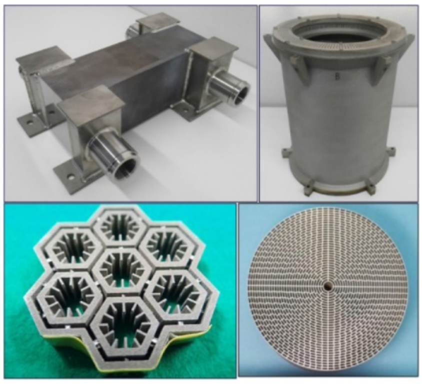
Development of Compact and High-performance Heat Exchangers Using Metal Additive Manufacturing



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Improvements in metal additive manufacturing (AM) technology in recent years have enabled forming very precise shapes. By utilizing this technology, it is possible to realize unprecedented high-performance heat exchangers. Heat exchangers are used in a variety of products, and for example, in products for mobility such as vehicles, space equipment and ships, reducing the size and weight of onboard equipment they have can contribute to improving fuel efficiency and enhancing dynamic performance. We have examined prototypes, performance tests, and quality assurance of heat exchangers for mobility products utilizing AM technology (hereinafter "AM heat exchanger(s)"), which this report introduces, and have confirmed that the weight and volume can be reduced by half compared to the conventionally used heat exchangers.

1. Introduction

Improvements in AM technology in recent years have enabled fabrication of very precise and complex structures that could not be made with conventional machining technology. By applying this technology to heat exchangers, it is possible to arrange precise heat transfer promoters in the internal channels and to design the channels themselves with complex curved surfaces, thereby increasing the amount of heat exchanged per pressure drop compared to conventional heat exchangers manufactured by machining. Furthermore, the use of AM technology improves the degree of freedom in the shape of the heat exchanger itself, enabling compact packaging combined with other equipment by designing the shape of the heat exchanger according to the installation space. Thus, the ability to not only reduce the size and weight of a heat exchanger alone, but also minimize the packaging space including other equipment, is one of the strengths of Mitsubishi Heavy Industries, Ltd. (MHI), which designs and manufactures heat exchangers as well as entire systems.

In addition, quality assurance is also essential for using AM heat exchangers with such excellent features in actual products. The AM heat exchanger described in this report is built using the powder bed method, which enables precise build. In general, various factors such as laser power, scan speed, and powder properties affect the build quality. Unless these factors are properly controlled, defects and incomplete fusion will occur within the built metal, which will result in a loss of strength.

MHI has been working on the development of AM heat exchangers focusing on performance improvement and quality assurance. This report introduces examples of the development and future prospects.

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2. Structure and features of AM heat exchanger

As mentioned above, MHI is developing AM heat exchangers of various concepts. This chapter introduces some of them.

2.1 Mini channel counterflow AM heat exchanger

Figure 1 shows a counterflow AM heat exchanger configured with mini channel. This heat exchanger has mini channel to increase the heat transfer area per unit volume, and contains a precise heat transfer prompter inside the channels to increase the amount of heat exchanged per the same pump power compared to smooth channel structure. The header is designed so that the flow is distributed evenly to each channel and that the performance degradation due to flow deviation is about 1% under the main operating environment.

