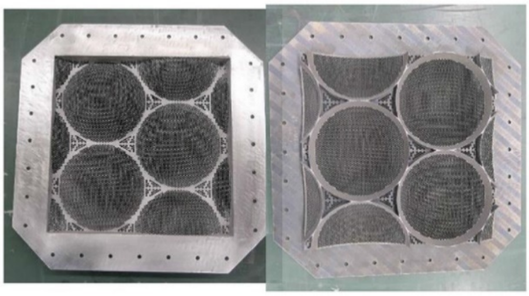
Development of EMP Shield for Vent Using Additive Manufacturing



AKIO IKEDA*1 TAKASHI IKEDA*2
YOSHIAKI ARAKAWA*3 HISASHI SHIMIZU*1
SHUJI TANIGAWA*4 MASASHI KITAMURA*4

Intense electro-magnetic waves generated by nuclear explosions at high altitudes or generated as intentional electro-magnetic interference using electro-magnetic pulse generators or the like are called EMPs (electro-magnetic pulses). EMPs have a great impact, causing damage to or destruction of electronic equipment and extensively paralyzing society. In today's highly electronics-oriented society, countermeasures against EMPs are an urgent issue. Generally, the countermeasures include shielding the electro-magnetic waves that propagate through space (e.g., blocking with metal, etc.) and absorbing the overvoltage and overcurrent induced in cables by EMPs with protection circuits. However, vents and other openings cannot be blocked because of their function. Mitsubishi Heavy Industries, Ltd. has developed, created, and fabricated a structure that can provide vents with countermeasures against EMPs while minimizing the reduction in their cooling (pressure loss) performance that should be inherent, utilizing detailed simulation, additive manufacturing, and other technologies. Then, we have confirmed that this structure can actually provide both electro-magnetic shielding and pressure loss performance.

1. Introduction

If irradiated by EMPs, electronic equipment may malfunction or be damaged or destroyed. EMPs can have long-term effects on critical infrastructure, etc., and can cause large-scale disruption to the economy and daily life. In recent years, the U.S. and other countries have become increasingly active in taking countermeasures against EMPs. Countermeasures against EMPs are an urgent issue for the information society, and we cannot be allowed to fall behind. This report presents a case study of the examination and evaluation of a countermeasure structure assuming application to vents, which needs to be established while ensuring their performance as an original cooling function, among the countermeasures against EMPs.

2. Target EMP

High altitude electro-magnetic pulses (HEMPs) generated by nuclear explosions at high altitudes are classified into three pulses, E1, E2, and E3, depending on their occurrence conditions. The E1 pulse has a electric field strength of 50 kV/m and a frequency of several hundred kHz to 300 MHz, which is higher intensity and higher frequency than that of lightning (1). Intentional electro-magnetic interference (IEMI) caused by high-intensity pulse generators, microwaves, etc., has a higher frequency than HEMP, and the upper frequency limit is often set at 10 GHz (2). Since general countermeasures against electro-magnetic waves are insufficient for protection against HEMP E1 pulses and IEMI, we used them as targets of the countermeasures against EMPs. **Figure 1** shows the relationship between electric field strength and frequency of HEMP and IEMI as defined by IEC, etc. The required countermeasure performance (electro-magnetic shielding performance) is 80 dB (1/10,000 attenuation) at 1 GHz (1). There is a difference between HEMP and IEMI. HEMP is a single pulse, whereas IEMI is a burst wave in which the pulse is applied repeatedly.

*1 Electron･Physics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*2 Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*3 Decarbonization Business Department, Mitsubishi Heavy Industries Engineering, Ltd.
*4 Manufacturing Technology Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

