

Research Article

Reactive Gas Flows Fluctuations in Hydrogen Powered Wankel – Experimental Research using a Novel Flowmeter

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Abstract:

This paper presents experimental research of gas flow fluctuations on a two-rotor direct injected Wankel engine fueled with Hydrogen using special mass flow meter. The flow parameters of two reaction components - air and pure Hydrogen were measured at 9 engine operation points. The research of reacting gases fluctuations focuses on testing and measuring of Hydrogen pressure oscillation and intake air phenomena by means of air mass flow oscillation. For this purpose, a special orifice flow meter measurement system was developed to evaluate the intake-air performances under consideration of intake air pressures and engine temperatures. The experimental engine setup is discussed in the first part of the paper. Then, the H₂-direct injection stochastic behavior and intake flow fluctuations were measured and analyzed to explain the combustion phenomena and engine performance, which were compared with the experimental data. The investigation confirmed that the developed airflow measurement system can be applied to understand behavior of the H₂-engine and to improve the quality of the engine filling, combustion and resulting efficiency.

Keywords: Flow measurement, Hydrogen engine, Hydrogen fuel, Wankel, pressure fluctuations, flow oscillations

1. Introduction

The global challenge of CO₂ emissions, together with increasingly stringent legislation, has placed the automotive and off-road sectors in a highly demanding case where technical progress is strongly shaped by environmental rules [3]. The internal combustion engines still remain one of the major contributors to greenhouse gases and other emissions, therefore they are subject to stricter emission standards. Hydrogen-fueled engines are regarded as a key technology for a cleaner future, offering high efficiency and zero CO₂ emissions compared to conventional gasoline engines. However, they still produce nitrogen oxides (NO_x), which currently limits their widespread application.

A large research work has been conducted on hydrogen engine development [12] during last decades, focusing on areas such as hydrogen injection systems, intake systems, exhaust after-treatment, exhaust gas recirculation technique, combustion chamber design and advanced ignition systems. However, to fulfill all future emissions requirements, Wankel engine offers the optimal possibility for Hydrogen use. The cold compression chamber of Wankel engine housing (trochoid) and internal exhaust gas recirculation due to circumferential allocation of inlet and exhaust slots make the Wankel very competitive against the piston engine during operation on Hydrogen. To achieve best EGR while both mentioned slots are opened, the geometry of inlet and outlet ducts has to be optimized.

The use of hydrogen as a fuel may provide a pathway to meeting emission regulations without requiring major or costly modifications to existing engine systems. Over the past decade, numerous studies have demonstrated the

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application of hydrogen in retrofitted diesel engines, either through intake port injection or direct injection [12]. Hydrogen produced via electrolysis using wind energy contains no fossil carbon and therefore offers a renewable alternative. However, its combustion properties—ignitability and lower heating value (LHV)—differ significantly from those of conventional diesel, making direct compatibility challenging.

Although hydrogen combustion produces small amounts of NO_x , it eliminates unburned HC, CO, and particulate emissions typical of Diesel engines. Its behavior, however, is highly dependent on operating point, engine configuration, intake flow conditions and injection pressure stability. Accurate intake-flow characterization requires costly and time-intensive experimental methods, while the complex interplay of governing phenomena presents significant challenges to conventional experiment-driven engine development.

A detailed investigation of intake flow and its impact on combustion performance can be achieved by tracking key intermediate or precursor species. Owing to these advantages, a variety of advanced intake flow diagnostic methods were developed and applied to study engine combustion, as demonstrated in [11].

In this paper an experimental research based on flow measurements according ISO 5167-1 [6, 7] was done. The effects of intake flow oscillation on engine performance are analyzed based on the measurements at the engine test bench running on pure Hydrogen as fuel.

The research work consists of three main parts: The first part describes the Wankel engine, the engine test bed, and the measurement procedure. This is followed by a brief overview of the fuel injection line and intake flow measurements. Finally, the engine test results are presented and discussed.

