16th World Congress in Computational Mechanics (WCCM)
21-26 July 2024, Vancouver, Canada
A. Korobenko, M. Laforest, S. Prudhomme, R. Vaziri (Eds)

MODEL-BASED DESIGN APPROACH FINDING OPTIMAL LIQUID COOLING FLOW PATH FOR ELECTRIC VEHICLE BATTERY

DAISUKE AKETO[1] AND KENJI ONO[2]

[1] Kyushu University
744 Motooka Nishi-ku, Fukuoka, Japan 819-0395
e-mail: aketo.daisuke.626@s.kyushu-u.ac.jp

[2] Kyushu University
744 Motooka Nishi-ku, Fukuoka, Japan 819-0395
e-mail: keno@cc.kyushu-u.ac.jp

Key words: Model-Based Analysis, Graph Data, CFD, Liquid Cooling System, Parametric Optimization.

Abstract. Today many electronic devices that generate significant heat are required to be equipped with liquid cooling systems to reduce their temperature. Since the liquid flow path in the cooling system affects cooling performance, determining flow path in the early development phase can improve the efficiency of the downstream development process and reduce the total cost. In this paper, we propose a model-based analysis system for thermo-fluid phenomena based on CFD results and demonstrate the parametric optimization of flow path.

1 INTRODUCTION

Recent industrial electrical devices are required to have higher capacity and power output, resulting in increased heat generation. Therefore, engineers must design heat management systems more carefully. For example, liquid cooling methods are becoming more popular due to their high cooling ability, even in devices that traditionally employed air cooling. When designing a device for liquid cooling, the liquid pathways greatly influence its thermal performance. If the flow pathways can be approximately determined in the early stage of development, we can estimate the heat performance and proceed efficiently with the subsequent design process. Currently, Computational Fluid Dynamics (CFD) is utilized as a tool to support a wide range of thermo-fluid problems in the engineering field[1, 2]. However, in the early stages of design process, it is rare to obtain detailed shape information of the cooling device. This leads to high costs for mesh generation for CFD execution, which poses a problem in conducting numerous trials and optimizations.

The objective of this paper is to propose an efficient estimation method for the thermal cooling performance of product pathways in industrial products while maintaining sufficient accuracy in a short time. Based on a model-based approach, the analysis is conducted using a graph data structure to evaluate the approximate thermal performance. To ensure accuracy, the coefficients in these equations are calibrated by sampling important parameters (mass flow rate, pressure, and temperature) derived from CFD simulation. In addition, the optimization of the flow pathway is demonstrated.

2 SIMULATION OF BATTERY COOLING PLATE

A battery cooling plate is a device installed adjacent to the battery, which transports the heat generated by the battery using coolant flowing inside it. Typically, the cooling plate is manufactured by pressing two aluminum plates to create beads and then bonding them together to form flow paths for the coolant. This device is incorporated as part of the refrigerant circulation cycle of the entire vehicle, and is supplied with coolant. As an example, figure 1 shows a commercially available product.

It has been reported that the capacity fade of Li-ion battery cells is accelerated in high-temperature environment [3, 4]. If the cooling performance of the battery cooling plate is non-uniform, differences in degradation rates may occur among the cell modules constituting the battery. As a result, non-uniform cooling could lead to a decrease in total battery life. Therefore, we should design the flow paths of the battery cooling plate so that all battery modules sholld be cooled at almost the same temperature. Generally, since the Biot number in the thickness direction of the plates is less than one, we may consider only their fluid temperature. Additionally, from the perspective of ensuring flow rate, flow paths with low pressure loss are also required.

Figure 1: Battery cooling plate[5]

3 IMPLEMENTATION OF SIMULATION SYSTEM

3.1 Graph data model

We employ a graph data structure to represent the flow pathways. By considering the minimum unit of flow path shapes in the actual configuration as unit elements, nodes can represent each unit element, while edges represent the connections between units. Therefore, nodes can

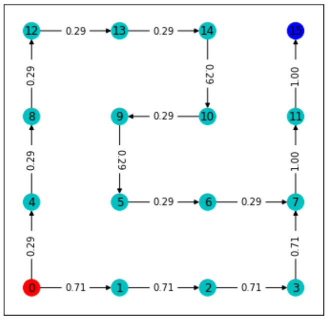


Figure 2: Abstracted graph data from flow path in battery cooling plate.

