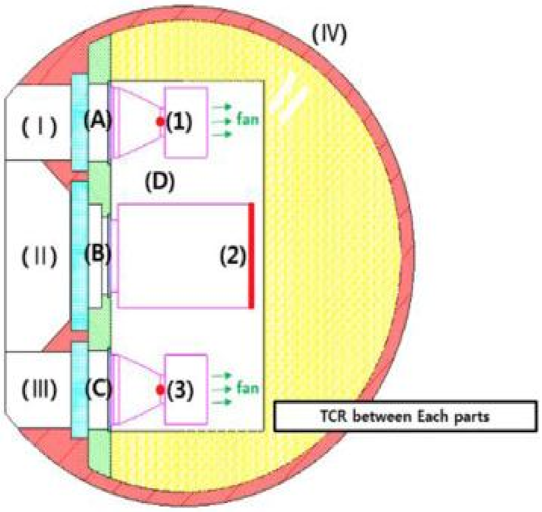


Fig. 7. Boundary condition of analysis model.

Boundary condition of thermal analysis 4.3.1. Operating condition To investigate the working time for the camera, two kinds of initial temperatures are used in this analysis. The two initial temperature conditions considered two real-working conditions (warm-start and cold-start). Heat transfer analysis of cryogenic camera was carried out with the above warm-start and cold-start conditions. In case of warm-start, a camera is switched on before inserting into the tank, and so the initial temperature is 25 °C. In case of cold-start condition, the camera is powered on in the cryogenic condition to operate without warm up so the initial temperature is −160 °C.

Double pane windows – (A), (B), (C)

In order to consider the convective heat transfer phenomenon of a cavity, equivalent conductivity that included average Nu was adapted as boundary conditions. As mentioned in Section 3.1, we assumed temperatures of internal air Tair = −70 °C, external window Tout = −150 °C and internal window Tin = −25 °C. Properties of air at −70 °Care used; α, ν, Pr and k are 8.01 × 10−6 m2/s, 5.95 × 10−6 m2/s, 0.74 and 0.016 W/m °C, respectively. Therefore, Rayleigh number of vertical cavity model was RaL = 2.925 × 105 and Nusselt number was derived from Eq. (3a) (calculated Nu = 4.94). In conclusion, equivalent conductivity was decided as below.

keff,DPW=k·Nu=0.016W/m°C×4.94=0.079W/m°C

. Internal cavity – (D)

Heat transfer of internal cavity (D) is influenced by forced convection derived cooling fans and fins attached to lights. For this reason, turbulent flow will occur in air cavity and it is difficult to decide Nu of the turbulent flow. A large Nu corresponds to more active convection such as this forced convection, with turbulent flow typically in the 100–1000 range (Cengel and Ghajar,)[1]. We chose the median value Nu = 100 for conservative design, and so equivalent thermal conductivity used in thermal analysis was 1.6 W/m °C.

keff,cavity=k·Nu=0.016W/m°C×100=1.6W/m°C

Two lights and a camera circuit board are used as heat sources and interactions of heat generation from that allow the camera to remain at a certain operating temperature range. But allowable power usage is restricted because of explosion-proof (Section 2.1). Therefore, each of the two lights generates 10 W and the circuit board generates 8 W.

Film coefficients in ABAQUS were used to describe heat exchange by convection on contact surfaces (glasses and cryogenic gas, outside housing and gas). The value of heat transfer coefficient used was 20 W/m2 K as general value of free convection between gas and solid surface (Cengel and Ghajar,)[1].

It might be considered to calculate the effect of thermal radiation over the surface. But it occurred only in warm-start condition because radiation is surface phenomenon and temperature of surface scarcely changed in cold-start condition. On the other hand, heat transfer by radiation occurred in the case of warm-start. But, its heat flux decreased sharply since the temperature of camera's skin converged to the ambient temperature. Most of all, emissivity of camera's skin made of polished aluminum is just 0.04–0.06 (Incropera and DeWitt)[4]. So, heat flux by radiation in warm-start condition is 8.76–26.28 W/m2 according to Stefan–Boltzmann's radiation law. For this reason, this study leaved radiation effect out of consideration in analysis to reduce analysis time.