2. Experimental Setup

2.1 Test engine

An experimental KKM 502 H_2 Wankel engine [18], originally designed for Diesel cycle operation was employed. The two-rotor engine, with a chamber volume of 508 cm^3 , is water-cooled and operates in direct hydrogen injection mode. The main design parameters are as follows: generating radius 108 mm, housing width 58 mm, and eccentricity 15.2 mm. The compression ratio was 10:1. The engine delivers a maximum power output of 50 kW at 4500 rpm and a peak torque of 110 Nm at 4000 rpm. At maximum load, the indicated mean effective pressure reaches 6.8 bar at 4000 rpm and 6.6 bar at 4500 rpm. The minimum SFC of 110 g/kWh was measured at 4000 rpm. At this operating point, the engine achieved its best SEC of 13.2 MJ/kWh on Hydrogen, corresponding to engine efficiency of 23.1%.

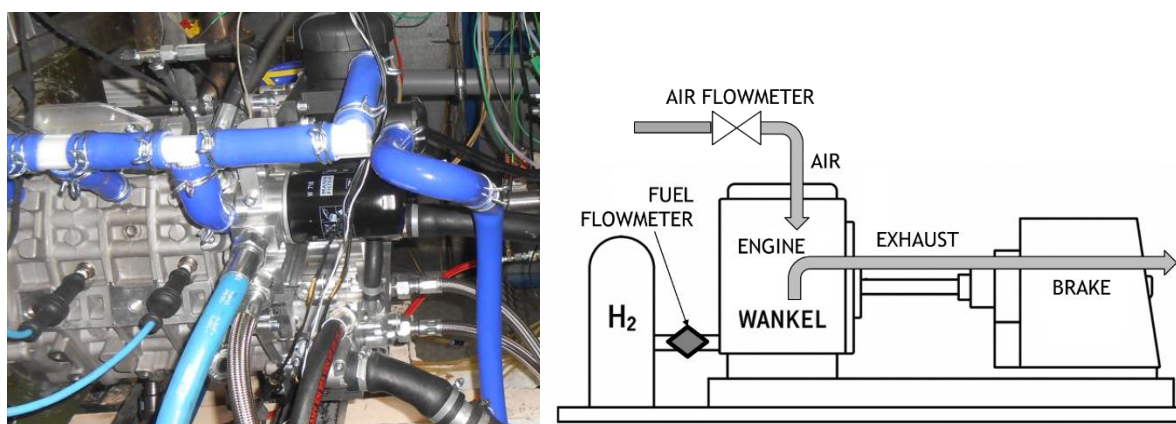


Fig. 1. Two-rotor Hydrogen-powered Wankel Engine KKM 502 H_2 (left) and the engine test bench schematic diagram (right).

Injection was timed at 90° crank angle before top dead center (BTDC). The engine was driven under load using a Schenk electric eddy-current brake, and fuel was injected directly into the combustion chamber via the Wankel engine trochoid.

The Table 1 compares the Wankel engine criteria with other internal combustion engines. More details about the development of Wankel technology can be found in [2 - 5]. It has to be mentioned that Wankel engine shows low level of mechanical oscillations compared to other engine types [8, 14]. On contrary to the piston engine, the design properties of Wankel where the compression stroke takes place in the colder part of the engine allows the Hydrogen injection without any self-ignition danger [10]. However, the physical properties of Hydrogen due to its low density combined with unique Wankel engine intake configuration cause fluctuations of reactive gases which leads to instabilities of engine combustion performance.

Table 1: Criteria of different engine types [4].

