

A New Approach to Analyzing Cooling and Interference Drag

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ABSTRACT

This paper presents a new approach to analyzing and developing low-drag cooling systems. A relation is derived which describes cooling drag by a number of contributions. Interference drag clearly can be identified as one of them. Cooling system parameters can be assigned to different terms of the relation, so that differences due to parameter variations of the individual drag contributions can be estimated.

In order to predict the interference-drag dependency on the outlet location and the local outlet mass flow, an extensive study on a standard BMW sedan has been carried out, both experimentally and by CFD. The results show the importance of providing consistent outflow conditions which take into account the outlet location and flow direction, in order to minimize cooling drag.

INTRODUCTION

COOLING AIR FLOW - INTERNAL FLOW ANALYSIS

In reducing the aerodynamic drag of a passenger car the cooling airflow is known to have significant influence, its contribution ranging approximately from five to ten percent [1]. A large number of geometrical parameters, such as inlet/outlet locations, sizes and outflow directions, define a cooling system and affect cooling airflow. Even within a given package, this variety renders the task of finding an optimal solution with respect to cooling requirements and minimum drag contribution very complex.

Cooling air flow is typically enforced by the suitable location of inlets and outlets of the system, so that a pressure gradient ensures air supply. If possible, the support by an electrically-powered cooling fan is avoided. In any case, the cooling airflow produces losses by friction on surfaces inside of the cooling duct, especially within the radiators, which increase with the mass flow. Therefore, the limitation of the cooling-air mass-flow is a standard requirement in designing aerodynamically efficient cooling systems, even if active or passive air throttles are not considered.

Losses in the cooling-air duct can be described with an extended Bernoulli's Equation, in which all viscous effects are collected in an additional loss term, and in which the flow is considered as incompressible:

$$\frac{\rho}{2} \bar{v}^2 + p - \Delta p_{\text{losses}} = p_{\text{tot}} - \Delta p_{\text{losses}} = \text{const.} \quad (1)$$

Equation (1) facilitates the analysis of total pressure along one or multiple cooling-air streamlines. Figure 1 has been created as a total pressure average of several thousand cooling air streamlines taken from the CFD simulation of a BMW sedan at high velocity. The flow enters the cooling-air duct with maximum total pressure and exits with significantly reduced values, which are usually altered by mixing with the surrounding external aerodynamic flow. As can be seen in Figure 1, there are large total pressure losses at the air inlets, grilles and especially at the radiators.

<figure 1 here>

If only the radiators are included in an analysis, as done by Jones [2], it can be found that the total pressure drop is an approximate function of the square of the through-flow velocity. Installed inside a car, the cooling air mass flow is typically reduced by a radiator with an increased pressure-loss characteristic. Therefore, a smaller mass flow results in lower flow losses at all other surfaces of the cooling duct and can lead to a lower cooling drag, as has been shown by Kuthada et al. [3]. By analyzing the effects of geometrical variations on cooling drag, Kuthada [4] recommends to take the effects on external aerodynamics into account.

Williams [5] investigates pressure losses from separate regions of the cooling duct and shows that the losses of the engine compartment are relatively small. This can also be seen in Figure 1. Beier [6] analyzes total pressure losses and cooling air mass flow of a BMW sedan at specific cross sections and at high vehicle speed. Variations of cooling-inlet geometries and grilles show a large influence whereas small effects result from variation of the shape and size of the engine block.

Wolf [7] uses a special formulation of the Bernoulli equation for the cooling air duct that is extended for the inclusion of power losses. Cooling air volume flow is introduced by the continuity equation, including radiator frontal area and cooling duct outlet area. By changing single or multiple parameters, such as total pressure loss, outlet pressure or outlet area, the effects on power losses and on volume flow are estimated. However, additional experiments raised some questions about the proposed combination of parameters.

Regarding body forces the airflow of a cooling air duct creates an internal aerodynamic drag that can be described as the x-component (direction of driving) of the integral of all surface-based stresses. In order to calculate this force with cooling air flow properties, the momentum equation is usually applied to a control volume enclosing all internal surfaces with inlets and outlets according to the interfaces to the external surfaces. Figure 2 shows an example of such a control volume.