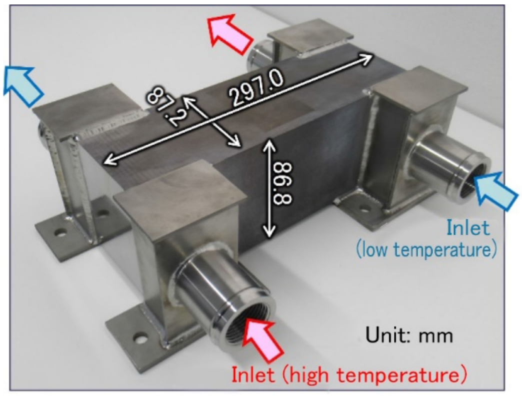

Figure 1 Mini channel counterflow AM heat exchanger

Figure 2 shows a test piece for elemental testing to evaluate the channel performance. The number of channels was set to five on both the high and low temperature sides, and the heat transfer coefficient and pressure drop characteristics of the channels were obtained using the smallest element. Tests were conducted using water, oil, and air as media to evaluate the heat transfer and pressure drop characteristics, as shown in **Figure 3**, and design equations were developed [(1)]. Here, the Reynolds number is a dimensionless number that expresses the ratio of viscosity and inertia, but in the same fluid, it expresses how much the flow rate is. The Nusselt number is a dimensionless number that represents the magnitude of heat transport (heat transfer coefficient) between the fluid and the bulkhead and varies with the Reynolds number. Since the Nusselt number also varies with the viscosity, specific heat, and thermal conductivity of the fluid, a dimensionless number called the Prandtl number, which is the ratio of the kinematic viscosity and temperature diffusivity, is generally used in addition to the Reynolds number when formulating heat transfer characteristics. The Prandtl numbers of the fluids used in this test, water, oil, and air are widely different from each other, and the design equations for a wide range of Prandtl numbers were developed in this study.

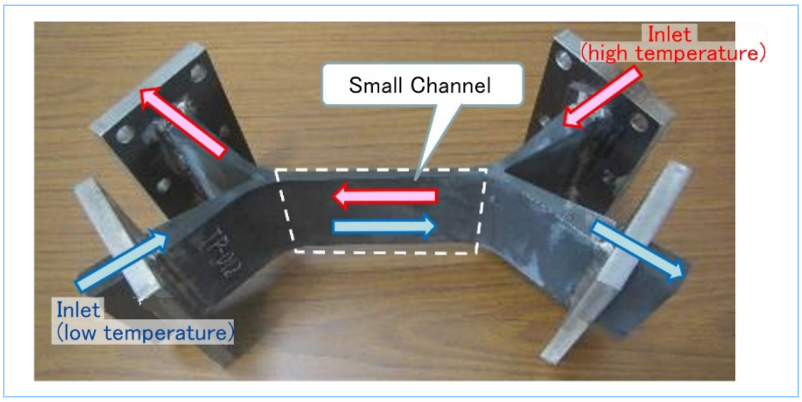

Figure 2 Test piece for elemental testing

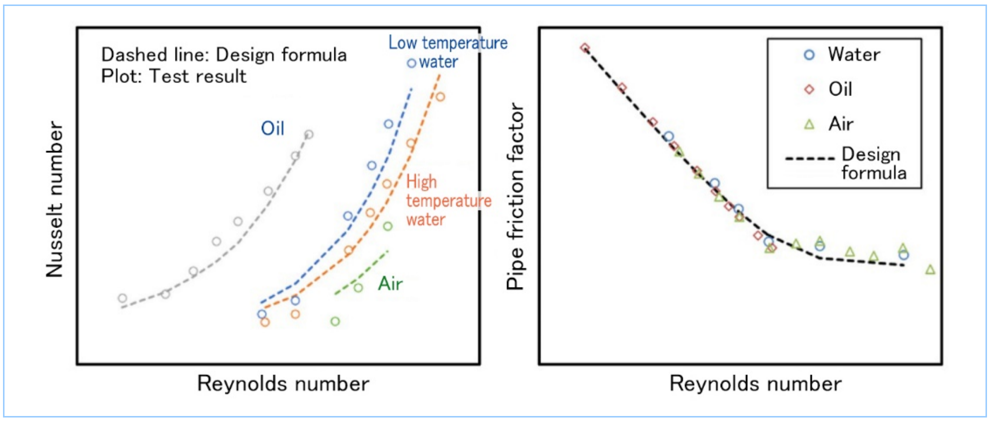

Figure 3 Heat transfer and pressure drop characteristics obtained from test

We are able to design heat exchangers with appropriate specifications by using AM heat exchanger performance evaluation equations developed based on elemental tests as above. **Figure 4** compares the designed and manufactured AM heat exchanger for mobility with a conventional heat exchanger; the AM heat exchanger is half the weight and volume of the conventional plate type heat exchanger.

