
Development of Wind Simulator Equipment for Analysis of Intake Phenomena in Formula One Engines

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ABSTRACT

Formula One vehicles repeatedly accelerate and decelerate, reaching maximum speeds of 300-370 km/h and facing maximum G forces of 4.0 G. Under driving conditions such as these, the vehicle's wind speed (ram pressure) has a significant effect on engine power. However, due to issues involving the fitting of measurement devices onto vehicles, the prioritization of vehicle set-up work, and other factors, time has not been available for measurements to be taken, and analyses of air intake phenomena due to ram pressure during circuit driving have not been conducted.

A wind simulator able to reproduce ram pressure during circuit driving was developed, enabling efficient development of intake systems using bench tests.

In addition, dyno equipment with identical inertia characteristics to those of a vehicle drivetrain and a vehicle simulator system able to simulate body characteristics, throttle and accelerator work, and the conditions of different courses were added to the system. This enabled circuit driving modes to be used in bench tests, making it possible to establish appropriate intake settings for each circuit.

1. Introduction

Recent Formula One regulations have reduced the number of days for running tests and placed limitations on the annual driving distance in order to reduce costs. This has necessitated a thoroughgoing reduction of engine-related running tests via higher accuracy of performance predictions at the diagram stage and the use of bench tests in place of running tests.

In order to realize this goal, items from running tests were not simply substituted in bench tests; a device was developed that would enable phenomena in the engine during circuit driving to be clarified.

The factors that affect dynamic performance in engine-related running tests are changes in the vehicle's wind speed (ram pressure) and atmospheric conditions (temperature and humidity). Conventional bench tests for intake system parts were unable to reproduce the vehicle's wind speed (ram pressure), temperature, and humidity conditions in the high-speed range for all circuits, and there were therefore cases in which specifications determined on the basis of bench test results were ineffective and were not applied.

A wind simulator (ram pressure generator) was developed as a means of resolving this issue. In addition, the use of a vehicle simulation system able to employ

circuit driving modes enabled engine phenomena during circuit driving to be reproduced.

The developed equipment, Real Vehicle Dyno bench (RV bench), consisted of a wind simulator, dyno equipment displaying identical inertia characteristics to the drivetrain of an actual vehicle, and a vehicle simulation system.

The vehicle simulation system was based on the Vehicle Simulation Module (VSM) produced by AVL List GmbH.

In addition to controlling engine torque based on engine speed and throttle opening via the dyno equipment, the system reproduced driving conditions through substitution of different vehicles, drivers, and courses, enabling lap times to be evaluated. The system featured a variety of modes, including cornering (deceleration and acceleration), full lap driving, and anti-stall (idling and take-off).

Because the system enabled evaluation of the effect of the parts employed on lap time in addition to power output, it provided race teams with a more informed perspective, and increased the efficiency of development.

This paper will provide an overview of the system, its correlation with circuit driving, and the results of its use in the analysis of engine air intake phenomena.

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2. Overview of Equipment

2.1. Overview of Wind Simulator

Figure 1 shows a section view of the RV bench, and Fig. 2 shows an overhead view of the test room. Figure 3 shows the bench test equipment with an engine fitted.

The air blowers were designed for transient performance enabling wind speed to be varied to reproduce typical acceleration (1.7 G) and deceleration (4.0 G) conditions for Formula One vehicles. In order to minimize temperature increases through adiabatic compression, the wind speed distribution was rendered uniform by positioning variable-flow cooling fins, the shapes of which had been designed based on CFD, in the air ducts.

To enable the temperature of the air used in the system to be adjusted appropriately in response to temperature-setting commands, a boiler and a refrigeration machine were positioned in the second-floor test room, and the air produced here was sent to the first-floor blower room.

Three blower motors were used to bring the air in the blower room to the target wind speed, after which

it was sent to the first-floor test room.

