

Underhood Air Duct Design to Improve A/C System Performance by Minimizing Hot Air Recirculation

Xu Song, Ryan Fortier, and Scott Sarnia
Hyundai-Kia America Technical Center Inc

ABSTRACT

The underhood hot air recirculation greatly impacts A/C system performance at idle and low vehicle speed conditions. The hot air recirculation can raise condenser inlet air temperature in some cases as much as 18°C above ambient, which lowers condenser cooling capacity and increases compressor work. Underhood airflow research in the following study suggests that a properly designed air duct is able to minimize hot air recirculation and improve the Compressors Coefficient of Performance (COP) at idle by 27%. This paper discusses underhood hot air recirculation testing methods, airflow distribution, air duct design concepts, as well as the cross wind and wind tunnel effects. This dedicated air duct design indicates it should improve A/C emissions, which could contribute to meeting the Environmental Protection Agency's (EPA) Green House Gas Emissions Regulations in North America.

CITATION: Song, X., Fortier, R., and Sarnia, S., "Underhood Air Duct Design to Improve A/C System Performance by Minimizing Hot Air Recirculation," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(1):2015, doi:10.4271/2015-01-1689.

INTRODUCTION

The maximum refrigeration capacity of production vehicle A/C system is typically designed for the worst case conditions, such as A/C Idle and City Traffic in extreme hot environment, for instance in Death Valley or Las Vegas during the summertime. During hot weather idle and City traffic driving cycles, the underhood cooling airflow management is one of greatest design challenges to achieve max A/C performance requirement without oversize A/C components.

Song et al [1] described an airflow bypass channel in a simple underhood airflow model as showed in Figure 1. According to this model, when vehicle speed is below a threshold, the ram airflow is too low to create positive static pressure in the plenum between the grill opening and condenser core, and the negative static pressure generated by cooling fan can bring a certain amount of hot air from engine bay to plenum via the bypass channel. This phenomenon of hot air moving from engine bay to plenum is underhood hot air recirculation. The common engineering practice to overcome hot air recirculation impact is to increase condenser size, compressor volume and compressor speed and use some simple foam or baffles to limit the hot air recirculation. Although this remedy can stretch the system to meet A/C performance requirements during idle and city traffic driving cycles, it increases vehicle cost, weight and fuel economy. Song et al suggested that eliminating the bypass channel was the most effective engineering solution. This not only minimizes hot air flow recirculation but also improves underhood airflow cooling efficiency [1].

Mathur applied air guides and seals in 12 production vehicles to close airflow bypass channels and then examined condenser and radiator cooling performance improvement through climate wind tunnel tests.

It was reported that this lowered the HVAC vent outlet temperatures by 1~3.5°C, cabin temperatures by 1~3°C, and to reduce head pressures by 30~77 psi. In addition, the recirculation of hot air temperature in engine compartment dropped approximately 14°C [2].

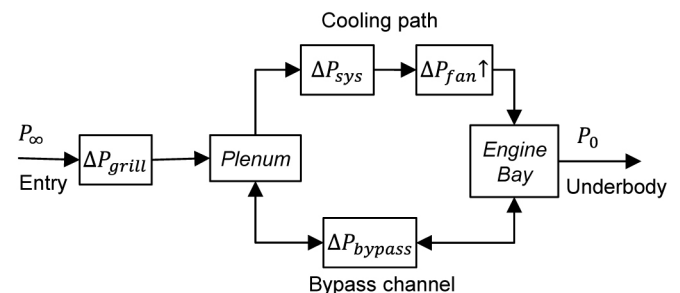


Figure 1. Underhood airflow bypass channel schematics

Lan et al conducted underhood airflow management improvement research with 3D CFD simulation and vehicle testing. The author reported that sealing around cooling package helped to reduce air temperature entering condenser at idle [3].

