Study of the air, water, and fuel flow measurement parameters for internal combustion engine test benches

Fernando Pavie Frejat
Universidade de Brasilia (UNB), Brasil
Applus IDIADA, Brasil

Fábio Cordeiro de Lisboa
Universidade de Brasilia (UNB), Brasil

ABSTRACT

Vehicle exhaust emissions reduction remains a global challenge. Fossil fuels significantly contribute to carbon dioxide emissions. The Biogas Project, part of the Rota 2030 Program, aims to replace ethanol, the current fuel in Volkswagen's EA 211 1.0L MPI engine, with biomethane. Understanding the engine's parameters is essential to optimize performance and efficiency based on test bench results to enable this transition. First, the engine was installed on the bench and adapted to use NGV (Natural Gas Vehicle) as an alternative fuel. The parameters studied included airflow, liquid and gaseous fuel, and coolant flow. The airflow measurement system was implemented and calibrated using a pulse damper box, orifice plate, differential pressure gauge, and constant flow apparatus. Gravimetric measurement determined ethanol flow, while gaseous fuel flow data came from the injection software. Coolant flow was calculated based on the engine's water pump performance. During testing, FuelTech, an ECU in the laboratory, collected data from air pressure and temperature sensors, along with fuel flow and air-fuel ratio readings. After collecting the results, the experimentally calculated values were compared to the ECU data, and the standard deviation was analyzed to evaluate accuracy.

THEORETICAL BACKGROUND

Understanding the principles of flow dynamics, fuel delivery, and measurement systems is essential for implementing reliable instrumentation in internal combustion engines. This section outlines the theoretical basis used to design and validate the airflow, fuel, and coolant flow measurement systems adopted in this work.

In engine applications, turbulent flow is predominant due to high velocities and small conduit dimensions. The flow regime is defined by the Reynolds number:

$$Re = \frac{\rho u D}{\mu} \quad (1)$$

where ρ is the fluid density, u is the average velocity, D is the hydraulic diameter, and μ is the dynamic viscosity. For $Re > 2400$, the flow is generally considered turbulent [5][11].

Pressure losses in turbulent internal flow are caused by friction and local disturbances such as bends, valves, and contractions. The total head loss is expressed as:

$$h_L = f\frac{L}{D}\frac{V^2}{2g} + K_L\frac{V^2}{2g} \quad (2)$$

where f is the Darcy friction factor, L is the pipe length, and K_L is the local loss coefficient [1][9].

To measure flow under such conditions, differential pressure devices are commonly used. These include orifice plates, Venturi tubes, and nozzles. The flow rate through a restriction is determined using Bernoulli's equation combined with the continuity principle:

$$\dot{m}_{theo} = C_D A_2 \sqrt{\frac{2\rho(p_1 - p_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}} \quad (3)$$

$$\dot{m}_{air} = C_D \cdot \dot{m}_{air\ theo}$$

where $\dot{m}$ is the mass flow rate, C_D is the discharge coefficient, A_1 and A_2 are the upstream and throat areas, and $p_1 - p_2$ is the pressure drop across the restriction [5][8][10].

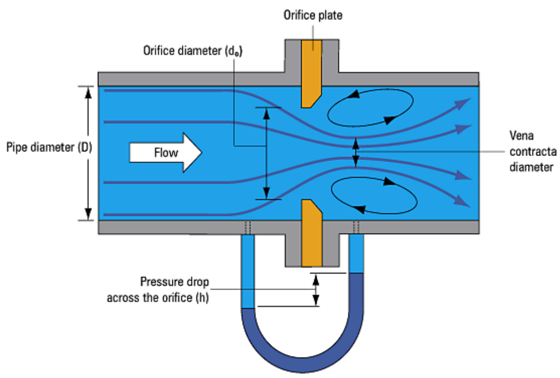

Figure 1 – Orifice plate. Adapted from Mohamed, Mansour and Dekam [8]

The air-fuel ratio (AFR), or equivalence ratio λ, is a critical parameter in engine operation. It is defined by:

$$\lambda = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} \cdot \frac{1}{(AFR_{stoich})} \quad (4)$$

Typical stoichiometric AFR values are approximately 14.7 for gasoline, 9.0 for ethanol, and 17.2 for GNV [2][3].