Three air ducts were set up in the first-floor test room, supplying air at a uniform wind speed (reproducing the vehicle wind speed during circuit driving) to the air box inlet, radiator, and oil cooler.

Wind could be blown by the equipment in response to simulated vehicle speed (0-360 km/h) while meteorological conditions (temperature and humidity)

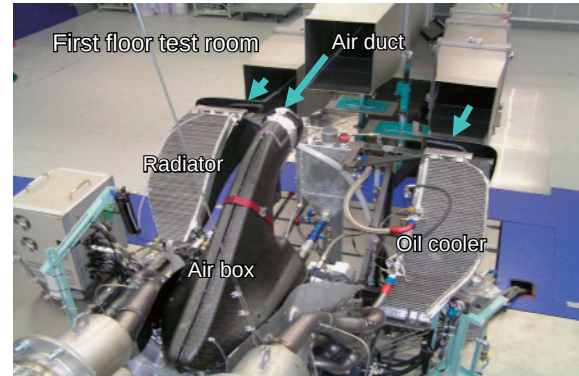


Fig. 3 Overview of test room

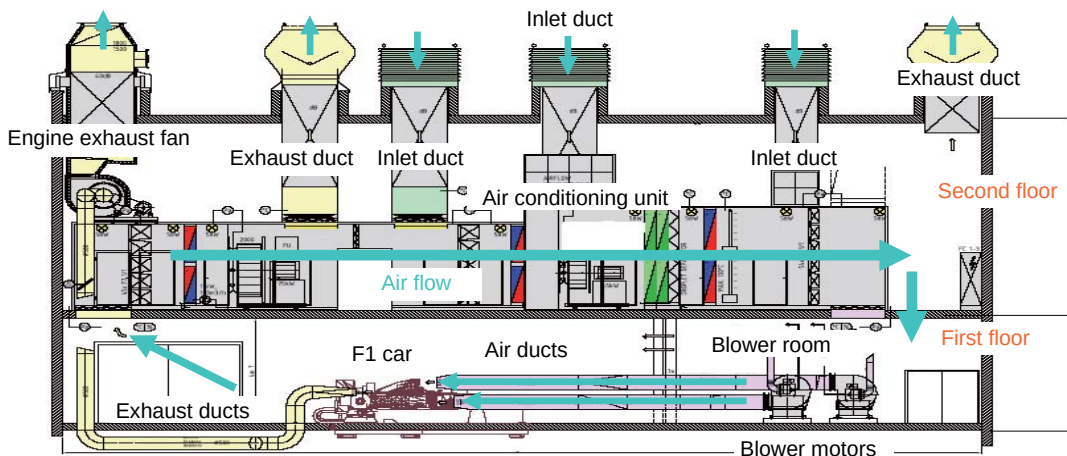


Fig. 1 Section view of RV bench

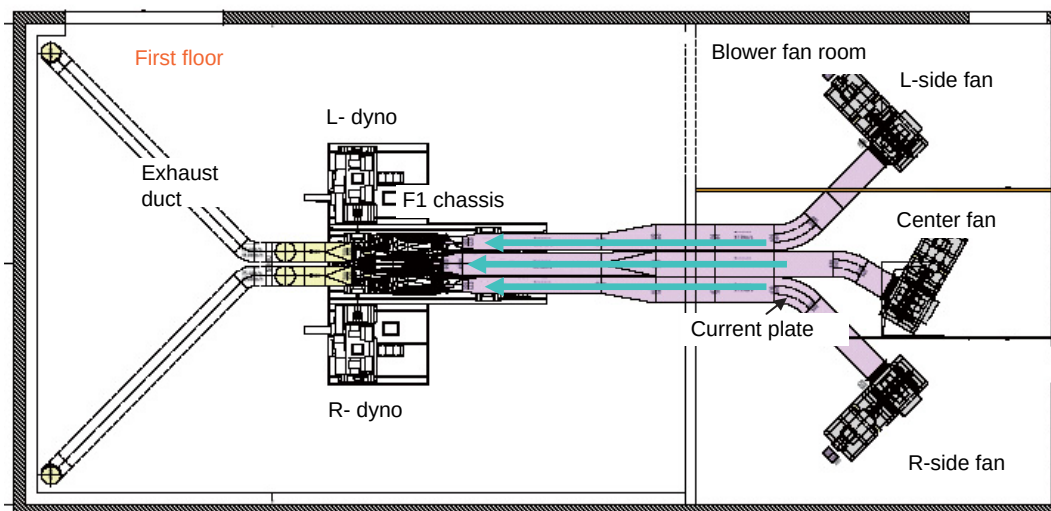


Fig. 2 Top view of 1F test room

Table 1 Control range

Windspeed	0-360 km/h (Max 380 km/h)
Acceleration and deceleration	Max 4.0 G
Temperature	10-40 °C
Humidity	30-90% (Rh)

Table 2 System specifications

<Dyna motor>

AC-motor mass Inertia	0.767 kgm ²
M dnom	2,000 rpm
P mon	400 kW
N max	3700 rpm

<Gear box>

Max input speed	22000 rpm
Transfer power	400 kW × 2 (Max 800 kW)
Gear ratio	9
Inertia	0.015 kgm ²
Acceleration	130000 rpm/sec
Control speed	9 kHz cycle

were controlled. The equipment was centrally controlled from an operating panel and a control panel, enabling wind speed, temperature, humidity, transient speed, and exhaust duct air flow to be controlled collectively.

The equipment was linked to an engine-side dyno controller and a vehicle simulation, creating a system in which a vehicle's wind speed could be varied in response to vehicle speed during a circuit driving simulation. The system was able to reproduce the atmospheric conditions of all the circuits used in Formula One racing. Table 1 shows the control range for the system.

2.2. Ultra-low Inertia Dyno Equipment

If the system was able to operate in circuit driving modes, it would become possible to conduct control system development, previously only possible using running tests, in a more concentrated manner. This would enable a consistent development process, in which control system development would be conducted following the evaluation of hardware and devices.

