

Force Based Measurement Method for Cooling Flow Quantification

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ABSTRACT

Quantification of heat exchanger performance in its operative environment is in many engineering applications an essential task, and the air flow rate through the heat exchanger core is an important optimizing parameter. This paper explores an alternative method for quantifying the air flow rate through compact heat exchangers positioned in the underhood of a passenger car. Unlike conventional methods, typically relying on measurements of direct flow characteristics at discrete probe locations, the proposed method is based on the use of load-cells for direct measurement of the total force acting on the heat exchanger. The air flow rate is then calculated from the force measurement. A direct comparison with a conventional pressure based method is presented as both methods are applied on a passenger car's radiator tested in a full scale wind tunnel using six different grill configurations. The measured air flow rates are presented and discussed over a wide range of test velocities. The advantages and draw backs of both approaches are compared and discussed in detail. The proposed method is non-intrusive, leaving the heat exchanger core intact, with no need for integration of measurement points over the core region. Due to the measuring principle, the load-cell method will inherently over-predict the air-flow rate. This error is quantified and an empirical correction function is investigated. This paper shows that the corrected force based method determines the air flow rate through a heat exchanger with an accuracy similar to that of traditional pressure/velocity methods while offering a considerable number of advantages.

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INTRODUCTION

Optimized heat exchangers are an essential part in most engineering systems. Different heat exchangers are commonly used to transfer heat from one coolant, which is typically a fluid running internally through channels, into another coolant, which is normally air flowing externally across the heat exchanger fins. A complicating factor in the optimization process is that in many technical applications, the heat exchangers are positioned in areas of complex flows. One example is the front heat transfer system of road vehicles, where the air flow rate through the compact heat exchanger core is optimized for minimum vehicle drag using both wind tunnel tests and Computational Fluid Dynamics(CFD) simulations. With the introduction of active aerodynamic devices such as grill shutters, this opens up the possibility to have variable control over cooling inlets and thus better control over cooling drag. In addition, modern design cycles require short lead time which calls for fast, accurate and simple methods to determine the air flow rate.

Traditional approaches for quantifying air flow rate through heat exchangers rely on measuring fluid properties such as pressure or velocity. Pressure measurements are commonly conducted using different types of Pitot tubes to determine local pressure drops across the heat exchanger from which the air flow rate can be determined. Alternatively, different types of Prandtl tubes can be used to measure local dynamic pressures, from which the air flow rate can be determined. Different experiments utilizing pressure based methods have been implemented [1, 2, 3]. Direct velocity measurements are also used for air flow rate quantifications; hot-wire anemometers or vane anemometers give the local velocities, from which the air flow rate can be computed by integration of local flow velocity. Several experiments exploiting direct velocity measurements have been published [1, 4, 5]. Combined methods have also been presented by Williams and Vemaganti [6].

These methods can be considered traditional approaches for air flow rate measurements through heat exchangers. These traditional approaches require several local measurement points, hence multiple sensor arrangements positioned on or close to the heat exchanger core

are used in order to obtain the velocity distribution over the core. Since there are gaps between the measurement points, integration over the core is required to calculate the air flow rate, this smooths out the velocity distribution and adds uncertainties to the final result. Moreover, heat exchangers are typically positioned in regions where a complex flow situation is prevailing, so external blockage from the equipment together with re-circulation across the core can have a significant influence on the accuracy of all pressure/velocity methods. In general, these methods are known to lack accuracy in low flow velocities and recirculating air flow.

This paper will explore an alternative approach for heat exchanger air flow rate quantification. Using load-cells, the total aerodynamic force acting on the heat exchanger core can be measured, from which total air flow rate can be calculated. This force based approach offers a number of benefits. The method is non-intrusive so the effect of external probe/wiring blockage is eliminated as well as the need for interpolation over the heat exchanger core area. Furthermore the effect of re-circulation and low flow velocities are included in the load-cell measurements, as the total force on the heat exchanger core is measured. To explore the functionality of the method in complex flow fields, this paper applies it to determine the air flow rate through a compact heat exchanger which is mounted in a passenger car vehicle. Also, a traditional pressure based method is applied simultaneously with the force based method, for comparison purposes.