Criterion	4 stroke Multi-fuel Wankel	4 stroke Diesel RPE	Gas-turbine engine
Weight	+	-	++
SFC	++	++	-
Vibration	++	--	++
Oscillation	+	--	++
Leading area	+	-	+
Modular concept	++	-	-
Nominal speed	+	+	--
Costs	+	+	-

For configuration with injection point in the trochoid, the high-pressure injection system (50 bar) is replaced by a low-pressure one. The 10 bar injection is conducted at the beginning of the compression stroke. This outline of the injection system allows a layering in the mixture. Tripple electrode spark plug is used. The homogeneous mixture formation is obtained from this outline. However, a knocking at full load can be anticipated to be a problem, which is depended on the various cycle and mixture pressure oscillations.

2.2 Engine instrumentation

Fuel line pressure was measured using a KISTLER 4818A2 transducer, flush-mounted at the trochoid injection point and interfaced via a KISTLER 5011 charge amplifier from Delphin Technology. Crankshaft position was recorded with a digital shaft encoder from Susinet AG. The test rig was instrumented with standard sensors, including thermocouples for oil, air, inlet manifold, and exhaust temperatures, as well as pressure gauges at relevant locations. Safety features appropriate for hydrogen operation were fully implemented. All data acquisition was conducted using custom in-house software. Hydrogen fuel bottles were allocated outside and allow a flexible fuel cut and line purge with Nitrogen in emergency cases. The system includes also software and a measuring amplifier for the TDC sensor and the pressure gauges.

2.3 Build-in airflow measurements and fuel metering

The RS 232 interface transmits the measured signals for further acquisition, display and recording. The air mass flow is measured using hot-film anemometer from Bosch. The exhaust gas temperature probes were installed in the test bed's exhaust line near the exhaust port to measure the exhaust gas temperatures.

Flow behavior of Hydrogen provided by Linde was investigated by engine test bed systems. For the gas fuel flow measurement, the Bronkhorst F-1113AC flow meter was employed before the injection valve. The fuel temperature was measured by temperature probe Type K.

3. Data Processing

3.1 Fuel pressure measurement

The involved fuel measurement procedure allowed investigation of pressure and flow oscillation in the fuel line components to understand both performance stability and maximal power properties of the engine.

The generation of the gas fuel flow wave's mechanism is performed due to the engine rotor procedures described in Ref. [17], which causes the phenomena described in [11].

As it was mentioned above, the air mass flow is determined indirectly via pressure and temperature at a measuring orifice. The mass flow is calculated according to the algorithm standardized in DIN EN ISO 5167 [6, 7], which was implemented in software 'Flowcounter' of the GFT. The absolute pressure in front of the orifice plate p_1 , the pressure drop across the orifice plate Δp and the temperature T are required as incoming measured values. The calculated outputs are the mass flow $\dot{m}_a$ in kg/s. The geometry values of the orifice plate (D , β) and the material parameters of the air (R , κ) are declared as constants in the code and therefore have to be changed accordingly when used with other orifices or fluids.

The method is essentially based on the iterative calculation of the flow coefficient C or the Reynolds number Re . The algorithm was implemented using equations as follows in a clear while loop and realized in the software 'Flowcounter' after several adjustments of sensors application.

The Reynolds number in front of the orifice plate is calculated using equation (1):

$$Re D = \frac{u_1 D}{\nu_1} \cdot \frac{\frac{4\dot{m}_a}{\pi D^2 \rho_1} D}{\nu_1} = \frac{4\dot{m}_a}{\pi \eta_1 D} \quad (1)$$

by rearranging (1) the mass flow can be defined (2):

$$\dot{m}_a = Re D \cdot \eta_1 \frac{\pi D}{\nu_4} \quad (2)$$

where

$$\eta_1 = \frac{1.71 \cdot 395}{T + 122} \left(\frac{T}{273} \right)^{1.5} 0.00001 \quad (3)$$

According to the standard [6], the empirical equation for determination of the expansion number ε_1 for orifice plates can be estimated

$$\varepsilon_1 = 1 - (0.41 + 0.35\beta^4) \left(\frac{\Delta p}{\kappa p_1} \right) \quad (4)$$

From these determined values, the invariant A_1 can now be calculated according to equation (5)

$$A_1 = \frac{\varepsilon_1 (\beta D)^2 \sqrt{2 \Delta p \rho_1}}{\eta D \sqrt{1 - \beta^4}} \quad (5)$$

The Reynolds number and flow coefficient are now determined by iteration {(4) and (5)}.

$$Re D = A_1 C \quad (6)$$

The starting value is $C=C_\infty=0.6276$. The termination condition for this iteration is the fulfillment of the accuracy criterion $Y < 0,0001\%$.