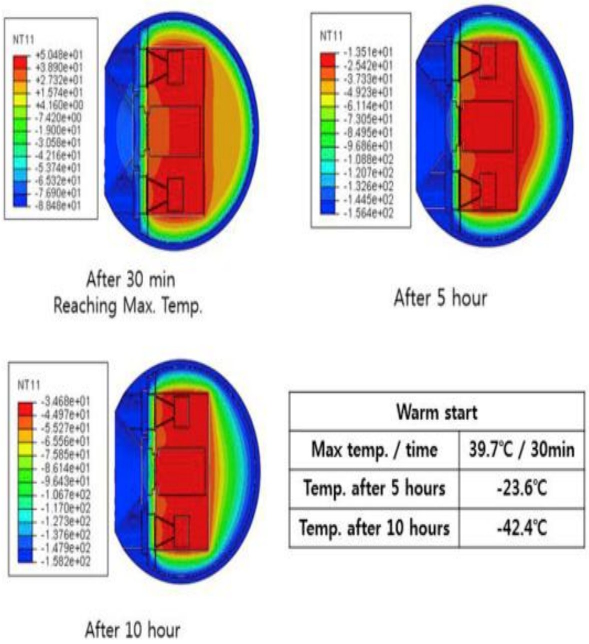
Contact boundary condition – thermal contact resistance the function of thermal conductance and contact condition in ABAQUS is applied to contact parts between different materials in order to consider Thermal Contact Resistance (TCR). TCRs between air and solid materials (aluminum, Teflon and Poly Urethane Foam (PUF)) were 2.75 × 10−4m2 K/W, and TCRs between solid materials were 0.2 × 10−4m2 K/W (Incropera and DeWitt)[4].

III. RESULTS

The thermal analysis was conducted under two analysis conditions (warm-start/cold-start). The results of them were showed through contour images and tables. The contour images show temperature distribution of the whole camera model, while tables show the values that are recorded at certain times and spot (the center of camera circuit board

Case 1 – warm-start condition

Fig. 8 shows temperature change of cryogenic camera from the analysis result in warm-start condition. The temperature inside the camera in the LNG tank increased and reached a maximum temperature of about 40 °C after 30 min. After 5 h, it reached about −23 °C and then decreased to −42 °C after 10 h. When the operating temperature assumes −60 °C, the analysis results shows that the possible working time is over 10 h; generally the minimum working time required is 5 h in real field for inspection.

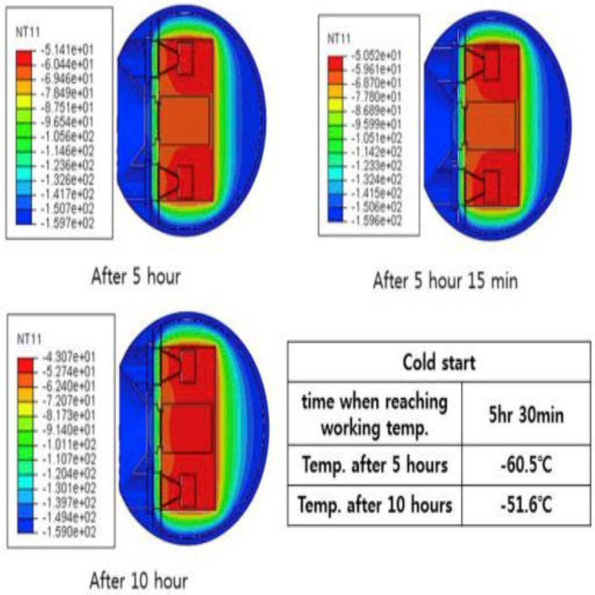


Warm start	
Max temp. / time	39.7℃ / 30min
Temp. after 5 hours	-23.6℃
Temp. after 10 hours	-42.4℃

Fig. 8. Analysis of cryogenic camera on warm-start condition.

Case 2 – cold-start condition

Fig. 9 shows the results of the cold-start case when the camera had been in the LNG tank without performance, and it starts in −160 °C cryogenic circumstance. It was expected to need a heating time of about 5 h when the temperature of the circuit board increased to the operation limit of −60 °C. In other words, it takes 5 h to start working properly. The temperature of the circuit board was −51 °C after 10 h. In conclusion, it means that a wait of 5 h before working is needed when the camera is located in the LNG tank with system power off.