THEORY

In the present approach, the total force acting on the heat exchanger is measured by load-cells located at the heat exchanger mounting points. Isothermal conditions are assumed and all velocities are well below a Mach-number of 0.3, so the fluid is considered incompressible with a constant density. The core area of the heat exchanger is also constant, so the volumetric flow rates, the mass flow rates, and the average core velocity, following the one-dimensional equation of continuity, are interchangeable variables with only constants separating them as expressed in [Equation 1](#).

$$\dot{m}_{core} = \dot{V}_{core} \times \rho = v_{avg_core} \times A_{core} \times \rho \quad (1)$$

where $\dot{m}_{core}$,

$\dot{V}_{core}$, and v_{avg_core} are, respectively, the mass flow rate, volumetric flow rate, and average velocity all through the core. A_{core} is the core area and ρ is the air density.

Moreover, the total aerodynamic force acting on the heat exchanger is equal to the product of the average pressure drop across the heat exchanger multiplied by the total surface area of the heat exchanger core, presented in [Equation 2](#).

$$F_{core} = \Delta P_{core} \times A_{core} \quad (2)$$

where F_{core} force acting on the radiator core and ΔP_{core} is the pressure drop across the core.

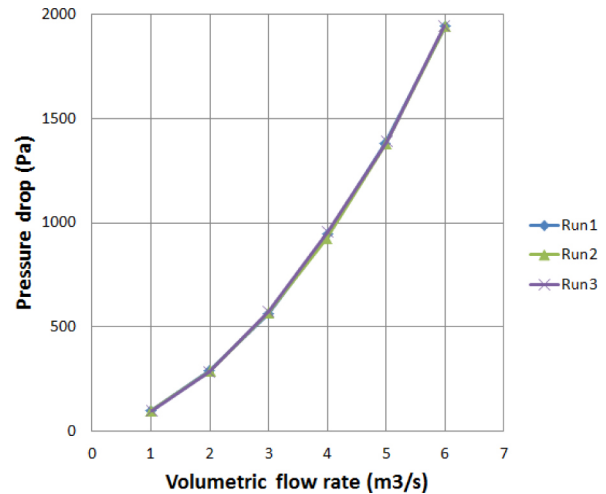


Figure 1. Pressure drop across the heat exchanger core versus volumetric flow rate measured in a plenum-to-plenum test rig over three test runs.

Figure 1 shows the pressure drop as a function of the volumetric flow rate measured in a plenum-to-plenum test rig at three separate occasions. The repeatability of the pressure characteristics is good. By [Equation 1](#) and [Equation 2](#), it is possible to calculate a relationship between the force acting on the heat exchanger and the average velocity through it. This is shown in [Figure 2](#). One can notice that both curves in [Figure 1](#) and [Figure 2](#) are of second order nature and can be described in equations [Equation 3](#) and [Equation 4](#) respectively, based on the Darcy-Forcheimer law.

$$\Delta P_{core} = \left(\frac{1}{2} \rho C_2 \frac{\dot{V}_{core}^2}{A_{core}^3} + \frac{1}{\alpha} \mu \frac{\dot{V}_{core}}{A_{core}} \right) \times \Delta x \quad (3)$$

$$F_{core} = \left(\frac{1}{2} \rho C_2 v_{avg_core}^2 + \frac{1}{\alpha} \mu v_{avg_core} \right) \times A_{core} \times \Delta x \quad (4)$$

where C_2 is the inertial resistance coefficient and

$$\frac{1}{\alpha}$$

is the viscous resistance coefficient through the heat exchanger core. These coefficients are both empirically obtained, Δx is the width of the heat exchanger core, μ and ρ are the air dynamic viscosity and density.

The principle idea behind the force based air flow method is to measure the total forces acting on the heat exchanger core and calculate the air flow rate using [Equation 4](#). Since it has been shown by Henriksson [7] that the pressure drop to average velocity characteristic of the heat exchanger is valid for various flow conditions, including non-perpendicular oncoming air flow, the force to average velocity curve in [Figure 2](#) can be used in complex flow fields.

One challenge in the prediction of air flow rate using load-cells is linked to the fact that the relationship between the force on the heat exchanger and the air flow rate through it is described by a quadratic polynomial. Due to the non-uniform flow, the average force acting on the heat exchanger will over-predict the average core velocity, a quantification of this over prediction and correction for this must be included in the method.