4. Results and Discussion

4.1 Initial conditions of experiment

The investigations conducted in this study consists of three main steps. Firstly, pressure fluctuations in the hydrogen fuel line were analyzed to assess the impact of fuel supply instabilities on engine performance. Second, the intake mass flow of the hydrogen-fueled test engine was measured at three different rotational speeds and three load conditions to examine the correlation between intake flow oscillations and engine performance. Finally, mass flow measurements were carried out using the existing engine setup as a reference, in order to characterize the flow behavior during engine start-up and shut-down phases. For simplicity in the following paragraphs, the main parameters of Hydrogen fuel will be limited by the lower heat value LVH. Table 2 introduces the most used fuels for Wankel engine and their main combustion parameters respectively.

Table 2: Comparison of main parameters of different fuel types

Fuel name	Cetane number [-]	LHV [MJ/kg]
Regular Diesel	50.6	42.55
Propane	49.8	45.80
Hydrogen	-	120.00

4.2 Hydrogen pressure fluctuation analysis

Pressure fluctuations in the fuel line were assumed to be a key factor reflecting the behavior of fuel flow oscillations at the injector, which directly influence engine power.

Since no flow check experiments were available for the chosen injectors operating with hydrogen, a cross-comparison was carried out using two types of gaseous fuel pressure dampers (with volumes of 100 ml and 180 ml) installed upstream of the injector. The aim was to verify the consistency between engine performance and the damping effect of fuel pressure oscillations in these volumes. Fig. 4 shows comparison of fuel mass flow fluctuations at 3000 RPM and 16 Nm with 4000 RPM and 24 Nm. Measurements were performed at $p = 10$ bar of fuel pressure without pressure dampers. Figure 4 illustrates the pressure behavior for two cases: the left diagram corresponds to shorter valve opening times (indicated by multiple narrow downward-pointing red tips), while the right diagram shows longer valve opening times (indicated by wider downward-pointing red tips).