In the past several years, the thermal system engineering team at Hyundai America Technical Center, Inc. (HATCI) has been utilizing anemometer grid (Figure 2a) and CFD simulation (Figure 2b) for underhood airflow cooling research. Since the underhood recirculated airflow at idle or low speed condition is too complex to be determined directly through static pressure, air speed or other measurement methods, the combination of these two methods helps to understand underhood recirculation rational. Based on physical measurement data from anemometer grid and CFD simulation analysis, the relationship between the airflow rate at radiator core face

and the airflow rate at grill opening was established. As demonstrated in Figure 3, when this particular vehicle speed is below 40kph, the airflow rate at radiator core face will be greater than that at grill openings. The airflow difference is caused by recirculation. Although this approach is able to analyze recirculation condition, the process itself takes too much effort in anemometer grid instrumentation and CFD modeling. Therefore, a simple way to evaluate hot air recirculation is to measure condenser airflow inlet temperature. An air temperature rise at the condenser inlet indicates hot airflow recirculation and the amount indicates the severity of recirculation and impact to the A/C system. The 7×4 thermocouple (T/C) grid was designed (See Figure 4) and was instrumented at the upstream and the downstream of condenser. The T/C grid design not only provides sufficient data for color map resolution, but also can capture a detailed footprint of refrigerant condensation, phase change and sub-cooling stages.

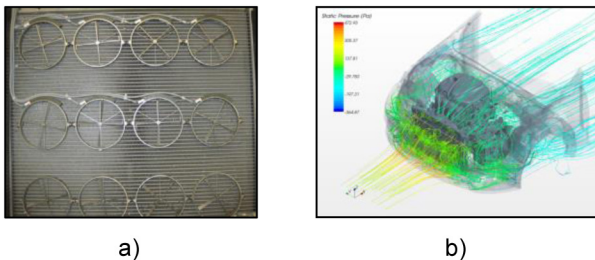


Figure 2. a) Anemometer grid to measure condenser airflow speed; b) CFD simulation to calculate airflow recirculation

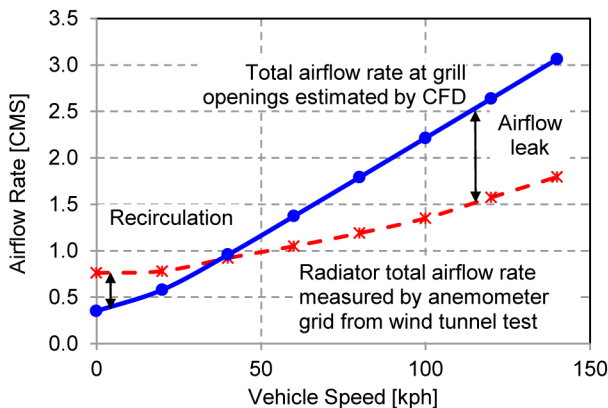


Figure 3. Underhood airflow study from a similar vehicle demonstrated bypass airflow effect: the actual airflow across radiator is greater than grill opening airflow at low vehicle speed, but is less at high vehicle speed. Fan speed was set at ~2100 RPM during the testing and simulation

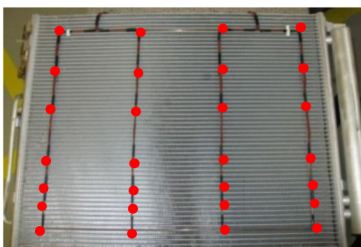


Figure 4. The 7×4 T/C grid is instrumented in front of condenser and behind condenser to measure condenser upstream and downstream airflow temperatures

This paper discusses a new method to determine hot air recirculation severity based on condenser inlet airflow temperature measurement data. Then based on averaged condenser air inlet temperature and A/C performance, the air duct design and function are compared to baseline production vehicle. Crosswind effects in climate wind tunnel and real world are also reviewed to discover air duct application feasibility under various environments.

