Structural Determination of Silica-Based Fire-Proof Heat Insulation

N. Oya*, Y. Kawajiri*, H. Kitajima*, K. Matsumoto*, K. Sugiura*, Y. Imae** and K. Imae**

*Osaka Prefectural College of Technology, Neyagawa, Osaka, Japan, oya@osaka-pct.ac.jp
**Imae Industry Co. Ltd., Takatsuki, Osaka, Japan, kenji@imae-kk.com

ABSTRACT

Many power plants need fire prevention measures that protect electric cables from fire incidents until the rescue from the fire department arrives. The purpose of this research is to verify performances of laminated fire-proof insulation developed by Imae Industry Co. Ltd. in Japan. The insulation includes sequential stacking of silica mats, aluminum foils, and aluminized glass-fiber woven fabrics that are placed all together inside the outermost layer of silica cloth. This research also aims to apply expanded graphite sheets and aerogel papers to make the structure more efficient. The optimum stacking sequence is verified with aids of combustion experiments and heat conduction simulations by 3D-FEM analysis. It is revealed that the graphite layer positioned near the fire can disperse and transfer heat effectively to the whole area of silica mats which generate more condensation reaction. The heat is further insulated by the aerogel layer which has the lowest thermal conductivity among incombustible materials.

Keywords: heat insulation, silica fiber, expanded graphite, aerogel paper, finite element method

1 INTRODUCTION

Currently, about 80% of the electric power supply in Japan relies on thermal power generation. Those power generation plants have higher risks of fire incidents, and it will be difficult to restore the facility if critical cables are lost or damaged. There are also numerous transformer substations networked throughout urban areas in Japan, and once a fire incident occurred in a substation, it would cause a massive blackout. Actually, in October 2016, an unattended substation located in the suburb of Tokyo had a fire from damaged cables, and it caused a huge blackout for more than 370,000 houses in the metropolitan area of Tokyo. It has been known that the fire incident occurred because insulation oil leaked out from deteriorated transmission cables and caught fire from electric spark. As numerous flammable cables are still used and left in Japan, this kind of fire incident may occur unless those cables are replaced or additional measures are taken. Therefore, it is urgently needed to have efficient fire-proof heat insulation to protect critical cables and prevent fire from expanding until the rescue from the fire department arrives.

Imae Industry Co. Ltd. in Japan has already started to develop a laminated silica-based fire-proof heat insulation which has a good fire prevention performance and flexible handling texture. The laminated fire-proof insulation has a stacked structure consisting of materials with different roles as shown in Figure 1. Belcotex mat is made from silica fibers that are developed as BELCOTEX® in Germany; this fiber can resist heat from fire and generate water by a condensation reaction enhancing the heat insulation. Belcotex mat is covered by aluminum (Al) foils on both faces to obtain heat reflection. The Belcotex mat with Al foils is further covered by aluminized glass cloth which has been developed as GENTEX® in USA. The aluminized glass cloth has the role of heat reflection and shape retention during burning. In the basic stacking sequence, 4 units of the above material assembly are consecutively placed all together inside the outermost layer of silica cloth to obtain a good fire prevention based on the repeated interactions of thermal resistances and heat reflections.

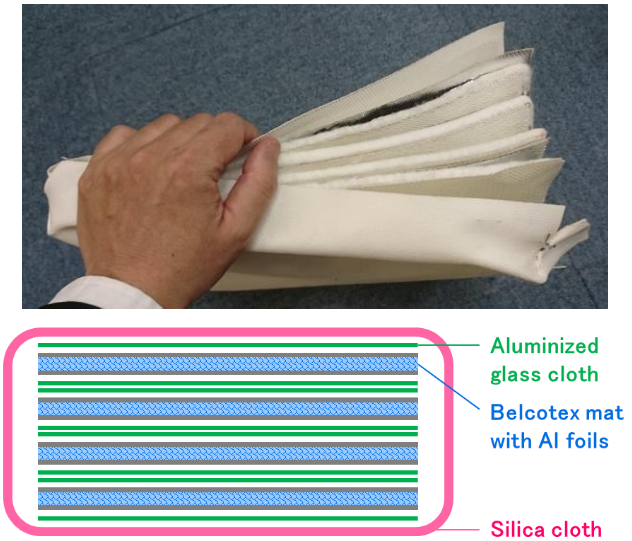

Figure 1: Appearance and the basic stacking sequence of the laminated heat insulation.