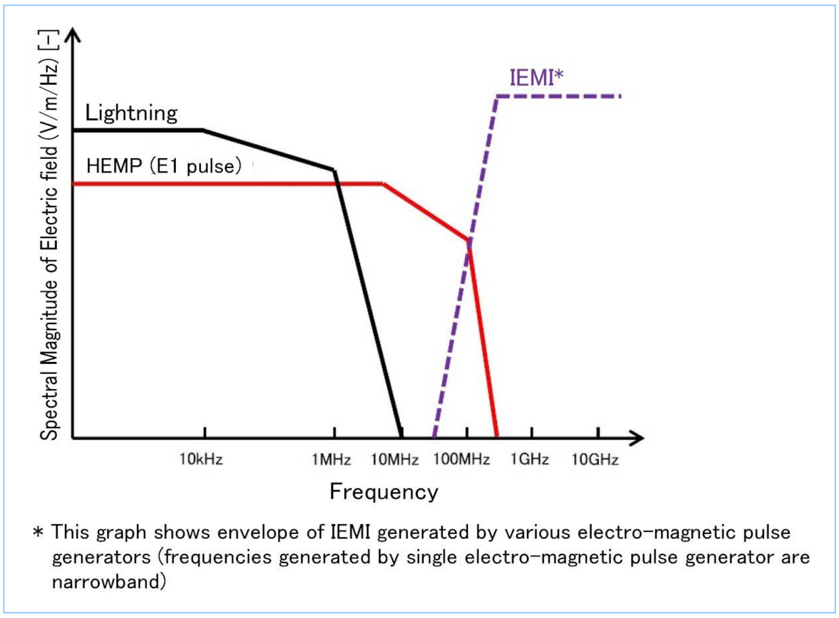


Figure 1 Frequency and electric field spectral intensity of EMP [2]

3. Concept of EMP shield for vent

In general, as a countermeasure against electro-magnetic waves for vents and the like, honeycomb shields are used. A honeycomb shield consists of thin metal plates laid in a honeycomb shape. The smaller the honeycomb diameter and the longer the honeycomb shield in the depth direction, the higher the electro-magnetic shielding performance. To provide electro-magnetic shielding performance, the honeycomb diameter needs to be less than 1/2 of the wavelength. Countermeasures against EMPs for vents require high shielding performance against frequencies above GHz. The insertion of honeycomb shields for satisfying the requirements significantly increases the pressure loss and makes cooling performance unsatisfactory, which is an issue.

Honeycomb cells have a shape that maximizes the opening area in plain view. In order to solve the above issue, however, it is necessary to create a structure that can reduce pressure loss compared to honeycomb shields. As shown in **Figure 2**, by making the honeycomb cell tapered, it is possible to lay more cells in terms of the projected area. For this reason, we decided to use tapered honeycomb cells as a concept for the EMP shield structure.

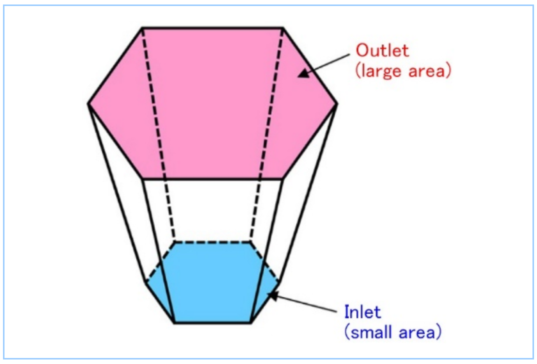


Figure 2 Tapered honeycomb cell

4. Shape examination of EMP shield for vents

The EMP shield for vents was constructed as an assembly of tapered honeycomb cells as described in chapter 3. To optimize the pressure loss and electro-magnetic shielding performance, we repeated simulations of pressure loss and electro-magnetic shielding performance, and examined a shape that satisfies both performance requirements.

The electro-magnetic shielding performance is affected by the honeycomb diameter, length, and taper ratio (i.e., ratio of inlet and outlet cell diameters) of the tapered honeycomb cell. In order to determine a honeycomb cell shape that satisfies the shielding performance required as a countermeasure against EMPs, we performed a 3D electro-magnetic field simulation of the tapered honeycomb cells with different inlet and outlet diameters shown in **Figure 3** using the finite-difference time-domain (FDTD) method to evaluate the effect of the taper on the electro-magnetic shielding performance. **Table 1** shows the evaluation result. The electro-magnetic shielding performance of the honeycomb cells with taper ratios of 1.5 and 2.0 was lower than that of the reference honeycomb cell without taper, and the ratio of the decrease in electro-magnetic shielding performance was in general agreement with (d) intermediate cell size ratio with reference to the intermediate cell size of the reference honeycomb cell without taper. To optimize the shape, it is necessary to change the inlet and outlet dimensions and taper ratios of the honeycomb cell in many ways, but this result shows that by simulation only the reference honeycomb cell without taper, it is possible to obtain the ranges of electro-magnetic shielding performance for different taper ratios and to efficiently examine the shape for its optimization.

