International Journal of Automotive Technology, Vol. 4, No. 2, pp. 57−64 (2003)

1229−9138/2003/012−01

DEVELOPMENT OF INTELLIGENT POWER UNIT FOR HYBRID FOUR-DOOR SEDAN

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(Received 10 October 2002; Revised 21 February 2003)

ABSTRACT−The Intelligent Power Unit (IPU) utilized in Honda's Civic Hybrid Integrated Motor Assist (IMA) system was developed with the aim of making every component lighter, more compact and more efficient than those in the former model. To reduce energy loss, inverter efficiency was increased by fine patterning of the Insulated Gate Bipolar Transistor (IGBT) chips, 12V DC-DC converter efficiency was increased by utilizing soft-switching, and the internal resistance of the IMA battery was lowered by modifying the electrodes and the current collecting structure. These improvements reduced the amount of heat generated by the unit components and made it possible to combine the previously separated Power Control Unit (PCU) and battery cooling systems into a single system. Consolidation of these two cooling circuits into one has reduced the volume of the newly developed IPU by 42% compared to the former model.

KEY WORDS : Battery, Cooling, DC-DC, Efficiency, HEV (hybrid electric vehicle), Inverter

1. INTRODUCTION

In recent years, the reduction of CO_2 emissions through increased automotive fuel economy has become a significant issue for the automotive industry. One solution to this has been an increased focus on hybrid vehicle systems combining internal combustion engines with electric motors. Honda itself developed and marketed a model of the Insight equipped with a lightweight and compact Integrated Motor Assist (IMA) system in 1999. This paper discusses the development of the components of the Intelligent Power Unit (IPU) utilized in the IMA system for the 2001 Civic Hybrid. With the fundamental aim of increasing the popularity of hybrid cars, this development succeeded in producing a lightweight and compact unit capable of being installed in a four-door sedan.

2. DEVELOPMENT GOALS FOR THE CIVIC HYBRID IPU

The IPU utilized in the Civic four-door sedan was developed to allow the IMA system to be installed in a conventional sedan with the amenity of passenger room and trunk space. The basic concept was to ensure cabin space and associated trunk space for five people. This necessitated a reduction in the volume of the IPU by 40% over the Insight unit to place behind the rear seat.

2.1. Reduction of the Size of the IPU

The IPU utilized in the Insight is shown in Figure 1. The volume of this former IPU was 138L, made up of:

(1) Power Control Unit (PCU)	33L (24%);
(2) Battery	43L (31%);
(3) Cooling units	62L (45%).

The target volume for the Civic Hybrid IPU is set as 80L, with the following make up of:

(1) PCU	20%;

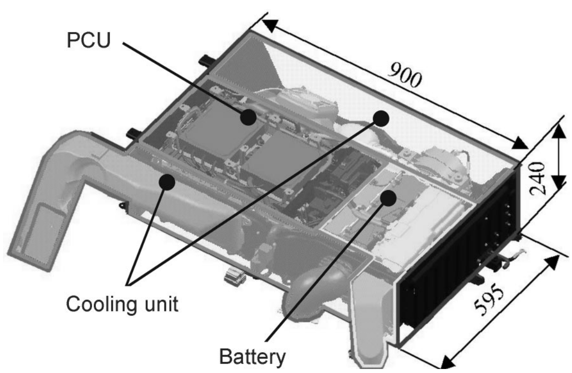

Figure 1. Dimensions of insight IPU.

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(2) Battery 30%;
(3) Cooling units 60%.

2.2. Integration of Cooling Units

Particular attention was focused on reducing the size of the cooling system by integrating the twin cooling circuits in the former IPU (battery and PCU cooling units). Giving consideration to the management of the appropriate battery temperature, it is necessary for the intake air, which functions as the battery cooling medium, to be at the normal temperature. It was therefore established on the assumption that intake and exhaust of cooling air would be conducted within a vehicle. Because internal intake and exhaust would increase the load for air-conditioning and cause noise in the cabin, target airflow volume was established as less than 90 m^3/hr. The airflow required by the Insight cooling system is:

(1) Inverter 138 m^3/hr;
(2) 12V DC-DC converter 120 m^3/hr;
(3) Battery 60 m^3/hr.