Ultra-low inertia dyno equipment displaying identical inertia characteristics to the drivetrain of an actual vehicle was introduced to the system to enable circuit driving modes to be realized. Table 2 shows the specifications of the AVL-manufactured equipment.

3. Correlation with Circuit

3.1. Pressure Distribution at Air Box Inlet

The wind simulator produced a uniform distribution of wind speed in the air ducts. However, under actual driving conditions, the pressure distribution at the air box inlet is not uniform, and it was necessary to reproduce this condition in the bench tests. Naturally, the ideal situation is to ultimately render wind speed uniform.

In order to achieve a correlation between the wind speed distribution during circuit driving and in the RV bench, airspeed was measured by taking measurements of the pressure distribution at the air box inlet using a pitot tube sensor (Fig. 4).

It was determined that the wind speed distribution in the RV bench was changed by 1) the vehicle's windscreen, and 2) changes in the air flow produced by the driver's helmet.

The effect of these factors on pressure distribution and engine output was analyzed in order to enable the pressure distribution in the RV bench to be correlated with the pressure distribution during actual driving.

Figure 5 shows the complete RV bench test room, and Fig. 6 shows the total pressure distribution at the air box inlet.

When the total pressure distribution during actual driving at an engine speed of 18500 rpm and vehicle speed of 300 km/h [total pressure distribution (a)] was compared with the total pressure distribution in the initial RV bench under the same conditions [total pressure distribution (b)], it was discovered that while the total pressure distribution at the air box inlet in the RV bench was uniform, part of the lower section of the air box displayed a lower pressure during actual driving.