Modern engines rely on electronic control units (ECUs) to manage injection and ignition. The FuelTech FT550 ECU used in this work receives input from sensors including MAP, IAT, TPS, coolant temperature, and lambda probe. It uses this data to adjust injection timing and duration, ensuring adequate fuel delivery and allowing precise measurement of key variables [2][3][12].

The properties of the fuels tested influence their measurement and combustion behavior:

- Ethanol: lower energy density and higher latent heat of vaporization.
- GNV: gaseous, compressible, and requires injection control adapted to pressure and temperature.
- Biomethane: similar to GNV, renewable and often blended in sustainable energy applications [4][7].

These fundamentals establish the justification for the flow measurement systems implemented in this study.

METHODOLOGY

The experimental procedures were carried out on a Volkswagen EA211 1.0 MPI engine mounted on a static test bench. Here it’s main parameters.

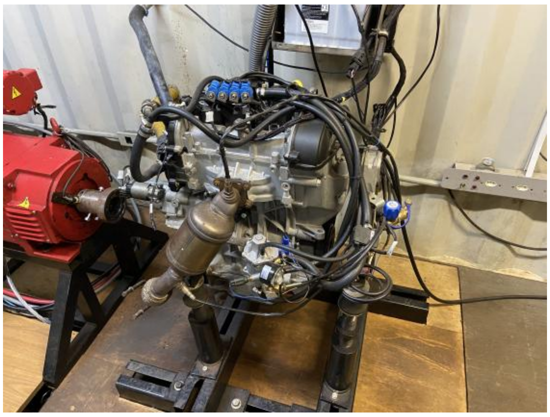

Figure 2 – Volkswagen EA211 1.0 MPI engine on the test bench

Table 1 – Technical specifications of the engine under study

Parameter	EA211 1.0 MPI VW
Design	3 cylinders in line
Total displacement volume	999 cm³
Cylinder diameter	7.45 cm
Stroke	7.64 cm
Valves per cylinder	4
Compression ratio	11.5:1
Maximum power	55 kW [G] / 60 kW [A] at 6200 RPM
Maximum torque	95 Nm / 102 Nm from 3000 to 4300 RPM
Original fuel system	Bi-fuel (gasoline and ethanol)

A programmable ECU (FuelTech FT550) was used for engine management and data acquisition. The goal was to validate air, fuel, and coolant flow measurements across six RPM points: 1130, 2000, 3000, 4000, 5000, and 6000 RPM under no-load conditions.

Instrumentation – The system included:

- Wideband lambda sensor (Bosch LSU 4.9)
- MAP sensor
- TPS (Throttle Position Sensor)
- Intake Air Temperature (IAT) sensor
- Coolant temperature sensors (inlet and outlet)
- GNV system with STAG 200 GoFast ECU [12]

The FT550 ECU enabled monitoring of RPM, injector duty cycle, AFR, and other parameters in real time [3]. Calibration curves and sensor parameters were configured using FT Manager software.

Airflow Measurement – An orifice plate was installed in a straight section upstream of the intake manifold. The pressure drop across the plate was measured using a U-tube manometer and a digital sensor.

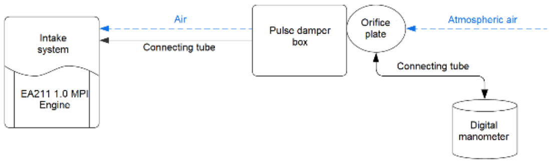

Figure 2 – Schematic layout for measuring air consumption for the engine. Adapted from Brunetti [2]

Calibration was conducted using a known airflow source (vacuum cleaner) and a handheld anemometer, allowing for determination of the discharge coefficient C_D under steady conditions [8][10].

