

A Review of Some Cooling Air Flow Measurement Techniques for Model Scale, Full Scale and CFD

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ABSTRACT

Each component of a drive train generates waste heat due to its limited efficiency. This waste heat is usually released to an air flow guided through one or more heat exchangers. So, the realized cooling air volume flow is one important characteristic value during the vehicle development process.

This paper presents some of the available techniques for the measurement of cooling air volume flow in the vehicle during the different stages of an aerodynamic development process in model scale and full scale. Additionally, it provides suggestions when comparing these experimental values to CFD results.

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INTRODUCTION

Most of today's passenger cars have the engine mounted in front of the passenger compartment. A standard cooling air flow system for such a car is positioned in the front with its air inlets positioned in the vicinity of the stagnation point and cooling air exits to the underfloor region and front wheelhouses. The flow through such a system is pressure driven by fan and ram air, starting with a high pressure due to the stagnating flow at the front of the vehicle and the energy added by the fan. After entering through the air intake grills, the flow loses energy due to turbulence, friction and to the pressure loss of the heat exchangers [1]. Depending on the vehicles features and the engine type, different kinds of heat exchangers can be found in a vehicle ranging from AC-condenser, charge air coolers to different types of radiators for the engine coolant.

Traditionally, the measurement of cooling air flow concentrates on the radiator, although most of the presented methods can also be used for other heat exchangers. The measurement usually takes place directly at or in the relevant heat exchanger. Measurement techniques for the determination of air flow entering the grille will not be considered, since this value can significantly differ from the flow passing the respective heat exchanger due to leakage flows around the heat exchanger package.

COOLING AIR FLOW MEASUREMENTS IN FULL SCALE

Since there are only a few methods to measure the integral value directly and most of these methods are integrating over a number of spatial samples, here, the techniques are subdivided by the measurement technique itself. The respective measurement techniques are either anemometer based (air vane anemometers or constant temperature anemometers) or pressure based. First, the influence of sample numbers will be discussed.

Influence of Spatial Sampling

The spatial sampling has to be considered thoroughly, since the discretization of the radiator surface can have a significant influence on the measurement results. The flow inhomogeneity I can be used to analyze the influence of the number of probes [2]. I is defined as

$$I = \frac{\sqrt{\frac{1}{n}(\sum_{i=0}^n (v_i - \bar{v})^2)}}{\bar{v}} \quad (1)$$

and represents the standard deviation of local flow velocities in the radiator v_i with respect to the average velocity $\bar{v}$.

Figure 1 shows for a virtual test case (CFD results with virtual probes) the differences in flow inhomogeneity and cooling air flow as a function of the used, evenly distributed probes referred to a maximum resolution of 100 probes. The decrease in flow inhomogeneity (right axis) with smaller probe numbers results from a reduced capability to resolve

local gradients. The determined cooling air flow (left axis) with more than 60 spatial samples for a standard passenger car radiator shows a deviation below 3% [3]. Similar results have been published by the author in [2].

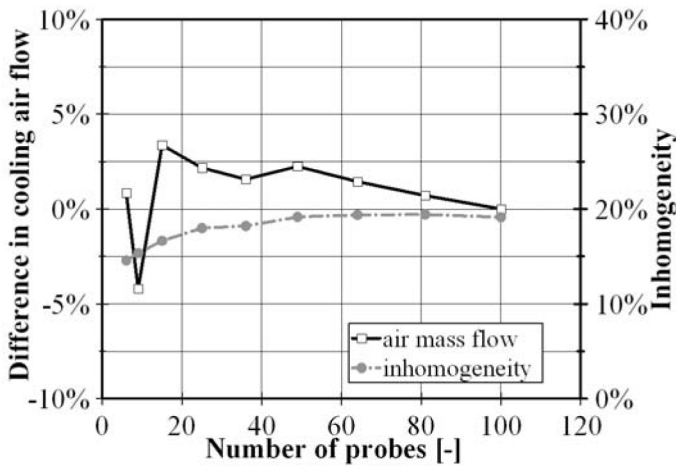


Figure 1. Difference in cooling air volume flow (left axis) referred to 100 probes and flow inhomogeneity as a function of the number of probes. Results are based on a virtual test case at 140 km/h [3].

Anemometer Based Techniques

Based on reports in the literature, the use of different anemometer types for measuring airflow in the vicinity of a radiator will be summarized in the following.

