

Investigations and Analysis of Working Processes of Two-Stroke Engines with the Focus on Wall Heat Flux

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ABSTRACT

Small displacement two-stroke engines are widely used as affordable and low-maintenance propulsion systems for motorcycles, scooters, hand-held power tools and others. In recent years, considerable progress regarding emission reduction has been reached. Nevertheless, a further improvement of two-stroke engines is necessary to cover protection of health and environment. In addition, the shortage of fossil fuel resources and the anthropogenic climate change call for a sensual use of natural resources and therefore, the fuel consumption and engine efficiency needs to be improved.

With the application of suitable analyses methods it is possible to find improving potential of the working processes of these engines. The thermodynamic loss analysis is a frequently applied method to examine the working process and is universally adaptable. Within this paper, a series production small displacement two-stroke engine is experimentally investigated on the test bench and adapted with measuring equipment in order to analyze the working process with focus on the wall heat flux. Due to high speed and vibrations, these investigations are complex. This publication considers an assessment of correlation predictability of heat transfer models, which are used in the thermodynamic loss analysis, by means of a comparison with experimental data. Thereto the measurement technique based on the surface temperature method applied to a small two-stroke engine is explained. From these investigations, the thermodynamic loss analysis regarding wall heat loss is reassessed and improvement potential is pointed out. Finally, an alignment of the thermodynamic loss analysis for small displacement two-stroke engines regarding the wall heat losses is performed. The results of the thermodynamic loss analysis demonstrate the occurring efficiency losses and therewith improvement strategies concerning the working process can be deduced.

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INTRODUCTION

Due to the fact, that small displacement two-stroke engines are used in many applications as propulsion, it is essential to enhance the efficiency of these power units. The share of these small engine applications on total emissions and fuel consumption is not negligible. Therefore, the demand to apply a meaningful and accurate analysis to these propulsion systems is necessary to detect optimization potential.

Internal combustion engines (ICE) and their working process comprise complex thermodynamic and chemical sequences. The occurring combustion during the high-pressure phase, when all transfer ports are closed, is crucial for the conversion from chemical energy stored in fuel to effective work. The combustion process needs to be analyzed in detail, because, for instance, a fast combustion in

combination with an increasing pressure and temperature gradient influences pollutant formation and wall heat losses rise. To get a deeper insight in this complex processes, chemical models, phenomenological approaches and combustion analysis can be included to the assessment [1]. For the analysis, different tools and system boundaries are applied depending on the topic [2]. For the assessment of the combustion processes, the thermodynamic loss analysis and the energy balance method are substantial tools. The use of the thermodynamic loss analysis as an analysis method is common and cost effective. The increased insight into this method leads to a continuous further development. As an example, in previously published literature the scavenging loss of two-stroke engines was introduced as a distinct loss [3] in the thermodynamic loss analysis. The accuracy of both thermodynamic loss analysis and energy balance analysis depends on the accuracy of the quantification of

each particular efficiency loss. A verification of this analysis method and the comparison to measurements is mandatory to get a further improvement in accuracy and therefore an optimal opportunity to assess working processes regarding optimization potentials.

This paper focuses the subordinated wall heat loss in the thermodynamic loss analysis, because the wall heat loss plays, amongst others, a relevant role since it represents about 5-7 % of the efficiency losses. These investigations focus the assessment of high speed two-stroke engines with small displacements. Therefore, a two-stroke engine, which typically finds application in hand-held power tools, has been adapted, in order to determine the heat flux from the working gas to the combustion chamber walls. Vibrations and high speed make investigations more complex in comparison to other engine types (compare with [4, 5, 6]). For that reason, a comparison of correlation predictability with experimental data of such small displacement high speed engines hasn't been assessed in detail yet. To achieve this, different positions in the combustion chamber have been investigated regarding wall heat. For this analysis, sensors based on the surface temperature method had been used as measurement technique. On this basis, the measured heat transfer can be compared to the results of simulations carried out with the program CORA, developed by the Institute of Internal Combustion Engines and Thermodynamic (Graz University of Technology). Wherein, wall heat loss is calculated by use of empirical correlations, which can introduce errors in the estimation. The applied heat transfer types have been analyzed followed by a revision of the compliance with the measurement results and an assessment of the improvement potential.