Fig. 4 Pitot sensor position

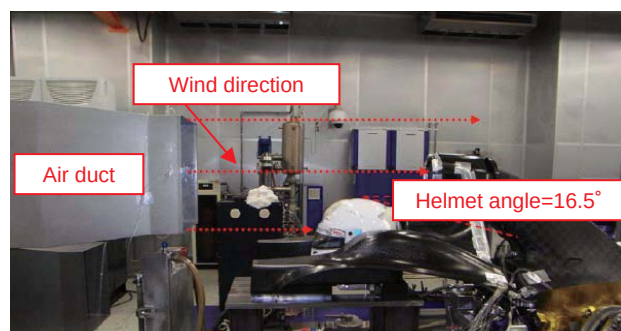


Fig. 5 View of RV bench test room

One difference between actual driving conditions and the RV bench was the windscreen used on the vehicle. The windscreen, a plate that sits at the front part of the cockpit and blocks wind, is shown in Fig. 7.

A dummy windscreen that produced the same effect as the actual windscreen and a vertical fin were positioned at the outlet of the RV bench (Fig. 8), and measurements were taken. The total pressure distribution under these conditions [total pressure distribution(c)] reproduced the lower pressure in the lower section of the air box, indicating that the system was now able to simulate actual driving conditions.

Next, in order to determine the effect of the total pressure distribution at the air box inlet on engine output,

comparative tests were conducted on the initial RV bench (b) and the RV bench following modification (c). At vehicle speeds of 240 km/h or more, there was a difference of 6 kW in output, equating to a difference of 0.12 sec in lap times. In order to correct the uneven pressure distribution, consideration of the vehicle shape and positioning of the roll hoop were important factors in addition to the shape of the air box.

3.2. Change in Amount of Fuel Compensation between Cylinders in relation to Vehicle Speed

Given the fact that optimization of the air/fuel ratio in each of the cylinders will increase power, fuel compensation values have been studied using conventional bench testing equipment, and refined on the circuits used for Formula One races. The system discussed here, however, enabled simulation of atmospheric conditions and maximum vehicle speeds, and thus did away with the necessity for refinement of fuel compensation values on actual circuits. This enabled the person-hours necessary for formulating settings to be