For integration of the cooling systems, it is necessary to reduce the airflow requirement of the inverter and the 12V DC-DC converter to below 90 m^3/hr. In the former PCU cooling air was taken in from outside the vehicle, meaning that it was necessary to set the intake temperature high under the situation of hot summer weather. But integration of the cooling systems in the new model would enable internal air circulation and therefore lower air temperatures, leading to a reduction of the airflow required. In combination with this, it would be necessary to reduce the heat generated by the PCU by increasing the efficiency of each component. In this way, the development process examined the possibility of integration of the former model's two cooling systems by reduction of the temperature of the intake air and increased efficiency in components.

2.3. Responding to Increased Assist and Regenerative Power

Civic Hybrid was heavier than the Insight, and was also adopted a Cylinder Idling System (CIS), meaning that the IPU had to respond to a 30% increase in assist and regenerated power. This also required increased efficiency in all the IPU components, and formed an important aspect of the development agenda for this project. Increased heat generation caused by increased input and output power to battery was a particular consideration. To respond to this, it was necessary to increase the battery cooling airflow 50% and decreasing internal resistance in the battery 20% over the former model to decrease the amount of heat generated, while maintaining the target for maximum airflow in the integrated cooling system mentioned in the previous section.

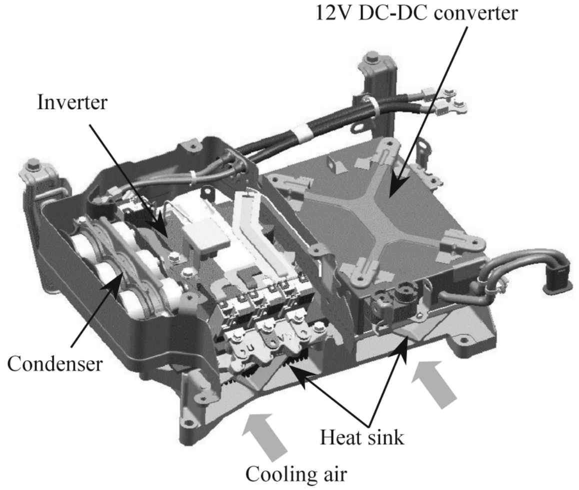


Figure 2. Power control unit.

3. POWER CONTROL UNIT (PCU)

To position the IPU behind the rear seat, it was necessary to make the PCU approximately 20% smaller and reduce energy loss in the inverter and the 12V DC-DC converter. This was achieved in the following way:

(1) Integration of the inverter and the pre-driver unit;
(2) Fine patterning of the Insulated Gate Bipolar Transistor (IGBT) chips;
(3) Reduction of energy loss and the adoption of a structure enabling high heat dissipation in the capacitor;
(4) Adopting a soft switching method for 12V DC-DC converter control.

These developments enabled a 20% reduction in the volume of the newly developed PCU, which is 26.8L against the 33L for the Insight PCU. Figure 2 shows the PCU utilized in the Civic Hybrid.

3.1. Inverter

To make the unit smaller and lighter and reduce energy loss, new technologies were developed for the components making up the inverter. This section provides details of these technologies.

3.1.1. Integration of inverter and pre-driver unit

The improvements of inverter which controls the motor drive are as follows:

(1) Custom integration of IGBT element drive circuits;
(2) Installation of a high-performance microcomputer to provide the software processing as a safeguard function;
(3) Simplification of interface circuits by adoption of serial communication between Motor ECU, etc..

These new technologies have enabled a 39% reduction in size and a 28% reduction in weight over the former

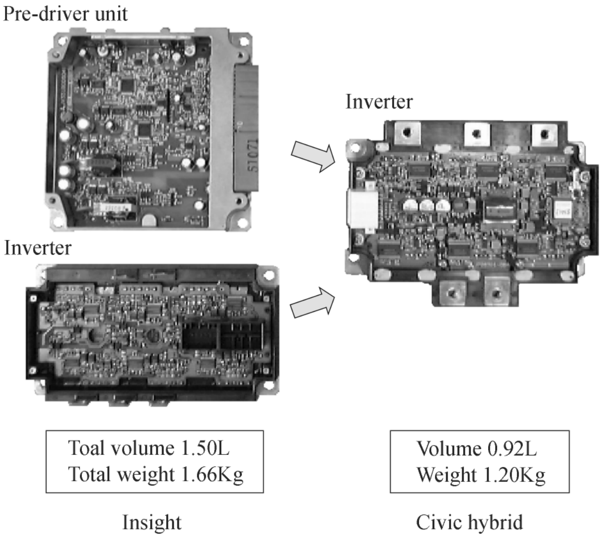


Figure 3. Inverter unit.