Hot film / hot wire anemometers

In hot wire anemometers, a small wire is heated up to above ambient temperature by an electric current. The airflow around the wire results in a lower temperature due to forced convection. Since the resistance of the wire changes with temperature, the resistance of the wire can be taken as a measure for the flow speed [4]. With a high sampling rate and due to the thinness of the wire, these sensors are good for measuring turbulent flow fluctuations. On the other hand, the wire is sensitive and even dust particles can break it and destroy the sensor. Hot film anemometers are small ceramic elements coated with a metal surface working with the same measurement principle. Compared to hot wire anemometers, they are less sensitive against destruction but their ability to measure turbulent fluctuations in the flow is also reduced.

Ambros [5] used a vehicle-fixed traversing gear with eight hot film anemometers, which were moved in equidistant steps in a plane between the ac-condenser and the radiator. These hot film anemometers of type FlowMaster 54N60 are robust enough for the usage in the underhood region with the benefit to measure the flow velocity and temperature simultaneously. However, the lack of ability to measure flow direction and parasitic errors from the cage around the sensors leads to measurement errors in the range of up to 70%. Additionally, the traversing gear was mounted on the

vehicle hood and fixed on the roof of the car, which made it impossible to measure the aerodynamic coefficients and cooling air flow measurements at once. A similar concept was pursued by Binner [6], who used ten hot wire anemometers mounted on a traversing gear in a location between the ac-condenser and the radiator. Despite the flow straightening effect of the radiator core, deviations between the measured and the prescribed volume flow were in the region of 20% to 60%.

Thibaut et al. [7] also described a traversing gear mounted behind the radiator moving 2 hot wire probes in a meandering pattern (see Figure 2). Thus, the complete radiator face can be reached to measure the local velocity. With a sampling rate of 1000 Hz the required measurement time for the radiator of a passenger car with $600 \cdot 10^3$ samples is approx. 5 min. The average velocity multiplied with the traversed area results in the cooling air flow. A clear advantage of this method is the high spatial resolution, which gives a good possibility to analyze the velocity distribution over the radiator. The deviation of the measured cooling air flow compared to a radiator test stand was determined within 2%. The disadvantage is that the water tanks of the radiator are damaged by mounting the traversing gear, which makes it impossible to measure during test drives. Additionally, operating the fan is not possible due to the resulting cross flow components, which reduce the measurement accuracy [8].

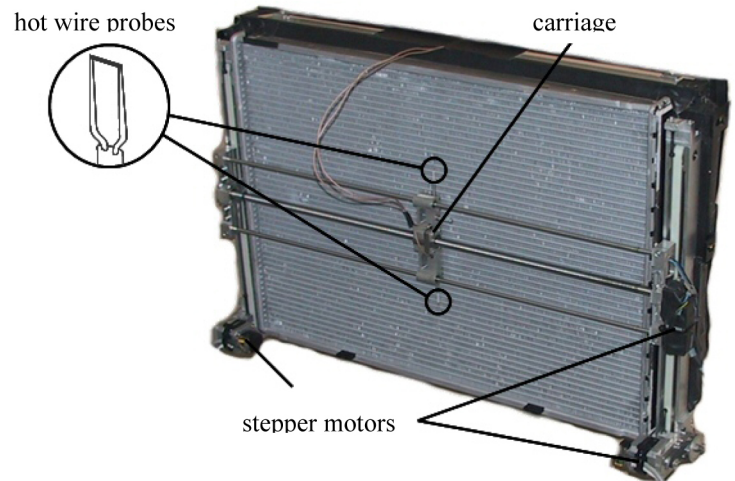


Figure 2. Radiator equipped with a traversing gear [7]

Another system based on the hot wire technology is the Thermal Transient Anemometer (TTA) presented by Foss [9, 10]. The system consists of several rectangular so-called sensing cells. Each sensing cell consists of a zigzag tensioned thin tungsten wire. For a typical vehicle radiator, 4×4 sensing cells are arranged in a frame and installed downstream of the radiator core. The TTA sensor wire provides a signal that is integrated over its length, which results in already averaged velocity values for each sensing cell. Due to its measurement principle, reverse flow cannot be