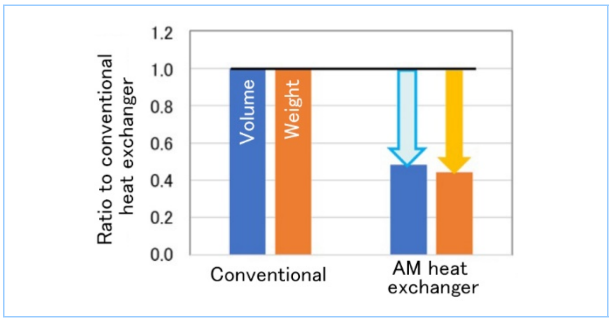

Figure 4 Comparison between conventional heat exchanger and AM heat exchanger

2.2 Catalyst-integrated AM heat exchanger

As mentioned in the introduction of this report, utilizing AM technology for heat exchangers improves the degree of freedom of the shape of the heat exchanger itself, allowing the design of a heat exchanger shape that is appropriate for the installation space. This enables compact packaging combined with other equipment. As an example, a catalyst-integrated heat exchanger is introduced here.

MHI designs and manufactures various products using catalysts, many of which use heat exchangers to control the temperature in the range suitable for the catalytic reaction. Therefore, piping for connecting the heat exchanger to the catalyst is necessary, and naturally, space is needed to route the piping. As a solution for this, we have developed a catalyst-integrated AM heat exchanger that greatly reduces the package space, including piping. **Figure 5** shows a photograph of its structure and appearance. In this example, the incoming gas is heated by the heat exchanger and electric heater and fed to the catalyst. Then the gas is cooled by the low-temperature gas that flows into the system to bring it close to the temperature of the inflow gas, and discharged.

We have completed prototyping and performance testing of this AM heat exchanger and have confirmed that it performs as expected. **Figure 6** compares the preliminary design values of this catalyst-integrated AM heat exchanger with the performance test results. The medium used was air for both the high and low temperature sides, and varied between 20 and 25°C for the low temperature side and between 170 and 230°C for the high temperature side. The design values were in good agreement with the measured values from the test. The difference in heat exchange and pressure drop was about ±5% and ±10%, respectively. Based on the results of this performance test, the designed catalyst-integrated AM heat exchanger is expected to reduce the conventional package space (including piping routing) by half.