First, the basics of thermodynamic loss analysis are explained and the occurring losses are illustrated. Subsequently, the energy balancing is performed and the wall heat loss is focused in detail. Therefore, different empirical correlations of heat transfer types are analyzed and compared to measurements to assess their predictability. In more detail, the measurement technology adapted to a high speed small displacement two-stroke engine and the basic principles of the heat flux measurement, including the surface temperature method, are explained. Finally, a comprehensive assessment of the accuracy of the applied heat transfer models is performed. The results are included in an adapted thermodynamic loss analysis with a revalued wall heat loss. In addition, a reassessed energy balance analysis of the two-stroke hand-held engine is conducted.

METHODOLOGY OF THERMODYNAMIC LOSS ANALYSIS

In this section, the theoretical basics regarding thermodynamic loss analysis and energy balance analysis are explained and the needed data is taken into account.

As described by Pischinger et al. [1] the corresponding losses within the thermodynamic loss analysis are differences in work, which get related to the energy added to the system in form of fuel. Thus, a detailed quantification of the particular efficiency loss is possible. A distinction is made between losses from imperfect combustion, real combustion, wall heat, gas exchange, scavenging losses and friction. Based on the distribution of losses, optimization measures concerning

the design and combustion processes can be derived. Starting from the efficiency of an ideal engine with real charge, the effective efficiency is calculated through a subtraction of all losses. In [1] a detailed description of the basic methodology can be found and the physical relations of each loss are presented. Further considerations with similar approaches for the loss mechanisms had been developed and investigated by Weberbauer et al. [7] and Schürig et al. [8].

For the analysis of the engine processes of an ICE a precise knowledge of many engine values, such as the charge mass along with the mixture and the conversion of energy, is essential. If scavenging losses m_{SC} occur (see figure 1), the fresh charge mass m_{FR} at the beginning of the high-pressure phase is less in comparison to the delivered fresh charge mass m_{FRdel} . These scavenging losses exist particularly for two-stroke engines with loop scavenging and are a substantial energetic loss, which is caused through the trapping efficiency of the fuel (TE_{Fuel}). This fuel scavenging loss leads to higher emissions and a reduced efficiency.

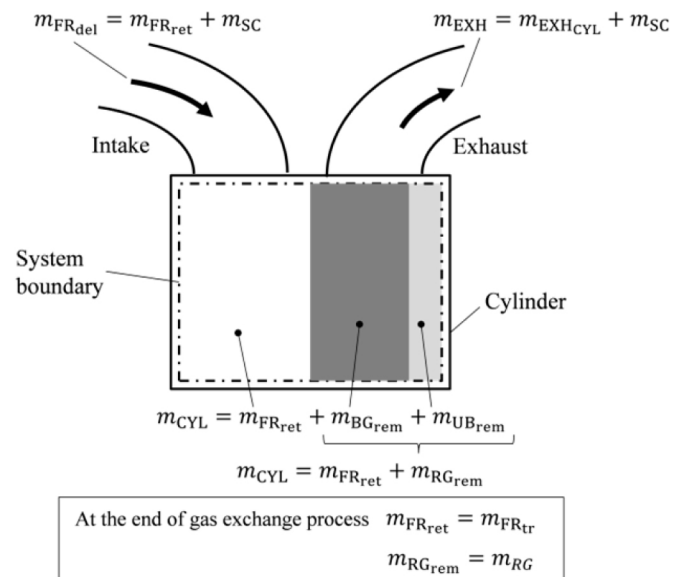


Figure 1. Mass distribution during gas exchange [9]