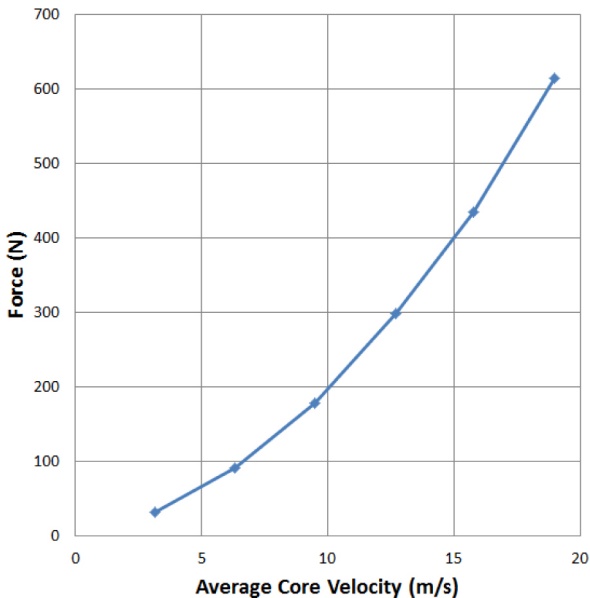


Figure 2. Calculated force versus average core velocity.

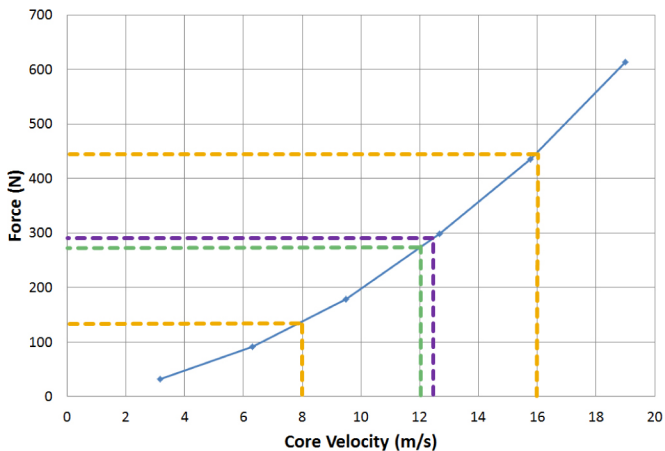


Figure 3. Over prediction demonstration on force versus velocity curve.

A simple example of such a typical over prediction is shown in Figure 3. Assuming that half of a heat exchanger is subjected to a core velocity of 8 m/s and the other half to 16 m/s (the two local velocities are marked in yellow). This results in an average core velocity of 12 m/s (marked in green) and an average total force (marked in purple). As it can be seen, the green and purple lines do

not match, thus measuring an average force will not enable a spot on prediction of average core velocity. This is due to the quadratic non-linearity of the pressure characteristic, the force average inherently over-predicts the average core velocity. In this severe non-uniform case it over predicts with 0.5 m/s, which is equivalent to 4 % higher mass flow.

To evaluate the performance of the force approach and necessary corrections, a traditional pressure based method has been carried out in conjunction with the force based method, thus providing a reference for comparison.

Given the deficit of the force based method, inhomogeneity of flow will be an important parameter of this paper. Inhomogeneity is a measure used to describe the deviation of the local velocity measurements from the average velocity through the core. The higher the inhomogeneity, the broader the spread of velocities, and the larger the over prediction will be, as explained in Figure 3.

The equation for calculating inhomogeneity used in this paper is taken from Hucho [8] and presented in Equation 5.

$$i = \frac{1}{n} \sum_{k=1}^n \left| \frac{\dot{m}_{local_k} \frac{A_{core}}{A_{local_k}} - \dot{m}_{core}}{\dot{m}_{core}} \right| \quad (5)$$

where n is the number of measurement points, $\dot{m}_{local_k}$ is the mass flow through one area section, A_{local_k} is the size of one area section, A_{core} is the size of the complete heat exchanger core area, and $\dot{m}_{core}$ is the total mass flow through the heat exchanger.

EXPERIMENTAL SETUP

Two separate experiments were conducted to be able to quantify the air flow rate. The first experiment is performed in a plenum-to-plenum test rig, for empirical calibration purposes, and the second is performed in an Aerodynamic Wind Tunnel, where the heat exchanger is mounted in its operative environment in a vehicle.

Plenum-to-Plenum Rig Test

A closed loop plenum-to-plenum test facility at Volvo Group Truck Technology (Volvo GTT) was used to test the pressure characteristics of the heat exchanger. The test rig is shown in Figure 4. The outlet chamber is kept at atmospheric pressure, and the pressure drop across the test object is measured plenum to plenum, while the air flow rate is measured using six Venturi type nozzles (ISA 1932). To operate the nozzles within their correct Reynolds number range for different mass flows, combinations of open and closed nozzles are used. More information on the Volvo GTT Test Rig can be found in Gullberg [9].