The pressure loss performance is affected by factors including the shape of individual tapered honeycomb cells, the degree of aggregation (number of cells), dead space where air cannot flow, and distortion of air flow inside the structure.

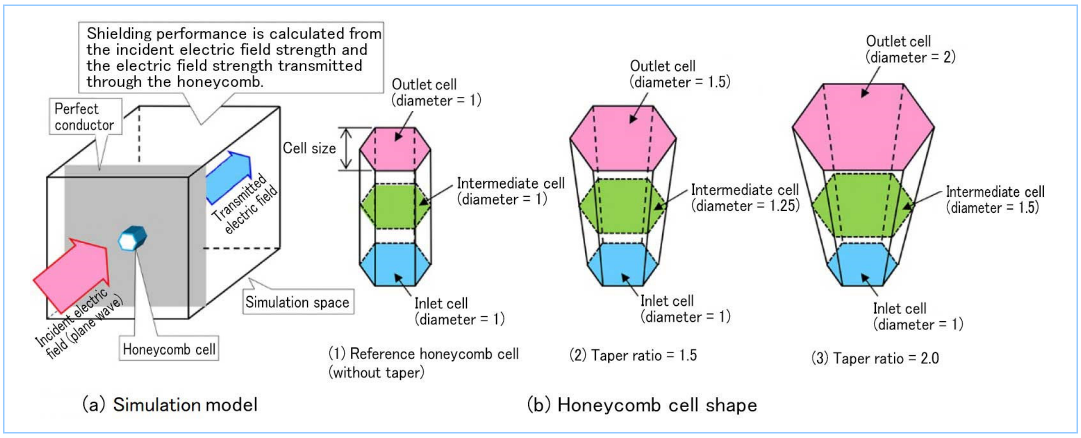


Figure 3 Models to evaluate effect of tapered honeycomb cell on electro-magnetic shielding

Table 1 Evaluation result for effect of tapered honeycomb cell on electro-magnetic shielding

Simulation condition	(1) Reference honeycomb cell (without taper)	(2) Taper ratio = 1.50	(3) Taper ratio = 2.00
(a) Inlet cell size	1.00	1.00	1.00
(b) Outlet cell size	1.00	1.50	2.00
(c) Intermediate cell size (Average of inlet and outlet cell sizes)	1.00	1.25	1.50
(d) Intermediate cell size ratio (Ratio of intermediate cell size with reference to (1))	1.00	0.80	0.67
Electro-magnetic shielding performance [-] @10 GHz	1.00	0.86	0.79

* All values in this table are relative to (1) reference honeycomb cell (without taper).

Figure 4 shows shape plans. When aggregated simply, tapered honeycomb cells form a hemispherical dome shape as shown in Figure 4(a). In this case, a large dead space is formed at the edge of the dome and the air flow distortion increases more toward the edge. In order to reduce the dead space and air flow distortion and to equalize the flow velocity distribution, we created an elliptical dome shape by aggregating honeycomb cells with different honeycomb diameters, lengths, and taper ratios at different locations, as shown in Figure 4(b), and added a rectifying structure for the dead space to further reduce the pressure loss.

We studied the parameters of pressure loss for different shapes of tapered honeycomb cells and determined the final shape that minimized the pressure loss and provided satisfactory electro-magnetic shielding performance. **Figure 5** shows the final shape. The final shape has a structure in which elliptical honeycomb cell domes are aggregated, but there remain areas that cannot be dome-shaped between the domes. Therefore, honeycomb-shaped holes were made in these areas in order to allow air to flow through.

