Three-dimensional Thermal Network Analysis of Multi-stage Heat Sink with Water-mist Injection Applied to Thermal Management of Electric Aircraft

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ABSTRACT

Electrification of aircraft has been realizing improvement in efficiency, reliability, and safety of the aircraft by substituting hydraulic and mechanical system with electric system. On the other hand, in future electric aircraft partially replacing the fan driving engines with motors, the thermal management of heat generation from the electric system will become crucial problem to be solved. In this study, for the future electric aircraft, thermal management in oil-cooling motors and air-cooling motor controllers was considered. Three-dimensional steady thermal network analysis (TNA) was performed for analyzing temperature field in an oil cooler for motor cooling and a heat sink for motor controller air-cooling. The present numerical procedure was verified by comparing the results of TNA with those of three-dimensional fluid-solid conjugate heat transfer analysis (3D-CFD). After the verification, TNA was performed for several aircraft flight scenarios, and the optimum geometry of the oil cooler and the heat sink was investigated under the constraints of allowable pressure loss of air flow and outlet oil temperature for oil cooler or maximum local wall temperature for heat sink using the weight (mass) as the object function to be minimized. Furthermore, the water-mist injection to the air flow was considered for lowering the air temperature and the weight of the heat sink.

INTRODUCTION

Aircraft have been continuously demanding improvements of not only reliability and safety but also reduction of fuel consumption as the economic and environmental factors: reduction in emission of environmentally hazardous substances. To attain these improvements, the electrification of aircraft systems has been partially accomplished so far. Conventional aircraft consisted of both hydraulic/pneumatic system and electric system, and the contribution of electric system was small. Recently, in order to accelerate the electrification of the aircraft systems, the concepts of More Electric Aircraft (MEA) and More Electric Engine (MEE) are vigorously investigated. MEA indicates replacing conventional auxiliary hydraulic/pneumatic system with electric system. On the other hand, MEE means the electrification of hydraulic/mechanical pumps and actuators of the engines [1].

The cooling systems required in MEA and MEE have also been investigated, because the substituted electric/electronic devices generate much heat which has to be removed [2]. As for the cooling system of MEA and MEE, some researches have been performed by Marilena, et al. [3] and Murata, et al. [4]. Morioka, et al. [5] and Oyori [6] further proceed to the concept of All-Electric Aircraft (AEA) in which the propulsion is also performed using electric motors. When realization of electrification of the propulsion system is considered, thermal management (cooling system) of the enormous heat generated from the fan-driving motors and motor-controlling power devices has crucial importance. So far the investigation on such cooling system for AEA has not been performed yet.

In this study, the thermal management of partially electrified propulsion case is examined. Motors used as auxiliary power unit are attached to turbo fans as shown in Fig.1. In the present system, the heat generation from motors and motor controllers (M/Cs) are cooled by oil and air, respectively. The oil is used as a coolant for motor cooling; the oil heated by passing through the motor is cooled by cooling oil coolers. M/Cs are cooled by air using plate-fin heat sinks. The cooling performance of the oil cooler and the heat sink is investigated by changing their geometric parameters, and the optimal geometries are investigated by performing computationally light three-dimensional thermal network analysis (TNA) under the constraints of the pressure loss of air flow and the outlet oil temperature for the oil cooler or...
maximum local wall temperature for the heat sink. Then, the water-mist injection to the air flow is considered for the heat sink. As an important index for the cooling system of aircraft, weight of the oil cooler and the heat sink is adopted, and the minimization of the weight is performed. In this study, cooling air is assumed to be supplied by compact blowers/compressors which re-use the cabin air and need no additional coolant (Murata, et al.[4]).

ANALYSIS METHOD

In this study, thermal network analysis (TNA) [7] was adopted for analyzing the air-cooling oil cooler and the air-cooling heat sink for M/C. In TNA, an analysis region is divided into cells and the temperatures are defined at the cell surfaces (right), unknown variables are temperatures at 3 positions: the values are defined at the cell center (left), and those at the cell surfaces (middle) are represented by node values. The governing equation of TNA is derived by considering energy conservation at each cell and by relating the neighboring cells through thermal resistance model. In this research, three-dimensional heat conduction of base walls and partition walls and three-dimensional heat transfer are considered, but the heat conduction of fins in streamwise direction was not considered.