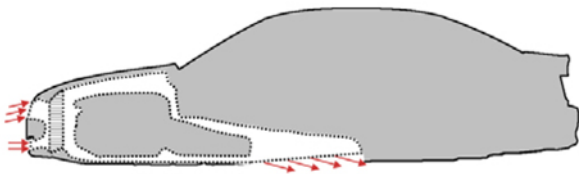


Figure 2. Control volume for determination of internal drag.

The momentum equation (2) is simplified by considering a stationary problem and by neglecting volume forces such as gravity. Equation (3) is the x-component of the momentum equation applied to a control volume as in Figure 2.

$$\iiint_V \frac{\partial(\rho \vec{v})}{\partial t} dV + \iint_S \rho \vec{v} (\vec{v} \cdot \vec{n}) dS = \iiint_V \rho \vec{f} dV + \iint_S [\vec{\sigma}] d\vec{S} \quad (2)$$

$$\begin{aligned} & \left(\iint_S (\rho \vec{v} \vec{n} dS) \cdot \vec{v}_x \right)_{in} + \left(\iint_S (\rho \vec{v} \vec{n} dS) \cdot \vec{v}_x \right)_{out} \\ &= \left(- \iint_S (p - p_\infty) n_x dS \right)_{in} + \left(- \iint_S (p - p_\infty) n_x dS \right)_{out} \\ &+ \left(\iint_S (-(p - p_\infty) + \tau_{xx} + \tau_{xy} + \tau_{xz}) n_x dS \right)_{interior_surf} \end{aligned} \quad (3)$$

The last term of equation (3) is the x-force acting on the fluid from interior surfaces. With an opposite sign, this is the internal drag. It can be seen that the internal drag does not only depend on the difference of entering and exiting momentum flux but also depends on the difference of pressure forces acting on the inlet and outlet areas. Assuming constant cooling air mass flow, a reduced outlet area typically results in a higher momentum outflux which is advantageous for a small internal drag. Additionally, if the pressure at the outlet location is exceptionally low, as it is in a wheelhouse, the internal drag is reduced.

Several theoretical investigations of the internal drag similar to this analysis using the momentum equation can be found in literature. One common example is the analysis by Soja and Wiedemann [8,9], where a control volume is chosen that expands upstream into the undisturbed flow. With an assumption for the upstream flow inlet area related to the projected outlet area, the internal drag is balanced against the situation without cooling flow.

Barnard et al. [10,11] use the formulation of Soja and Wiedemann to analyze effects of the variation of cooling-air outlet area and flow direction. For instance, an increased outlet momentum flux is targeted by reducing the outlet area. However, tests from Barnard et al. on a wind tunnel model primarily show a dependency on cooling air mass flow, so that drag changes can hardly be evaluated. By iteratively adjusting the radiator size, a combination of parameters is found that results in sufficient cooling mass flow and slightly reduced drag. Their recommendation is to adjust the cooling-air outlet to the mass-flow requirement in dependence on the current operating point.

Ivanic et al. [12] compare results from the momentum equation analysis for the cooling-air duct with wind-tunnel force results. Inlet and outlet areas, velocity directions, and positions are varied. Under the assumption of a constant cooling-air mass flow, noticeable differences of the results

are mainly attributed to interference effects between cooling air and external aerodynamics.

In summary, it can be seen that both ways to analyze the cooling air flow have their merits. With the application of the Bernoulli equation on CFD results the origins of flow losses inside of a cooling air duct can easily be located. The total pressure loss between inlet and outlet can be calculated to estimate the contribution to the car's aerodynamic power loss. To calculate the body force from the cooling duct, the momentum equation is usually applied to cooling air flow. Effects of variations of different cooling air flow parameters can be estimated thereupon. However, a fair comparison of different cooling air systems is only given if the mass flow stays constant. Additionally, exit losses from sudden flow expansion and interferences with external aerodynamics are not included in the analyses mentioned above, but will be part of the new formulation that is introduced in this paper.