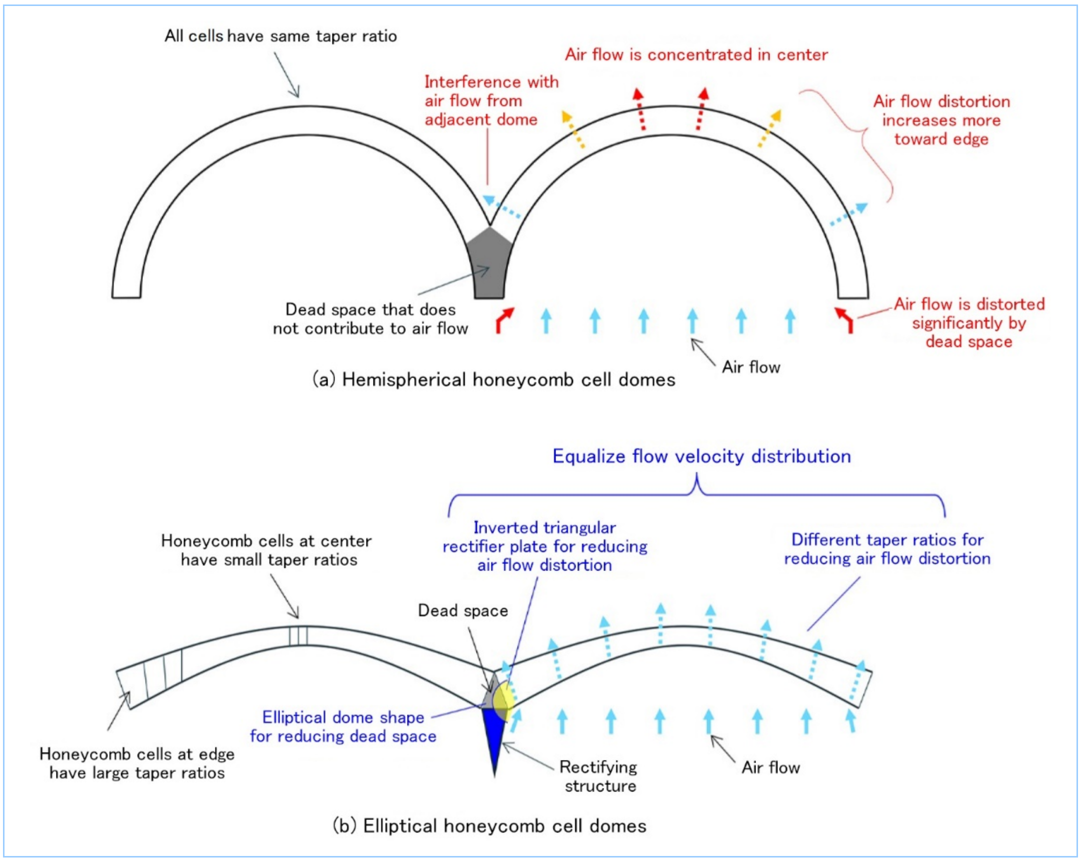


Figure 4　Shape plans of EMP shield for vents

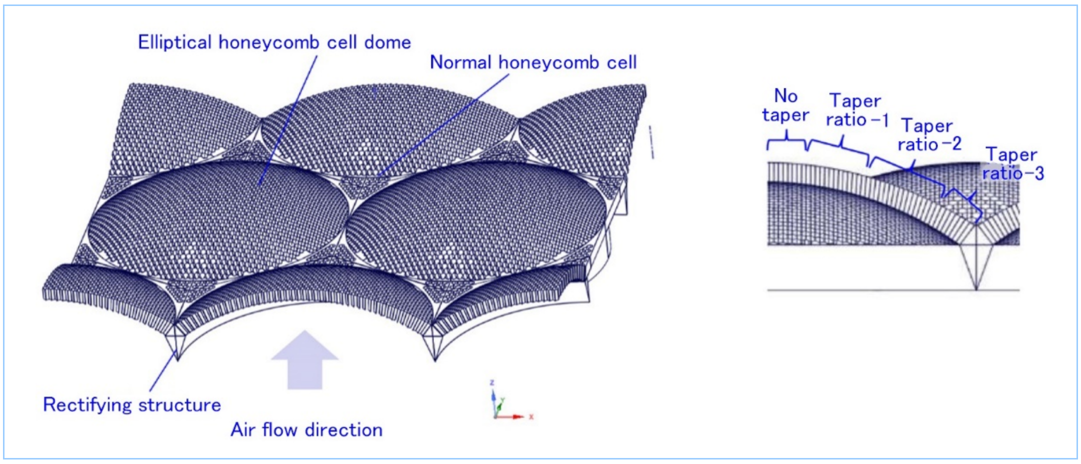


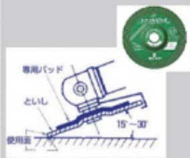
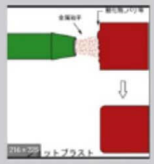
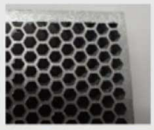
Figure 5　Final shape of EMP shield for vents

5. Fabrication and performance evaluation of EMP shield for vents

5.1 Fabrication of test piece

Because the shape determined in chapter 4 is very complex and cannot be fabricated by general machining, we employed the additive manufacturing method. This structure has thin-walled honeycomb cells, the overall manufactured size is large, and the dome shape has a large overhang, so it is necessary to use support materials during the manufacturing process. However, the honeycomb structure may be damaged in removal of the support materials due to the honeycomb cells being thin-walled, so the difficulty of fabrication is high. Therefore, we evaluated several methods to remove the support materials without damaging the honeycomb shape. **Table 2** shows the evaluation result. It was confirmed that not only support materials but also burrs could be removed without damaging the honeycomb structure by using Skill Touch (soft grinding wheel) to roughly remove the support materials and then performing shot blasting.

Table 2 Evaluation result of methods to remove support materials from dome honeycomb structure

	Chisel	Nippers	Endmill	Skill Touch	Skill Touch + shot blasting
Appearance					