Oil cooler

The conventional method of analyzing heat exchanger performance is e-NTU method [8]. In the e-NTU method, however, the temperature averaged between the inlet and outlet is used in evaluation of physical properties, and local changes in physical properties cannot be treated. On the other hand, TNA can treat locally varying physical properties. As shown in Fig.2, cross-flow oil cooler with fluids unmixed is chosen. In general, cross-flow type facilitates the flow path design and that is why this type is used. In the height direction, ten pairs of oil and air flow passages are considered. As shown in Fig.2 (right), considering the symmetry in the height direction, the half of the fin height is taken as a computational region for both oil and air sides: both top and bottom boundaries are symmetric planes. The computational region is divided into three regions: oil, air, and wall material (fin and partition wall). Three energy equations for the three regions are obtained, and as an example that of oil is shown below:

\[
\dot{m}_{oil}(c_{p,oil,1-4}T_{oil,1-4}) + \frac{Tw,1-2 - Tw,1}{R_{oil,1}} + \frac{Tw,1-2 - Tw,1-3}{R_{oil,2}} + \frac{Tw,1-3 - Tw,1-4}{R_{oil,3}} = \frac{Toil,1-4 - Toil,1}{R_{oil,4}} \tag{1}
\]

where \( \dot{m}_{oil} \) [kg/s]: mass flow rate of oil passing through a cell, \( c_{p,oil} \) [J/(kg K)]: specific heat, and \( R \) [K/W]: thermal resistance. Thermal resistance is calculated by using empirical correlations for fully developed straight pipe and fin efficiency. For fluids, temperatures are defined at the cell surfaces (\( T_{oil,1-4} \)) and the values at the cell center (\( T_{oil,4} \)) are calculated by arithmetic mean; for solid, the values are defined at the cell center (\( T_{w,4} \)) and those at the cell surfaces (\( T_{w,1-3} \)) by arithmetic mean. In the oil cooler of Fig.2 (right), unknown variables are temperatures at 5 positions: \( T_{oil,1-5} \) and \( T_{w,1-5} \) since \( T_{oil,1-4} \) and \( T_{air,1-2} \) are determined from boundary conditions at inlet. In TNA, the temperatures at nodes are iteratively solved for the three regions of oil, air and wall material.

The constraint conditions are outlet oil temperature of 90 °C and air pressure loss of 15 kPa. The oil flows in a closed loop and reused for cooling motor. The pressure loss of air flow is important because it is related to compressor size which drives the air flow. The pressure loss of air flow is calculated from empirical straight pipe value.

Heat sink

The cooling performance of multi-stage (three- and five-stage) heat sink and single-stage heat sink using plate-fins with spanwise expansion is examined. In the heat sink case, it is assumed that temperature also varies in the height direction. The constraint conditions of air-cooling heat sink for M/C are maximum local wall temperature (equal to M/C temperature) of 90 °C and pressure loss of air flow of 15 kPa.

For multi-stage heat sink, the computational region is shown by red broken lines in Fig.3 and symmetric condition is applied at top and side boundaries. The heat sink with spanwise expansion is considered in order to increase the cooling performance and at the same time to reduce the pressure loss by increase the air flow passage area. To enhance the thermal diffusion in the spanwise direction, the heat spreader is used as shown in Fig.4. The heat spreader consists of flat laminate vapor chamber [9][10] and it efficiently dissipates heat both in spanwise and streamwise directions. In single-stage heat sink with spanwise expansion, the computational region shown by red broken lines in Fig.4 is adopted considering the symmetry at centers in both the height and spanwise directions.

As performed by Murata, et al. [4], water-mist injection is applied in order to enhance the cooling performance of the heat sink by lowering the air flow temperature due to evaporation. In this study, the latent heat of evaporation is set to 2500 kJ/kg. It is...
assumed that the evaporation occurred uniformly in space and all the water evaporates at the outlet.

**VERIFICATION OF RESULTS OF THERMAL NETWORK ANALYSIS (TNA)**

**Oil cooler**

In order to verify the results of TNA, they are compared with those of the ε-NTU method. The analysis is performed under the air conditions shown in Table 1.

As the most severe condition for cooling is “hot day” and “take off” in Table 1, all analyses in this study are performed for the condition of “hot day” and “take off”. In the comparison between TNA and ε-NTU in Table 2, the difference of the outlet oil temperature is 10.29 °C and that of the energy efficiency is 0.1456(19.72%). As this large difference is observed, computation is performed again by changing the followings:

- In TNA, physical properties are calculated using the pressure and temperature averaged between inlet and outlet as performed in the ε-NTU method.

Table 3 shows the computed results using spatially uniform physical properties due to the averaged pressure and temperature. As seen in Table 3, the differences in both the outlet oil temperature and the energy efficiency become much smaller as compared to those in Table 2. Therefore, it is confirmed that the differences between TNA and ε-NTU in Table 2 was mainly due to the variable physical properties.

**Heat sink**

In order to verify the results of TNA, the results of TNA are compared with those of 3D-CFD which uses finite volume method (OpenFOAM-2.3.x [11]). The analysis was performed under the air and heating conditions shown in Table 4. The inlet air temperature condition and outlet air pressure are identical to those of Table 1. As performed for oil cooler, all analyses were performed for the condition of “hot day” and “take off”. In the results of 3D-CFD, the temperature distribution in the width direction was small and almost uniform. Therefore, only the temperature distribution in the streamwise direction at the spanwise center is shown for five-stage heat sink case here.