One aspect of the application of Momentum Equation on cooling air, that is to be considered neither an internal nor an interference effect, is the influence of outlet size and position. The reduction of internal drag by downsizing the outlet area on surfaces with normal vectors in x-direction in a surrounding with low pressure creates new surfaces on the car exterior. The low pressure will act on them as well and will create an additional external drag that may compensate the internal drag change. Overall, the change of pressure by the cooling air flow will decide if drag can be reduced.

COOLING AIR FLOW - INTERFERENCE EFFECTS

Besides the common internal losses of cooling airflow and the internal drag of the cooling air duct, several indications of aerodynamic drag contributions are found in literature, that are supposed to originate from an interference of the entering and exiting airflow with the external aerodynamic flow of the car. However, the consideration of interference effects in the design of cooling air ducts has not become standard procedure yet. This is partly due to the fact that the interference drag lacks a common definition. Its contribution to the aerodynamic drag is part of the cooling drag, which is defined as the difference between the drag of a car with cooling air flow and the drag of a car without cooling air flow, [Equation \(4\)](#).

$$\Delta C_D = C_{D,w \text{ cooling air}} - C_{D,wo \text{ cooling air}} \quad (4)$$

<figure 3 here>

As it becomes apparent from [Figure 3](#), the cooling drag combines internal drag and interference drag, the latter commonly considered as the change of drag on external flow. To be determined is the exact handling of those additional

surfaces closing the body when there is no cooling air flow. Whether their contribution to aerodynamic drag is included in the interference drag needs to be assessed.

Even the measurement of the interference drag is problematic. In the wind tunnel, a separate acquisition of forces on interior and external surfaces would be necessary in order to separate effects. This may be the main reason why merely indications of interference effects are found in literature.

In an early experimental investigation of different cooling air ducts on a vehicle Buchheim et al. [13] observe large differences in drag. Even with the cooling-air mass flow changing between different outlet positions, some differences in drag cannot be related to internal drag changes. Especially the version with an outlet in front of the windshield shows a major reduction in drag, with only a minor reduction of cooling air mass flow.

Garrone et al. [14] present results of an extensive wind tunnel measurement campaign, where in addition to the standard wind tunnel scales there are internal scales installed on the car model that separate major vehicle areas from each other. It is possible to separate forces acting on the underbody with wheels and wheelhouses, on the upper external surfaces, and on the cooling air duct with outlets in the front wheelhouses. Additionally, in order to estimate the force acting on the vehicle's base, static pressure probes are installed. By comparing measurements with and without cooling air flow an interference drag can be calculated. The results also show that the traditional way of gaining the cooling drag, see [Equation \(4\)](#), is critical if there are major flow field changes when the cooling air flow is suppressed.

One of the most famous cooling air ducts using positive interference effects is the one from the 1996 Porsche 911 Carrera [15]. Its special characteristic is an outlet on the underbody just in front of the wheelhouse that acts as a spoiler lip. For the successor model, the outlet has been extended with an additional outlet inside the wheelhouse in order to gain cooling air mass flow [7].

Jehle [16] investigates cooling air systems with different outlet locations on a Mercedes coupe. After adjusting the porosity characteristics of the radiators in such a way that for each case a similar cooling air mass flow settles, interference effects of the outflow can be compared by approximation, while the internal drag varies. In some cases, an interference with the front wheelhouse flow results in low cooling drag values. An analysis of the cooling air streamlines on the vehicle exterior indicates areas where the flow field changes for the benefit of the cooling drag.

One way of dealing with interference drag is proposed by Williams [17]. In order to explain low values of cooling drag

measurements, additional terms in the cooling-air flow momentum equation for the inlet and outlet interference effects are introduced. By application of the momentum equation on different wind tunnel results it is concluded that the main reason for low cooling drag values is flow separations on the closed inlets that result in a positive interference effect when opened.

Several other authors notice interference effects when cooling drag is investigated. However, the lack of methods for analyzing and comparing cooling drag with respect to the origin of energy losses prevents a clear picture of the range of influence. This hinders the design and development of efficient, low-drag cooling air ducts.

COOLING DRAG FORMULATION

A new formulation of cooling drag is introduced in order to separate drag contributions from internal losses, the substitution of surface areas with inlets and outlets, and the interference effects. As usual, cooling drag is initially described by [Equation \(4\)](#).