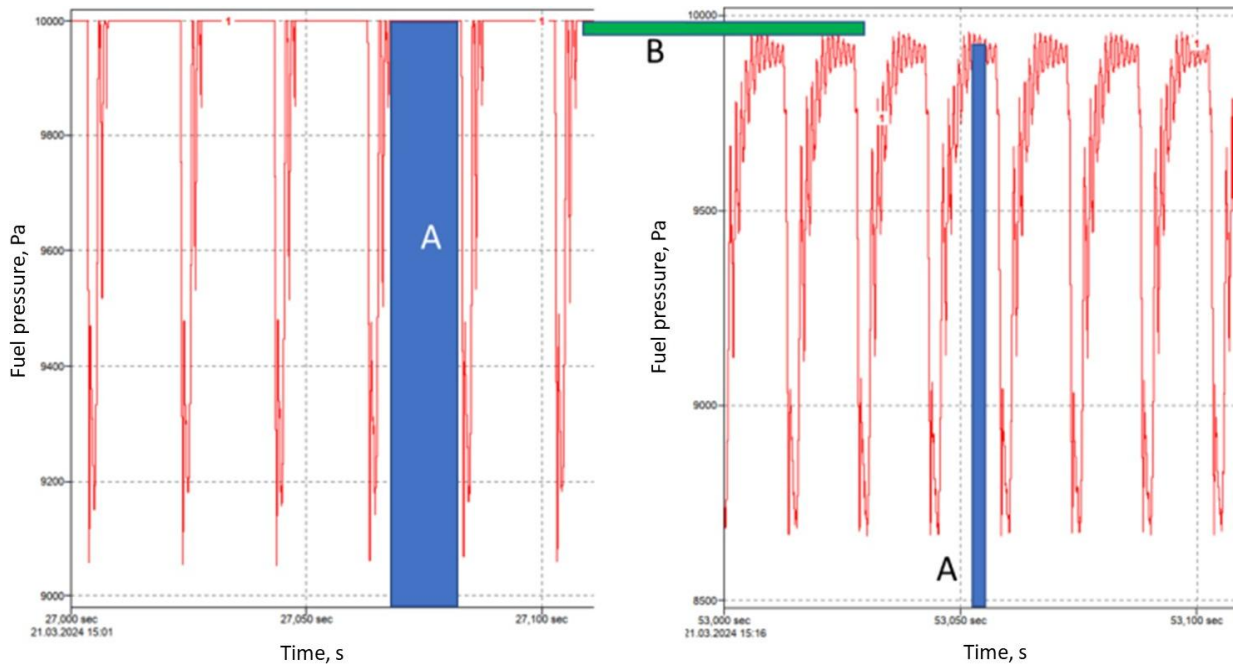


Fig. 4. Comparison of fuel mass flow fluctuations at 3000 RPM and 16 Nm (left) versus 4000 RPM 24 Nm at $p_{inj} = 10$ bar.

The two blue rectangles marked ‘A’ in Fig. 4 illustrate that a longer injector opening time results in a shorter duration of the constant pressure plateau and a less steep pressure rise after valve closure. In the left diagram, the wider rectangle indicates the longer plateau observed with a shorter injector opening time. In contrast, the narrower rectangle in the right diagram highlights the reduced plateau duration caused by the longer injector opening time. The green rectangle “B” shows, that the longer injector opening time at higher load (24 Nm) causes decrease of maximal pressure values before the injector.

Fig. 5 shows comparison of fuel mass flow fluctuations in case of two different damper-voluminous installed (100 ml and 180 ml) in the fuel line at 3000 RPM and 16 Nm. Measurements were performed at 10 bar of fuel pressure.

