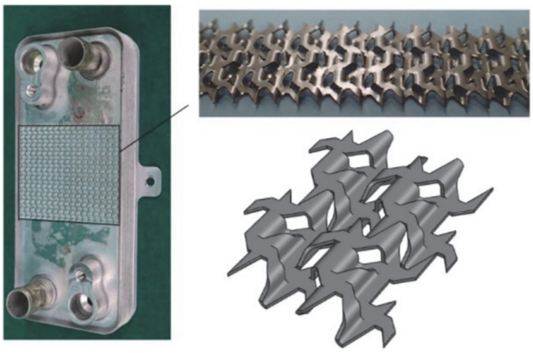
Development of Offset Fins for Compact Heat Exchanger Mounted on Vehicles



SHUNSAKU EGUCHI*1 HIROYUKI NAKAHARAI*2
YOICHI UEFUJI*3 KOICHI TANIMOTO*1

In recent years, as CO_2 emission regulations have become stricter, electrification of vehicles and improved fuel efficiency has rapidly progressed worldwide. When a vehicle is electrified, the internal combustion engine is no longer needed, resulting in the loss of a heat source. Consequently, the importance of thermal management has increased. One important component of the thermal management system of a vehicle is the heat exchanger. Reducing the size and weight of the heat exchanger in order to suitably control battery temperature and improve the range and dynamic performance of the vehicle is necessary.

A novel three-dimensional offset fin structure that can increase heat transfer by a factor of 1.5 or greater compared to conventional fins at the same pressure was developed using thermal hydraulic analysis technology. Next, a prototype of the offset fins was manufactured by press processing, which can be applied to mid-size to mass production, and performance tests to confirm effectiveness in improving heat transfer performance were carried out. In this report, we introduce the results of these efforts.

1. Introduction

From the viewpoint of space limitation and improvement in range and dynamic performance of the vehicle, mounting smaller and lighter components on a vehicle is needed. Heat exchangers are one such component which has become smaller and lighter by stacking inner fins with equivalent diameters of 1-2 mm and plates in an alternating manner and then brazing them together. This improves the heat transfer coefficient due to a finer heat transfer flow path and increases the heat transfer area density due to the fin area expansion effect. Offset fins have been widely used for the inner fins, exhibiting high heat transfer performance in the laminar flow area due to the leading edge effect.

Generally, offset fins have a structure that is offset in the span direction with respect to the flow direction. However, in such offset fins, there are paths that do not have fin steps in the flow direction on the heat-transfer surface where the plate and fin contact, and thicker thermal boundary layers develop, inhibiting heat transfer. By improving this area, it is possible to optimize heat transfer performance.

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has improved the performance of offset fins using thermal hydraulic analysis to eliminate uneven flow velocity distribution in the flow path, utilizing cross-sectional secondary flow associated with the fin shape, and promoting the leading edge effect at the installation surface of the plate and fins. In addition, a three-dimensional fin structure formed by press processing, which can be carried out at a relatively high-speed and can be applied to products for medium to high volume production such as vehicles, could be achieved. This report describes the development status and future prospects of the new offset fins.

*1 Heat Transfer Research Department, Research & Innovation Center
*2 General Manager, Heat Transfer Research Department, Research & Innovation Center
*3 Research Manager, Special Machine System Research Department, Research & Innovation Center

2. Concept and shape of new offset fins

Offset fins have step surfaces of the fin plate thickness at the plate-fin contact area because the fins are offset in the span direction with respect to the flow direction. At these step surfaces, the same as in fin area expansion regions, heat transfer is enhanced by breaking down the thermal boundary layer. In conventional offset fins, some flow paths have this step surface and some do not, causing uneven flow velocity that balances the pressure in the same fin cross-section. In addition, flow paths that do not have the step surface exhibit early development of a thermal boundary layer, which reduces the heat transfer coefficient. In general, reducing the thickness of the thermal boundary layer can be achieved by adding a swirling or secondary flow component to the flow field to promote heat transfer in the heat exchanger.