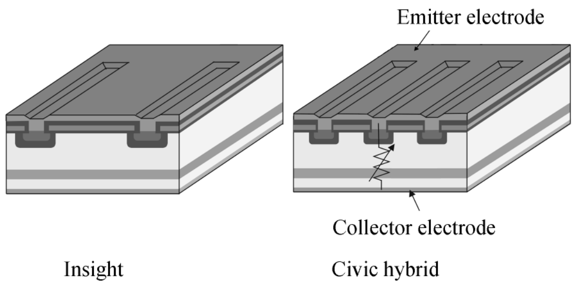


Figure 4. Model of IGBT fine patterning.

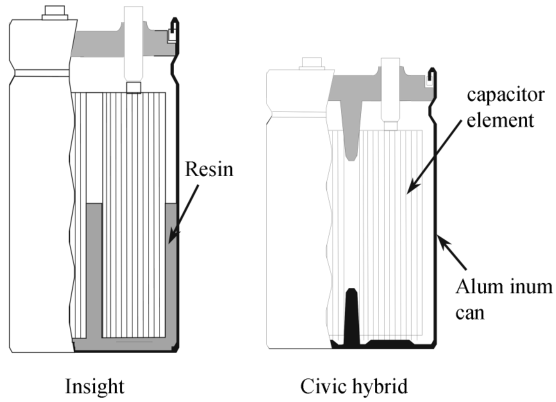


Figure 5. Capacitor structure.

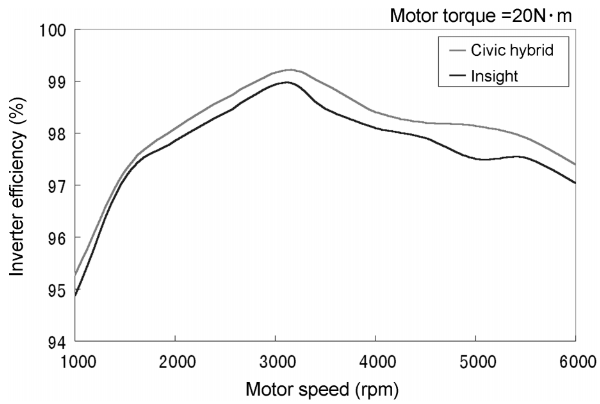


Figure 6. Inverter efficiency.

model. Figure 3 shows the inverter unit utilized in the Insight and the Civic Hybrid. In the former PCU, overheating was prevented by heat-detecting thermistors positioned near the IGBT chips. The responsiveness of temperature detection in the new model has been improved by locating temperature sensors above the IGBT chips.

3.1.2. Reduction of loss by fine patterning of IGBT chips
Figure 4 shows the cell pattern of the IGBT chip, the power element in the inverter. Refinement of the cell pattern compared to the former model has enabled approximately three times more cells to be mounted on the same surface area and reduction of channel resistance per unit of surface area (Rch). Therefore, ON voltage for the IGBT has been lowered and loss has been reduced a maximum of 25% over the former model.

3.1.3. Reduction of capacitor size
In the former PCU, elements of the electrolytic capacitor were fixed in resin for vibration resistance and heat dissipation. In the new model, heat dissipation occurs through direct contact between the bottoms of the elements and aluminum cases (Figure 5), improving heat

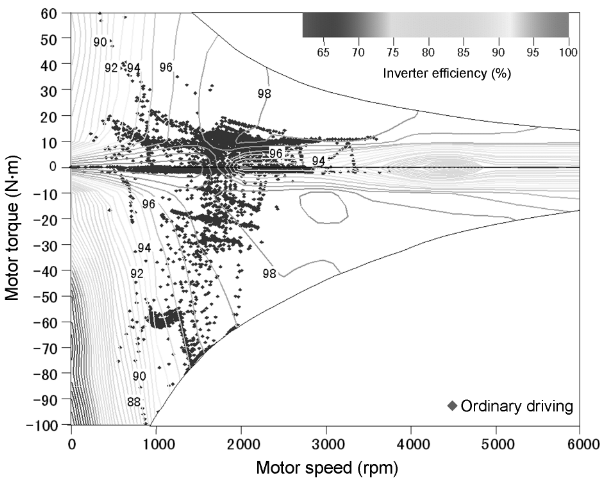


Figure 7. Inverter efficiency map.