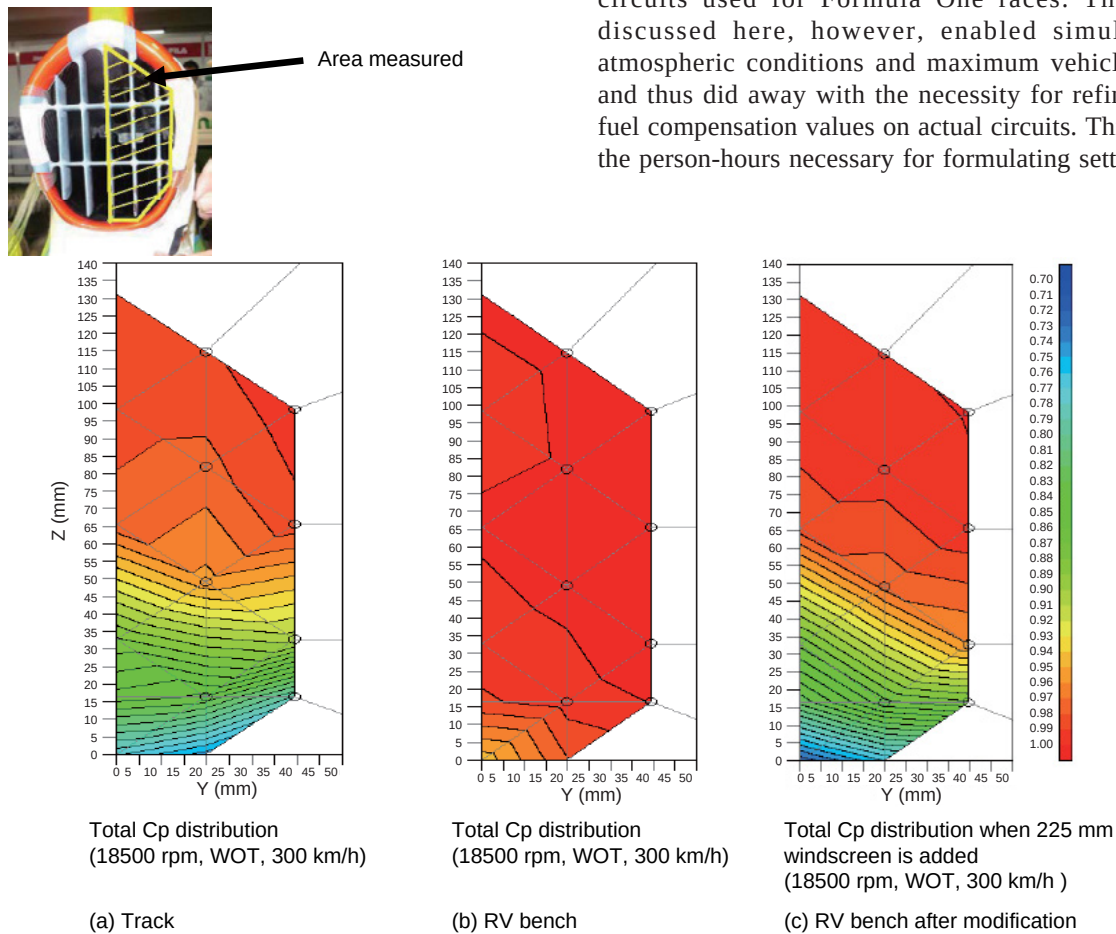


Fig. 6 Total Cp at inlet air box

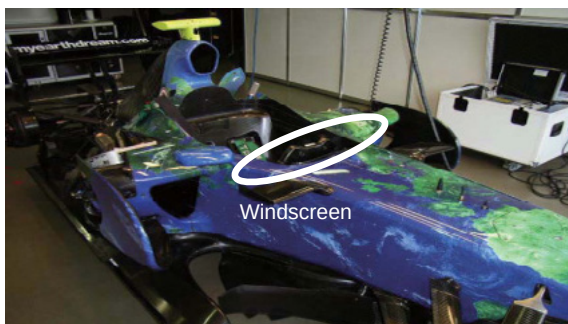


Fig. 7 Windscreen

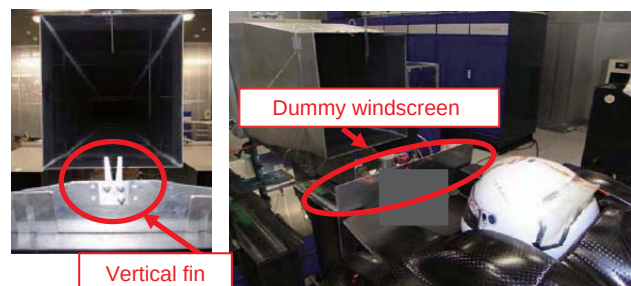


Fig. 8 Vertical fin and dummy windscreen

reduced and data for pit strategy, such as the amount of fuel to be carried by the vehicle, to be formulated in a more timely fashion. Figure 9 shows the fuel compensation values for each cylinder resulting from different ram pressures. The cylinders are compared at vehicle speeds of 120 km/h and 340 km/h, with engine speed set at 18500 rpm. On the low vehicle speed and high vehicle speed sides, increases in ram pressure result in changes in the flow of air in the air box, and the fuel allocation to each cylinder (fuel compensation) therefore also changes. As a result, the fuel compensation values for the forward cylinders (#1, 2, and 5), which receive minimal air intake at 120 km/h, increase by 2-4% at 340 km/h. Fuel compensation increases output by 3 kW.