New offset fins were designed to solve the above issues and further promote heat transfer by (1) arranging the fins so that the step surfaces at the fin-plate contact points exist uniformly in all flow paths and (2) adopting a slanted structure for the step surfaces and fin expansion surfaces to form a secondary flow in the flow path cross-section and reduce the thickness of the thermal boundary layer (**Figure 1**).

Additive manufacturing and machining are not suitable for medium to high volume production of the new offset fins due to production capacity and cost, and therefore shearing/bending (press processing), which has superior mass production capability, was selected. Since fins are formed by pressing a single sheet material, a shape that avoids interference between materials, as well as between the fin material and the press die, is needed when forming the fin shape. A structure that solves this issue has been achieved by providing a slit in the thin plate material before pressing.

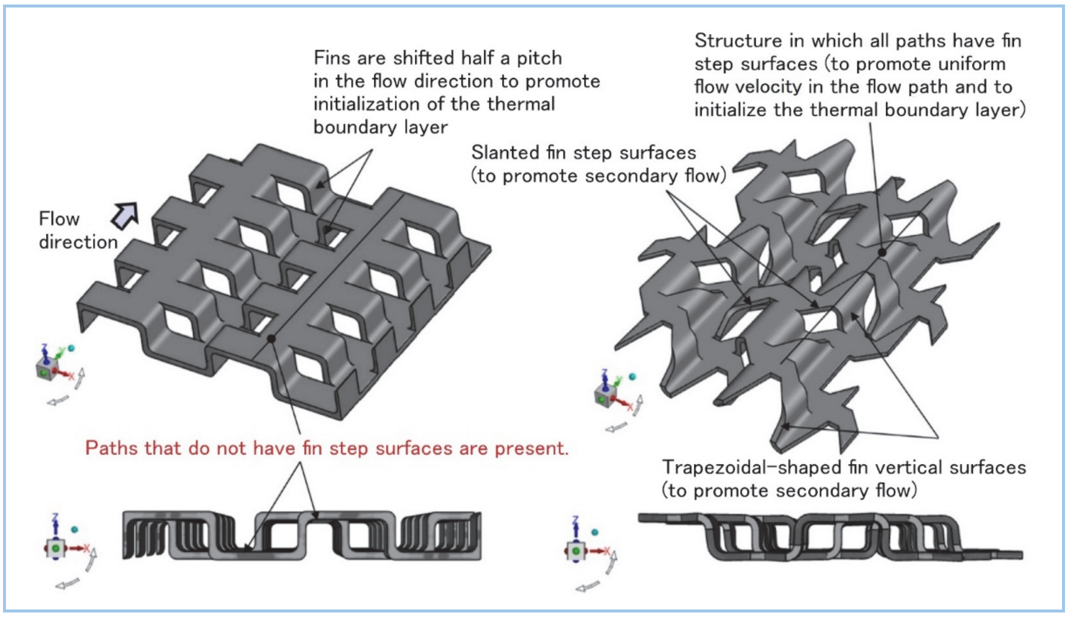


Figure 1 Conventional offset fin structure (left) and new offset fin structure (right)

3. Evaluation of heat transfer performance of new offset fins

In this chapter, concept verification results of the new offset fins by thermal hydraulic analysis, validation of the thermal hydraulic analysis through prototyping and performance evaluation tests, and comparison with the conventional fins and evaluation results of heat transfer performance are described.

3.1 Performance evaluation by analysis

Thermal-hydraulic analysis of the new offset fins was carried out in order to verify whether performance improvement as described in Chapter 2 could be achieved. Thermal hydraulic analysis was performed using ANSYS Fluent, a general-purpose thermal hydraulic analysis code. In this analysis, the SST k-ω model, a turbulence model, was used as the viscosity model due to the effects of turbulence in the flow behind the fins, collision, and secondary flow. In addition, evaluation of the flow near the wall surface is important. The fins have a periodic structure with respect to the span direction, so one period was cut out, periodic boundary conditions were set in the span direction, and a distance of about 50D from the inlet was modeled in order to analyze up to the region where the flow is fully developed (**Figure 2**).