The drag of the vehicle with cooling air flow is the x-component of the integration of surface-forces, [Equation \(5\)](#). Inner surfaces are separated from external surfaces. On the vehicle without cooling air flow, internal surfaces can be neglected (assuming that ambient pressure acts inside the isolated space) and substituted with the closed inlet and outlet surfaces, [Equation \(6\)](#). Surfaces labeled “external” are those that are no inlet and outlet surfaces when cooling air flow is suppressed.

$$D_{w \text{ cooling air}} = \iint_S ((-p + \tau_{xx})n_x + \tau_{xy}n_y + \tau_{xz}n_z) dS_{\text{interior_surf}} + \iint_S ((-p + \tau_{xx})n_x + \tau_{xy}n_y + \tau_{xz}n_z) dS_{\text{external}} \quad (5)$$

$$D_{w o \text{ cooling air}} = \iint_S ((-p + \tau_{xx})n_x + \tau_{xy}n_y + \tau_{xz}n_z) dS_{\text{cl.inlet/outlet}} + \iint_S ((-p + \tau_{xx})n_x + \tau_{xy}n_y + \tau_{xz}n_z) dS_{\text{external}} \quad (6)$$

In [Equation \(5\)](#) the drag of the inner surfaces can be expressed by flow properties on inlet and outlet locations through the momentum [equation \(3\)](#). In computing the cooling drag, the difference of the x-forces with and without cooling air flow is constructed. As a result, the cooling drag will be a function of flow properties on the inlet and outlet areas, as well as at the unchanged external surfaces. In summary, there are corresponding surfaces to integrate over when computing the cooling drag. The subtraction of terms,

according to [equation \(4\)](#), can be simplified by computing the difference of changing values inside integrals. This is shown in [Figure 4](#) and described in [Equation \(7\)](#).

<figure 4 here>

$$\Delta D = - \iint_S \rho v_x (\vec{v} \cdot \vec{n}) dS_{\text{inlet}} - \iint_S \rho v_x (\vec{v} \cdot \vec{n}) dS_{\text{outlet}} - \iint_S \Delta p n_x dS_{\text{inlet}} - \iint_S \Delta p n_x dS_{\text{outlet}} - \iint_S (\tau_{xx}n_x + \tau_{xy}n_y + \tau_{xz}n_z) dS_{\text{inlet/outlet}} + \iint_S ((-\Delta p + \Delta \tau_{xx})n_x + \Delta \tau_{xy}n_y + \Delta \tau_{xz}n_z) dS_{\text{external}} \quad (7)$$

The cooling drag, as described in [Equation \(7\)](#), first includes the difference of momentum flow between cooling air inlets and outlets. Internal losses, flow deflections and deceleration will alter this difference.

[Equation \(7\)](#) further includes the differences of pressure-based x-forces on inlet and outlet areas. If the local pressure is changed by opening the cooling air duct, there will be a difference. For example, a pressure rise on the outlet becomes significant if the outlet area contributes heavily to overall drag because of low static pressure and an x-aligned surface normal. Additionally, [Equation \(7\)](#) expresses the x-component of shear force acting on the closed inlet/outlet areas. In most regions of a vehicle surfaces shear forces are small compared to the pressure forces and may be neglected.

Finally the interference drag is clearly defined as the change of x-forces on external vehicle surfaces. Any change of the external air flow field will result in a stress change on some external surface. For example, if the exiting cooling air flow collides with an external surface, an increased drag will be originated on that surface.

The advantage of this formulation for the cooling drag is the separation into four main contributions, namely the momentum flow difference, the difference in pressure force on the inlet and on the outlet areas, and the interference drag. Even though a geometric parameter change on the cooling air duct can lead to multiple variations of cooling air contributions, some origins of physical effects that are mentioned above can be applied to certain contributions.

If CFD results of a vehicle with a certain cooling air duct are processed and compared to the results of the vehicle without cooling air flow, [Equation \(7\)](#) can be applied and the contributions to cooling drag can be calculated. Starting with such filtered information, optimization of a cooling air duct and its exiting flow becomes feasible. Plotting the contributions successively as bars, as it is shown in [Figure 5](#),