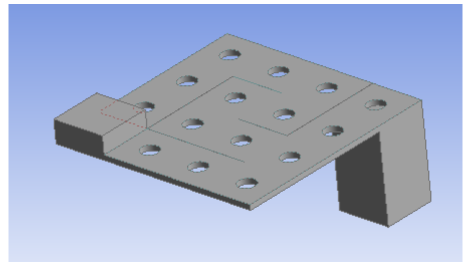


Figure 3: Geometory for CFD calculation.

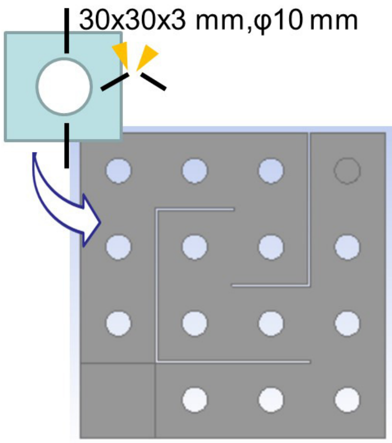


Figure 4: The base shape is indicated at the upper left and the whole geometry is constructed with 4×4 base shapes.

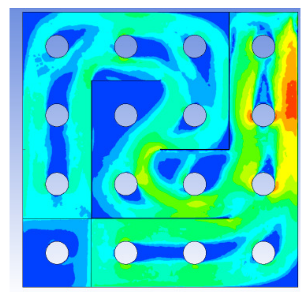


Figure 5: The computed velocity contour of the flow. Red colour means a high magnitude of velocity.

express spatial properties, and edges can express network properties. In this situation, nodes and edges have the following properties:

- node … pressure, temperature and position.
- edge … flow rate.

These flow rates have directional information, so these graphs are digraph. There are four flow and thermal relational expressions established between node and edge properties.

- The conservation of mass flow rate in each edge which are incident a node.

$$\sum M_{ij} = 0 \tag{1}$$

- The relationship between flow and pressure assumes Hagen-Poiseuille equation.

$$M_{ij} = \frac{h^3}{12\mu}\frac{dp}{dx} = c_n(P_i - P_j) \tag{2}$$

- The equation of heat transfer is written down in terms of intensive and extensive properties.

$$C(T_{\mathrm{out}n} - T_{\mathrm{in}n}) = C_{\mathrm{me}} M_n T_{\mathrm{in}n} - C_{\mathrm{me}} M_n T_{\mathrm{out}n} + q \tag{3}$$

- The inlet/outlet temperature of endpoints of an edge are same.

$$M_n T_{\mathrm{in}n} = \sum M_m T_{\mathrm{out}m} \tag{4}$$

These equations are closed-form and can be solved much faster than by iterative methods.

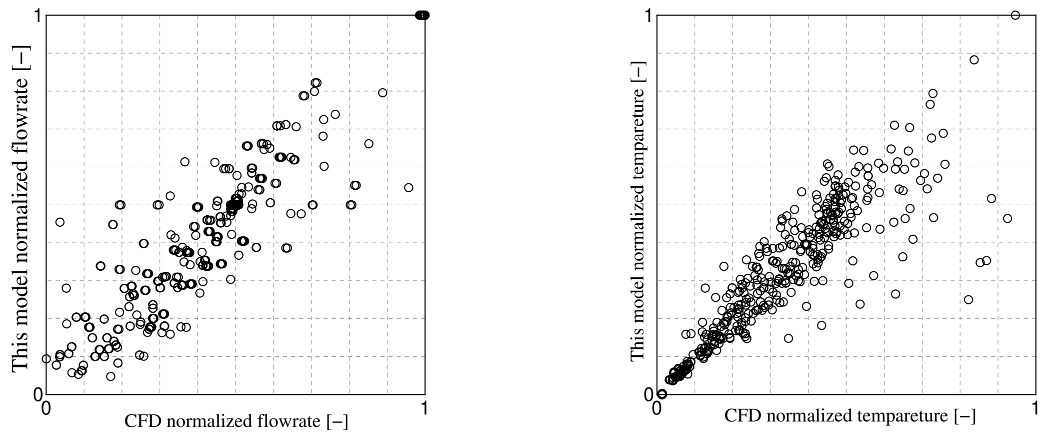
3.2 Adjusting model-based analysis parameters to fit CFD results