The purpose of this research is to evaluate the fire prevention properties of the laminated fire-proof heat insulation by combustion experiments and to find the optimum stacking sequence to reduce the total weight and thickness, as it is vital to facilitate the installation work especially in power plant sites. The optimization of the stacking sequence was carried out with aids of heat conduction simulations by 3D-FEM analysis. It is also attempted to apply expanded graphite sheets and aerogel papers to add more innovative heat insulation mechanism and make the stacking structure furthermore efficient.

2 METHODS

2.1 Materials Used

Silica clothes (t=0.8mm, Figure 2), belcotex mats (t=5.1mm, Figure 2), aluminized glass clothes (t=0.4mm, Figure 3), and aluminum foils (t=0.02mm) were trimmed to 150mm square shape and stacked to form laminated fire-proof heat insulations which were used as samples of combustion tests.

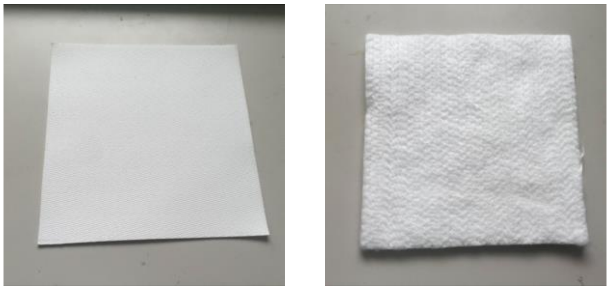

Figure 2: Silica cloth (left) and belcotex mat (right).

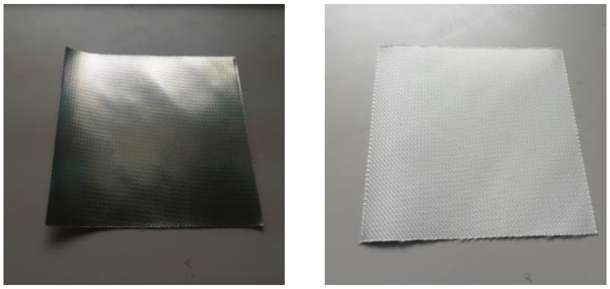

Figure 3: Aluminized glass cloth; aluminized face (left) and glass cloth face (right).

In this research, expanded graphite sheets (t=0.4mm, Figure 4) and aerogel papers (t=4mm, Figure 4) were added to the insulation. The graphite sheet has a higher heat conductivity compared with the thickness direction[1]. The aerogel paper is made by mixing rock wools and silica-aerogels in 70:30 including other organic binders and fibers, and diluting it into 1% solution to process it into a uniform thickness using a paper machine. It was then processed into the aerogel paper through several dehydration processes.

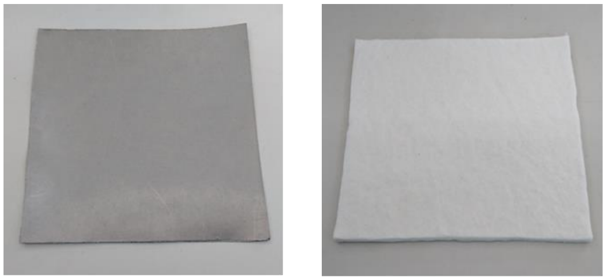

Figure 4: Graphite sheet (left) and aerogel paper (right).

2.2 Combustion Tests

Heat insulation behavior of the heat insulations were studied by combustion tests using a propane gas burner in open-air environment (Figure 5). The test sample was fixed in a steel frame and exposed to flame which was regulated to be a uniform heating power by maintaining outlet pressure of the gas cylinder to 0.3kgf/cm^2. Each test was conducted for 60 minutes to verify the sustainability of the heat insulation. Temperature of the back surface of the sample was measured by a thermocouple (K-250PC, Sanwa Electric Inst.) and recorded by a digital multimeter.