The results of five-stage heat sink are shown in Figs.5 and 6. Fig.5 shows the dry air case and Fig.6 shows the cases with various water-mist injection rates with air mass flow rate 0.143kg/s. The temperature distributions in the streamwise direction of 3D-CFD and TNA are almost same, and the largest difference is 0.8°C in the water-mist mass flow rate of \( m_{w} = 0.528g/s \) in Fig.6. From these results, the TNA result of five-stage heat sink is verified to be reliable. In addition, the verification of the node-number independency was also performed. The cases of 100 and 200 nodes in the streamwise direction gave almost identical bottom wall temperatures, and it is confirmed that node number of 100 in the streamwise direction is sufficient for the present TNA. Furthermore, the verification of the single- and three-stage heat sinks and the single-stage heat sink with spanwise expansion are also performed by comparing TNA with 3D-CFD, and the TNA results are confirmed to be reliable.

**RESULTS AND DISCUSSION**

**Oil cooler**

The analysis is performed under 20 geometric combinations of the oil cooler under the air conditions shown in Table 1. The fin height, \( l_{w} \), is varied among \( l_{w} = 1, 2, 3, 4, 5 \) mm, and the air flow path length, \( L \), is varied among \( L = 0.03, 0.05, 0.10, 0.15 \) m. The air-side width of oil cooler, \( W \), and air mass flow rate are changed to satisfy the constraint conditions at each geometric combination. At the same time, the other geometries and oil mass flow rate are fixed.

| Inlet air temp. [ºC] | Take off | Cool day | Hot day |
|----------------------|----------|----------|--------|
|                      |          |          |        |
| Outlet air pressure  |          |          |        |
| [kPa]                |          |          |        |
| Outlet oil temp. [ºC]|          |          |        |
|                      |          |          |        |
| Pressure loss [kPa]  |          |          |        |
|                      |          |          |        |
| ε [-]                |          |          |        |

| Table 1 | Air conditions for oil cooler. |
|---------|--------------------------------|
| Inlet air temp. [ºC] | Take off | Cool day | Hot day |
|                      |          |          |        |
| Outlet air pressure  |          |          |        |
| [kPa]                |          |          |        |
| Outlet oil temp. [ºC]|          |          |        |
|                      |          |          |        |
| Pressure loss [kPa]  |          |          |        |
|                      |          |          |        |
| ε [-]                |          |          |        |

| Table 2 | Comparison between results of ε-NTU and TNA under valuable properties in TNA (\( l_{w} = 5 \) mm, \( L = 0.05m, W = 0.737m \)). |
|---------|---------------------------------------------------------------|
| Outlet oil temp. [ºC] | ε-NTU | TNA | diff. (value) | diff. [%] |
|                      |          |          |              |          |
| Outlet air temp. [ºC] |          |          |              |          |
|                      |          |          |              |          |
| Pressure loss [kPa]  |          |          |              |          |
|                      |          |          |              |          |
| ε [-]                |          |          |              |          |

| Table 3 | Comparison between results of ε-NTU and TNA under constant properties in TNA (\( l_{w} = 5 \) mm, \( L = 0.05m, W = 0.737m \)). |
|---------|---------------------------------------------------------------|
| Outlet oil temp. [ºC] | ε-NTU | TNA | diff. (value) | diff. [%] |
|                      |          |          |              |          |
| Outlet air temp. [ºC] |          |          |              |          |
|                      |          |          |              |          |
| Pressure loss [kPa]  |          |          |              |          |
|                      |          |          |              |          |
| ε [-]                |          |          |              |          |

| Table 4 | Air and heating conditions for cooling M/C. |
|---------|---------------------------------------------|
| Outlet air pressure [kPa] | Take off | Cruise |
|                      |          |        |
| Heat input [KW]        |          |        |

**Fig.5** Streamwise distribution of bottom wall temperature for five-stage heat sink (dry air case; red solid line: experimental result, blue dotted line: TNA result, and black solid line: 3D-CFD result).

The most severe air condition is “hot day” and “take off” in Table 1. Therefore, the results for this condition are explained below.

The oil-cooler weight and the air-side width of oil cooler, \( W \), of various geometric combinations are shown in Fig. 7. As a result of TNA, the combination of geometric parameters which gives the lowest weight is \( l_{w} = 2 \) mm and \( L = 0.05 \) m as shown by yellow circle in the figure. The air-side width of oil cooler, \( W \), which satisfies the constraint conditions of the pressure loss of air flow...
and the oil outlet temperature is \( T_{out} = 0.851 \, m \). The temperature distributions of oil and air when \( L = 0.05 \, m \) and \( \ell_{air} = 2 \, mm \) are shown in Fig.8. As shown in Fig.8, the temperature difference between oil and air is the largest at inlet and the smallest at outlet.