Equations (1-4) contain undefined parameters such as c_n, C and C_{me}. To determine these parameters for a useful simulation, we performed CFD simulations to align with the results. An example CAD geometry of the CFD simulation is shown in Figure 3. This geometry is constructed by connecting 30×30×3 mm cuboid with a 10 mm diameter hole base geometry in a 4×4 arrangement. By switching the connection/disconnection of neighboring geometries, the flow path is changed(Figure 4). The inlet/outlet zones are extended 30 mm in the thickness direction. By randomly varying these connections within the design space, different 100 sampling cases were created. Before running the simulations, we excluded some cases that were obviously unsuitable as cooling device.

- With dead-end.
- Without any path for inlet/outlet node.

These shape cause flow stagnation and lost cooling potential.

From these sampling results as shown as Figure 5, we obtained flow rates to each adjacent element, the average pressure of each element, and the mass-average temperature. Various coefficients in equations were fitted using the least squares method to minimize the differences between the results of the CFD simulations and the model-based analysis. Figure 6 shows the comparison between the normalized temperatures and flow rates of each node and edge of the model-based analysis using the fitted coefficients and the results from the CFD simulations. It seems that the flow rate plot is more scattered than the temperature one. This is because temperature is cumulative value in this analysis and conservation law of flow affect to correct.



(a) Flow rate

(b) Temperature

Figure 6: The comparison of CFD and model-based analysis results.

4 CASE STUDY: OPTIMIZATION OF FLOW PATH

As a usage example, we optimized the flow path of a 6×6 size plate using this method. The objective functions are the minimization of pressure loss and the maximization of temperature uniformity. Here, the minimization of pressure loss is defined as reducing the pressure difference between inlet and outlet, and temperature uniformity is defined as minimizing the difference between the maximum and minimum temperatures at all nodes.

Considering the trade-offs between these two values, a multi-objective optimization approach was required. In this study, we used NSGA-II algorithm [6, 7] for optimization. The number of nodes was set to 6×6, with 60 binary design variables defined each edge as on or off. The inlet and outlet nodes were set at the top and bottom left positions. The constraints were defined to avoid configurations where the product performance was obviously inadequate.

- Each node, excluding the inlet/outlet nods, had a degree greater than 1 to avoid "dead-end" shapes (degree 0 or 1).
- All nodes had at least one path to the inlet or outlet node, ensuring that the plate was not disconnected.
- Additionally, the flow rate through all edges was greater than 0, as stagnant flow results in very high temperature, which is inadequate.

Under these conditions, the optimized calculation results are shown in Figure 7 and Figure 8.

Figure 7 shows Pareto solutions of this optimization. The Pareto front is convex, indicating a successful optimization. Figure 8 shows the case of the minimized pressure loss (a) and the maximized temperature uniformity (b) among the Pareto solutions. In the case of the minimized