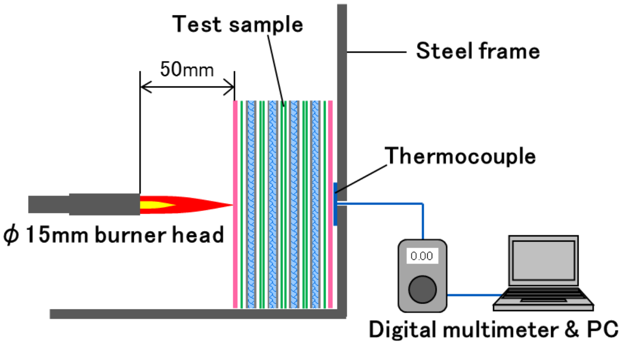

Figure 5: Combustion test using a propane gas burner.

2.3 FEM Simulations for Heat Distribution

Femap with NX-Nastran v11.3.1 (Siemens PLM Software) was used to predict heat distribution inside the heat insulation. Each material layer was modelled by 3D solid element with the same dimension as the experiment and was assigned material constants shown in Table 1. Thermal load of 1000°C was applied per 1cm^2 square area on the center of the heated surface, and natural convection with heat transfer coefficient of 0.02W/mm^{2}K@20°C was assumed on the opposite surface as shown in Figure 6.

Material	Heat conductivity [W/mK]	Specific heat [kJ/kg°C]	Emissivity [-]
Silica cloth	0.20	1.046	0.30
Belcotex mat	0.20	1.046	0.30
Al-glass cloth	1.03	0.795	0.05/0.66
Al foil	256	0.913	0.05
Graphite	400/3.00[1]	0.650	0.80
Aerogel	0.03[2]	1.006	0.30

Table 1: Material constants used in FEM simulation.

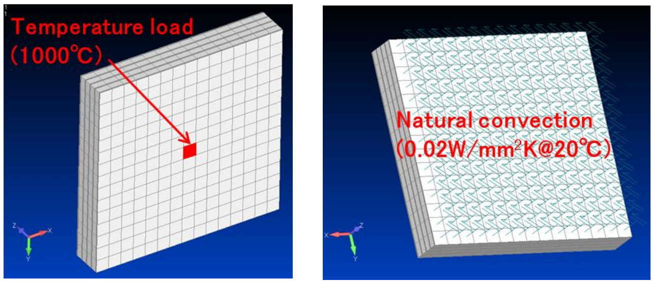

Figure 6: Temperature load and convection applied.

3 RESULTS AND DISCUSSIONS

3.1 Burning Behavior in Combustion Tests

Figure 7 shows temperature measured at the back surface of the heat insulation with the basic stacking sequence. The total thickness of the test sample was 25.4mm. Temperature gradually increased to 70°C within 30 minutes, and eventually kept at a constant temperature around 75°C. Considering that most of generally used insulation oil have flash points above 130°C, the sample proves the sufficient heat insulation performance.

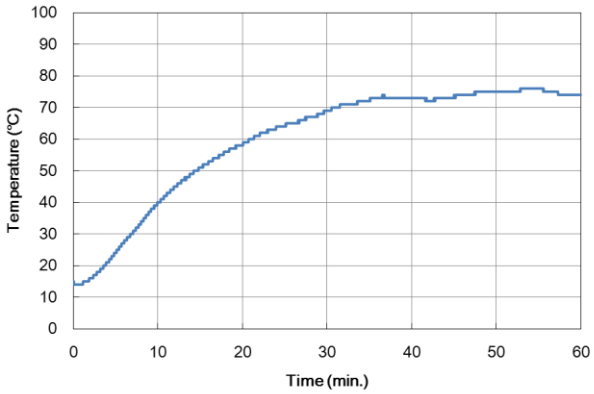

Figure 7: Change of temperature at the back surface of the heat insulation with the basic stacking sequence.

The sample was visually checked for traces of heat penetration and damage propagation after the test. As shown in Figure 8, thermal damages were confirmed from the heated surface until the 14th layer out of 22 layers. The other layers near the back surface remained intact. It is noted that the aluminum foil located at the 7th layer had been partly melt, which indicates that temperature around this layer raised more than the melt point of aluminum (660°C). Therefore, heat insulation was attained for the rest of layers through consecutive interactions of condensations by belcotex mats and heat reflections by aluminum.