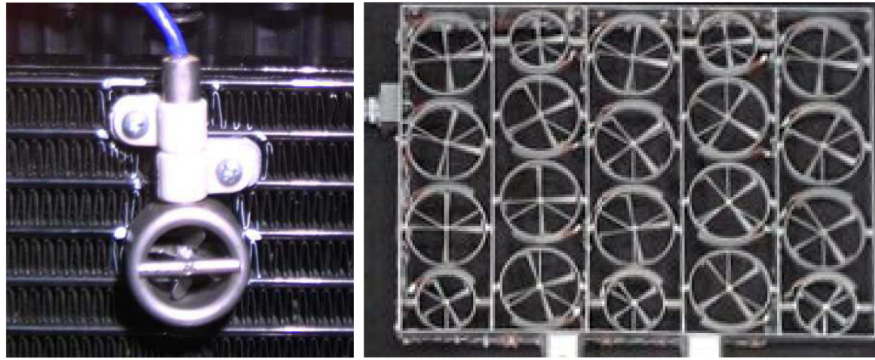


Figure 3. Single vane anemometer located on a radiator core (left) and frame with a set of anemometers [13] (right)

detected by the TTA. A comparison to test stand measurements has not been presented so far.

Burton [9] introduced a procedure with 160 NTC (negative temperature coefficient) sensors within a flow straightening device, which replaces the radiator core. NTC sensors represent a semi conductor element with a non-linear dependency between its temperature and its resistance. The sensors are low cost elements and therefore available in large numbers [12]. However, this method requires the replacement of the radiator core, which makes it impossible to determine the cooling air volume flow with running engine. Additionally, the pressure loss of the measuring insert requires it to be matched to the pressure loss of the radiator to avoid a mistuning of the cooling air flow system that could result in wrong cooling air flows compared to the actual system.

Vane anemometers

Vane anemometers are small propellers usually mounted in a circular housing, where the speed of the propeller rotation is used to determine the flow velocity [4]. Different type of vane anemometers for cooling air flow measurements are shown in Figure 3. Depending on the diameter of the vane anemometer, it can have an averaging function.

Herbig [14] used the traversing gear developed by Ambros [5] in combination with 6 fixed air vane anemometers to measure the cooling air volume flow. This approach again shows the above mentioned problems with a vehicle-fixed traversing gear. The usage of a fixed number of vane anemometers in fixed positions behind the radiator is reported from GM [15] and Ford [16]. The approach in presented in [16] consisted of 9 vane anemometers and 16 pressures probes mounted on the rear face of the radiator inside a rectangular fan shroud. This setup has been calibrated in a flow test stand to correct for areas not covered by the anemometers, overspeeding of the anemometers due to upwind effects of the fan and non-uniform velocity gradients due to shroud and fan. The achieved accuracy after calibration was about $\pm 2\%$.

Williams [17] reported the usage of a number of vertical aligned, specially designed vane anemometers, which are

moved by a small electric motor in a plane behind the radiator in ten different positions in front of the fan package. Depending on size of the radiator and the number of vane anemometers, this leads to a total number of 50 - 100 spatial samples. Comparisons with test stand measurements showed an accuracy of the setup of up to 3%.

Berneburg and Cogotti [18] introduced a system, where the radiator core has been replaced by a traversing gear with 11 vane anemometers. The pressure loss of the replaced radiator core is adjusted by sieves. The measurement accuracy of the system was not described. Due to the replacement of the radiator core, this system can only be used for aerodynamic measurements and not for thermal tests on road or in a wind tunnel.

Pressure Based Techniques

Pressure based techniques can be subdivided into two approaches. One approach is to measure the pressure loss over the radiator and calculate the velocity from the pressure loss curve of the radiator. Another approach is to determine the dynamic and static pressure inside the radiator core to calculate the respective air velocity.

Porsche [18] uses cylindrical pressure probes mounted directly in front of the radiator and on its the rear face (see figure 3 left) to measure the static pressure difference for the respective area (figure 3 right). The deviation of the measured value from the actual value is better than 3% [20].

A nearly similar approach was proposed by Ng et al. [21]. Pressure probes stuck from the opposite site of the radiator to match with the respective radiator face were arranged in pairs to determine the pressure loss over the radiator. However, there was no accuracy given for this method.

All pressure-based methods require pressure tubing, which can lead to a significant blockage of the radiator face and take therefore a strong effect on the pressure loss. Due to turbulence generators featured in today's automotive radiators to increase heat transfer, mixing and turbulence results inside the radiator core. Therefore it is questionable, whether the measurements are really taken on the same streamline, which is at least from a theoretical point a pre-requisite for this measurement approach.