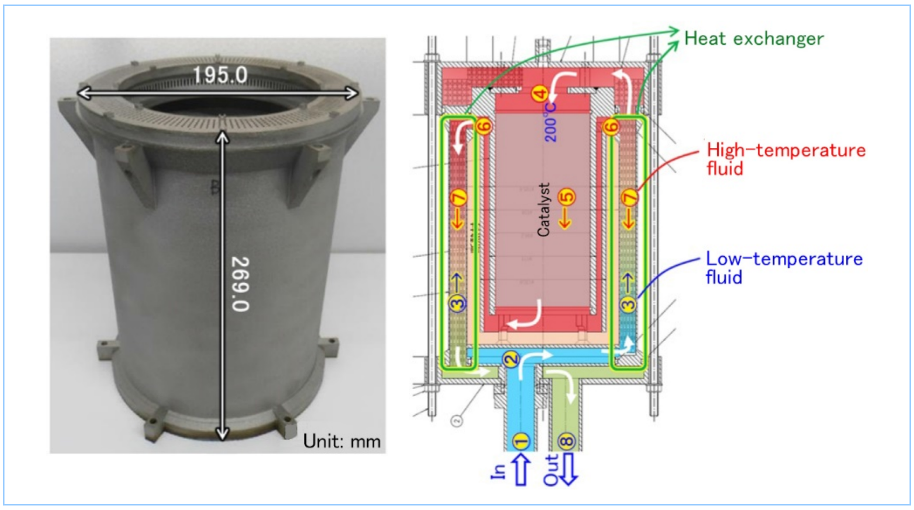

Figure 5 Catalyst-integrated AM heat exchanger

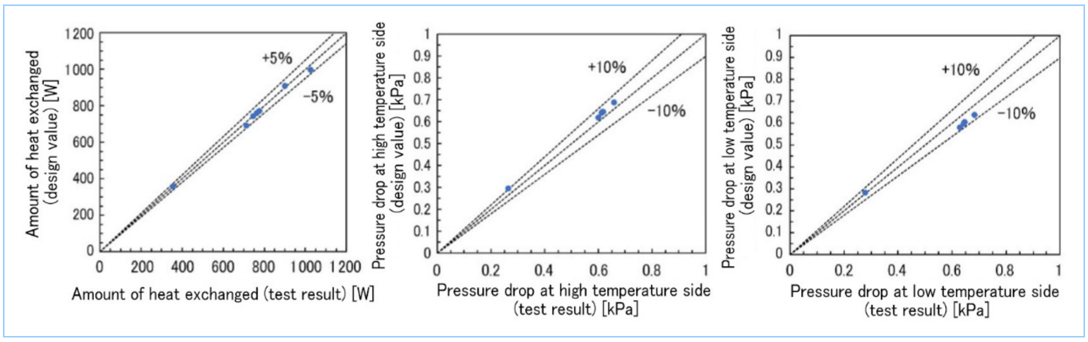

Figure 6 Comparison of design values and test results

2.3 In-pipe embedded AM heat exchanger

Figure 7 shows an AM heat exchanger designed to be embedded inside a pipe. Recovering and reusing waste heat is very important from the perspective of improving the performance and efficiency of products, but some products having many components packaged compactly may not have enough space to add a heat exchanger. In such cases, heat exchangers that can be installed inside pipes are considered to be very useful.

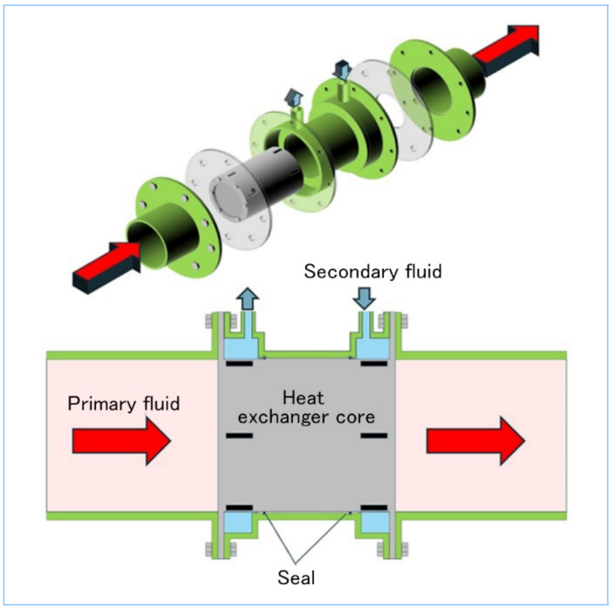

Figure 7 In-pipe embedded AM heat exchanger

Figures 8(a) and 8(b) show the photographs of prototypes of in-pipe embedded AM heat exchangers. Figure 8(a) shows the core of the in-pipe embedded AM heat exchanger, which corresponds to the part labeled "Heat exchanger core" in Figure 7. The channels inside the core are arranged so that the high-temperature fluid and low-temperature fluid flow in counter directions, with the first fluid passing straight through the core inside the piping and the second fluid flowing through a slit on the side into the core. In the case of the prototype shown in Figure 8(b), the first fluid flows inside the hexagon and the second fluid flows in the gap around it. Generally, when the volume flow rates of the first and second fluids differ greatly, it is necessary to increase the cross-sectional area of the channel with the larger volume flow rate. This heat exchanger, which has a large difference in the channel cross-sectional area between the inside of the honeycomb and the gap, is suitable for fluids with significantly different volumetric flow rates (e.g., liquid and gas). Currently, we are also developing a high-performance honeycomb heat exchanger in which a heat transfer enhancing structure created by topology optimization is placed in the gap. Analytical calculations of this heat exchanger have shown that it is half the volume of a typical double-tube-type heat exchanger.