From the analysis results, (1) the new offset fins eliminated the unevenness of flow velocity in each flow path, and high heat flux could be maintained over a wide area, and (2) a secondary flow formed in the fin cross-section, resulting in a thinner thermal boundary layer (**Figure 3**). The heat transfer coefficient and pressure loss were approximately double and 1.0 to 1.2 times higher, respectively, compared to the conventional offset fin heat transfer characteristic equation by Manglik & Bergles[(1)], showing significant improvement in heat transfer performance (**Figure 4**). In addition, when the new offset fins were attached to a conventional heat exchanger mounted on a vehicle, a 70% reduction in the heat exchanger volume, including the header section, could be obtained (**Figure 5**).

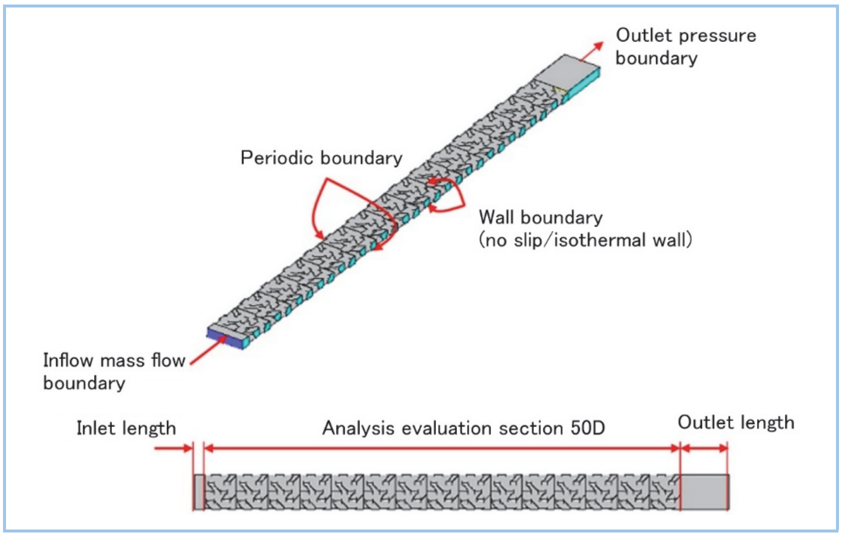


Figure 2 New offset fin analysis model

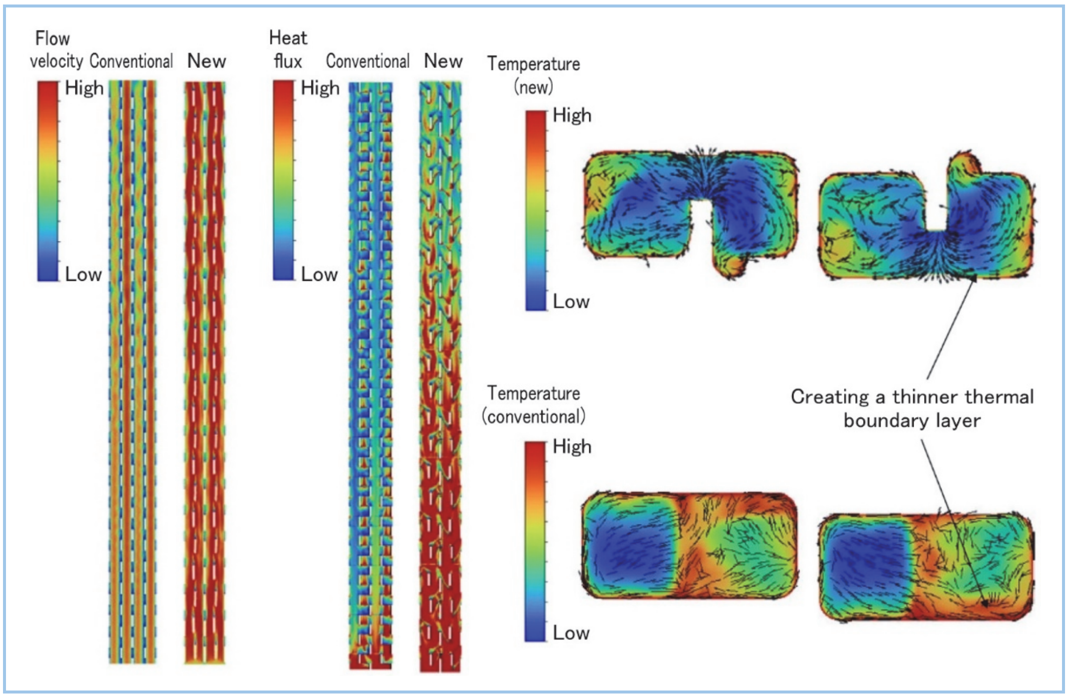


Figure 3 New offset fin analysis results (flow velocity, heat flux, and temperature contour diagram)

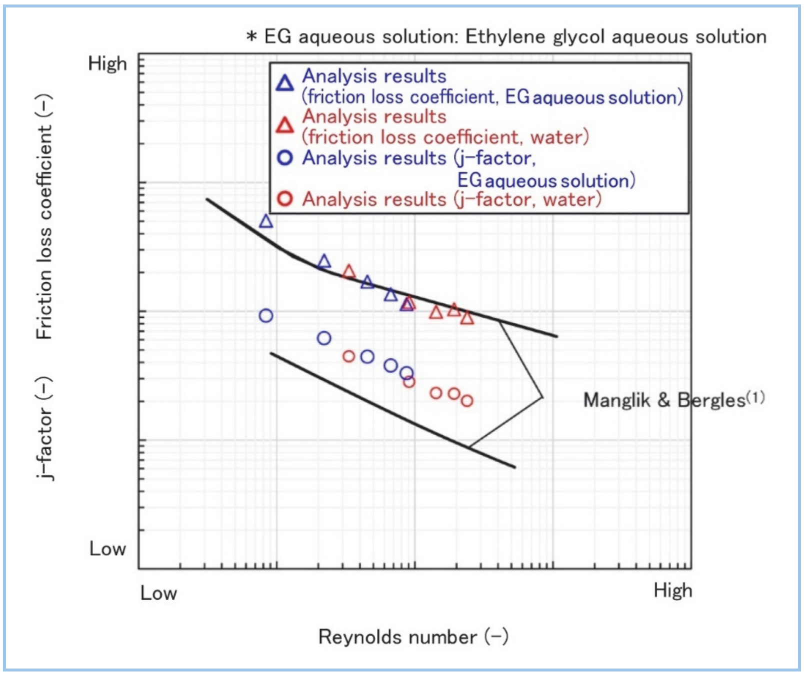


Figure 4   Evaluation of heat transfer coefficient (j-factor) and pressure loss (friction loss coefficient)