Advantages	− High removal efficiency	− Low risk of damaging thin-plate honeycomb	− High removal efficiency − Removal along curved surface is possible with use of 5-axis machining (good shape accuracy)	− High removal efficiency	− Can remove burrs left from removal with Skill Touch
Disadvantages	− Removal on curved surface is difficult − High risk of deforming thin-plate honeycomb	− Low removal efficiency − Cannot get support materials from root and finish processing is required	− Difficulty in removal on thin plates (Generated heat causes thin plates to crush. Refer to photo.)	− Some burrs left (refer to the photo) − Cannot guarantee the accuracy because operated manually	− Surface roughness is inferior to machined products (but better than surface roughness of built product)
Implementation results	Not conducted because of high risk of deforming honeycomb	Not conducted because of large amount of time required			

Using the above method, test pieces for performance evaluation were fabricated. **Figure 6** shows the fabricated test piece.

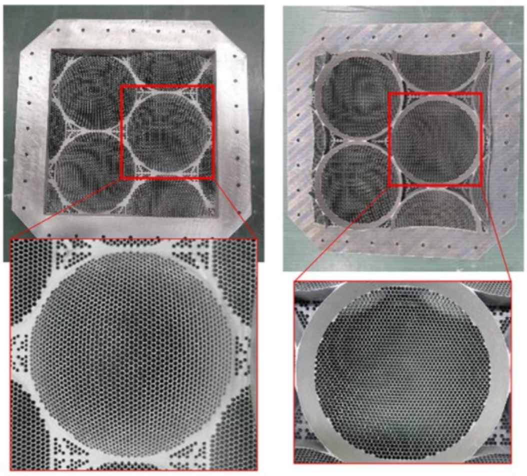


Figure 6 Metal test piece fabricated by additive manufacturing

5.2 Evaluation of pressure loss

We evaluated the flow velocity distribution in the final-shape honeycomb dome by CFD (Computational Fluid Dynamics) simulation. **Figure 7** shows the evaluation result. It is indicated that the elliptical dome shape and rectifying structure resulted in equalization of the flow velocity distribution and reduction of the pressure loss.