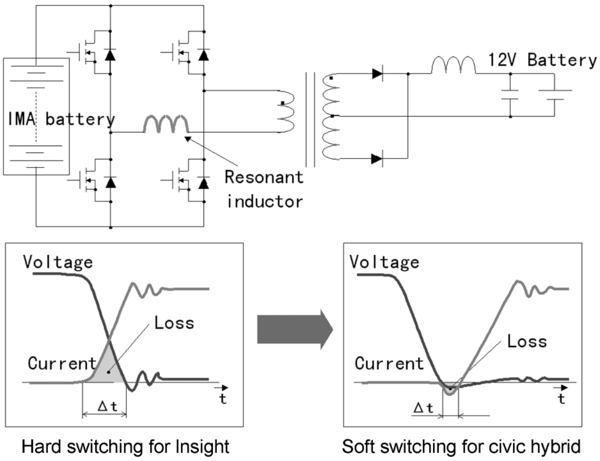


Figure 8. 12V DC-DC converter circuit.

dissipation 20% over the former model. Improvement of the electrolyte and electrode foil etching has reduced resistance, leading to decrease of the Equivalent series resistor (ESR) and 18% less heat generation in the new elements. These improvements have enabled the capacitor to be reduced 30% in size and 27% in weight.

3.1.4. Increased inverter efficiency

The technologies described above have reduced loss and increased inverter efficiency under all motor drive conditions. Figure 6 shows a graph of inverter efficiency against motor speed. A map of inverter efficiency plotted against motor speed and torque is shown in Figure 7. When motor speed and torque data sampled during actual driving are plotted on this graph, it becomes clear that during actual driving the inverter's high-efficiency range is mainly used. Reducted of energy loss by improvement of efficiency also contributes increase of fuel economy.

3.2. 12V DC-DC Converter

The adoption of soft switching in the new 12V DC-DC converter has reduced loss against the former hard switching method. Figure 8 shows a conceptual diagram of operation of the circuit.

In switching operation of Metal Oxide Semiconductor Field Effect Transistor (MOSFET) which drives a transformer, when the MOSFET are switched on, and current from the IMA battery to the transformer via the MOSFET, switching timing is controlled by a resonant inductor in the current path, reducing the overlap time between the MOSFET drain-source voltage and the drain current, therefore reducing switching loss. As Figure 9 shows, the adoption of this soft switching circuit has improved efficiency an average of 2% over the former model. This technology has also enabled internal simplification of the converter, allowing a 22% size

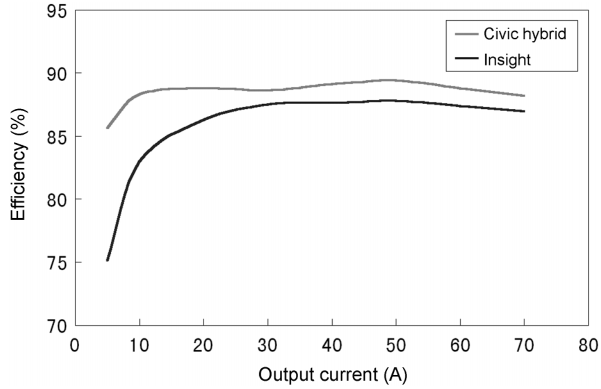


Figure 9. 12V DC-DC converter efficiency.

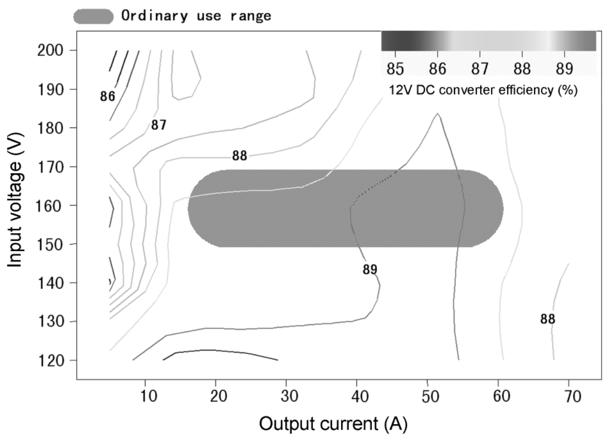


Figure 10. 12V DC-DC converter efficiency map.

reduction and a 9% weight reduction compared to the Insight model.