The following equation shows the air flow, using volume V [m^3], engine rotations n [RPM], air density ρ [kg/m^3], environment temperature T [K], universal gas constant R = 0,287 [kJ/kg.K] and engine volumetric efficiency η_v.

$$\dot{m}_{air} = \frac{\rho \cdot V \cdot n}{R \cdot T} \cdot \frac{\eta_v}{2} \quad (5)$$

Fuel Flow Measurement – Ethanol flow was measured gravimetrically. A precision scale (Toledo 9094C) recorded the mass of the fuel tank before and after each 60-second run:

$$\dot{m}_{ethanol} = \frac{\Delta_m}{\Delta_t} \quad (6)$$

Measured values were compared to ECU estimates based on injector duty cycle and AFR [2][3].

For GNV, the STAG GoFast ECU monitored injection pulse width and MAP/IAT readings to calculate delivered fuel. Lambda values were logged and used to estimate the combustion mixture [4][12]. Because the fuel is gaseous, direct flow metering was not applied.

Coolant Flow Estimation – Coolant flow was not measured directly but estimated analytically using the water pump flow equation:

$$\dot{V}_{\omega} = \frac{632 \cdot N_e \cdot fs}{\Delta T} \quad (7)$$

Where radiator temperature drop is T [ºC], effective engine power N_e [cv], security factor fs = 1,05% and water flow $\dot{V}_w$ [L/min].

RESULTS

The flow measurement systems were tested across six RPM points for ethanol and GNV. Data from the orifice plate, gravimetric scale, and ECUs were analyzed and compared.

Table 2 – Data used for ethanol fuel flow calculation

Variable	Value
Engine displacement	0.000999 m³
Injector flow rate	0.0065 kg/s
Ethanol density	811 kg/m³
Number of injectors	3
Stoichiometric air-fuel	9
Universal gas constant (R)	0.287 kJ/kg·K
Ethanol LHV	7 kWh/kg

After system is calibrated and ready to test, these were the parameters observed.

Table 3 – Equation variables for mass air flow, discharge coefficients and their values

Variable	Value
T_{amb}	27 ± 0.05 °C
p_m	102 kPa
ρ_{air}	1.2929 kg/m³
p_{local}	8.0 ± 0.05 Pa
D_s	0.0889 ± 10^{-3} m
D_T	0.0445 ± 10^{-5} m
D_a	0.032 ± 10^{-5} m
v_u	12.58 ± 10^{-3} m/s
v_{boost}	3.542 ± 15^{-3} m/s
v_{air}	41 ± 0.5 m/s
A_l	$6.21\times10^{-4} \pm 10^{-6}$ m^2
A_s	$1.556\times10^{-4} \pm 10^{-6}$ m^2
A_a	$8.06\times10^{-5} \pm 10^{-6}$ m^2
A_T	$1.55\times10^{-4} \pm 10^{-6}$ m^2
$\dot{m}_{air}$	0.025 ± 10^{-4} kg/s
$\dot{m}_f$	0.028 ± 10^{-4} kg/s
$C_{D,plate}$	0.595 ± 10^{-4}
$C_{D,local}$	0.667 ± 10^{-4}

Airflow Results – Measured airflow using the orifice plate method showed strong agreement with the theoretical values calculated by the ECU using the speed-density model. The deviation remained below 5% across most RPM ranges [5][8].

The equation used was shown by Brunetti [2] shows orifice plate area A_P [m^2], plate discharge coefficient C_{DP}, air density ρ_a [kg/m^3] and orifice plate pressure read by manometer p_2 [Pa]:

$$\dot{m}_{air} = C_{D_P} \cdot A_P \cdot \sqrt{-2 \cdot \rho_a \cdot p_2} \quad (8)$$

From this experiment, the result was on Table 4.