**Heat sink**

At first, the effect of the heat spreader on the temperature profile is shown in Fig.9. The base plate width, \( W \), is expanded by the factor of two (\( e=2 \)) in the width direction, and the cases with and without the heat spreader are compared. The maximum wall temperature without heat spreader (w/o H.S.) is about 20 °C higher than that with heat spreader (w/ H.S.). The temperature distribution without heat spreader is far from uniform profile because the heat input from M/C is diffused more slowly in the spanwise (\( z \)) direction. The temperature gradient in the streamwise (\( x \)) direction is also observed in the case without heat spreader in the heating area.

The single-stage heat sink with spanwise expansion using heat spreader (width of heat sink=\( eW \)) the multi-stage heat sink without heat spreader (width of heat sink=\( W = 180 \, mm \)) are compared under the same fin geometries (fin height, \( \ell_{air}=10 \, mm \), fin spacing, \( s = 0.685 \, mm \), and fin thickness, \( t = 0.415 \, mm \), partition wall thickness, \( \delta = 0.8125 \, mm \), heat sink streamwise length, \( L = 0.12 \, m \), base plate thickness, \( b = 3.0 \, mm \)). The analyses were performed changing the air mass flow rate to draw one line in the figure for the axes of the pressure loss of air flow and maximum local wall temperature as shown in Fig.10. The single-stage heat sink without spanwise expansion cannot satisfy the constraint conditions (yellow area in the figure). The single-stage heat sink with spanwise expansion using heat spreader of \( e=3 \) is close to the constraint condition but cannot satisfy it. The three-stage heat sink can satisfy the constraint conditions. When the spanwise expansion effect is compared among \( e=1, 2, \) and 3, the enhancement of the cooling performance by the spanwise expansion shows saturation tendency. As for the weight of a whole heat sink, the three-stage heat sink is 35.5% lighter than that of the single-stage heat sink with spanwise expansion of \( e=3 \).

Then, the effects of the fin geometries on the cooling performance are examined. Fin geometric parameters were changed among 9 combinations by varying both the fin height, \( \ell_{air} \), and the fin spacing, \( s \), in three levels as shown in Table 5. TNA for each combination was performed changing the air mass flow rate to draw one line in the figure for the axes of the pressure loss of air flow and maximum local wall temperature as shown in Fig.11. The fin spacing of \( s = 0.757 \, mm \) (solid line) gives the higher cooling performance for the same fin height, and the fin height of \( \ell_{air}=8.255 \, mm \) (blue line) only satisfies the constraint conditions. Wider fin spacing makes the heat sink lighter under fixed \( W \). The geometric combination of \( s = 0.757 \, mm \) and \( \ell_{air}=8.255 \, mm \) gives the best performance for dry air case among the geometries investigated.

The cooling enhancement by the water-mist injection is investigated. The fin geometries shown in Table 5 were examined. As a result, by the water-mist injection, fin height of \( \ell_{air}=6.350 \) and 8.255 mm can satisfy the constraint conditions (figure not shown). Due to the shorter fin height, the weight of the heat sink is reduced by 4% by the water-mist injection as compared to the dry air case.

**CONCLUSIONS**

The three-dimensional steady thermal network analysis (TNA) was performed to analyze the temperature field of air-cooled oil cooler and air-cooling heat sink for motor controller which are the key devices in the thermal management of future electric aircraft. The geometric parameters of the oil cooler and the heat sink was optimized under the constraints of the pressure loss of the air flow and the outlet oil temperature for the oil cooler or the maximum local wall temperature for the heat sink. Considering the application to the aircraft, the weight was also evaluated. The
optimizing procedure of geometric parameters of the oil cooler and the heat sink giving the highest cooling performance and the lowest weight was proposed.

In this study, for the oil cooler, the geometry giving the lowest weight was the fin height of $\ell_{\text{air}} = 2\text{mm}$ and the air-flow path length of $L = 0.05\text{m}$. As for the heat sink, cooling performance of the three-stage heat sink was the highest, and it can satisfy the present constraint conditions of the air-flow pressure loss and the maximum local wall temperature. The fin geometries giving the lowest weight was the fin spacing of $s = 0.757\text{mm}$ and the fin height of $\ell_{\text{air}} = 8.255\text{mm}$ for the three-stage heat sink for the dry air case. Furthermore, the water-mist injection to the air flow was considered for lowering the air temperature by the water-mist evaporation and the weight of the heat sink was reduced by 4% by the water-mist injection.

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