Figure 10 shows a map of efficiency of the 12V DC-DC converter against input voltage from the IMA battery and output current from the 12V battery. Efficiency has been improved in the areas utilized in actual driving as shown in this graph, and loss has been reduced during actual use. Therefore, it become possible to cool the unit with a smaller airflow than required in the Insight, and the consumption of electric power has also been reduced. This has enabled the size of components to be reduced, and fuel economy to be improved.

4. IMA BATTERY

Compared to the Insight, the weight of the new vehicle has increased, and it has also been provided with a Cylinder Idling System (CIS), increasing the energy available from regeneration. It was predicted that the increase of energy in assist and regeneration, that is, the

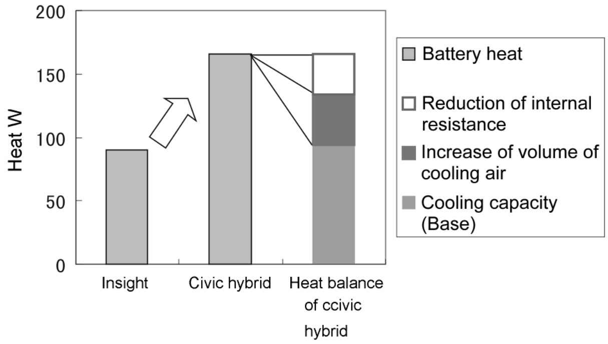


Figure 11. Battery heat balance.

Figure 12. IMA battery module.

increase of input and output average power of the battery during driving, would increase the amount of heat generated by the battery. The following solutions were examined to respond to this:

(1) Approximately 20% reduction in internal resistance of the battery module;

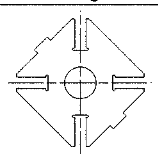
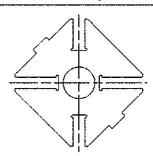
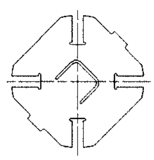
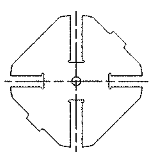
	Insight	Civic hybrid
Positive current collector		
Negative current collector		
Number of welding points	84	118
Internal resistance	21mΩ	17mΩ (−19%)

Figure 13. Current collecting plate.

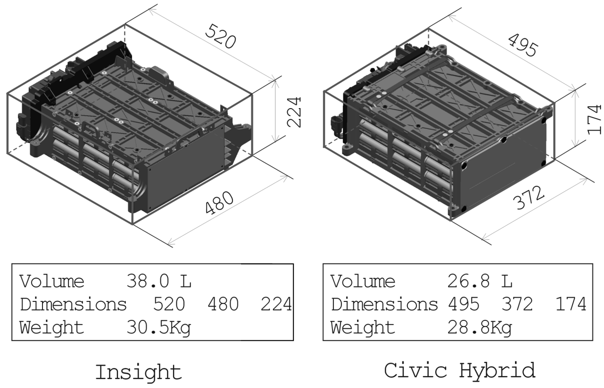


Figure 14. IMA battery box.

(2) 50% increase in cooling airflow provided to battery against the former model.

Figure 11 shows the amount of heat generated in the battery and the battery heat balance of the Insight and the Civic Hybrid during actual driving. The Civic Hybrid battery generates 1.8 times as much heat as the Insight battery, but a 20% decrease in internal resistance and a 50% increase in the cooling airflow provided to the battery have enabled temperature increase to be maintained at the level of the former model.

4.1. Battery Module

The battery module was improved for exclusive use in the Civic Hybrid. The electrodes and the current collector structure were reexamined and the shape of the current collecting plate in particular was altered to reduce internal resistance. Figure 13 shows a comparison of the shapes of the current collecting plate in the former and new models.