Table 4 – Data obtained for air mass flow from the test

RPM	CD	Orifice Area (m²)	Air Density	Avg. Pressure	Air Flow (kg/s)
1130	0.595	0.00155179	1.205	-1.3	0.001735629
2000	0.595	0.00155179	1.21	-6.5	0.003661218
3000	0.595	0.00155179	1.209	-20.5	0.007391128
4000	0.595	0.00155179	1.208	-36.5	0.009628083
5000	0.595	0.00155179	1.208	-63.0	0.011839899
6000	0.595	0.00155179	1.207	-128.0	0.016228816

The result given by FuelTech using lambda sensor was calculated using the following formula:

$$\dot{m}_{air} = AF_{stoich} \cdot \lambda_{FT} \cdot \dot{m}_{fuel} \quad (9)$$

Table 5 – Data obtained from FuelTech airflow readings from the test

RPM	λ_s	Lambda FuelTech	Fuel Flow (kg/s)	Air Flow – FuelTech
1130.0	9.0	1.002	0.000192026	0.001731691
2000.0	9.0	1.008	0.000358428	0.003401157
3000.0	9.0	1.009	0.000763933	0.007029983
4000.0	9.0	0.994	0.001069344	0.009705928
5000.0	9.0	0.977	0.001252121	0.01149509
6000.0	9.0	0.977	0.001759344	0.015469913

Fuel Flow Results – For ethanol, gravimetric results aligned well with ECU estimations. At 3000 and 4000 RPM, slight deviations (up to 10%) were noted, likely due to transient effects or sensor delay [2][3].

Table 6 – Data obtained for fuel flow from the test

Initial Mass (kg)	Final Mass (kg)	Difference (kg)	Real Time (s)	Fuel Flow (kg/s)
9.025	9.01	0.015	78.0	0.00019
9.68	9.645	0.035	86.0	0.00041
9.61	9.555	0.055	67.0	0.00082
9.52	9.45	0.07	69.0	0.00101
9.4	9.3	0.1	78.0	0.00128
9.26	9.11	0.15	80.0	0.00188

Table 7 – Data obtained from air-fuel ratio and stoichiometric ratio

RPM	Air Flow (kg/s)	Fuel Flow (kg/s)	λ	λ_e	λ_r
1130.0	0.001735629	0.00019	9.129	9.0	1.014
2000.0	0.00366178	0.00041	8.998	9.0	1.0
3000.0	0.007391128	0.00082	9.012	9.0	1.001
4000.0	0.008670283	0.00101	8.588	9.0	0.954
5000.0	0.011839869	0.00128	8.884	9.0	0.987
6000.0	0.016228816	0.00188	8.653	9.0	0.962

Figure 3 – Graph of friction power and bsfc by engine speeds operating without load

For GNV, lambda readings at lower RPMs (1130–3000) showed instability, indicating inconsistent air-fuel mixture control. At higher speeds (4000–6000 RPM), lambda stabilized around 0.85, suggesting rich but controlled combustion [4][6][12].

Coolant Flow Results – Using the engine effective power (82cv), the mass flow of coolant was calculated for 89ºC. The results were 6,11 L/min of water flow for a naturally aspirated 1.0L engine operating under no-load conditions [1][9].

The consistency between experimental and ECU data validates the proposed measurement systems for use in academic and applied engine research [5][6].