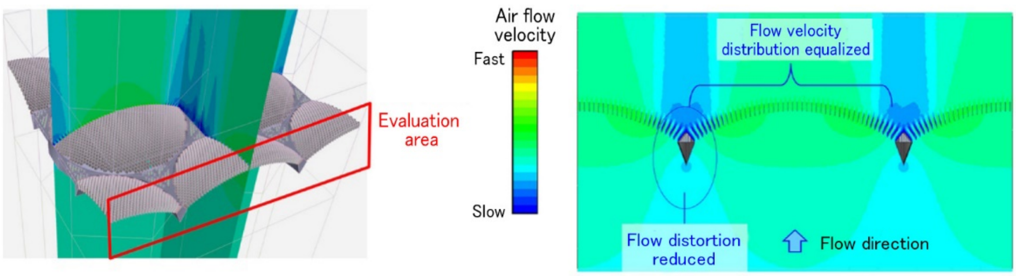
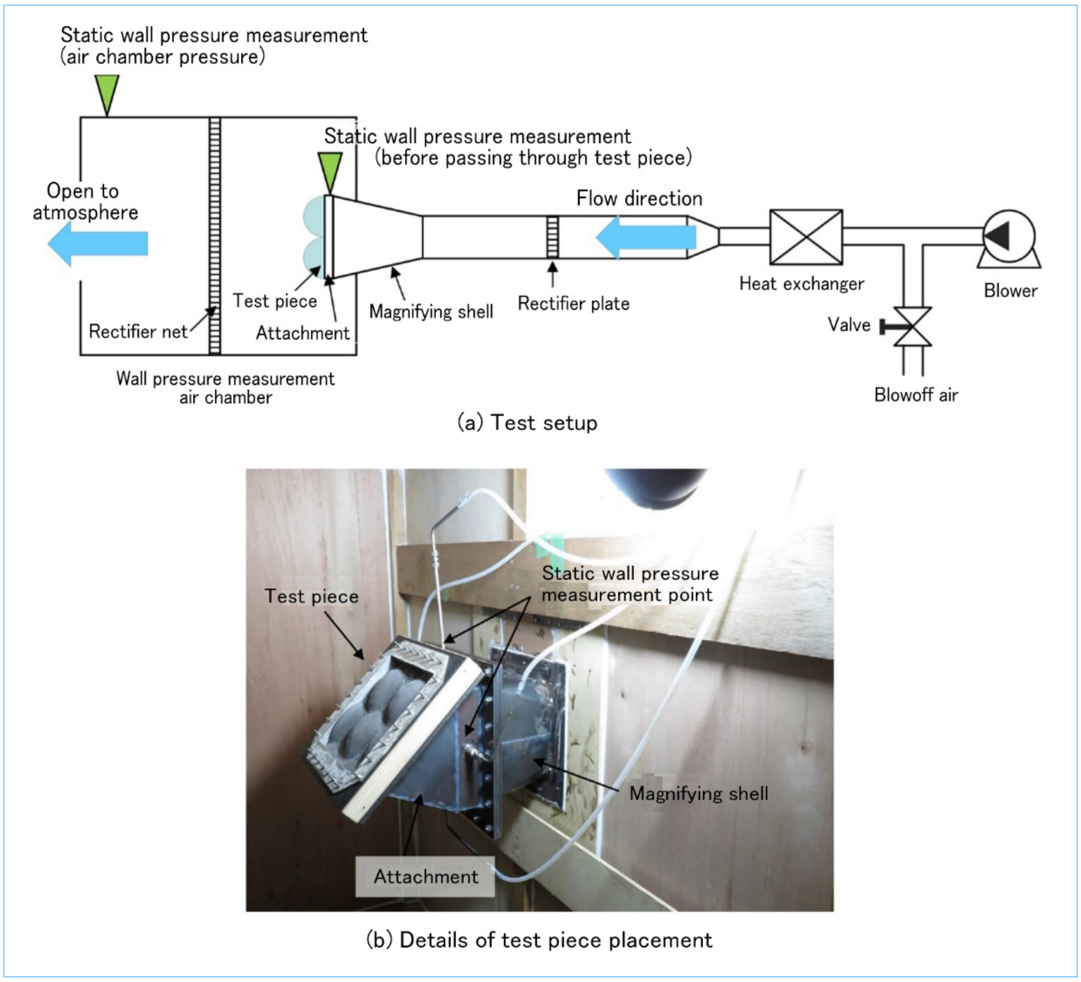