HOT AIR RECIRCULATION ESTIMATION

The simple way to estimate hot air recirculation severity is to use weighted temperature average value. If T is the averaged air temperature at condenser inlet, then T is defined as

$$T = \frac{M_{amb}T_{amb} + M_{Rec}T_{Rec}}{M_{amb} + M_{Rec}} \quad 1)$$

Where, M_{amb} is the mass airflow rate of fresh air from ambient; M_{Rec} is the mass airflow rate of hot air from engine compartment; T_{amb} is the temperature of fresh air from ambient; T_{Rec} is the temperature of recirculated air from engine compartment. Rewrite equation 1 to following:

$$T(M_{amb} + M_{Rec}) = M_{amb}T_{amb} + M_{Rec}T_{Rec} \quad 2)$$

Regroup equation by factoring airflow rates:

$$M_{amb}(T - T_{amb}) = M_{Rec}(T_{Rec} - T) \quad 3)$$

The ratio of recirculated hot air to fresh cold air is expressed as:

$$\frac{M_{Rec}}{M_{amb}} = \frac{T - T_{amb}}{T_{Rec} - T} \quad 4)$$

Moreover, the percentage of recirculated hot air in total condenser cooling airflow is defined:

$$\frac{M_{Rec}}{M_{amb} + M_{Rec}} = \frac{T - T_{amb}}{T_{Rec} - T_{amb}} \quad 5)$$

To apply this method for evaluating the underhood hot air recirculation, it is required to collect the averaged condenser air inlet temperature data from a grid of thermocouples at condenser airflow inlet, as well as ambient air temperature and engine compartment air temperature.

It is noticed that Equation 5 only estimates a rough percentage of recirculated hot air to total condenser cooling airflow. It doesn't determine the actual airflow rates. Therefore, a grid of anemometers or other meaningful measurement methods are still necessary in obtaining actual total cooling airflow rate from which recirculated hot airflow rate can be estimate. Furthermore, this estimation method separate structural heat transfer from, such as hot bumper beam.

effect or air duct wall heating effect, from direct hot air recirculation. Therefore, Equation 5 may be applied to compare thermal insulation abilities of different air duct design.

BASELINE VEHICLE HOT AIR RECIRCULATION

The A/C maximum performance (A/C max) test is initially designed to test maximum heat loads for vehicle cabin interiors using a repeatable driving cycle, from which A/C system cooling capacity requirements can be defined. The A/C max testing is conducted in a climate wind tunnel at 45°C ambient by 45% Relative Humidity with 1000W/m² of solar Load. The vehicle runs for 20 min at 120kph and then the speed is decreased by 20kph for every 20min down to 0kph (as showed in Figure 5). The HVAC settings are high blower, full cold, outside air and vent mode. The wind tunnel used for baseline steady cool down test has relatively small internal dimensions of L9.0m × W7.4m × H4.2m. It is labeled as WT-A to distinguish another large scale wind tunnel, labeled as WT-B used in this paper.