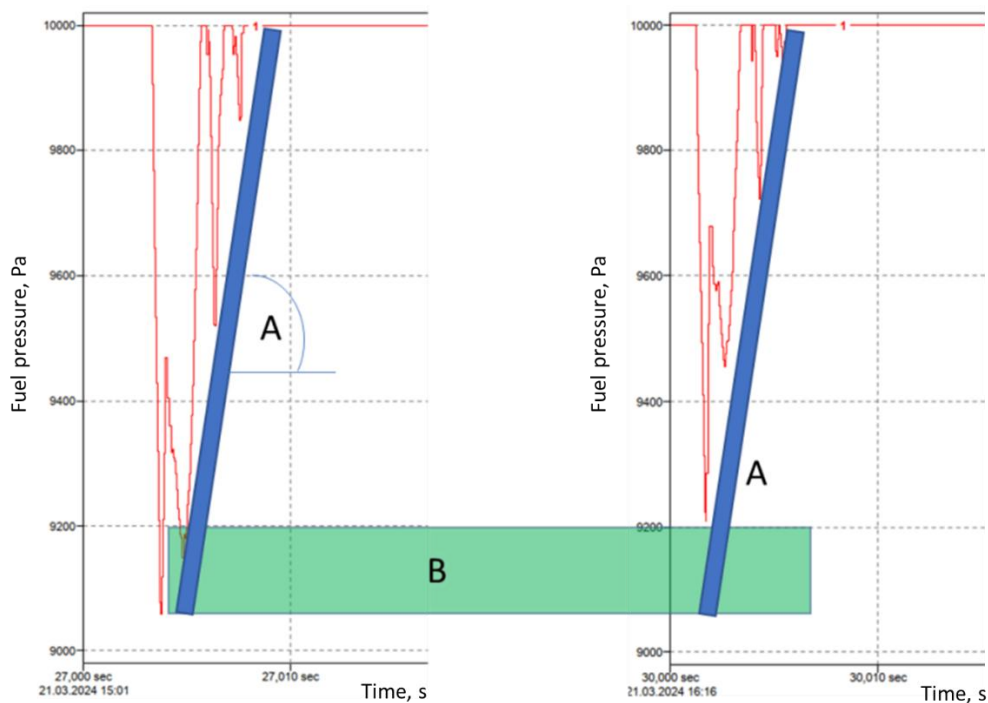


Fig. 5. Fuel pressure oscillations in case of 100 ml damper volume (left) vs 180 ml damper volume (right) at 3000 RPM and 16 Nm torque and $p = 10$ bar.

The blue tilted line “A” in Fig. 5 indicates no significant changes or improvements in dynamic pressure differential performance or pressure intensity increase in two measured configurations.

However, the rectangle “B” in the bottom of Fig. 5 indicates the difference in minimal measured fuel pressures in case of 100 ml damper compared to 180 ml damper. Thus, ca. 2% higher lower fuel pressure in case of 100 ml volume was measured. Hence, the higher volume before injector installed, the smaller pressure fluctuation amplitude is measured, the smaller impact on engine performance. Furthermore, a direct connection or integration of injector and damper volume may cause a positive effect.

4.3 Air Flow Fluctuation Measurement

The built-in air flow meters as described above provides smooth signal corresponding to a stable air mass flow. This signal leads to assumption that the measured mass flow is not depending on rotor revolutions. Therefore, the mixing process during the compression phase can be reasonably approximated by a linear function. In contrast, the subsequent fuel injection events, which induce intensive turbulence and thereby impact the mixing between the injected fuel and the in-cylinder gas, are often modeled in engine control software using a constant mixing time. This approach, however, does not fully capture the dynamic and transient nature of the real process. Understanding the actual airflow behavior is crucial for accurately representing the fluctuations in mixing intensity during both the mixing process and the subsequent spark-ignition-controlled combustion phase. The definition and analysis of the time-dependent behavior of the mixing flows were carried out following the methodology presented in [14, 19].

In the first step the impact of load at defined engine speed on the air flow fluctuations has to be investigated. Fig. 6 illustrates a comparison of measured air mass flow values at 3000 RPM and three different engine loads. Blue curves indicated by “A” demonstrate the maximal load, The red “B”-curves describe the middle load and low load is indicated by gray “C”-curves.

An analysis of plots in the Fig. 6 shows no significant impact of load at 3000 RPM on the air flow fluctuations amplitude. The majority of air mass flow values which belongs to 6σ -rule are fluctuating in the range around 10 – 12 g/s at each RPM.

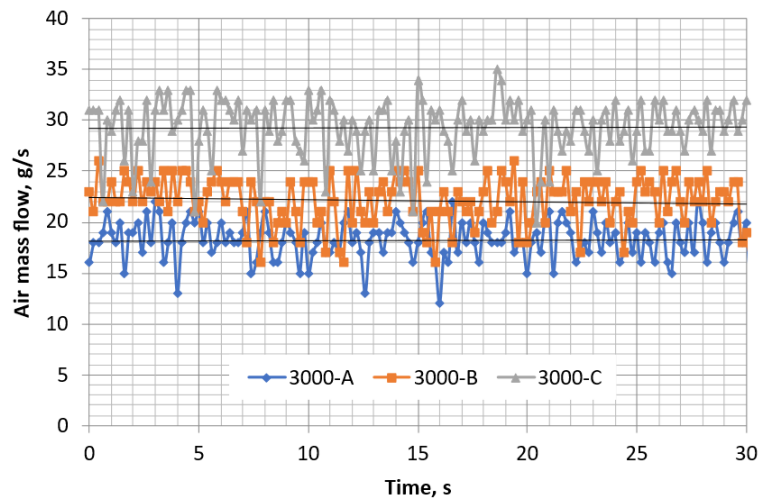


Fig. 6. Comparison of air mass flow fluctuations at 3000 RPM load and different engine loads.