3.3. Effect of Intake Air Temperature in Engine Cowl

A monocoque used in an actual vehicle was placed in the RV bench, and temperature measurements were conducted in the air box and the engine cowl. Measurements were taken of the:

- (1) Temperature of the intake air at the air box inlet
- (2) Temperature distribution inside the air box
- (3) Temperature distribution around the bulkhead
- (4) Temperature distribution around the rear of the engine
- (5) Temperature distribution of the pneumatic air cylinder
- (6) Temperature distribution around the oil cooler
- (7) Temperature distribution around the radiator

Figure 10 shows the interior of the air box.

The temperature distribution in the air box (Fig. 11) was the point of focus among the measurement results. The results showed that the temperature at the front of the air box was 8 °C higher than the temperature at the rear. The cylinders at the front were taking in higher temperature air than the cylinders at the rear.

This was a phenomenon that could not be reproduced without using a monocoque and engine cowl in the system; the use of an engine in isolation in bench tests

was insufficient to reproduce the temperature environment of an actual vehicle.

The results of analysis of the temperature increase in the front of the air box showed that the increase was synchronized with changes in the oil temperature in the oil tank positioned between the engine and the bulkhead rather than radiant heat from the engine and the exhaust pipe, and the front of the air box was thus being affected by heat from the oil tank.

The fact that the bulkhead was an enclosed structure with no channels for cooling air resulted in an increase in the temperature of the front wall of the air box, and a consequent increase in the temperature of the intake air. Results showed that the temperature of the wall reached 90 °C.

To help resolve this issue, a duct for cooling air was added between the bulkhead and the engine.

As Fig. 12 shows, this enabled cooling air to flow around the oil tank and between the V-banks, reducing the temperature of the air box wall to 45 °C and the temperature of the intake air at the front of the air box by 6 °C.