Figure 7 CFD simulation result of final shape

We evaluated the pressure loss in the fabricated test piece while varying the air volume, test piece installation angle, and temperature. **Figure 8** shows the test setup, which allowed this evaluation to be made by measuring the wall pressure in the static pressure recovery space at the outlet and eliminated the need to adjust the instrumentation according to the installation angle of the test piece during the test. **Figure 9** shows the evaluation result of the pressure loss performance obtained through the simulation and test. It was confirmed that the pressure loss of the elliptical dome honeycomb was significantly reduced compared to the normal honeycomb shield which has dimensions with the same electro-magnetic shielding performance as the test piece, and that the simulation and test result were in good agreement.



(a) Test setup

(b) Details of test piece placement

Figure 8　Pressure loss evaluation test setup

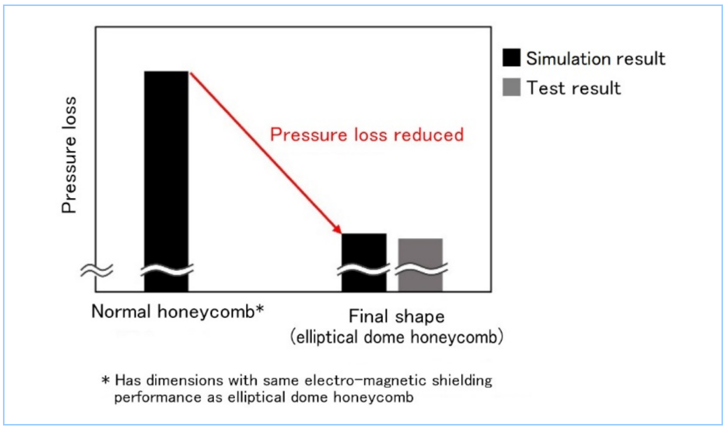


Figure 9　Evaluation result of pressure loss performance of final shape

5.3　Evaluation of electro-magnetic shield performance

The evaluation of electro-magnetic shield performance was conducted using a setup in accordance with IEEE-STD-299, a representative method to evaluate electro-magnetic shield performance, as shown in **Figure 10**. Radio waves were emitted from the transmitting antenna located in the transmitting room with and without the test piece installed, and power received with the antenna located in the receiving room was measured. The electro-magnetic shielding performance was calculated as the ratio of the received power values with and without the test piece. In addition, as in the evaluation of tapered honeycomb cells, the same setup as the test was modeled as shown in **Figure 11**, and a three-dimensional electro-magnetic field simulation using the FDTD method was performed to evaluate the electro-magnetic shielding performance. As in the case of the evaluation by the test, the electro-magnetic shielding performance was calculated as the ratio of the electric fields that passed through the dome honeycomb with and without the test piece in the evaluation in the simulation. **Figure 12** shows the results of the test and simulation. The two were in good agreement, and it was confirmed that the target performance of 80 dB@10 GHz was achieved.