The behavior of the air mass flow fluctuations depending on engine rotor speed can be observed in Fig. 7. The air mass flow performance was measured at middle engine load at 2000 RPM, 3000 RPM and 4000 RPM.

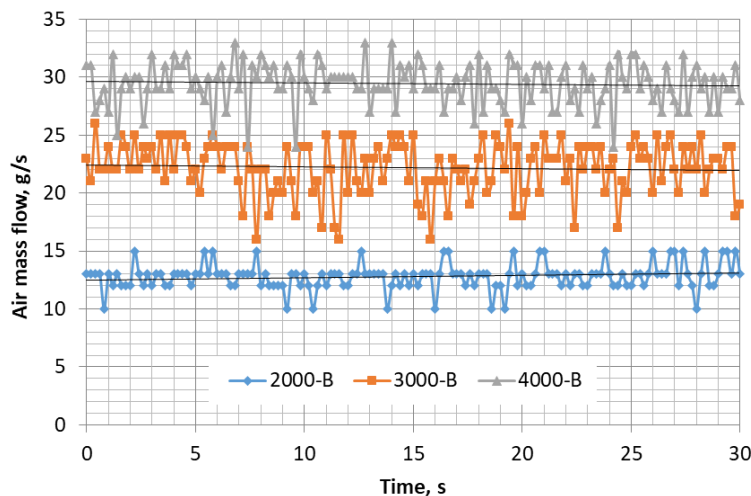


Fig. 7. Comparison of air mass flow fluctuations at middle engine load and different RPM.

A rough estimation of curves in the Fig. 7 shows a light impact of engine speed at various values of engine load on the airflow fluctuations amplitude in the time frame of 30 seconds. The of air mass flow fluctuations amplitude at lower engine speed is several times lower compared to fluctuations at higher engine speeds.

For a more detailed analysis, the plots of the Fig. 7 were scaled-up to achieve a possibility of observation in the time frame of 10 seconds starting from the 10th second of presented above measurements results. After a visual analysis of tree curves of Fig. 8 impact of engine RPM on the air flow fluctuations amplitude can be confirmed. The air mass flow values at 2000 RPM are fluctuating in the narrowest range of around 2 g/s with regularly peaks of 5 g/s every 2nd second. Similar behavior of mass flow curve can be observed at 4000 RPM. However, the maximal mass flow amplitude in this range of around 3 g/s.

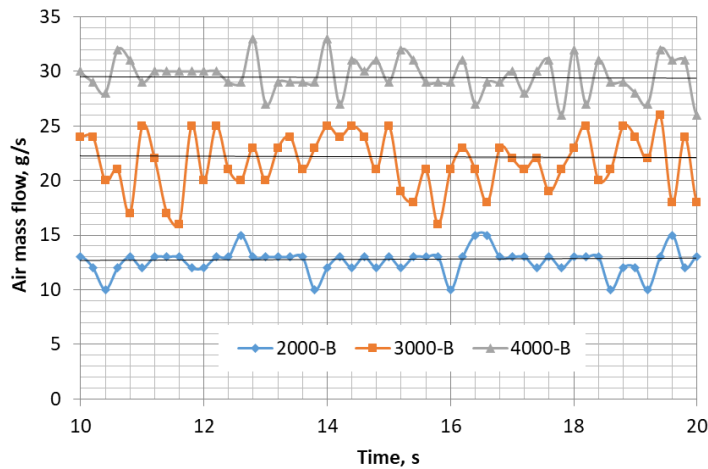


Fig. 8. Scaled-up comparison of air mass flow fluctuations at middle engine load.

