Numerical Analysis Research and Experimental Verification of the Heat Leak of a Cryogenic Vacuum Jacket Valve

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Abstract. The need for natural gases has recently been increasing for energy production and demand. Accordingly, many different studies are now being conducted on ways to supply liquefied natural gases (LNG) and on the valves that are used to supply those gases. Although there are various types of valves that are used at extremely low temperatures, vacuum jacket valves, which minimize the heat leak by using lean gases in the vacuum layer, are mostly used. In this regard, this study verified the results of a numerical analysis through thermal analysis and experiments on a vacuum jacket valve at extremely low temperatures (-179°C). Based on this data, a heat leak was calculated to evaluate thermal performance. In addition, a thermal-structural coupled field analysis was conducted in order to consider thermal stress and deformation caused by extremely low temperatures. Based on this analysis, the study aims to evaluate the structural stability of a vacuum jacket valve and provide the results as basic data.

Introduction

Lately, questions are being raised by many countries with regard to environmental conventions. Environmental regulations are being tightened, which in turn calls for the use of clean fuels that could minimize pollutant emissions. Even though many studies are being conducted in relation to clean fuels, in fact, many problems arise at the commercialization stage [1,2]. For this reason, natural gases are increasingly becoming necessary for energy production and demand, and research and development efforts are focused on liquefying natural gases at high pressure, and supplying and transferring those gases. Since liquid natural gas (LNG) is unique because its liquid temperatures are extremely low (-179°C) [3-5], the valves used for LNG should be designed for extremely low temperatures. There are many different types of insulation valves available now, but a vacuum jacket valve is most commonly used [6].

A vacuum jacket valve is a valve that uses lean gases in the vacuum layer to shut off conduction and convention currents, and minimizes the heat leak to the outside [7]. However, as the outside air temperature is considered fairly high when an extremely low-temperature liquid flows through the pipe, boil off gas frequently occurs depending on the vacuum level and insulation technology [8]. Much research is being conducted to determine methods of minimizing such occurrences.

There are various key design variables that minimize the heat leak from a vacuum jacket valve at extremely low temperatures: the jacket thickness, the jacket area, and the internal diameter and length. However, no basic data or research related to these variables have been clearly presented to date [9].

Therefore, this study determined the temperature distributions through a thermal analysis of a vacuum jacket valve designed for extremely low temperatures, and verified the thermal analysis results by comparing them with experimental results. Based on the temperature distributions gained from a numerical analysis, this study calculated the heat leak and evaluated the thermal performance. After evaluating the structural stability of a vacuum jacket valve through thermal stress and deformation based on thermal-structural coupled field analysis, this study also aimed to provide the results as basic data.
Numerical Analysis

Finite Element Model. ANSYS V16.0, a commercial program widely used for numerical analysis, was used to conduct a numerical analysis. The finite element model used in the analysis is shown in Fig. 1.

![3D model and finite element model](image)

(a) 3D model (b) Finite element model

Fig. 1 Three-dimensional model for thermal analysis and thermal-structural analysis.

In Fig. 1, (a) shows the entire appearance of the vacuum jacket valve model that was used in this study, while (b) illustrates the finite element model that was used for thermal analysis and thermal-structural coupled field analysis. The model was simplified to more effectively conduct the numerical analysis and is broadly divided into three parts: body, stem, and jacket. Since the internal and external shapes were nonlinear and showed many drastic changes, unstructured grids were used to enhance the accuracy of the numerical analysis.

Thermal Analysis. This study conducted a thermal analysis beforehand to check temperature distributions. This was done to verify the structural stability related to low temperatures when a vacuum jacket valve, which was connected to LNG pipes designed to be used aboveground, was used. Table 1 below lists the required conditions for the analysis.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature inside the pipe</td>
<td>-179°C</td>
</tr>
<tr>
<td>Temperature outside the pipe</td>
<td>25°C</td>
</tr>
<tr>
<td>Convective heat transfer coefficient</td>
<td>5 W/m² K</td>
</tr>
<tr>
<td>Pipe emissivity</td>
<td>0.1</td>
</tr>
<tr>
<td>Insulation material emissivity</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 1. Boundary conditions for thermal analysis.

Transient thermal analysis, which can observe the results as time passes by, was used. This increased the accuracy of the thermal analysis in order to observe how the status changed in accordance with actual operation conditions, in order. Transient thermal analysis was set to last for 30 min, and numerical analysis was conducted at 10-s intervals. However, this is a simple thermal analysis, and the resulting values from the numerical analysis do not have enough reliability to accurately observe what actually happened. Therefore, a thermal-structural coupled field analysis is required in order to increase the accuracy of the numerical analysis results.

Thermal-structural Coupled Field Analysis. Temperature data acquired from the thermal analysis conducted in advance was applied to the structural analysis to proceed with a thermal-structural coupled field analysis. In this manner, changes in heat stress and deformation that actually took place in a vacuum jacket valve were analyzed. The boundary conditions needed for the thermal-structural coupled field analysis are listed in Table 2. Forced displacement constraints were applied and fixed at both ends of the valve.
Table 2. Boundary conditions for thermal-structural coupled field analysis.