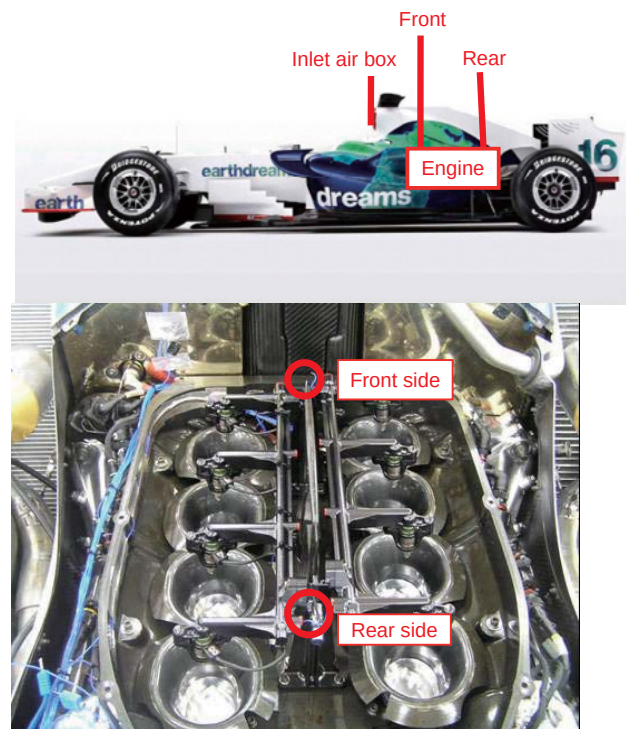


Fig. 10 View of engine cowl and air box

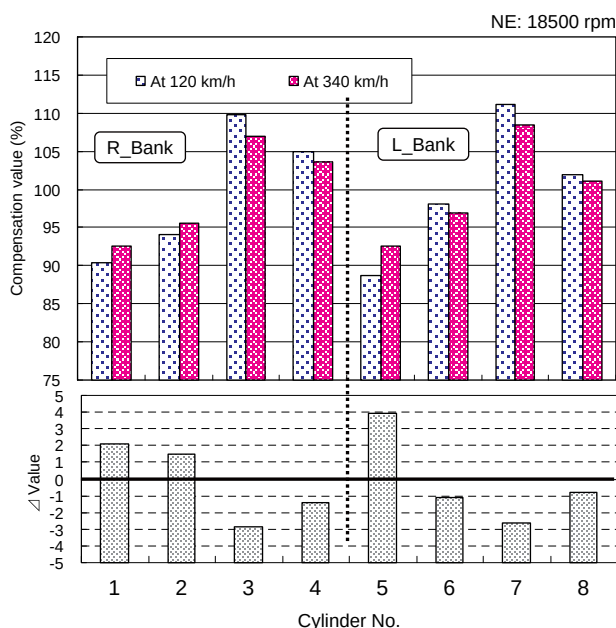


Fig. 9 Speed-fuel distribution for each cylinder

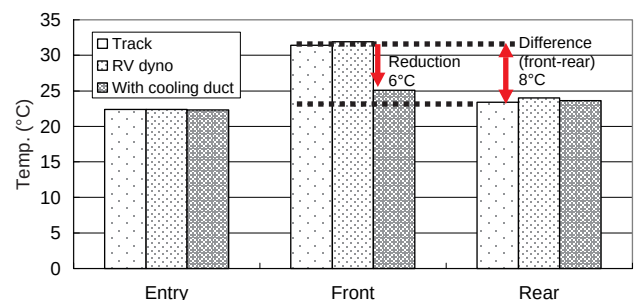


Fig. 11 Temperature distribution in air box

Because, based on the regulations, Formula One engines have not been able to employ variable induction systems from 2006, when these types of changes occur in the temperature of the intake air, the engine speed for peak output changes. An increase in the temperature of the intake air may reduce intake efficiency and become a factor in reducing output.

Heat insulating sheets were tested as a measure against radiant heat, but it was found that temperature increased over time, and that the sheets had no effect in 10-lap mode.

Scavenging by the cooling duct would be an effective measure, but it would be necessary to study the shape of the cooling duct with consideration of its effect on the aerodynamic performance of the vehicle.

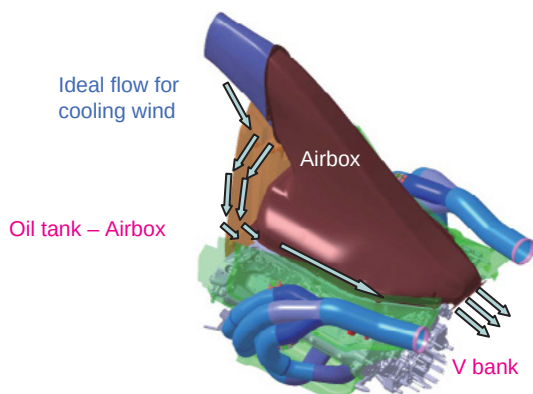


Fig. 12 Cooling duct (ideal flow)

4. Substitution of Data in the System

The RV bench enabled data for settings measured in running tests to be verified in bench tests. The following items were substituted in bench tests:

- (1) Pressure and temperature measurements from new vehicle shakedown
- (2) Radiator and oil cooler function checks
- (3) Verification of vibration and heat damage (verification of reliability of parts)
- (4) Verification of performance in relation to atmospheric conditions and ram pressure
- (5) Verification of performance and reliability of electrical system
- (6) Evaluation of drivability using vehicle simulation
- (7) Evaluation of lap time, evaluation of fuel efficiency
- (8) Settings for control data
(race start, traction control, torque mapping for each circuit)

5. Conclusion

- (1) A wind simulator (ram pressure generator) and a vehicle simulation system with circuit driving modes were developed, and used to reproduce engine intake phenomena during circuit driving on the bench.
- (2) The establishment of a correlation between circuit driving and bench test conditions enabled the length of time necessary for air box development, the formulation of settings for fuel compensation between cylinders, the selection of intake pipe length, and other tasks to be reduced.
- (3) The use of a monocoque vehicle in the system enabled the effects of heat damage to be verified, contributing to the achievement of increased power in actual race vehicles.

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