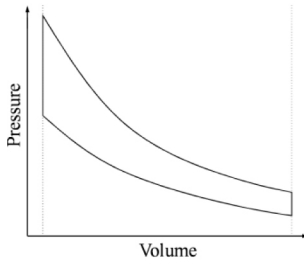
The loss analysis methodology applied in this paper differs from previous approaches. Figure 2 shows a visualization of the thermodynamic loss analysis methodology. All calculations are based on the real masses and the real delivered fuel caloric value. In earlier approaches of Schmidt et al. and Winkler [12, 13] the caloric value of fuel was decreased according the energy of fuel scavenging losses. That way, all losses, except the loss through scavenging losses, were referenced to the trapped fuel energy. The studies from Schmidt et al. [12] assigned the scavenging losses to imperfect combustion; Winkler [13] already distinguished the scavenging losses as a separate loss arranged below imperfect combustion (compare to figure 2). The applied methodology places the scavenging losses as a separate loss between losses due to real gas exchange and mechanical losses.

CORA, a 0D program, is used to calculate distinctive losses. Starting from the ideal engine process with real charge down to the loss from gas exchange, the trapped fuel energy is applied for calculations. The

losses below the share of gas exchange, scavenging and friction losses, are calculated with the delivered fuel energy. The same air fuel ratio is used for all calculations steps.

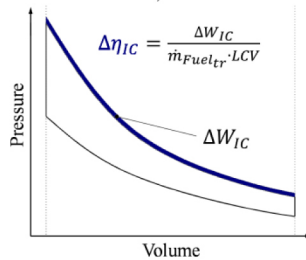
1.) Ideal Engine

- Isochoric process
- Incomplete combustion
- Real charge
- Dissociation



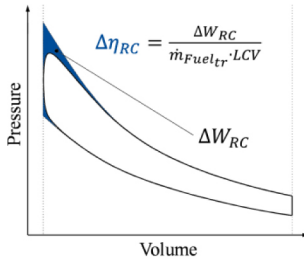
2.) Imperfect Combustion

- Consideration of unburnt energy (difference between imperfect and incomplete combustion)



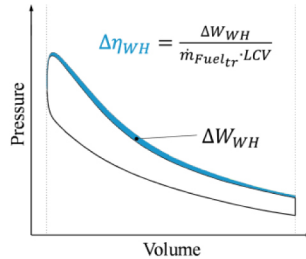
3.) Real Combustion

- Start (SOC)
- Duration (DOC)
- Shape of heat release
- Adiabatic



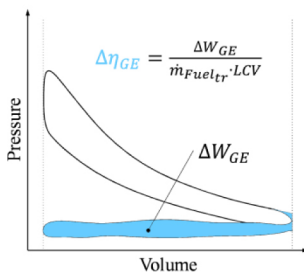
4.) Wall Heat

- Heat transfer to combustion chamber walls



5.) Gas Exchange

- Difference to ideal isochoric gas exchange
- Expansion/compression losses
- Flow losses



6.) Scavenging Loss

- Lost fuel during GE to exhaust

$$\Delta\eta_{SL} = \eta_{i_{woSL}} - \eta_i$$

$$\eta_{i_{woSL}} = \frac{W_i}{m_{Fuel_{tr}} \cdot LCV}$$

$$\eta_i = \frac{W_i}{m_{Fuel_{del}} \cdot LCV}$$

$$TE_{Fuel} = \frac{m_{Fuel_{tr}}}{m_{Fuel_{del}}} = \frac{\eta_i}{\eta_{i_{woSL}}}$$

7.) Friction

- Mechanical losses

$$\Delta\eta_M = \eta_i - \eta_e$$

8.) Effective Efficiency

- Effective work per delivered fuel energy

$$\eta_e = \frac{W_e}{m_{Fuel_{del}} \cdot LCV}$$

through real charge and incomplete combustion due to lack of oxygen up to chemical equilibrium. A dissociation of the working gas during combustion is also considered for this.