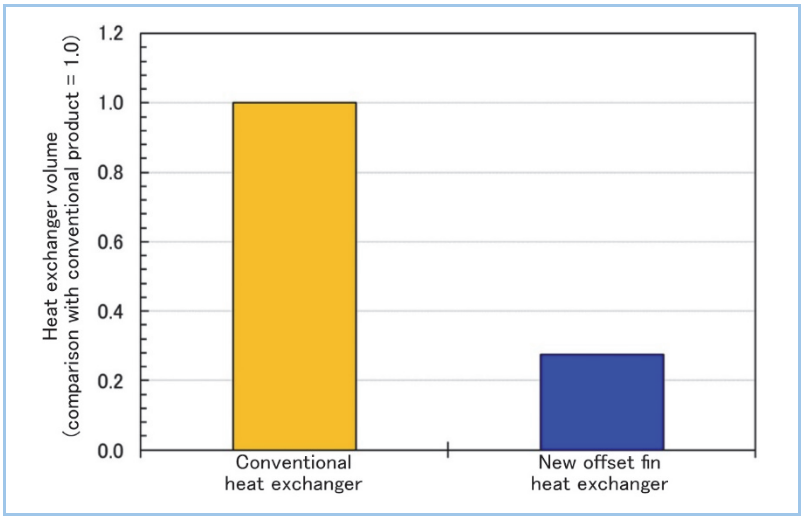


Figure 5   Comparison of heat exchanger volume

3.2   Analysis validation test

To validate the thermal hydraulic analysis of the new offset fins, the heat transfer coefficient and pressure loss were measured using two types of fluids (water and ethylene glycol aqueous solution) which are used in vehicles. To prepare the test piece, fins were cut out for one flow path among the flow paths applied to the heat exchanger as shown in **Figure 6**, to create a structure where fluid flows uniformly in the fin span direction, the same as in the analysis. For the heat transfer coefficient measurement, testing was carried out with both sides of the test piece heated. Measurement of the pressure loss was carried out in an adiabatic condition. The fin heat transfer coefficient was calculated by the Wilson-plot method. Under the condition of a relatively low flow rate and a temperature difference between the inlet and outlet of the specimen, the overall heat transfer detected by the heat flux sensor installed between the heat sink and the specimen was compared with the sensible heat change of the fluid flowing through the specimen, and the integrity of the test apparatus was confirmed by the heat balance being within about 5% (**Figure 7**).

From the results of the test, the measured heat transfer coefficient and pressure loss were within ±15% and ±5%, respectively, and agreed well with the results of the thermal hydraulic analysis (**Figure 8**), thus validating the analysis.