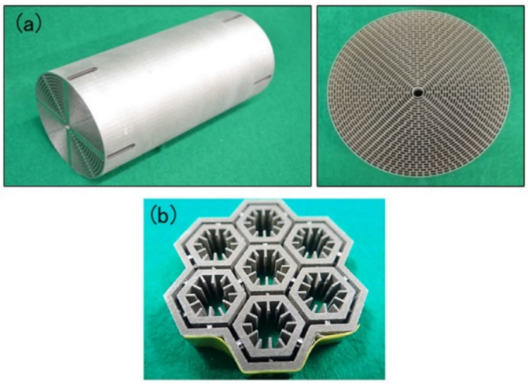

Figure 8 Prototypes of in-pipe embedded AM heat exchanger

3. Quality assurance initiatives

For mounting AM heat exchangers in products, it is necessary to guarantee quality according to the product. For example, in the powder bed method currently used for building AM heat exchangers, the build quality varies depending on various conditions, such as laser output, scan speed, powder particle size, control method, and build posture. **Figure 9** compares built products in the case where the heat input is intentionally excessive by actually varying the laser power and in the case where the heat input is appropriate. When the heat input is excessive, the amount of metal vapor generated during powder melting is entrained, resulting in numerous voids occurred as shown in the figure. In contrast, it is known that insufficient laser power also results in voids due to poor fusion. If such voids exist, depending on the environment in which the product is used, cracks may propagate starting from the voids due to thermal stress, vibration, or other factors. Therefore, it is important to accurately understand the impact of each factor on quality and to properly control the build conditions. We conduct the build under various conditions in advance to understand the effects of these factors, and have accumulated the necessary data for design through strength evaluation tests of the build material, etc.

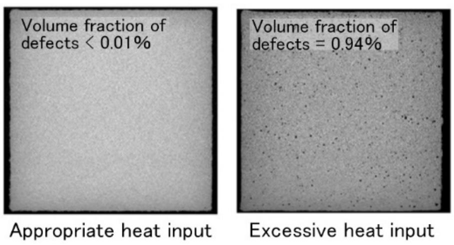

Figure 9 Cross-section of AM product

Figure 10 shows a contour diagram of Mises equivalent stress, which is the result of the calculation of thermal stresses caused by the temperature distribution and thermal deformation constraints at the four corner fixation points in the heat exchanger shown in Figure 1 above by FEM analysis through modeling up to the internal structure. The photograph in Figure 10 shows the appearance of a fatigue element test piece that simulates the channel of the AM heat exchanger and was manufactured under the same build conditions as the heat exchanger. The test piece in the photograph is shown after being ruptured in a test. By conducting such tests, we have accumulated basic data for evaluating the strength of AM heat exchangers.

Thus, we ensure reliability in designing AM heat exchangers by conducting life evaluations based on detailed FEM analysis and test data after understanding product-specific requirements such as vibration conditions, the number of start-ups and shutdowns, and thermal stresses.

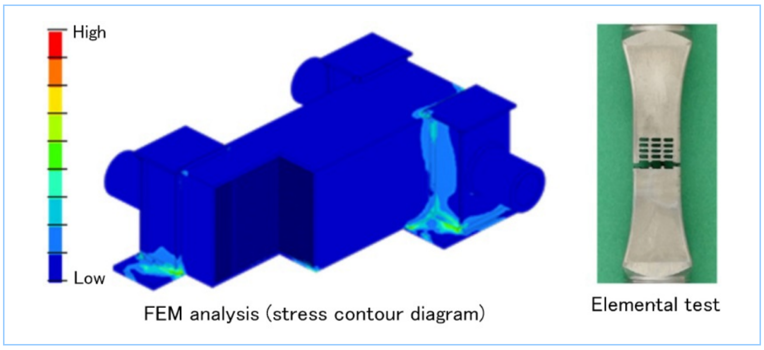

Figure 10 Strength reliability evaluation by elemental test and FEM analysis

4. Conclusion

This report introduced our initiatives to improve the performance and reduce the size of heat exchangers by utilizing AM technology, which has been rapidly developing in recent years. It also introduced examples of integrating heat exchangers into other equipment to reduce its packaging space for equipment including the heat exchanger.

MHI has been conducting a series of studies from concept creation, prototyping, performance evaluation, vibration/strength evaluation, and quality assurance, and have already achieved a 50% reduction in weight and volume for some products compared to conventional heat exchangers. In addition, we are continuing to work on further performance improvement and size reduction by utilizing topology optimization methods and other techniques. We will continue to contribute to the advancement of energy management (improvement of efficiency, reduction of energy consumption, etc.) for our variety of products through high-performance, compact, and lightweight heat exchangers.

References

(1) Shunsaku Eguchi et al., Heat Transfer Characteristics of the Flow in Ribbed Channel, The 58th National Heat Transfer Symposium of Japan Proceedings (2021-5)