4.4 Air Fluctuations during Start- and Stop-phases

The test results (air mass flow fluctuations) during engine start are illustrated by the blue lines in Fig. 9. The red curve in Fig. 9 illustrates the engine mass flow behavior during the engine stop.

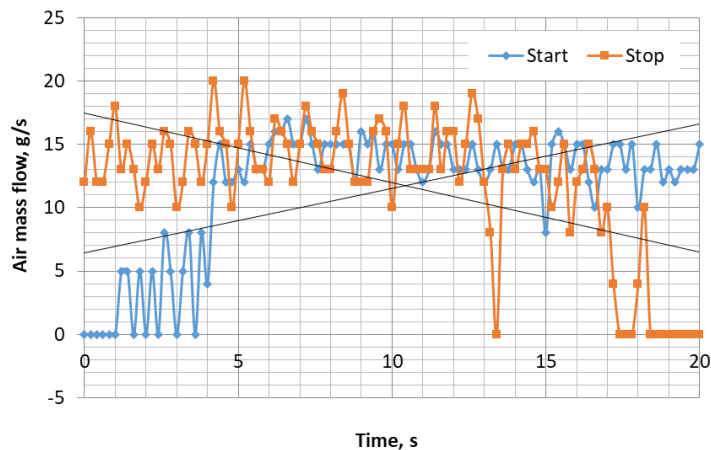


Fig. 9. Comparison of air mass flow fluctuations during start (blue line) and engine stop (red line).

An analysis of plots in the Fig. 9 shows higher air fluctuation amplitude in case of engine stop. This fact can be explained by a possible self-ignition from the hot combustion chamber walls after ignition off. Furthermore, no significant impact of load or engine speed variation on the air flow fluctuations amplitude was observed.

5. Conclusion

The flow measurement system for intake air of Wankel engine at different configurations have been proposed and tested. Performed tests on Wankel confirmed the effectivity of orifice measurement system for investigations of flow fluctuations in the intake manifold and resulting combustion instabilities. It was shown with the help of GFT that the character of fluctuations in the intake manifold is depending on engine operation point. Due to implementation of the orifice flow meter, the increase of fluctuations intensity, especially higher amplitude at middle RPM was detected. These measured fluctuations can explain the visible stochastic performance decreases of the engine and several instabilities in combustion effectivity at mentioned above operational points.

Therefore, the orifice measurement system has to be applied at the test engine beside the standard air flow measurement procedure for investigation of engine performance and combustion instabilities caused by the inlet air flow fluctuations.

The presented results proved to be highly promising for future research. Ongoing work, which builds on the present study, is focused primarily on analyzing flowmeter performance at higher frequencies (40 Hz). With the support of a newly developed measurement algorithm, these investigations will also address aspects of mixture formation, such as high-frequency oscillations. The corresponding findings will be presented in a separate publication.

Nomenclature

A	invariant
$BTDC$	before top dead center, deg
B	orifice plate coefficient
C	flow coefficient
ε_1	expansion number
GFT	gas flow tester
EGR	exhaust gas recirculation
h	convective heat transfer coefficient, $W/m^2\cdot K$
k	adiabatic exponent
L	length of test section, m
LHV	lower heating value, MJ/kg
$\dot{m}$	mass flow rate, kg/s
ΔP	pressure drop, Pa
Pr	Prandtl number
Q	heat transfer rate, W
R	gas constant, J/mol K
Re	Reynolds number
RPM	Revolutions per Minute
SFC	Specific Fuel Consumption, g/kWh
SEC	Specific Energy Consumption, MJ/kWh
T	temperature, K
TDC	top dead center
U	mean air velocity, m/s
ρ	fluid density, kg/m^3
ν	kinematic viscosity, m^2/s
Y	accuracy criterion

Subscripts

1	inlet
a	air
f	fuel
inj	injection
o	outlet
w	wall

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