<table>
<thead>
<tr>
<th>Inside pressure conditions</th>
<th>320 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum pressure</td>
<td>$10^{-3}$ Torr (-6.6661e-7 MPa)</td>
</tr>
</tbody>
</table>

Experiment

To verify the temperature distributions acquired from the thermal analysis above, an experiment to measure temperature distributions was conducted on the actual vacuum jacket valve. Descriptions related to temperature measurement are illustrated in Fig. 2, while the boundary conditions applied to the experiment are listed in Table 3.

![Fig. 2 Temperature measurement experiment needed to verify numerical analysis.](image)

Table 3. Boundary conditions for experiment.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>-179°C</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>Working Pressure</td>
<td>320 bar</td>
</tr>
</tbody>
</table>

A type T thermocouple was used for temperature measurement, and a data logger was applied as a way to record data. The attached parts of the thermocouple were welded in order to reduce errors in temperature measurement caused by the conventional conditions for the measured locations.

Results of Numerical Analysis and Experiment

Verification of Temperature Distributions in Numerical Analysis and Experiment. By analyzing temperatures in eight locations through the thermal analysis and experiments, the resulting values from the numerical analysis were verified. The temperatures that were acquired from the numerical analysis and experiments are shown in graphs in Fig. 3.

![Fig. 3 Temperature distributions acquired from numerical analysis and experiment.](image)
According to the comparison results, although there were some differences, the numerical analysis results were considered to be reliable because they had a margin of error of less than 5% compared with the experiment results. When an experiment is required for other valves in the future, this method could help to reduce the number of experiments to consider.

**Structural Stability Evaluation.**

**Results of heat leak based on thermal analysis.** A heat leak was calculated based on temperature distributions. In Fig. 4, the results are divided into (a) results from numerical analysis and (b) results calculated in the experiment.

![Fig. 4 Heat leak of a vacuum jacket valve.](image)

> (a) Heat leak based on numerical analysis (b) Heat leak based on experiment

According to the results of the heat leak calculations, it was determined that the heat leak occurred at no more than 0.8 W/m despite several differences between the measured locations. It is thought that the results had almost no gap from the results calculated with an air temperature of 25°C. It was demonstrated that the heat leak was extremely small for a currently designed vacuum jacket valve. When only thermal performance was considered, the results show that the valve would operate with no problems. However, these results concerned only a vacuum jacket valve of one size. Follow-up studies are required to consider various variables such as the jacket thickness, the jacket area, and the internal diameter and length.

**Results of thermal-structural coupled field analysis.** Since it was impossible to evaluate the heat stress and deformation arising at a vacuum jacket valve by simply using thermal analysis, temperature distributions from the thermal analysis were applied to the thermal-structural coupled field analysis in order to conduct a numerical analysis. The results are divided into the body and stem, and are shown in Fig. 5. In the figure, (a) shows the heat stress of the body and stem, while (b) indicates the heat deformation of the body and stem.

![Fig. 5 Results of thermal-structural coupled field analysis.](image)

> (a) Stress (b) Deformation

The results of the thermal-structural coupled field analysis showed that the largest heat stress occurred at the joint area between the stem and disk. It is believed that the pressure of a liquid inside caused this heat stress. It is also believed that the working pressure of the liquid had more impact on the structural stability of the vacuum jacket valve than the heat stress and deformation caused by...
temperature gaps between the inside and outside. The maximum stress of 184.68 MPa that occurred in the vacuum jacket valve was below the material yield strength, and therefore the valve was deemed to be structurally stable. Furthermore, the deformation was less than 0.016 mm, which was considered to have very little impact.

Conclusions

This study measured the temperatures on a vacuum jacket valve and looked into its structural stability. The following conclusions were drawn from an experiment, thermal analysis, and thermal-structural coupled field analysis:

1. The temperature distributions gained from the thermal analysis on a vacuum jacket valve showed a margin of error of less than 5% from the temperature distributions acquired from the experiment. These distributions could be applied as basic data to measure the outside temperatures of a vacuum jacket valve in the future.

2. According to the results of calculating a heat leak based on the thermal analysis of a vacuum jacket valve, a heat leak of up to 0.8 W/m occurred. However, this leak did not seem to have much impact when the valve worked, as it had a very small gap when the heat leak was calculated in consideration of the air temperature.

3. According to the results of the thermal-structural coupled field analysis on a vacuum jacket valve, the maximum heat stress was 184.68 MPa, which was below the material yield strength, and a heat deformation of no more than 0.016 mm occurred. Since these variables had very little impact, the valve was considered to be structurally stable.

4. The study used a vacuum jacket valve of one size when analyzing the heat leak. In reference to this study, follow-up studies are required to look further into changes in the jacket thickness, the jacket area, and the internal diameter and length of the vacuum jacket valve.

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References