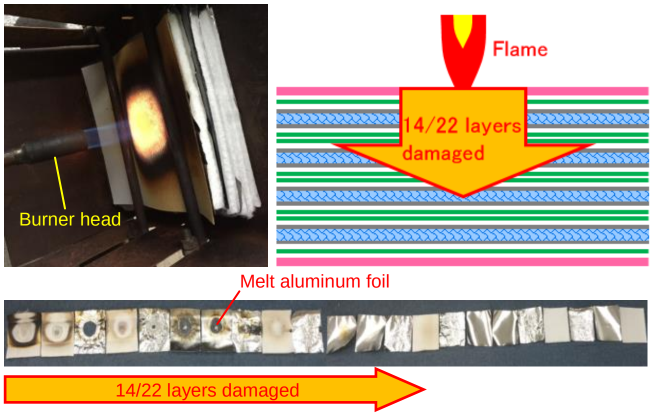

Figure 8: Thermal damages visually observed in the heat insulation with the basic stacking sequence.

3.2 Thermal Distribution in FEM Simulation

Figure 9 shows thermal distribution obtained from FEM analysis of the heat insulation with the basic stacking sequence. It indicates that heat propagates from the thermal load (1000°C) and temperature at the center of the back surface of the model decreases down to 77.62°C. This calculation result shows a good agreement with the experimental result which indicated 75°C at the back surface of the sample in the end of the combustion test.

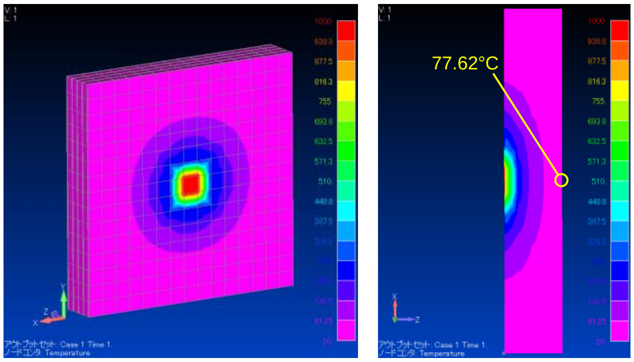

Figure 9: Thermal distribution obtained from FEM analysis of the heat insulation with the basic stacking sequence.

Several attempts using expanded graphite sheets and aerogel papers have been made to optimize the stacking sequence of the heat insulation in this research. Figure 10 shows one of such approaches; in each of the eight analytical cases, some of the aluminized glass clothes are replaced by the graphite sheet (indicated by the black solid line), which has much higher in-plane thermal conductivity than that along the thickness direction. The result indicates that heat is dispersed throughout the model in the presence of the graphite sheets, especially when they are introduced near the heated upper surface. Such a heat distribution may contribute to enhanced cooling effects, as it increases the effective heated areas in belcotex mats which generate more water by their condensation reactions.

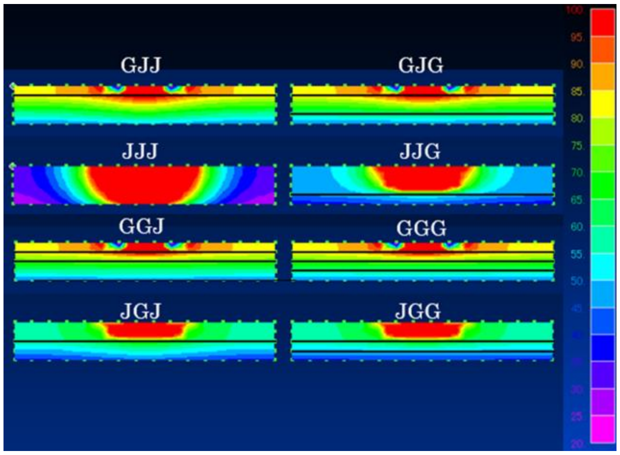

Figure 10: Comparison of thermal distributions including expanded graphite sheets at different locations.

3.3 Improvement of the Stacking Sequence

Following the experimental and analytical results, the optimum stacking sequence of the heat insulation was examined. Figure 11 depicts a comparison between the basic stacking sequence and the optimum stacking sequence including expanded graphite sheets and aerogel papers. In the optimized structure, two belcotex mats, three aluminized glass clothes, and four aluminum foils were replaced by two graphite sheets and one aerogel paper to obtain a considerable thickness reduction of 28%. Two graphite sheets were placed near the heated part and one aerogel paper was placed near the back surface to finally cutoff the residual heat with its low thermal conductivity.