In real processes, the chemical equilibrium is not reached and unburnt emissions additionally arise during combustion. This energy loss, due to unburnt fuel components, is counted as the efficiency loss through imperfect combustion. Moreover, it is an efficiency difference between incomplete combustion up to the chemical equilibrium and imperfect combustion. A further energy loss occurs due to of real combustion and depends on the duration of combustion (DOC), the shape of the heat release and the center of combustion (CoC). This loss is determined by calculating the real gross heat release by means of the measured cylinder pressure curve. Hence, the difference of efficiency of the adiabatic high-pressure process with constant volume combustion and real combustion is calculated [10]. Another loss mechanism - the wall heat loss - appears as a result of heat transfer from the gas to the combustion chamber walls. This wall heat loss and the loss through real combustion interact with each other. According to [1] an optimum regarding CoC depends on the wall heat loss and real combustion. With a CoC near the top dead center (TDC) losses due to real combustion are low, but in contrast wall heat losses increase because of higher temperatures in the combustion chamber. In this presented methodology, the wall heat loss is analyzed in detail. In this context, wall heat loss is calculated by use of semi empirical formulas, whereas different wall heat transfer models, Woschni [15], Woschni-Huber [16] and Hohenberg [17], are investigated. By comparing the applied transfer models to measurements, the best approach for small displacement two-stroke engines can be found and the accuracy of the methodology will be improved.

Continuing the thermodynamic loss analysis, the loss due to gas exchange contains losses caused by losses concerning expansion, compression, and low pressure. It is calculated by the difference of total indicated work and indicated high-pressure work. Starting from the ideal engine (step 1 in figure 2) down to the loss of gas exchange (step 5) the efficiency differences are based on the trapped fuel energy. The scavenging loss difference (step 6) is calculated with the trapped fuel mass and delivered fuel mass, so that the indicated efficiencies (η_i , $\eta_{i_{woSL}}$) are related to different fuel energy amounts. Two-stroke engines especially suffer from scavenging losses in comparison to four-stroke engines. The friction loss is referenced to the delivered fuel mass und represents mechanical losses. Subtracting all efficiency differences from the efficiency of the ideal engine, the result is effective efficiency. This effective efficiency is the effective work of the engine divided by the delivered fuel energy.

Analytic Process with Thermodynamic Loss Analysis

The thermodynamic loss analysis is performed with experimental data. Amongst others, the cylinder pressure curve, the raw gas emissions, the delivered fuel mass and fresh air mass are mandatory. Besides, the amount of the residual gas in the cylinder is also necessary. As the measurement of the residual gas ratio is costly and laborious, it has not been performed in detail yet and is herein determined with a verified gas exchange simulation. After measurement and simulation, input data can be prepared for the analyses including a pressure curve analysis. For verification reasons,

Figure 2. Methodology of thermodynamic loss analysis [10]

In accordance with [1] and [7], constant-volume combustion is chosen as the ideal process for loss analysis of the ideal engine process with real charge. At the start of the high-pressure phase, the real engine is equivalent to the ideal engine with real charge, so that the same charge mass, temperature, pressure and gas composition, which leads to the same air-fuel and residual gas ratio, is available. The efficiency of the ideal engine provides for changes in efficiency

the quality of the input data is controlled by the energy balance method. Therefore, the cumulative gross heat release, derived from the measured pressure curve, is compared with the trapped fuel energy minus the energy from imperfect combustion. Subsequently, the thermodynamic loss analysis can be performed using the calculated gross heat release.

HEAT FLUX MEASUREMENT

To evaluate the results of the thermodynamic loss analysis regarding wall heat losses, the heat flux for the applied small-displacement two-stroke engines needs to be investigated in more detail. For this, a suitable measurement technique must be selected and adapted to these high-speed engines. The demands for sensors are stringent, as the required response time is very short and the needed accuracy is high. Furthermore, the sensor itself must have the smallest possible size, so that the influences on the heat flux field and temperature level are negligible. The sensors must withstand the occurring temperatures and vibrations to have a sufficient durability [14]. In principle, there are two different measurement methods, which can be applied to ICEs to measure the heat flux in high resolution [18]. The first measurement technique is based on sensors measuring the surface temperature [2]. A second method is available, which measures the temperature drop through sensors with a thin thermal resistance layer inside. Due to packaging restrictions, when using small displacement two-stroke engines, this method is not applicable. In addition, these sensors have high production costs and a limited durability [14]. Therefore, sensors based on the surface method are preferred for the application in two-stroke engines.