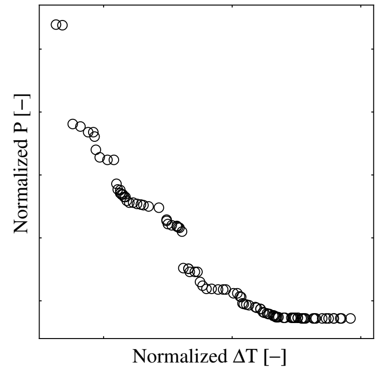
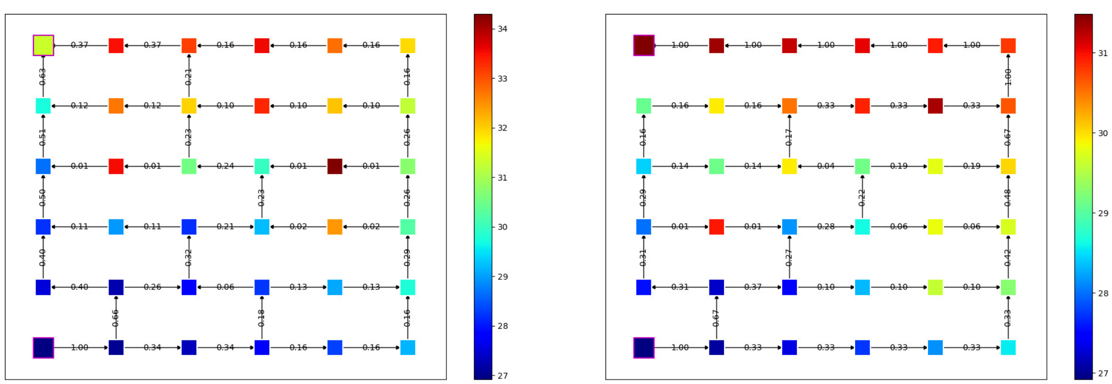


Figure 7: Pareto solutions from optimization results

pressure loss, almost all fluid passes through the shortest path between the inlet and outlet. On the other hand, in the case of the maximized temperature uniformity, the flow is distributed uniformly on the upstream side and gathered on the downstream side to prevent temperature increase. These trends in flow path connections provide engineers with insights into designing battery cooling plate flow paths to meet performance requirement. It takes about one day to complete this optimization with a an AMD Ryzen 5 PRO 4650U in serial operation, which is sufficient for adoption in the industrial development process.



(a) Minimized pressure loss

(b) Maximized temperature uniformity

Figure 8: The example of optimized shapes among the Pareto solutions.

5 CONCLUSION

In this study, to evaluate the thermal performance of flow paths in an automotive battery plate by model-based approach, an analysis system described by a graph data structure was developed. It was demonstrated that this analysis system can derive values sufficiently close to those obtained from CFD results, making it usable for performance design. In addition,by using this analysis system for optimization calculations, it was confirmed that shapes of flow paths can be generated and evaluated in a sufficiently short time.

REFERENCES

[1] Ono, K., Himeno, R., Fujitani, K., and Uematsu, Y. Simultaneous Computation of the External Flow around a Car Body and the Internal Flow Through its Engine Compartment. *SAE Technical Paper*. (1992) 920342.

[2] Akasaka,K. and Ono, K. Development of Rapid Simulation Method for Automotive Aerodynamics. *ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting: Volume 1, Symposia Parts A, B, and C*. (2011) 2633-2639.

[3] Wang,J., Purewal,J., Liu,P., Hicks-Garner,J., Soukazian,S., Sherman,E., Sorenson,A., Vu,L., Tataria,H. and Verbrugge,M.W. Degradation of lithium ion batteries employing graphite negatives and nickel–cobalt–manganese oxide + spinel manganese oxide positives: Part 1, aging mechanisms and life estimation. *Journal of Power Sources* .(2014) **269**:937–948.

[4] Broussely,M., Herreyre,S., Biensan,P., Kasztejna,P., Nechev,K. and Staniewicz,R.J. Aging mechanism in Li ion cells and calendar life predictions. *Journal of Power Sources* .(2001) **97–98**:13–21.

[5] Battery Liquid Cold Plate. URL https://www.valeo.com/en/catalogue/ths/large-battery-liquid-cooler-for-ev/ (Accessed May 12, 2024.)

[6] Deb,K., Pratap,A., Agarwal,S. and Meyarivan,T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*.(2002) **6**:182–197.

[7] Blank, J. and Deb, K. pymoo: Multi-Objective Optimization in Python. *IEEE Access*. (2020) **8**: 89497-89509.