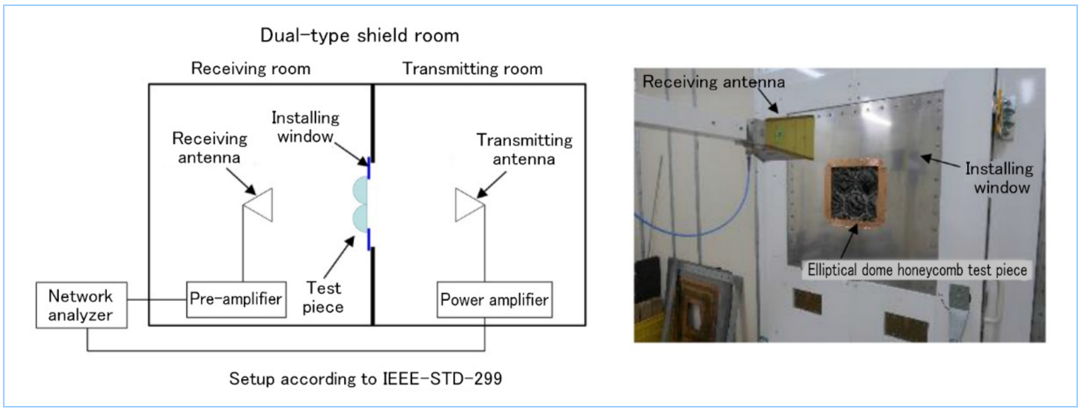


Figure 10 Test setup for evaluation of electro-magnetic shield performance

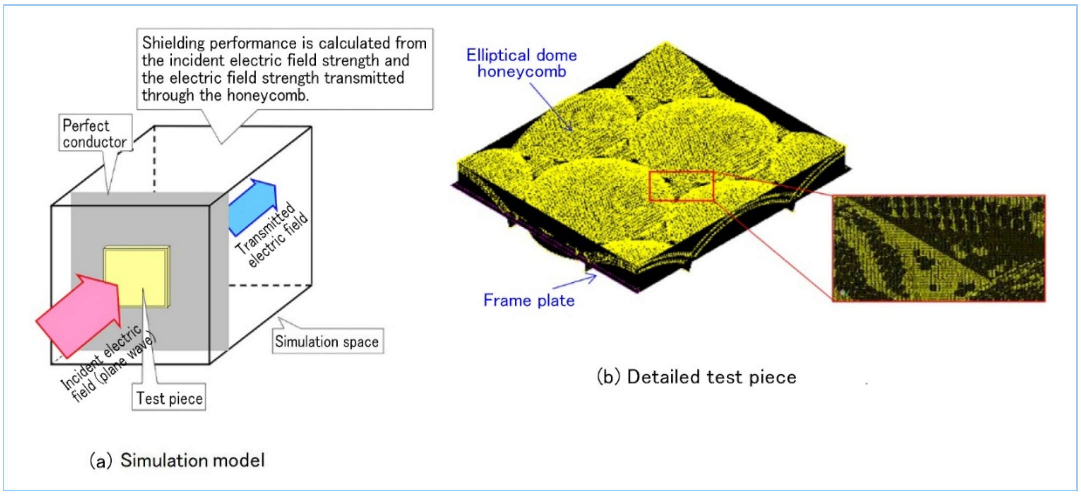


Figure 11 Setup for evaluation by electro-magnetic field simulation

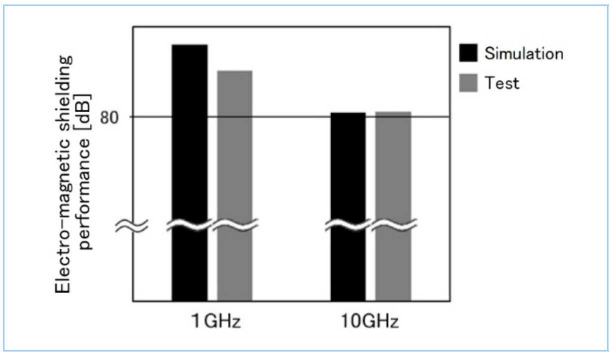


Figure 12 Evaluation result of electro-magnetic shield performance

6. Conclusion

In recent years, as equipment has become more electronic and information-oriented, countermeasures against EMPs have become an issue. We sought a new shape for the shield structure for countermeasures against EMPs to be applied to vents, which need to be open due to their function and have a small design margin for cooling performance due to the restrictions, that surpasses the existing honeycomb shield shape. We have created an optimum shape that satisfies both pressure loss and electro-magnetic shielding performances by repeating trade-offs between the two performances using CFD and FDTD methods based on tapered honeycomb cells. Since the created dome honeycomb shape is complicated and the honeycomb cells are thin-walled, it is difficult to manufacture it by ordinary machining as well as casting, so we adopted additive manufacturing. Since the shape of the dome is large and has a large overhang, its additive manufacturing required support materials, which were difficult to remove. We devised their removal method. By conducting an actual evaluation using the fabricated test pieces, we confirmed that the simulation and test results were in agreement and that the target electro-magnetic shielding performance and pressure loss performance were satisfied.

References

(1) IEC 61000-2-11 Electromagnetic compatibility (EMC) -Part2-11: Environment-Classification of HEMP environments

(2) IEC 61000-2-13 : Environment-High-power electromagnetic (HPEM) environments-Radiated and conducted