The change in the shape of the current collecting plate enabled the amount of welding points with the electrodes

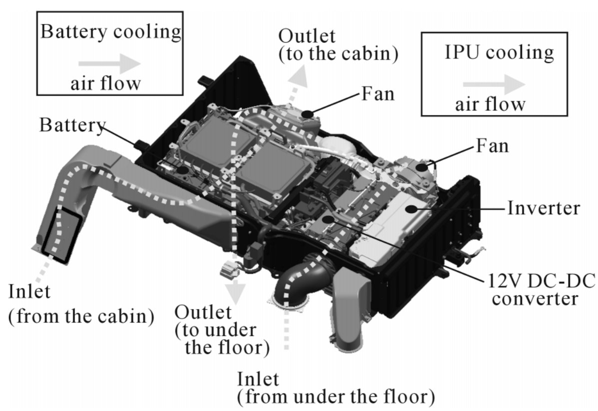


Figure 15. Cooling airflow in Insight IPU.

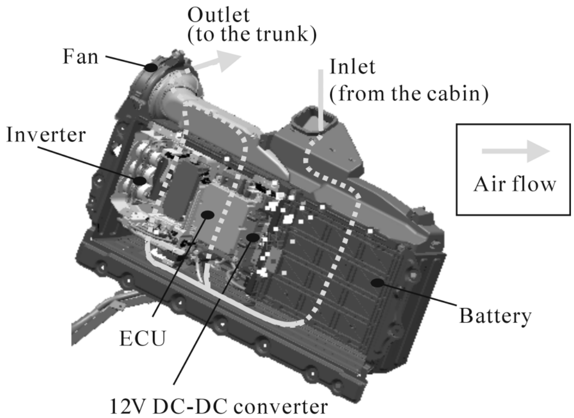


Figure 16. Cooling airflow in Civic hybrid IPU.

to be increased, and standardized the current density on the plate. In combination with internal improvements to the battery, resistance has been decreased 19% over the Insight model.

4.2. IMA Battery Box

Battery box parts were also re-examined to reduce the weight and size.

(1) The placement of the components attached to the battery box (battery ECU, harness, etc.) was optimized, enabling reduction of the size of the box unit.

(2) The intensity of the box was increased, and its size and weight were reduced by the design of couplings optimized for the Civic Hybrid.

As a result, the volume of the new box has been reduced by 29.5% and the weight by 5.6% compared to the box used in the Insight.

5. INTEGRATION OF COOLING SYSTEMS

Figure 15 shows the Insight IPU and its cooling circuit. In this model there are separate cooling circuits for the PCU and the battery. The PCU cooling system takes in air from outside the cabin, and exhausts the air outside the cabin after cooling the inverter and the 12V DC-DC converter. The battery cooling system takes in air from the cabin, and exhausts the air back into the cabin after cooling the battery. These cooling systems make up approximately 45% of the volume of the entire IPU. Integration of the cooling systems was examined as a method of reducing the size of the cooling system in the Civic Hybrid by 60%.

Figure 16 shows the Civic Hybrid IPU and its cooling circuit. The Civic Hybrid IPU is positioned behind the rear seat. Cooling air for the battery is taken in through the inlet located above the rear tray inside the vehicle. After cooling the battery, the air is reused to cool the

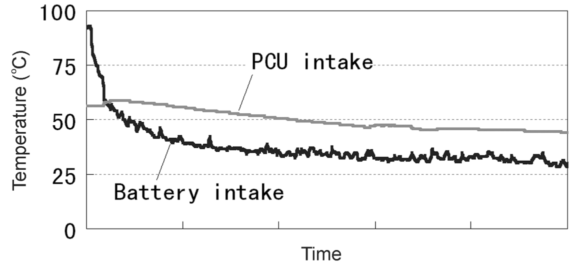


Figure 17. Cooling air temperature when driving in hot weather.

PCU, and exhausted into the trunk. A section of the IPU case is used as a cooling circuit from the battery exhaust to the PCU inlet instead of a duct, and it enables reduction of the number of components. The main points of difficulty encountered with this cooling system are as follows:

(1) Establishment of PCU cooling system by battery cooling air exhaust;

(2) Suppression of cabin noise caused by IPU cooling air;

(3) Responding to increase in battery temperature on hot days caused by vertical placement of battery box behind rear seat.

The results of studies on (1) will be discussed here; (2) and (3) will be discussed in the following sections.