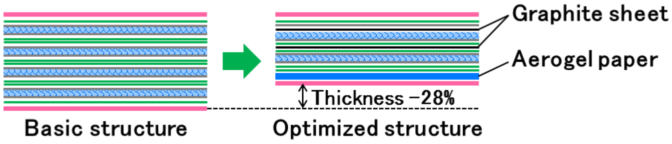

Figure 11: Illustration of the optimum stacking sequence for the heat insulation giving a considerable size reduction.

Figure 12 shows temperature measured during the combustion test at the back surface of the heat insulation with the optimized structure in comparison with the result of the basic structure. Temperature increased at a higher rate than the basic structure; however, it must be noted that the optimized structure had a considerably reduced total thickness. Temperature reached at 75°C within 30 minutes, then kept that level until the end of the combustion test. Despite the thinner stacking size, the heat insulation with the optimized structure provided the stable protection as well as the heat insulation with the basic structure.

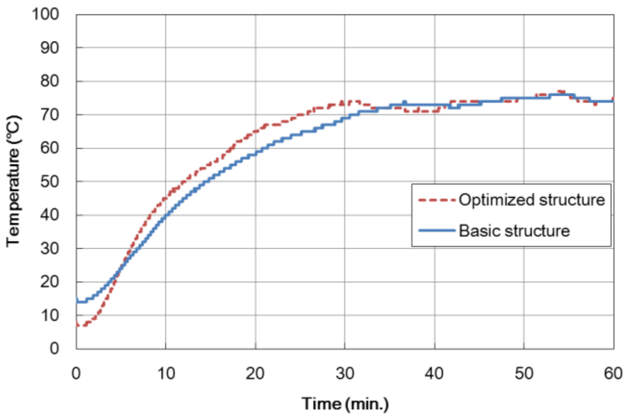

Figure 12: Change of temperature at the back surface of the heat insulation with the optimum stacking sequence.

Figure 13 shows a comparison of thermal damages visually observed after the combustion tests of the heat insulations with both of the basic and optimum stacking sequences. 14 layers had been damaged in the heat insulation with the basic structure, but thermal damages were found only from 11 layers out of 16 layers in the case of the optimized structure. It is also noted that only one aluminum foil in front of the graphite sheet had been melt in the optimum stacking sequence. It clearly explains that the first graphite sheet near the heated surface dispersed heat effectively throughout the whole area of the sample and prevented the heat penetration into the back surface. In fact, the aerogel paper placed next to the back surface remained intact to cutoff the residual heat until the end of the combustion test. Considering such a protection mechanism, the heat insulation with the optimum stacking sequence might have sustained even longer than the basic stacking sequence if the combustion test had been performed for more extended period.

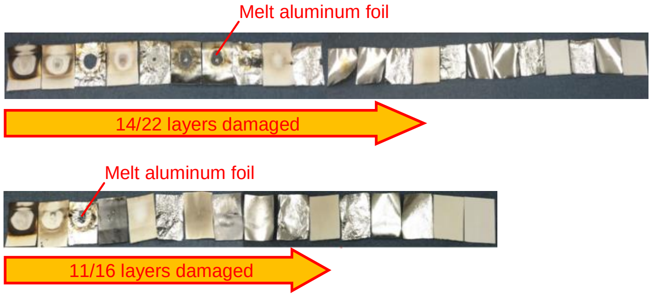

Figure 13: Comparison of thermal damages between the basic stacking sequence and the optimum stacking sequence.

4 CONCLUSIONS

Heat insulation performances of the laminated fire-proof insulations including belcotex mats, silica clothes, aluminized glass clothes and aluminum foils were studied by the combustion experiments and the FEM simulations. The combustion test result showed that the heat insulation with the basic stacking sequence provided sufficient protection for the duration of 60 minutes. By introducing expanded graphite sheets and aerogel papers into the heat insulation according to the analytical results, the considerable size and weight reductions were attained. It was revealed that the graphite sheets placed near the heated surface could disperse and transfer heat effectively to the whole area of belcotex mats which should have generated more water by enhanced condensation reactions. The heat dispersion mechanism obtained by the graphite sheet may also have contributed to prevention of melting in aluminum layers. Such a protection mechanism should have a good potential to make the heat insulation be more sustainable for extended period.

REFERENCES

[1] D. D. L. Chung, Journal of Materials Science, 22, 4190, 1987.
[2] E. Cuce et al., Renewable and Sustainable Energy Reviews, 34, 273, 2014.