Table 8 – Comparison between air flow obtained experimentally and at FuelTech

RPM	Air Flow FuelTech (kg/s)	Real Air Flow (kg/s)	Deviation (%)
1130	0.001731691	0.001735629	1%
2000	0.003491157	0.00366178	5%
3000	0.007029983	0.007391128	3%
4000	0.009705523	0.008670283	6%
5000	0.010754902	0.011839869	5%
6000	0.015469913	0.016228816	5%

Table 9 – Comparison between ethanol flow obtained experimentally and at FuelTech

RPM	Fuel Flow FuelTech (kg/s)	Real Fuel Flow (kg/s)	Deviation (%)
1130	0.000192026	0.000192038	0%
2000	0.00038428	0.000409677	5%
3000	0.000793303	0.001014493	22%
4000	0.001069344	0.001282051	17%
5000	0.001232121	0.001282051	5%
6000	0.001753344	0.001875	6%

CONCLUSION

This study presented the implementation and validation of low-cost, effective systems for measuring airflow, fuel flow, and coolant flow in a spark-ignition internal combustion engine. The experimental setup was designed using a Volkswagen EA211 1.0 MPI engine equipped with a programmable ECU, and tests were conducted under controlled, no-load conditions across six engine speeds using ethanol and natural gas (GNV) as fuels.

The orifice-based airflow measurement system demonstrated consistent results, with deviations under 5% compared to the ECU's theoretical values, confirming its suitability for academic and research applications. The gravimetric method applied for ethanol flow yielded reliable measurements, with deviations averaging 6.8%. For GNV, the ECU-based approach provided valid results at medium and high engine speeds, although low-speed instability in lambda readings highlighted the need for improved mixture control in gaseous injection systems. Coolant flow was estimated analytically using water pump.

The results confirmed the viability of the proposed measurement methods in educational and development environments. The systems proved to be affordable, replicable, and sufficiently accurate for characterizing engine behavior under different fuel conditions.

REFERENCES

[1] BIRD, R. B.; STEWART, W. E.; LIGHTFOOT, E. N. Fenômenos de Transporte. [S.l.]: LTC, 2004. ISBN 8521613938.

[2] BRUNETTI, F. Motores de Combustão Interna. [S.l.]: Editora Blucher, 2012. v. 1. ISBN 9788521207085.

[3] BRUNETTI, F. Motores de Combustão Interna. Editora Blucher, 2012. v. 2. ISBN 9788521212942. Disponível em: https://books.google.com.br/books?id=CQm2DwAAQBAJ.

[4] FAN, B. et al. Computational study of hydrogen injection strategy on the combustion performance of a direct injection rotary engine fueled with natural gas/hydrogen blends. Fuel, v. 328, p. 125190, 2022. ISSN 0016-2361. Disponível em: https://www.sciencedirect.com/science/article/pii/S0016236122020294.

[5] FOX, R.; MCDONALD, A.; PRITCHARD, P. Introdução à mecânica dos fluidos. LTC, 2014. ISBN 9788521614685.

[6] GARCIA, M. P. R. Estudo de desempenho de motor três cilindros alimentado com GNV como combustível. 118 f. Bacharelado — Universidade de Brasília, Brasília, 2022.

[7] KUKOYI, T. O. et al. Biogas use as fuel in spark ignition engines. In: 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). [S.l.: s.n.], 2016. p. 1064–1069.

[8] MOHAMED, S.; MANSOUR, M.; DEKAM, E. A 5-30 kg/s orifice plate cooling water flow meter design. mar. 2017.

[9] MORAN, M.; SHAPIRO, N. Introdução à engenharia de sistemas térmicos: termodinâmica, mecânica dos fluidos e transferência de calor. Livros Técnicos e Científicos, 2005.

[10] OLIVEIRA, S. et al. Determinação do coeficiente de descarga para orifícios de parede delgada considerando números de Reynolds reduzidos. Revista DAE, v. 67, p. 24–34, abr. 2018.

[11] POPE, S. B. Turbulent flows. Cambridge: Cambridge Univ. Press, 2011. Disponível em: https://cds.cern.ch/record/1346971.

[12] STAG, A. S. Connection and programming manual for STAG 200 GoFast controller. Poland: [s.n.], 2021. v. 1.7. Disponível em: https://www.ac.com.pl.