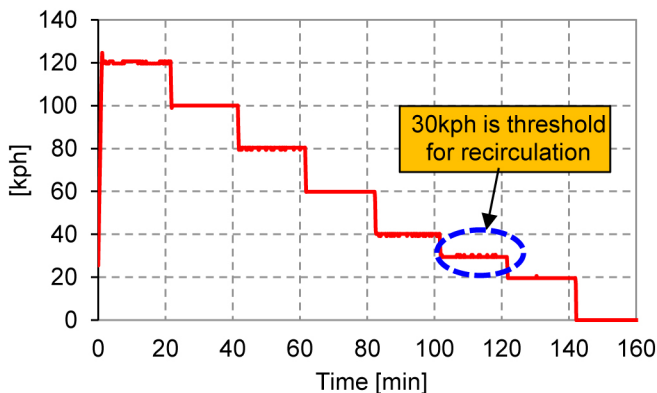


Figure 5. Vehicle speeds during steady cooldown test

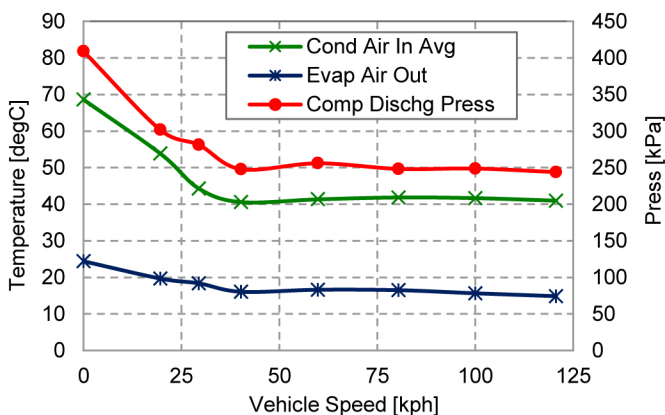


Figure 6. Condenser cooling airflow averaged temperature, evaporator discharged airflow temperature and compressor discharge pressure indicate that hot air recirculation threshold is 30kph

The data shows that the A/C performance starts to degrade at or below 30kph (See Figure 4) where averaged condenser air inlet temperature rapidly rise from an ambient of 40°C up to 68°C and results in refrigerant pressure jump and evaporator cooling ability

drops (showed in Figure 6). Based on underhood airflow recirculation model, the vehicle speed of 30kph is the threshold that hot airflow recirculation occurs for this particular vehicle.

AIR DUCT SEALING DESIGN AND EVALUATION

Sealing plenum from grill to condenser core face is an effective method to reduce underhood hot air recirculation. In this research project, an air duct is built from plastic board and all hard edges are wrapped with dense foam strips to form tight seals at contacts to facial, bumper beam and other body surface (See Figure 7). The air duct presents ideal production intent design which is expected to minimize hot air recirculation as much as possible. However, air duct sealing cannot stop heat transfer through vehicle structures, such as air duct wall, bumper beam and fascia. These structure surfaces can possibly be heated up by engine compartment hot air and indirectly impact condenser cooling air temperature. In addition, many small gaps among bumper, bumper beam and fascia, as well as hollow channels of bumper beam also allow a small amount of hot air recirculation to occur.

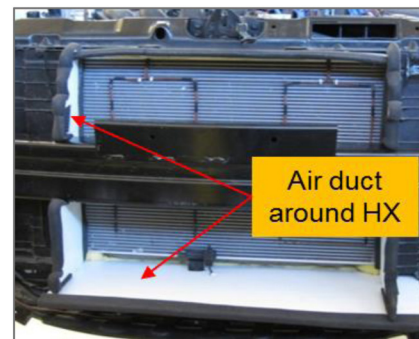


Figure 7. Underhood Air Duct sealing design

The baseline vehicle A/C max test data has showed that hot air recirculation at idle condition has the worst impact to A/C performance. Therefore, the idle condition was tested in climate wind tunnel WT-A to compare underhood hot air recirculation effect to A/C performance between production baseline and underhood sealed with Air Duct. During these wind tunnel tests, the chamber conditions are the same as described earlier. In addition, during this idle test, no wind condition was applied (crosswind study is discussed later). To evaluate underhood airflow sealing benefits, averaged condenser inlet air temperatures, refrigerant state points, system heat transfer and COP were analyzed.

The averaged condenser inlet air temperature was determined by the T/C grid at the condenser inlet. Figure 8 shows that the averaged condenser inlet airflow temperature of the production vehicle jumps rapidly in the first 2 minutes after the A/C compressor engages and rises to 68°C in 18 minutes. In contrast, Air Duct sealing dramatically lowers condenser cooling airflow temperature by 14°C. Based on Equation 5, it estimates that hot air recirculation is reduced from 36% (production vehicle) to 15% (air duct design), which is 21% improvement.