Cold start	
time when reaching working temp.	5hr 30min
Temp. after 5 hours	-60.5℃
Temp. after 10 hours	-51.6℃

Fig. 9. Analysis of cryogenic camera on cold-start condition.

IV. EXPERIMENTS

Verification of numerical analysisAs a verification step, we carried out a cryogenic experiment and the test data was compared with the results of the analysis. In this experiment, liquid nitrogen (LN2) was used instead of LNG due to its explosiveness property. Fig. 10 shows the test equipment and the actual camera product in the test. The equipment consists of a liquid nitrogen vessel and measurement module of temperature in the vessel. The experiment test and numerical analysis conditions are cold-start as initial temperature −160 °C in camera and the temperature in vessel keeps about −160 °C.


(a) Experiment equipment (b) Cryogenic camera in LN_2 tank

Fig. 10. Test of cryogenic camera in LN2 tank.

The comparison of the analysis and experiment results shows favorable similarity as shown Fig. 11 although the discrepancy of between both temperatures is about 15 °C at about 5 h (18,000 s). The design factors used in this heat transfer analysis are conservative, for example, the Nu was selected 100 in the 100–1000 range, to secure safety of the working time in severe industry condition including uncertainty. If we adopt the average value, the discrepancy of the temperatures will decrease.

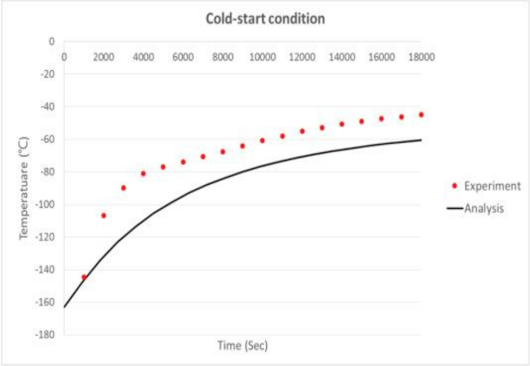


Fig. 11. The comparison of experiment and analysis results in cold–start condition.

Working time for industry field

In general, more severe conditions than design conditions are used at the real test in industry fields in order to secure safety considering uncertainty. The test temperature condition in vessel changed −190 °C to get the working time for industry fields. In the same way of the analysis, test is conducted under warm-start and cold-start conditions. The test results are shown at Table 1. The cryogenic camera worked for over 10 h after putting in liquid nitrogen under warm-start condition. The test was finished after 10 h because the time was more than the minimum working time of 5 h. In the next case, it took 4 h before the camera started working properly under cold-start condition. As shown in Table 1, similarity between the results of experiment and analysis shows that results of analysis are appropriate.

Table 1. Results of experiment and analysis for cryogenic camera.

	Test results	**Analysis results**
Working time at warm-start condition (Initial temp.: 25 °C)	10 h (runout)	10 h
Preheating time at cold-start condition (initial temp.: −190 °C)	4 h	5 h

V. CONCLUSION

In this study, we evaluated the thermal performance of cryogenic camera to inspect LNG carrier tank and decided on the working condition needed for use in the actual field. Gap width of double pane windows was designed and thermal analysis was carried out for cryogenic explosion-proof camera in LNG carrier tank by using ABAQUS with equivalent thermal conductivity method to consider convective heat transfer of air without any fluid analysis.

Gap width of double pane windows was decided as 12.5 mm; a value that minimizes the total heat flux by convection and conduction using simplified vertical cavity model. The concept of equivalent thermal conductivity was applied to solve the convection problem efficiently. This simple method is suitable for industry field where engineering problems are complex and require rapid problem resolution. The thermal analysis and cryogenic experiment was carried out under warm-start and cold-start conditions and were compared to each other.

As a result, it was found that the working time was more than 10 h under warm-start condition (initial temperature of 25 °C) while it needed at least 5-h preheating time to activate the camera under cold-start condition (initial temperature of −160 °C).

The comparison of the results of analysis and experiment shows favorable similarity. The similarity shows that the simplified vertical cavity model and the equivalent thermal conductivity method adopted in this study are very efficient and valid approach.

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