For the determination of the heat flux in ICEs surface thermocouple sensors with a coaxial design, as shown in [figure 3](#), are often used. With this design, the probe, when installed in the wall, is flush with the wall surface. The two thermocouple materials are electrically insulated by ceramic oxide powder (MgO), which makes up a layer of 12.7 μm . The contact between the thermocouples is established by an evaporated thin metal layer (thickness of 1-2 μm). These sensors are available with various thermocouples materials (Typ T, J, E, K and S) and variable junction plating materials (Cr, Ni, Pt, and Cu) at the hot junction [14].

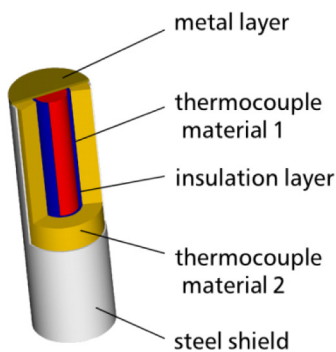


Figure 3. Mineral-insulated surface thermocouple sensor [14]

Applying this surface sensors to small displacement two-stroke engines, sensors with a thermocouple material of Type K (temperature range: - 270 to + 1372 °C) and a diameter of 0.79 mm

have been chosen. The sensors are adapted flush to the combustion chamber wall by small bores through the cylinder head. On this basis, temperature gradients can be measured during one cycle.

Basic Principles of the Surface Temperature Method

In the following, the basic principles of the transient wall heat flux from the gas-side to the combustion chamber wall, determined with measured temperature gradients, are described.

The surface temperature method is based on the commonly known Fourier differential equation for heat conduction and can be used to characterize the temperature field inside the wall of the combustion chamber. Therefore, it is assumed, that no heat source exists in the considered object and a one-dimensional heat flow in the combustion chamber wall is present. Temperature gradients occur only perpendicularly to the combustion chamber surface in x-direction. With these assumptions, the commonly Fourier differential equation is reduced to the following form:

$$\frac{\partial T_w}{\partial t} = a \frac{\partial^2 T_w}{\partial x^2} \quad (1)$$

In [equation \(1\)](#), T_w is the wall temperature and t the time. Further, a is the thermal diffusivity of the wall material and is determined by a quotient of the thermal conductivity λ and the product of the material density ρ and the specific heat capacity c_p [14].

$$a = \frac{\lambda}{\rho c_p} \quad (2)$$

The transient heat flow through the combustion chamber wall can be calculated with the temperature gradient and the thermal conductivity:

$$\dot{q}_w = -\lambda \frac{\partial T_w}{\partial x} \quad (3)$$

For the periodic work process of the ICE and with the assumption of an infinitely extended wall, the differential equations above can be solved with a mathematic sequence. From this, the unsteady temperature field and the unsteady heat flux density field can be derived. The results are presented in [equation \(4\)](#) and [\(5\)](#).

$$T_w(x, t) = T_{ws_m} - \frac{c}{\lambda} x + \sum_{i=1}^{\infty} e^{-x \sqrt{\frac{i\omega}{2a}}} \left[A_i \cos \left(i\omega t - x \sqrt{\frac{i\omega}{2a}} \right) + B_i \sin \left(i\omega t - x \sqrt{\frac{i\omega}{2a}} \right) \right] \quad (4)$$

$$\dot{q}_w(x, t) = C + \lambda \sum_{i=1}^{\infty} \sqrt{\frac{i\omega}{2a}} e^{-x \sqrt{\frac{i\omega}{2a}}} \left[(A_i + B_i) \cos \left(i\omega t - x \sqrt{\frac{i\omega}{2a}} \right) + (-A_i + B_i) \sin \left(i\omega t - x \sqrt{\frac{i\omega}{2a}} \right) \right] \quad (5)$$