5.1. Study of Temperature of IPU Cooling Air

Because cooling air for the PCU was drawn from outside the vehicle in the Insight, the maximum temperature for PCU cooling air intake was set at 60 deg.C, in consideration of operation during hot summer weather, etc. For the Civic Hybrid, to lower the intake temperature of PCU the cooling systems were integrated and the PCU cooling system uses air exhausted from the battery cooling system, which is drawn initially from within the cabin. Figure 17 shows the transition of the battery and PCU intake temperatures in the Civic Hybrid when

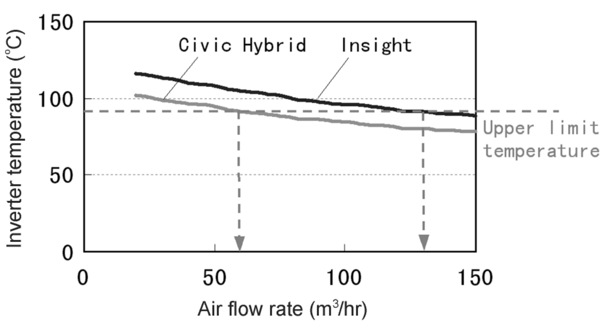


Figure 18. Characteristics of cooling inverter.

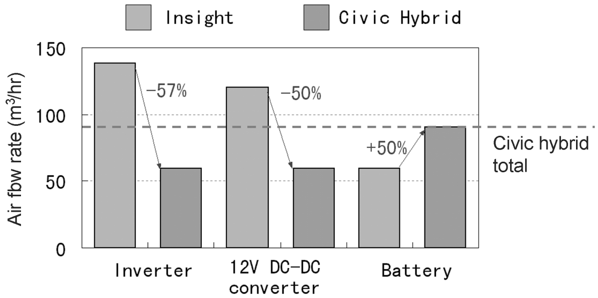


Figure 19. Airflow rate.

driven after having been left outside on a hot day. The intake temperature above the rear tray (battery intake temperature) falls with the commencement of operation and when the vehicle is cruising reaches around 35 deg.C. The air reaches about 50 deg.C from cooling the battery, and is used to cool the PCU. This fact was the basis of a study of the possibility of establishing a cooling system with a maximum temperature of 50 deg.C.

5.2. Study of Feasibility of Reduction of Cooling Airflow

It was possible to reduce the maximum temperature of the air intake to 50 deg.C, 10 deg.C lower than in the Insight, by using battery cooling air to cool the PCU. A study was conducted to determine the relative reduction of necessary cooling airflow granted by this method and the previously mentioned reduction of loss in each component. As an example, Figure 18 shows the relationship between the temperature of the inverter and the cooling airflow.

The reduction of loss by a maximum of 25% through increased inverter efficiency and the reduction of the intake air temperature has enabled cooling with an airflow of 60 m^3/hr, 57% less than the previous model. Results for the 12V DC-DC converter similarly show that cooling is possible with an airflow of 60 m^3/hr, 50% less than required in the previous model. Despite increased efficiency through reduction of internal resistance in the battery, increased vehicle weight and increased regenerative energy have meant a higher level of battery input and output power, necessitating 90 m^3/hr of cooling air, 50% more than required in the previous model. Figure. 19 shows the results of the reduction of cooling airflow. As this graph shows, the maximum cooling air requirements for the battery, inverter and 12V DC-DC converter are all below the target maximum of 90 m^3/hr. As a result, it has been possible to cool all components within the system at an airflow rate less than a maximum established on the basis of consideration of increased load for air conditioning and in-cabin noise caused by internal intake and exhaust of cooling air.

Reduction of the airflow required to cool each component to within the target and reduction of the size of the components themselves has enabled integration of the cooling circuits. The number of cooling fans and ducts has also been reduced, and the amount of volume of the IPU taken up by the cooling system has been decreased 62% against the former model.

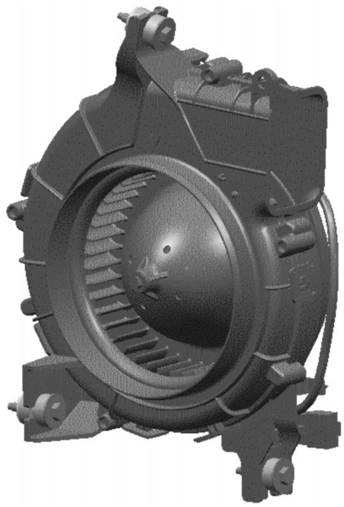


Figure 20. IPU cooling fan.

6. REDUCTION OF COOLING FAN NOISE

In addition to integration of the IMA cooling circuits, a PWM control type IPU cooling fan was newly developed for the Civic Hybrid. This new fan has realized step-less fine control.