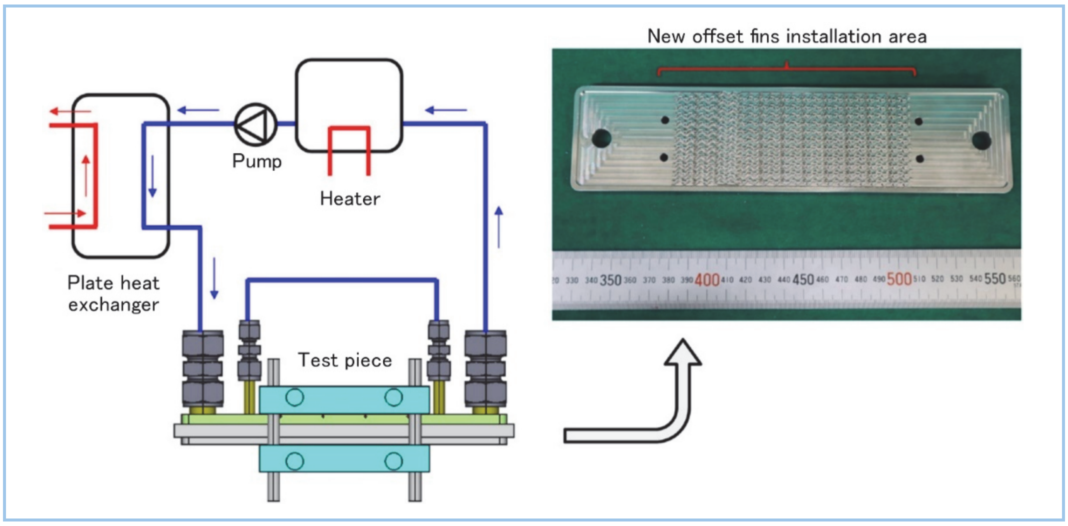


Figure 6　Test circuit diagram and photograph of test piece

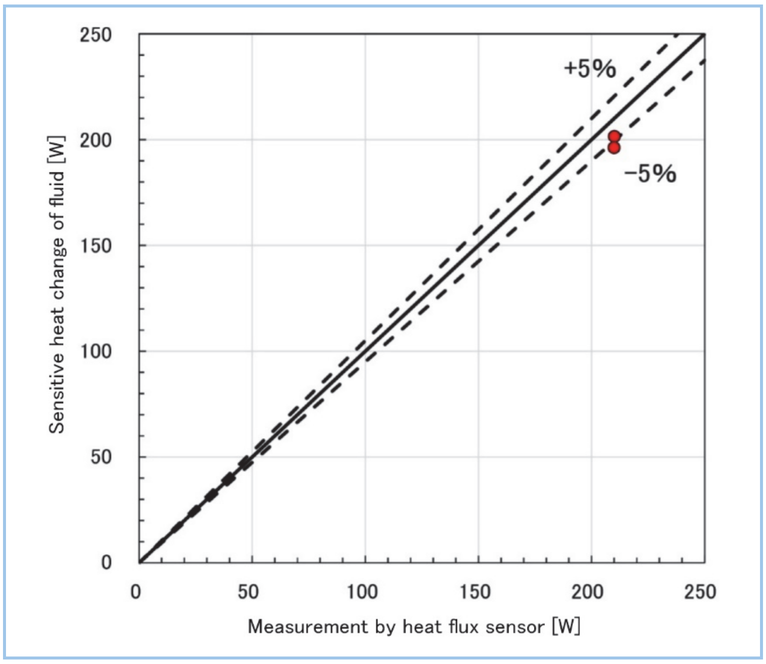


Figure 7　Heat balance evaluation results

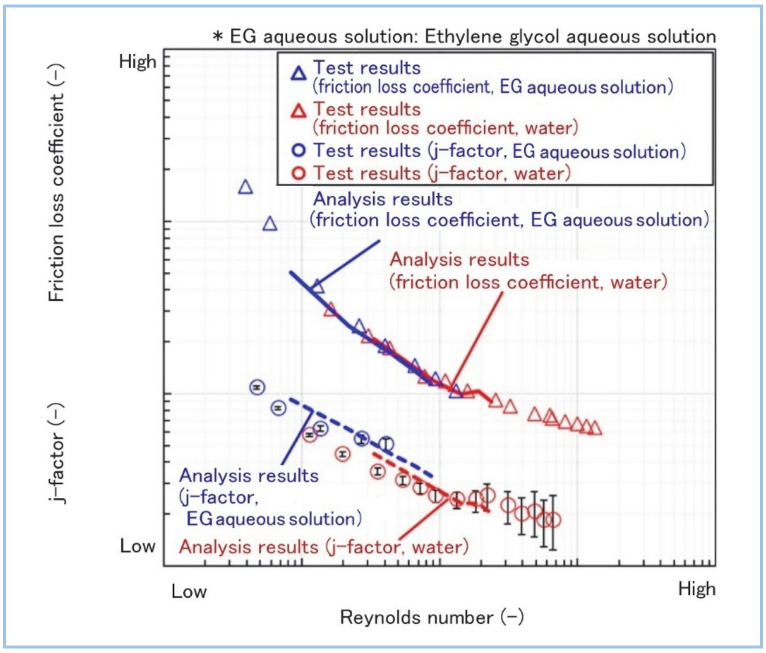


Figure 8　Comparison results of heat transfer coefficient (j-factor) and pressure loss (friction loss coefficient) by analysis and testing

4. Conclusion

In this report, efforts by MHI to develop a small-size and light-weight heat exchanger to be installed in vehicles, by proposing a new offset fin structure with enhanced heat transfer that improves the leading edge effect and secondary cross-sectional flow, have been introduced. A prototype was fabricated and performance verification was carried out. As a result, a higher heat transfer performance compared to conventional offset fins at the same pressure loss could be demonstrated.

MHI is promoting the optimization of fin shape and heat exchanger structure from the viewpoint of quality assurance such as vibration and strength evaluation of heat exchanger as well as concept design of fin introduced in this paper, performance evaluation by CFD analysis, trial manufacture and performance evaluation by press forming. MHI will continue to contribute to the advancement of products by developing heat exchangers that can be applied to vehicles and other products.

References

(1) M. Manglik, E. Bergles, Heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger, Exp. Thermal and Fluid Science, Vol. 10 p. 171~180