Increasing airflow is a simple method to improve cooling ability, but the higher intake of air required from the cabin increases noise, with a consequent negative effect on the market appeal of the vehicle. A new fan control method was therefore developed for the Civic Hybrid in order to achieve a high level of balance between cooling performance and product appeal. The fan control duty factor was chosen as the larger of

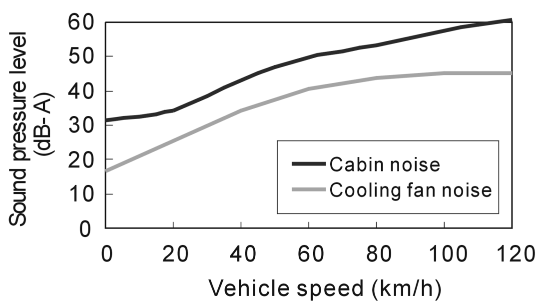


Figure 21. Cooling fan noise.

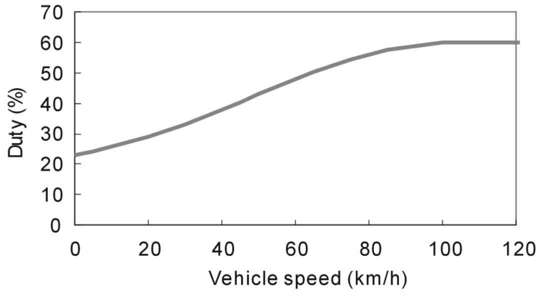


Figure 22. Cooling fan control.

(1) The factor determined by the battery temperature and the input and output current.

or

(2) The factor determined by the difference of temperature between each battery modules.

To further reduce fan noise, a restriction was applied depending on the upper limit for the duty factor determined by vehicle speed. The target here was to minimize the fan noise felt by passengers using the change of cabin noise due to variations in vehicle speed, while maintaining cooling performance. The target for fan noise for the Civic Hybrid was established as 8dB less than the level of in-cabin background noise. Figure 21 shows vehicle speed and noise level, and Figure 22 shows a graph of the upper limit of duty for fan operation.

The adoption of the fan control described above has made possible a silent cooling system which still provides the required cooling performance.

7. PREVENTION OF BATTERY MODULE HEATING

Positioning of the IPU behind the rear seat has necessitated vertical placement of the battery box, meaning that when the vehicle is left out on hot days the battery module, which is located in the upper section of the box, can become overheated in the sun. In the Civic Hybrid, heat insulators have been placed around the battery box to prevent this phenomenon.

The main insulation measures are:

(1) Placement of insulators around the battery box;

(2) Manufacture of the intake duct out of forming resin to give it an heat insulating function. It is also provided with a rubber heat isolation valve.

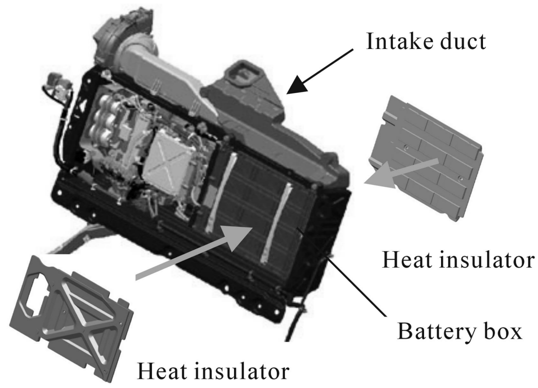


Figure 23. Heat insulating device for IMA battery.

As a result, the battery temperature rises approximately 10 deg.C less when the vehicle is left out in the sun, effectively preventing overheating. Because expandable polypropylene beads with excellent impact absorption properties are used as the heat insulator, it doubles to protect the battery box in the event of a collision.

8. CONCLUSION

New technologies have been utilized in each component, enabling reduced generation of heat through increased efficiency, and each component to be made smaller. In particular, increased efficiency in the inverter and the 12V DC-DC converter has reduced the amount of heat generated despite the increased electrical load. Simplification of the overall IPU cooling system has also been possible, with the two cooling systems of the Insight IMA system being integrated into one. As a result, the volume of the newly developed IPU is 42% lower than the Insight model. This means that the IMA system can be installed behind the rear seat in the trunk while maintaining the same passenger space as a conventional sedan and with minimal loss of trunk space.

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